I

ICE-BORDERED COASTS

Introduction

Since the publication of *The Encyclopedia of Beaches and Coastal Environments* (Schwartz, 1982), the term "cold coasts" has come into common use even serving as a chapter title in the book *Coastal Problems*. The authors, Viles and Spencer (1995), use the 1961 definition by R.L. Nichols that cold coasts ". . . are those where there is or has been abundant sea ice, lake ice, water-terminating glaciers or deeply frozen ground" (p. 254). The advantage of such a definition is that it avoids the latitudinal restriction placed by such locational designators as Arctic and Antarctic and thus can accommodate lower latitudinal examples including the tidewater glaciers of Chile and southern Alaska and the presence of sea ice along the Labrador and Hokkaido coasts or even the coast of Spain during the Pleistocene.

This entry treats two of these types of cold coasts: namely, water-terminating glaciers and sea ice. Glacial ice is land-derived and tends to be perennial; sea ice, on the other hand, develops seaward of the coastline and is usually seasonal. They both can serve as erosional, transportational, and depositional agents along coastlines, although the rates and intensities of their action vary greatly between the two and with time and location.

Glacial ice and the coast

One of the conspicuous features of the landscape at present and during much of the past three million years is glacial ice. Although today it is dominant (as a coastal feature) only in Antarctica, Greenland, and a few smaller islands in high latitudes, it is still sufficiently abundant to affect more than 35,000 km of the world's coastline. Glacial ice impacts the coastline in several ways including burying and depressing the coast as it moves across it into the sea, flowing in preexisting valleys into the sea as tidewater glaciers, and replacing the traditional shore with an ice margin that then interfaces directly with the sea.

Ice sheets, such as those in Antarctica and Greenland, serve as the source of ice that moves under its own weight and in response to gravity from inland to sea. Glacial ice is so extensive in Antarctica that only about 5% of the coastline is ice-free (Figure I1). Greenland contrasts with most of Antarctica in that glacial ice does not dominate the coastal zone but flows through relatively few high passes in the coastal mountains (Figure I2). A major exception is where inland ice reaches Melville Bay along a 460 km front.

A further characteristic of ice sheets is that their great weight depresses the landmasses upon which they form. Near the coastline the depressed continental shelf slopes downward inland thereby reversing the general slope of the coastal zone. Large parts of Antarctica and Greenland have been depressed to such extents that their present elevation is below sea level. Although, with rebound, much of this depressed land would be above sea level, large areas beneath the West Antarctic Ice Sheet (which averages 440 m below sea level) would still be a series of islands with lengthy coastlines even after the rebound that would accompany deglaciation (Paterson, 1994).

Ice shelves, which are large ice masses floating on the sea, range in thickness up to several hundred meters. They are especially common in Antarctica (Figure I1), but also occur as small shelves in Greenland, Ellesmere Island, and Franz Josef Land. The ice shelves of Antarctica fill many of the continent's embayments giving the continent a nearly circular form excepting the northward trending Antarctic Peninsula.

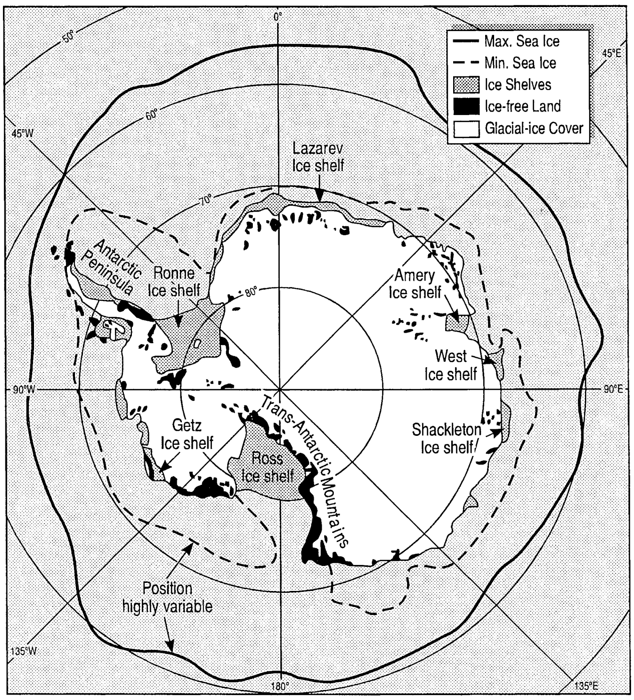

Figure I1 Ice and the Antarctic coastline (modified from Mellor, 1964; Paterson, 1994; and Crossley, 1995).

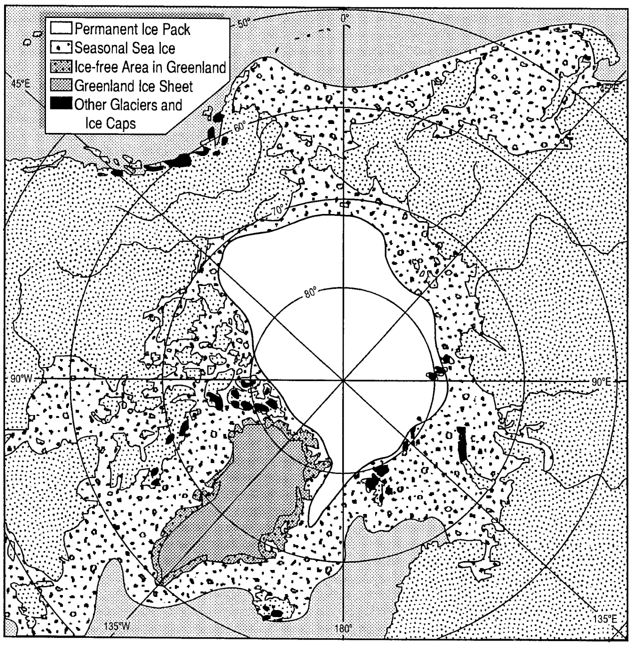

Figure I2 Ice and the Northern Hemisphere Coastline. Note that within the ice-free coastal area of Greenland there are numerous small ice caps (modified from Mellor, 1964; Field, 1975; and Williams and Ferrigno, 1995).

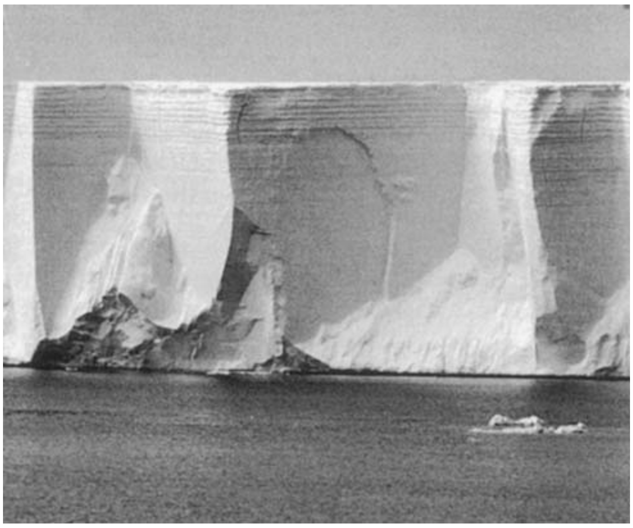

Figure I3 Ice cliff, Antarctica. (Williams and Ferrigno, 1995. Photograph by Charles Swithinbank, courtesy of Richard S. Williams, United States Geological Survey.)

Thus, the 11,000 km (more than one-third of the total) of Antarctica's coastline occupied by ice shelves, possesses ice cliffs (Figure I3) at the ocean interface. These ice cliffs are impressive coastal features as illustrated by the Ross Ice Shelf (Figure I1) where the front edge is more than 200 m thick with a 20–30 m cliff above water. The ice landward of the Ross ice cliff thickens to 700 m at land's edge (Robe, 1980). The exposed ends of these floating glaciers are impacted by the same agents and processes as the coast proper including waves, tides, currents, and sea ice.

Many of the coastal glaciers in Antarctica (~38%) and most in the Northern Hemisphere do not have floating shelves or tongues but are grounded at their termini (Powell and Domack, 1995). For example, part of the west coast of the Antarctic Peninsula has glaciers that have formed ice walls at the shore because of undercutting and calving at the ice front where they override a gravelly beach (Robin, 1979).

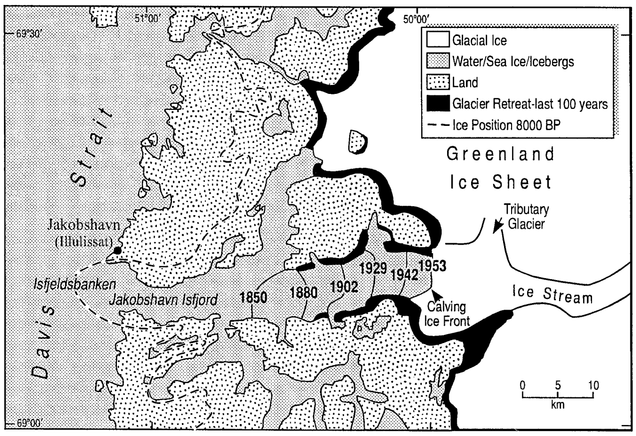

Figure I4 Tidewater glacial retreat (1850–1953) and ice-margin retreat in Jakobshavn Isfjord (modified from Williams and Ferrigno, 1995).

Tidewater glaciers are found in nonpolar areas such as southern Alaska and Chile as well as at higher latitudes. In the Arctic, tidewater glaciers are present in Jan Mayen, Svalbard, Novaya Zemlya, Severnaya Zemlya, Ellesmere, Baffin Island, Bylot Island, and Devon Island as well as Greenland and Alaska (Figure I2). The termini of temperate tidewater glaciers are grounded as are many in higher latitudes (Hambrey and Alean, 1992). Most tidewater glaciers are confined in fjords of variable length and terminate at some distance inland from their mouth. Many are very long, such as the combined 350 km long Nordvestfjord and Scoresby Sund in east Greenland. Such fjords not only have glaciers at their inner ends but also are icebound with icebergs and sea ice. Because of the nature of the coastal mountain rim around the Greenland Ice Sheet the coastal impact is highly varied at the front of outlet glaciers. Although many flow into the sea, others terminate on land (Figure I4) and in glacially created lakes (Warren, 1991).

A major characteristic of glaciers is their changeable rate of advance and retreat. Thus, their position and therefore their impact on the coastlines they border is continuously varying. Jakobshavn Isbrae (Figure I4) in west Greenland, for example, retreated 26 km between 1851 and 1953 (Williams and Ferrigno, 1995) exposing sizable sections of the fjord's shore that it formally bordered.

The most important mechanism for the loss of glacial ice, whether it be the large ice shelves of Antarctica or the smaller tidewater glaciers of Alaska, is calving at their termini. Calving produces icebergs that range in size from very small, as those produced in constricted fjords, to very large such as those tabular icebergs that calve from ice shelves. On March 17, 2000, iceberg B-15, with a length of 295 km and a width of 37 km calved from the Ross Ice Shelf. It broke into two parts a few months later (Lazzara *et al.*, 1999).

Icebergs, once formed, essentially become floating islands. The act of calving increases the number of sides in contact with the sea, hastening their disintegration. Many of them float for years as exampled by those ice islands that have been used as research bases in the Arctic Ocean. Others become trapped, even if temporarily, in sea ice and some become grounded in shallow water. They can also be erosional agents, often in association with the floating pack ice that forms around them, creating deep gouges in the nearshore bottom.

Glaciers, whether they terminate onshore, at the shore, along fjords or at some distance offshore, are major morphological agents. If terminating inland, meltwater drainage carries the sediment formed by the glacial scour that accompanies the advancing ice to the sea creating depositional facies along the shore. Those glaciers that terminate at the shore and those that have overridden the shore leave behind ice-scoured surfaces and depositional forms including a variety of morainal types. Such coasts, once released from their overburden of ice, rebound as is happening in northern Canada, Scandinavia, and many parts of Antarctica especially on the Antarctic Peninsula. Some of the raised beaches on the Peninsula are as much as 60 m above present sea level (Kirk, 1985).

Sea ice and the coast

Sea ice, one of the most variable elements in the oceanic system, varies seasonally in areal coverage by nearly 500% in the Southern Hemisphere but by less than 200% in the Northern Hemisphere (Figures I1 and I2).

These percentages show that sea ice is more strongly seasonal in the Antarctic than the Arctic. It is again a reflection of the nature of the two ocean areas involved. Because the Arctic Ocean is surrounded by land and the Antarctic Ocean surrounds a continent, ice formation and movement and therefore, impact on the coastlines is quite different. Most of the Arctic Ocean sea ice is of the multi-year type whereas most (~85%) of that of the Antarctic is first-year ice.

During the Arctic winter, sea ice not only affects the coasts surrounded by the Arctic Ocean but also extends south to locations such as Hokkaido, Japan in the North Pacific Ocean and New Foundland in the North Atlantic (Figure I2). In contrast, during summer virtually all Arctic coasts are free of sea ice for varying lengths of time. Exceptions include northern Greenland, Ellesmere, and part of the Canadian Arctic Archipelago where sea ice may last throughout the year. Of major interest and concern is the great variability in sea ice cover and thickness. An analysis of satellite passive microwave observations shows those areas exhibiting negative trends in the sea ice season are larger than those exhibiting positive trends (Parkinson, 2000). If such negative trends continue, ice-free periods along Arctic coasts will continue to lengthen.

During the austral winter, sea ice extends north several hundred kilometers from Antarctica even reaching 55°S in the Indian Ocean (Figure I1). During that period of the year, sea ice is present along the entire coastline although nearshore in many locations are polynyas—some maintained by katabatic winds. As summer approaches, sea ice drifts out and away from most of the coast except for a few locations where it remains attached to the shore throughout the summer (Wadhams, 2000).

Sea ice and its impact on coasts during summer

For a few months during summer most of the coasts in both the Antarctic and Arctic are ice-free. However, in the Arctic Ocean especially, the permanent (although highly mobile) pack is often close enough to shore to dampen waves and thus reduce their impact on the coast. During those periods of time when the pack retreats from the coast thereby increasing fetch over coastal waters, storms can cause severe erosion as happened at Barrow, Alaska in October 1986 (Walker, 1991). The shorter the ice-free period and the narrower the shore lead, the more limited the wave action alongshore.

Under certain wind and current conditions pack ice can move onto shore even at the height of the summer season causing some ice scour and sediment transport. This situation is especially true along the Beaufort Sea coast.

Freeze-up and the ice foot

The factors affecting the timing of freeze-up include temperature, wind, snow, waves, tides, and the nature of the shoreline. When the temperature is lowered to the value at which seawater freezes, ice forms on the foreshore and within the interstices of shore sediments. Ice buildup occurs through the addition of the spray, swash, slush ice, and ice floes brought by waves and tides plus the addition of snow. The accumulation becomes the ice foot, a major characteristic of ice-bordered shore (Figure I5). The form, structure, and extent of the ice foot varies with shore gradient as well as tidal range and wave conditions during formation (Taylor and McCann, 1983). A gently sloping shore face and a high tidal range favor the development of a wide ice foot whereas variable wave conditions often produce complex structures (Owens, 1982).

The ice foot, composed of a mixture of sediments, snow and ice, rests on a beach surface that is also frozen. As waves approach the ice foot, they continue to deliver sediment from offshore either as loose particles or as material already incorporated into the pancake and brash ices that are added to the ice foot mix (Evenson and Cohn, 1979).

The ice foot is bottomfast and immobile. At its seaward edge it abuts floating ice that moves vertically with tidal and wave action. They are separated by tidal cracks along a line which has been referred to as a "hinge zone" (Forbes and Taylor, 1994). The degree of roughness of the sea ice at the hinge zone tends to increase with increasing tidal range.

Once freeze-up is complete, wave action on the coast ceases and any sediment transport by longshore currents is confined to locations seaward of the bottomfast ice zone. However, exceptions do occur. In the case of the Beaufort Sea, for example, severe winter storms can produce override with ice being forced over the ice foot high up on the shore. These features are known among the Inuit as "ivu."

Although bottomfast ice usually extends out to water depths of two or more meters, shorefast ice extends out over deeper water to distances of as much as 20–30 km (Taylor and McCann, 1983) where it merges with drifting pack ice. Shorefast ice is relatively immobile especially when present between islands as in the Canadian Arctic Archipelago. However, along open coasts, as those facing the Beaufort and Chukchi Seas, shorefast ice may be subject to occasional drift. The area between the outer limit of shorefast ice and the drifting pack, known as the "stamukhi" zone, is characterized by large pressure ridges some large enough so that they last through the summer.

Ice melt and breakup

Although shore leads in the sea ice may open early during the breakup period, the ice foot is not directly affected. Its ice melts in place. The rate and timing depend mainly on temperature conditions and depending on the amount of ice and snow present, may last into summer (Figure I5). During winter, snow accumulates on the irregular surface and may be quite thick especially if there is a cliff behind the beach. As sea ice begins to move, especially with offshore winds, it breaks apart and floats the outer edges of the bottomfast ice. In the process, much of the sediment that has been incorporated into the sea ice is transported off and alongshore. The last ice to be removed from the coast are the large ice masses that become stranded and often buried onshore. Their melt rate is affected by the sediment that may cover them (Figure I6).

In contrast to the shore ice melt and breakup that occurs along the exposed shore is that occurring out from river mouths. Off river mouths the gradients of subaqueous deltas are usually more gentle than those along other coastlines so that the bottomfast sea ice zone is wider. During river breakup, floodwaters progress out over the sea ice and in the larger rivers beneath it in the subice distributary channels that do not freeze to the bottom. The water flowing over the sea ice deposits much of its sediment on top of the ice before it reaches pressure-ridge cracks or potholes out from the bottomfast/shorefast ice boundary where it drains to continue flowing seaward (Walker, 1974). The drainage through these holes (Figure I7) create in the bottom what Reimnitz has labeled strudel-scour holes (Reimnitz and Bruder, 1972). Most of the sediment deposited on top of the sea ice is later deposited in the delta as the ice melts. However, some of it is transported seaward and alongshore as the offshore ice begins to drift.

Figure I5 Stranded ice-foot at Barrow, AK in June.

Figure I6 Five-meter-high sea ice pileup with accumulated snow onshore during melt season. Note the gradual settling of incorporated beach materials as ablation occurs.

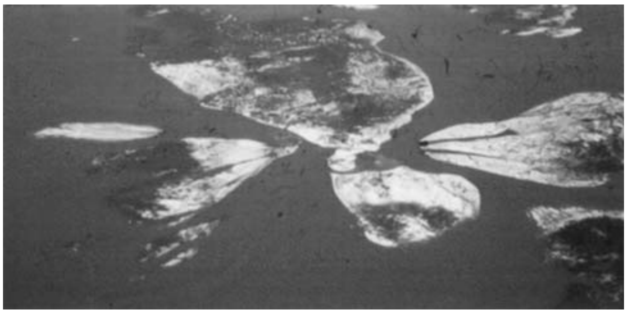

Figure I7 Drainage hole in sea ice at the Colville delta front. The floodwaters from the river drain from the ice creating strudel scour in deltaic sediments.

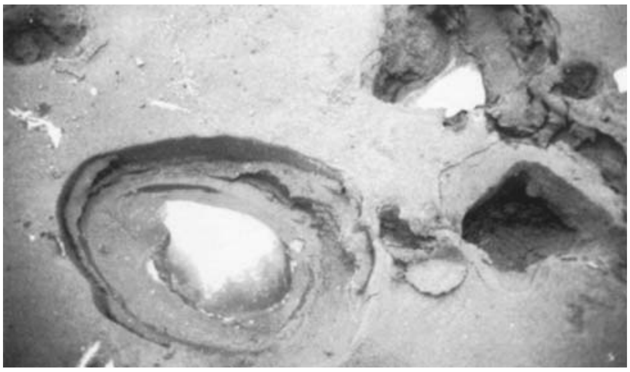

Figure I8 Small kettles forming in the beach at Wainwright, AK as stranded ice blocks melt.

Sea ice: its role in erosion, transportation, and deposition

In addition to the transport of sediment and the development of strudel mentioned above, sea ice is involved in other geologic processes along coastlines. The movement of sea ice on the beach and near the shore can produce scour marks and ridges. The uneven bottom of sea ice and especially when present as pressure-ridge keels gouge bottom materials as the ice drifts along the shore or up to the beach. As sea ice rides up onto the shore it both erodes and transports beach materials some distance above the high-tide shoreline. If the moving ice is impeded, ice pileups develop. They form not only at the high-tide shoreline but also at the hinge-line that joins bottom- fast and shorefast ice and around grounded floes. Such ice pileups impact heavily on both shore and nearshore sediments. Pileup heights of 20 m are common; some grow to double that (Forbes and Taylor, 1994).

The beach which can have a very irregular surface at the end of the melt season because of the presence of ice-push ridges, kettles left by the melting of stranded ice blocks (Figure I8), and a variety of scour forms is generally reworked by waves during the ice-free season. Only those forms that are especially large or that have been produced at the back of the beach may last through the summer.

Sea ice like glacial ice serves as both an agent of erosion and of protection. In the case of sea ice, the period of time it protects the coast from erosion varies from hours or days to year round in some very sheltered locations, whereas in the case of glacial protection the time period may be reckoned in millennia. With the rapid changes taking place in the icescapes of the world (e.g., the 15% reduction in sea-ice cover in the Arctic Ocean in the past 20 years (Krajick, 2000)), the impact on the coastlines of ice-bordered coasts is continually in flux.

