Title
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LITTORAL CELLS

A littoral cell is a coastal compartment that contains a complete cycle of sedimentation including sources, transport paths, and sinks. The cell boundaries delineate the geographical area within which the budget of sediment is balanced, providing the framework for the quantitative analysis of coastal erosion and accretion. The sediment sources are commonly streams, sea cliff erosion, onshore migration of sand banks, and material of biological origin such as shells, coral fragments, and skeletons of small marine organisms. The usual transport path is along the coast by waves and currents (longshore transport, longshore drift, or littoral drift). Cross-shore (on/offshore) paths may include windblown sand, overwash, and ice-push. The sediment sinks are usually offshore losses at submarine canyons and shoals or onshore dune migration, rollover, and deposition in bays and estuaries.

The boundary between cells is delineated by a distinct change in the longshore transport rate of sediment. For example, along mountainous coasts with submarine canyons, cell boundaries usually occur at rocky headlands that intercept transport paths. For these coasts, streams and cliff erosion are the sediment sources, the transport path is along the coast and driven by waves and currents, and the sediment sink is generally a submarine canyon adjacent to the rocky headland. In places, waves and currents change locally in response to complex shelf and nearshore bathymetry, giving rise to subcells within littoral cells.

The longshore dimension of a littoral cell may range from one to hundreds of kilometers whereas the cross-shore dimensions are determined by the landward and seaward extent of the sediment sources and sinks. Littoral cells take a variety of forms depending on the type of coast. Cell forms are distinctive of the following coastal types: collision (mountainous, leading edge), trailing edge, marginal sea, arctic, and coral reef. The first three types are determined by their position on the world's moving plates while the latter two are latitude dependent.

Background

The concept of a littoral cell followed from the observation that the southern California coast was naturally divided into discrete sedimentation cells by the configuration of the coastal drainage basins, headlands, and shelf bathymetry. The principal sources of sediment were the rivers which periodically supplied large quantities of sand to the coast. The sand is transported along the coast by wave action until the longshore drift of sand is intercepted by a submarine canyon that diverts and channels the flow of sand into offshore basins (Figure 1a). It was found that littoral cells, because they contain a complete cycle of sedimentation, provided the necessary framework for balancing the budget of sediment. These concepts were first presented at the International Geological Congress, Copenhagen (Inman and Chamberlain, 1960). The littoral cell now plays an important role in the U. S. National Environmental Protection Act (1974) and the California Environmental Quality Act (1974), and it has become a necessary component of environmental impact studies. In the realm of public policy and jurisdictions, the littoral cell concept has led to joint-power legislation that enables municipalities within a littoral cell to act as a unit (Inman and Masters, 1994).

The configuration of littoral cells depends on the magnitude and spatial relations among the sediment sources, transport paths, and sinks. These in turn have been shown to vary systematically with coastal type. Because the large-scale

