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Accretion and Water-Levels in Enclosed, Seepage Lagoons: Examples from Nova Scotia

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ABSTRACT

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Lithostratigraphic and biostratigraphic examination of lagoonal sequences in close proximity to an enclosing gravel ridge, has shown a linkage between lagoon accretionary characteristics and the developmental domain (growth, consolidation, breakdown and reformation) of the gravel barrier. Seepage lagoon water-level rise has occurred on instantaneous time-scales following barrier inlet closure, whereas lagoon accretion has developed over time-scales of 10^1–10^2 years. Despite this lag, lagoon stratigraphies have accreted more rapidly than relative sea-level (RSL) rise. Switching of lagoons between enclosed seepage and tidal states, as a result of barrier dynamics, has an important control on lagoon accretion, and further renders the use of the resultant stratigraphies for sea-level interpretation difficult.

ADDITIONAL INDEX WORDS: *Sea-level, pollen, salt marsh, gravel barriers.*

INTRODUCTION AND AIMS

The examination of salt marsh and mudlfat stratigraphies is a standard technique for the reconstruction of changes in relative sea-level (RSL) and in shoreline position. An important consideration arises when the marsh/mudflat system switches between two states; one, an open estuarine or tidal marsh domain, with a free tidal exchange of water and sediment; and two, an enclosed lagoonal domain whereby tidal exchange is limited to seepage through an enclosing barrier (CARTER *et al.,* 1984) so that sediment input is restricted either to fluvial sources, overwash processes or is eliminated altogether.

Precise definition of coastal lagoons is difficult (CARTER, 1988; COOPER, 1994). BIRD (1982) distinguishes between "open" and "tidal" lagoons according to the ratio of barrier length to channel size connecting the lagoon to the sea, although a measure of water exchange (*i.e.* the tidal prism) compared to channel cross-sectional area may more accurately differentiate these two lagoon types. There is a gradation of lagoon type from seepage lagoons (both freshwater and brackish) to those with ephemeral and stable channels (CARTER, 1988; CARTER *et al.,* 1989), which may be further subdivided according to whether the channel acts as an outlet or as an inlet. CARTER and ORFORD (1984) and CARTER *et al.* (1984) recognised the importance of barrier texture as a control on the type of lagoon formed, with seepage lagoons preferentially located behind coarse clastic (*i.e.* gravel dominated) barriers, while tidal lagoons with inlet channels are usually associated with fine clastic (*i.e.* sand dominated) barriers.

This paper aims to explore the relationship between RSL rise and enclosed, seepage lagoon water-level change and accretionary characteristics, with reference to three sites on the Eastern Shore of Nova Scotia, where late-Holocene RSL has risen at rates of between 2.0 mm/a to 3.0 mm/a (SCOTT *et al.,* 1987; SHAW and FORBES, 1990; SHAW *et al.,* 1993), and is rising presently by between 3.8 mm/a to 4.31 ± 0.97 mm/a according to tide gauge records (CARRERA *et al.,* 1990; ORFORD *et al.,* 1992). This rapid RSL rise may be forcing rapid responses within the coastal system, particularly the release of sediment from drumlin headlands by wave action, with the finer fraction (silts and clays) transported into estuaries and tidal lagoons in volumes sufficient to produce regressive stratigraphies despite RSL rise (JENNINGS *et al.,* 1993); and the retreat of gravel barrier beaches that have become susceptible to overwashing processes, resulting in gravel barrier rollover (ORFORD *et al.,* 1991). However, the response of gravel barriers along the Eastern Shore to RSL rise and to sediment supply variations is spatially variable, so that examples of prograding, stable and rollover barriers can be found, often in close proximity to one another (FORBES *et al.,* 1990; ORFORD *et al.,* 1991). Under rapid RSL rise, gravel barriers may be initiated, established and may breakdown, which can simultaneously force the formation and destruction of adjoining lagoons (CARTER *et al.,* 1989). This link between the development of gravel barriers and that of adjoining lagoons will be examined in this paper.

The lagoons discussed below are enclosed from the sea by

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gravel barriers, and have an insignificant fluvial input, although seasonal snow melt and run off may periodically alter lagoon water levels.

TECHNIQUES AND METHODOLOGY

The lagoons were cored by gouge auger and vibracore to determine their lithostratigraphies and to obtain samples for pollen analysis and radiocarbon dating.

The sites chosen for coring were located close to the barrier in order to examine barrier-lagoon linkage in terms of facies changes and their associated biostratigraphies. It was not the intention of the coring to establish lagoon-wide stratigraphies, but to focus on palaeoenvironmetal changes within the immediate back-barrier area of the lagoon. These changes have been examined principally by the analysis of fossil pollen and spores (and by the frequencies of Hystrichospheres, which are diagnostic of mudflats and tidal channels). Fossil pollen assemblages can reveal shifts between reedswamp, salt marsh and mudflats within estuarine and lagoonal environments (JENNINGS *et al.*, 1993). Although perhaps lacking the detailed resolution of environmental change achievable with Foraminifera (*e.g.* SCOTT *et al.*, 1980) and diatoms (*e.g.* PALMER and ABBOTT, 1986), nevertheless assemblages of pollen and spores permit a reconstruction of the vegetation surrounding the core-site, provided that the complexities of pollen provenance are appreciated (JENNINGS *et al.*, 1993). Although some pollen types provide only a general indication of (palaeo)environments (*e.g.* Chenopodiaceae pollen that may originate from vegetation growing on low and high marsh areas), the relative importance of salt marsh aquatics (*e.g. Ruppia*) may allow more diagnostic environmental inferences to be made. This is discussed below in relation to the sites investigated, and in JENNINGS *et al.* (1993).