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Cross-references

Antarctica, Coastal Ecology and Geomorphology
Arctic, Coastal Ecology
Arctic, Coastal Geomorphology
Glaciated Coasts
Paraglacial Coasts

INDIAN OCEAN COASTS, COASTAL ECOLOGY

Introduction

The coastal zone is the area covered by coastal waters and the adjacent shore lands, strongly influenced by each other. Coastal lands are some of the most productive and invaluable habitats of the biosphere, including estuaries, lagoons, and coastal wetlands. They are a place of high-priority interest to people, commerce, military, and to a variety of industries. Because it contains a dense population, the coast undergoes environmental modification and deterioration through reclamation, dredging, pollution, industry, and anthropogenic activities.

India has a vast coastline of approximately 7,000 km along the Arabian Sea in the west and the Bay of Bengal in the east. The western coastal plains lie between the Western Ghats and the Arabian Sea, further split into the Northern Konkan Coast and the Malabar Coast. The eastern coastal plains on the other hand, lie between the Eastern Ghats and the Bay of Bengal. Indian coasts have a large variety of sensitive ecosystems—sand dunes, coral reefs, sea grass beds, wetlands, mudflats, and rocky and sandy shores.

As shown in Figure I9, there are number of backwaters, estuaries and coastal lagoons that support the rich and diverse flora and fauna (Figure I10). These coastal habitats are considered to be highly productive areas in terms of biological productivity and one of the "*hotspots*" of marine biodiversity. Over 11,000 faunal (10,400 invertebrates and 625 vertebrates) and over 800 floral (624 algae, 50 mangrove, 32 angiosperms, 71 fungi, 14 lichens, 12 sea grass) species have been identified from Indian coastal areas (Untawale *et al.*, 2000; Anon, 2002). The majority of the shallow coastal and backwater areas form an important spawning and nursery ground for commercially important fishes, molluscs, crustaceans, and various other species that constitute the coastal fishery of India.

Type of marine habitats

Mangroves

Mangroves are woody plants that grow at the interface between land and sea in tropical and subtropical latitudes where they exist in conditions of high salinity, extreme tides, strong winds, high temperatures,

Figure I9 Some of the important coastal lagoons and marine biosphere reserves of India.

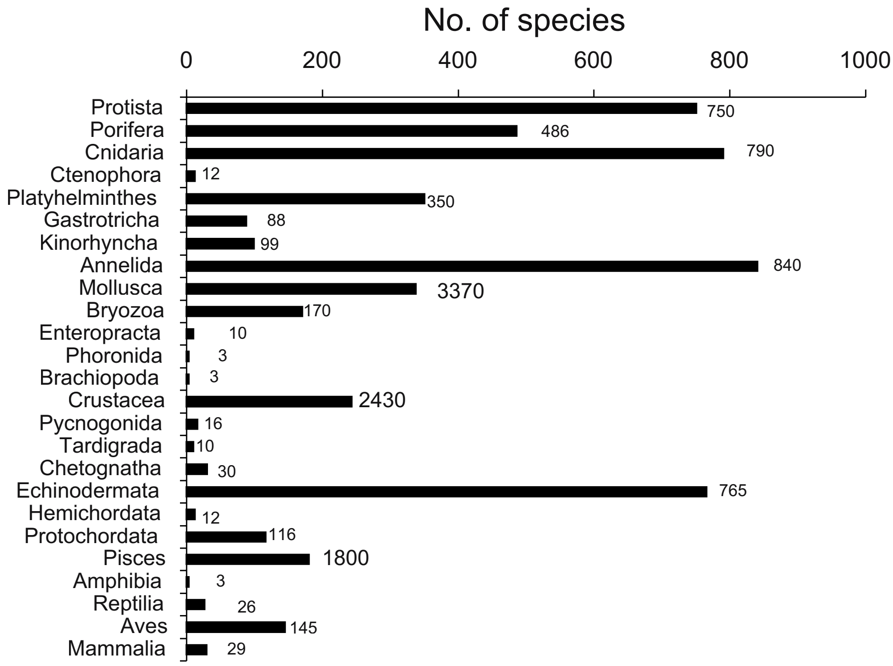

Figure I10 Marine faunal diversity of India. (After Anon, 1997; Untawale *et al.*, 2000; Anon, 2002)

Figure I11 Estuarine mangrove habitat along the Indian coast.

and muddy, anaerobic soils (Kathiresan and Bingham, 2001). Mangroves are usually present in estuarine and muddy shores (Figure I11), but can also be found on sand peat.

They are a complex and highly productive ecosystem that forms the interface between land and sea. The mangroves are widespread along the east and west coast of India. A detail of areas covered by mangrove habitat is given in Table I1.

On the Indian subcontinent, the mangrove ecosystems are distributed within the intertidal or tidal, supra-tidal or subaerial deltaic zones of both the east coast, facing the Bay of Bengal, and the west coast, facing the Arabian Sea. Mangrove flora of India comprises 50 exclusive species belonging to 20 genera, and 37 mangrove-associated floral species (Jagtap *et al.*, 2002; Upadhyay *et al.*, 2002). The maximum species diversity occurs in the Mahanadi delta along the Orissa coast, with 36 mangrove species present. Mangroves in India are estimated to cover about 4,871 km^2 (Upadhyay *et al.*, 2002). The mangrove ecosystem on the Indian subcontinent is of three types.

1. *Deltaic mangroves*: These are found along the mouth of different major estuaries on the east coast, and two gulfs (Gulf of Kachehh and Gulf of Khambhat) on the west coast. However, deltaic mangroves cover up to 53% of the total Indian mangals, which are estimated to be about 2,560 km^2, out of which the Gangetic delta popularly, known as *Sunderbans*, alone covers about 78%. About 48 species of mangroves have been recorded from the east coast (Upadhyay *et al.*, 2002). Mangrove distribution is scattered along the west coast with stunt growth and less species diversity.

Table I1 State-wise mangrove forest cover in India (in 1999)*

States along the east coast	Area (km^2)
Tamil Nadu	21
Andhra Pradesh	397
Orissa	215
West Bengal	2125
Andaman & Nicobar Islands	966
Sub-total	3724
States along the west coast	
Karnataka	3
Goa	5
Maharashtra	108
Gujarat	1031
Sub-total	1147
Grand Total	4871

* Source: Forest survey of India (1999)

2. *Coastal mangroves:* These are found along the intertidal coastlines, minor river mouths, sheltered bays, and backwater areas of the west coast. They extend from Gujarat to Kerala, and constitute to 12% of the mangals area of India. Due to less freshwater supply the mangals in the west coast are less, sparse, and show stunted growth. About 41 species have been reported from the west coast (Jagtap *et al*., 2002).
3. *Island mangroves:* They are found along the shallow but protected intertidal zones of bay islands, Lakshadweep and Andamans. These are estimated to be about 16% (800 km^2) of the total mangrove area. About 30 true species of mangroves have been recorded from the island areas.

Species of *Avicennia* and *Aegicera* are dominant vegetation in the Godavari–Krishna and Cauvery deltaic system while *Ceriops decandra, Sonneratia apetala* are dominant on the Mahanadi delta. About 33 species of mangroves have been reported from the Gangetic Sunderbans, with species such as *Heritiera fomes, C. decandra, Xylocarpus* spp., *Lumnitzera* sp., *Sonneratia alba, Kandelia candel, Nypa fruticans*, and *Phoenix paludosa*. The mangroves of the West Bengal are dominated by *Excoecaria agallocha, C. decandra, S. alba, Avicennia* spp., *Bruguiera gymnorhiza, Xylocarpus granatum, Xylocarpus moluccensis, Aegiceras corniculatum*, and *Rhizophora mucronata*.

Species such as *R. mucronata, Rhizophora apiculata, Avicennia officinalis, Avicennia marina, Ceriops tagal, E. agallocha*, and *Acrostidum aureum* are most dominant along the west coast. Mangrove habitats harbor a variety of flora and fauna species (Figures I12 and I13). Until recently, mangroves were treated as unwanted plants and were used largely as a source of timber and charcoal. Therefore, mangrove ecosystems have been severely depleted during the last two decades. According to recent surveys, deforestation has destroyed about 44% and 26% of mangroves along the west and east coast, respectively (Upadhyay *et al*., 2002). It is only in recent years that they have been recognized as ecologically vital. Mangroves play a very important role in protecting the shore from major erosion. The ecosystem forms an ideal nursery for the juvenile forms of many economically important fish and prawn species. A large percentage of the detrital food, which supports a variety of young fish and shrimps, is generated from mangroves.

Management

Traditionally, mangroves have been utilized for their wood, mainly for construction, fuel, and stakes. The bark of *Rhizophora* and *Bruguiera* spp., are used for tannin extraction. The leaves and fruits of *Avicennia* are used as fodder. *Avicennia* forests in the Gulf of Kachchh are constantly grazed by cattle. Mature fruits of *Sonneratia* as well as young fruits of *C. tagal* are consumed as vegetables in the human diet. Similarly, the young shoots of *A. aureum* and *Salicornia brachiata*, associated fern and an obligate halophyte, respectively, are also used as vegetables (Jagtap *et al*., 2002). Mud from the mangrove regions is used as manure for paddy and coconut fields. The roots and leaves of *Derris heterophylla* are used for narcotizing and stupefying fish. Extracts of *Acanthus* leaves are used for rheumatic disorders, while that of *Bruguiera* species for high blood pressure and *Rhizophora* extracts as a cure for jaundice. The bark and the leaves of *E. agallocha*, though poisonous, are used to cure rheumatism.

Mangrove fisheries

Mangroves have a rich and diverse fish assemblage and the habitat is commercially exploited for capture as well as captive fisheries. The capture

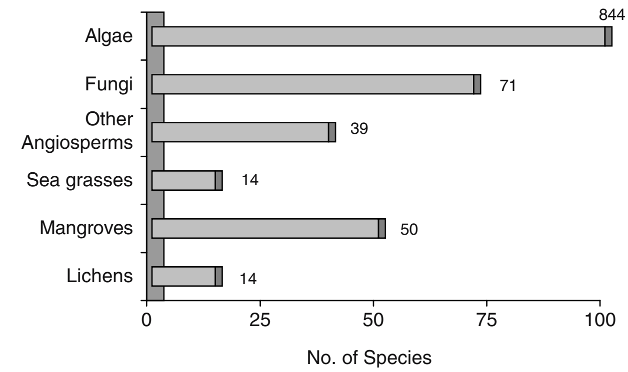

Figure I12 Floral diversity in mangrove habitat. (Compiled from Anon, 2002)

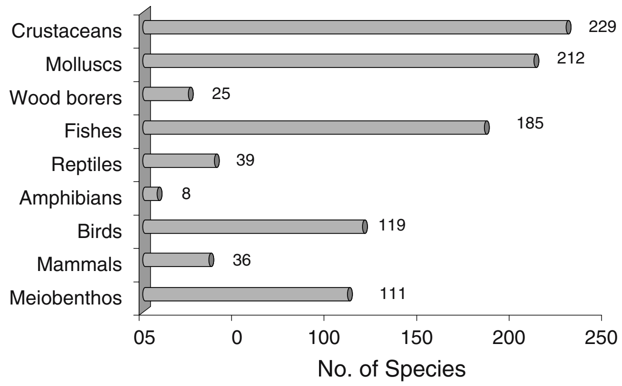

Figure I13 Faunal diversity in mangrove habitat. (Complied from Untawale *et al*., 2000)

fisheries mainly consist of various species of bivalve and gastropod, crabs, prawns, and fishes from the proper mangrove regions and estuarine waterways. The captive fishery includes fish and prawn farming in the mangrove regions as well as mussels and oyster culture in the estuarine region. The salt-affected, water-logged, tidal regions in the vicinity of mangrove environments are commonly used for paddy-cum-prawn farming and salt production.

Lagoons

Coastal lagoons are shallow water bodies lying parallel to the coastline and separated from the open sea by a narrow strip of land or salt bank (Figure I14). They are a very rich and fragile natural ecosystem. As shown in Figure I9, lagoons are distributed all along the Indian coast.

There are eight important lagoons along the east coast; they are the Chilika, Pulicat, Pennar, Bendi, Nizampatnam, Muttukadu, Muthupet. Chilika is the largest brackish water lagoon and Pulicat is the largest saltwater lagoon on the eastern seaboard of India. Chilika lagoon (Figure I15) is spread over 1,100 km^2 while Pulicat lagoon is spread over 350 km^2.

There are nine important lagoons along the west coast of India (Figure I9). They are Vembanad, Ashtamudi, Paravur, Ettikulam, Veli, Murukumpuzha, Talapady lagoon of the Bombay coast, and the Lakshadweep lagoons (Kavaratti and Minicoy). Vembanad and Ashtamudi are the largest coastal and backwater lagoons found in Kerala.

Halophila spp., *Thalassia* spp., *Cymodocea* spp., *A. marina, Acanthus* spp., *Xanthium* spp., *Acacia* spp., *Gracilaria, Asterionella* spp., *Enteromorpha* spp., are some of the floral species found in the lagoons of India.

The benthic fauna of lagoons constitute various species of, foraminiferas, nematodes, gastrotrichs, oligochaetes, polychaetes, calanoids, amphipods, isopods, decapods, tanaids, and molluscs. Among all the lagoons, Chilika has the richest biodiversity. Ecologically, it is

Figure I14 Coastal lagoon at Vadhawan.

Figure I15 Chilika lagoon (Orissa, India).

endowed with a wealth of flora and fauna (Figure I16). A total of 788 faunal species has been reported form the Chilika (Ingole, 2002). The majority of these are aquatic and almost 29% (225) are fish species (Figure I16). About 61 are protozoan species, 37 nematodes, 29 platyhelmenthes, 31 polychaetes, 58 decapods and brachyuran crabs, 37 amphibians and reptile, 136 molluscs, 18 mammals, and 156 bird species.

Chilika Lake contributes to a major portion of the fish catch in the region. The lagoons provide an excellent opportunity for aquaculture and get a good foreign exchange. The rich demersal fishery (especially of prawn, crabs, and molluscs) supports over 80,000 fishermen from 122 villages. The lake supports one of the largest populations of waterfowl during winter season. The area is known as an ideal habitat for crocodile, dolphin, and a variety of birds. An area of 15.53 km^2 of this lake has been designated as wildlife sanctuary. However, Chilika has been facing some natural and manmade problems, particularly frequent shifting of the mouth region, reduced seawater inflow, siltation, and encroachment. With a rise in human population in the lagoon periphery, pollution from domestic sewage, pesticide, agriculture, chemical, and industrial effluent have become major threats to the lagoon ecosystem. The lagoon was rapidly shrinking at the rate of about 2 km^2 per year. According to Ingole (2002) fish catches which used to be about 8,500 tonnes per year in 1980s were dwindling during 1985–2000.

However, due to the timely action taken by the Chilika Development Authority (CDA, Government of Orissa), the lake environment is being restored under the “Chilika Development Plan.” Substantial increases

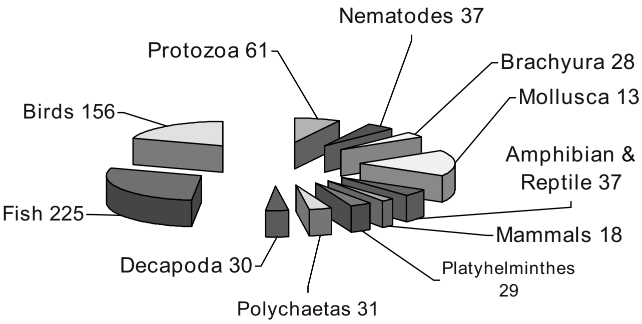

Figure I16 Biodiversity of Chilika Lake ((No. of species); Ingole, 2002).

in the fish production (11,989 tonnes) during 2001–02 (Ingole, 2002) clearly demonstrated the efforts of CDA toward the sustainable development and conservation of this important ecosystem. Recently, due to the rapid recovery of the lake ecosystem, the CDA Authority has been awarded the International *Ramsar Award* and Chilika is also included in the list of *Ramsar Sites*.

Estuaries

Estuaries are an integral part of the coastal environment. They are the outflow regions of rivers, making the transitional zone between the fluvial and marine environment. Estuaries are the focal point of studies, and activities. Fourteen important estuaries have been reported along the east coast and west coast of India (Anon, 1997; Qasim, 1999). Hooghly, Rushikulya, Godavari and Krishna, Edaiyur-Sadras, Araniar, Ennore, Cooum, Adyar, Uppanar, Vellar, Kollidam, Kaveri, Agniyar, Kallar along the east coast, and Ashtamudi, Korapuzha, Beypore, Periar, Kadinamkulam, Vembanad, Netravathi and Gururpur, Gangolli, Pavenje, Kali, Narmada Amba, Purna, Mandovi, and Zuari estuary on the west coast of India.

Biodiversity in the estuaries is very impressive. Some floral species are *Oscillatoria* spp., *Enteromorpha* spp., *Spirogyra* spp., *A. marina, Excoecaria* spp., and *Sonneratia* spp. Various species of polychaetes, crustaceans, molluscs, echinoderms, and fish are the faunal component of estuaries.

Estuaries are semi-enclosed water bodies and thus, they provide a natural harbor for trade and commerce. They are also effective nutrient traps and provide a vital source of natural resources for people and are used for commercial, industrial, and recreational purposes. They also act as nursery grounds for a variety of shrimps and finfish and are the best settling places for clams and oysters.

Indian estuarine ecosystems are deteriorating day by day through human activities, and the dumping of an enormous quantity of sewage into the estuary has drastically reduced the population of spawning fishes. It has also caused considerable ecological imbalance and resulted in the large-scale disappearance of the flora and fauna. Introduction of untreated municipal wastewater and industrial effluents into these water bodies has led to serious water pollution including heavy-water pollution, which becomes bio-magnified and reaches people through the food chain.

Mudflats

Mudflats develop in sheltered places of the intertidal area. Twice each day, water flows in and out with the tides, filling or draining the flat. The mudflat receives nutrients from the tidal flow and the nearby marsh, particularly as it decays. This means that mudflats have rich plant and animal communities.

They are important as sedimentation areas and provide a rich source of organic material for the endo- and epibenthic community. Because of this high availability of organic substances, oxygen content in the pore water is rather low and may limit chemical and biological degradation processes.

Phytoplankton and zooplankton are abundant, as are mud snails. Filter-feeding animals such as oysters and clams live in mudflats because of the availability of plankton. Fish and crabs move through the flats at high tide. Birds and predatory animals visit tidal flats at specific times for feeding.

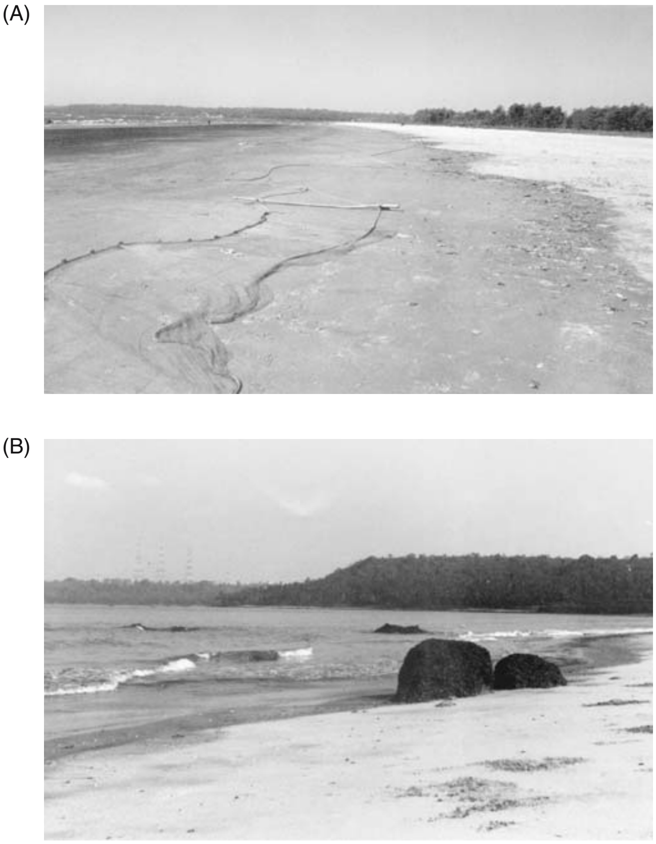

Figure I17 Sandy beaches of Goa (Central west coast of India).

Sandy beaches

The sandy beaches seem to be barren. There is no lush growth of macroalgae and apart from sea grasses there is no obvious plant life. Few animals live on the surface and most of them live below the sand. The organisms found here have suitable burrowing mechanisms, which may take the form of proboscis, parapodia of a polychaeta, and foot of molluscs.

Vast stretches of sand are seen along the east and west coast of India forming the boundary between land and sea. The beaches are subjected to the forces of waves, tides, currents, and winds. Sandy beaches along the Gujarat coast are limited between muddy and rocky shores. Although sandy strips along rocky cliffs are also observed along the Maharashtra and Goa coast, beaches along the central west coast of India are of sandy nature. The sandy shores of Goa and Karnataka (Figure I17) are of limited width, while Kerala has extensive sandy beaches interspersed with coastal lagoons. Tamil Nadu has sand strips along the deltaic shores and rock-bound beaches. Beaches along the Andhra Pradesh coast are of limited width interspersed by the rivers Godavari, Krishna, and their tributaries. Orissa has extensive sand strips at Konark—Puri. The coast of Andaman and Nicobar Islands have sand strips interspersed with bluffs, rocks, or shingle along the coastline. The Lakshadweep atolls have long stretches of coralline sandy beaches with unique vegetation.