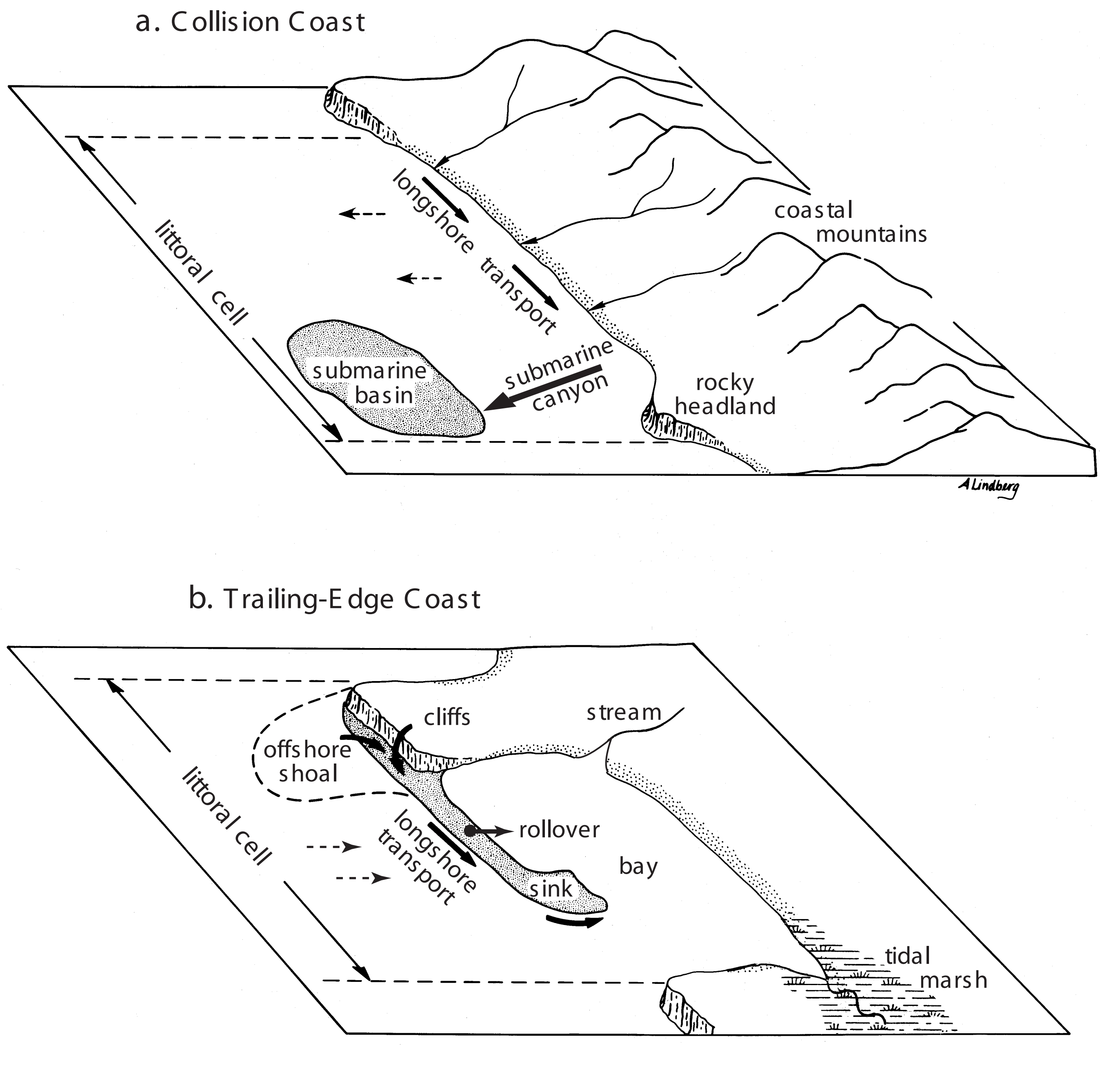

Figure 1. Typical (a) collision and (b) trailing-edge coasts and their littoral cells. Solid arrows show sediment transport paths; broken arrows indicate occasional onshore and offshore transport modes. [after Inman, 1994]

features of a coast are associated with its position relative to the margins of the earth's moving plates, plate tectonics provides a convenient basis for the first-order classification of coasts (Inman and Nordstrom, 1971; Davis, 1996). This classification leads to the definition of three tectonic types of coast: (1) collision coasts that occur on the leading edge of active plate margins where two plates are in collision or impinging on each other, for example, the west coasts of the Americas; (2) trailing-edge coasts that occur on the passive margin of continents and move with the plate, for example, the east coasts of the Americas; and (3) marginal sea coasts that develop along the shores of seas enclosed by continents and island arcs, for example, coasts bordering the Mediterranean Sea and the South and East China Seas.

It is apparent that the morphologic counterparts of collision, trailing-edge, and marginal sea coasts become, respectively, narrow-shelf mountainous coasts, wide-shelf plains coasts, and wide-shelf hilly coasts. However, some marginal sea coasts such as those bordering the Red Sea, Gulf of California, Sea of Japan and the Sea of Okhotsk are narrow-shelf hilly to mountainous coasts. A more complete coastal classification includes the latitudinal effects of climate and other coastal forming processes such as ice-push and scour and reef-building organisms. The examples of the latter two coastal types described here are (4) arctic form of cryogenic coasts and (5) coral reef form of biogenic coasts. The kinds of source, transport path, and sink commonly associated with littoral cells along various types of coast are summarized in Table 1.

Collision coasts

Collision coasts form at the active margins of the earth's moving plates and are best represented by the mountainous west coasts of the Americas. These coasts

Table 1. Typical source, transport path, and sink for littoral cells of various coastal types.

Coastal Features	Collision	Trailing-Edge	Marginal Sea		Arctic Form of Cryogenic	Coral Reef Form of Biogenic
Morphology	Narrow-shelf mountainous	Wide-shelf plains	Narrow-shelf mountainous	Wide-shelf hilly	Wide-shelf [a] plains	Coral reef
Latitude/ climate	Temperate & subtropical	Temperate & subtropical	Temperate & subtropical	Temperate & subtropical	Arctic	Tropical
Forcing [b]	Waves (1-10 kw/m)	Waves (1-5 kw/m)	Fetch-limited waves (1-2 kw/m) Tides [c]	Fetch-limited waves (1-2 kw/m) Tides [c]	Winters ice-push Summer waves	Waves 1-10 kw/m
Littoral Cell						
Sediment source	Rivers Cliffs Blufflands	Headlands Cliffs Shelves	Rivers Deltas	Rivers Deltas	Shelf Rivers Thaw-erosion	Reef material
Transport path	Longshore (river of sand)	Longshore & rollover [d] (braided river of sand)	Longshore	Longshore & rollover [d]	Ice-push Rafting Longshore	Reef surge channels to beach, longshore to awa
Sink	Submarine canyons Embayments Dune migration	Estuaries Shoals Rollover Dune migration	Various including submarine canyons	Embayments Shoals Rollover Dune migration	Shoals Spit-extension	Awa channels to shelf

a All high latitude coasts appear to be trailing-edge coasts.
b Average incident wave energy-flux per m of coastline (Inman and Brush, 1973).
c Tides may be important along any ocean coast, but are sometimes amplified in marginal seas.
d Rollover processes include overwash and dune migration.

