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Gravel Barrier Morphology: Olympic National Park, Washington State, U.S.A.

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ABSTRACT

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Three gravel barriers studied along the Olympic Coast of Washington State display morphology and textural characteristics similar to those barriers reported along the coasts of Ireland, England and Nova Scotia. Resistant headlands serve as anchor points for two of the three barriers. Headlands are not, however, a necessary prerequisite for their development. These barriers seem to follow an evolutionary model of development and destruction somewhat similar to those in the literature.

ADDITIONAL INDEX WORDS: *Gravel barriers, barrier evolution, barrier morphology.*

INTRODUCTION

Research conducted on gravel beaches has been scarce as compared to that of sandy, fine-grained beaches. The processes occurring on coarse clastic beaches have received attention mainly from coastal geomorphologists outside the United States, predominantly in Britain, Ireland and New Zealand. This paper describes the morphology and processes associated with gravel barriers along the Olympic National Seashore and compares them to similar systems described by investigators along other shorelines of the world. In this study, barriers are defined as any shore-parallel, gravel ridge of marine origin with both seaward and landward slopes, including beach, swash, bar, berm, washover fans and flatforms (ORFARD and CARTER, 1982a). Gravel refers to particles which are at least 2 mm in diameter.

EVOLUTIONARY FRAMEWORK

An evolutionary framework for the development and morphology of gravel barrier coasts was given by CARTER *et al.* (1987). The model focuses on the North Atlantic coasts of Ireland and Canada. Several environmental factors seem to "precondition" the evolution of gravel barriers. Chief among those factors is a source of coarse-grained sediments. CARTER *et al.* (1987) and FORBES and TAYLOR (1987) point to paraglacial coasts, where large quantities of coarse-grained sediments are available to littoral processes.

The volume of coarse-grained sediments in the littoral zone also appears to influence the morphology of barrier development. For example, CARTER and ORFORD (1984) and ROSEN and LEACH (1987) found multiple symmetrical barrier ridges forming where sediment input was high; whereas a single asymmetrical ridge develops in regions of lower sediment availability. Furthermore, CARTER *et al.* (1987) found that changes in the delivery rate influence the morphological "stretching" of barriers along the shore between headlands.

Shoreline configuration and the position of headlands also influence gravel barrier development. First, headlands distort the incident wave field through refraction and diffraction. Headlands may also provide an important local sediment supply to the beach. Finally, headlands may control the rate and pattern of sediment transport along the coast (CARTER *et al.*, 1987).

Storm wave conditions are noted by many researchers as a major factor in gravel barrier development (ORFORD and CARTER, 1982a; BOYD *et al.*, 1987; CARTER *et al.*, 1987; FORBES and TAYLOR, 1987). In the British Isles, barriers with southwestern approaches are exposed to frequent, low-

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er magnitude storms associated with southwest to northwest passing cyclonic depressions. Deep-water storm waves often exceed 10 m in height and easily transport gravels along the shore (CARTER and ORFORD, 1984).

Finally, CARTER *et al.* (1987) and ORFORD *et al.* (1991) conclude that the evolution of barriers is associated with changes in relative sea level. Under a slowly rising relative sea level (<1 mm/yr) the erosion and dispersal of sediments is associated with patterns of sediment availability, shoreline configuration, and the capacity of the coastal system to store eroded products or disperse them beyond the coastal zone. Where a rapid relative sea level rise is occurring (>2 mm/yr) the potential for the barrier crest to become destabilized and washover to occur is much greater, significantly altering the morphology of the barrier.

BOYD *et al.* (1987) presented a six-state evolutionary model for barriers along the Nova Scotia coast. Stages 1 and 2 are the geologic and oceanographic pre-conditions necessary for barrier development. Stage 3 includes ample supplies of glacial sediments driven by littoral processes to form the barriers across estuary mouths. Sediment depletion and/or rapidly rising sea level leads to stages 4 and 5, frequent washovers and the ultimate destruction of the barrier. Rejuvenation occurs in Stage 6 as remnants of destroyed barriers become re-established in transgressive locations.

BARRIER MORPHOLOGY

Many researchers of coarse-grained beaches have observed zonation and sorting of sediments. BLUCK (1967) and ORFORD (1975) independently reported on a relationship between particle shape and zonation. Large flat disks dominate the barrier crest; disks, rods, and spheres tend to occupy the imbricate zone; and the infill zone consists of rods and spherical shapes infilled with finer clasts. The "outer frame" provides a seaward fringe to barriers consisting of cobbles underlain by sand or rock. Both researchers found a close association between particle shape and zonation.

The relationship between grain size, sorting and foreshore slope on mixed sand and gravel beaches was studied by MCLEAN and KIRK (1969) at various sites along the South Island of New Zealand's east coast, reporting on a strong linear relationship between grain size and beach slope. However, poorly sorted "mixed" sediments showed a more gradual increase in slope with coarsening grain size than did less sorted environments.

KIRK (1980) expanded on his work with McLean on mixed sand and gravel beaches. He divided the beach profile into zones: a backshore zone consisting of washover fans; a planar foreshore divided into a steep run-up zone and lower foreshore step; and a very steep nearshore face grading to gently sloping, fine sand. He also observed the welding of sediments to the foreshore during intervals of smaller waves and swell.

PROCESSES

An understanding of the threshold and conditions of transport of differing particle sizes and shapes remains incomplete, however, work at different coastal locations provides some insights. KIDSON (1963) operated on the hypothesis that counter drifts are responsible for the growth of shingle spits on both sides of an estuary mouth rather than spit breaching. He observed that larger grains often move in the opposite direction to smaller grains thus explaining opposing barrier formation exclusive of spit breaching.

CARR (1969, 1971) found that large clasts were stranded on the berm crest by large storm waves, whereas sediment samples from the lower intertidal zone tended to be bimodal in size. Pebbles were removed from circulation when they became buried or transported outside the limits of wave action. Backwash may roll or slide particles larger than dominant size downslope.

A long-accepted mechanism for storm beach sedimentation cites plunging breakers as the primary force by which gravel clasts are transferred up-beach (KING, 1972). However, ORFORD (1977) proposed a mechanism by which high tide levels, onshore storm force winds and associated wave surge and spilling breakers promote shoaling and beach profile changes.

ORFORD and CARTER (1982b) studied overtop and washover sedimentation at sandy-gravel barriers in southeast Ireland. They found overtopping deposition occurred when the swash just reached over the barrier crest leading to the accretion of the backbarrier.

