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Lecture 6: Beach and barrier coasts

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Colin Woodroffe (2002) “Coasts: Form, Process and Evolution”, Outline of Chapter 6:

6.1. Historical Perspective, 6.1.1. Beach Studies

Equilibrium Profile -- Wave asymmetry vs. gravity
- Cornaglia (1889) – wave asymmetry vs. gravity
- Cornish (1898) – null point hypothesis (stable point for particular grain size)
- Johnson (1919) – bathymetric surveys

Entropy-maximizing profile
- Keulegan & Krumbein (1949) – uniform dissipation of energy
- Bruun (1954) – exponential profiles
- Dean (1977) – $y = Ax^{2/3}$ for over 500 US beach profiles

World War II landings – ONR studies of beach morphology
- Shepard (1940s) – summer constructional swell vs. winter erosional storm beach
- Davies (1950s) – refraction drives longshore transport and beach straightening

Modern beach studies – 1970s to today
- 1970s Data explosion – Davis, Fox, Komar
- 1980s Beach morphodynamic states – Wright/Short/Thom

6.1.2. Barrier Studies
- Evolution from submarine bars or platforms – Beaumont (1845), Johnson (1919)
- Drowning of coastal ridges – McGee (1890)
- Spit elongation – Gilbert (1885), Penck (1894)

6.2. Beach Morphology; 6.2.1. Beach Planform

Compartments – sections of coast separated by headlands that act as major barriers to longshore transport. Compartments are often relatively large scale.

Littoral cells – sections of coast in which sediment is circulated. Sediment can be communicated ("leak") across cells. Cells occur at multiple scales, e.g., rip cells, cells bounded by sandy inlets, cells between sandy capes, cells bounded by canyons, by rivers, by headlands.

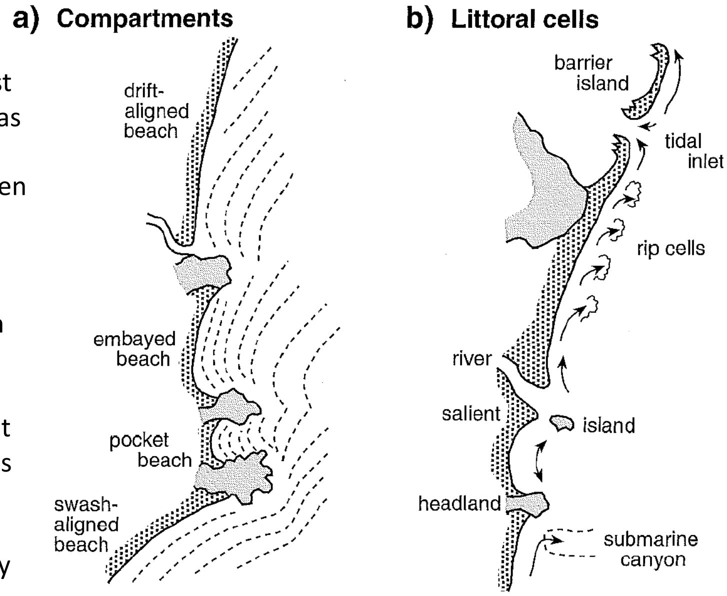


Figure 6.2. Sediment compartments and littoral cells along a coast. (a) Several sediment compartments similar to these examples can be seen in Figure 6.1. (b) Littoral cells can occur bounded by 'fixed' natural topographic features, or they may be 'free', and liable to change.

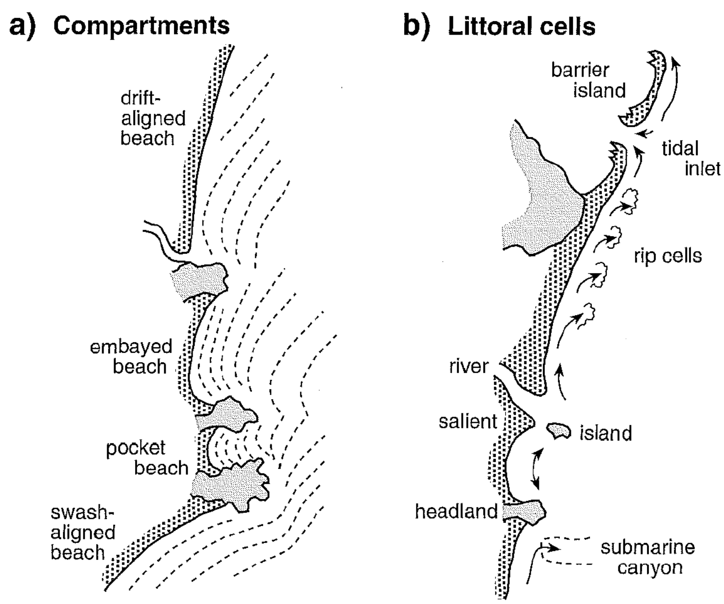
Drift-aligned beach – waves arrive at an angle, leading to longshore transport. Drift-aligned beaches tend to be straight and long. (If not straight, transport convergence/ divergence will occur.)

Swash-aligned beach – waves arrive parallel to beach. Minimal longshore transport. Swash-aligned beaches tend to be more curved to compensate for irregular refraction.

Embayed/pocket beach – Increasing shoreline curvature with increasing confinement by headlands.

Fixed littoral cell – Cell fixed in space by permanent feature like headland, island, breakwater, groin or jetty.

Free littoral cell – Cell able to move in space, e.g., bound by bars, spits, sandy inlets, etc.



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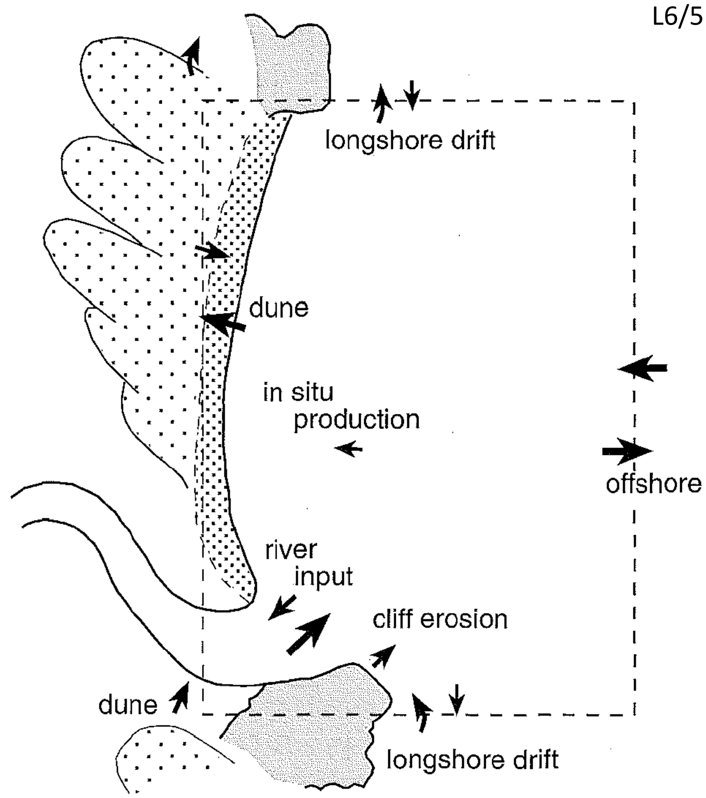
Compartment Sediment Budget

Example sources
-- rivers
-- dune/cliff erosion
-- in situ production
-- beach nourishment

Example sinks
-- dune growth
-- overwash
-- tidal inlets, -- estuaries
-- canyons

Example sinks/sources
-- exchange with offshore
-- longshore drift

Events which change terms
-- storms, -- floods
-- wind direction
-- wave direction
-- sea level
-- coastal development



(Woodroffe Fig. 6.3)

Littoral power = additive function of angle of incidence (up to 45 deg) and wave power.

Wave power increases at headlands and decreases at embayments due to refraction.

Longshore component of wave power is very sensitive to incoming wave angle.

Sediment transport rate is proportional to longshore component of wave power.

Spatial gradients in sediment transport determine net erosion or deposition.

Therefore the littoral power gradient predicts patterns of shoreline erosion or deposition.

Shoreline is stable if littoral power gradient is zero (dashed case in (b)-(d)).

