Changes on barriers and spits enclosing coastal lagoons

Barriers
Spits
Holocene transgression
Geomorphology

Barrières
Flèches littorales
Transgression Holocène
Géomorphologie

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ABSTRACT

Coastal lagoons have formed where marine inlets or embayments have become partly or wholly enclosed by depositional spits and barriers, built up as a sequel to the world-wide Holocene marine transgression, though sometimes incorporating relics of similar Pleistocene features. Spits and barriers consist of sediment (sand, shingle) derived from the sea floor or carried alongshore from river mouth or eroding cliff sources ; they have been shaped primarily by wave action, some migrating landward while others have remained in position or prograded seaward. Recent work by the International Geographical Union (IGU) Commission on the Coastal Environment has demonstrated a modern prevalence of erosion on barrier coastlines, recession resulting from net losses of sediment offshore, alongshore, or landward (as overwash fans and dunes migrating across the barrier, or inwash through tidal inlets into lagoons). This is the outcome partly of rising sea level and partly of diminishing sediment supply, often the consequence of man's impacts on coastal environments. Previously prograded barriers have become narrower, and landward movements of sediment mark a transition towards mobility, with barriers encroaching on the lagoon system. Many lagoons have been modified by the initiation or enlargement of tidal entrances, as well as by accessions of sediment carried over spits and barriers to the inner, lagoon, shorelines. Examples are given of changes that have resulted from the cutting of artificial entrances through barriers or the building of barrages across tidal inlets to exclude marine penetration.

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RÉSUMÉ

Évolution des barrières et des flèches littorales abritant les lagunes.

Les lagunes côtières se sont formées là où des criques marines ou des baies ont été partiellement ou totalement fermées par des flèches littorales ou des barrières de dépôt, qui sont restées comme des séquelles de la transgression marine Holocène mondiale, et qui ont incorporé parfois aussi des reliques similaires du Pléistocène. Les flèches et les barrières sont constituées de sédiment (sables, galets) d'origine océanique ou fluviale ou, enfin, elles proviennent d'un matériel érodé des falaises ; elles ont été façonnées à l'origine par l'action des vagues, certaines ont migré vers les terres tandis que d'autres sont restées en place ou ont migré vers l'océan. Un travail récent effectué par la Commission sur l'environnement côtier de l'Union internationale de géographie (UGI) a démontré l'importance actuelle de l'érosion sur les barrières littorales, recul résultant de pertes de sédiment en direction du large, du littoral ou encore vers le continent. Ceci peut être le résultat partiel d'une élévation du niveau de la mer et d'une diminution de l'apport de sédiment, mais souvent aussi c'est la conséquence d'un impact de l'homme sur l'environnement côtier. Les barrières deviennent de plus en plus étroites, et les mouvements de sédiment vers les terres deviennent momentanément mobiles, et empiètent peu à peu sur la lagune. De nombreuses lagunes ont été modifiées par l'élargissement des passes, ainsi que par des transports répétés de sédiment amenés des lagunes et de leurs flèches et barrières sur le littoral. On donne des exemples de changements qui résultent d'ouvrages artificiels coupant une barrière ou de la construction de barrages à travers des criques soumises à la marée, dans le but d'éviter la pénétration marine.

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INTRODUCTION

Coastal lagoons may be defined as areas of relatively shallow water that have been partly or wholly sealed off from the sea by the formation of spits or barriers built up above high tide level by wave action. They generally occupy inlets or embayments that were produced when valley mouths or coastal lowlands were submerged by the sea. This took place during the Holocene marine transgression, the world-wide rise of sea level that accompanied global warming and deglaciation, and brought the oceans up to approximately their present level relative to the land about 6000 years ago.

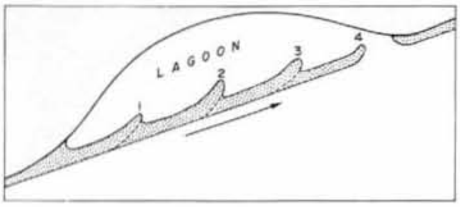

Figure 1
Evolution of a lagoon where a coastal embayment is enclosed by the growth of a spit.

The enclosing spits or barriers have been formed by the deposition of sediment derived from hinterland, alongshore or offshore sources and delivered to the coastal zone. On the world scale these depositional features are mainly built of sand, but some consist of gravel, or mixtures of sand and gravel. Most beach gravels consists of well-rounded waterworn pebbles, and may therefore be described as shingle. Spits that have grown along the shore may be extended to form barriers (barrier spits) enclosing lagoons (Fig. 1), but many barriers originated by shoreward movement of sediment accumulated from the sea floor (Fig. 2), and some have been formed by a combination of longshore and onshore sediment supply. Some lagoons are completely cut off from the sea, but most have at least one marine entrance (tidal inlet) bordered by paired spits or separating barrier islands.

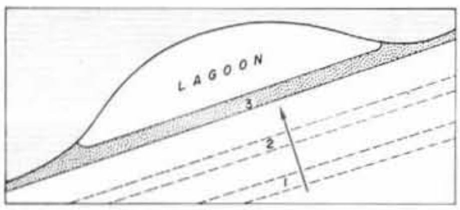

Figure 2
Evolution of a lagoon where a coastal embayment is enclosed by a barrier that develops offshore and is driven landward.