Seepage, another frequent process associated with barriers, was also studied by CARTER and ORFORD (1984). The large grain size creates high permeability, allowing seepage to occur between backbarrier lagoons and the open sea. Thus tidal inlet processes are often absent due to the uninhibited seepage through barriers. Barrier sedi-

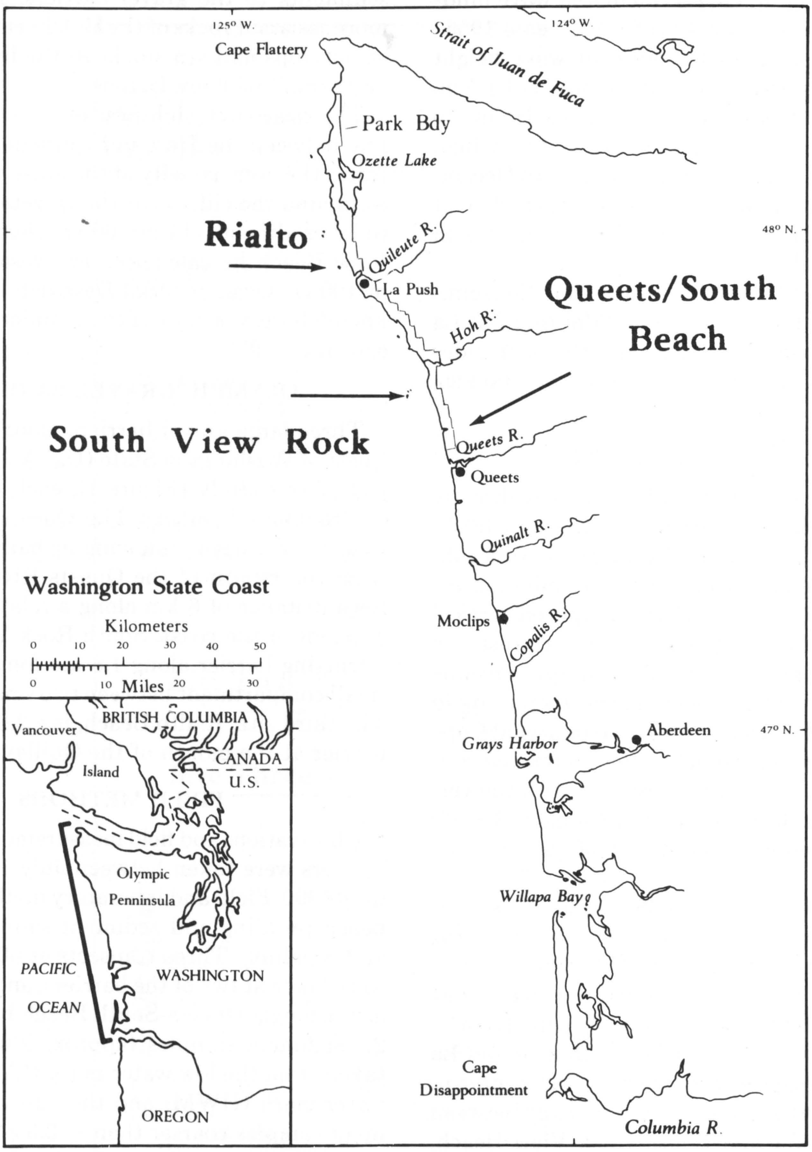

Figure 1. Study sites along the Olympic Peninsula of Washington State, USA.

ments are transported landward as a result of washover processes, but there is no comparable process for seaward transport due to seepage. As a result, gravel barriers migrate steadily landward.

STUDY AREA

The Olympic Coast stretches from the Quinault River north to Cape Flattery along the Pacific coast of Washington state (Figure 1). The Olympic National Park coastal strip has been under the jurisdiction of the National Park Service since 1953. It is one of the few undeveloped coastlines in the continental United States. Remarkably, few studies have been published on the coastal processes of this pristine region.

COASTAL ENVIRONMENT

Davies (1980) classified the entire Pacific Coast of Washington State as a storm-wave environment. CORSON *et al.* (1987) calculated wave hindcast statistics for this region for the years 1956–1975. The mean annual significant wave height (Hs) is 2.8 m, with a standard deviation of 1.3 m. This clearly exceeds the mean annual Hs of 1.0 m minimum used by BIRD (1984) to define high energy coasts. The highest waves occur in December with a mean monthly Hs of 4.3 m, the lowest in August with a mean monthly Hs of 1.5 m (BOURKE, 1971).

Tides on the Olympic Coast are of the semidiurnal mixed type. The spring tidal range at La Push is approximately 4.0 m and the neap tides about 2.0 m (U.S. ARMY CORPS OF ENGINEERS, 1974).

RELATIVE SEA LEVEL

The morphology of gravel barriers is directly impacted by relative sea level (CARTER *et al.*, 1987). ATWATER (1987) has provided evidence for a subsidence at selected Oregon and Washington estuaries. HOLDAHL *et al.* (1988) computed vertical velocity contours for the Pacific Northwest. On the Olympic coast, he found a 0.0 mm/yr hingeline in the vicinity of the Queets River, increasing in vertical velocity to greater than 2.0 mm/yr at Cape Flattery. He maintains that the increasing vertical uplift of the coast is consistent with the vertical deformation generated by a younger (6×10^6 yrs), hotter, more buoyant part of the Juan de Fuca plate.

WEST and MCCRUMB (1988) found some variation on the rates of the late Quaternary uplift based on the elevations of the Whiskey Run late Pleistocene high sea-level-stand terrace. They found vertical velocities on the Washington-Oregon coast between Cape Blanco, Oregon and La Push, Washington to vary from + 1.62 mm/yr to + 0.2 mm/yr. At Kalaloch, about midway between the Queets River and South Rock View Beach, the uplift rate sags to about + 0.3 mm/yr, which is less than the estimated Holocene eustatic worldwide sea level rise of 2.4 ± 0.90 mm/yr (PELTIER and TUSHINGHAM, 1989). Thus, along this section of the Olympic coast, the sea is rising faster than the land accounting for the submergence of the coast and ongoing sea cliff retreat.

SEA CLIFF EROSION

The unconsolidated Pleistocene deposits which make up much of the Olympic coast sea cliff are particularly susceptible to erosion. The glacial cliffs are an important source of coarse-grained sediments to the gravel barriers. However, the more resistant rocks of the Hoh Formation remain as outcrops and sea stacks in the intertidal zone or as small offshore islands.

The relative straightness of the Olympic coastline between the Hoh and Quinault Rivers illustrates the homogeneity of the erosion. RAU (1973) estimated the cliffs near the Queets River mouth to be eroding at 114 m/100 yr. Near South Rock View Beach he calculated an erosion rate of 90 m/100 yr suggesting that Destruction Island, 5.63 km offshore, was part of the mainland 6,000 years ago (RAU, 1973).

OLYMPIC GRAVEL BARRIERS

Three large gravel barriers along the Olympic Coast of Washington State (U.S.A.) were the subject of this study (Figure 1), each in a different environmental setting. The Queets River-South Beach site is a spit and fringing barrier extending from the mouth of the Queets River northward for a distance of 6 km along a relatively straight segment of the coast. South Rock View Beach is a fringing barrier along 1.6 km long occupying a small compartment between two small headlands. The third site, Rialto Beach, is a 2.6 km long spit barrier at the mouth of the Quillayute River.