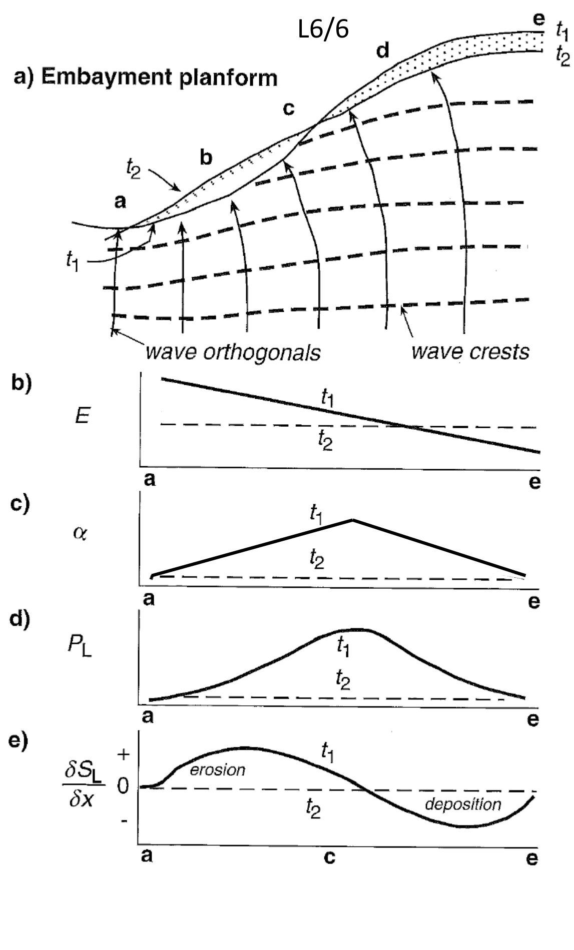
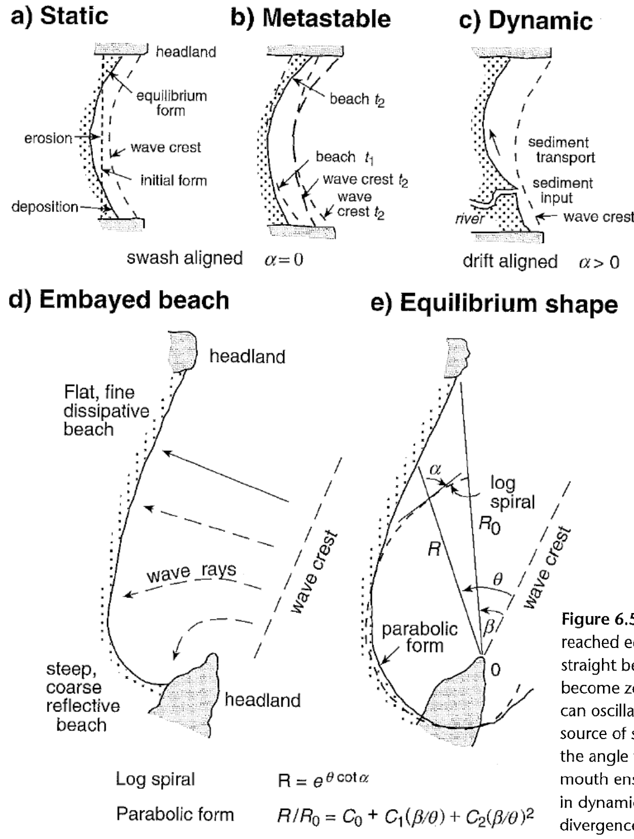


Figure 6.4. The concept of littoral power gradient (after May and Tanner, 1973). (a) Embayment planform, (b) wave energy, (c) angle of wave approach, (d) longshore component of wave power, and (e) sediment transport rate. Wave energy decreases into an embayment whereas longshore wave power is a function of the angle that waves make with the shoreline. Where the waves reach the shoreline parallel, there is no angle of incidence and hence no net movement of sediment. Points (a)–(e) define the cell. See text for discussion.



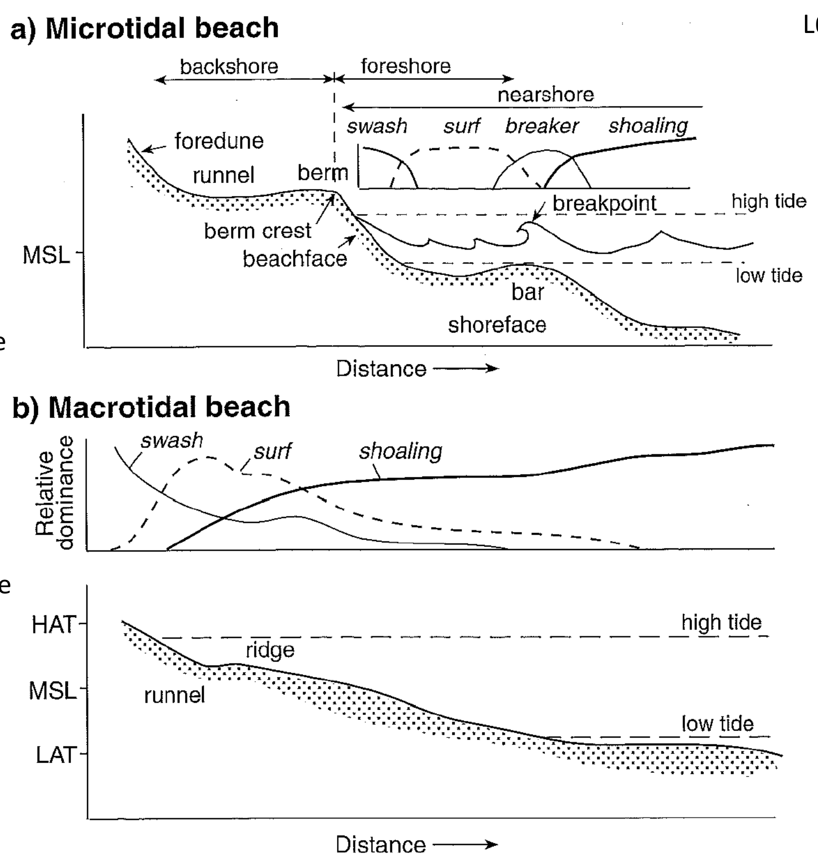
In the absence of sediment input, beach planform tends to evolve toward shapes that minimize the incident angle as influenced by refraction.

With continual sediment input, non-zero incident angle is required to drive sediment away from sediment source in a dynamic equilibrium (case (c)).

Extreme shoreline curvature results in an embayed beach in order to keep angle zero throughout. Also, changes in H drive changes in beach steepness.

Figure 6.5. Planform equilibrium of beaches. (a) An embayed beach that has reached equilibrium (based on Rea and Komar, 1975; Komar, 1998). An initially straight beach will adjust to reduce the angle of wave approach at all points to become zero. (b) Where wave trains come from different directions, the beach can oscillate or rotate, an example of metastable equilibria. (c) If there is a source of sediment, in this case a river, the beach will continue to accrete and the angle that wave crests make to the sand added to the beach at the river mouth ensures its distribution along the beach. The beach is drift-aligned, and in dynamic equilibrium. (d) An embayed, or zeta-form, beach, showing the divergence of wave orthogonals behind a controlling headland. (e) Contrasting characterisation of an embayed beach by log-spiral or parabolic geometry

6.2.2. Beach Profile



4 wave zones: shoaling, breaker, surf, swash

5 morphologic zones: foredune, runnel, berm, beachface, bar

backshore = zone above normal high tide

beachface = zone b/w high & low tide

shoreface = from berm crest to depth of closure

Macrotidal beach = less distinct because zones move with tide, smearing morphology

(Woodroffe Fig. 6.6)