are erosional and characterized by narrow shelves and beaches backed by wave-cut sea cliffs. Along these coasts with their precipitous shelves and submarine canyons, as in California, the principal sources of sediment for each littoral cell are the rivers that periodically supplied large quantities of sandy material to the coast. The sand is transported along the coast by waves and currents primarily within the surf zone like a *river of sand*, until intercepted by a submarine canyon. The canyon diverts and channels the flow of sand into the adjacent submarine basins and depressions (Figure 1a).

However, in southern California most coastal rivers have dams that trap and retain their sand supply. Studies show that in this area the yield of sediment from small streams and coastal blufflands has become a significant replacement for river sediment. Normal wave action contains sand against the coast and, when sediment sources are available, results in accretion of the shorezone. However, cluster storms associated with El Niño-Southern Oscillation events as occurred in 1982/83 produced beach disequilibrium by downwelling currents that carried sand onto the shelf (Inman and Masters, 1991). The downwelled sediment is lost to the shorezone when deposited on a steep shelf such as that off Oceanside, California, or it may be returned gradually from a more gently sloping shelf to the shorezone by wave action. The critical value of slope for onshore transport of sand by wave action varies with sand size, depth, and wave climate, but for depths of about 15 to 20 m it is approximately 1.5 percent (1.0 degree).

Trailing-edge coasts

Trailing-edge coasts occur along the passive plate margins of continents and include the coasts of India and the east coasts of the Americas. The mid-Atlantic coast of the United States, with its wide shelf bordered by coastal plains, is a typical trailing-edge coast where the littoral cells begin at headlands or inlets and terminate at embayments and capes (Figures 1b and 2). This low-lying barrier island coast has large estuaries occupying drowned river valleys. River sand is trapped in the estuaries and does not usually reach the open coast. For these coasts, the sediment source is from beach erosion and shelf sediments deposited at a lower stand of the sea, whereas the sinks are sand deposits that tend to close and fill estuaries and form shoals off headlands. Under the influence of a rise in relative sea level, the barriers are actively migrating landward by a rollover process in which the volume of beach face erosion is balanced by rates of overwash and fill from migrating inlets (e.g., Inman and Dolan, 1989). For these coasts, the combination of longshore transport and rollover processes leads to a distinctively "braided" form for the *river of sand* that moves along the coast.

The Outer Banks of North Carolina, made up of the Hatteras and Ocracoke Littoral Cells, extend for 320 kilometers and are the largest barrier island chain in the world (Figure 2). The Outer Banks are barrier islands separating Pamlico, Albemarle, and Currituck Sounds from the Atlantic Ocean. These barriers are transgressing landward with average rates of shoreline recession of 1.4 m/yr between False Cape and Cape Hatteras. Oregon Inlet, the only opening in the nearly 200 km between Cape Henry and Cape Hatteras, is migrating south at an average rate of 23 m/yr and landward at a rate of 5 m/yr. The net southerly longshore transport of sand in the vicinity of Oregon Inlet is between one-half million and one million m^3/yr.

Averaged over the 160 km from False Cape to Cape Hatteras, sea level rise accounts for 21 percent of the measured shoreline recession of 1.4 m/yr. Analysis of the budget of sediment indicates that the remaining erosion of 1.1 m/yr is