FIELD METHODS

Observations and field measurements of all three barriers were taken between July 1988 and January 1990. Field and laboratory methods included beach profiling and sediment sampling, sieving, and weighing. Three transects at 500 m intervals were taken at two of the barriers, and six transects at the longer Queets-South Beach barrier (Figure 2). Sediment samples (approx. 500 grams) were taken from the low water mark (LWM), the high water mark (HWM) and the barrier crest. Sediment samples coarser than $-3.5\ \phi$ were individually measured along the intermediate axis (EMERY, 1955). Other samples were sieved using a Rotap shaker at $0.5\ \phi$ intervals to a size limit of $4.0\ \phi$ and each fraction weighed to 0.1 gram. A spreadsheet program was used to calculate the size fraction (%) of cobbles, pebbles and sand as well as the moment measures mean grain size (M) and sorting (SD) as described by FOLK (1966).

RESULTS AND DISCUSSION

Queets River-South Beach Barrier

This long barrier changes from a barrier spit to a fringing barrier along its 6 km length (ORFORD

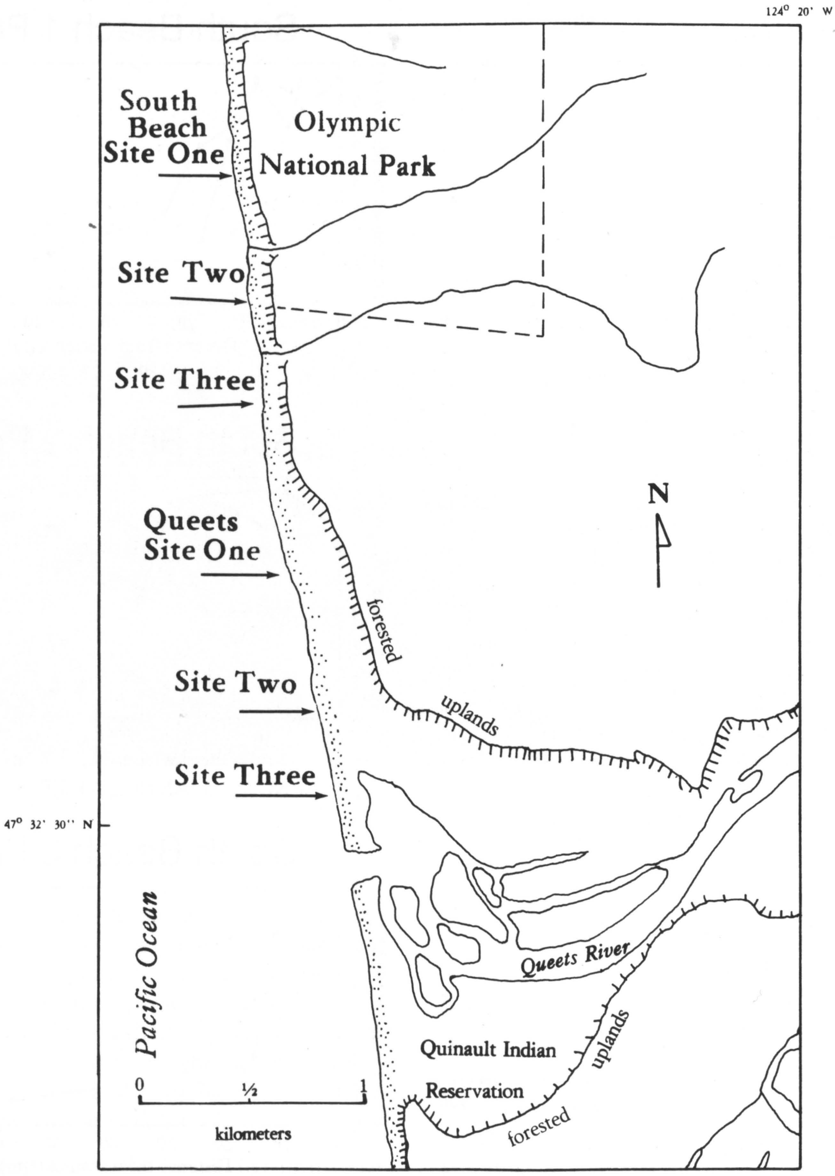

Figure 2. Queets-South Beach study sites.

and CARTER, 1982a,b). The 25 meter high glacial cliffs to the south and the Queets River are the primary sources of sediments to the barrier (PETERSON *et al.*, 1991). These cliffs are retreating at a rate of about 1 m/yr (RAU, 1973) with the northern end anchoring the barrier which stretches across the Queets River mouth (Figure 2).

The barrier crest reaches its highest elevations (6.5 m above MLW) about 1 km north of the river mouth. The crest elevation and barrier width progressively lowers and narrows to the north until the entire barrier pinches out.

Profiles across the barrier show some seasonal differences (Figure 3A and B). The winter foreshore slope steepens and the barrier crest lowers with increasing frequency of overwashing. It