Shoreface Equilibrium:
Gravity vs. Wave Asymmetry

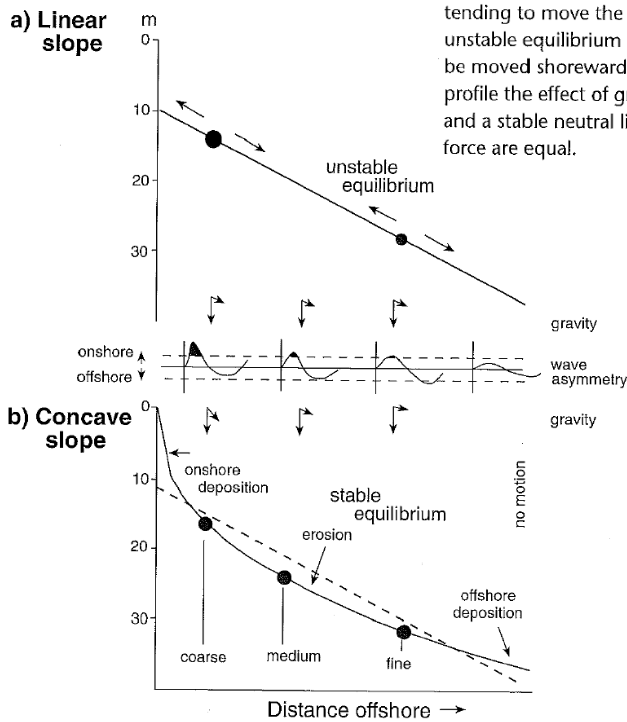


Figure 6.7. The concept of an equilibrium profile as envisaged by Cornaglia (1889). (a) The case of a linear slope, and (b) the case of a concave slope. Wave asymmetry increases closer to the shore. A neutral line (null point) exists at which sediment of particular grain size reaches an equilibrium between the effect of wave asymmetry tending to move the grains onshore and gravity tending to move the sediment offshore. On a linear slope the null point is an unstable equilibrium because if the grain is displaced from the null point it will be moved shoreward by wave velocities or seaward by gravity. On a concave profile the effect of gravitational force increases shoreward as slope increases, and a stable neutral line can be envisaged where gravitational force and wave force are equal.

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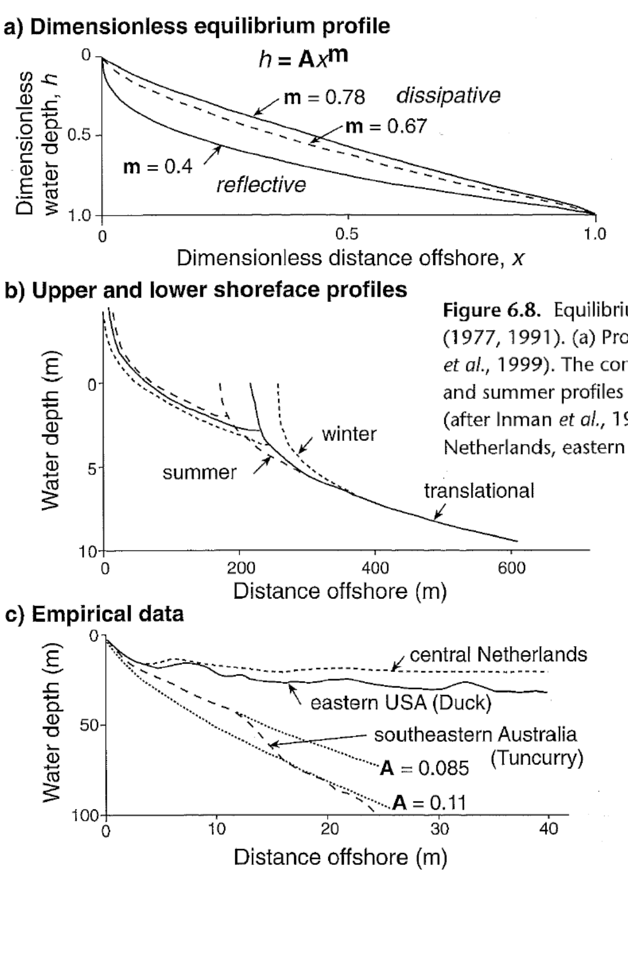


Shoreface Equilibrium:
Maximum Entropy/
Uniform Energy Dissipation

Figure 6.8. Equilibrium shore profile following the concepts proposed by Dean (1977, 1991). (a) Profile shape expressed on dimensionless scale (after Cowell *et al.*, 1999). The constant A expresses the shape factor. (b) Variation of winter and summer profiles recognising an upper bar-berm and a lower shorerise (after Inman *et al.*, 1993). (c) Comparison of offshore profiles from central Netherlands, eastern USA and southeastern Australia (after Cowell *et al.*, 1999).

1. Assume wave breaking produces a uniform distribution of energy dissipation (with logic is that net sediment transport is proportional to energy dissipation).

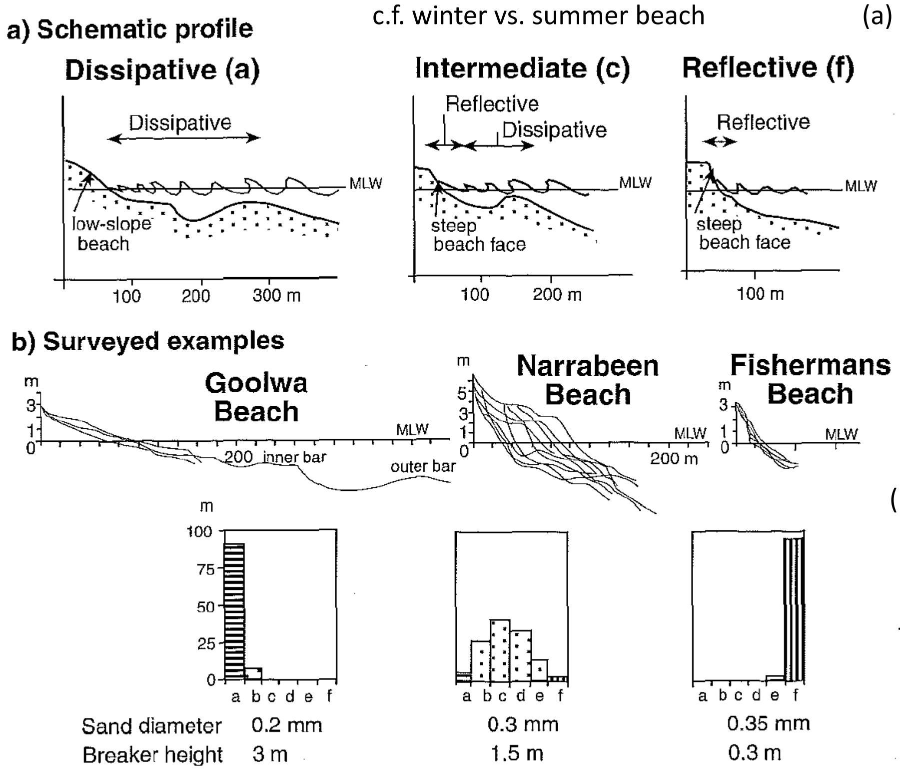
2. Solution yields a profile of form:

depth $y = Ax^m$

A = “shape factor” related to sediment properties

6.3. Beach Morphodynamics; 6.3.1. Beach Types (Wright & Short, 1984)

c.f. winter vs. summer beach



(a) Dissipative = flatter, finer sediment, larger waves, wider surf zone, smaller sub-aerial beach volume

(c) Reflective = steeper, coarser, smaller waves, narrow surf zone, larger sub-aerial beach volume

(b) Intermediate = larger bar, often 3D w/rip current cells

Type = function of grain size, wave height (& period)

(Woodroffe Fig. 6.9)

6.3.2. 3-D Beach Morphology

Cusps types (w/lengths):

- Swash cusps (8 – 25 m)
- Storm cusps (70-120 m)
- Giant cusps (700-1500 m)

Favored by coarser sediments and low to moderate wave energy breaking directly on beach.

Associated with edge waves.