RESULTS AND DISCUSSION

Seaforth–Cape Antrim (Chezzetcook Inlet)

A series of cores was taken along the lagoon margin of a barrier beach in the Seaforth–Cape Antrim area. The lagoons in this area originated from a channel that was a former extension of Chezzetcook Inlet, which has become truncated by rapid, landward migration of the gravel barrier against drumlins (Figure 1). This landward movement of the barrier follows the breakdown of an earlier structure to seaward, and the subsequent reforming of the barrier (CARTER and ORFORD, 1993). Air photographic evidence covering the last 60 years illustrates substantial gravel barrier transgression which, by 1973, had resulted in the formation of a seepage lagoon behind the gravel barrier in the Seaforth area. Subsequent organic accumulation upon washover sediment emplaced around 1945 divided this original lagoon into two (numbers 1 and 2 in Figure 1). This barrier rollover also resulted in the formation of the larger enclosed lagoon behind a sand barrier (lagoon 3), which is often cut artificially to control water levels. The tidal lagoon adjacent to Cape Antrim (lagoon 4 and the location of boreholes 3 and 4) is connected to Chezzetcook Inlet via a narrow channel further up the estuary.

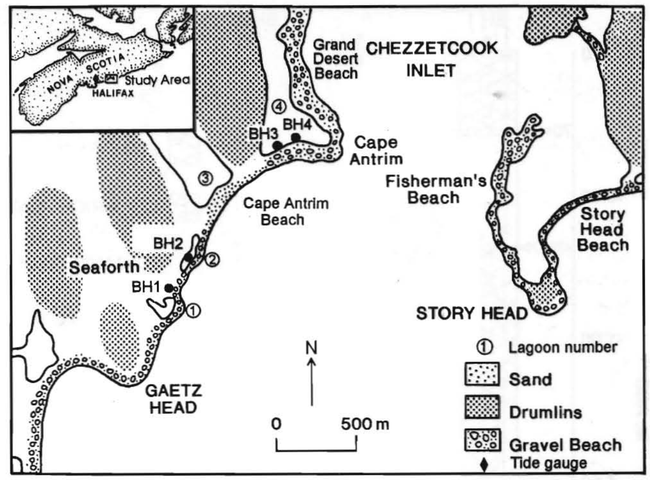

Figure 1. Seaforth–Cape Antrim (Chezzetcook Inlet) showing the location of the lagoons and boreholes. SCOTT (1980, Figures 14.2 and 14.5) illustrates the position of this shoreline in 1974 and 1945, from air photographic evidence.

The lithostratigraphy of the boreholes is described in detail in CARTER *et al.* (1992) and in JENNINGS *et al.* (1993), and is illustrated in Figure 2. The stratigraphy of BH2 (within lagoon 2) covers approximately the last 2,000 years and registers the onset of tidal channel and mudflat conditions at 1,840 ± 150 ^{14}C years BP (Beta-28288; cal. BC 199–AD 540 (2σ)). The pollen record, which is presented in JENNINGS *et al.* (1993), depicts a succession from Chenopodiaceae to *Ruppia* within the upper 0.2 m of sediment, marking a transition from high marsh and open estuarine conditions to a tidal lagoon. The continuing, but diminished presence of Hystrichospheres in this sequence confirms the maintenance of tidal conditions. The establishment of the present enclosed, seepage lagoon, around AD 1973, is not recorded in the stratigraphy examined, which is probably due to a combination of rapid (instantaneous) water-level rise following barrier closure and a much slower sedimentation rate within the lagoon. Mean water depth at BH2 was approximately 0.5 m in 1988, with the site submerged permanently.

BH1, located approximately 200 m from BH2, lies in reedswamp between lagoons 1 and 2. As noted above, this reedswamp has developed on a buried washover fan which currently separates the two lagoons. Prior to the overwash event, the environment was one of tidal channels and flats with low salt marsh (JENNINGS *et al.*, 1993). Therefore, despite their close proximity, the site of BH1 has emerged while that of BH2 has submerged as a consequence of the recent barrier migration and formation of enclosed, seepage lagoons. Boreholes 3 and 4 comprise fining and coarsening sequences, probably of flood-tidal depositionary origin (CARTER *et al.*, 1992).

The stratigraphy from the four cores illustrates the considerable facies variation within the length of this former inlet, from flood tidal delta deposits to mudflat, salt marsh and