Macrofaunal species (benthic organisms having body size >0.5 mm) such as *Donax incarnates, Donax spiculum, Donax faba, Donax scortum, Suneta scriptta, Mactra* spp., *Paphia malabarica, Bullia melanoides, Umbonium* spp., Oliva *spp*., *Emerita holthuisi, Eurydice* spp., *Gastrosaccus* spp., *Ocypode ceratophthalma, Ocypode macrocera, Ocypode platyarsus, Dotilla intermedia, Glycera alba, Lumbriconereis latreilli*, *Onuphis eremita* are some of the common species found on the sandy beaches of India.

Sand dunes

The term “sand dune” reflects the image of vast amounts of shifting sand, barren of plants, and hostile to human habitation. Hot and dry winds shape and arrange the sand in geometric and artistic patterns.

Dunes are of two types. The first type is found in the extremely dry interior desert such as Rajasthan in India and the other type is the coastal sand dune, which occur along the coast of India.

Dunes are composed of wind-blown sand. Fore-dunes are built up at the back of the beaches on the crest of berms and dune ridges where vegetation or other obstacles trap wind-blown sands. During periods of coastline advancement, successful dunes may develop to form a series of parallel dunes (Figure I18).

The common vegetation found in the fore-dune are *Hydrophylax maritima, Ipomoea pes-caprae* (Saurashtra), *Canavalia maritima, Cyperus arenarius, I. pes-caprae, Launea sarmentosa, H. maritima* (Orissa), *H. maritime, I. pes-caprae, C. maritima, C. arenarius, I. pes-caprae, L. sarmentosa, H. maritime, Sporobolus virginicus* and *Zoysia matrella* (Andhra Pradesh), *I. pes-caprae, L. sarmentosa, Dactyloctenium aegypticum, C. arenarius* (West Bengal), *I. pes-caprae, Spinifex littoreus* (Goa). In the parabola dune the following vegetation have been recorded along the west coast of India: *Halopyrum mucronatum, Borreria articularis, Lotus garcinii, Asparagus dumosus, Enicostema hyssopiflorum, Peplidium maritimum, Cassytha filiformis*, and along the east coast of India *Euphorbia rosea, Geniospermum tenuiflorum, Phyllanthus rotundifolius, S. littoreus, Goniogyne hirta, Perotis indica, Brachiaria reptens, Elusine indica, Rothia indica, Trianthema pentandra*.

Sand dunes throughout the world have been recognized for their ecological significance. The coastal dune vegetation acts as shelter belts protecting the inner land. When the dune system and the vegetation are destroyed for short-time benefits in the name of development, disaster occurs. Floods and cyclones on the east coast of India are eye-opening examples. The cause and effect of destruction are not short-termed or locally limited.

Rocky shores

In contrast to sandy beaches where many individuals live unseen in the soil, many of the plants and animals of the rocky shores are conspicuously displayed. Another feature of the rocky shore is the distinctly noticeable zonation of plants and animal communities.

The rocky coast shows a richer fauna than that of the sandy beach and is varied in composition. The rock and crevices give shelter to numerous crabs, molluscs, and fish. *Grapsus grapsus, Tectarius trochoid, Littorina scabra, Littorina angulifera, Littorina undulat, Trohcus* sp., *Cellana radiata, Planaxis sulcatus, Thais bufo, Drupa* sp., *Hemifusus pugulinus, Perna viridis, Nereis* spp., amphipods, isopods, Holothuria, Sea Urchin, nudibranch, *Aplasia* spp., are some of the common fauna of the rocky shores. Common flora of the rocky shore are different species of *Porphyra*, *Gracilaria,* and *Enteromorpha*, *Padina, Ulva*, *Gelidium*, *Sargassum*, and *hypnea*, *Chaetomorpha* spp.

Sea grass

Sea grasses are submerged flowering plants (angiosperms) that have adapted to life in the sea. They differ from what we refer to as "seaweed," in that they are plants with vessels and well-defined root and shoot systems. Sea grasses have been able to successfully colonize the marine environment because of five properties:

- the ability to live in a salty environment;
- the ability to function normally when fully submerged;
- a well-developed anchoring system;
- the ability to complete their reproductive cycle while fully submerged;
- the ability to compete with other organisms under the more or less stable conditions of the marine environment.

Sea grass habitats are mainly limited to the mudflats and sandy regions from the lower intertidal zones to a depth of ca. 10–15 m along the open shores and in the lagoons around islands. The major sea grass meadows in India occur along the southeast coast (Gulf of Mannar and Palk Bay) and along a number of the islands of Lakshadweep in the Arabian Sea and of Andaman and Nicobar in the Bay of Bengal. The largest area (30 km^2) of sea grass occurs along the Gulf of Mannar and Palk Bay, while it is estimated that ca. 1.12 km^2 occurs in the lagoons of major islands of Lakshadweep. A total of 8.3 km^2 of sea grass cover have been reported from the Andaman and Nicobar Islands (Jagtap *et al*., 2003).

The sea grasses of India consists of 14 species belonging to 7 genera. The Tamil Nadu coasts harbor all 14 species, while 8 and 9 species have been recorded from Lakshadweep, and Andaman and the Nicobar group of Islands, respectively. The east coast supports more species compared to the west coast of India. The main sea grasses are *Thalassia hemprichii, Cymodocea rotundata, Cymodocea serrulata, Halodule uninervis* and *Halophila ovata*. Species such as *Syringodium isoetifolium* and *Halophila* spp., occur in patches as mixed species. Gulf and bay estuaries mostly harbor low numbers of species, dominated by *Halophila beccarii* in the lower intertidal region and by *Halophila ovialis* in the lower littoral zones.

Sea grass beds are:

- Major primary producers (food manufacturers) in the coastal environment. Their high primary productivity rates are linked to the high production rates of associated fisheries;
- Stabilizers of bottom sediments; they provide protection against erosion along the coastline;
- Important nutrient sinks and sources, that is they help in the recycling of nutrients.

With root-like stems, which extend horizontally under the sea bottom, sea grasses act to stabilize the sediment. These sediments, that

Figure I18 Typical sand dune found along the east coast of India.

would otherwise settle on coral and prevent contact with sunlight, tend to accumulate and become trapped in the sea grass. Turtle grass, the most common type of sea grass thrives in areas that are protected from wind-driven current and surf. The broad leaves of turtle grass act as huge filters, removing particles from the water and depositing them as fine sediment. These sediments often contain organic matter, which contribute to the high productivity of this habitat. For this reason, the sea grass habitat attracts various species of fish, conch, lobster, turtles, and manatees for feeding and breeding. Numerous species of reef fish use sea grass as a protective nursery, hiding amid the grass from predators. Moreover, adult fish that hide in the coral reef during the day and venture out at night to feed, take advantage of the rich source of food that exists in the sea grass.

The natural causes of sea grass destruction in India are cyclones, waves, intensive grazing, and infestation of fungi and epiphytes as well as "die-back" disease. Exposure at the ebb tide may result in the desiccation of the bed. Strong waves and rapid currents generally destabilize the meadows causing fragmentation and loss of sea grass rhizomes. The decrease in salinity due to extensive freshwater run-off also causes disappearances, particularly of the estuarine sea grass bed.

Anthropogenic activities such as deforestation in the hinterland or mangrove destruction, construction of harbor or jetties, loading and unloading of construction materials as well as anchoring and moving of boats and ships, dredging and discharge of sediments, land filling and untreated sewage disposal are some of the major causes of sea grass destruction of India.

As of yet, there is no specific legislation protecting sea grasses, although generally the Fisheries Department is responsible for this habitat. Green Reef recommends that in addition to controlling the use of pesticides and decreasing run-off, dredging activities need to be strictly monitored and limited. Sea grass beds should be thought of as an indication of the health of the ecosystem; when they begin to disappear, we know there is trouble.

Coral reefs

Coral reefs are among the most biologically productive, taxonomically diverse, and aesthetically important living organisms among all the aquatic ecosystems.

The major coral formation in India is around the Lakshadweep (816 km^2) and Andaman Islands (960 km^2), as well as in the Gulf of Mannar (94 km^2) and the Gulf of Kachchh (406 km^2). Reefs in the Gulf of Kachchh, Gulf of Mannar, and Andaman and Nicobar Islands are mostly of the fringing type, with a few platform, patch and atoll reefs, and coral pinnacles. Lakshadweep Islands on the contrary are mostly atolls with a few coral heads, platform reefs, and sand cays. Coral, though rare in occurrence, are reported at many locations along the west coast.

About 44 species of scleractinian coral and 12 species of soft corals occur in the Gulf of Kachchh (Figure I19). The submerged reefs of these areas harbor 18 species of stony coral and have 45% coverage. *Acropora, Porites, Pseudosiderastrea*, and *Favia*, and one species of soft coral *Juncella juncea* are common. Two species of hard coral (*Pseudosiderastrea tayamai* and *Porites lichens*) have been recorded in patches along the central west coast. Large well-developed hard colonies have also been sighted at Colaba near Mumbai.

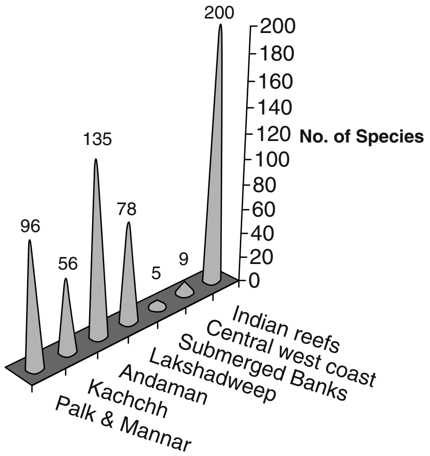

Figure I19 Coral distribution along the Indian coast.

Malvan is considered to have the richest marine biodiversity along the central west coast. *Porits*, a stony coral is most common in Malvan waters. Nine species including a rare coral species belonging to the genera *Coscinaraea*, *Favites, Goniastrea, Synaraea* and *Pseudosiderastrea, Cyphastrea, Turbinaria* have been recorded in this region. Angria bank—a submerged reef off Ratnagiri has stony corals. A few patches of scleractinian corals have been reported in subtidal waters off the Goa coast (Rodrigues *et al*., 1998). Five coral species have been recorded from Gaveshani Bank off Malpe along the Karnataka coast (Qasim and Wafar, 1979; Wafar, 1990). *Pocillopora eydouxi* has recently been reported from Vishakhapatnam on the east coast.

About 96 species belonging to 36 genera of Scleractinian and 7 species of Ahermatypic corals are reported from Palk Bay and the Gulf of Mannar (Figure I19). *Montipora* and *Acropora* represent 40% of the species in the Palk Bay. Thirty species of stony corals are reported from Manauli reef, of which the dominant corals are *Acropora, Porites, Goniastrea, Favia, Pocillopora* and *Montipora*. Krusadai island has a well-developed coral reef and sustains 96 species belonging to 26 genera of hermatypic corals.

Massive occurrences of corals provide much needed protection from waves to the coastline; and coral productivity yields a multitude of flora and fauna dependant on the coral ecosystem. Coral reefs also provide opportunities for skin diving, under-water photography, sport fishing, and shell collection, thus, providing a vital stimulus to the tourist industry. Coral reefs are often exploited for calcium carbonate—a raw material for many lime-based industries. The fishery resources of the reefs are extremely rich and diversified. They are also exploited for their beautiful associated fauna such as molluscs and ornamental fish.

Due to population pressure, most of the coral reefs have become extremely vulnerable to industrial development and pollution along the coastline. Unless protection is offered to the coral reefs, most of them will diminish in size in the future and ultimately die. The reefs that will probably flourish are on the atolls of Lakshadweep and some of the islands of Andaman and Nicobar Islands.

Marine protected areas

There are 26 Marine Protected Areas (MPAs) in India comprised of national parks and wildlife sanctuaries declared as coastal wetlands; especially mangrove, coral reefs, and lagoons, under Wildlife (Protection) Act, 1972. These 26 MPAs are located in 7 coastal states and 2 union territories and cover 13% of the total coastal wetland area of the country. Some of these MPAs are shown in Figure I9 and Table I2. The Gulf of Kachchh Marine Sanctuary and Marine National Park, the Gulf of Mannar National Park, and the Wandoor Marine National Park (Andaman Islands) have been established primarily to protect marine habitats.

Table I2 Marine national parks and sanctuaries along the Indian coast (Anon, 2002).

States	Location	Name of the biosphere
Gujarat	Gulf of Kachchh	National Marine Park, Bird Sanctuary, and coral reef
Maharashtra	Mahaim (Mumbai) Malvan	Natural Mangrove Park Marine Park (coral reef)
Goa	Chorao island	Bird Sanctuary
Lakshadweep islands	Kawaratti, Agatti, Minicoi islands	Marine Park (coral reef)
Tamil Nadu	Gulf of Mannar	National Marine Park, Sanctuary, and coral reef
	Muthupet	Reserve Mangrove Forest
Andhra Pradesh	Coringa	Wildlife Sanctuary
Orissa	Nalaban (Chilika)	National Marine Park and Bird Sanctuary
	Bhittarkanika	Wildlife Sanctuary (Turtle project)
West Bengal	Haribanga	National Marine Park and Bird Sanctuary (Tiger project)
Andaman and Nicobar Island	Wandoor	National Marine Park

Management of coastal ecology

As shown in Figure I20, there is great demand for industrial development along the Indian coast. This in turn amounts to the increase in pressure on the coastal zone due to concentration of population, development of industries and ports, discharges of waste effluents and municipal sewage, and spurt in recreational activities which have adversely affected the coastal environment. Coastal resources are affected by activities far distant from the coast (viz., deforestation, damming of rivers, bunding/barraging of the coastal water bodies, river sand mining, discharge of pesticides, heavy metals, domestic and factory wastes, garbage, and other substances that are harmful to the coastal areas. Lagoons, estuaries, wetlands, and nearshore shallow water areas are particularly vulnerable to these activities. Considering the urgent need for protecting the Indian coast from degradation, the Government of India enacted "Coast Regulation Zone (CRZ) Act, 1991." The area influenced by tidal action up to 500 m from High Tide Line (HTL) and the land between the Low Tide Line (LTL) and the HTL has been declared as Coastal Regulation Zone (CRZ).

Mangroves and coral reef ecosystem

The mangroves are constantly threatened by increasing anthropogenic pressures such as indiscriminate cutting, reclamation mainly for agriculture and urbanization, fuel and construction, and overgrazing by domestic cattle. Mangrove ecosystems along the west coast, particularly in the States of Gujarat, Maharashtra, and Kerala, have been degraded to a large extent. However, West Bengal (Sundarbans), Orissa, and the Andaman and Nicobar Islands still form the best mangrove ecosystems of India. Considering various estimates for the mangrove cover in the country, 30% of the mangrove area was reclaimed for different anthropogenic activities during the period 1975–90 (Jagtap *et al*., 1993).

Realizing the importance of mangroves and coral reefs, the Government of India initiated efforts for their conservation and management. They were declared as ecologically sensitive areas under the Environment (Protection) Act, 1986, banning their exploitation, and followed by a CRZ Notification 1991 prohibiting development activities and disposal of wastes in the mangroves and coral reefs. The Ministry initiated a plan-scheme on conservation and management of mangroves and coral reefs in 1986 and constituted a National Committee to advise the Government on relevant policies and programs. On the recommendations of this committee, 15 mangrove areas in the country have been identified for intensive conservation (Anon, 1997 & 2002; Jagtap *et al*., 2002).

Considering the importance of coral reefs and the factors responsible for their deterioration, Andaman and Nicobar Islands, Lakshadweep Islands, Gulf of Mannar, and Gulf of Kachchh have been identified for conservation and management. Efforts have been initiated to establish Indian Coral Reef Monitoring Network (ICRMN) to integrate various activities on coral reefs through national and international initiatives.

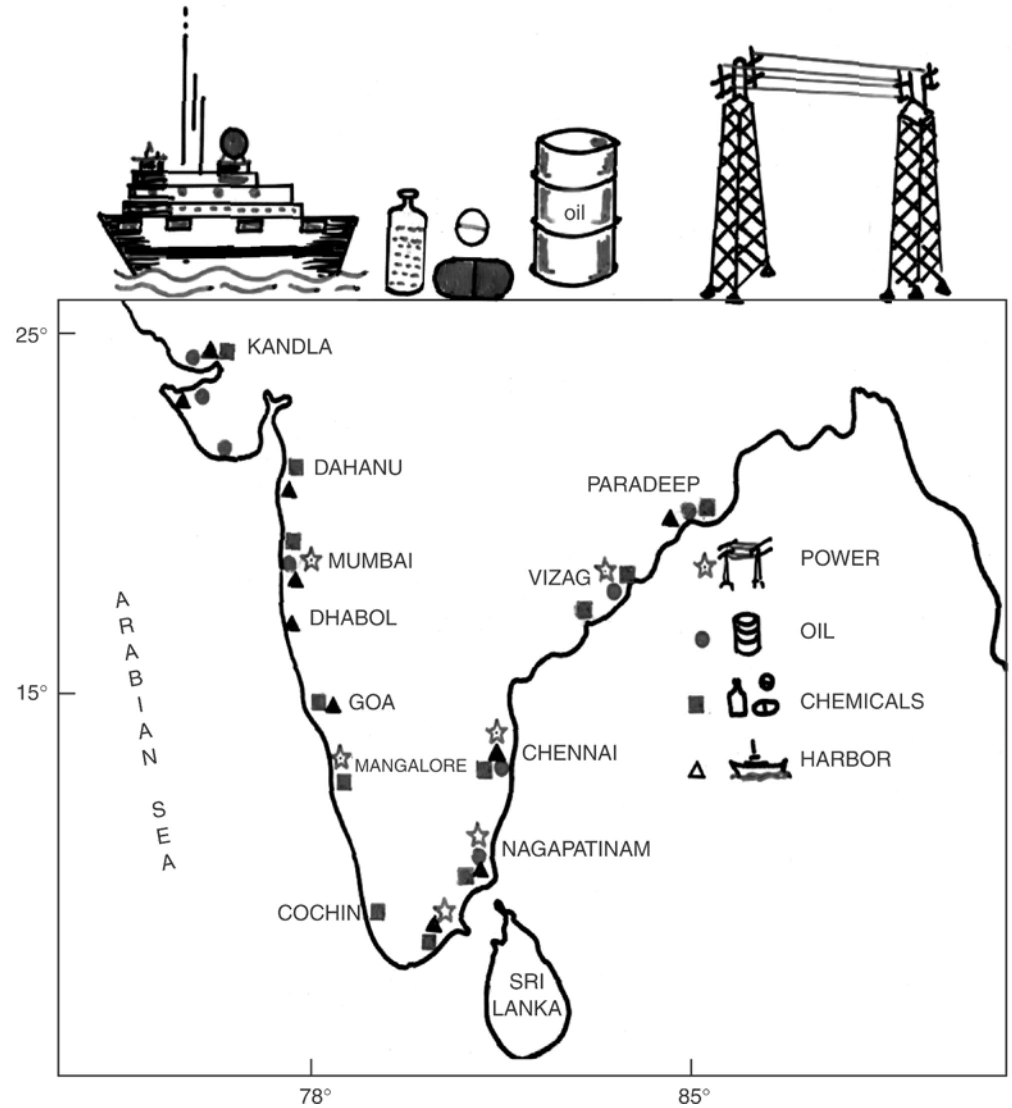

Figure I20 Patterns of industrial development along the Indian coast.

Institutions of database networking and capacity building and training on coral reefs have been identified. With the establishment of the National Mangrove Committee (NATMANCOM), attempts are being made to protect, conserve, and restore the mangrove habitats. Mangrove regions in the country have been categorized presently under the Ecologically Sensitive Zone; vide CRZ Act of the country. As per the CRZ Act, no development in the mangroves or in the vicinity is allowed prior to an environmental impact assessment (EIA) and clearance from the Ministry of Environment and Forests (MoEF), Government of India. Few of the mangrove regions in the country have been conserved as Biosphere reserves for germplasm and wildlife sanctuaries.

Shrimp culture activities

The aquaculture industry is growing at a faster rate than many of the sectors of the coastal zone in India. Socially, its product is seen as a currency. However, if aquaculture expansion is not regulated, its long-term consequences will be felt in the quality of water bodies. In fact some adverse effects of shrimp culture are already seen along the east coast of India, particularly along the coast of Andhra Pradesh.

Sandy shores

Mining of beach sand is a widespread activity in many of the coastal areas. Though sand is an important constituent of construction activities, it has to be borne in mind that it is these sand deposits that provide the natural protection to the coast from erosion. Storms, waves, currents, and wind temporarily displace vast quantities of beach sand that is then held in storage as sand bars. These sand bars then become the protectors of the coasts against those forces, which finally return the sand to the beach. Thus, removal of sand from any part of the beach can aggravate the erosion and recession of the beach front altogether.

For the above reasons and also for the sustainable management of the coastal resources, many countries are now developing Coastal Zone Management (CZM) strategies, and some have already begun to adopt such programs. The CZM has to manage, develop, and conserve natural resources and, while doing so, it has to integrate the concerns of all relevant sectors of the society, economy, and prosperity.