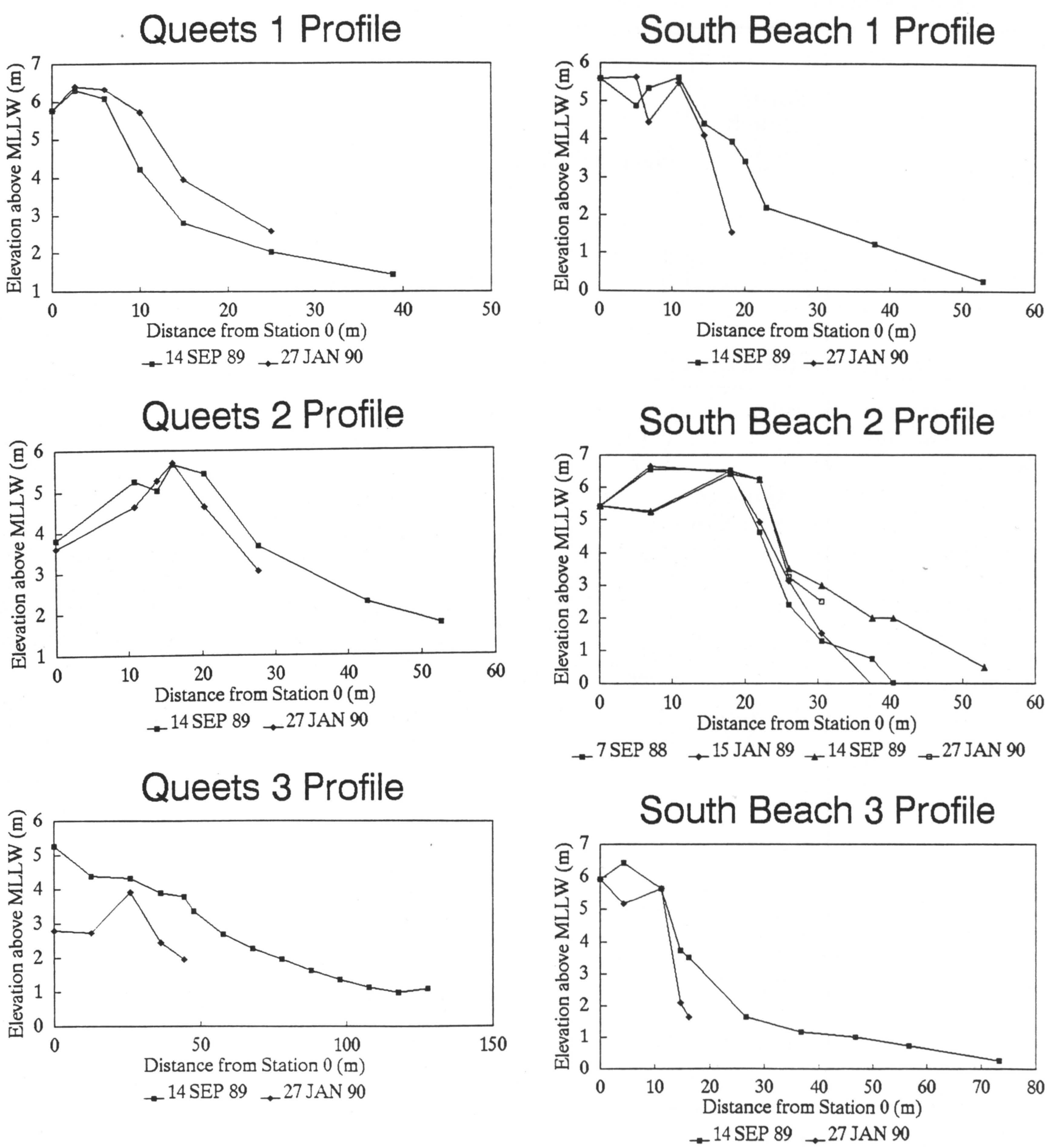

Figure 3A, B. Queets beach barrier study sites.

should be noted that profile irregularities at the barrier crest and backshore are greatly influenced by a dense driftwood cover.

At South Beach, the lower foreshore slope flattens in the summer because of sand deposition. In addition, a small berm, not seen in winter, becomes welded to the foreshore face.

Overwashing occurs most frequently along the lower elevations of the northern and southern ends of the barrier. Since the 1960's, the river mouth has shifted up to 1 km to the north then back to its present position. As a result, the barrier crest is lower, allowing for more frequent storm surge overwashing. Sediment is taken from the barrier crest and deposited as washover fans on the back-barrier (Figure 4).

Figure 4. Washover fans.

Where the barrier blocks small stream outlets, drainage across the barrier occurs by seepage (Figure 5). Small swales in the barrier are created at seepage sites becoming preferential locations for wave and swash driven drift logs to accumulate.

Analysis of the sediment characteristics sampled at six transects along the barrier yielded the following observations (Table 1A):

(1) At every transect the mean (ϕ) grain sizes increase with increasing elevation from the LWM to the barrier crest.
(2) Save for the three Queets transects where the sand contribution from the river is high, the mean size decreases downdrift (northerly) along the barrier.
(3) Sediment becomes coarser in the winter LWM and HWM, but much less so at the barrier crest. Even at the Queets transects, nearer the river, the sand fraction tends to drop out in the winter due to offshore transport of sand by storm waves.
(4) There is evidence for a downdrift decrease in sediment size.

South Rock View Beach

This 1.6 km long fringing barrier occupies a small compartment along the coast. Two small headlands, Wet Foot Point to the north, and Destruction Island Viewpoint to the south, anchor the ends of this barrier (Figure 6). The headlands are composed of massive sandstone of the Hoh Assemblage (Rau, 1973). The unconsolidated Pleistocene cliffs supply sediment to the barrier.

The barrier has probably evolved through three stages (Figure 7). First, loosely consolidated Pleistocene deposits dominated the shore, which retreated during the Holocene transgression. As blocks of more resistant Hoh Rocks were exposed, differential erosion occurred creating littoral compartments. The headlands become anchor points for the evolving barriers fed by the continuing erosion of the glacial cliffs. Eventually, the barrier

Figure 5. Seepage through the gravel barrier.

ends welded together. Presently, South Rock View Beach appears to be in stage 2 (barrier and estuarine sediment accumulation) in the BOYD *et al.* (1987) barrier evolution model. However, unlike the Boyd model, there is a forested wetland behind the barrier slowing its landward migration. The rate of sediment supply is expected to decrease as the glacial deposits, which once surrounded the resistant headlands, diminish. This decline in sediment supply will eventually lead to successive stages of the model, where the barrier, no longer anchored by the headlands, stretches along the shore and forested shore-bluffs (CARR and BLACKLEY, 1973).

Three transects each 500 m apart were established along the 1.6 km long barrier. Profiles and sediment samples were taken in September (late summer) and January (winter) (Figure 8). The barrier crest heights ranged from 5.0 m to 6.0 m above MLLW and the barrier width ranged from 20 m to 30 m at MSL. Each profile displayed a great deal of seasonal variability. All summer profiles have a distinct fair weather berm between the 3.0 m and 4.0 m elevations. In the field, this berm was clearly evident, stretching along the entire length of the barrier. Scattered drift logs lay on the accreted foreshore berm. In the winter, this berm was absent and the entire barrier foreshore changed into a concave upward profile similar to that noted by SHERMAN (*in preparation*) along the Irish coast. The crest and backshore is covered by drift logs (Figure 9). The logs are generally resting parallel to the shore interrupting wave overwash processes. During severe storm events, both the logs and overwash sediments are thrown against small sitka spruce trees, at the seaward edge of the forest, scaring the tree trunks and in some cases uprooting small trees. The drift log and standing trees behind the barrier slow but do not halt the landward migration of the barrier.

At South Rock View, the largest mean sediment size ranged between coarse pebbles ($-$ 4.0 to $-$ 5.0 ϕ) to very coarse pebbles ($-$ 5.0 to $-$ 6.0 ϕ). The mean grain sizes generally showed a downbeach decrease in size at all elevations both in summer and winter. One exception was site 1 (HW

Table 1. *Sediment size data.*
B. Winter (January 1990): South Rock View Beach barrier.

Sample	Size Fraction (%) c	p	s	M [ϕ]	SD [ϕ]
South 1					
LW	0	100	0	−4.0	0.4
HW	55.5	44.5	0	−6.0	0.6
Crest	60.1	39.9	0	−6.1	0.4
South 2					
LW	15.6	84.4	0	−4.9	0.9
HW	83.6	16.4	0	−6.6	0.6
Crest	45.6	54.4	0	−6.0	0.5
South 3					
LW	10.5	89.5	0	−4.9	0.5
HW	80	20	0	−6.3	0.5
Crest	79.4	20.6	0	−6.4	0.5
Queets 1					
LW	40.9	59.1	0	−5.9	0.7
HW	72.5	27.5	0	−5.5	0.5
Crest	22.6	77.4	0	−6.1	0.5
Queets 2					
LW	0	100	0	−5.7	1.2
HW	72.5	27.5	0	−6.4	0.7
Crest	86.9	13.1	0	−6.7	0.7
Queets 3					
LW					
HW	0	0	100	2.3	0.3
Crest					