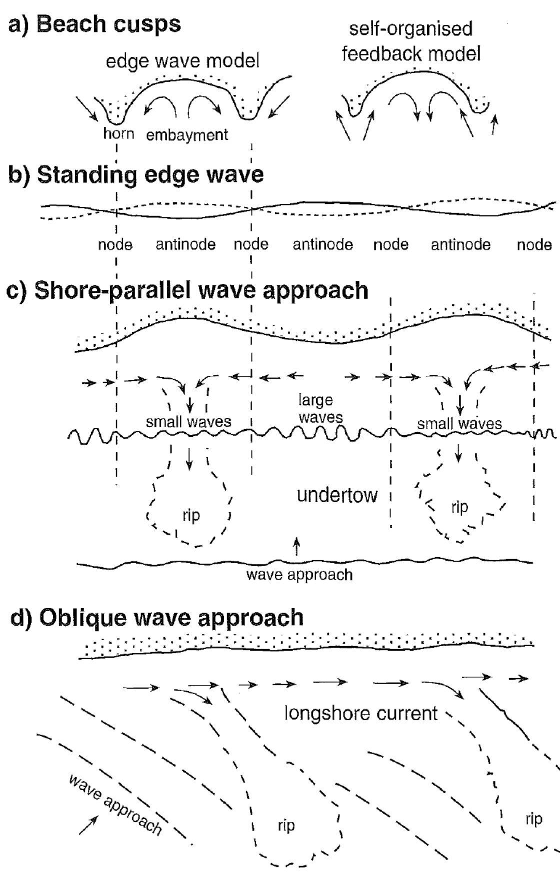
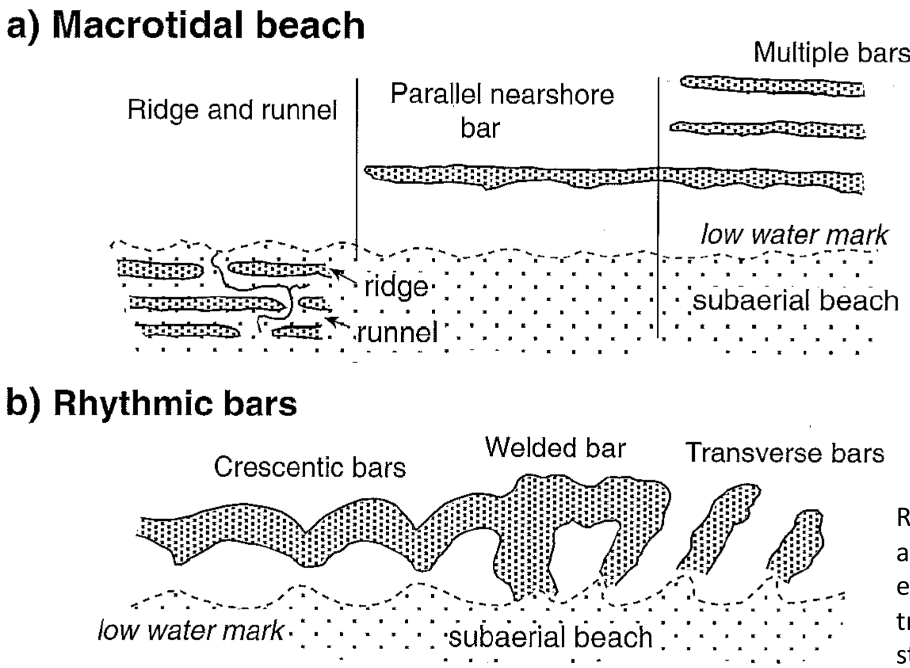


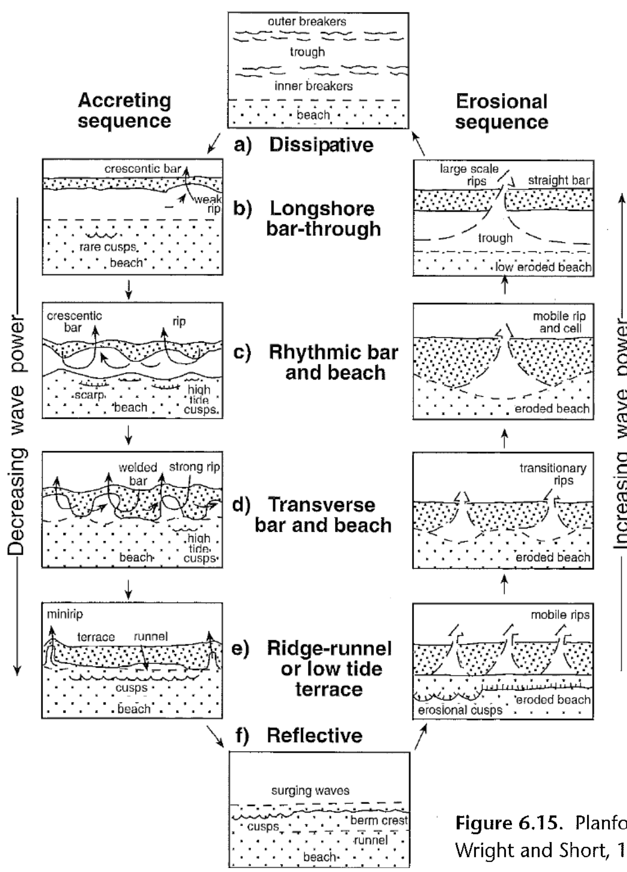
Figure 6.12. Rhythmic cusps and the occurrence of rip currents, undertow and longshore currents in the surf zone. (a) Beach cusps may form either as a result of edge waves (here shown in phase with edge waves), or through self-organisation and feedback (based on Holland and Holman, 1996). (b) Development of a standing edge wave along the shore; no variation occurs in water level at nodes. (c) Relation of rip currents to edge waves (based on Komar, 1998). (d) Longshore current where waves approach the shore obliquely.

Bar types: e.g., multiple, shore parallel or oblique, continuous or compartmented, linear, sinuous, or crescentic. Large steady waves favor single bar, large tides favor multiple bars.



Rhythmic bars associated with edge waves, transition between states, antecedent geology.

Figure 6.14. Bars found on beaches. (a) Beach planform, showing types of shore-parallel bars. (b) Types of rhythmic bars.



6.3.3. Beach Variation Over Time

Northern hemisphere = response to seasons (winter vs. summer waves).

Australia = response to temporal wave changes less tied to seasons.

Erosion usually occurs more rapidly than accretion.

During accretion, bar becomes rhythmic as it migrates landward and welds onto shore.

During erosion, multiple rips develop as erosional features in the shoreface, merging into fewer and fewer rips as a straight bar reforms offshore.

Relict states persist during accretion.

Figure 6.15. Planform evolution of beach states (based on Short, 1979, 1999b; Wright and Short, 1984; Sunamura, 1989; Lippman and Holman, 1990b).

6.4. Beach and Backshore Change Over Decadal-Century Time Scales

Common time scales for response – tidal, diurnal, storm, seasonal, ENSO, PDO

"Sediment transport equations, often linearising complex non-linear relationships, are poor predictors of long-term patterns of change… Morphodynamic approaches offer valuable alternatives to the scaling up of fluid dynamics." (p.289)

6.4.1. Recession, Accretion and Stable Shorelines

-- 90% of world's beaches are eroding at decadal scales

Major causes contributors to new erosion – Sea level rise, reduced sediment supply (natural or human-induced), increased wave energy.

Long-term monitoring: direct repeated surveying (e.g., Duck, NC; Moruya, Warilla, Stanwell Park, NSW)

Sweep zone = region of active morphological subaerial change on a beach over a given period.