A major thrust in implementing the CRZ notification is in the conservation of coastal resources, to achieve their sustainability, and long-term protection of its natural assets. The criterion for sustainable use is that the resource shall not be harvested, extracted, or utilized in excess of the quantity that can be produced or regenerated over the same period. It is important to learn the acceptable limits of coastal environmental degra-dation and the limits of sustainability of coastal resources. Hence, in order to achieve the goals set forth in the notification, it is imperative to have first-hand-information on the present land use practices and availability of the resources in the coastal zone. Contribution No.3897 of NIO, Goa.

Baban Ingole

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Cross-references

Aquaculture
Bioconstruction
Coastal Lakes and Lagoons
Coral Reef Coasts
Estuaries
Human Impact on Coasts
Indian Ocean Coasts, Coastal Geomorphology
Indian Ocean Islands, Coastal Ecology and Geomorphology
Mangroves, Ecology
Mangroves, Geomorphology
Muddy Coasts
Vegetated Coasts
Wetlands

INDIAN OCEAN COASTS, COASTAL GEOMORPHOLOGY

The coastal geomorphology of the Indian Ocean coast, with special reference to coasts of Pakistan, India, SriLanka, Bangladesh, and Myanmar, is mainly governed by the processes associated with monsoons.

Pakistan

The coastline of Pakistan, from the Iranian border on the west to the Indian border on the east is about 990 km long. This coastline is one of the active tectonic regions. The coast here is associated with a narrow continental shelf, except off Indus delta. The coast of Pakistan is divided into the Makran coast, Las Bela coast, Karachi coast, and Indus Delta coast.

The Makran coast, with approximately 473 km length, from the Iranian border to Ras Malan, consists of long sandy beaches associated with either wide coastal plains or valleys landward. These plains and valleys are interrupted by uplifted marine terraces at places. Also the Makran hill ranges, which lie about 32 km from the coast, become part of the coast at Ras Malan with massive headlands. Spits and bars are common seasonal morphologic units along sandy beaches. At places, well-developed beach ridges are seen. Dasht is the only river which brings a small quantity of sediment from land to the Arabian Sea along this coast.

The Las Bela coast, with about 260 km length, extends from Ras Malan to Ras Muari. The Ras Malan range is made up of sandstone and shelly limestone and presents gorges and cliffs as high as 600 m, which drop directly to the sea. Followed by this, on the east, is the Las Bela plain. The coast here consists of a series of beach ridges, sand dunes, bars, tidal flats, and lagoons with mangroves (Bird and Schwartz, 1985). Between the Ras Malan ranges and the Las Bela main valley notable mud volcanoes are present, the largest among them is called Chandragup (Snead, 1964). On the eastern side of the Las Bela valley, promontories of limestone are present. Here marine terraces at different elevations have wave cut sea caves and blow holes (Snead, 1966). Along this coast, the Hab River joins the Arabian Sea at its mouth compound bars, shallow lagoons, and sandy beaches are present.

The Karachi coast, about 48 km in length from Ras Muari to Clifton beach, consists of low rocky cliffs and sandy beaches of almost equal length. Marine terraces, sea caves, and arches are common in the sandstone and shale rocks. Sandy barrier beaches, spits (the longest one 15 km in length), shallow lagoons, tidal flats, and salt evaporation ponds are common along the sandy beaches.

The Indus delta coast is about 200 km long with uniform landforms namely large tidal channels with mudflats in between, barrier bars and spits with hooks, and beaches, and a few small mangrove shrubs. The sand bars and delta channels are dynamic in nature as they change their morphology due to tidal currents, waves and channel floods. The coastal area in this region is very flat and therefore up to 6.5 km from the coastline it is submerged during high tide. The river Indus brings a large quantity of sediment from land to sea and joins the Arabian Sea along this coast.

India

Most of the early literature on Indian coastal geomorphology was essentially of a descriptive nature based on the nature, location, and relationships of the landforms and sea level. Ahmad's (1972) was possibly the first and only book on coastal geomorphology of India, and contains data collected from large-scale maps and inferences drawn on the nature of the coasts. In addition, there are some isolated studies by Vaidyanathan (1987), Baba and Thomas (1999). The Space Application Centre (SAC, 1992) has carried out a comprehensive study on the coast using LANDSAT and IRS data. The information on Indian coastal geomorphology presented in this article is based on these and many more isolated published studies.

India has about a 7,500-km long coastline. The coastline of India has been undergoing morphological changes throughout the geological past. The sea level fluctuated during the period of last 6,000 years and recorded marked regression during the period between 5,000 and 3,000 years before present (Rajendran *et al.*, 1989). The present coastal geomorphology of India has evolved largely in the background of the post-glacial transgression over the preexisting topography of the coast and offshore (Baba and Thomas, 1999).

The major rivers that cut across the coast and bring large quantities of water and sediment to the coast from Indian continent are the Ganges, Brahmaputra, Krishna, Godavari, and Cauvery on the east coast, and the Narmada and Tapti on the northwest coast. In addition, there are about 100 smaller rivers, these also supply considerable quantities of water and sediment. While larger rivers have well-developed deltas and estuarine systems, almost all the small rivers have estuarine mouths with extensive mud flats and salt marshes and some of them with estuarine islands.

The continental shelf of India is very wide on the west coast with about 340 km in the north, tapering to less than 60 km in the south. The shelf is narrow along the east coast. The coastline on the west receives southerly winds that bring high waves during the monsoons (June–September). The east coast generally becomes active during the cyclones of the northeast monsoon period (October–November). The tidal range varies significantly from north to south. It is around 11 m at the northwest, 4.5 m at the northeast and around 1 m at the south.

Considering geomorphic characteristics, the Indian coast is divided into two categories, namely coasts on the west coast of India and coasts on the east coast of India. The coast on the west coast of India differs from the east in that there are practically no deltas on the west coast. The coastline here is modified by headlands, bays, and lagoons at irregular intervals. There is distinct evidence of the effect of neotectonics in some sections (Vaidyanathan, 1987). The east coast on the contrary is known for the number of deltas especially along the northern portion, West Bengal and Orissa coast. Deltas in the southern portion have helped in recognizing ancient channels, ancient beach ridges, former confluences, and strandlines.

West coast of India

Though there are a large numbers of small rivers bringing enormous quantity of sediment to the Arabian Sea along the west coast, deltas are not formed, possibly due to the high-energy condition of the coast. Beach morphological changes along the west coast are controlled by the southwest monsoon. The maximum morphological changes occur during early monsoons (June–August). During this period most of the material is transported to the offshore and some alongshore. Most of the material appears to be returned again during the fairweather season.

The west coast of India is further divided into the Gujarat coast, Maharashtra, Goa and northern Karnataka coast, and southern Karnataka and Kerala coast based on their geomorphological distinctions. The coastal area of Gujarat is the largest in the country with about 28,500 km^2. The coast in Gujarat, from west to east, varies from a deltaic coast, the irregular drowned prograded coast, the straightened coast, the spits and cuspate foreland complex, and the mudflat coast. The Gujarat coast is further divided, from west to east, into five regions, namely Rann of Kutch, the Gulf of Kutch, the Saurashtra coast, the Gulf of Khambat, and the South Gujarat coast, based on coastal geomorphic characteristics.

The Rann of Kutch remains saline desert for the larger part of the year and is further divided into the Great Rann and the Little Rann. On the west of the Great Rann of Kutch is the area of the lower Indus deltaic plain which is characterized by tidal creeks and mangroves. The coastline in the Gulf of Kutch has extensive mudflats and is highly indented with a number of cliffed rocky islands (Baba and Thomas, 1999). Migration, joining of different creeks, reorientation of tidal current ridges, and regression of the sea are seen and are related to tectonically activated lineaments. The coast here is fringed by coral reefs and mangroves. Algae, salt marsh, dunes, and salt pans are very common. The Saurashtra coast has numerous cliffs, islands, tidal flats, estuaries, embayments, sandy beaches, dunes, spits, bars, bays, marshes, and raised beaches at some places. The coast, in Gulf of Khambat is indented by estuaries and consists of mudflats, dunes, and beaches. Here mudflats are seen at different levels and paleo-mudflats have been related to regression. The south Gujarat coast is relatively uniform and is indented by a series of creeks, estuaries, marshes, and mudflats. The Gujarat coast, from Great Rann to the south Gujarat coast, presents evidence for both emergent and submergent coasts.

The Maharashtra, Goa, and northern Karnataka coasts are characterized by pocket beaches flanked by rocky cliffs, estuaries, bays, and at some places mangroves. Beaches in southern Goa and some places along northern Karnataka, however, are long and linear in nature with sand dunes. The Mandovi and Zuari estuarine system in Goa is the largest in this part of the coast. Mudflats are found mainly along estuaries and creeks. Rocky promontories on the Maharashtra coast are made up of Deccan basalts whereas in the south they are mainly of granite gneisses. A number of raised platforms can be seen all along the coast. There are a few islands along the southern parts of this coast near Karwar. This coastal stretch is typical of a cliffy coastline with raised platforms and strong evidence of a submergent coast. The beaches in Goa and northern Karnataka are well-studied and classified as stable beaches with seasonal morphological changes and annual cyclicity (Nayak, 1993).

The southern coast of Karnataka is characterized by long linear beaches, estuaries, spits, mudflats, shallow lagoons, islands, and a few patches of mangroves. Satellite image studies revealed northward shifting of the mouth of estuaries along this coast (SAC, 1992). Beach erosion is severe in some areas along this stretch. The Kerala coast is known for the presence of laterite cliffs, rocky promontories, offshore stacks, long beaches, dunes, estuaries, lagoons, spits, and bars. Using Landsat images, three sets of sand dunes have been identified. The mud banks are unique transient nearshore features appearing during monsoons (Mathew and Baba, 1995) at Kerala. They are unique phenomenon occurring at particular locations along the Kerala coast during the southwest monsoon season, which act as natural barriers to coastal erosion. Along the coast, sand ridges, extensive lagoons, and barrier islands (700 landlocked islands) are indicative of a dynamic coast. About 420 km of the 570 km coastline is protected by seawalls and about 30 km of the coast is undergoing severe erosion. Maximum loss of material has been reported along the southern sections. The predominant southwest wave approach during monsoons, result in northerly littoral drift with varying speed. Some parts of the Kerala coast are known for rich heavy-mineral deposits. The characteristic coastal geomorphology provides an ecosystem, which supports both agriculture and fisheries. Evidences of both emergent and submergent coasts are available for the southern Karnataka and Kerala coast.

East coast of India

The deltaic systems of the east coast experience the high sedimentation rate and periodic cyclones which result in extensive floods.

The east coast in the south, along Tamil Nadu and Pondicherry, is straight and narrow except for indentations at Vidyaranyam. The major landform along this coast is the presence of a large delta formed due to the Cauvery River and its tributary system. The other landforms are mudflats, beaches, spits, coastal dunes, rock outcrops, salt pans and strand features. At a few places mangrove systems, and at Gulf of Mannar and Rameshwaram fringing and patchy reefs, are seen. Deposition and erosion have been reported at different beaches along this stretch. Rich heavy-mineral deposits have been reported at Muttam–Manavalakuruchi.

The coastline of Andhra Pradesh, mainly the deltaic coast, is 640 km long and comprised of bays, creeks, extensive tidal mudflats, spits, bars, mangrove swamps, marshes, ridges, and coastal alluvial plains. Inundations are seen in the extreme south of the Andhra Pradesh coast, that is, in the saltwater lagoon of Pulicate lake and also between the Godavari and Krishna deltas. The Kolleru lake, situated in the interdelta, formed due to coalescence of the deltaic deposits of the rivers and later it cut off from the sea (SAC, 1992), is shrinking on the northern side. The deltaic and southern coasts are rich in agriculture and aquaculture production. The deltaic coast is well vegetated with mangroves. The Pulicate lake has extensive tidal flats and a 12 km long spit. In the north, residual hills and ridges are seen close to the sea. Rocky outcrops and bay beaches are seen here. Storm wave platforms, sea caves in rocks, and cliffs are common coastal features in the north. A critical examination of the relief chart off the region around the Krishna River confluence has indicated the presence of extensive banks in the shelf zone (Varadarajulu *et al*., 1985). The islands of the Krishna delta front are intertidal and submerged to a large extent during spring tide. The Krishna delta front has been growing through spits and barrier bars (SAC, 1992).

The Orissa coast is a site of deposition formed and controlled by the Mahanadi and Brahmani–Baitarani deltas. Mudflats, spits, bars, beach ridges, creeks, estuaries, lagoons, flood plains, paleo-mudflats, coastal dunes, salt pans, and paleo-channels are observed all along the Orissa coast. The Chilka lagoon is the largest natural water body of the Indian coast. The inlet mouth of Chilika lake is exposed to high annual northward littoral drift and observed to migrate about 500 m northward per year (Chandramohan *et al*., 1993). The width of beaches at Orissa vary. Littoral transport of sediments in the coastal region is a strong process. The coast is also exposed to severe cyclones. Turbidity in the nearshore as well as in the estuarine region is very high. Progradation of the coastal region in the north of the Devi estuary, and drifting of beaches has been observed. The Bhitarkanika and Hatmundia mangrove reserves are as extensive as 190 km^2. Gopalpur is rich in heavy minerals. Prominent and well-developed sand dune deposits containing monazite, zircon, rutile, ilmenite, and sillimanite occur along the southern coast of Orissa.

The West Bengal coast represents a typical deltaic strip with almost a flat terrain. The Hooghly and its distributaries form the conspicuous drainage system and forms an estuarine delta. The major geomorphic features are mudflats, bars, shoals, beach ridges, estuaries, a network of creeks, paleo-mudflats, coastal dunes, islands like sagar and salt pans. The Sundarbans, one of the largest single block of halophytic mangrove systems about 1,430 km^2, of the world need a special mention.

SriLanka

SriLanka has a coastline of about 1,700 km including that of the Jaffna lagoon. It is a tectonically stable tropical island consisting mainly of Precambrian rocks, and in the northwest, Miocene limestones, and Quaternary sediments. The central portion of the island is a highland surrounded by lowland coasts. Two-thirds of the island's coastline consists of sandy beaches bounded by Precambrian headlands (Swan, 1979). The remaining one-third of the coastline, in the northwest and north, consists of sedimentary rocks. Beach material is predominantly terrigenous. Coastal dunes occur along some sections depending on prevailing energy conditions.

The continental shelf between the Gulf of Mannar and Pak Strait in the northwest and north, respectively, is considerably wide across to India. Elsewhere it is narrow.

The coastline of the island is affected by northeast and southwest monsoons. Wave energy is relatively low in the north and northwest because of shallow seas and barriers. In general, however, beaches are open to seasonal strong wave action. In the north and northwest where energy is low, sheltered lagoons with mangroves, estuaries, barrier beaches, spits, and tidal flats are common. Corals forming fringing and small barrier reefs are also seen. Beaches here are narrow and composed of coarse calcareous material. In the Pak Bay and Gulf of Mannar many depositional morphological units are seen. They include, intertidal barriers, multiple sand bars, dunes, and in the southern part of the Gulf of Mannar a stable sand spit growing toward the northwest. Net sediment movement toward the north along the west coast causes this spit to maintain a stable sand body. From this spit to Colombo in the South, important morphological features that are seen are relict beaches, sand dunes, flood plains, deltas, lagoons, and swamps backed by raised beaches. Dune deposits here overlie limestone. From Colombo, further to the south, lateritized Precambrian rocks form promontories. A sandstone reef offshore, opposite Colombo, acts as a barrier to incoming large waves and the supply of sand material. Raised beaches up to 8 m above sea level are seen at Colombo. Further south the coastline is smooth and sandy, with bays and headlands, backed by raised beaches, flood plains, swamps, and laterite terraces. Along the southwest coast, wave energy is high and sand supply is poor and therefore the coast is undergoing severe coastal erosion. Yun-Caixing (1989) studied coastal erosion and protection using remotely sensed data between Colombo and the southernmost point of the island. The southernmost part of the island consists of low platforms of resistant granitic rocks. The coast here is indented and morphologic units seen are promontories, cliffs, barrier beaches, lagoons, and swamps.

The east coast adjacent to the southern tip, consists of wide coastal plains and low coastlands. Headlands are spaced far apart, and behind long barrier beaches are lagoons, and estuarine deltas. Sand-rich rivers traverse this sector. This change in coastal morphology is in response to a change in geological structure (Cooray, 1967). Further north along the east coast, there are two linear submarine structures, namely the Great and the Little Basses (reef) ridges. These ridges are composed of calcareous sandstone (Throckmorton, 1964). The landforms of bedrock and sand dunes are replaced by broad flood plains, river terraces, and lagoons, further north small barrier beaches are present. A series of large lagoons which are interconnected are called Batticaloa lagoon, a major feature along east coast. Further north, the coastline is made up of bays and headlands of coral, backed by beach ridges and lagoons. Estuaries, deltas, lagoons, and bay-head barrier beaches are common features along the coast. Along the northeast, bays and headlands backed by raised beaches, lagoons, and low residual rises are the common morphological features. Old beach deposits and dunes are seen, which are rich in ilmenite and rutile minerals.

Bangladesh

The coastline of Bangladesh is around 654 km long from the Indian border in the west to the Myanmar border in the east. This excludes tidal channels and delta estuaries. If estuaries, islands, and tidal channels are included it is more than 1,320 km long. The Bangladesh coast is divided into four parts from west to east; Sundarbans, cleared Sundarbans, Meghna, and Chittagong. Except for the last one Chittagong, the coastline is low, swampy, and rapidly changing and composed of sediments of the Quaternary period in large alluvial basins. The source is from two vast river systems, the Ganges and the Brahmaputra.

The Sundarbans are thick mangrove and nipa palms swamps, with a total distance of about 280 km (about 195 km in Bangladesh) from the Hooghly River in India to the Tetulia River in Bangladesh. About 68 km long, sundarban forests have been cut and destroyed. This area, is presently, being used for extensive farming. Tidal estuaries, flat marshy islands, creeks and channels, banks of soft muds and clays with thick mangrove and nipa palms are characteristic features of the Sundarban coast. It represents the older deltaic plain of the Ganges with the presence of old beach ridges in the western swamps. The Meghna is a single main channel which after collecting water and material from the Ganges, Brahmaputra, and Meghna rivers, joins the Bay of Bengal. The characteristic feature is the series of extensive shoals called the Meghna flats developed at the mouth of the River Meghna. These shoals are barren mud and sand bodies. This strongly supports a drowned coastal region.

The geomorphic history of the deltaic plain, which includes Sundarbans and Meghna, is continuous shifting of the river course. In recent times, the Ganges has shifted to the east, resulting in the Meghna as a major course. The shifting is explained as tectonic by Morgan and Mcintire (1956). Sediment supply and tectonic history at the delta with reference to the last glacial period is explained by Chowdhury (1996).

The Chittagong coast extends 274 km between two rivers, namely River Feni in the north and River Naf on the Myanmar border. Small beaches and broad sand flats between headlands along this coast are the common features. There are many islands and shoals found along this stretch of the coast.

Myanmar

The Myanmar coast is about 2,300 km long from the Bangladesh border to the border of Thailand. The coast is divided into three parts namely the Arakan, Irrawaddy, and the Tenasserim.

The Arakan coast runs parallel to a mountain chain of strongly folded Mesozoic and Tertiary rock. Near the Bangladesh border, the coast is elongated with steep-sided rocks and islands, but further south the coast consists of estuarine channels, mangrove forests, patchy coral reefs, and islands. The coast is an example of an emerged coast with many raised beaches and old sea cliffs. Another significant feature of this coast is the presence of mud volcanoes which form temporary islands. With wave action, coming in slowly, they transform to shoals.

The Irrawaddy delta coast runs west to east, and is a large delta with deposition of silt and sand. The delta features a number of shoals, estuarine distributaries, channels, and mangrove forests. From the delta region a large volume of sediment is shifted to the east to the Gulf of Martaban by southwest waves during monsoons.

The Tenasserim coast is composed of rocky promontories, valleys, estuaries, mangrove-fringed creeks, and sand spits. Estuarine lagoons and bays are silted up and transformed into mangrove swamps and saline marshy lands. Beaches are rich in heavy minerals, namely ilmenite and monazite. Some beaches are also backed by coastal sand dunes.

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Cross-references

Barrier Islands
Coral Reef Coasts
Coastal Lakes and Lagoons
Desert Coasts
Indian Ocean Coasts, Coastal Ecology
Indian Ocean Islands, Coastal Ecology and Geomorphology
Mangroves, Geomorphology

INDIAN OCEAN ISLANDS, COASTAL ECOLOGY AND GEOMORPHOLOGY

Geographically, the Indian Ocean islands (Figure I21) range from oceanic to continental, geologically from volcanic, limestone, granite, metamorphic to mixed, and physiographically from low to high. Most of these types of islands, though, are not sharply separated.

Oceanic islands are those considered never to have been part of, or connected with, any continental landmass. Their biota is commonly poor in diversity, with unbalanced or uneven representation of taxa, compared with those of continents or continental landmasses. Chagos archipelago, Diego Garcia, and Cocos-Keeling are some such examples. Continental islands may vary in dimensions from subcontinental sizes down to small rocky outposts, the essential characteristics being their continental type rocks and their history showing a former land connection to an adjacent continent. Madagascar, the Malay archipelago, Seychelles, Sri Lanka, and Indonesian islands are examples of continental islands. Seychelles in the north-west Indian Ocean is an extreme case that is totally isolated today, but in Mesozoic and possibly early Tertiary time it was connected to Madagascar. Volcanic islands are rather small (1–100 km across) but often very high, ranging in elevation from 500 m to 3,000 m. They occur generally in irregular clusters, in sub-rectangular patterns or in long lines. Coral islands appear either as an accumulation of coral sand and gravel on the surface of coral reefs or as a slightly emerged limestone platform of formerly live coral not more than a few meters above mean low water. Barrier Islands are constructed entirely by the terrigenous or bioclastic sands from barrier beaches and are built up by longshore drift, probably first as offshore bars, and gradually gaining size later by eustatic oscillations, dune building, and colonization by vegetation.