B. Summer (September 1989): Queets, South Beach barrier.

Sample	Size Fraction (%) c	p	s	M [ϕ]	SD [ϕ]
South 1					
LW	0	0	100	2.3	0.2
HW	0	0	100	2.4	0.3
Crest	72	28	0	−6.2	0.5
South 2					
LW	0	0	100	2.3	0.3
HW	17	77.1	5.9	−4.5	1.9
Crest	47.3	52.7	0	−6.0	0.5
South 3					
LW	0	76.4	23.6	−2.7	2.6
HW	68.4	31.6	0	−6.2	0.4
Crest	82.1	17.9	0	−6.3	0.4
Queets 1					
LW	0	30.5	69.5	−0.2	3.5
HW	36.7	63.3	0	−5.7	0.9
Crest	76	24	0	−6.3	0.4
Queets 2					
LW	0	0	100	2.3	0.3
HW	45.2	43.1	11.7	−5.0	2.4
Crest	0	100	0	−5.2	0.5

Table 1. *Continued.*

Sample	Size Fraction (%) c	p	s	M [ϕ]	SD [ϕ]
Queets 3					
LW	0	0	100	2.3	0.2
HW	0	92.9	7.1	−4.0	1.8
Crest	28.9	71.1	0	−5.7	0.6

c = cobbles (−6 ϕ to −8 ϕ); (64 mm to 256 mm)
p = pebbles (−1 ϕ to −6 ϕ); (2 mm to 64 mm)
s = sand (4 ϕ to −1 ϕ); (1/16 mm to 2 mm)

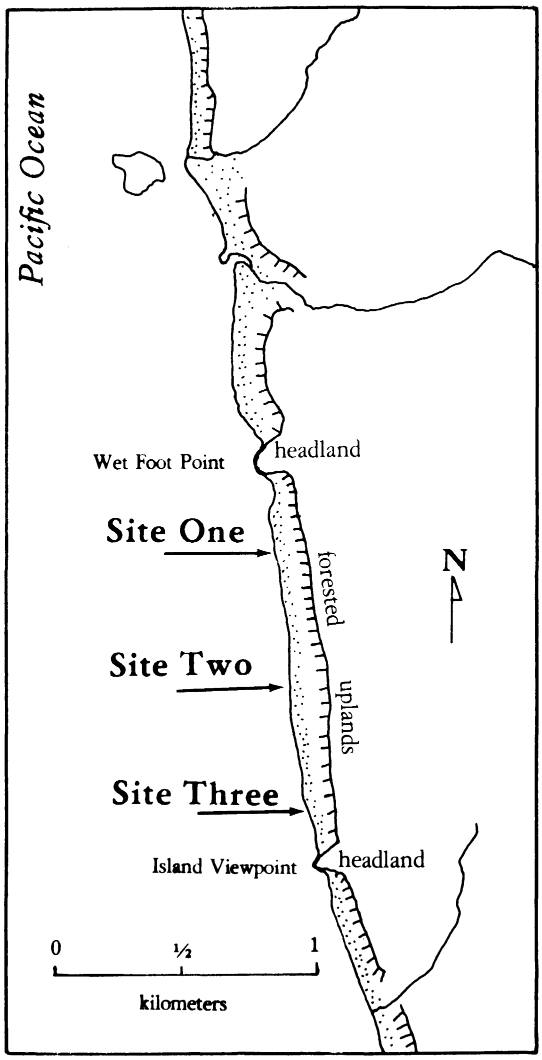

Figure 6. South Rock View study sites.

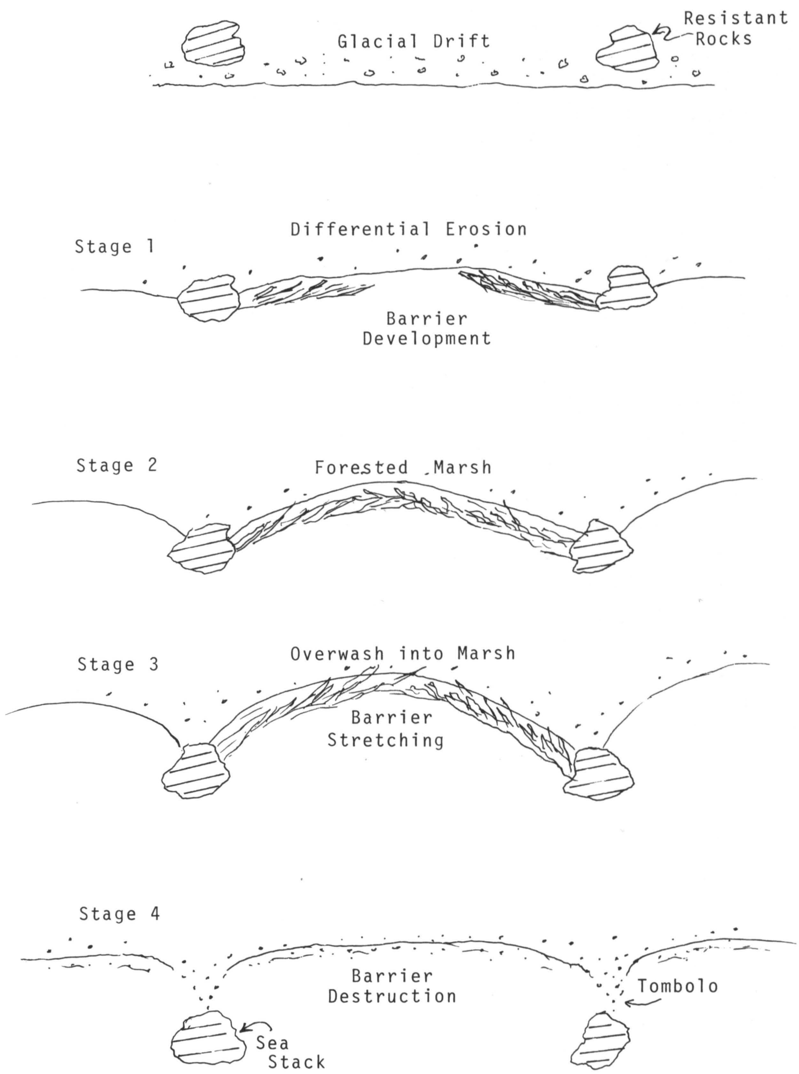

Figure 7. Model of Barrier Evolution.

- summer) where large drift logs had interrupted long shore transport. Similar to the Queets-South Beach barrier, mean sediment size increased with increasing elevation along the barrier. The sediment at the barrier crest showed the least seasonal change. This is because these sediments are out of reach of most wave activity and protected by a cover of drift logs.

Clast size variation shows opposite trends at the HWM and the barrier crest. Typically, sediment size decreases with distance downdrift (SCHWARTZ, *et al.*, 1985). However, the data show mean sediment size decreasing downdrift at the barrier crest, while it increases at the HWM. KIDSON (1963) noted a similar pattern on the Somerset coast of England, concluding that only large waves transport shingle along the beach face, whereas currents of any kind may carry smaller sediments in the opposite direction along the lower part of the beach. Although this barrier does not show a strong longshore variation, perhaps the sediment size data reflect differences in the mode of sedimentation at the barrier crest (KIDSON, 1963).