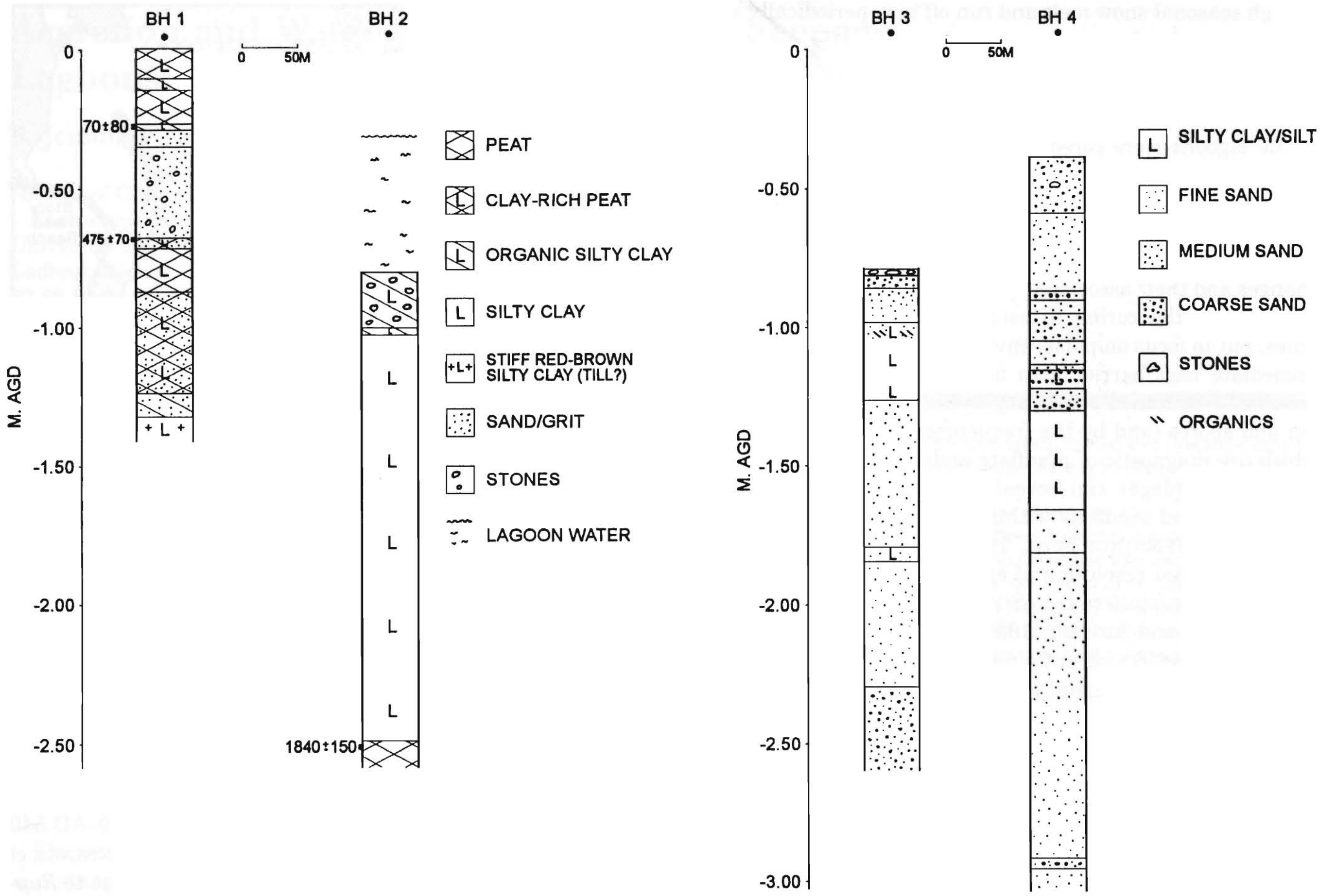

Figure 2. The lithostratigraphy of Seaforth–Cape Antrim boreholes.

reedswamp environments. The entire sequence is being rolled-over by a gravel and sand barrier beach.

Oyster Pond

Oyster Pond, located approximately 12 km east of Chezzetcook Inlet, is an enclosed lagoon behind the swash-aligned portion of a gravel barrier, although there is tidal exchange over a rock step which connects the pond to Musquodoboit Harbour (Figure 3). Much of the immediate back-barrier area of the lagoon contains at least a 2 m depth of sand, but in the south east corner an interbedded organic and minerogenic sequence was recovered, using initially a gouge auger, from which pollen samples were taken, and subsequently a vibracore to take ^{14}C samples (Figure 4). There was approximately 0.5 m of water depth over the core site in 1990. The interbedded organic and minerogenic sequence was traced across the south east corner of Oyster Pond, using a gouge auger (Figure 5). This sequence is located at the junction of the drift-aligned with the swash-aligned sections of the gravel barrier, a zone which is often a weak-point in a barrier's longshore and cross-shore profile (CARTER *et al.,* 1992), susceptible to overwash and breaching. It is probable that the cored sequence represents deposition associated with a former inlet, at this weak point.

The summary pollen diagram (Figure 4) shows the presence of aquatics (*e.g. Ruppia*) virtually throughout the entire sequence which covers in excess of the last 700 ^{14}C years. The Hystrichospheres, which are usually diagnostic of tidal channels and mudflats, peak firstly, in the sand/grit layers, which may have been formed as a result of ephemeral openings in the barrier, thereby creating brief periods of tidal lagoon conditions; and secondly, at the top of the sequence (within local pollen assemblage zone 5) which, as a consequence of RSL rise, probably records the onset of tidal exchange over the rock step which links the lagoon to Musquodoboit Harbour. The data suggest that during the period covered by the pollen record, the marsh/mudflat was submerged, although the expansion of Gramineae pollen frequencies towards the top of the sequence indicates a shallowing of the water depth.

The data presented in Table 1 indicate a conservative estimate of lagoon accretion rates outpacing RSL rise by 1.1 to 2.3 times over the period covered by the two ^{14}C dates. However, because the two sigma error range of the radiocarbon chronology was used in the calculation, the accretion rates