Because of the very high number of the islands within some island groups in the Indian Ocean it would be difficult to describe them all. Instead, salient features of major groups are given below (see also Table I3).

Western Indian Ocean

Gulf of Kachchh islands

The 42 islands of the Gulf of Kachchh (22°15′N–23°40′N; 68°20′–70°40′E) are the northernmost coralline or sandstone based islands in India. Almost uninhabited, the vegetation inland consists only of shrubs. Several of the islands have dense mangrove patches on the coast, 34 islands have fringing reefs (often called as patch reefs) confined to intertidal sandstones or wave-cut, eroded, shallow banks. The region is tectonically unstable and evidence of uplift can be seen in the form of raised reefs near the mouth of the Gulf, not far from extant islands.

The coastal geomorphology and the fauna and flora of the islands are influenced considerably by the sediment depositional regime, high-velocity tidal currents (up to 5 knots), and a large range in environmental parameters (e.g., temperature 15°–30°C, salinity 25–40). The extreme conditions also limit coastal biodiversity to 37 species of corals and a smaller number of other invertebrates. However, algal growth along these coasts can be substantial at certain times of the year. The mangroves already constrained by high salinity and high tidal exposure also have been heavily impacted due to felling for fuel and fodder. Areas around some of the islands have earlier been good pearl oyster and chank fishing grounds, and one of the islands is even called Chank island. However, overexploitation has decimated both these fisheries.

Laccadive–Chagos ridge

Lakshadweep islands. These are the northern-most islands of the Laccadive–Chagos ridge (9°–12°N; 72°–74°E). Located about 200–400 km off the southwest coast of India, this part of the ridge comprises of 12 atolls, 3 reefs, and 5 submerged banks. Of the 36 islands on the atolls, only 10 (Minicoy, Kalpeni, Andrott, Agatti, Kavaratti, Amini, Kadamat, Chetlat, Kiltan, and Bitra) are inhabited. The northernmost Bitra Island is the smallest inhabited island in India. Among these, Minicoy is separated from the rest by the 9° channel. It is culturally and linguistically closer to the Maldivian islands.

Basically coralline, and no more than a few square kilometers in area, all these islands are low-lying with profuse coral growth all around. The only cultivated plant is coconut, besides a few vegetable and horticultural

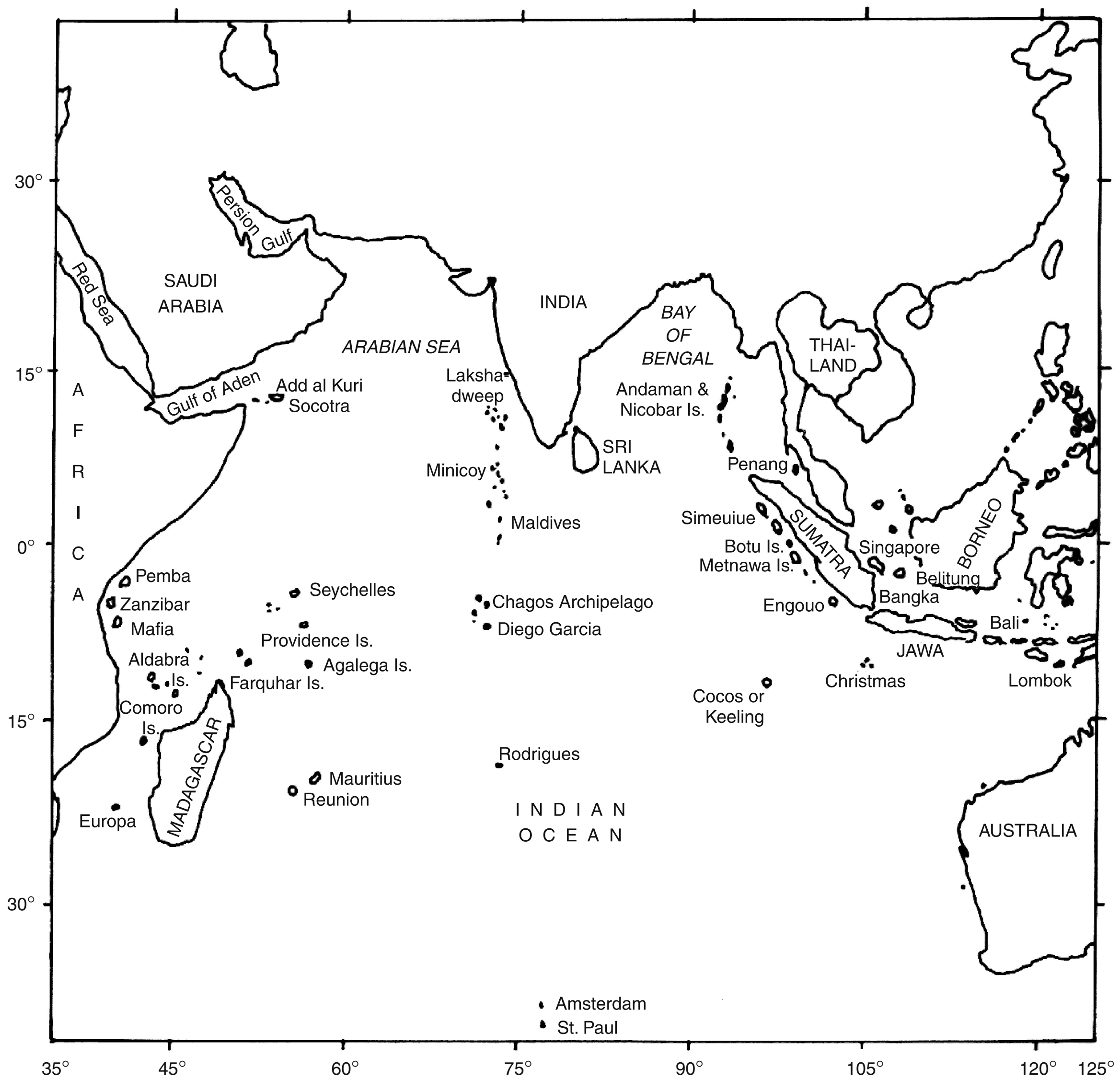

Figure I21 Major islands of the Indian Ocean.

plants introduced from the mainland. The coast toward the lagoon is sandy and habited by sand dune flora *Spinifix* and *Ipomea*. The seaward shore is rocky and typical of all oceanic atolls, with a steep drop in profile. Radiocarbon dating of the storm beach at Kavaratti island gave an age of about 6,000 BP indicating their recent origin. Some of the uninhabited islands are only sand cays; one of them is an important nesting ground for seabirds.

The littoral and sublittoral fauna and flora have been studied reasonably well. The known biodiversity status is as follows: hard corals—104 species, soft corals—37 species, fishes—163 species, invertebrates—about 2,000, and algae—119 species. The bleaching event of 1998 has, however, caused a serious reduction in coral biodiversity. Shore erosion and silting are additional causes for loss of coral cover and reduction in species abundance.

Maldivian islands. The double chain of Maldivian islands (7°N–0.5°S, 73°E) is the largest part of the Laccadive-Chagos ridge that extends southwards from India to the center of the Indian Ocean. The more-than 1,200 islands, clustered in 19 groups of atolls, are entirely low-lying. The geologic history of the island chain is a complicated picture of sea-level changes, reef and carbonate platform development, and erosional events.

As would be expected in the case of small islands on the atolls, the coastal ecology of the islands is reef-dominated. The reefs, though principally atolls, have the unusual features of broken rims that consist of numerous patches or faroes, many of them with islands, and the presence of lagoonal islands which are simply knolls with their emergent surfaces capped with vegetation.

Biological and ecological information on Maldivian islands is rather poor, with stress on only some groups. About 200 species of corals under 60 genera have been recorded so far. No comprehensive checklist of other groups of coastal marine fauna exists; however, the cowry shells and groupers (40 species) are important components of reef biodiversity. Similarly, descriptions of zonations of the reefs are known from some islands but detailed studies of the ecology, either at community or at species level, are scarce.

Islands of Chagos archipelago. The Chagos archipelago (5°–8°S 71°–73°E), the southern part of the Laccadive–Chagos ridge, consists of five coral atolls with islands, besides several reefs that are partially or wholly exposed at low tide. The five atolls are: Great Chagos Bank, Peros Baňhos, Salomon, Egmont, and Diego Garcia. The number of islands on these atolls varies from 4 in Diego Garcia, to 24 in Peros Baňhos. The total land occupied by these islands is about 40 km^2.

Most of these islands are located on the atoll rims with elevation of no more than 2–3 m. Raised reefs with small, uplifted, and vertical cliffs rising to over 6 m occur in two atolls—southern Peros Baňhos and northwestern part of the Great Chagos Bank. Isotopic dating of fossil corals in the emerged beach rock of the islands and some extant corals

Table I3 Indian Ocean Islands

Name of island	Position	Location	Geomorphology	Major disturbance
Barrow islands (Middle Boodie, Pasco & Double islands)	20°40′–20°58′S, 115°18′–115°30′E	West Australia (56 km off Pilbara coast)	Fossiliferous Miocene Limestone	Oil fields
Christmas island	10°35′S, 105°35′E	290 km south of Indonesian islands	Guano deposits	Anchorage and phosphate loading dock
Cocos–Keeling islands	12°00′S, 96°56′E	South east Indian Ocean	Atoll	Storms, earthquakes, red tides
Dampier archipelago (six main and many small islands)	20°20′S–20°50′S, 116°20′E–117°10′E	Eastern Indian Ocean (northwest Australia)	Igneous rock of Archean age	Dredging for shipping
Houtman Abrolhos islands (Total 35 islands)	28°15′–29°00′S, 113°30′E–114°05′E	Eastern Indian Ocean		Oilfield
Kimberley coast reefs		Northwestern coast of Australia	Steep rocky shores	Iron ore mining
Broome	17°58′S, 122°14′E			
Wyndham	15°28′S, 128°06′E			
Holothuria and Lacepede reefs	16°52′S, 122°08′E			
Adele	15°31′S, 123°09′E			
Monte Bello islands and Lowendal islands	20°20′S–20°33′S, 115°27′E–115°37′E	West northwest of Dampier	Vacant Crown islands	Tourism and oil exploration activities Reef damage by *Acanthaster plancii*
Muiron island and Ningaloo island	21°40′S, 114°2′E	Eastern Indian Ocean	Limestone islands. Part barrier and part fringing reefs	Overexploitation of marine resources Petroleum tenements
Rowley shoals		Northwest Australian shelf	Atoll	Fishing, anchor damage
Mermaid reefs	17°7′S, 119°36′E			
Clarke reef	17°10′S, 119°20′E			
Imperieuse reef	17°35′S, 119°56′E			
Scott reef and Seringapatam reef	14°5′S, 121°51′E 13°40′S, 122°00′E	–	Atolls	Exploitation of molluscs and holothurians
Bahrain Mubarraq, Sitra and other islands	26°N, 50°E	Persian Gulf, Saudi Arabia coast	Limestone and deserts	Oil and gas
Lampi island (30 islands)	10°50′N, 98°10′E	Near Burma	Coral reef	Undisturbed
Moscos island	13°50′N–14°20′N	Burma Sea	Rocky shoreline	Illegal logging, collection of turtle eggs
Chagos archipelago				
Blenheim reef	5°12′S, 72°29′E	East Chagos Archipelago	Atoll	Undisturbed
Diego Garcia	7°20′S, 72°25′E	South of Chagos	Atoll	Military presence, dredging and blasting
Egmont atoll (five islands)	6°40′S, 71°20′E	West of Chagos	Atoll	Undisturbed
Peros Bañhos atoll	5°20′S, 71°55′E	Northwest of Chagos	Atoll	Undisturbed
Salomon atoll	5°20′S, 72°15′E	North of Chagos	Atoll	Undisturbed
Speakers bank	5°32′S, 72°25′E	North of Chagos	Submerged atoll	No manmade changes
Victory bank	5°32′S–72°15′E	–	Submerged atoll	Undisturbed
Comoros island	12°S, 44°E	North of Mozambique	Four high islands, fringing reef	Dredging
Mayotte barrier reef	12°30′S, 45°10′E	Southernmost islands of Comoros group	Extinct volcano surrounded by reef	Siltation from erosion, mining of coral rocks
Andaman islands	10°30′N–14°N, 92°E–93°E	Bay of Bengal	Emerged part of mountain chain	Massive siltation due to deforestation
Nicobar islands	6°30′N–9°30′N, 93°E–94°E	Bay of Bengal	Emerged part of mountain chain	Overexploitation of corals and shells for ornamental use
Lakshadweep islands	9°N–12°N, 72°E–74°E	Arabian Sea	Atolls	Dredging, mining, siltation, and *A. plancii* infestation
Indonesian islands				
Kepulauan Aru	0°50′–1°25′N, 131°16′E	Irian Jaya	Coral island	
Pulau Mapia	1°1′N–134°10′E	Irian Jaya	Coral island	
Raja Ampat (proposed wildlife reserve)	0°25′N–130°08′E	Irian Jaya	Coral island	
Sabuda-Tataruga	2°30′N–130°50′E	Irian Jaya	Coral island	

Table I3 (*Continued*)

Name of island	Position	Location	Geomorphology	Major disturbance
Karimunjawa (proposed wildlife reserve)	5°50′N–110°20′E	Java	Coral island	
Pulau Seribu (strict nature reserve)	5°26′–5° 37′S, 106°24′–106°37′E	Java	Coral island	Fishing activities
Karimata	1°30′S, 109°00′E	Java Kalimantan	Coral island	
Pulau Maratua (Karang Muaras proposed strict nature reserve)	1°50′–2°10′N, 118°30′–118°55′E	Java Kalimantan	Coral island	
Pulau Sangalaki (Marine park)	2°05′N–118°15′E	Java Kalimantan	Coral island	
Pulau Semama (wildlife reserve)	2°05′N–118°15′E	Java Kalimantan	Coral island	
Aru Tenggare (proposed marine reserve/marine park)	6°35′S – 7°11′S, 134°12′– 135°E	Moluccas	Coral island	Fishing and exploitation of marine resources
Kepulauan Kai Barat Tayandu (proposed marine multiple use reserve)	5°30′S, 133°0′E	Moluccas	Coral island	
Pulau Angwarmase	7°55′S, 131°20′E	Moluccas	Coral island	
Pulau Banda (marine park)	4°30′S, 130°E	Moluccas	Volcanic origin	
Pulau Pombo (marine park)	3°31′S, 128°22′E	Moluccas	Coral island	Overexploitation
Pulau Renyu–Pulau Lucipara (proposed strict nature reserve)	5°40′S, 127°50′E	Moluccas	Coral island	Overexploitation
Komodo National Park	8°35′S, 119°30′E	Nusa Tenggara	Rocky island	Dynamite fishing
Pulau Rakit	8°35′S, 118°E	Nusa Tenggara	Coral island	
Pulau Satonda	8°10′S, 117°45′E	Nusa Tenggara	Volcanic	
Kepulauan Peleng	1°50′S, 123°14′E	Sulawesi	An archipelago	
Kepulauan Sangihe	3°45′S, 126°35′E	Sulawesi	Islands and reefs	
Pulau Kakabia	6°55′S, 122°30′E	Sulawesi	Islands and reefs	
Pulau Pasoso	0°10′S, 119°45′E	Sulawesi	Limestone island	
Pulau Smalona	5°10′S, 119°10′E	Sulawesi	Coral islands	
Selat Muna	5°05′S, 122°05′E	Sulawesi	Coral islands	
Spermonde islands	5°30′S, 119°10′E	Sulawesi	Coral islands submerged reef, patch reefs	Dynamite fishing, sedimentation
Tiga island	3°50′S, 123°15′E	Sulawesi	Islands and reefs	
Togian island	0°10′N–0°40′S, 121°32′E–122°12′E	Sulawesi	Extended mountains surrounded by limestone	Dynamite fishing
Tukang Besi	5°35′S, 123°50′E	Sulawesi	Archipelago	
Muara Siberut (five islands)	1°30′S, 99°25′E	Sumatra	Islands with coral reefs	Overfishing
Pulau Weh	6°0′S, 95°30′E	Sumatra	Coral reefs	
Sheedvar island	27°0′N, 53°E	Iran	Coral reefs	
Pulau Paya (group of islands)	6°02′N–6°05′N, 99°54′–100°04′E	Malaysia	Coral islands	Fishing activities
Pulau perak	4°41′N, 98°56′E	Malaysia	Conical rocky islands	
Pulau Tiga	5°44′N, 115°40′E	Malaysia	Volcanic island	Legal protection and management
Sembilan islands	2°03′N, 100°33′E	Malaysia	Volcanic island	
Pulau Bohey dulong Pulau Bodgaya Pulau Tetagan	4° 38′N, 118°46′E	Malaysia	Volcanic island	Domestic pollution, overexploitation of marine fauna
Pulau Sipadan	4°05′N, 118°40′E	Malaysia	Coral reef	
Pulau gaya Pulau Sapi Pulau Mamutik Pulau Manukan Pulau Sulung	6°04′N–5°55′N, 116°E	Malaysia	White sandy beaches with rocky interruption	Coral mining, overexploitation of reef fauna
Maldives (a group of atolls)	7°N–0°30′S, 73°E	Central section of Chagos archipelago	Atolls	Growing urbanization, domestic pollution
Mauritius	20°S, 58°E	180 km northeast of Réunion island	Remains of old emerged coral reefs	
Cargados Carajos shoals	16°23′S, 59°27′E	North northeast to Mauritius	Coral islands	Exploitation of marine products, Guano mining
Île Plate	19°53′S, 57°39′E	–	Volcanic rock	Dynamiting, fishing, anchoring, and boat grounding

Table I3 (*Continued*)

Name of island	Position	Location	Geomorphology	Major disturbance
Rodrigues	19°42′S, 63°25′E	North eastern Mascarene island	Volcanic island	Public interference
Mozambique				
Ilhas da Inhaca e dos Portugueses (Inhaca islands)	26°S, 33°E	Southern most island of Mozambique	Pleistocene dune rock –	Goat overgrazing denudation, public interference
Primeira and Segundo islands	16°S–17°S, 38°E–41°E		–	
Quirimba islands	10°45′S–12°42′S, 41°E		–	
Réunion islands				
Réunion	21°7′S, 53°32′E			
Europa and Basses de India	22°20′S, 40°20′E	In Mozambique channel	Atolls	Undisturbed
Iles Glorieuses	11°30′S, 47°20′E	100 km northwest of Europa	Atolls	Undisturbed
Tromelin	15°52′S, 54°5′E	390 km east of Madagascar	Atolls	Undisturbed
Saudi Arabia				
Al Wajhto Qalib	26°16′N, 36°28′E	Northern Red Sea	Rocky island	Undisturbed
Farasan archipelago	17°40′N, 42°10′E	Red Sea	Coral islands, swamps, and reefs	Undisturbed
Seychelles	5–10°S, 45–56°E	NE of Madgascar		
Platte island	5°50′S, 55°E		Granitic and coralline islands	– –
Doivre island	5°50′S, 55°E			
Aldabra island	9°25′S, 46°25′E	North of Mozambique channel	Atoll, limestone	–
Bird island	3°43′S, 55°13′E	Northern edge of Seychelles	Sandy clay and calcareous	–
Dennis island	3°48′S, 55°40′E	–		Phosphate mining
Cousin islands	4°20′S, 55°40′E	Southwest Seychelles	Granite island	Tourism
Curieuse island	4°05′S, 55°43′E	–	–	–
Singapore		–	–	Growing urbanization
Pulau Hantu	1°20′N, 103°50′E			
Pulau Suelong	–			
Pulau Salu	–			
SriLanka			Extended part of Indian mainland (limestone-granite)	Mining for lime, dynamite fishing, tourist pressure, overexploitation of marine fauna
Trincomalee and Pigeon island	8°N, 82°E	16 km from Trincomalee		
Sudan				
Mukkarwar island	20°50′N, 37°17′E	North of port Sudan	Well-formed reefs	
Sanganeb atoll	19°45′N, 37°25′E	Red Sea	Atoll	*A. plancii* infestation, overexploitation
Suakin archipelago	19°14′N, 37°51′E			Fishing, tourism pollution, and human interference
Sultanate of Oman				
Daymaniyat islands (10 islands)	23°45′N, 58°10′E	Gulf of Oman	Corals	Litter, *A. plancii* infestation
Tanzania				
Latham island	6°50′S, 39°50′E	64 km off Dar es Salaam	Atoll	Undisturbed
Mafia island	7°40′S, 40°40′E	South of Dar es Salaam		–
Maziwe island	5°30′S, 39°5′E	Northern Tanzania		–
Thailand				
Koh Larn Koh Sak Koh Krok	12°55′N, 100°47′E	Northern Gulf of Thailand	Coral reefs	Tourism and pollution
Koh Phuket	8°N, 98°20′E	Andaman Sea	Rocky extended mountains	Extensive sedimentation, dredging, mining

gave an age not more than 5,200 years BP, indicating that all these islands are relatively recent in origin.