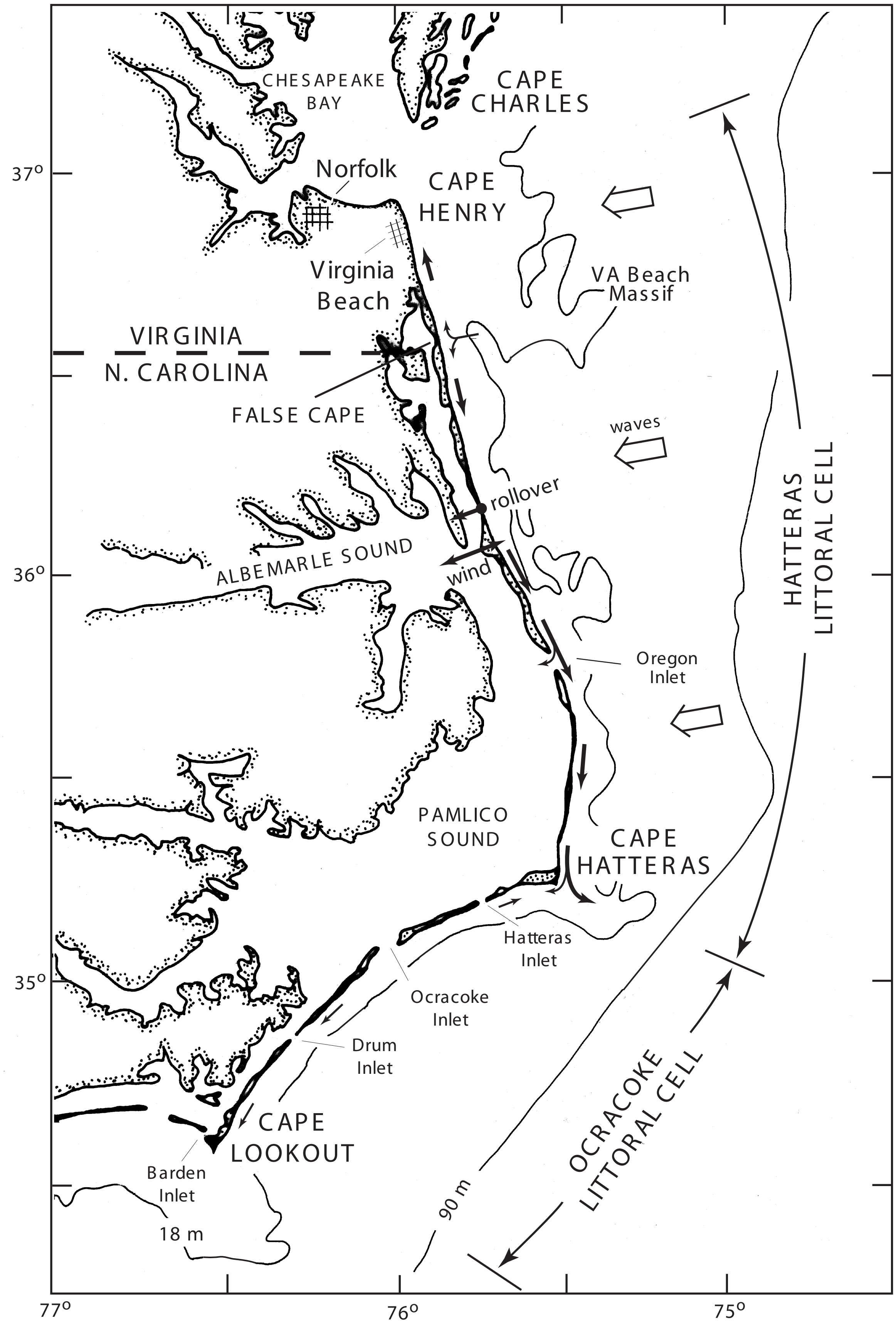

Figure 2. Hatteras and Ocracoke littoral cells along the Outer Banks of North Carolina. [after Inman and Dolan, 1989]

apportioned among overwash processes (31 percent), longshore transport out of the cell (17 percent), windblown sand transport (14 percent), inlet deposits (8 percent), and removal by dredging at Oregon Inlet (9 percent). This analysis indicates that the barrier system moves as a whole so that the sediment balance is relative to the moving shoreline. Application of a continuity model to the budget suggests that, in places such as the linear shoals off False Cape, the barrier system is supplied with sand from the shelf (Inman and Dolan, 1989).

Marginal sea coasts

Marginal sea coasts front on smaller water bodies and are characterized by more limited fetch and reduced wave energy. Accordingly, river deltas are more prominent and are often important sources of sediment within the littoral cell. Elsewhere, barrier island rollover processes are similar to those for trailing edge coasts. Examples of marginal sea coasts include the shores of the Gulf of Mexico with the prominent Mississippi River delta, the seas bordering southeast Asia and China with the Mekong, Huang (Yellow), and Luan river deltas, and the Mediterranean Sea coasts with the Ebro, Po, and Nile river deltas.

Although the Mediterranean area is associated with plate collision, the sea is marginal with restricted wave fetch and prominent river deltas. The Nile littoral cell extends 700 km from Alexandria on the Nile Delta to Akziv Submarine Canyon near Akko, Israel, one of the world's longest littoral cells (Figure 3). Before construction of the High Aswan Dam, the Nile Delta shoreline was in a fluctuating equilibrium between sediment supplied by the river and the transport along the coast. Now the sediment source is erosion from the delta, particularly the Rosetta promontory, in excess of 10 million m^3/yr. The material is carried eastward in part by wave action but predominantly by currents of the east