Decadal sweep zone active volumes ~25 m^3/m (U.S.) to 200 m^3/m (Australia)

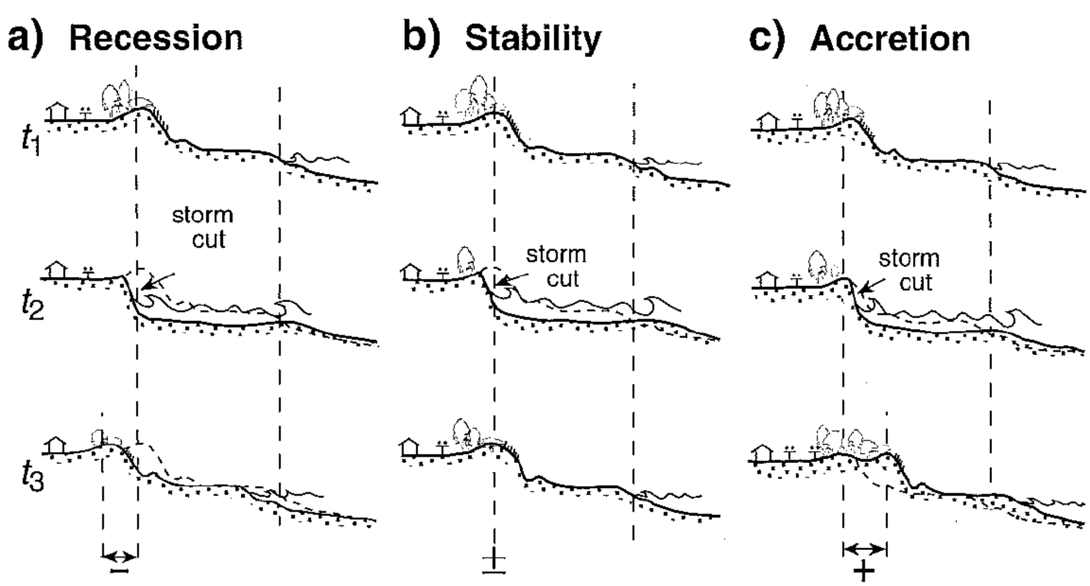
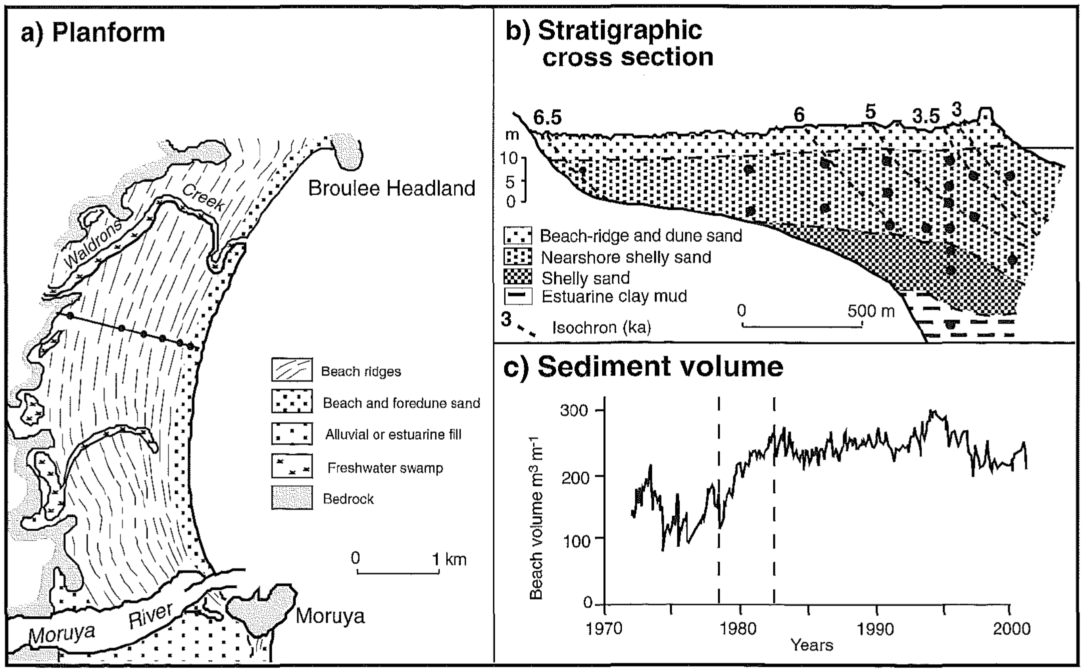


Figure 6.17. A beach undergoes erosion and subsequent recovery, but the extent to which the long-term profile shows (a) recession, (b) stability and (c) accretion can vary.

Moruya Beach, NSW: Monitored 30+ yr, 1970s erosion by storms, early 1980s rapid accretion, late 1980s to 2000 relatively stable. Embayment shows long-term accretion. Decadal sweep volume 200 m^3.



(Woodroffe Fig. 6.18)

6.4.2 Beach Ridges

Ridge = an along-shore continuous mound of beach/dune material formed in part by waves and currents, but located beyond the present limited of common storm waves or ordinary tides.

Ridges can be built by waves (c.f. berm crest) during storms/periods of high water levels and reinforced by wind-blown deposits. Falling sea level or prograding beach can isolate ridges inland.

Multiple beach ridges (“beach ridge strandplain”) are common to accreting beach coastlines. Past ridges can be used to date previous shorelines.

6.4.3 Beach-Dune Interactions

Dune = hill of sand formed by aeolian processes. Formation favored by: on-shore directed winds, large supply of fine sand available for wind movement, vegetation to stabilized dune growth.

Foredunes = first dune ridge forming at the back of the beach (at landward edge of backshore).

On- and offshore winds couple beach and dune. Dune can be beach sand reserve during erosion.

Causes of beach-dune decoupling: Dune vegetation (keeps wind from blowing sand back to beach), armoring of beach by coarse lag (isolates fine beach sediment from wind movement).

Wide beaches favor dune formation (e.g., dissipative beaches, finer sediment beaches, large tide range beaches) because of extensive exposure to across-shore wind.

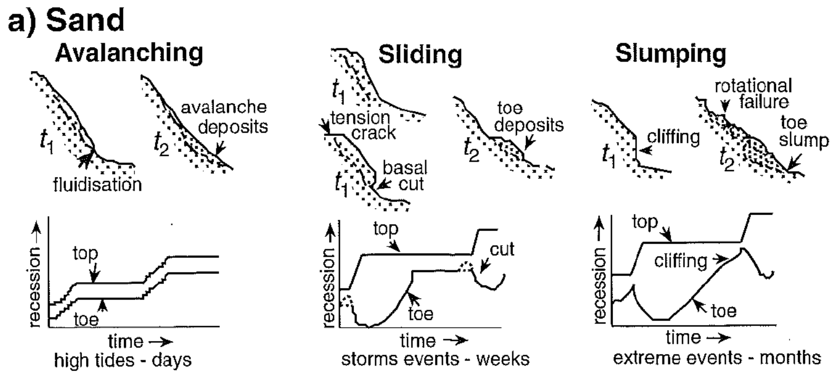
Initial dune growth: Favored by a backshore beach perturbation that locally slows wind, e.g., clump of vegetation, fence, wave-formed beach ridge, trash.

Dune vegetation: Sand binding plants on foredune, other shrubs and trees behind foredune. Species zoned by exposure on foredune (e.g., salt, wind, arid tolerant). Dunes can be "arrested" or preserved by vegetation when physical processes alone would favor migration or erosion.

Stabilizing vegetation and abundant beach sediment favors a continuous linear foredune. Less vegetation and more sediment bypassing favors irregular, lower and hummocky dunes. Dune growth can be facilitated or easily destroyed by human impacts.

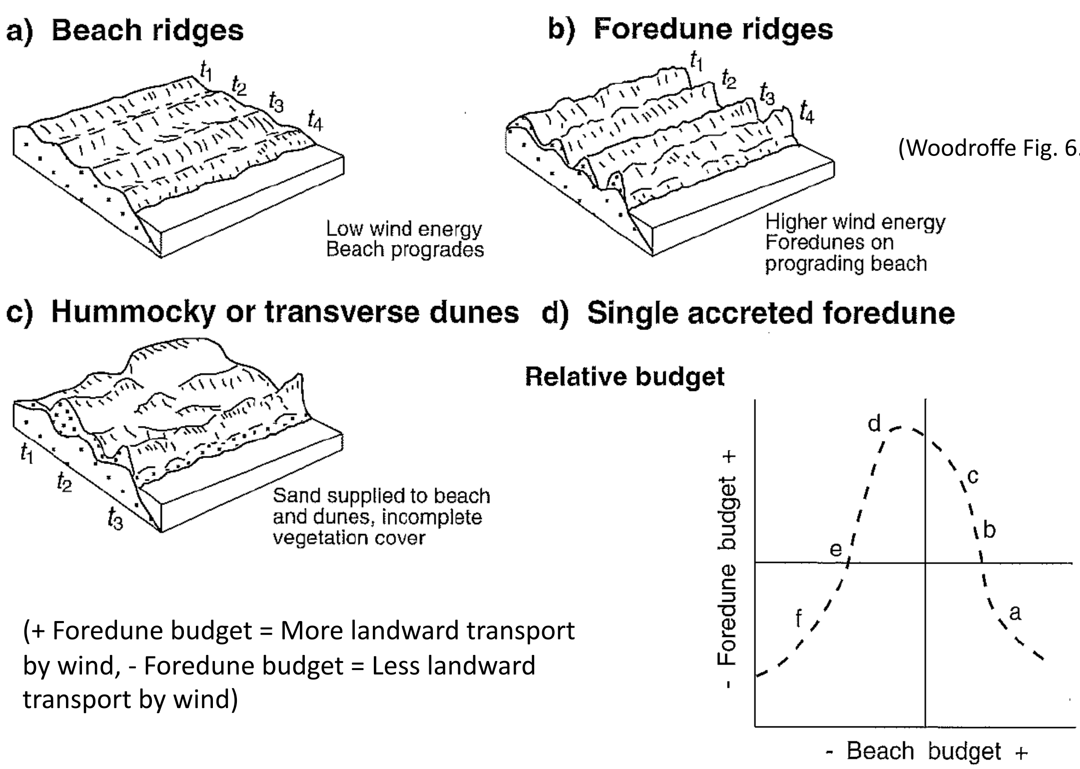
Wind transport/dune migration > beach supply leads to blow-outs (via positive feedback) and isolated parabolic dunes.