The greatest seasonal variation in sediment size occurred at the LWM. Summer samples were bimodal which corresponds with the findings of CARR (1969, 1971) at Chesil Beach, England. The winter increase in sand fraction is peculiar since it is expected that the sand would travel offshore during storms, leaving behind gravel.

Rialto Beach

The barrier at Rialto Beach is the most dynamic of the three barriers studied. The northern half is a fringing barrier, while the southern half, adjacent to the Quillayute River, is a barrier spit connecting James Island to the mainland (Figure 10). This barrier evolved as the coastline retreated during the Holocene marine transgression. The rate of relative sea level rise in this region is estimated to be 0.7 mm/yr (WEST and MCCRUMB, 1988). Glacial sediments associated with both the Cordilleran ice sheet and Olympic alpine glaciers were deposited across the mouth of the Quillayute River. Eventually, the coastline retreated into and beyond large resistant blocks of Hoh Rocks which stand today as James Island and Little James Island. The barrier's northern terminus is attached to the mainland at approximately transect site 1.

The mouth of the Quillayute River has changed throughout history. In 1882, the river mouth was located at its present position, just south of James Island (REAGAN, 1909), and by 1889 the mouth shifted nearly 2 km to the north (U.S. ARMY CORPS OF ENGINEERS, 1974). By 1911, the river discharged at its present position and the channel was stabilized in 1932 with the construction of a dike between James Island and the southern end of the barrier (U.S. ARMY CORPS OF ENGINEERS, 1974).

The Rialto Beach barrier is retreating, in the fourth stage of barrier evolution (BOYD, *et al.*, 1987). In this stage, sediment supply from the glacial cliffs has long since ended and the present position of the Quillayute River mouth no longer supplies sediment, leading to frequent overwashing and landward migration of the Rialto barrier. As a result, the barrier, which attached to the mainland to the north and James Island to the south, is "stretching" as it migrates landward and toward the Quillayute River. Waves frequently overwash the barrier, in some cases threatening to breach the barrier, allowing storm waves to reach the boat harbor across the river. Bulkheads, sediment fill, and rip rap have been used by the U.S. Army Corps of Engineers since 1953 to maintain the barrier. The middle section of the spit had been completely rip rapped by 1977. In 1980, the Corps built a 700 m long low tide line breakwater in front of the rip rap. It disappeared in less than three months time. In the summer of 1982, the Corps rebuilt and extended the rip rap

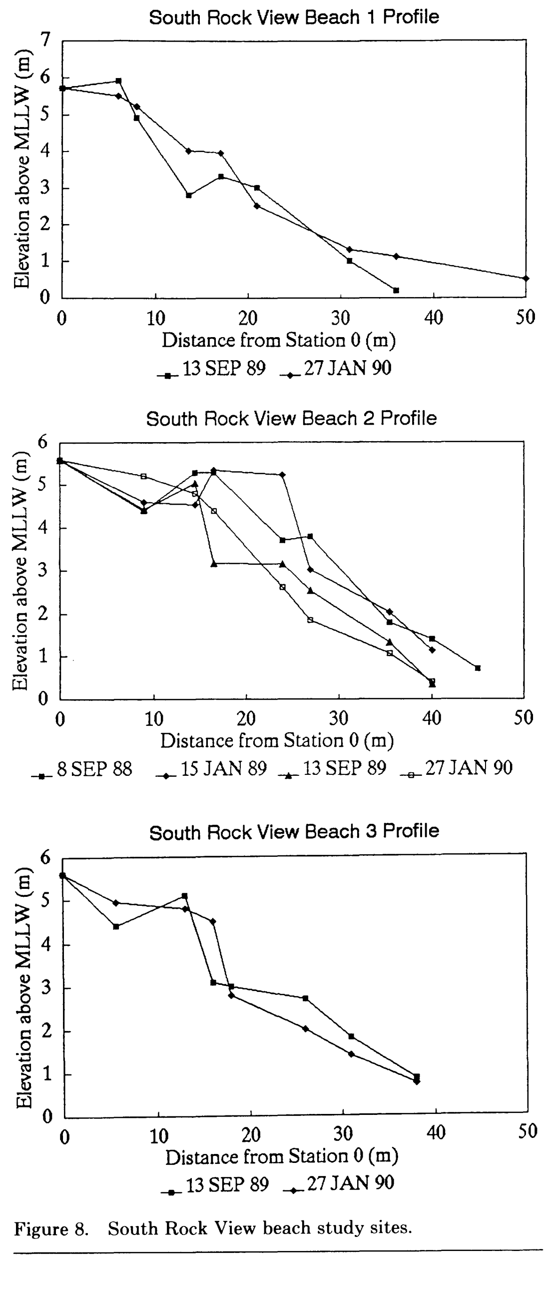

Figure 8. South Rock View beach study sites.

Figure 9. The upper barrier surface covered with drift logs.

dike to a length in excess of 800 meters (SCHWARTZ, 1983).

The barrier crest reaches about 6.5 m above MLLW at transect site 3, and about 5.5 m at site 2 (Figure 11). The width of the barrier is about 40 to 50 m at mean sea level (MSL). South of site 3, the barrier has been modified by rip rap.

Just north of site 1, the barrier "pinches out," no longer exhibiting typical fringing barrier morphology, and exposing wave-eroded Quaternary alluvial deposits (TABOR and CADY, 1978). There was no barrier crest to profile or sample at site 1, hence Table 3 presents no data for this site. Similarly, the profiles at site 1 show no morphologic evidence of a barrier, save one small summer berm at the 15 m mark.

Seasonal profiles from transects 2 and 3 are clearly asymmetrical, indicating barrier instability and frequent wave overtopping (CARTER and ORFORD, 1984). The landward (back barrier) slopes are gradual as compared to the seaward foreshore slopes. The steep beach face and presence of beach cusps indicates the beach is highly reflective. It is evident that frequent overwashing occurs along this part of the barrier and the entire barrier is retreating into the forested area (Figure 12). Profile 2 shows the barrier crest migrated inland nearly 10 m in one year, between September, 1988 and September, 1989. As it moves landward, trees are being killed by saltwater intrusion and eventually are toppled by high waves and drift logs. Overtopping and overwashing occur mainly during winter high tides and storms. Overwashed sediment flows into the Rialto Beach picnic area immediately behind the barrier (TIM MCDANIEL, *personal communication,* 1990).