Being coralline islands, the coastal morphology is typically characterized by vast and profuse reef growth. Mangroves and associated flora are absent. The coastal and inland flora consists primarily of native vegetation (*Tournifortia*, *Scaevola*, and *Casuarina*), disturbed by coconut plantations in inhabited islands. None of the 250 species of flora are endemic. Two faunal groups—birds and turtles—are important biological components. The islands provide nesting grounds for over 50 species of seabirds and several species of green and hawksbill turtles.

Seychelles

A total of about 42 granitic and 74 coralline islands, spread over 5°–10°S and 45°–56°E, with a total land area of 455 km^2 comprise the Seychelles. The inner Seychelles islands to the north are granitic, remnants of ancient Gondwanaland, rugged, mountainous, and rise up to 1000 m in the Morna Seychellois on Mahé island. Coralline islands and atolls of the Amirantes, Farquhar, and Aldabra groups, spreading westwards and southwards from the granitic group, constitute the second group. They are composed of numerous low islands or atolls in several clusters, each located on top of volcanic structures of various sizes. Principal granitic islands in the Seychelles archipelago are Mahé, Praslin, Silhouette, La Digue, Curieuse, Felicité, North Island, St. Anne, Providence, Frigate, Denis, Cerf, and Sea Cow island. Among the coralline islands and atolls, Alphonse, Bijoutier, St. François, St. Pierre, Astove, Assumption, Coetivy, and Aldabra are the major ones. Some of the coralline islands, though relatively low-lying by comparison with granitic islands, are often taller, reaching as much as 8 m above sea level. These include Aldabra, Assumption, Astove, Cosmoledo, and St. Pierre. These limestone atolls have formed on top of volcanic structures and rise from water depths of over 2,000 m. The high limestone islands are also characterized by terraces that reflect changes in sea levels during the last glacial cycle. The Amirantes island group is the second largest group after Inner Seychelles and comprises 10 islands and atolls and several shoals and submerged reefs. The major atolls in the Farquhar (or Providence) group are Farquhar and Providence, each rimmed with several islands. St. Pierre Island in this group is a circular, uplifted atoll, with coastal cliffs rising to 10 m. In the Aldabra group, Aldabra and Cosmoledo atolls have several islands on their rims, whereas Astova and Assumption are elevated atolls: in the Assumption island, reef rocks rise to 7 m above sea level, with dunes on the east and south rising to nearly 30 m.

Coastal geomorphology of all the islands is characterized by the presence of reefs. Three major types—fringing, platform, and atoll reefs—are recognized. The granitic islands have well-developed fringing reefs. Among the outer islands, several are raised platform reefs (e.g., Assumption and St. Pierre) and others are atolls (e.g., St. Joseph, St. François).

There are pronounced differences in the coastal ecology of these islands. The northern islands lie in the path of the east-flowing Equatorial Counter Current whereas the southern islands lie in the path of the west-flowing South Equatorial Current. Besides, the granitic islands receive more rainfall and are often forested. As a result, the nutrient regimes in the coastal waters are distinctly different between these two groups. The high nutrient levels around the granitic islands favor dominance of crustose coralline algae and frondose macroalgae whereas nutrient-poor waters around the coralline islands support a hermatypic coral dominance. The raised reefs were used as nesting sites by seabird colonies and have been extensively mined for guano.

Description of coastal ecology has primarily been with reference to coral reefs, though not all have been studied as extensively as Mahé or Aldabra islands. The coral diversity is more or less same between granitic and outer islands, the former with 51 genera and the latter with 47 genera. The total species count is 161, and this does not include those of *Acropora*. Though the coasts with well-developed reefs can be expected to sustain a high faunal and floral diversity, there is still poor documentation from most islands. The recorded forms include 128 species of marine caridean shrimps, 49 species of brachyuran decapods, 150 species of echinoderms, 450 species of molluscs, about 1,000 species of fish, 8 species of sea grasses and 4 species of turtles. Among these the gigantic land tortoise of Aldabra atoll and the double coconut, *coco de mer*, of Mahé Island are unique.

Mascarene islands

Mauritius. Mauritius (20°S, 58°E) represents the southern part of the Mascarene Plateau, which is an arcuate series of banks extending for 2,000 km from the Seychelles Bank. The Mauritius island is volcanic in origin and is composed of olivine basalt and doleritic basalt.

Mauritius, along with several small adjacent islands, spreads over 1,865 km^2. The northern part of the island is a plain while the center is a plateau rising to a peak height of 826 m at Piton de la Rivière Noire and bordered by low mountain remnants of a large volcano. The south of the island is largely mountainous.

The crenulated coastline, exposed to varying wave activity, extends to about 200 km. The southwest coast is made up of basaltic rocks while carbonate sands, the bulk of which is coral debris, largely cover the remaining parts. A large submarine platform with extensive fringing coral reefs that cover three-fourth of its coastline surrounds the island. There are also the remains of old, emerged coral reefs, recalcified to varying degrees, indicating recent uplift.

Sugarcane and tea cultivation are the major revenue sources for the islands. Conversion of forest lands to plantations has, however, reduced the original forest cover to less than 1%. The other important revenue sources for the island are coastal fishing and tourism. Reef fisheries yield about 200 tons per year and reef tourism caters to more than 300,000 visitors a year.

Considering that the entire coastline is reef-rimmed, the corals- and reef-associated fauna and flora are important components of coastal biodiversity. The reefs cover an area of about 300 km^2, with a maximum reef width of 4 km. Mauritius reefs are notable for the absence of reef flats; consequently, sediments accumulate in the lagoon providing a favorable environment for sea grass growth. A total of six sea grass species—*Thalassiodendron ciliatum, Syringodium isoetifolium, Halophila ovalis, Halophila stipulacea, Halodule universis*, and *Halodule* sp.—are known from Mauritius.

A total of about 186 species of corals belonging to more than 50 genera have been reported from the Mascarene archipelago, with 75% of these recorded in Mauritius reefs. The fish diversity, with 263 species, is also high. The molluscan fauna is another important biological constituent of Mauritius reefs. A detailed survey has revealed the presence of more than 3,500 species, with approximately 10% of them being endemic. These include the Imperial Harp shell *Harpa costata* and the cowry *Cypraea mauritiana*, besides species like *Clanculus mauritianus* and *Bursa bergeri*. Diversity of marine macro algae is also high: 127 species, mainly red and green algae, have been recorded from the littoral zone.

Higher freshwater flux, more siltation, and high humidity favor the growth of mangroves on the northeast and east coasts of Mauritius. Dense mangroves dominated by *Rhizophora mucronata* cover an estimated area of 20 km^2.

Rodrigues. Rodrigues island (area 110 km^2; 19°42′S, 63°25′E) and two cays at 10°24′S and 56°38′E (known as Agalega island) are part of the Republic of Mauritius. Rodrigues, the smallest of Mascarene islands, is of volcanic origin and consists of subhorizontal basaltic flows. The northeastern part of the island is mountainous but not very tall, the peak height not exceeding 400 m.

Like Mauritius, Rodrigues island is also reef-rimmed, with a wide expanse of reef platform extending without a break for 90 km around the island, providing a fringing reef cover of about 200 km^2. Presence of reef flats, with a width ranging from a low of 50 m in the east to as much as 10 km in the west distinguishes Rodrigues from Mauritius. The reef flats also provide habitat for large sea grass beds, though the species diversity is much less; only two species—*H. ovalis* and *Halophila balfouri* are known from Rodrigues. Muddy accumulations, hence development of mangroves, are rare.

Coral species diversity is high, with a similar number of species as in Mauritius. Information on other coastal marine fauna and flora are scarce; however, the small islands around Rodrigues are important nesting sites for brown noddy, lesser noddy and white tern.

Réunion. Réunion (21°7′S, 53°32′E) is the most southwesterly of the Mascarene islands. Covering an area of 2,512 km^2, Réunion is a large Hawaiian-type volcano that includes an older part, the massif of Piton des Neiges (peak height 3,069 m), incised by three large cirques, and an active volcano to the southeast. Several small islands—Tromelin to the north of Réunion, Europa and Bassas de India atolls in the Mozambique Channel, Juan de Nova off the west coast of Madagascar, and Iles Glorieuses to the north of the Mozambique Channel, are the other island dependencies of Réunion. These are relatively very small. Tromelin is no more than a cay of 1.1 km^2, Juan de Nova is a raised fossil reef of 9.6 km^2 and the Grande Glorieuse Island covers only 3.9 km^2.

The coast of Réunion is generally rocky, with low cliffs cut in lavas. Sectors of low coast correspond with the three large depositional cones built below the three cirques and show pebbly beaches while the rare sandy beaches are related to embryonic fringing reefs. Because of the relatively young age, reefs are less developed, discontinuous, narrow with their widest part no more than 550 m, and cover only an area of 7.3 km^2. In contrast with Mauritius and Rodrigues, reef platforms are abundant on Réunion but muddy accumulations and mangroves are totally absent. Lack of organic and terrigenous material also limits the diversity of sea grasses and their extent: only one species, *H. stipulacea*, that too not in abundance, has been known from Réunion.

Coastal marine fauna and flora have been better inventoried in Réunion than in the other two islands. This includes 40 species of dinoflagellates, 150 species of macro algae, 120 species of corals, 90 species of hydroids, 2,500 species of molluscs, and more than 650 species of fish. Coastal fisheries, however, are relatively less developed, with no more than 1,500 tons yield per year, of which only 100–150 tons are truly reef fishes, Tourism, likewise, is also less developed compared with Mauritius.

Madagascar

Madagascar is a fragment of a lost continent (Lemuria) and this severance from the ancient land mass is evident from the sheer drop of mountain into ocean depths of 3,000 m or so, especially on the eastern side. The island's rocks, volcanic structure, besides the subsoil formed of granites, gneiss, and crystalline schists, warm water springs and frequent earthquakes also provide evidence for this origin. Paleontological evidence for this comes from the remains of many large prehistoric birds and even the present day fauna of the island has a special individuality. The large number of endemic flora also confirms that Madagascar is an island that has been long since isolated from other regions. Madagascar is also one of the largest islands in the world (5,87,000 km^2) with a coastline of about 4,000 km. The east and west coasts are asymmetrical in physiography. The east coast presents an almost unbroken appearance, with few bays and indentations. The continental shelf here is narrow and coral reefs and mangroves are poorly developed. The west coast, on the other hand, has a broad continental shelf and has the majority of the island's reefs and mangroves.

Reefs and mangroves are important coastal ecosystems of Madagascar. The reefs cover an area of 200 km^2. Most of the west coast has large tracts of tidal marshes (4,250 km^2) of which 3,200 km^2 are populated by mangroves. Sea grass beds are also extensive on the west coast. Emergent fossil reefs up to 10 m above present sea level are found in the far northwest coast. A barrier reef, 10–16 km offshore, also exists at the edge of the continental shelf.

There is an extensive bibliography of the various coastal and marine fauna and flora, synthesized from numerous studies of many French scientists. Most of the information is from Toliera and Nosy-Bé and biodiversity of the whole island could be still higher than what is known—200 species of corals, 1,500 species of fishes, 28 species of sponges, 227 species of echinoderms, 1,158 species of mollusks, 779 species of crustaceans, 121 species of worms, 182 species of ascidians, 108 species of algae, besides 5 species of turtles and 32 species of mammals.

Comoros islands

The Comoros archipelago consists of four major islands—Grande Comore, Anjouan, Moheli and Mayotte—at the northern end of the Mozambique Channel (12°S, 44°E). All these islands are of volcanic origin and mountainous, and are surrounded by numerous coralline and granitic islets. The Grand Comore is the largest island among these, with an area of 1,131 km^2. While three of these islands have fringing reefs, Mayotte is surrounded by a 140 km long barrier reef lying 13–15 km offshore. The coastal features include the mangroves, which, in some islands, are expanding due to influx of terrestrial sediments from hillsides.

Among these islands, only Mayotte has been studied to some extent. These studies are essentially related mainly to the description of the barrier reef and its faunal and floral composition, since it is one of the few barrier reefs in the world, and the best developed in the Indian Ocean. The reef, which had a good live coral cover, was heavily impacted during a bleaching event in 1983 related to El Nino.

Islands off Tanzania

The islands off the coast of Tanzania are Mafia, Pemba, Unguja (Zanzibar), and those of Songo Songo archipelago. Mafia island (7°40′S, 40°40′E), along with the four small adjacent islands, are continental islands off Rufiji delta. The coastline consists of vast stretches of sheltered and exposed fringing reefs and mangroves besides beds of sea grasses, algae, and soft corals. The Unguja island, slightly larger than the Mafia island, as well as the Mnemba island lying to the north, also have coral development all around the coast. The Pemba island is 62 km long and 22 km wide, with a reef area of 1,100 km^2 along its coastline. All these islands show evidence of several terraces, along with indication of a relatively recent subsidence. Another feature common to these is the 3,300–3,400 m of marine sediments, ranging from Miocene to Cretaceous, underlying them.

The Songo Songo archipelago (8°30′S, 39°30′E) consists of a 7 km long island, with four smaller islands in the vicinity. As with other islands off Tanzania, these islands support some of the largest expanses of shallow water coral reefs, with the estimated reef cover of about 40–50 km^2. No other remarkable coastal features are known from these islands.

Islands off Mozambique coast

The islands off the Mozambique coast are grouped into Quirimbas archipelago, Primeiras and Segundas archipelago, Bazaruto archipelago, and Inhaca and Portuguese islands. Besides these, the Mozambique, Goa, and Cobras islands are located just 4 km off the mainland coast.

The Quirimbas archipelago (10°45′–12°42′S) comprises a 200 km chain of 32 islands along with numerous reef complexes. The Primeiras and Segundas archipelagos, located at 16°12′– 17°17′S consists of 10 islands and two reef complexes. The Bazaruto archipelago consists of five islands located between 21°30′ and 22°10′S. All these islands are small, with the largest no more than 25 km^2 in area and all lie close to the coasts.

Coastal morphology of these islands is composed of grasslands, scrubs, and mangroves, with varying degrees of development in the different islands. All of these, however, support good fringing reef growth. As with most islands, it is the coral fauna and fish that were widely studied. About 50 genera of reef building corals and 300 species of fish are known from Quirimbas archipelago. A total of about 155 molluscan forms, with 6 endemic species among them, have been reported from Bazaruto archipelago. The western coasts and the area between the islands and the mainland coast have good sea grass beds.

Socotra island

The Socotra (8°N, 53°E), off the mouth of Gulf of Aden, is an island that has survived the subsidence of the great primeval continent, which embraced present-day Africa, the Middle East, southern Asia, and the Northwestern part of the Indian Ocean. It is a fairly large island (3,582 km^2) with its mountainous interior rising to 1,520 m. The coastline is varied, consisting partly of low-lying plains and partly of steep limestone cliffs, edging an undulating plateau (500–600 m high) that covers much of the island.

Bahrain

This consists of a group of low-lying islands, largely of limestone outcrop and desert, off the Saudi Arabian coast. Ranging from a rocky out crop (Jidda Island) to the large Bahrain Island (660 km^2), these are low and sandy islands, except for clusters of barren rocky hills in the center.

Eastern Indian Ocean

Gulf of Mannar islands

A chain of 20 islands (8°45′–9°16′N, 79°4′–79°29′E) constitutes the coralline islands of the Gulf of Mannar between southeast India and Sri Lanka. None of these Islands is inhabited. Spreading over not more than 2 km^2 individually, most of these islands have only shrubs as vegetation and occasionally some patches of mangroves. The fringing reef growth in profuse all around the islands. The sea grass beds associated with the reefs have been important feeding grounds for the Dugong species.

Geologically, these islands are connected with those of northern Sri Lanka through a series of shallow banks called Adam's bridge between Rameswaram in India and Talaimannar in Sri Lanka. As a consequence, there is a good similarity in island geomorphology, coastal ecology, and fauna and flora among these islands.

Sri Lanka

Sri Lanka lies off the southeast tip of India between 6° and 10°N and 80° and 82°E (65,610 km^2). The island is basically a central mountain mass of Pre-Cambrian crystalline rocks ringed by a broad coastal plain. The highest point is the Pidurutalagala peak (2,700 m). The plains are fairly level in the north but the extensive soft limestone deposits are broken elsewhere by outcrops of the main rock core. The coastal region is characterized by fringing reefs, shallow lagoons, marshes, and many sandy bars, especially in the north. Though not a very large island, three distinct climatic features are evident: the low country Dry Zone that receives low rainfall, the East Coast Plains that experience one monsoon, and the Low Country Wet Zone which receives rainfall from both the monsoons.

Coastline features vary considerably, from sandstone to granite, but detailed studies are scarce. Along the west coast, coral growth is mainly on ancient sandstone and on the east coast, it is on gneiss or granite outcrops. Fringing reefs are found only along 2% of its 1,585 km coastline and not all of these are comprehensively mapped. Surveys have mainly been carried out for reef-building corals and fishes. A total of about 183 species of corals and over 350 species of fishes have been recorded. Though a number of faunal groups occur in these reefs, their systematic records are not known. Mangroves occur along the southwest, northwest, and northern coasts. The total area covered by mangroves is 36 km^2. *Rhizophora, Avicennia, Excoecaria, Lumnitzera, Aegiceras* and *Sonneratia* are the mangrove genera recorded.

Extensive damage to coastline habitats has been recorded where reefs and mangroves are abundant. The reefs are mined for lime manufacture and the mangrove wood is used to fuel the limekilns. Often coastal forests are also exploited for use as fuel in the limekilns. Though detailed information on the impacts are not available, damages to coastal habitats at local scales are considerable.

Andaman and Nicobar islands

These are the emerged parts of a mountain chain that stretches from the Arakan Yoma in Myanmar to the islands of Indonesia. Spread meridionally between 6° and 14°N, and between 91° and 94°E in the Bay of Bengal, these islands number more than 500, of which only 38 are inhabited. All the islands are mountainous, sedimentary in nature, and have fringing reefs towards the east. The total area covered by these islands is 8,293 km^2. The Andaman group of islands is separated from the Nicobar group by the 10° channel which has a heavy tidal flow and difficult to navigate with conventional crafts. As a result, the biogeography of the Andaman has more of Malay affinities whereas that of the Nicobar has Indonesian affinities.

Most parts of these islands are covered with thick forests and the low-lying areas are covered with mangrove swamps. Biodiversity of the islands is quite high, with an abundance of corals, fishes, algae, turtles, and the unique saltwater crocodile. Avifauna is more endemic in nature, with distinct local species of eagles, parakeets, and orioles. The islands have a few land mammals like deer and elephants, which were introduced from the mainland India.

Indonesian islands

Indonesia is an island nation of 13,700 islands having a coastline of about 60,000 km. The islands form a region of tectonic instability, marked by frequent earthquakes and volcanic eruptions. These tectonic movements have also shifted out of the sea some of the numerous coralline reef formations along the island coast.

Typically tropical in climate, the larger islands (e.g., Java, Sumatra, Borneo, and Sulewasi) have varied coastal geomorphology ranging from mangrove-bordered shores through estuarine deltas to coral reefs. Borneo is the third largest island in the world and lies between the Sulu Sea, Java Sea, and South China Sea. It is densely forested, with extensive swampy lowlands in the southern and southwestern coastal areas.

Smaller islands are more coralline in nature. The Indonesian region is known for the highest diversity of corals and mangrove species, in the latter case practically all known mangrove species from the new world are present here.

Cocos or Keeling islands

These islands (12°S, 96°56′E), numbering 27 and covering a total area of 30 km^2, lie about 960 km southwest of Sumatra (not to be confused with Cocos Island, a small uninhabited island of 26 km^2 area off Costa Rica). The largest among them is the West Island, with an area of 3.2 km^2. These are extremely coralline islands but also with a luxuriant growth of land vegetation that includes coconut palms, sugarcane, and banana. No quantitative accounts of other fauna are available but the coconut eating crab *Birgus latro* is an interesting species from these islands.

Christmas island

Christmas island, with an area of 128 km^2, and lying 650 km south of Java Head, is a strongly uplifted island surrounded by high cliffs of coral limestone. It is well-known for its extremely rich phosphate deposits and the coconut crab *B. latro* (another Christmas island is an atoll in the Line islands, central Pacific).

In summary, the major features of Indian Ocean islands are:

- Wide range in size, from sand cays to some of the largest islands in the world.
- Coralline origin in most of the oceanic regions and granitic or sedimentary origin in coastal regions.
- Coasts characterized by fringing reefs in almost all cases, and mangroves and other wet lands in most others.
- Endemism in some islands, with native flora and fauna.
- Most of the smaller islands are uninhabited. Where settlements have taken place, marked erosion in biological diversity and resources are noticeable.

Suggested further reading on this subject may be found in the bibliography listing.

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Cross-references

Atolls
Cliffed Coasts
Coral Reef Coasts
Coral Reef Islands
Coral Reefs
Coral Reefs, Emerged
Indian Ocean Coasts, Coastal Ecology
Indian Ocean Coasts, Coastal Geomorphology
Mangroves, Geomorphology Ecology
Mining of Coastal Materials
Rock Coast Processes
Small Islands
Tors

INGRESSION, REGRESSION, AND TRANSGRESSION

A transgression is a landward shift of the coastline while regression is a seaward shift. The terms are applied generally to gradual changes in coast line position without regard to the mechanism causing the change. In addition, these terms usually are applied to changes over periods greater than 10^3 years as can be expected to be recorded by facies distributions in the geologic record or the stratigraphic interpretation of seismic reflection. "Transgressions" and "regressions" are commonly used, for example, to refer to coast line changes due to glaciations, which cause both eustatic sea-level changes and subsidence or rebound. Of particular significance is the "Holocene transgression" which corresponds to a eustatic rise in sea level of between 100 and 130 m and between 18,000 and 6,000 yr BP. The terms also have been applied, however, to changes occurring over shorter time scales in, for example, Lake Chad.