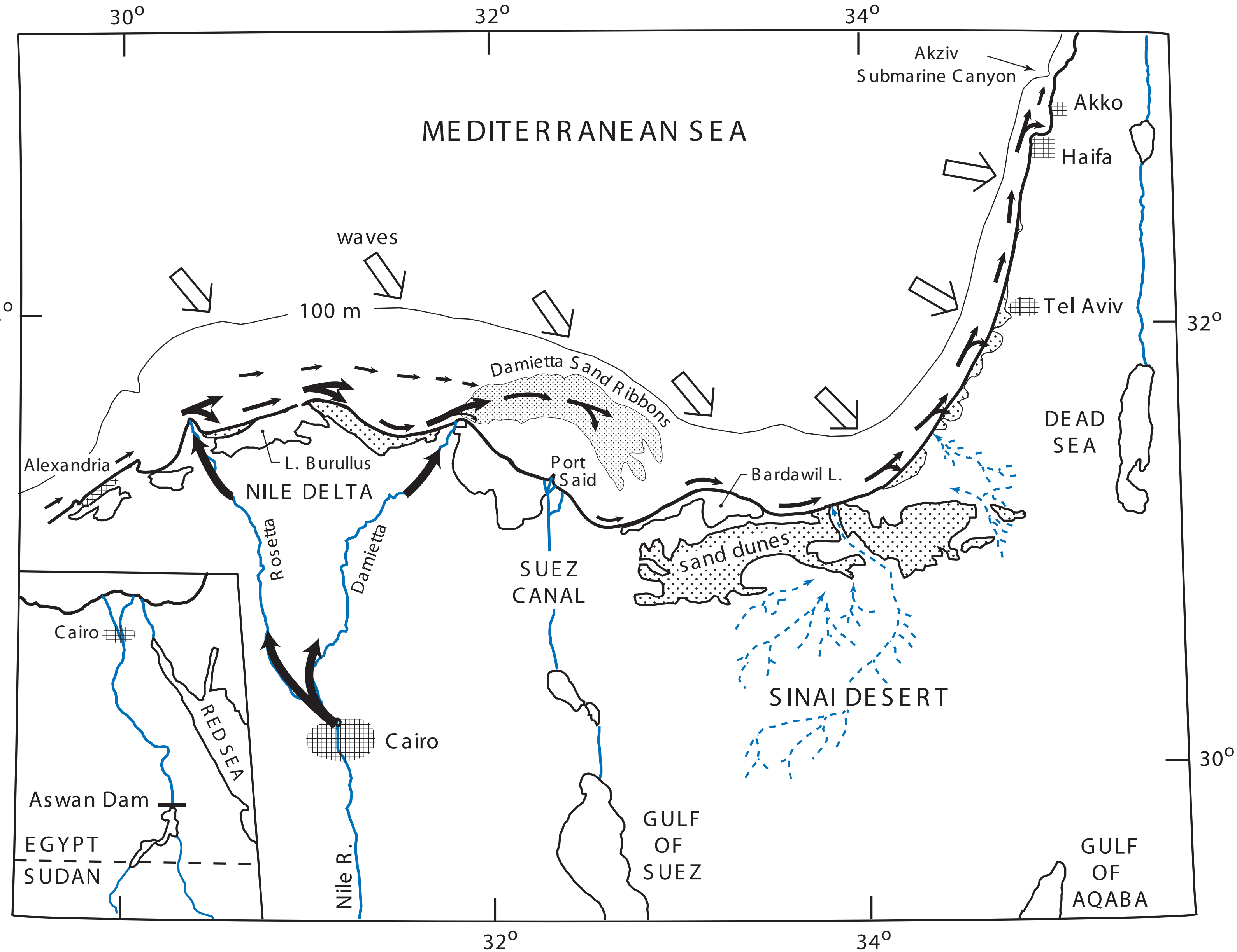

Figure 3. The Nile littoral cell extends along the southeastern Mediterranean coast from Alexandria, Egypt to Akziv Submarine Canyon off Akko, Israel. Sediment transport paths shown by solid arrows. [after Inman and Jenkins, 1984]

Mediterranean gyre that sweep across the shallow delta shelf with speeds up to 1 m/s. Divergence of the current downcoast from Rosetta and Burullus promontories forms accretionary blankets of sand that episodically impinge on the shoreline. The sand blankets move progressively downcoast at rates of 0.5 to 1 km/yr in the form of accretion/erosion waves. Along the delta front, coastal currents augmented by waves transport over 10 million m^3/yr, and the longshore sand transport by waves near the shore is about 1 million m^3/yr (Inman and Jenkins, 1984; Inman *et al.*, 1992).

The Damietta promontory causes the coastal current from the east Mediterranean gyre to separate from the coast and form a large stationary eddy that extends offshore of the promontory, locally interrupting the sediment transport path. The jet of separated flow drives a migrating field of sand ribbons northeasterly across the delta (Figure 3). The ribbons arc easterly then southeasterly towards the coast between Port Said and Bardawil Lagoon (Murray *et al.*, 1981). The Damietta sand ribbons form the eastern edge of a subcell within the Nile Littoral Cell.