Erosive dune profiles:



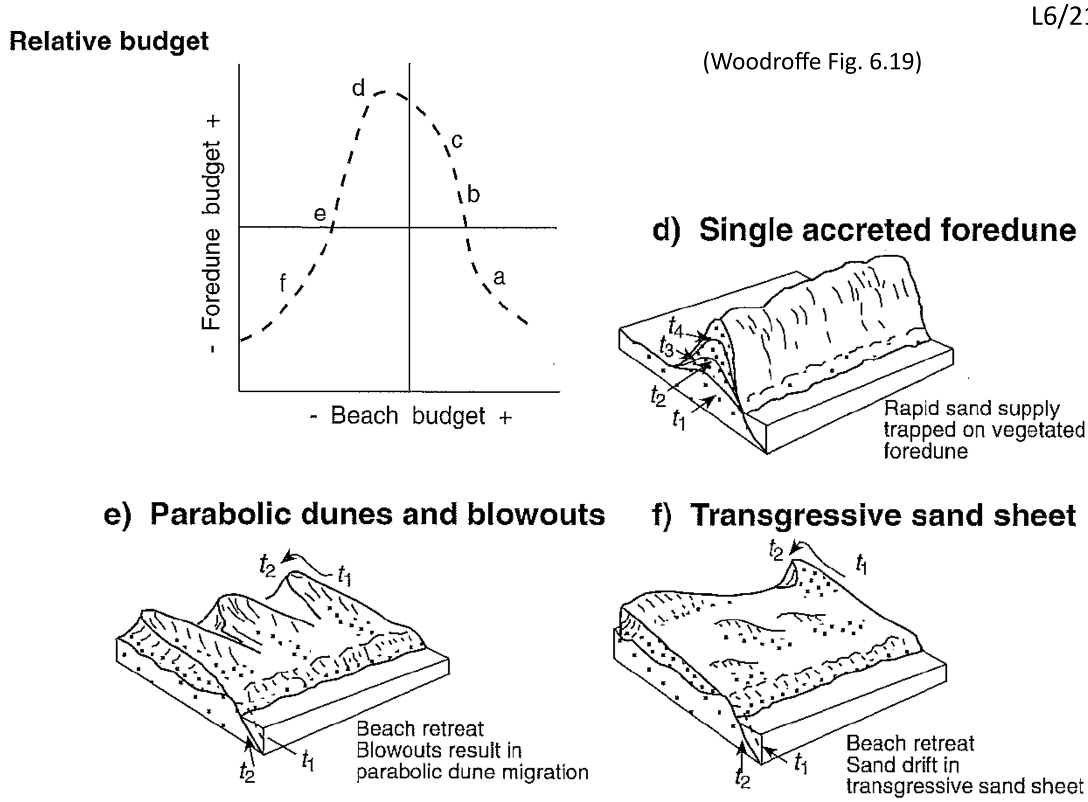
(Woodroffe Fig. 4.22)

Dune formation and occurrence in relation to beach and foredune sediment supply
(+ Beach budget = shore prograding seaward, - Beach budget = shore transgressing landward)



(Woodroffe Fig. 6.19)

(+ Foredune budget = More landward transport by wind, - Foredune budget = Less landward transport by wind)



(Woodroffe Fig. 6.19)

6.5. Barriers and Barrier Islands

Barrier = Elongate deposit of sediment formed by waves, winds or currents, parallel to shoreline, rising above sea level, and impounding terrestrial drainage or blocking off lagoon/marsh/ flat.

Barrier development usually requires: substrate gradient, wave energy (relative to tide energy), sediment supply (relative to accommodation space), and appropriate rate of sea-level change.

Barriers = time-integrated depositional record of past (but recent) beach, backshore and dune.

Barriers are not prominent in sedimentary record because they are often reworked by the moving shoreline. (e.g., They can roll-over themselves without leaving island deposit behind.)

6.5.1 Barrier Morphology

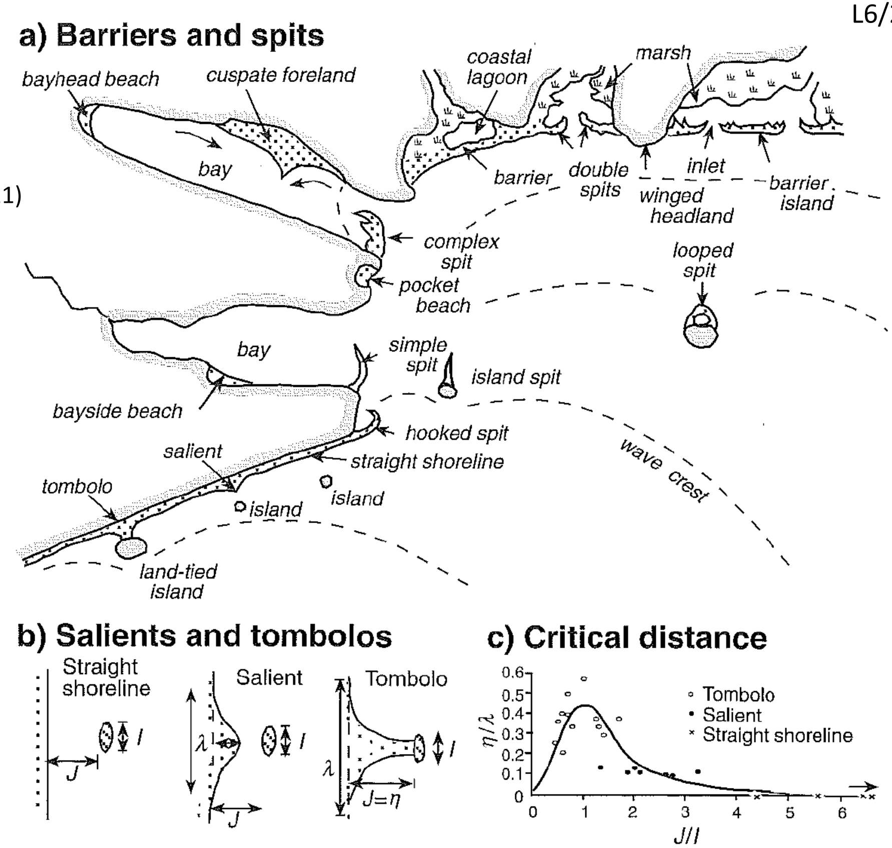
Spit = subaerial projection of sediment accumulating by alongshore transport. Favored at abrupt changes in direction of upland shoreline. Require relatively abundant sediment and wave energy.

Cuspate barrier = pointed protrusion from alignment of coast, usually containing a sequence of ridges. Indicate persistent waves from two directions and a convergence of alongshore transport.