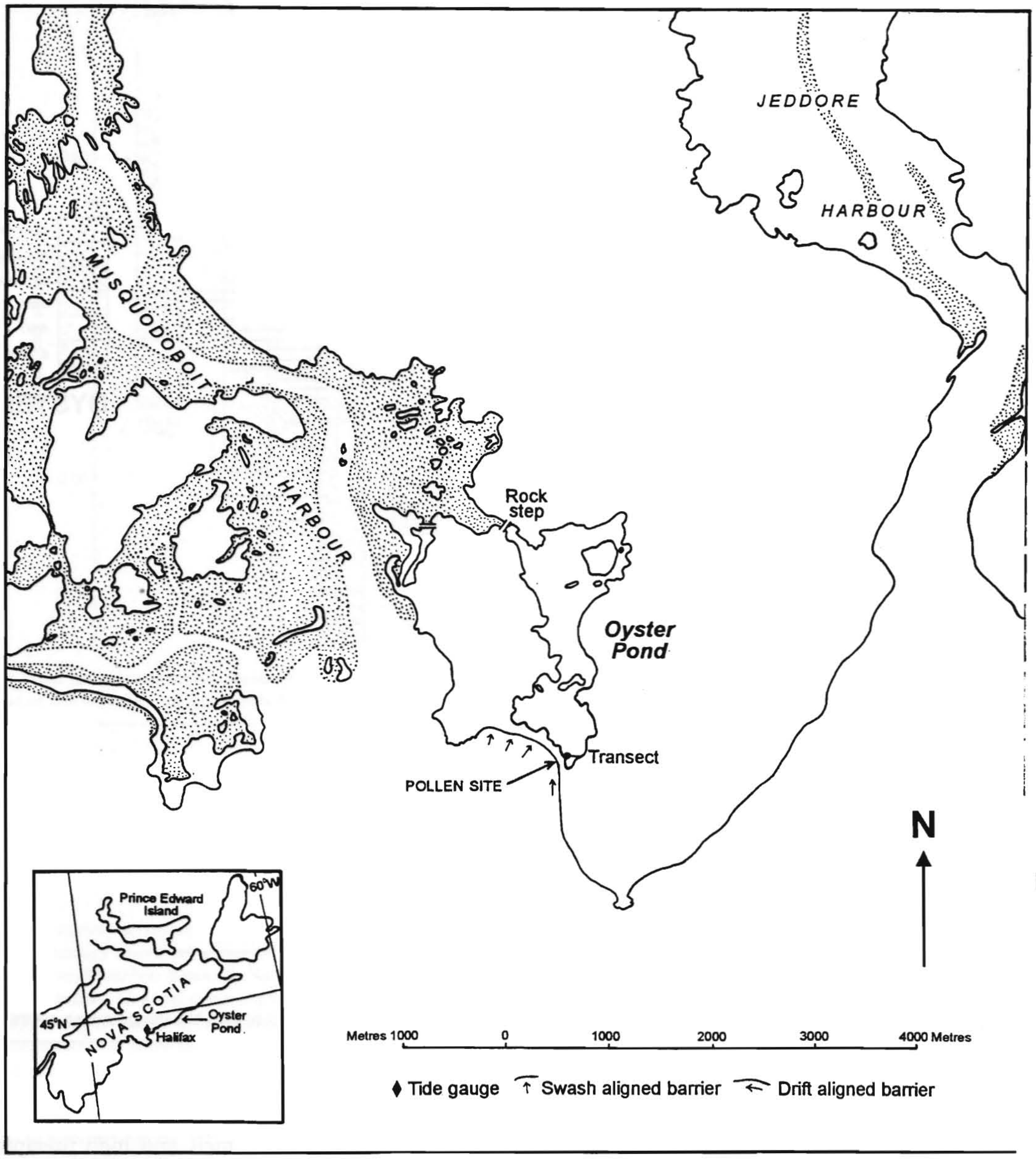

Figure 3. Oyster Pond showing the location of the pollen site and the lithostratigraphic transect.

have almost certainly been underestimated. It should be noted that the radiocarbon dates overlap (using 2σ error range), which indicates that accretion may have been rapid within Oyster Pond, at least over the period covered by the dated samples. Additionally, the lower figure is certainly an underestimate caused by compaction of the sediments in the vibracore. Lagoon water-level rise was probably instantaneous as the lagoon switched from tidal to enclosed, although the water level attained was ultimately controlled by the rock step, and more recently by the construction of sluice gates which form part of the causeway that links the islands within the southern part of Oyster Pond.

Ragged Head

The site at Ragged Head is illustrated in Figure 6. A radiocarbon date from the base of a 2 m organic sequence which has built up behind the most landward beach ridge to the north east of Ragged Head (Figure 6) indicates that the Ragged Head barrier system has been developing for at least 1,500 ^{14}C years. A small and ephemeral channel has been cut by local fishermen, linking the lagoon to Chedabucto Bay. The stratigraphy of the site investigated, located on the lagoonal margin of the prograded part of the barrier, comprises a shallow sequence (0.35 m) of organic layers interbedded