The definition of a coastal lagoon implies that these entrances from the sea are narrow compared with the coastwise extend of enclosing barriers, or with the length of the lagoon along the coast. The Wadden Sea, lying behind the Frisian barrier islands, is not usually considered a coastal lagoon because the combined width of the openings to the sea (including the broad gap east of Wangeroog) is more than one-third of its coastwise extent. However, some have classified the Wadden Sea as an " open lagoon " (e.g. Lasserre, 1979), an appellation that could also be used for water areas in the lee of recurved spits such as Blakeney Point in England, where the connection with the sea is again broad and open. In the geomorphological literature the term coastal lagoon has generally been applied where the width of marine entrances at high tide is less than one-fifth (20 %) of the total length of the enclosing barriers.
Coastal lagoons are found on many parts of the world's coastline, ranging from arctic to tropical environments (Guilcher, 1981). They are best developed on coasts where the Holocene marine submergence produced extensive inlets and embayments, and where wave action has delivered an abundant sediment supply to form the enclosing spits or barriers. In arctic environments the rapid summertime erosion of tundra bluffs, which consist of morainic or glacifluvial deposits, has provided material for the building of extensive spits and barriers that enclose lagoons. There are good examples south of Icy Cape and east of Point Barrow in northern Alaska, and on the Siberian coast, particularly in Novaya Zemlya. In south-eastern Iceland shallow lagoons have been impounded by barriers built from glacio-volcanic outwash. Spits and barriers formed by the re-working of glacial drift deposits are more extensive, enclosing lagoons on the coast of Puget Sound, on Rhode Island and in Massachussets, and on the southern shores of the Gulf of St Lawrence, as well as in equivalent parts of northern Europe (notably the southern Baltic and the Danish archipelago) and eastern Asia (particularly on Kamchatka, Sakhalin, and northern Hokkaido). Fluvial sediment has been incorporated with material carried in from the sea floor to build spits and barriers impounding lagoons on the Caribbean and Mediterranean coasts, some of them bordering deltas (e.g. the Mississippi, Ebro, Danube and Nile). On the shores of the Azov Sea barrier spits and beaches are composed of molluscan shells washed in from the sea floor, and in the Caspian Sea similar formations are built of marine oolites washed onshore (Zenkovich, 1969). Sediment from the sea floor has also been built into barriers and spits on the coasts of the Red Sea and the Arabian Gulf, enclosing lagoons which in these arid environments have become hypersaline sebkhas with extensive, often zoned, evaporite deposits. Similar features are seen on the dry north-western coast of Australia (Plate 1).

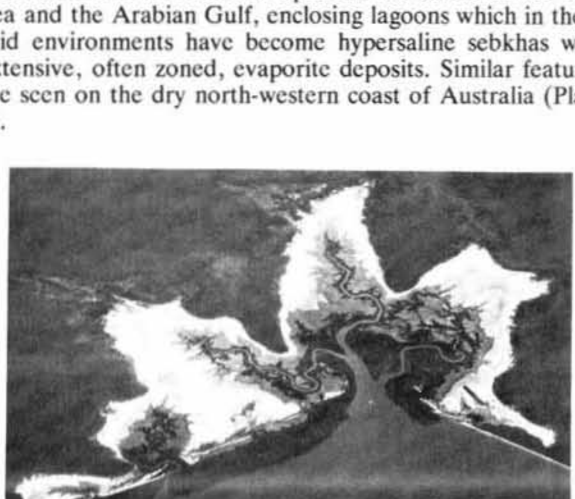

Plate 1
A sebkha on the west coast of King Sound, north-western Australia, where a tidal lagoon formed by submergence of earlier valleys and partly enclosed by spits and barriers shows the development of saline evaporite plains in the zone submerged only by rare exceptionally high tides (photo : E. C. F. Bird).

Within the tropics barriers and lagoons are also well developed on oceanic coasts, as in the Gulf of Guinea and in Sri Lanka and south-eastern India. In the southern continents similar features are extensive in Brazil and equivalent parts of South Africa, Australia and New Zealand. On these oceanic coasts the bulk of the barrier sediment is sandy material that has been swept in from the sea floor, augmented locally by fluvially-supplied sediment delivered to river mouths and distributed along the coast, but in the South Island of New Zealand the barriers are gravelly, being derived from partly submerged and locally cliffed deposits of glacifluvial outwash, re-worked by wave action and supplemented by similar material delivered to the coast by rivers during episodes of floodwater discharge.
Lagoons are poorly developed on the ice-girt Antarctic and Greenland coasts, on the steep and rocky fjord coasts of Norway, British Columbia, Chile, and southern New Zea-

land, on coasts dominated by high cliffs, as in the Great Australian Bight, and on the rapidly emerging coasts of northern Canada and the Gulf of Bothnia. Elsewhere, the combination of embayed and indented coastlines of submergence, the availability of beach material, and its emplacement as spits or barriers by wave action has produced a wide distribution of coastal lagoons of varying scale and configuration. Once enclosed, their evolution has been determined by environmental factors, including hydrology, climate and ecology ; by rates of sedimentary infilling, and vegetation encroachment ; by re-shaping in accordance with internal regimes of waves and currents ; and by changes continuing on the enclosing spits and barriers (Bird, 1967 ; Day, 1951 ; Emery, Stevenson, 1957 ; Gierloff-Emden, 1961). This paper considers how changes in progress on barriers and spits have influenced the dynamics of coastal lagoon systems.