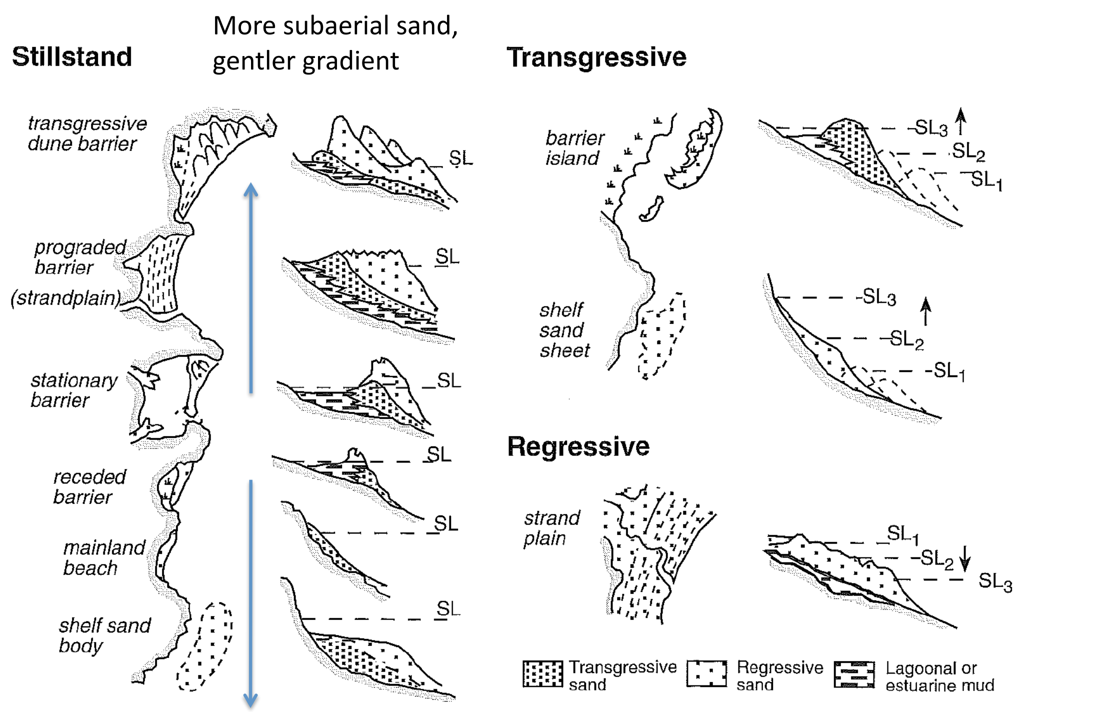
Tombolo = Spit-like projection connecting mainland to island/breakwater. Built by wave refraction/ diffraction around island/breakwater. Forms if offshore distance to island length (J/I) < ~ 1.5.

Salient = Tombolo like spit that doesn’t reach the island. Forms where ~ 1.5 < J/I < ~ 3.5.

(Woodroffe Fig. 6.21)



6.5.2. Stillstand Barriers



(Woodroffe Fig. 6.22)

L6/25

Progading barrier = shoreface sand under barrier,
extensive barrier preserved in stratigraphy

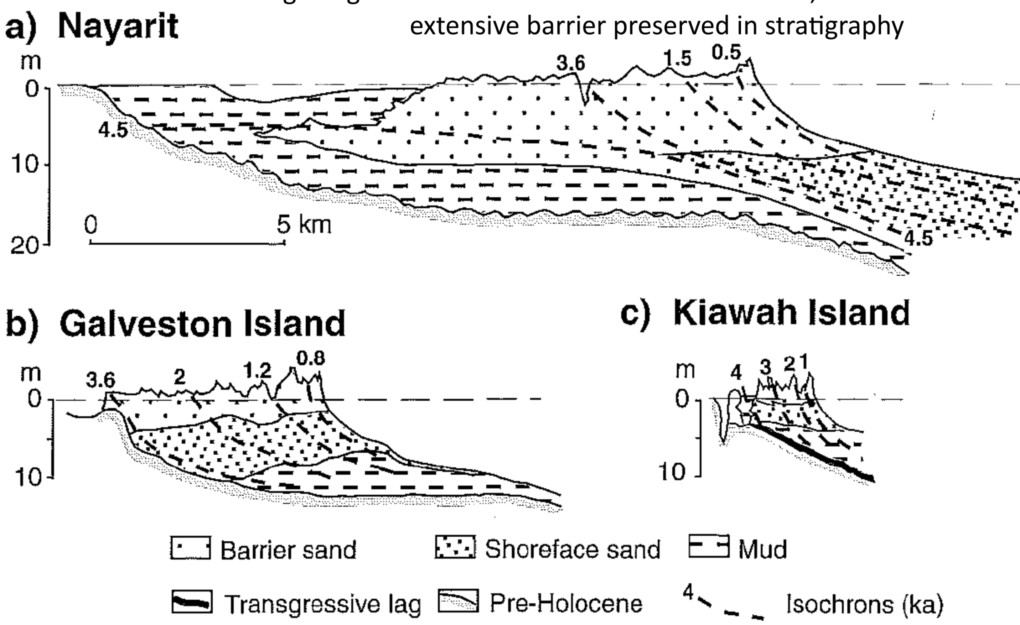
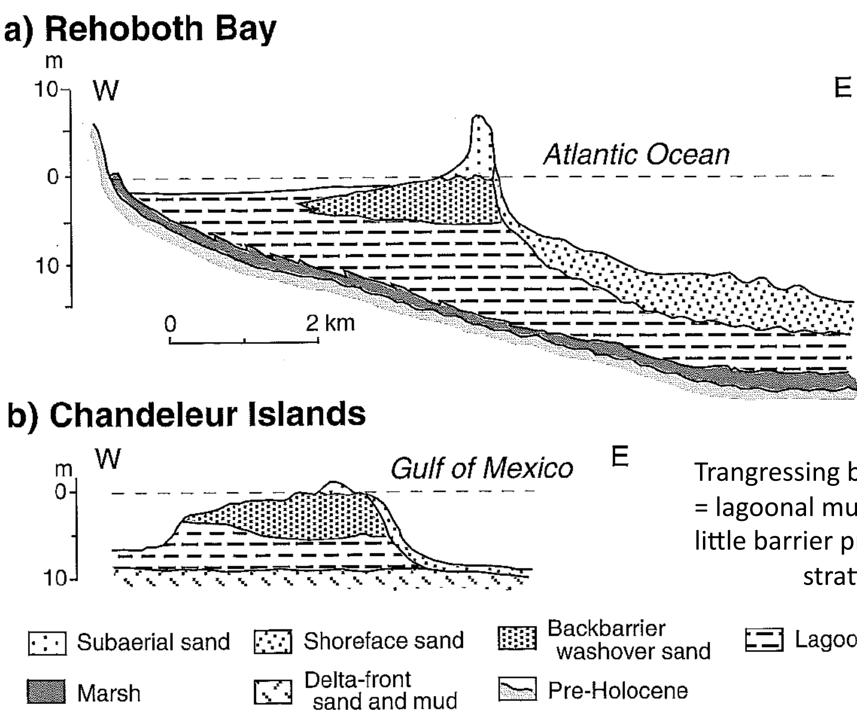


Figure 6.23. Morphostratigraphy of prograded barriers from Nayarit, Mexico (based on Curray *et al.*, 1969), Galveston Island (based on Bernard *et al.*, 1962), and Kiawah Island, South Carolina (based on Hayes, 1994).

L6/26



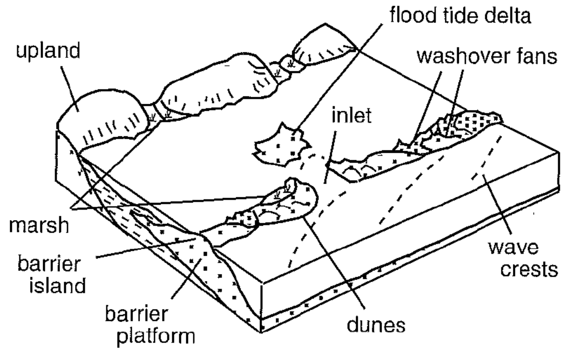
Trangressing barrier
= lagoonal mud under barrier,
little barrier preserved in
stratigraphy

Figure 6.27. Morphostratigraphy of transgressive barrier islands as indicated by Rehoboth Bay, Delaware (based on Belknap and Kraft, 1981), and the northern Chandeleur Islands, Mississippi Delta (based on Otvos, 1986).