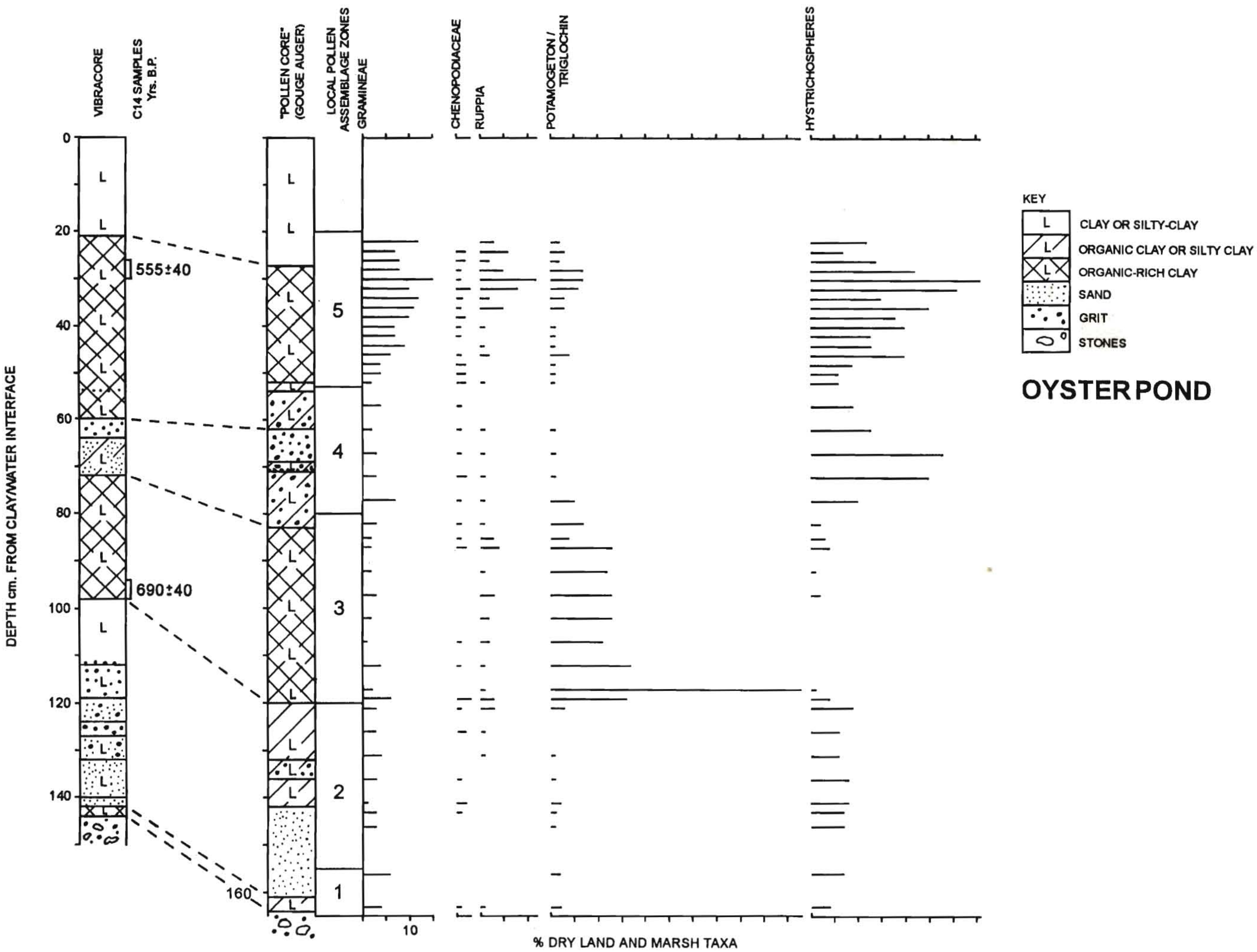

Figure 4. Oyster Pond summary pollen diagram with the lithostratigraphy constructed from the vibracore and the gouge auger coring.

with sandy-gravel. The buried gravel layers probably represent small berms formed by waves generated within the lagoon; they are not washover features. The two ^{14}C dates suggest that the sequence has formed over approximately the last 40 years. The two main organic layers have distinct pollen records (Figure 7); the lower layer representing a more terrestrial habitat, while the upper layer, with an increase in the frequencies of Chenopodiaceae and *Plantago maritima* pollen, representing succession to high salt marsh. The present-day vegetation is dominated by *Spartina* sp. with Chenopodiaceae, *Scirpus* sp. and *Plantago maritima*.

The stratigraphy implies that the lagoon water-level rise outpaced local accretion, but did not result in submergence. The absence of Hystrichospheres signifies that there were no tidal channels, and therefore the maintenance of an enclosed, seepage lagoon. There are two possible interpretations for this sequence. First, that the lagoon water-level has risen incrementally over the last 40 years, outpacing RSL rise (see below). However, it is not clear what the mechanism for this rise would be. Seasonal oscillations in water level are explicable in terms of snow melt and high precipitation events, but these would not necessarily cause a longer term (>40 years) rise. Second, that the stratigraphy is recording a *relative* water-level rise along the lagoon margin of the barrier due to compaction of the organic beds by the gravel layers.

The nearest tide gauge, at Point Tupper, where the data begin in 1971, recorded one of the fastest rates of RSL rise in Atlantic Canada; 4.31 ± 0.79 mm/a (CARRERA *et al.*, 1990). The stratigraphic data from Ragged Head demonstrate a (relative) lagoon water-level rise of at least 0.33 m over approximately the last 40 years which is the equivalent of 8 mm/a, around twice the RSL rate.

Barrier-Lagoon Linkage

The three seepage lagoons examined in this paper have formed in association with a variety of gravel barrier types; prograding barriers (Ragged Head), stationary, single ridged

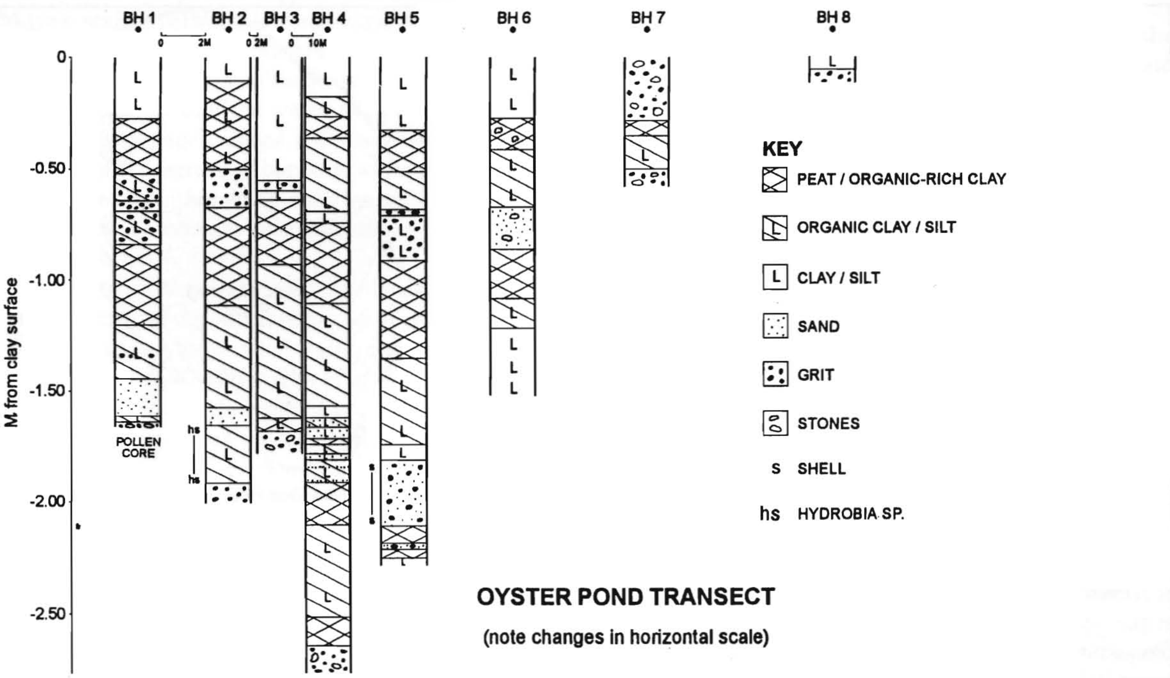

Figure 5. Oyster Pond lithostratigraphic transect. The location of the transect is shown on Figure 3. The very soft nature of the surface prevented any accurate surveying of the elevation of the boreholes.