EVOLUTION OF SPITS AND BARRIERS

The origin of spits and barriers has been the subject of a considerable geomorphological literature (cf. Schwartz, 1972 ; 1973 ; Leatherman, 1979 ; Zenkovich, 1969). In general these features have been built during and since the world-wide Holocene marine transgression, attaining their present outlines within the past 6000 years, whence on most coasts the sea has been close to its present level relative to the land. Longshore growth of spits (Fig. 1) has often occurred in stages marked by the formation of successive terminal recurves, and where spits have been prolonged into barriers they may retain remnants of such recurves, protruding into the lagoon. The long barrier spit known as the Langue de Barbarie, which has deflected the mouth of the Senegal River about 30 km southward to form an elongated lagoon on the West African coast (Guilcher, Nicolas, 1954) is of this type, as are the barrier spits that have grown northward on the west coast of Sri Lanka to enclose lagoons at Negombo, Chilaw, and Puttalam (Swan, 1982). But many barriers and barrier island chains originated on alignments that lay offshore from an earlier coastline, enclosing the intervening water area as a lagoon (Fig. 2). Barriers on the Atlantic coast of the United States, especially those forming the Outer Banks of North Carolina in front of the broad lagoon known as Pamlico Sound, formed in this way, as did the similar barriers on the Texas coast, enclosing lagoons such as Galveston Bay, Matagorda Bay and the Laguna Madre.

It was formerly thought that " offshore barriers " were indications that an emergence of the coast had taken place, the deduction being that wave action in nearshore water shallowed by a relatively sudden emergence had re-shaped the sea floor in such a way as to pile up a sand or gravel ridge on an alignment some distance offshore (and often parallel to) the earlier coastline. This sequence of events has occurred, for example on the Danish island of Laesø, where a new barrier island, Knotten, has been built up off the south-west coast during the past two centuries, the shallowing of nearshore water here being due to the continuing isostatic uplift of Scandinavia. Offshore bars have emerged and been built up as barriers off parts of the Caspian coast during the phase of sea level lowering that has occurred there in the past half century (Leontiev, 1978).

But emergence is not essential for barrier initiation. If nearshore waters are shallow and there is plenty of unconsolidated sediment on the sea floor, wave action can build an " offshore barrier " during a period of sea level stillstand, or even while a gradual submergence is taking place. Many barriers came into existence during the later stages of the Holocene marine transgression as the result of shoreward drifting of sediment by the wave action, the sediment being derived from earlier beach and barrier deposits as they were submerged by the rising sea. On the Gulf and Atlantic coasts of the United States stratigraphical studies have shown that barriers initiated when the sea stood 5 to 10 m below its present level relative to the land were built upwards and driven landwards as the Holocene marine transgression proceeded (Shepard, 1960 ; Kraft, John, 1979). The shingle barrier of Chesil Beach in southern England developed during the Holocene marine transgression and has subsequently migrated shoreward in such a way as to prevent waves from the open sea reaching the mainland coast, so that the gentle slopes behind the Fleet lagoon lack marine cliffing (Steers, 1953) : the Mehechkyn shingle barrier of the Soviet Bering Sea coast is evidently of similar origin (Zenkovich, 1969).

Sand barriers initiated in this way on the Gulf and Atlantic coasts of the United States continue to move landward as the outcome of storm overwash and the drifting of dunes by onshore winds. In some sectors these barriers consist largely of coalescent overwash fans formed in successive storm surges and trimmed back by wave action on the seaward margins (Leatherman, 1979 ; 1981). Elsewhere, barriers thus initiated have remained in position parallel to the pre-existing coastline, and some have been widened seaward by progradation resulting from the deposition of further sediment arriving on their shores. This has occurred on barrier islands at Galveston in Texas and on St Vincent Island in Florida. On the Pacific coast of Mexico at Nayarit the barrier enclosing the Laguna Agua Brava has prograded to form a beach ridge plain up to 15 km wide (Curray *et al.*, 1969), and similar accretion has taken place on the barrier fronting Laguna Guerra Negro in Sebastian Vizcaino Bay to the north (Phleger, 1969). In south-eastern Australia a history of intermittent progradation is shown by the numerous successively-formed beach and dune ridges parallel to the coastline of the Ninety Mile Beach (Bird, 1978) and on sectors of the New South Wales coast, notably in Disaster Bay where Thom *et al.* (1981) have dated stages in Holocene accretion on the broad barrier that encloses Lake Wonboyn.

On some coasts the evolution of barriers may have been influenced by minor oscillations of sea level ($\pm$ 2 m) relative to the land during the past 6000 years. In such cases it is possible that phases of slight emergence aided coastline progradation and the addition of beach ridges and dune ridges, while intervening phases of submergence led to the trimming back of these deposits. Separation of beach and dune ridge systems would thus be related to sea level oscillations, but episodic progradation can also result from fluctuations in rates of sediment supply to the coast or alternations of stormier and calmer conditions in coastal waters : on some coasts, parallel beach and dune ridge systems have been formed by these processes independently of any sea level oscillations.

It is possible that the transgressive barriers on the Atlantic coast of the United States are moving in response to a continuing rise of sea level relative to the land, and that stationary and prograded barriers have developed on coasts where land and sea levels have remained stable, or where an emergence has taken place.