Off Bardawil Lagoon, the longshore sand transport is about 500 thousand m^3/yr and gradually decreases to the north with the northerly bend in coastline. This divergence in the littoral drift of sand results in the build up of extensive dune fields along the coasts of the delta, Sinai, and Israel. This sediment loss by wind blown sand constitutes a major "dry" sink for sand in the Nile Littoral Cell.

Arctic coasts

Arctic coasts are those near and above the Arctic Circle (66º 34' North Latitude) that border the Arctic Ocean and whose littoral cells have drainage basins in North America, Europe and Asia. Tectonically, Arctic coasts are of the stable, trailing-edge type, with wide shelves backed by broad coastal plains built from fluvial and cryogenic processes. The coastal plains are permafrost with tundra and thaw lakes. A series of barrier island chains extends along the Beaufort Sea coast of Alaska (Figure 4). For these coasts, cryogenic processes such as ice-push and permafrost thaw compete with river runoff, waves, and currents as important sources, transport paths, and sinks for sediment. Ice-push is a general term for the movement of sediment by the thrust of ice against it. Some common features include ice-push ridges and mounds, ice-gouge, ice pile-up, ride-up rubbling, and bulldozing.

During the nine months of winter, arctic coasts are frozen solid and coastal processes are entirely cryogenic. Wind stress and ocean currents buckle and fracture the frozen pack ice into extensive, grounded, nearshore, pressure-ridge systems known as stamukhi zones. The stamukhi zone is a shear zone of ice grounded in 10-25 m depth that molds and moves shelf and barrier island sediment. The keels from the individual pressure ridges groove and rake the bottom, plowing sediment toward the outer barrier islands. Ice-gouge relief up to 2 m occurs across the shelf to depths of about 60 m (Barnes *et al.*, 1984).

Winter is terminated by a very active transitional period of a few days to a few weeks during spring breakup when a combination of factors associated with ice movement, waves, and currents, and extensive fluvial runoff all work in concert along the coast. The grounded ridges in the stamukhi zone break up and move, producing ice-push features and vortex scour by currents flowing around the grounded ice, creating an irregular bottom known as ice-wallow topography. Closer to shore, vertical drainage of river flood water and sediment through cracks