Table 1. *Oyster Pond lagoon accretion rates compared to RSL rise. As a consequence of the chronology employed, using the extremes of the two sigma error bands on the radiocarbon dates, the lagoon accretion rates estimates are conservative values. General compaction of the sediments is not allowed for, but differences between the vibracore and gouge auger depths are probably the consequence of differential compaction between these two coring techniques.*

Chronology:
(1). C^{14} age: 550 ± 40 BP (SRR-4847)
Calibrated age (2σ): 651–518 BP
(2). C^{14} age: 690 ± 40 BP (SRR-4848)
Calibrated age (2σ): 691–560 BP

Vibracore sequence:
0.72 m maximum depth difference between radiocarbon samples
173 calibrated years maximum time difference between radiocarbon samples (2σ)
Pollen core sequence (gouge auger):
0.93 m maximum depth difference between radiocarbon samples (equivalent stratigraphic level)
Time difference as for vibracore

Sea level:
Late-Holocene average rise: 2.3 mm/a (SHAW and FORBES, 1990)

Halifax tide gauge record (last 70 years mean): 3.8 mm/a (ORFORD et al. 1992)

Lagoon accretion rate compared to RSL rise:
Vibracore sequence: 1.1 to 1.8 × faster
Pollen core sequence (gouge auger): 1.4 to 2.3 × faster

barriers (Oyster Pond) and transgressive barriers (Seaforth–Cape Antrim). All three of the barriers and their lagoons are extant, which removes the problem of reconstructing barrier and lagoon palaeoenvironments from solely Holocene stratigraphic data. There is a substantial difference in the age of these features, ranging from approximately 20 years at Seaforth to at least approximately 700 years at Oyster Pond and around 1,500 years at Ragged Head. This age difference is a reflection of the stage that the enclosing barrier has reached in its development. ORFORD *et al.* (1991) recognised three stages in the development of gravel barriers; initiation, establishment and breakdown. This sequential development is driven by the passage of an 'erosional front' advancing landward through the coastal zone, causing the release and redistribution of sediment within its bounds (ORFORD *et al.,* 1991, Fig. 5b). This concept was developed further in ORFORD *et al.* (in press). Four distinct domains of barrier development were recognised; 'growth', 'consolidation', 'breakdown' and 'reformation'. At Seaforth, the site with the youngest lagoons, the barrier has passed through the 'breakdown domain' and has reformed 80 to 300 m landward of its former position (CARTER and ORFORD, 1993). This reformed barrier is itself transgressing landward (via rollover) and forcing the rapid development, and ultimately the demise, of seepage lagoons 1 and 2 (Figure 1). Since this domain in a barrier's development is associated with the dominance of overwashing processes relative to overtopping processes (ORFORD *et al.,* 1991, 1995a,b), washover deposits form an important contribution to the sediment budget of the seepage lagoon (*e.g.* BH1 at Seaforth). Therefore, seepage lagoons associated with this type of barrier will be ephem-