Some coastal lagoons are bordered by or interspersed with remnants of older barriers that formed during Pleistocene phases when the sea stood at or above its present level. These barriers were stranded inland during the Last Glacial low sea level phase, and usually show evidence of dissection by incised rivers or rearrangement by aeolian action during this subaerial interval. For example the Gippsland Lakes (Fig. 3) in south-eastern Australia are enclosed by an outer barrier of Holocene age, but retain extensive remnants of Pleistocene barrier formations, all of quartzose sand (Bird, 1978). The barrier of calcareous sand that encloses the Coorong lagoon on the coast of Encounter Bay in South Australia is the last in a series of late Quaternary barriers which are preserved as uplifted calcarenite ridges in the hinterland. The origin of the youngest barrier is here complex, being the outcome of partial submergence, dissection and re-working of earlier calcarênite barriers that existed at the seaward of the present coastline (Bird, 1973). On the coast of Western Australia similar parallel barriers

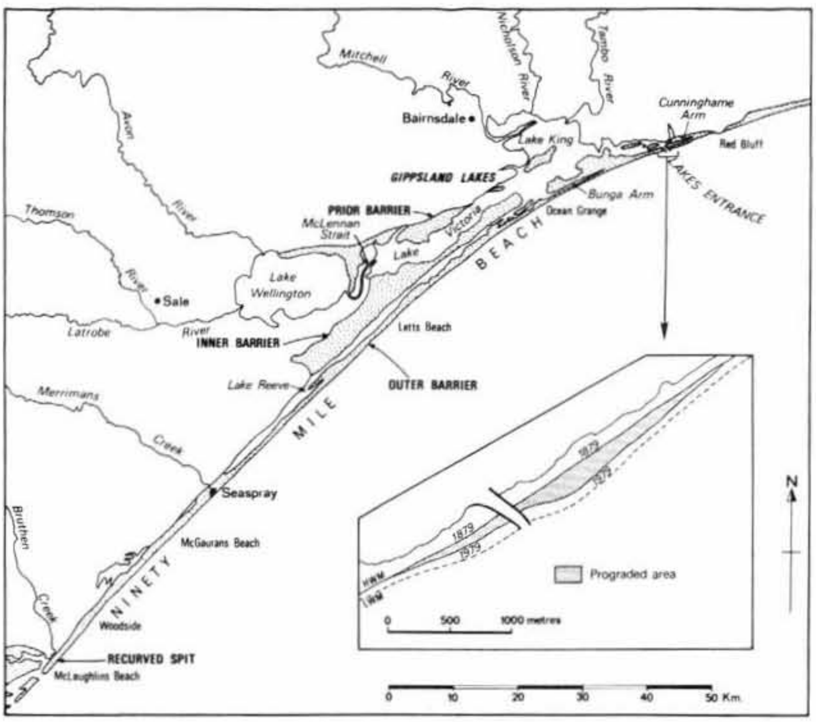

Figure 3

The Gippsland Lakes in south-eastern Australia are coastal lagoons enclosed by an Inner Barrier, largely of Pleistocene age, and a Holocene outer barrier (cf. Plate 5) bordered seaward by the Ninety Mile Beach. During the past century, this beach has been cut back by marine erosion (cf. Fig. 4), except in the sector (inset) on either side of the artificial entrance (cf. Plate 2).

of calcarenite separate swale lagoons, one of which, the Harvey estuary, is linked to the sea by way of Peel Inlet, an estuarine lagoon (Hodgkin *et al.*, 1980). Relics of Pleistocene barriers also occur in association with lagoons on the Zululand coast in south-east Africa (Orme, 1972), in the depositional lowlands around Lagoa dos Patos in southern Brazil (Delaney, 1963), and interspersed with coastal lagoons and swamps in West Africa (Le Bourdiec, 1958) and Pacific Central America (Gierloff-Emden, 1961). This wide distribution of relict Pleistocene barriers signifies that many lowland coasts have had similar sequential histories of submergence by marine transgressions, formation of barriers enclosing lagoons, emergence when the lagoons drained out and barries were dissected, and renewed phases of submergence and younger barrier development culminating in the Holocene. In general the barriers that now enclose coastal lagoons have been shaped in Holocene times, although they often incorporate re-worked Pleistocene sediments and in many cases are underlain by older barrier deposits that date from the Pleistocene.

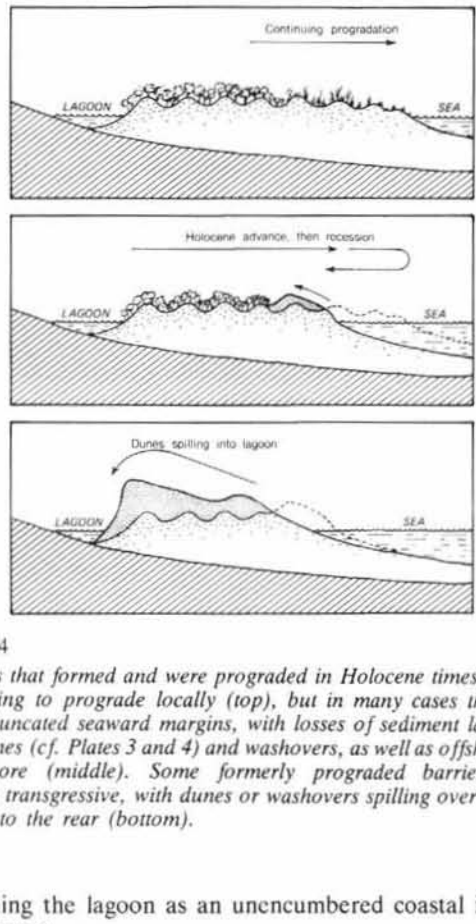

Figure 4

Barriers that formed and were prograded in Holocene times are still continuing to prograde locally (top), but in many cases they now show truncated seaward margins, with losses of sediment landward into dunes (cf. Plates 3 and 4) and washovers, as well as offshore and alongshore (middle). Some formerly prograded barriers have become transgressive, with dunes or washovers spilling over into the lagoon to the rear (bottom).