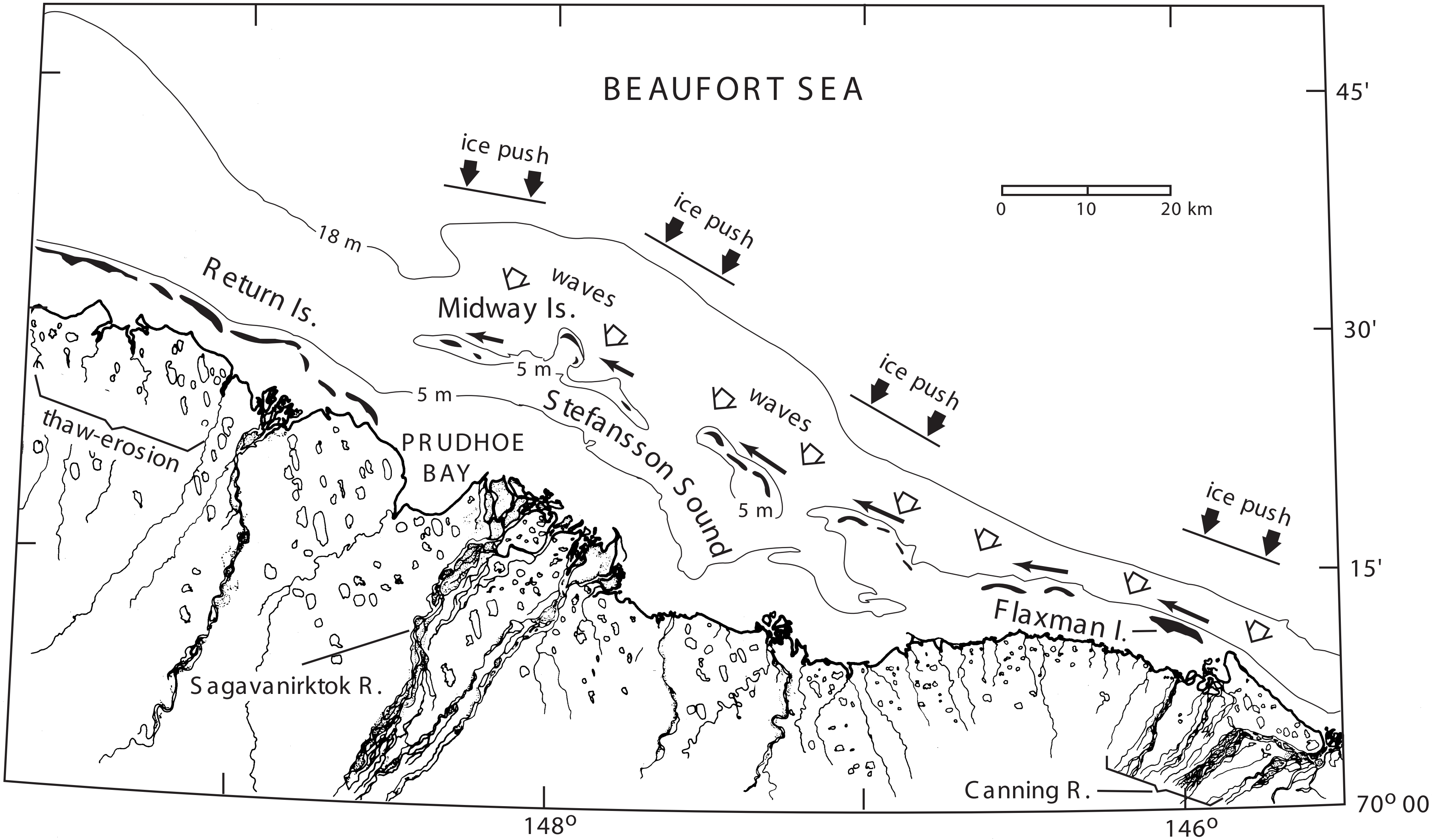

Figure 4. Flaxman Littoral Cell extends 100 km from the mouth of Canning River to the Midway Islands. The barrier chain of islands is enclosed by the 5 m depth contours. Major axes of thaw lakes are oriented normal to the direction of summer winds. [after Inman, 1994]

in the shorefast ice form large strudel-scour craters in the bottom (Reimnitz and Kempema, 1983).

Finally, a short summer period occurs in which the ice pack withdraws from the Beaufort Sea coast forming a 25-km to 50-km wide coastal waterway. Although the summer season is short, storm waves generated in the band of ice-free water transport relatively large volumes of sand, extending barrier islands and eroding deltas and headlands. The summer processes are classical nearshore phenomena driven by waves and currents as shown by the beaches and barrier island chain beginning with Flaxman Island in the vicinity of Prudhoe Bay (Figure 4). The sediment sources include river deltas, onshore ice-push of sediment, and thaw-erosion of the low-lying permafrost sea cliffs. Thaw-erosion rates of the shoreline are typically 5 to 10 m/yr in arctic Russia and, over a 30-year period, averaged 7.5 m/yr for a 23-km coastal segment of Alaska's Beaufort Sea coast midway between Point Barrow and Flaxman Barrier Islands (Reimnitz and Kempema, 1987).

The Flaxman Barrier Island chain extends westward from the delta of the Canning River. It appears to be composed of sand and gravel from the river, supplemented by ice-push sediments from the shelf (Figure 4). The prevailing easterly waves move sediment westward from one barrier island to the next. The channels between islands are maintained by setdown and setup currents associated with the Coriolis effect on the wind-driven coastal currents. The lagoons behind the barrier islands appear to have evolved in part from collapse and thaw-erosion of tundra lakes (Wiseman *et al*., 1973; Naidu *et al*., 1984).

However, even the summer period is punctuated by occasional "Arctic events," including ice-push phenomena and unusually high and low water levels associated with storm surges and with Coriolis setup and setdown, a phenomenon whose intensity increases with latitude. The active summer season ends with the beginning of fall freeze-up.

Coral reef coasts

Coral reef coasts are a subset of the broader category of biogenous coasts where the source of sediment and/or the sediment retaining mechanism is of biogenous origin as in coral reef, algal reef, oyster reef, and mangrove coasts. Coral reefs occur as fringing reef, barrier reef, and atolls, and they are common features in tropical waters of all oceans at latitudes within the 20ºC isotherm.

Although the concept of the littoral cell applies to all types of coral reef coast, the most characteristic are littoral cells along fringing reef coasts bordering high islands, where both terrigenous and biogenous processes become important. Reefs may be continuous along the coast or occur within embayments. In either case, the configuration of the fringing reef platforms themselves incorporates the nearshore circulation cell into a unique littoral cell (Figure 5). The circulation of water and sediment is onshore over the reef and through the surge channels, along the beach toward the awas (return channels), and offshore out the awas. An awa is equivalent to a rip channel on the sandy beaches of other coasts (Inman *et al.*, 1963).

Along coral reef coasts, the corals, foraminifera, and calcareous algae are the sources of sediment. The overall health of the reef community determines the supply of beach material. Critical growth factors are light, ambient temperature, salinity, and nutrients. Turbidity and excessive nutrients are deleterious to the primary producers of carbonate sediments. On a healthy reef, grazing reef fishes bioerode the coral and calcareous algae and contribute sand to the transport pathway onto the beach.