Wave overtopping and overwash processes were observed during a major storm with gale force winds which struck on January 27, 1990. Storm waves washed gravel over the barrier crest. The movement of drift logs was also very active. Smaller drift logs on the beach face were easily moved by the huge breakers and in some cases taken out into the surf zone, while the largest logs, some up to 8 feet (2.5 m) in diameter (SWAN, 1971), reflected incoming waves. Some logs rolled down

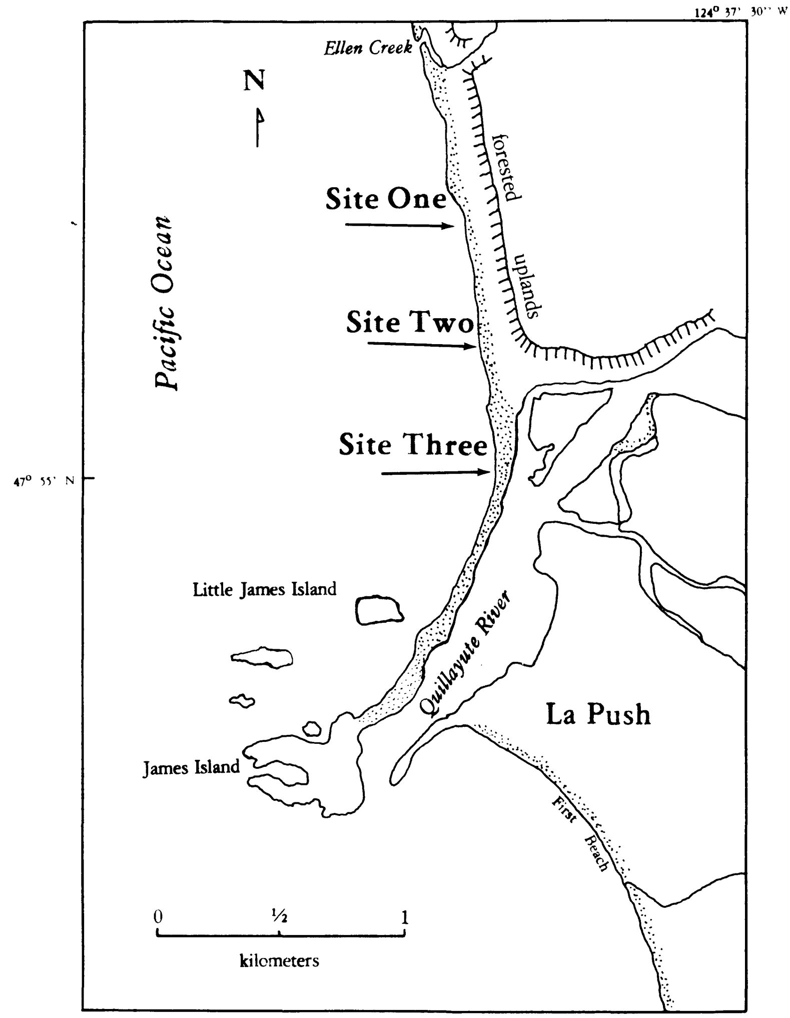

Figure 10. Rialto Beach study sites.

the beach face where intercepting waves would carry them to other locations along the shore. Those logs remaining on the barrier crest and back barrier interrupt overwashing, slowing the landward migration of the entire barrier.

Study of the seasonal sediment data reveals some similarities and differences with the other two barriers (Tables 1–3). First, like the other barriers, Rialto Beach sediments show a "coarsening" in the winter. Unlike the other barriers, the overall mean sediment sizes at nearly every elevation are smaller. Also, there tended to be a lower percentage of cobbles in the Rialto barrier as compared to the other barriers. One explanation could be the absence of cobble-sized gravels in the region leaving smaller gravels to dominate the barrier.

DISCUSSION AND CONCLUSIONS

The gravel barriers along the Olympic Coast of Washington State (U.S.A.) display many similar characteristics to those found in other parts of the world's coastline. As in the British Isles and Atlantic coast of Canada, the Olympic coast barriers have developed along a paraglacial coast where storm waves occur and glacial deposits are the major source of sediments.

There are also many contrasts between the

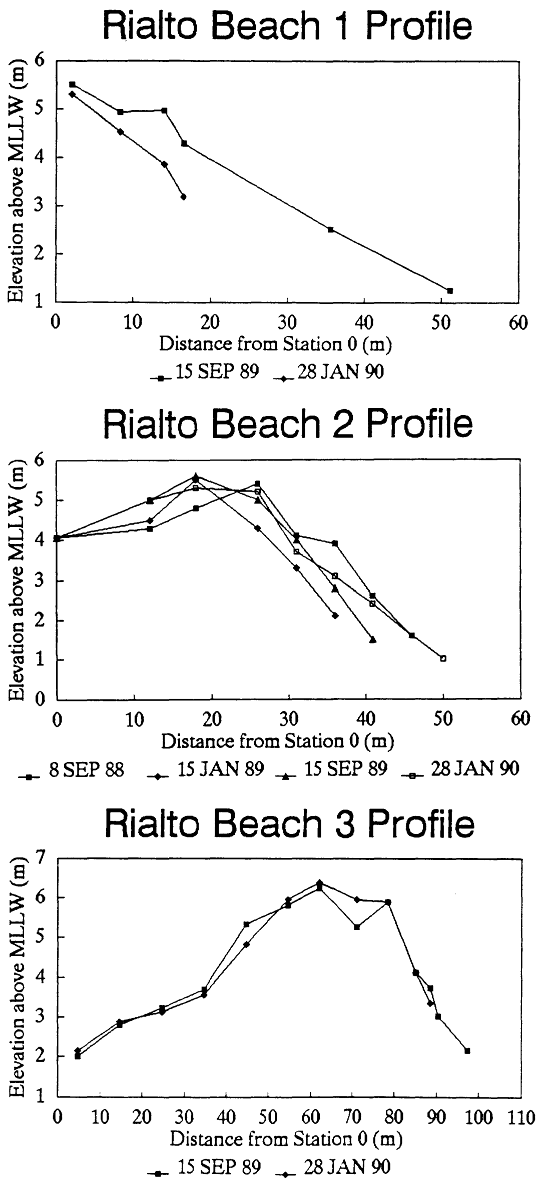

Figure 11. Rialto Beach barrier study sites.

Table 2. *Sediment size data.*
A. Summer (September 1989): South Rock View Beach barrier.

Sample	Size Fraction (%) c	p	s	M [ϕ]	SD [ϕ]
SRV 1					
LW	0	74.9	25.1	−1.9	2.5
HW	0	100	0	−5.3	0.5
Crest	0	100	0	−4.9	0.7
SRV 2					
LW	2.4	84	13.6	−1.9	2.5
HW	0	100	0	−4.4	0.7
Crest	25.4	74.6	0	−5.0	0.9
SRV 3					
LW	0	46.2	53.8	−0.7	2.8
HW	0	100	0	−4.4	0.7
Crest	12.4	87.6	0	−5.4	0.5

B. Winter (January 1990): South Rock View Beach barrier.

Sample	Size Fraction (%) c	p	s	M [ϕ]	SD [ϕ]
SRV 1					
LW	0	0	100	2.5	0.3
HW	0	100	0	−4.9	0.5
Crest	19.1	80.9	0	−4.9	1.0
SRV 2					
LW	0	24	76	0.8	2.5
HW	0	100	0	−4.5	0.4
Crest	9.7	90.3	0	−5.1	0.5
SRV 3					
LW	0	0	100	2.3	0.4
HW	0	100	0	−4.2	0.7
Crest	12.9	87.1	0	−5.4	0.5

c = cobbles ($-6\ \phi$ to $-8\ \phi$); (64 mm to 256 mm)
p = pebbles ($-1\ \phi$ to $-6\ \phi$); (2 mm to 64 mm)
s = sand ($4\ \phi$ to $-1\ \phi$); (1/16 mm to 2 mm)

Olympic barriers and those described elsewhere. Resistant headlands tend to anchor the Olympic barriers, while in Nova Scotia, eroding drumlins not only serve as anchors but are the primary sediment sources. Nearly all of the surveyed Olympic barriers displayed the development of a summer-type profile similar to those at Malin Head, Ireland (SHERMAN, *in preparation*). The sediment size data showed coarsening with elevation on the barriers and a bimodality at the lower foreshore. On the Olympic coast, sediment size is dictated by sediment source, which in most cases was glacial outwash or river sediments. In Nova Scotia, however, sediments up to boulder size are found because the sediment source is poorly sorted diamicts from drumlim headlands.