CHANGES IN PROGRESS ON SPITS AND BARRIERS

Some of the changes taking place on spits and barriers are modifying the configuration of the enclosed lagoon. Continued spit growth, for example, is likely to reduce the dimensions of a marine entrance to a coastal lagoon, or to cause that entrance to migrate along the coastline. In some cases, continued spit growth may result in the lagoon becoming completely sealed off from the sea, at least temporarily.

Progradation of the seaward margins of spits and barriers, resulting from continued delivery of sediment and its deposition by wave action, has little influence on the enclosed lagoon : as the barrier is widened the lagoon is left farther inland (Fig. 4). There is more likely to be modification of a lagoon where the seaward margin of an enclosing barrier is retreating, either as the result of submergence due to a rise of sea level relative to the land, or as the outcome of erosion of sediment from the coastline, or as a combination of these two effects. Where a barrier is narrowed by such erosion, sediment is more likely to be carried across it into the lagoon by overwash during storm surges or by the movement of sand dunes inland by onshore winds (Fig. 4). Breaching of new marine entrances may then occur, and if erosion continues the barrier may be removed completely, reopening the lagoon as an unencumbered coastal inlet or embayment.

Alternatively the barrier may be driven landward by overwash processes and sand drifting by onshore winds so that it encroaches on the lagoon, which is thereby narrowed, and may eventually be extinguished as the sand or shingle comes to rest against its inner or landward margin as a fringing beach. This has happened in Lyme Bay, on the south coast of England, where the shingle barrier of Chesil Beach has been driven landward ; locally it has overrun lagoon marsh deposits, which outcrop on its seaward side. South-east of Abbotsbury it still stands in front of the Fleet lagoon, but the north-west it has reached the mainland, and

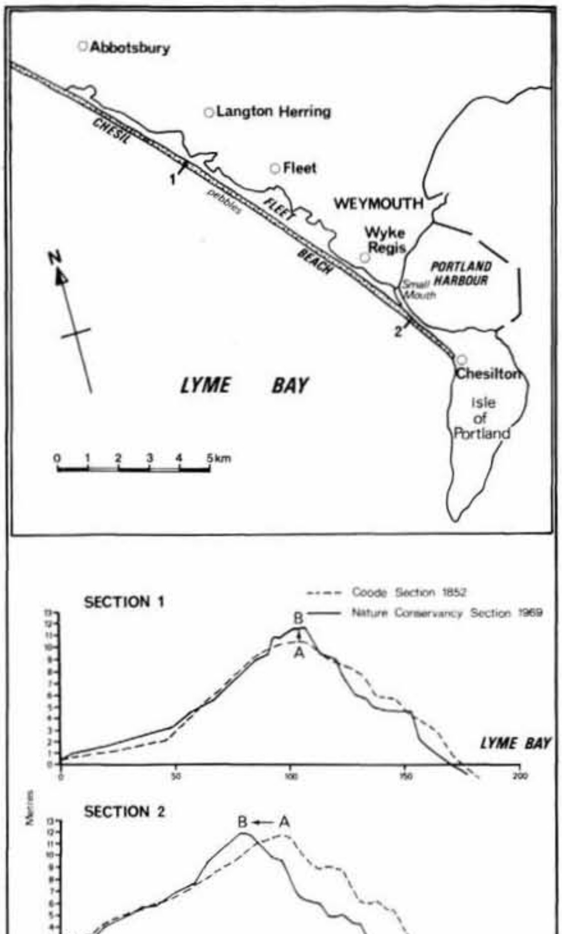

Figure 5

Chesil Beach, a shingle barrier on the south coast of England, has migrated landward (cf. Fig. 2) to enclose the Fleet lagoon. Comparison of surveys made in 1852 and 1969 showed slight retreat and a raising of the beach crest off Langton Herring, and a more definite landward movement near Small Mouth at the south-eastern end. Diagrams based on Carr and Gleason (1972).

forms a beach extending past residual lagoon segments to the cliffs of West Bay. Chesil Beach is occasionally overwashed by storm surges, and comparisons of surveys made in 1852 and 1969 indicate slight re-shaping, with some minor landward movement, especially near Small Mouth at the south-eastern end (Fig. 5).

Such changes have been observed on various barrier and spit formations around the world. Some are still prograding, but most now have receding coastlines. This applies not only to barriers with a history of landward migration but also to anchored barriers, including many that previously prograded, but now show margins consisting of dunes or beach ridges truncated by cliffs of sand or shingle.

Studies by the International Geographical Union's Commission on the Coastal Environment during the past decade have documented this world-wide prevalence of erosion on depositional coastlines (Bird, Koike, 1981). Analysis of the distribution of prograding sectors has shown that these are generally related to a continuing sediment supply to the nearshore zone, particularly in the vicinity of river mouths where sand or gravel are being delivered to the coast, as in the north-west United States where prograding beaches and barriers are receiving sand from the Columbia River. Progradation has also continued where shoals of sediment are moving in from the sea floor. In south-eastern Australia, for example, the Outer Barrier is no longer prograding along the length of the Ninety Mile Beach, but to the south-

Plate 2

Artificial entrance to a coastal lagoon system, the Gippsland Lakes in south-eastern Australia. The entrance was cut through an enclosing sandy barrier, and opened in 1889. Its navigability has been limited by the persistence of a curved sand bar to seaward, and training walls in the left foreground were added to intensify outflow currents in the hope of dispersing the sand bar, but it still remains (photo : E. C. F. Bird).

west, in the lee of Wilson's Promontory, barrier islands are still growing seaward as sand moves in from nearshore shoals. Local progradation has occurred where breakwaters built to stabilise lagoon entrances have intercepted beach material drifting alongshore. At the entrance to Lagos Lagoon, in Nigeria, sand carried eastward along the coastline has accumulated west of a breakwater while Victoria Beach, to the east, deprived of a sand supply, has been cut back. Where longshore drifting alternates there may be accretion on both sides of protruding breakwaters (Fig. 3 and Plate 2).