6.5.3. Barrier Islands

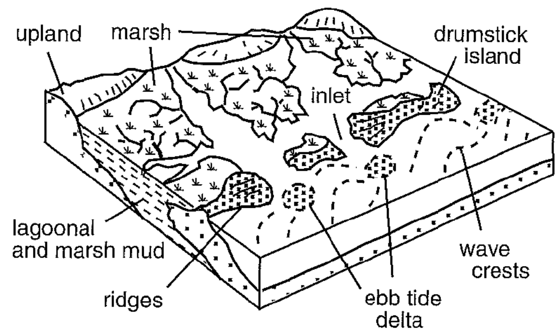
Barrier Islands = elongate, shore-parallel islands, composed of sand or gravel, separated from the mainland by a back-barrier lagoon (or channelized tidal marsh?)

a) Wave-dominated



b) Mixed-energy

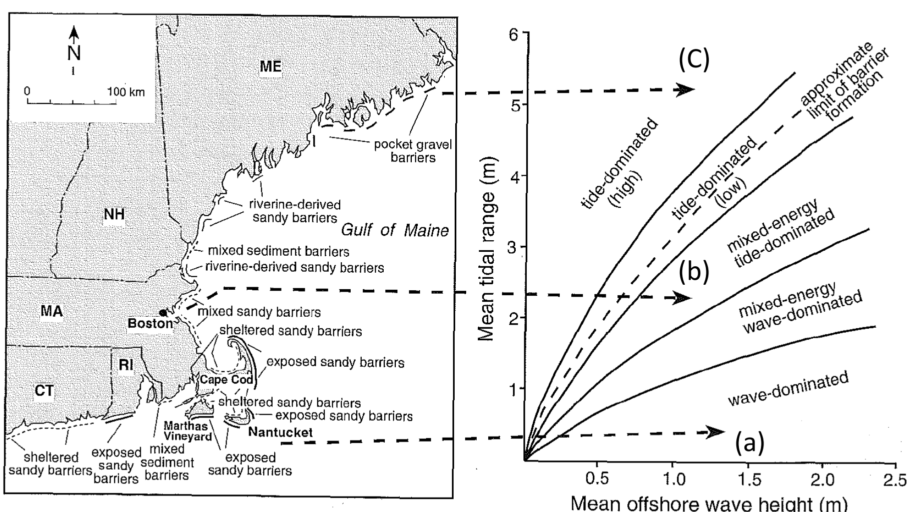
(Woodroffe Fig. 6.24)



Large waves relative to tides
Large flood tide delta
Open lagoon, small marsh area
Straight, long barrier islands
Overwash important
e.g., Outer Banks, NC

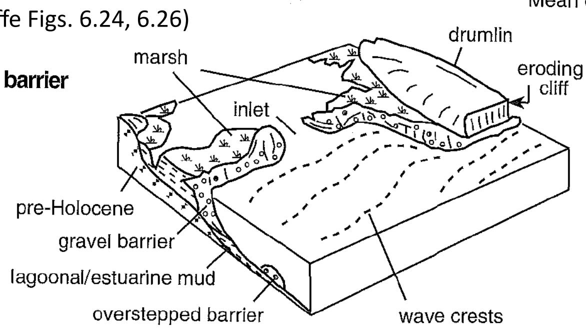
Tides important as well as waves
Large ebb tide delta
Channelized lagoon, extensive marsh
Shorter, drumstick-shaped barriers
Tidal transport important within lagoon
e.g., Eastern Shore, VA

L6/28



(Woodroffe Figs. 6.24, 6.26)

c) Gravel barrier



Macrotidal barriers are possible if sediment is very coarse, i.e., "gravel barrier".

New England gravel barriers complicated by glaciated and rocky coast.

6.5.4. Gravel Barriers

Concatenated = prograded gravel beach ridge plain

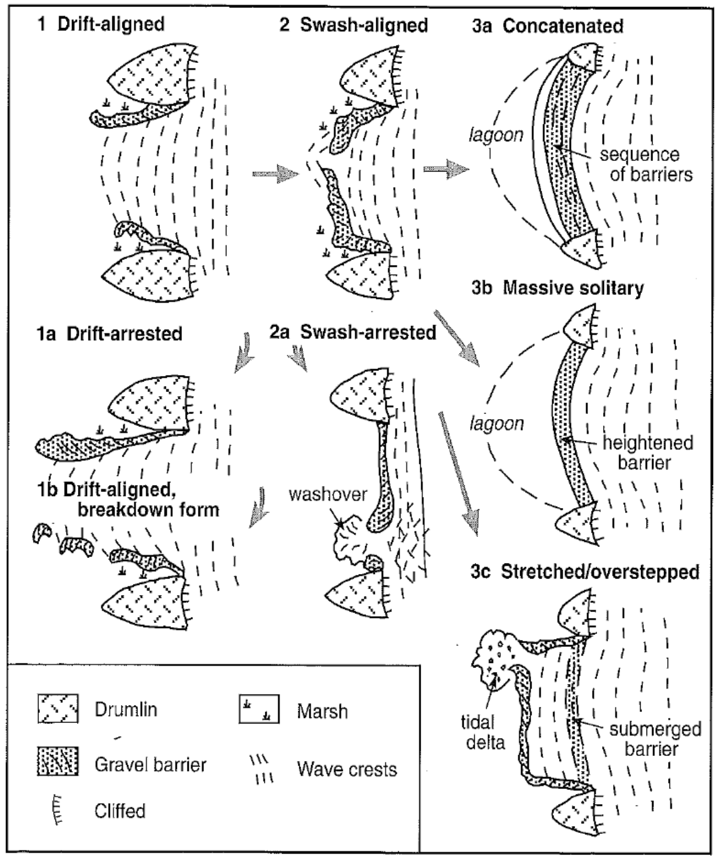


Figure 6.28. Evolutionary stages of gravel barriers in Nova Scotia

L6/29

L6/30

6.5.5. Dune-Building Phases

Dunes grow when unconsolidated sediment becomes available.

Rising sea level may lead to coastal erosion which may provide abundant sediment to form coastal dunes.

Eolianite = Fossil dune limestone.

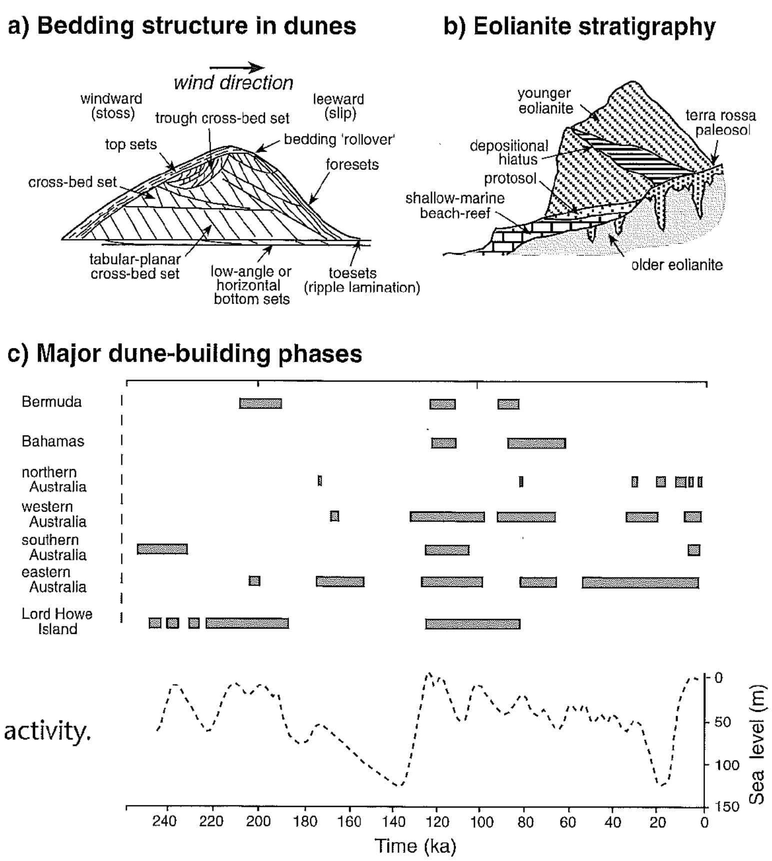


Figure 6.31. Phases of dune activity.