Seepage across barriers occurs on the Olympic coast as it does in southeast Ireland (CARTER *et al.*, 1984). On the Olympic barriers, seaward seepage occurs draining back barrier streams. On the Irish coast, the seepage process drains both low discharge streams and lagoons. Landward seepage has been noted both in southeast Ireland and at Chesil Beach, England (CARR and BLACKLEY,

Figure 12. The migrating barrier invades and kills the forest trees.

1974), due to extremely high tides or storm conditions. On the Olympic coast, there was no evidence of landward seepage.

The three barriers studied along the Olympic coast appear to be in three different stages of evolution (BOYD *et al.,* 1987). The Queets-South Beach barrier is in stage 3 of the evolutionary model. The high glacial cliffs continue to provide a positive sediment yield, which delivers sediment well beyond the Queets River estuary forming a downdrift fringing barrier. Except near the river mouth, this barrier showed the least amount of wave overtopping and sediment overwashing of the three barriers. The relative stability of this barrier is also shown by the little summer versus winter change in profile and sediment size proportions.

South Rock View Beach also appears to occupy stage 3, but it is moving into stage 4 (BOYD *et al.,* 1987). Unlike the Queets-South Beach barrier, this barrier has a diminished sediment supply. The dense mat of drift logs that covers the top of the barrier and the forest into which it is migrating are slowing the evolution of the barrier into stage 4-barrier retreat.

The barrier at Rialto Beach is clearly in retreat (stage 4) and nearing destruction (stage 5). Sediment is no longer available for rebuilding or poststorm recovery. The crest occupies a progressively landward position and overwashing is a frequent event. This barrier has the least amount of cobble sized sediments indicating a long past supply loss. Here, as at South Rock View Beach, the evolutionary stages are slowed by drift logs and the forest into which the barrier is migrating. Nonetheless, the evolutionary processes are operating and this barrier, which shelters small boats moored on the Quillayiate River will require maintenance rip rapping.

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Table 3. *Sediment size data.*
A. Summer (September 1989): Rialto Beach barrier.

Sample	Size Fraction (%) c	p	s	M [ϕ]	SD [ϕ]
Rialto 1					
LW	0	57	43	−1.7	2.6
HW	0	0	100	−4.6	1.4
Crest					
Rialto 2					
LW	0	30.9	69.1	0.1	1.5
HW	11.7	85.5	2.8	−4.5	1.5
Crest	13	85.5	1.5	−4.0	1.4
Rialto 3					
LW	0	91.8	8.2	−0.7	1.9
HW	0	100	0	−4.4	0.5
Crest	8.8	91.2	0	−4.2	1.0

B. Winter (January 1990): Queets, Rialto Beach barrier.

Sample	Size Fraction (%) c	p	s	M [ϕ]	SD [ϕ]
Rialto 1					
LW	3	97	0	−3.6	1.0
HW	0	100	0	−4.4	0.5
Crest					
Rialto 2					
LW	0	3.5	96.5	0.2	0.9
HW	0	96.6	3.4	−3.3	1.0
Crest	11.7	88.3	0.1	−4.9	0.7
Rialto 3					
LW	0	91.8	8.2	−1.5	0.7
HW	0	100	0	−3.0	0.5
Crest	11.1	88.9	0	−5.0	0.7

c = cobbles ($-6\ \phi$ to $-8\ \phi$); (64 mm to 256 mm)
p = pebbles ($-1\ \phi$ to $-6\ \phi$); (2 mm to 64 mm)
s = sand ($4\ \phi$ to $-1\ \phi$); (1/16 mm to 2 mm)

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□ RÉSUMÉ □

Les trois barrières de graviers étudiées le long de la côte Olympique (Etat de Washington) montrent des caractères morphologiques et texturaux semblables à ceux des barrières des côtes d'Irlande, d'Angleterre et de Nouvelle Ecosse. Deux d'entre elles sont ancrées sur des promontoires résistants; ces derniers ne sont toutefois pas une perèquation nécessaire à leur développement. Ces barrières semblent suivre un modèle de développement et de destruction en évolution, quelque peu semblable à ceux de la littérature avec une différence: aucune des trois barrières ne migre vers des lagunes ou des estuaires, mais vers des marais recouverts de forêts ou des hautes terres et dans l'un des cas, les arbres sont tués par l'intrusion d'eaux salées et de graviers.—*Catherine Bousquet-Bressolier, Géomorphologie E.P.H.E., Montrouge, France.*

□ RESUMEN □

En la costa Olympic del Estado de Washington, se estudiaron tres barreras de grava, que muestran una morfología y características texturales similares a las barreras de las costas de Irlanda, Inglaterra y Nueva Escocia. Los cabos resistentes sirven como puntos de anclaje para dos o tres barreras. Sin embargo, estos cabos, no son un prerequisito necesario para el desarrollo de las mismas. Esta barreras parecen seguir modelo de evolución de desarrollo y destrucción, similares a los mencionados en la literatura pero con una diferencia: Ninguna de las tres barreras se hallan migrando hacia lagunas o estuarios, pero si hacia las marismas o tierras elevadas, y en algunos casos la intrusión de agua salada y grava mata a los árbles.—*Néstor W. Lanfredi, CIC-UNLP, La Plata, Argentina.*

□ ZUSAMMENFASSUNG □

Drei Schotterstrandwälle wurden an einem Küstenabschnitt des Staates Washington (USA) untersucht, der den Olympic Mountains vorgelagert ist. Morphologie und Textur dieser Strandwälle sind denen an den Küsten Irlands, Englands und Neuschottlands vergleichbar. Widerständige Küstenvorsprünge dienen als Ankerpunkte für zwei der untersuchten Strandwälle. Diese Vorsprünge sind aber nicht notwendige Voraussetzung für die Entwicklung der untersuchten Wälle. Diese scheinen einem klassischen Entwicklungsmodell zu folgen, in dem sich Aufbau und Zerstörung abwechseln, wie dieses auch von anderen Lokalitäten berichtet wird. Im Unterschied hierzu wandern aber alle drei Strandwälle nicht in eine Lagune oder ein Ästuar, sondern in bewaldete Marschen und höhergelegene Flächen außerhalb des Tidenbereiches; in einem Fall werden sogar die Bäume durch die Intrusion von Salzwasser und durch Schotter vernichtet.—*Ulrich Radtke, Geographisches Institut, Universität Düsseldorf, Germany.*