The modern prevalence of erosion is also the outcome of several factors. In some sectors it can be related to diminished fluvial sediment yields, notably where dams have been constructed across rivers to impound reservoirs of water that also intercept the sediment that moves downstream. In others it appears that a formerly abundant supply of sediment from the sea floor has diminished, and is no longer being carried shoreward to maintain or prograde the coastline. This sediment consisted of deposits that had accumulated on the emerged sea floor during the Last Glacial low sea level phase, notably the beach and barrier formations stranded during the preceding marine regression, as well as accumulations of fluvial sediment laid down by the rivers that extended their courses as the sea retreated, and material produced by the subaerial weathering of rock outcrops exposed on the emerged continental shelf. The Holocene marine transgression encountered and re-worked these deposits, wave action moving some of them onshore to prograde the coastline, but once a smoothed transverse « profile of equilibrium » had been attained the shoreward drifting came to an end, and progradation ceased. On some coasts, erosion has been initiated or accelerated by coastal submergence, a rise of sea level relative to the land having led to a deepening of nearshore waters and the augmenting of wave energy reaching the coastline. On others, erosion is the outcome of man's interference with the coastal system, notably the construction of breakwaters that have cut off a longshore sediment supply. It is possible that erosion has increased in some sectors because of climatic changes, such as an increase of storminess in coastal waters (Thom, 1978). There is no single, simple explanation for the modern prevalence of erosion on barrier coastlines ; it is a question of ranking the relevant factors to apportion their contribution to changes that have taken place on particular coastline sectors.

Sandy barriers that were previously anchored and prograding but now show coastline recession have become unstable because of the development and growth of dune blowouts

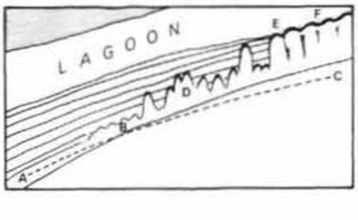

Figure 6

The sequence given in Figure 4 is displayed in plan : a barrier with successively-formed parallel ridges is still prograding at A, but in the sector BC it has been cut back with the formation of blowouts (D) which eventually spill over to the lagoon (E), delivering sand that is distributed by waves and currents to lagoon-shore beaches (F). A stationary, prograded barrier has thus become a landward-migrating feature, encroaching on the lagoon to the rear.

behind their cliffed seaward margins. These are hollows excavated by wind scour, with onshore winds driving the sand inland. They may grow into large parabolic dunes, with advancing noses of bare sand and trailing arms of partly-vegetated sand on either side of a corridor of deflation, where sand has been blown away, usually down to the level of the water-table. Enlargement and coalescence of blowouts may lead to the formation of extensive sheets of unvegetated, drifting sand which move inland across the barrier (Fig. 6).

Dune activation can also result from the weakening or destruction of the vegetation cover by repeated burning, grazing, trampling, and damage by vehicles, particurlaly in the less consolidated sands near the seaward margin. Thus the dunes on the Coorong barrier, behind Encounter Bay in South Australia, were well-vegetated until the arrival of European settlers in the early 19th century, whereupon the vegetation was cleared, or burned to stimulate regrowth of herbs and grasses for grazing by cattle and sheep, and the dunes became extensively unvegetated and mobile (Plate 3).

Plate 3

Transgressive sand dunes moving inland from the shore of Encounter Bay, South Australia, across the barrier that encloses the Coorong Lagoon, segments of which can be seen in the background (photo : E. C. F. Bird).

Such changes have begun to affect the geomorphology and ecology of lagoon systems behind formerly stable coastal barriers. When sediment from the barrier is washed or blown over its landward margin it forms features that protrude into the lagoon in the form of washover fans and spilling dunes (Fig. 4). Thus the lagoon shoreline is locally prograded, and sediment supplied for circulation within the lagoon system. Some of this material is deposited on the floor of the lagoon, and some as spits and beaches along the lagoon shoreline (Plates 4 and 5).

With increasing instability many formerly anchored barriers have become transgressive, advancing landward upon enclosed lagoons. Under these circumstances, breaching is likely to form new marine entrances to the lagoon. The

Plate 4

Dunes spilling across the barrier behind Encounter Bay and invading the Cooring Lagoon, South Australia (photo : E. C. F. Bird).

transgressive barriers on the Atlantic coast of the United States have had a long and complicated history of breaching, enlargement, reduction and closure of tidal inlets to such lagoons as Pamlico Sound (Dunbar, 1956).

Plate 5

The outer barrier on the Gippsland coast, south-eastern Australia, between the oceanic Ninety Mile Beach and a narrow lagoon, Lake Bunga, which is backed in turn by a forested inner barrier. Sand blown and washed over the outer barrier has formed salients on the lagoon shore and a submerged spit extending more than half way across the lagoon (photo : N. J. Rosengren).