"Ingression" refers to the advance of marine conditions into more-or-less confined areas, like the drowning of a river valley (Schieferdecker, 1959, terms 1260 and 1840, as cited in Jackson, 1997) or to the infiltration of water to an interior low-lying area of land creating an inland body of water. In the former application, at least, neither mechanism or time period is implied although the tendency seems to be to use "ingression" to refer to more rapid, if not catastrophic, transitions rather than to more gradual changes. An example might be the marine invasion of a glacial lake by breeching of a morainal barrier during post-glacial, sea-level rise. A rise in relative sea level will also raise the water table in coastal aquifers causing the appearance of lakes and ponds but the same could be accomplished by changes in recharge (percipitation–evapotranspiration).

Facies relationships and implications

Regressions or transgressions can be due to any combination of (1) eustatic sea-level rise or fall; (2) subsidence or uplift; and (3) sedimentation or erosion. In sedimentology, transgressions are also referred to as "retrogradation" in which a depositional environment due to the rate of creation of accommodation space exceeds the sediment supply (Curray, 1964; Nichols, 1999). This results in a landward shift of coastal facies belts, although it is possible that the advance of the marine conditions had occurred so quickly that sediment deposition could not remain in equilibrium with changing conditions. In this case, relict, subaerial sediments may be found drowned in place or shallow water deposits covered discontinuously by deep water facies. Transgressions are usually associated with a rise in relative sea level due to eustatic sea-level rise and/or coastal subsidence. Even during periods of stable sea level or slowly rising sea level, however, erosion of coastal deposits can result in a transgression.

Regressions are also referred to as "progradations" in which the sediment is supplied at a higher rate than the potential space for sediments to be accommodated is created. In the geologic record, this can be preserved by up-column transitions to distinctly shallow water facies. A regression is usually associated with a falling sea level, but even in the face of a stable or slightly rising local sea level, the shoreline may still be displaced in a seaward direction by the rapid deposition of coastal sediments. Progradation is, for example, associated with delta formation. The relationship between the rate sea level changes and the rate of deposition or erosion was discussed by Curray (1964).

Onlaps and offlaps

The terms seem to have entered the literature associated with "onlaps" or "offlaps." Onlaps are overlapping relationships of shallower water sediments over deeper water sediments, which progressively pinch out toward the margins of a sedimentary basin. "Marine transgressive sequence" is used as a synonym for onlaps. Offlaps occur when progressively younger sediments have been deposited in layers offset seaward, often associated with an upward coarsening. Curray, accordingly, came to refer to the occurrence of a shift in the shoreline independent of the evidence found in the geologic record for these changes.

Further suggested readings are also included in the following bibliography.

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Cross-references

Changing Sea Levels
Coastal Sedimentary Facies
Sea Level Indicators, Geomorphic
Sequence Stratigraphy

INSTRUMENTATION—See BEACH AND NEARSHORE INSTRUMENTATION

ISOSTASY

Numerous observations point to a complex and changing relationship between land and sea surfaces throughout geological time. In some localities elevated coral reefs, wave-cut rock platforms, and molluscs embedded in their original marine sediments attest to past sea levels having been higher than present. At other sites, drowned forests and submerged sites of human occupation point to sea levels having been locally lower than present. These observations represent a measure of relative sea-level change which can involve a land-movement signal as well as an ocean-volume signal. The indicators of submerged or elevated coastlines therefore point to one of three occurrences: land has moved up or down, ocean volumes have changed, or both have occurred simultaneously.

Tectonic process operating within the earth have caused uplift and subsidence throughout the Earth's history, resulting in relative sea-level change on a wide range of spatial and temporal scales. They include uplift and subsidence at convergent plate margins where the relative sea-level change is usually episodic and abrupt but cumulative over long periods of time resulting in, for example, the marine mollusc beds high in the Andes of South America that were first described by Charles Darwin. The tectonic processes also include slower and longer-duration events such as the initiation of continental rifting and sea floor spreading with the concomitant changes in the displacement of water by the developing ocean ridge system. Long-term thermal contraction of the cooling outer layers of newly created ocean crust at the ocean ridge results in sea-floor subsidence, creating basins into which sediments accumulate, thereby magnifying the subsidence. Large volcanic edifices stress the earth and cause more local subsidence and deformation of the earth's surface in the vicinity of the load.

At the same time that the tectonics events shape the earth's surface and shift the relative positions of land and sea surfaces, ocean volumes also change, largely because of climate-driven changes in the extent of glaciation of the planet. During extended cold periods large ice sheets form, extracting water from the oceans and lowering sea levels. As the climate warms up sufficiently to melt the ice sheets sea levels again rise. Such glacial cycles have occurred at intervals throughout much of the earth's history but they have been most significant during recent times, the Quaternary period, for which the record has not yet been wholly overprinted by the subsequent tectonic and land-shaping events.

The combined result of the tectonics and glacial cycles is a sea-level signal that has varied significantly in time as well as being geographically variable. The record of this variability is, however, far from complete, and to be able to model and predict the migration of coastlines, an understanding and separation of the underlying causes of sea-level change is essential. Isostatic processes are key elements in this understanding and separation.

The isostatic process

Isostasy is the tendency of the earth's crust and lithosphere—the upper, effectively elastic layer of the earth—to adjust its vertical position when loaded at its surface by, for example, ice, water, volcanos, or sediments. For this purpose, the earth can be represented to a good approximation as a spherically symmetric body with a fluid core of about 3,400 km radius. The upper layer is called the lithosphere and includes the crust. Its thickness is typically between 50 and 150 km, varying with the tectonic history of the region. The lithosphere is characterized by being relatively cold and to behave elastically when subjected to load stresses below a critical failure limit. The mantle, between the lithosphere and core, is at a temperature that is relatively close to the melting point of terrestrial materials. As a result the mantle flows viscously, with characteristic relaxation times of 10^4–10^5 years, when subject to non-hydrostatic stress. It is this zonation of a "rigid" lithosphere over "viscous" mantle that gives validity to the isostatic models.

The simplest representation of isostasy is by "local" response models which are statement of Archimedes' principle: a load of heights h, density ρ, placed on the earth's surface results in a subsidence of the underlying surface of $\delta = h\rho/\rho_m$, where ρ_m, the density of the mantle, exceeds the density of the lithosphere (see Figure I22(A)). This model assumes that the crust or the lithosphere has no shear strength (or has failed under the load) and overlies a fluid mantle. This model, while unrealistic in many respects, is nevertheless useful for estimating magnitudes of crustal deflection beneath loads. For example, under a 3 km thick ice sheet the crust is predicted to deflect by about 1 km. A more reasonable model is one in which the load is supported by both the "elastic" strength of the crust-lithophere and by the buoyancy forces at the base of the layer (Figure I22(B)). In this model, the mantle also behaves as a fluid and it provides a reasonable description of the earth's response to loads with time constants that are longer than the relaxation times of the mantle. These models have been extensively used to represent the response of the earth to sediment loads or to volcanic loads. They are usually referred to as regional isostatic models.

When the load duration is of the order 10^3–10^5 years any load-generated stresses that have propagated into the mantle will not have relaxed and the viscosity of the mantle must be taken into account. In these cases the isostatic models are usually represented by an elastic layer over a viscous or viscoelastic halfspace or, in the case of global problems, by spherical shell models of an elastic lithosphere over a viscoelastic mantle and fluid core. Both lithosphere and mantle may be represented by some degree of layering in physical properties (elastic moduli, viscosity, and density). Formulation of these spherical response models are well developed and solutions for the surface deformation under complex

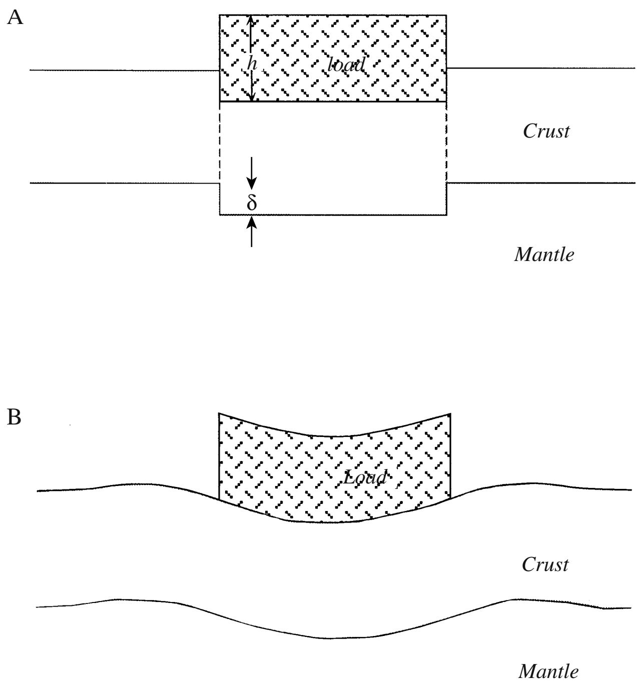

Figure I22 Models (A) local isostasy (B) regional isostasy. In (A) the load is supported by the buoyancy force at the base of the crust or lithosphere, whereas in (B) the load is also supported by the elastic stresses created in this layer. As the load diameter in (B) increases the isostatic response at the center of the load approaches that of local isostasy.

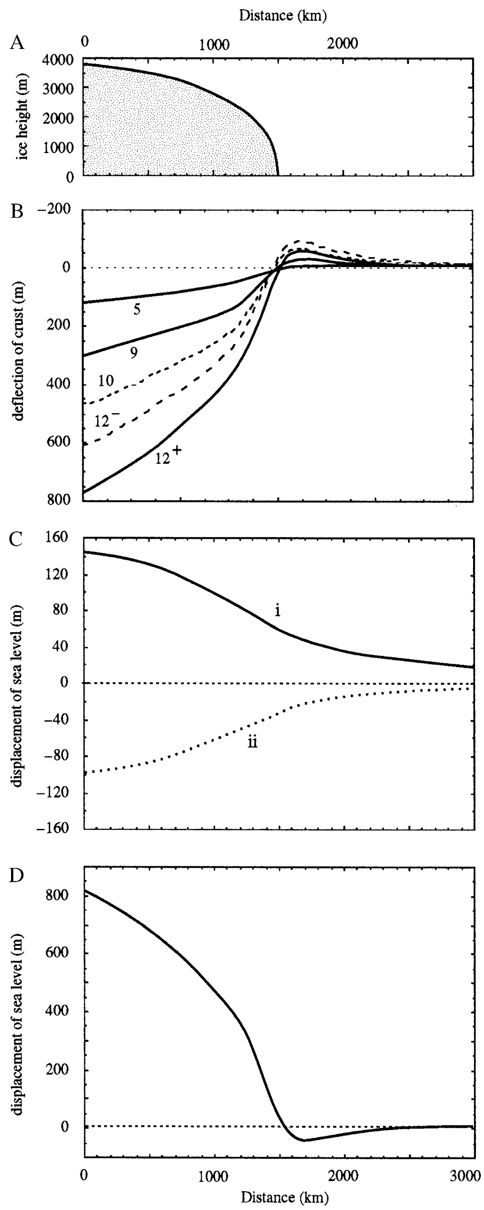

Figure I23 (A) Radial cross section of axisymmetric ice sheet. (B) Deformation of the earth's surface under the ice that has loaded the earth for 20,000 years (curve 12+). At 12,000 years ago the load is removed instantaneously. The initial response is elastic (curve 12−) and this is followed by viscoelastic creep, the surface being shown at 10,000 years (10), 9,000 years, and 5,000 years ago. (C) The gravitational attraction of the ice load, represented as the deflection of the geoid (i), and the change in geiod from the change in the planets gravity due to the deformation of earth under the load (ii). The results are shown for a period before unloading starts. (D) The relative sea-level change, due to the combination of crustal deformation, change in gravitational attraction, and ocean volume change long after the load has been removed. The sea level is expressed with respect to its present position. If the a coastline formed near the center of the load soon after the ice melted, it would now be at nearly 800 m elevation.

surface load geometries exist. Figure I23 illustrates an example of surface deformation where a large-diameter axi-symmetric ice sheet has been instantaneously removed. The rheology (viscosity structure) of the planet is realistic (see Figure I27, below) and the results indicate that the crustal readjustment continues for thousands of years after the unloading is completed.

In addition to the surface deformation, the gravity field of the planet also changes under the load: the shape of the envelope containing the mass is modified by the deformation and material is redistributed within this envelope. At the same time there is a redistribution of the material on the surface: sediments are transported from mountains into basins, or the meltwater from land-based ice sheets flows into the oceans. Surfaces of constant gravitational potential—surfaces on which the gravity vector is everywhere perpendicular—therefore, change with time as the load and planetary response evolve. One such equipotential is the geoid, the shape of the ocean. (If the ocean is not an equipotential surface then the gravity vector has a component along the surface and ocean currents result until an equilibrium state is reached; thus in the absence of winds and other perturbing forces, the ocean will be an equipotential surface. This is called the geoid.) Figure I23 illustrates the change in the equipotential surface resulting from the unloading. It includes a contribution from the surface load itself—the ice "attracts" the ocean water and pulls the ocean surface up around it (curve *ii*)—and a contribution from the earth's deformation (curve *i*). The illustration is for the period while the ice is intact and when melting starts both curves will evolve with time.

The example in Figure I23 illustrates that relative sea-level change resulting from the removal of the ice sheet contains several elements. The crust is displaced radially, the ocean surface is deformed by the redistribution of surface and internal mass, and water is added to the ocean. The rebound resulting from the melting (or growth) of the ice sheet is referred to as glacio-isostasy. The water added to (or withdrawn from) the oceans has its own isostatic effect and is referred to as hydro-isostasy.

The combined glacio–hydro-isostatic processes are of global extent. The melting of an ice sheet in one location modifies sea level globally, not just by changing the amount of water in the ocean but because of the planet's isostatic response to the changing surface load of ice and water. Other loading processes, such as by sediments or volcanic loads, are usually more local in their consequences. Also, these tectonic process generally occur on longer time scales so that the mantle response can usually be approximated as a fluid, and the local or regional isostatic models are mostly appropriate.

Glacio-isostasy

Ice sheets represent surface loads that reach radii in excess of 1,000 km and thickness approaching 3 km. These loads are large enough to deform the earth and to produce substantial changes in sea level as illustrated in Figure I23. Glacio-isostasy is the major cause of sea-level change in areas of former glaciation. When a large ice sheet melts the rebound of the crust is of larger amplitude than the rise in sea level resulting from the addition of the meltwater to the oceans (typically 120–130 m, see Figure I29 below) from all of the ice sheets. If ΔV_i is the change in volume of ice on land and A_o the area of the ocean, then this second signal is

$$-\frac{\rho_i}{\rho_w}\int\frac{1}{A_o(t)}\frac{d}{dt}\Delta V_i(t)dt$$

where ρ_i, ρ_w are the densities of ice and water, respectively, and both A_o and ΔV_i are functions of time. This contribution is referred to as the ice-equivalent sea-level change.

Because of the viscosity of the mantle, the crust continues to rise long after the ice has vanished and sea level appears to have fallen since deglaciation. This is seen in the Gulf of Bothnia and northern shores of the Baltic Sea, as well as in the Hudson Bay area of northern Canada. For these locations near former centers of glaciation the rebound signal dominates and the observed sea-level curves are characteristic relaxation curves (although only the post-glacial part of the change is recorded) (Figure I24 (Angermanälven)). Near the ice margins the rebound is reduced in magnitude and may become comparable to the rise resulting from the increase in ocean volume. Now the time dependence of the sea-level change becomes more complex, with its character depending on the relative importance of the two contributions. In Figure I24(Andøya), for a site just within the ice-sheet margin, the rebound initially dominates but later, because of the melting of other and distant ice sheets, the ocean volume increase becomes the dominant factor and sea level rises until a time when all ice sheets have melted. The remaining signal is a late stage of the relaxation process and sea levels continue to fall up to the present.

The rate and magnitude of the sea-level change is a function of the earth's viscosity and the ice history: of the duration of the ice load, of its areal extend, and of its thickness. The importance of the rebound phenomenon is that it provides a means of estimating the earth's rheology: if climate models and geomorphological observations constrain the ice geometry through time, then observations of sea-level change provide a constraint on the mantle viscosity. If the ice models are not sufficiently well-known then it becomes possible to learn something about the ice sheets as well. Figure I25 illustrates observational results for sea-level change across Scandinavia. Here, the ice sheet reached its maximum at about 20,000 years ago and most melting occured between about 16,000 and 10,000 years ago. As the ice retreated, coastlines formed on the emerging land providing a comprehensive description of the rebound across northern Europe. The rebound did not cease at the time melting ceased and coastlines have continued to retreat in formerly glaciated regions up to the present. This can be seen in tide gauge records across the Baltic, with present sea-level falling locally at rates approaching 1 cm/yr in the northern part of the Gulf of Bothina. Figure I26 illustrates the rate of crustal rebound and to obtain relative sea-level change these values must be increased by about 1–1.5 mm/yr. Coastlines here continue to retreat despite other factors that may contribute to an increase in global ocean volume.

Glacio-isostasy does not cease at the ice sheet margins. Because the mantle flow generated by the changing surface load is constrained within a deformable shell, when some areas are depressed under a growing load others are uplifted. The latter areas form a broad zone or swell around the area of glaciation of amplitude that may, depending on the size of the ice sheet, reach a few tens of meters. When the ice sheet melts this peripheral swell subsides and for island or coastlines on it sea level will be seen to be rising at a rate that is over and above the ice-volume equivalent contribution (Figure I24(Store Bælt)). Beyond the Scandinavian relic ice margins this occurs in areas of the North Sea and as far away as the western and central Mediterranean and here the sea level continues to rise even when all melting has ceased. Beyond the North American ice sheet this zone of recent crustal subsidence and marine flooding occurs as far away as the southern USA and Caribbean.

Observations of sea level within and beyond the former ice margins provide the principal source of information on mantle viscosity. A typical result for northwestern Europe is illustrated in Figure I27 where the rebound phenomenon provides a good constraint on the viscosity of the upper mantle. The main features of the viscosity profile include a lithosphere of thickness 65–75 km, a relatively low value for the viscosity of the mantle immediately below the lithosphere, and increasing viscosity with depth, particularly at a depth of about 700 km. Analyses for different regions produce comparable results although actual values for the viscosity and lithospheric thickness may differ because of the possibility that the rheology is laterally variable. The determination of such variability is one of the important research areas in glacio-isostasy.

While the glacio-isostatic models are well understood, one of the key limitations of their application is the inadequate knowledge of the former ice sheets. The ice margins at the time of the Last Glacial Maximum, some 20,000 years ago, are usually well-defined by geomorphological markers but the timing of their formation is not always known. This occurs particularly where the ice margins stood offshore and left few datable traces of both the time of their formation and of their retreat. Also, the ice thickness cannot usually be inferred from observational evidence alone and is inferred instead from glaciological and climate models. The sea-level observations can nevertheless help constrain the ice models in important ways. Thus, the total ice volumes in the models for all the major ice sheets must yield a global sea-level curve that is consistent with the changes observed far from the ice sheets (see hydro-isostasy). Also, details in the ice models can also be derived from the sea-level data from sites within and near the former ice margins. The shape of the sea-level curve from a near-margin site (Figure I24) changes quite rapidly with distance from the former ice margin, with the signal evolving from that for a central-load site to that for a site on the peripheral swell, and observations across the margin can constrain the former ice distribution within the ice-marginal region. One of the more recent research directions in glacio-isostasy is the use of this sea-level and crustal-rebound evidence to improve models of the ice sheets during the last deglaciation phase.