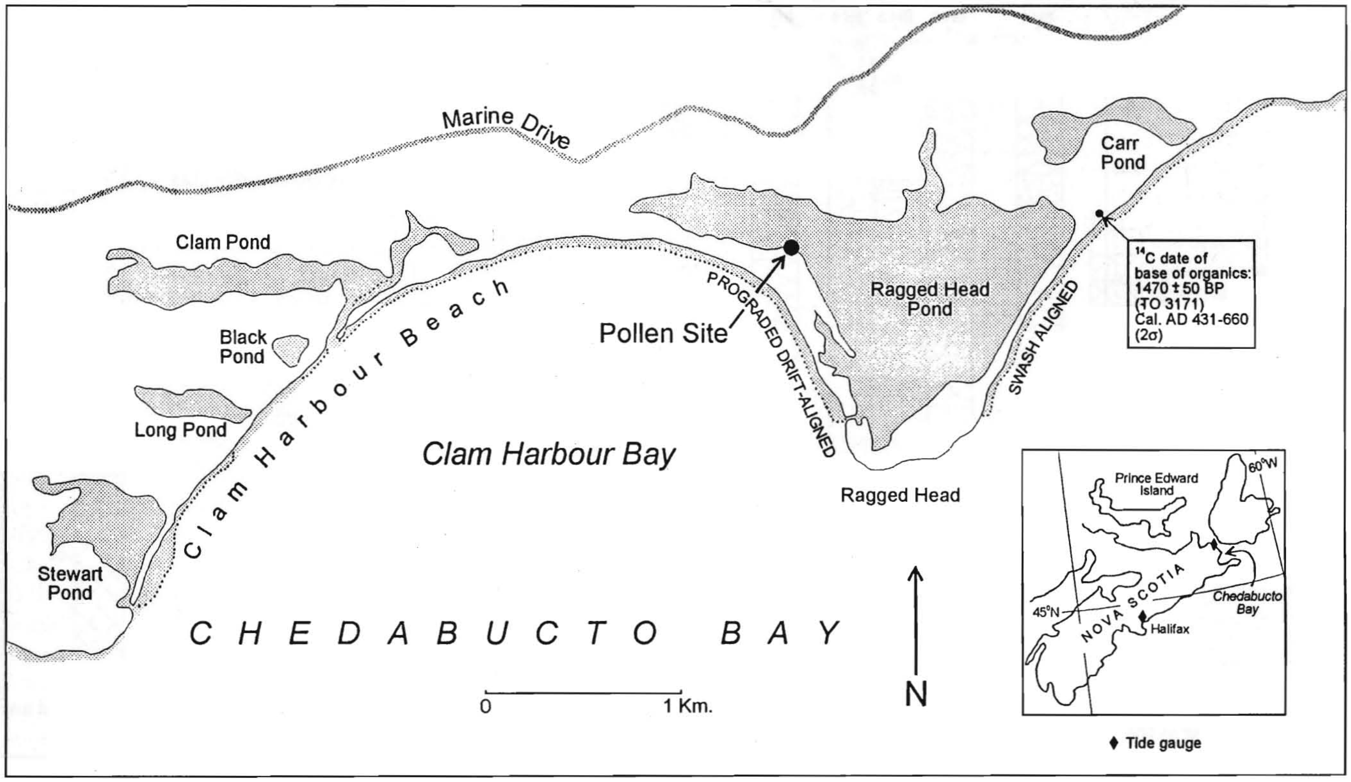

Figure 6. Ragged Head lagoon showing the location of the pollen site. The 'boxed' radiocarbon date was obtained from the base of a 2 m organic sequence which has built up against the landward slope of the inner-most beach ridge.

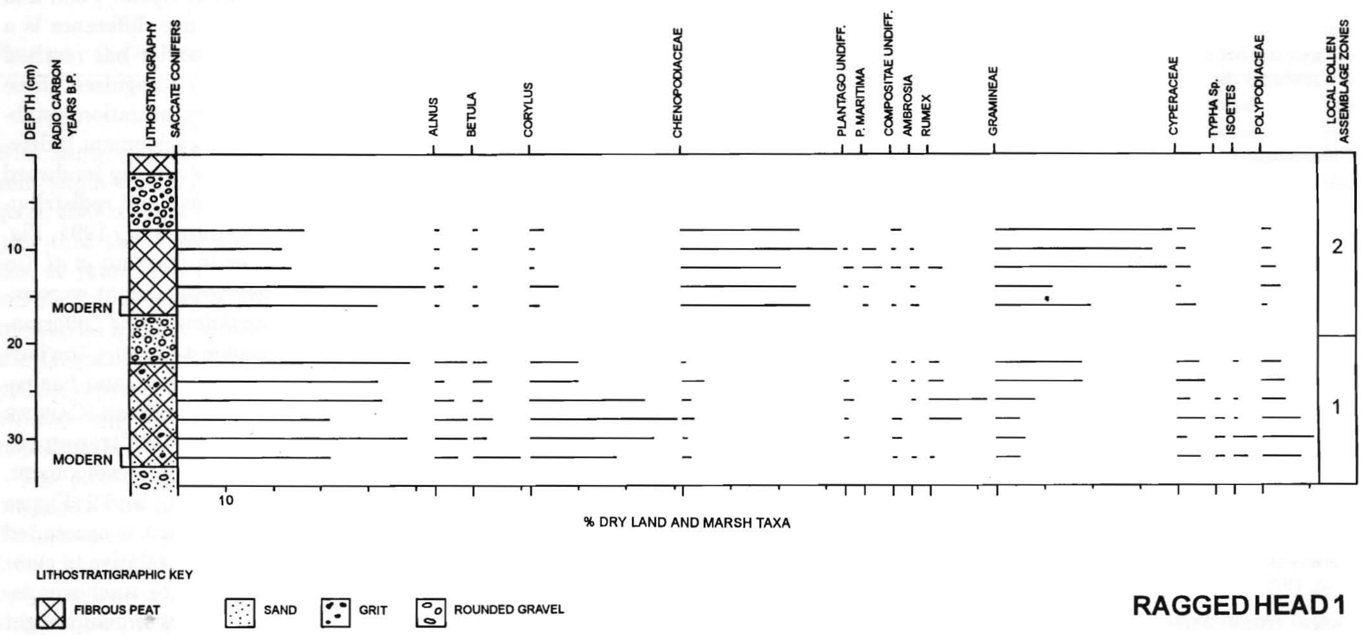

Figure 7. Ragged Head summary pollen diagram.

eral and the coastal system will switch rapidly (instantaneously on geological time-scales) between low and high energy domains as the barrier breaks down, reforms and transgresses into newly formed lagoons. At this stage a feedback exists between the rate of barrier rollover and the water depth of the lagoon. Sediment deficient, seepage lagoons with deep water inhibit the rate of rollover of transgressive barriers, while shallow, seepage lagoons, caused by either sedimentation during a tidal phase, or by a shallow basement, form a platform that may assist rollover (FORBES *et al.*, 1991).

The stratigraphic record resulting from barrier rollover will comprise a sudden coarsening of the sediments and decrease in organic content, which is similar to the stratigraphic signature of a RSL rise (CARTER *et al.*, 1989). The brief life-span of lagoons associated with rollover barriers may result in their seepage stages being unrecorded stratigraphically, unless there are inputs of catchment-derived sediment or there is rapid organic deposition (*e.g.* BH1 at Seaforth) during the period of barrier closure.

In contrast to Seaforth, the lagoons at Oyster Pond and at Ragged Head are linked to barriers that are in the 'consolidation' and 'growth' domains respectively. At Oyster Pond, crestal overtopping processes dominate relative to overwashing, so that the barrier has remained fixed in its present location for at least the last 70 years, the period covered by air photographic evidence. In the longer term (10^2 years) the barrier has opened and closed, but there is no evidence for sustained rollover. Radiocarbon dating of the sediments at Oyster Pond (Figure 4) suggests that switches between tidal and seepage lagoon environments occurred on time-scales of 10^1 to 10^2 years, although the duration of any single episode of seepage or tidal lagoon conditions cannot be resolved by the radiocarbon dating of these stratigraphies. This lack of resolution in dating lagoonal stratigraphies may be hiding environmental changes that operate on very short time-scales. For example, FITZGERALD *et al.* (1987) have shown that changes from tidal to seepage may be due to seasonal discharge variations in snow melt which, in spring, raise lagoon water-levels sufficient to breach a barrier. The resultant inlet/outlet is normally closed again by the following summer.