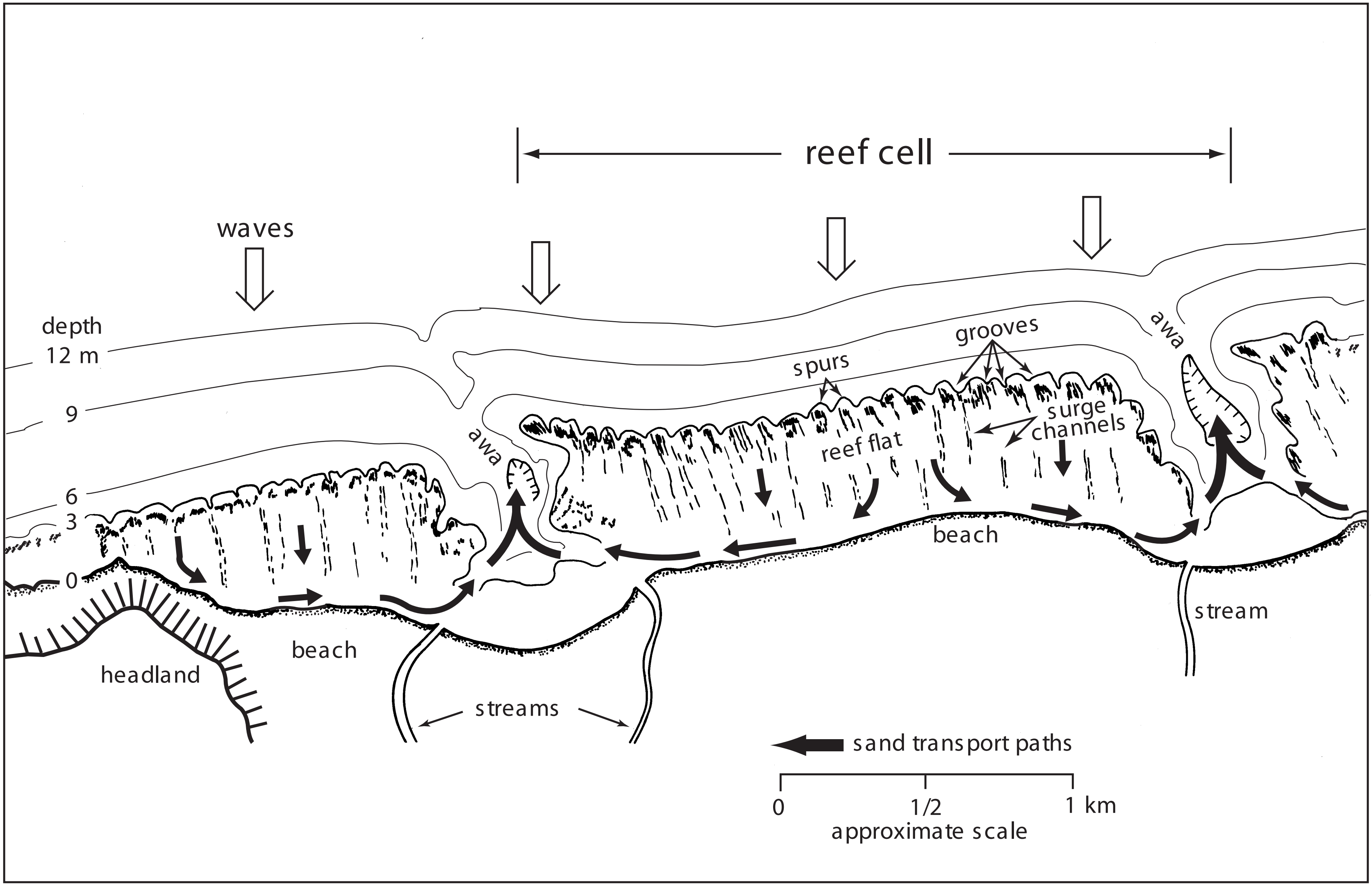

Figure 5. Schematic diagram of littoral cells along a fringing reef coast. [after Inman, 1994]

The beach behind the fringing reef acts as a capacitor, storing sediment transported onshore by the reef-moderated wave climate. It buffers the shoreline from storm waves and releases sediment to the awas. In turn, the awas direct runoff and turbidity away from the reef flats and out into deep water. Where the reef is damaged by excessive terrigenous runoff, waste disposal, or over fishing, the beaches are imperiled.

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Cross-references

Arctic, Coastal Geomorphology
Barrier Islands
Classification of Coasts
Climate Patterns in the Coastal Zone
Coral Reefs
Deltas
El Niño-Southern Oscillation
Energy and Sediment Budget of the Global Coastal Zone
Sediment Budget
Tectonics and Neotectonics