Hydro-isostasy

As ice sheets melt, the additional water entering the world's oceans loads the sea floor, load stresses are propagated through the elastic lithosphere into the mantle, the newly stressed mantle material flows toward unstressed regions and the sea floor subsides. The shape and holding-capacity of the ocean basin is thereby modified and the ocean water is redistributed, changing sea level. This adjustment of the earth

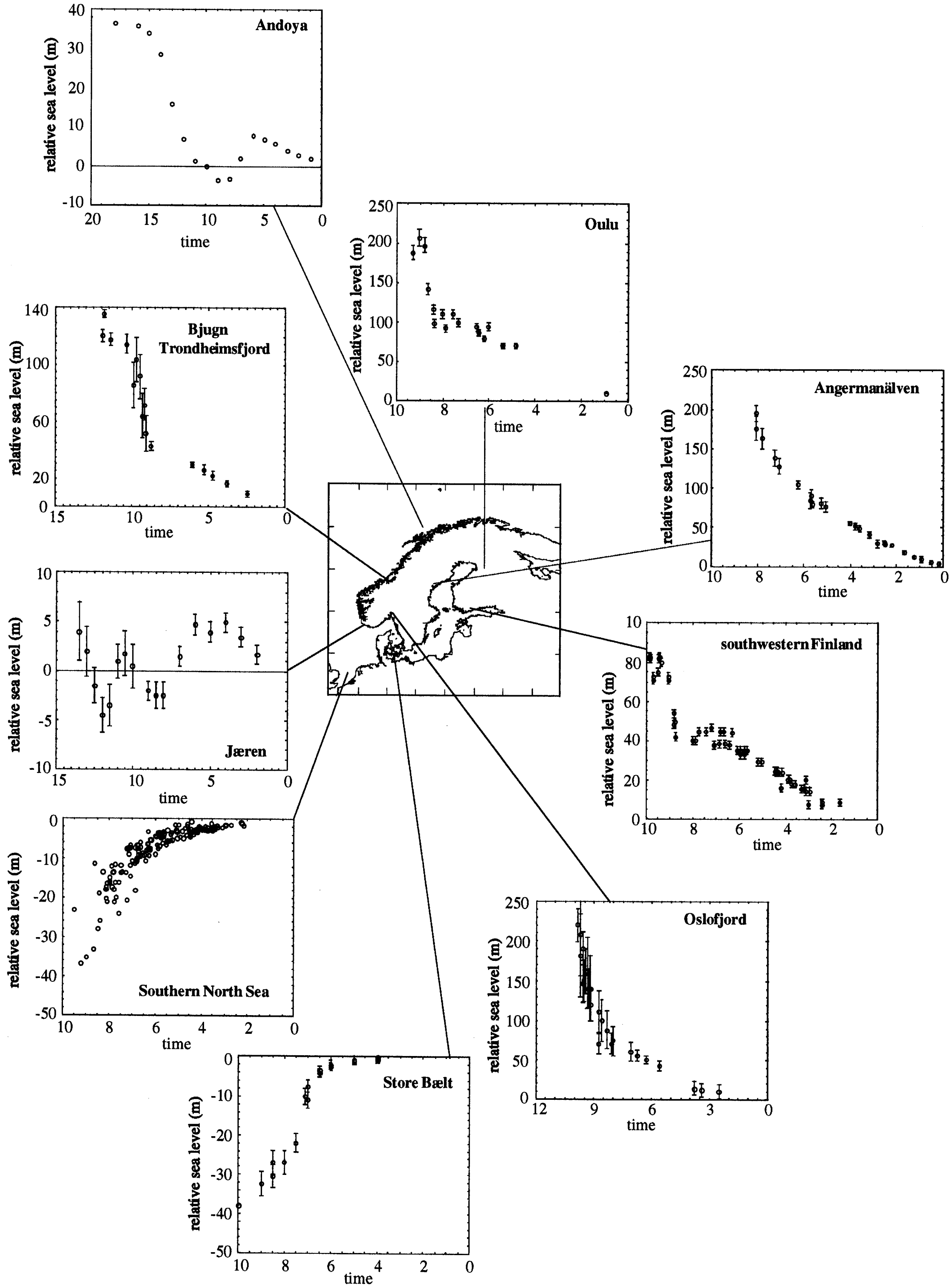

Figure I24 Observed relative sea-level change for sites in Scandinavia illustrating some of the spatial variability in the response. The ice sheet covered all of Scandinavia and spread onto the German, Polish, and Russian plains. Retreat started at about 18,000 years ago and the final disappearance of ice occurred at about 10,000 years ago. The time scale used in these plots corresponds to the radiocarbon time scale which differs from a calendar time scale by about 10–15% for this interval (1 C^{14}years ≈ 1.1–1.15 calendar year).

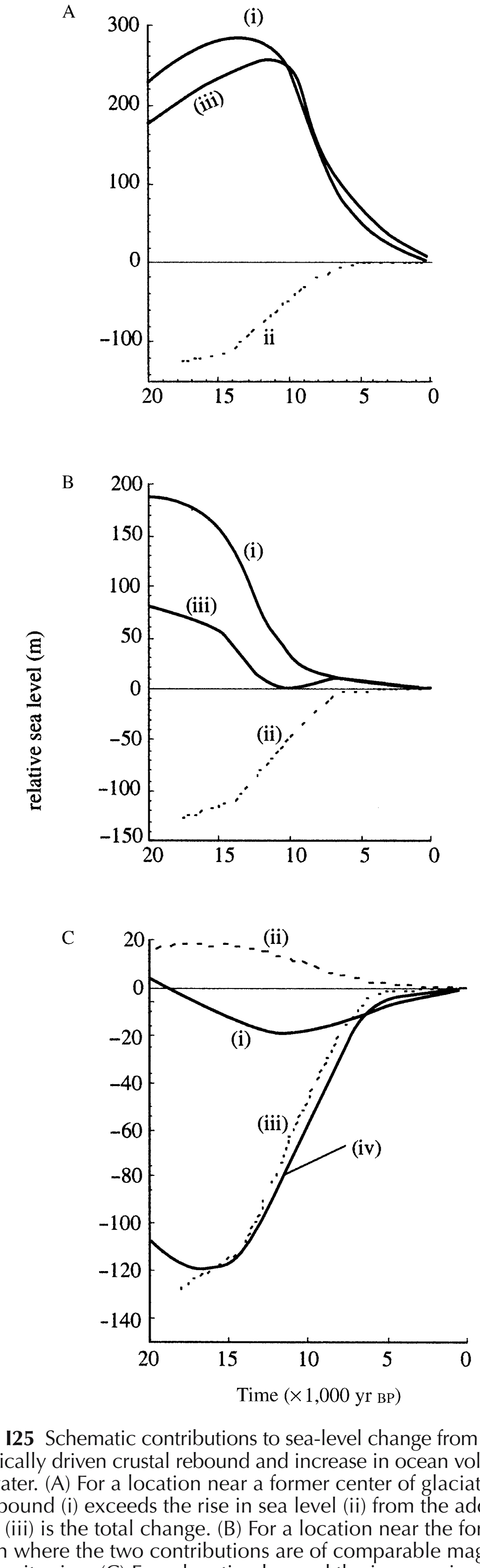

Figure I25 Schematic contributions to sea-level change from the glacio-isostatically driven crustal rebound and increase in ocean volume from meltwater. (A) For a location near a former center of glaciation where the rebound (i) exceeds the rise in sea level (ii) from the added melt-water, (iii) is the total change. (B) For a location near the former ice margin where the two contributions are of comparable magnitude but of opposite sign. (C) For a location beyond the ice margin where the crustal uplift is replaced by subsidence. The effect of the water load (ii) now is important as well as the ice-load effect (i). The meltwater contribution is given by (ii) and the total change by (iv).

under the time-dependent water load and the concomitant sea-level change is referred to as hydro-isostasy. Since the onset of the last deglaciation, sea levels have risen on average by about 120–130 m and

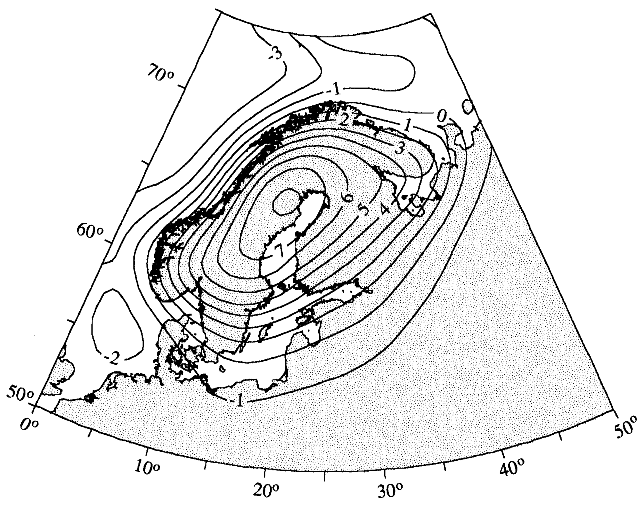

Figure I26 Present rates of crustal uplift (in mm/yr) of Scandinavia based on rebound models and on observed rates from tide gauges across the region (from Lambeck *et al.*, 1998; with permission of Blackwell Publishing).

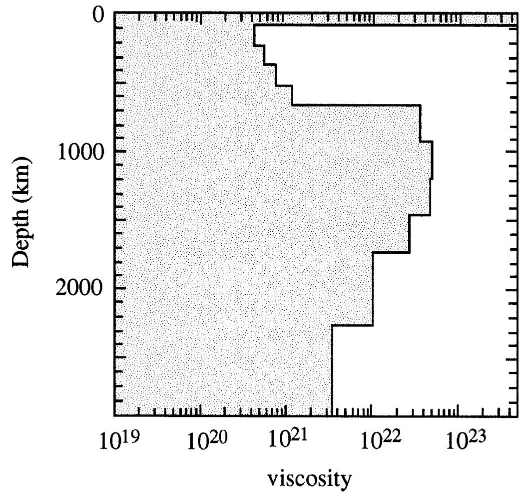

Figure I27 Profile of mantle viscosity (in units of Pa s) inferred from glacial rebound analysis of European sea-level data (G Kaufmann, with permission).

the additional load has been sufficient to modify the shape of the earth. This is a result of the long wavelength nature of the water load. Loads of dimensions less than the thickness of the lithosphere are supported mainly by the strength of the lithosphere and the resulting surface deformation is small. But large-dimension loads effectively see through the lithosphere and are supported by the much more ductile mantle which flows even under small changes in the stress field.

At continental margins the hydro-isostatic deformation of the earth's surface describes quite complex patterns because of the geometry of the load. The lithosphere acts as a continuous elastic layer or shell and the continental margin is dragged down by the subsiding ocean lithosphere but, because of the asymmetry of the load, not by the same amount as in mid-ocean. At the continental coastlines, therefore, the subsidence will be less than it would be in mid-ocean. At the same time, some of the mantle material flowing away from the stressed oceanic mantle flows beneath the continental lithosphere, causing minor uplift of the interior. The net effect of the ocean volume increase is a seaward tilting of the continental margin which will be seen as a variable sea-level signal across the shelf. This effect is clearly seen for tectonically stable continents that lie far from former ice sheets, as in the case of Australia.

While the ice sheets are still melting the dominant sea-level signal here is from the increase in ocean volume and the glacio- and hydro-isostatic effects are second order. But when melting ceases the on-going isostatic effects come into their own. Now sea level appears to be falling at the coastal site as the ocean waters recede to fill the still-deepening ocean. In consequence, small sea-level highstands are left behind with peak amplitudes of 1–3 m occurring at the time global melting ceased (Figure I28). Such highstands are common features along many continental margins and manifest themselves as relic shorelines or fossil corals above the present formation level or habitat. If the coast is deeply indented, sites at the heads of gulfs, being furthest away from the water load, experience greatest uplift while offshore islands experience least uplift. This differential movement provides a direct measure of the viscosity of the mantle across the continental margin.

Like the glacio-isostatic effect, the water load does not only deform the surface of the earth, it also results in a redistribution of mass and a change in gravity and in the shape of equipotential surfaces. The total sea-level changes associated with the hydro-isostasy include, therefore, both the crustal radial deflection and the associated geoid change. Also, the glacio- and hydro-isostatic effects are closely linked when their cause is the deglaciation of the last ice sheets. Near the edge of the ice sheets, for example, the water is pulled up (Figure I23) and the waterload is increased above what would result from a uniform distribution of the meltwater over the entire ocean. Here the hydro-isostatic signal is a function of the magnitude of the glacio-isostatic effects. Elsewhere, the broad zone of crustal rebound surrounding a large ice sheet may occur in an oceanic environment. Then, when the ice sheet melts this swell subsides, increasing the volume of the ocean basin, water is withdrawn from other parts of the ocean, and a further global adjustment of sea level occurs. Thus, the treatment of hydro–glacio isostasy requires a global and consistent formulation that ensures that these various interactions are included.

The hydro-isostatic signal is an on-going one even when major melting of the world's ice sheets ceased about 6,000–7,000 years ago. Thus sea-level change today will contain a small but not insignificant component of hydro-isostatic origin (cf. Figure I28 for the Australian region). This signal must, of course be superimposed upon any other changes, including possible global warming signals. The results indicate that sea levels around the Australian margin are slowly falling under the combined glacio–hydro-isostatic response to the past melting of the large ice sheets (with the possible exception of Tasmania where the glacio-isostatic effect of Antarctic ice volume changes becomes significant, canceling out the hydro-isostatic signal such that little overall change now occurs). Similar isostatic effects will be present at all coastline, increasing in magnitude as the locality approaches the regions of former glaciation.

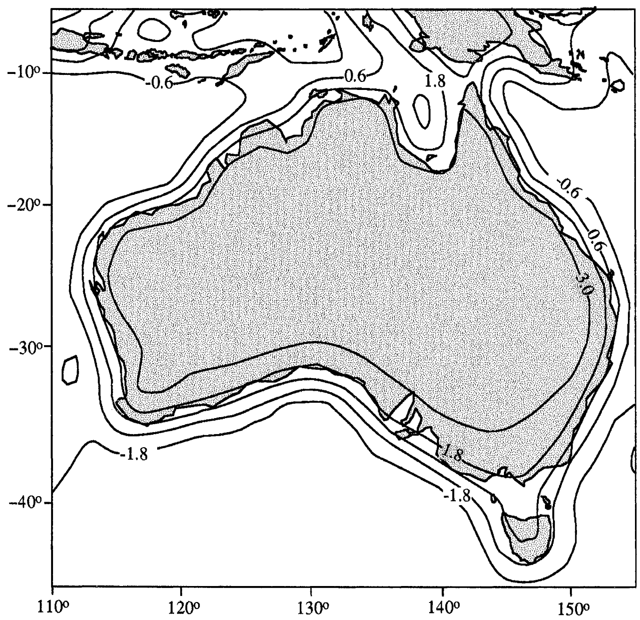

Figure I28 Sea level at 6,000 years ago around the Australian margin illustrating the effect of hydro-isostasy as a tilting of the margins of the continents. Sea levels are present relative to present mean sea level. Contour intervals are 1.2 m. The present-day rate of change in mm/yr given approximately by dividing the contour values by 6 and changing the sign, the resulting negative value for most locations indicating a fall in sea level from isostasy alone.

The importance of the sea-level observations far from the ice margins is that because the glacio–hydro isostatic effects are relatively small (10–15% of the total signal) they provide an estimate of the change in volume of the oceans when corrected for the isostatic effects: the observed sea level, less the isostatic correction yields the ice-equivalent sea level defined above and hence an estimate of the change in ocean volume ΔV_i. Several long records, extending back to the Last Glacial Maximum, of local sea-level change exist which provide evidence for the change in ice volume since this time. They indicate (Figure I29) that maximum ice volumes globally were (50–55) x 10^6 km^3 greater than today but, they do not indicate necessarily where this extra ice was stored. To resolve that issue recourse to the study of the glacio-isostatic process from formerly glaciated regions is necessary.

Sediment and volcanic loading

Large accumulations of sediment occur along many of the continental margins reaching, in some instances, a thickness of 10 km or more. The rate of accumulation is usually slow and continuous, occurring over periods of tens of millions of years with the sources of sediments coming from continental interiors where tectonic processed have caused uplift and erosion processes have carried the sediments to the sea. Examples include the Bay of Bengal, the northwestern margins of Europe, the eastern margin of North America, and the Gulf of Mexico. Thick accumulations of sediments are possible because of the subsidence of the lithosphere under the growing sediment load. With the above model of local isostasy an ocean basin of depth d_o can, with adequate sediment supply, lead to a maximum subsidence of $d_o\rho_s(\rho_s-\rho_m)$ where ρ_s is the density of sediments. This assumes that the basin is ultimately filled to sea level. For $d_o = 4$ km, $\rho_s = 2.5$ g cm^3, $\rho_m = 3.5$ g cm^{3}the maximum thickness of sediment that can be attained is about 10 km. However, in this case the deeper sediments will have been deposited in water depths initially of $d_o = 4$ km, whereas the characteristics of the fauna preserved in the basin sediments usually indicate that deposition invariably occurred in relatively shallow waters. Isostasy alone, therefore, cannot produce thick sediment sequences but it does act as an amplifier of subsidence that is the result of other processes: in this case mostly the thermal contraction of ocean lithosphere as it cools from an initially hot layer formed at the ocean ridges and then moves away from the heat source.

On short time scales, sediment loading can lead to substantial coastal subsidence. This may occur in conjunction with deglaciation cycles where sediments are eroded from the continents during the deglaciation stage and delivered to coastal environments at some later stage. An example of such subsidence occurs along the US coast of the Gulf of Mexico, particularly for the Mississippi delta. Here, coastal subsidence occurs at rates approaching 10 mm/yr and are attributed in part to the isostatic response to recently delivered sediments, but also in part to the extraction of fluids from the sediments and the associated compaction. Here, as in most isostatic problems, several factors will contribute to the observed signal.

Volcanic loading of the crust provides another example of isostasy at work. Large volcanic complexes form on the sea floor, and elsewhere, because of upwelling convection currents in the mantle that lead to an injection of magma into the crust and ultimately onto the surface as volcanos. The mantle source regions for the magma appear to be long-lived and as the lithosphere moves over the earth's surface under the forces of plate tectonics, a trail of volcanos is left on the surface. The Hawaiian chain provides the type example. Other examples include the Society Island chain whose current center of volcanic activity lies to the east of Tahiti. The subsidence of the lithosphere beneath the volcano is adequately described by the regional isostatic model in which the load is supported by the elastic stresses within the lithosphere and by the buoyancy force at the base of the layer (Figure I22(b)). Because of the elastic properties of the lithosphere small peripheral bulges, concentric about the center of loading, develop and any islands located in this zone at the time of volcano development are uplifted by some tens of meters. An example of this is provided by the uplifted atoll that forms Henderson island, southeast of Pitcairn island. This small island about 200 km from the volcanic island of Pitcairn, appear to have been uplifted some 20–30 m at the time of Pitcairn's formation, perhaps 700,000 years ago. The location of the zone of maximum peripheral uplift provides a measure of the flexural wavelength of the lithosphere, a parameter that characterizes the physical response of the layer to loading. With time, some relaxation of the loading stresses can be expected to occur within this layer such that the isostatic state evolves

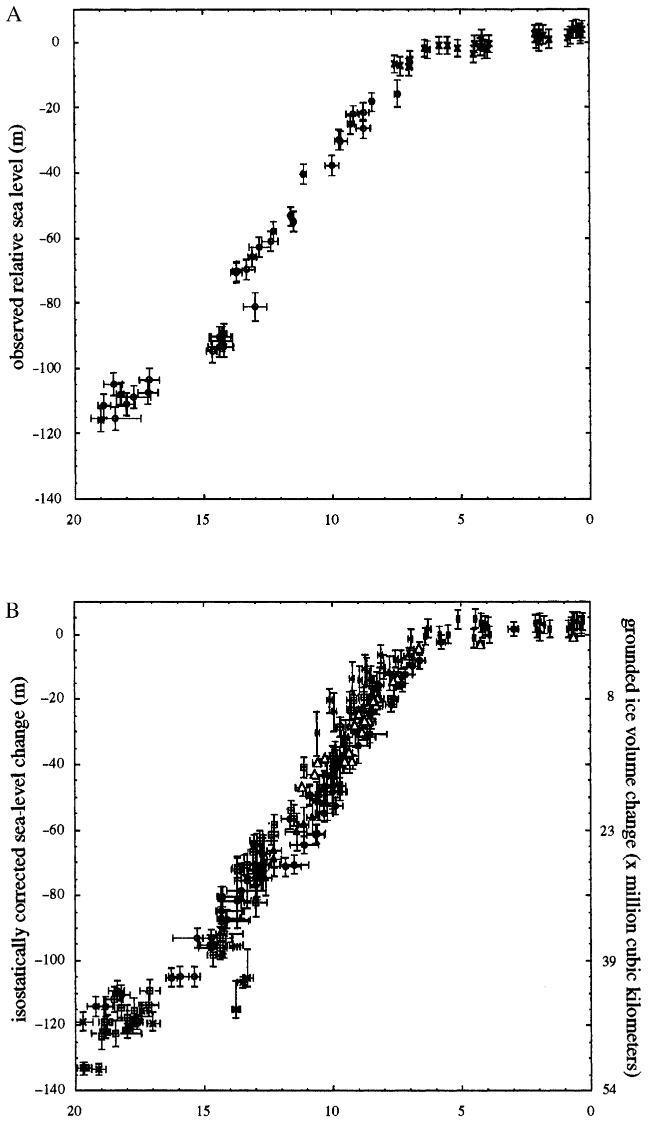

Figure I29 Sea-level change for the past 20,000 years. (A) A record of observed local relative sea-level change from Barbados and other Caribbean sites, and (B) isostatically corrected sea level from a number of sites distributed globally and combined into a single ice-equivalent sea-level curve. Scale on the right hand side gives the corresponding change in volume of ice on land and grounded on shallow sea floor.

slowly from regional to local isostasy and that the volcano slowly subsides. Thus Tahiti, a relative young volcanic load of about 1–2 million years, may be subsiding at a rate of about 0.2 mm/yr or less.

These examples of vertical movements driven by sediment or volcanic loading illustrate the interaction that occur between the various isostatic contributions to sea-level change. To estimate rates of tectonic uplift or subsidence, heights of identifiable coastlines are measured with respect to present sea level. Thus, the fluctuations in sea level of glacio-isostatic origin must be known, but these fluctuations are inferred from the same observational evidence. An important research area is to develop methods for separating out these effects, through observational improvements and through improved modeling of the physical processes.

Suggested further reading on this subject may be found in the following bibliography.

Kurt Lambeck

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Cross-references

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