The site at Ragged Head is on the lagoon margin of the prograded section of the barrier and therefore, has not been affected by overwash nor the opening and closing of inlets, except by the artificial cut mentioned above. The stratigraphic data presented here cover only the last 40 years, which represents a small percentage of the total age of the lagoon. However, this period coincides with that of the seepage lagoons at Seaforth and is therefore illustrative of the differences in sedimentation between seepage lagoons linked to a rollover barrier and those linked to a stationary and prograding barrier. Although gravel deposits are common to the stratigraphy at both sites, the mode of formation of these deposits is different, resulting from overwash at Seaforth and from lagoonal wave action at Ragged Head. The question arises as to whether this difference in lagoonal depositionary history, and therefore, by inference the difference in barrier-type, could be recognised and inferred stratigraphically in the absence of the enclosing gravel barrier.

Lag Between Water-Level Change and Accretion

STEVENSON *et al.* (1986) and NICHOLS (1989) examined the accretionary status of tidal lagoons along the U.S. Gulf and Atlantic coasts. NICHOLS (1989) concluded that the majority of lagoons had an accretionary balance with RSL rise, although there were substantial spatial and temporal variations within the data. This conclusion is akin to the concept of salt marsh maturity (ALLEN, 1990a,b; FRENCH, 1993), whereby the marsh surface grows vertically at the same rate as RSL rise.

However, an important consideration when examining the controls on enclosed, seepage lagoon environments are the differences between the rate of lagoon water-level rise, accretion and RSL rise. Lagoon water-level rise is probably 'instantaneous' as a lagoon becomes enclosed, but with subsequent seasonal fluctuations in water level. The rate of accretion within an enclosed lagoon will be temporally and spatially variable. Minerogenic sedimentation may also be on an 'instantaneous' time-scale if controlled by storm-induced overwash or catchment run-off processes. However, rates of organic accretion are likely to be much slower than the lagoon water-level rise. It is the time taken for the lagoon stratigraphy to develop that is being measured directly when using stratigraphic data, and this is likely to lag lagoon water-level rise by 10^1 to 10^2 years (*e.g.* Oyster Pond). However, the enclosed lagoon accretion rates from the Nova Scotian examples discussed here, have outpaced their contemporary RSL rise rates, and therefore, cannot be used to infer past rates of RSL rise.

CONCLUSIONS

This work is based upon stratigraphic data from back-barrier positions in close proximity to an enclosing, gravel ridge. Therefore, the conclusions reached concerning accretion and palaeoenvironmental reconstruction are confined to this specific, and perhaps narrow, (palaeo)geographical area. The complexity and diversity of the facies examined, illustrates some of the linkages between gravel-barrier dynamics and lagoonal deposition.

It appears that accretion and water-levels in the lagoons examined are controlled more by barrier dynamics than by RSL forcing. It is therefore probable that different barrier types produce diagnostic signatures within lagoonal stratigraphies, especially in the immediate back-barrier area. This barrier-lagoon linkage can be conceptualised with reference to the four domain-based development of gravel barriers as discussed in ORFORD et al. (in press), whereby the nature of back-barrier sedimentation is controlled by the developmental stage reached by the adjoining barrier. Enclosed, seepage lagoons with no fluvial input will be stratigraphically linked to the enclosing gravel ridge by local organic accretion, and/or through washover fans confined to the back-barrier edge. Because the occurrence of washover fans must be regulated by the propensity of a barrier to overwashing, this type of deposit will be associated with rollover barriers, that is with barriers which are in the breakdown and reforming stages. Barriers in either the breakdown, reformed or the consolidation domains may have fossil washover features with actively accreting organic deposits that may use the fossil washover fans as a basement for development. In the former cases (the breakdown and reformed domains), the rate of rollover must be sufficiently slow to allow organic accretion to take place, and here the feedback between lagoon water depth and the rate of barrier rollover is important. Within large seepage lagoons, wave activity may rework the gravel along the barrier's lagoon shore, which may also result in interbedded gravel and organic layers. Tidal lagoons are likely to result in more extensive stratigraphic suites, especially if sedimentation is dominated by flood-tidal processes. In these lagoons, alternating sequences of minerogenic and organic deposits are again likely, but in this case the minerogenic deposits will be the legacy of open, tidal conditions, while the organic layers represent closed-lagoon conditions. This type of sequence will mimic the transgressive-regressive sedimentary signature of RSL oscillations.

Therefore, lagoons associated with the consolidation, breakdown and reformed barrier domains may have similar suites of gravel and organic layers, at least in the immediate backbarrier area. In the absence of an existing barrier, or where the longer-term (Holocene) development of the barrier and back-barrier areas is to be reconstructed, the gravel component of these deposits should be examined, as well as the biostratigraphy of organic layers, in order to identify the processes leading to their formation. Where back-barrier sedimentation has proceeded subaerially (*e.g.* between salt marsh, reedswamp and fen environments), the recognition of linkages between back-barrier deposition and the developmental stage of the barrier may serve as a useful framework for palaeoenvironmental reconstruction, provided other depositional processes within the back-barrier area, not linked to barrier dynamics, are considered (*e.g.* LONG and INNES, 1995).

Because of the control by barrier dynamics, seepage lagoon stratigraphies are not likely to provide reliable data for the reconstruction of sea-level altitudes and tendencies. Within enclosed lagoonal systems, lags between water-level rise and, particularly organic, accretion rates, both of which outpace their contemporary longer-term (Holocene) RSL rise rates, demonstrate the presence of micro-, meso- and macro-timescale rates of change within the variables that control lagoon environments and environmental change.

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