LAGOON ENTRANCES

Some lagoon entrances are residual gaps that have persisted between spits or barrier islands where the lagoon has never been completely sealed off from the sea. Others are the outcome of breaching, either by storm waves or by the overflow of floodwaters out of the lagoon ; and some are artificial, having been excavated and maintained by man. Lagoon entrances are usually backed by partly or wholly submerged fans or " tidal deltas " of inwashed sediment, which may thence be distributed farther into the lagoon. Such features are less common on the seaward side, where stronger wave action disperses outwashed sediment offshore or alongshore

The configuration of a lagoon entrance is the outcome of interactions between waves from the sea, which tend to wash sediment in to reduce and eventually seal off the gap, and currents generated by tidal ebb and flow and the discharge of floodwaters from the lagoon, which tend to keep it open. Tidal inlets are larger, more numerous, and more persistent on barrier coastlines where relatively large tide ranges generate strong currents, as in the Frisian Islands on the German North Sea coast, than where tidal action is weak, as on the long sandy *nehrungen* which fringe the southern shores of the Baltic Sea. Lagoon entrances often show seasonal variations, being shallowed or sealed in dry seasons, then reopened, widened, or deepened when the wet season brings greater volumes of water outflow from the lagoon. This sequence is well known on the Zululand coast, where most lagoons are sealed off by sand deposition in relatively dry winter season (May through August) and entrances are reopened in the summer when rains in the hinterland increase fluvial discharge into the lagoons, raising their levels until they spill over into the sea. In south-eastern Australia lagoon entrances are often either reduced in dimensions or sealed off in dry summer periods, then reopened or enlarged in the wet winter season.

Some lagoon entrances are persistent and stationary gaps between paired spits or permanent channels through an enclosing barrier ; others are migratory inlets that change in location as well as in form and dimensions in response to the interactions of wave and current action (Bruun, Gerritsen, 1961). Persistent lagoon entrances are often found adjacent to rocky headlands or in the lee of islands or reefs, where wave action is weakened and the ebb and flow of currents sufficient to maintain a gap. An example of this is seen at the entrance to Tauranga Harbour, a lagoon that extends behind a sandy barrier (Matakana Island) with an outlet alongside the rocky promontory of Mount Maunganui (Healy, 1977) on the north coast of New Zealand.

Migration of lagoon entrances has occurred on many barriers, and is well exemplified on the Danish North Sea coast where the barrier enclosing the lagoon known as Ringkøbing Fjord has had an entrance in various positions since 1650, with a tendency to migrate southward. In 1909 this variable entrance was replaced by an artificial cut at Hvide Sande, which is maintained between bordering stone jetties. In New Jersey, curving channels lead from the lagoon into the rear of the barrier towards entrances that have been deflected along the coastline by longshore drifting of sand, and on the Gippsland coast in Australia similar curved channels lead towards the sites of entrances that have now been sealed off by sand deposition. Efforts to maintain stabilise lagoon entrances on a barrier coastline have been particularly intensive in the Venice region, where breakwaters up to 2 km long have been built alongside the channels that lead into the Venetian lagoon, and intervening barrier islands (*lidi*) have been armoured by large sea walls (Zunica, 1976).

Lagoon entrances thus show a variety of features. At one extreme is the permanent entrance, natural or man-made, and often maintained by bordering and protruding jetties (Plate 2). Such an entrance allows a perennial, unhindered exchange of water, sediment, dissolved materials, and organisms between the lagoon and the open sea, the lagoon showing estuarine characteristics, such as a transverse salinity gradient and inwardly diminishing tidal movements. At the other extreme is the completely enclosed lagoon behind an impermeable barrier : in humid environments this becomes a freshwater lake (e.g. Slapton lagoon in south-west England), while in arid environments it becomes a hypersaline lagoon (e.g. the Laguna Madre in Texas), or an evaporite plain (e.g. the sebkhas of the Arabian coast, as at Abu Dhabi). Between the two extremes are the many lagoon entrances that vary in form, dimensions and location, and are sometimes sealed off altogether. Such variations result in fluctuations in tidal ventilation, floodwater levels, marine incursions, salinity regimes, and related ecological conditions within the lagoon system.

Examples of changes resulting from the modification of lagoon entrances can be quoted from south-eastern Australia (Bird, 1978). The Gippsland Lakes (Fig. 3), an extensive coastal lagoon system behind a formerly prograded sandy barrier, had only an intermittent and variable entrance from the sea when European explorers arrived in 1839. The lakes, fed by five substantial rivers and a number of smaller streams in a humid temperate environment, had become relatively fresh, and their shores were extensively fringed by reedswamp, dominated by *Phragmites* spp., and backed by swamp scrub, chiefly *Melaleuca ericifolia*. The unreliable entrance posed problems for navigation, and in 1889 an artificial entrance was opened, bordered by breakwaters (Plate 2), alongside the town that became known as Lakes Entrance. Once established, this permanent entrance allowed both rapid outflow of river floodwaters in wet periods and unrestricted inflow of sea water in dry seasons. Over subsequent decades, salinity has increased in the Gippsland Lakes, and a number of changes have taken place. The reedswamp fringe has largely disappeared, surviving only in the relatively fresh water areas close to river mouths, and augmentation of soil salinity from recurrent brackish flooding has resulted in extensive die-back of swamp scrub and its replacement by salt marsh vegetation. Moreover the lagoon shorelines formerly protected from wave scour by reedswamp began to erode (Plate 6), and in the absence of a reed fringe the deltas are withering.

Plate 6

Erosion of a lagoon shoreline in the Gippsland Lakes, south-eastern Australia, has followed the die-back and disappearance of a former reedswamp (mainly Phragmites*) fringe in the ninety years since the opening of an artificial entrance (Plate 2) initiated an increase in salinity in a lagoon system that was previously relatively fresh. The water is now too brackish to sustain reedswamp growth, and in its absence the bordering swamp land is being cut away by lagoon wave action (photo : E. C. F. Bird).*

The Gippsland Lakes are thus becoming larger and shallower, and in a more brackish environment there have been changes in hydrophytic vegetation (e.g. replacement of fresh-water plants such as *Vallisneria* by *Zostera* species) and associated ecological variations, notably an increase of estuarine and marine fish and crustaceans at the expense of the earlier fresh-water ecosystems. Bordering farmland is subject to salt damage from brackish flooding ; on the other hand, the now more brackish lakes are probably of greater interest to fishermen and boat users than the relatively enclosed fresh-water lakes would have been. An ancillary change is the formation of dune spillovers across the enclosing sandy barrier, as a sequel to coastline recession and backshore dune cliffing along the Ninety Mile Beach. Some of these have developed as low transverse corridors, which became the sites of temporary breaching during storm surges. If erosion along the Nine Mile Beach continues it is possible that additional entrances will form through the sandy barrier, modifying the Gippsland Lakes system still further.

Conversely, the coastal lagoons at the mouth of the Murray River in South Australia (Lakes Albert and Alexandrina) were naturally brackish systems, with several permanent natural entrances from the sea, when Europeans settled this region in the mid-nineteenth century. The climate here is sub-arid, and prolonged droughts occur frequently. Under natural conditions sea water used to invade the Murray-mouth lakes to compensate for high evaporation losses in dry seasons, and the system became strongly saline. In the droughts that occurred during the nineteen-thirties, incursion of brackish water extended upstream into the lower reaches of the Murray River, and rendered irrigation there impracticable. In consequence, five barrages were constructed to seal off the entrances from the sea, designed in such a way as to permit the outflow of river floodwaters but prevent marine inflow (Fig. 7). These were completed in 1940, and in subsequent decades the Murray-mouth lakes have freshened to such an extent that their waters can now

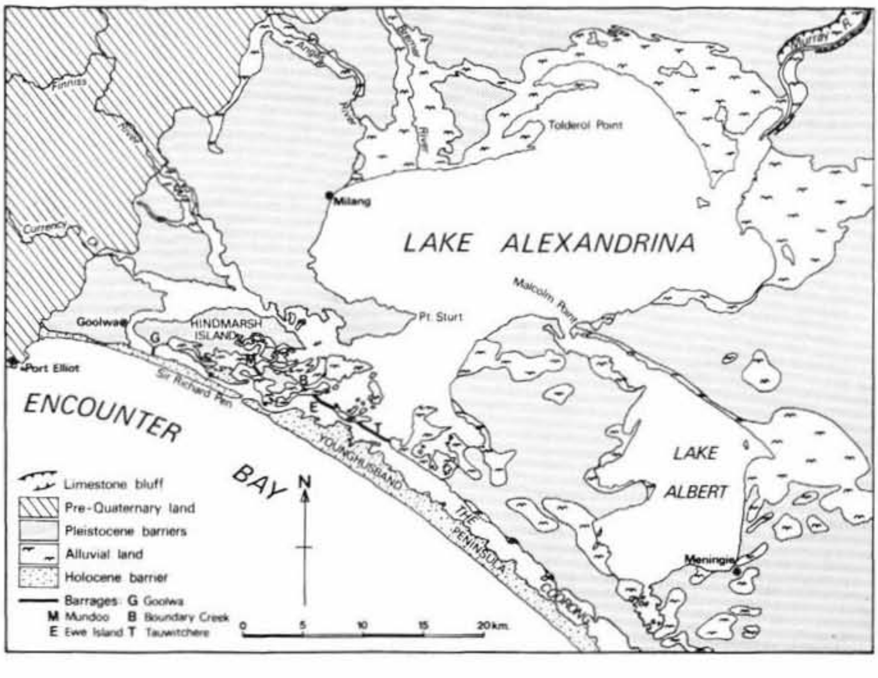

Figure 7

The Murray-mouth lakes, coastal lagoons in south-eastern Australia that were formerly brackish and open to the sea, but have become fresh water since the construction of barrages to seal the five gaps in the coastal barriers through which sea water previously entered.

be used for irrigation of bordering farmland. The salt marshes that previously bordered them have been replaced by luxuriant reedswamp vegetation, which is spreading forward into the lagoon waters and trapping sediment that would otherwise have been dispersed, or swept out to sea. The barrages also exclude marine organisms, so that the Murray-mouth lakes have become a fresh-water ecosystem, containing such fish as the Murray cod.

Modification of lagoon entrances has thus converted the Murray-mouth lakes into a system similar to the natural Gippsland Lakes, and changed the Gippsland Lakes towards the condition of the Murray-mouth lakes prior to barrage construction.

CONCLUSION

An awareness of changes in progress on the enclosing spits and barriers is of fundamental importance in understanding the physiography and ecology, and in planning the management and conservation, of coastal lagoons because these changes vary the patterns of interaction and exchange of water, dissolved materials, sediments and organisms between the lagoon and the sea. Unfortunately, the morphodynamics of barriers and spits enclosing coastal lagoons have not been widely investigated ; they require further consideration within the framework of a more comprehensive documentation of the various coastal lagoon systems around the world. The existing scientific literature on coastal lagoons is indeed patchy and variable, ranging from studies that emphasise Quaternary geological evolution to investigations that focus on the biology of particular lagoonal organisms. It is hoped that this conference has prepared the way for more thorough investigations of the evolution and dynamics of the world's coastal lagoon systems.

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