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REGIONAL SEAS

UNITED NATIONS ENVIRONMENT PROGRAMME

Oil spills and shoreline clean-up on the coasts of the Eastern African region

UNEP Regional Seas Reports and Studies No. 57

Prepared in co-operation with

IMO

UNEP 1985

<u>Note</u>: This report was prepared jointly by the International Maritime Organization (IMO) and the United Nations Environment Programme (UNEP) under projects FP/5102-83-08 and FP/5102-77-03 as a contribution to the development of an action plan for the protection, management and development of the marine and coastal environment of the Eastern African region.

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PREFACE

The Regional Seas Programme was inititated by UNEP in 1974. Since then the Governing Council of UNEP has repeatedly endorsed a regional approach to the control of marine pollution and the management of marine and coastal resources and has requested the development of regional action plans.

The Regional Seas Programme at present includes eleven regions 1/ and has over 120 coastal States participating in it. It is conceived as an action-oriented programme having concern not only for the consequences but also for the causes of environmental degradation and encompassing a comprehensive approach to controlling environmental problems through the management of marine and coastal areas. Each regional action plan is formulated according to the needs of the region as perceived by the Governments concerned. It is designed to link assessment of the quality of the marine environment and the causes of its deterioration with activities for the management and development of the marine and coastal environment. The action plans promote the parallel development of regional legal agreements and of action-oriented programme activities 2/.

Decision 8/13(C) of the eighth session of the Governing Council of UNEP called for the development of an action plan for the protection and management of the marine and coastal environment of the East African region. As a first activity in the region, UNEP organized in October and November 1981 a joint UNEP/UN/UNIDO/FAO/ UNESCO/WHO/IMCO/IUCN exploratory mission which visited the region.

The findings of the mission were used to prepare the following six sectoral reports:

- UN/UNESCO/UNEP: Marine and coastal area development in the East African region. UNEP Regional Seas Reports and Studies No. 6. UNEP, 1982;
- UNIDO/UNEP: Industrial sources of marine and coastal pollution in the East African region. UNEP Regional Seas Reports and Studies No. 7. UNEP, 1982;
- FAO/UNEP: Marine pollution in the East African region. UNEP Regional Seas Reports and Studies No. 8. UNEP, 1982;

1/ Mediterranean Region, Kuwait Action Plan Region, West and Central African Region, Wider Caribbean Region, East Asian Seas Region, South-East Pacific Region, South Pacific Region, Red Sea and Gulf of Aden Region, Eastern African Region, South-West Atlantic Region and South Asian Seas Region.

2/ UNEP: Achievements and planned development of UNEP's Regional Seas Programme and comparable programmes sponsored by other bodies. UNEP Regional Seas Reports and Studies No. 1. UNEP, 1982.

- WHO/UNEP: Public health problems in the coastal zone of the East African region. UNEP Regional Seas Reports and Studies No. 9. UNEP, 1982;

- IMO/UNEP: Oil pollution control in the East African region. UNEP Regional Seas Reports and Studies No. 10. UNEP, 1982; and

- IUCN/UNEP: Conservation of coastal and marine ecosystems and living resources of the East African region. UNEP Regional Seas Reports and Studies No. 11. UNEP, 1982.

The six sectoral reports prepared on the basis of the mission's findings were used by the UNEP secretariat in preparing a summary overview entitled:

- UNEP: Environmental problems of the East African region. UNEP Regional Seas Reports and Studies No. 12. UNEP, 1982.

The overview and the six sectoral reports were submitted to the UNEP Workshop on the Protection and Development of the East African Region (Mahé, Seychelles, 27-30 September 1982) attended by experts designated by the Governments of the East African region.

The Workshop:

- reviewed the environmental problems of the region;

- endorsed a draft action plan for the protection and development of the marine and coastal environment of the Eastern African region;

- defined a priority programme of activities to be developed within the framework of the draft action plan; and

- recommended that the draft action plan, together with a draft regional convention for the protection and development of the marine and coastal environment of the Eastern African region and protocols concerning (a) co-operation in combating pollution in cases of emergency, and (b) specially protected areas and endangered species, be submitted to a conference of plenipotentiaries of the Governments of the region with a view to their adoption.

In consultation with the Governments of the Eastern African region the further development of the action plan was focused on activities directly related to preparations for the conference of plenipotentiaries and to other regional activities which received a first priority rating in the programme recommended by the Mahé workshop [3/]. This included the preparation of a series of country reports by experts from the region on:

3/ Report of the Workshop on the protection and development of the marine and coastal environment of the East African region, Mahé, 27-30 September 1982, (UNEP/WG.77/4).

- national legislation;

- natural resources and conservation; and

- socio-economic activities that may have an impact on the marine and coastal environment.

The national reports were synthesized in regional reports 4/5/6/ which were prepared with a view to assisting the Governments of the Eastern African region in their negotiations on the regional convention and its protocols. In addition, a technical training Workshop on oil pollution prevention, control and response in the Eastern African region was convened jointly by the International Maritime Organization (IMO) and UNEP from 24 November - 2 December 1983 in Mombasa, Kenya.

The present document is a collection of the workshop notes and field guide prepared for participants attending the training workshop. The assistance of a consultant firm, Woodward-Clyde Oceaneering, in the preparation of this document, is gratefully acknowledged.

4/ FAO/UNEP: Legal aspects of protecting and managing the marine and coastal environment of the East African region. UNEP Regional Seas Reports and Studies No. 38. UNEP, 1983.

5/ IUCN/UNEP: Marine and coastal conservation in the East African region. UNEP Regional Seas Reports and Studies No. 39. UNEP, 1984.

6/ UNEP: Socio-economic activities that may have an impact on the marine and coastal environment of the East African region. UNEP Regional Seas Reports and Studies No. 41. UNEP, 1984.

TABLE OF CONTENTS

INTRODUCTION

Pursuant to the recommendation of the UNEP Workshop on the Protection and Development of the Marine and Coastal Environment of the East African Region (Seychelles, 27-30 September 1982), a workshop on oil pollution prevention, control and response in the Eastern African region was held in Mombasa, Kenya, from 24 November to 2 December 1983. Organized by IMO in co-operation with UNEP, the workshop brought together 20 experts from Comores, France (Réunion), Kenya, Madagascar, Seychelles, Somalia, Tanzania and observer/experts from Djibouti and Sudan.

The workshop formed part of the framework of the development of an Action Plan for the protection and development of the marine and coastal environment of the Eastern African region. Its purpose was to provide training in oil pollution prevention, control and abatement with the main emphasis on oil spill combating and national and regional contingency planning.

The course programme which consisted of lectures, audio-visual aids and written manuals provided participants with an understanding of shoreline character and of the factors that control shoreline stability so that the methods selected for protection or clean-up are appropriate to the local environment and do not cause more damage than that which results from stranded oil.

The programme included two field excursions to beach and mangrove sites which were characteristic of shorezones in the region.

Recognizing that control of oil pollution begins with prevention, an overview of relevant international marine pollution conventions was presented with an emphasis on the role of the port State in enforcing international regulations developed by IMO. The economic impact of an oil spill was highlighted in presentations dealing with liability and the existing legal regimes and procedures to follow in obtaining compensation.

In discussing national and contingency planning, the workshop benefitted greatly from the individual presentations by experts from Kenya and the United Republic of Tanzania who outlined the status of national contingency planning in each of their countries. Considerable interest was shown by the participants in the possibilities for regional co-operation and development of the draft protocol concerning co-operation in combating marine pollution incidents in the Eastern African region.

Although the workshop was more of a training course, there was at the end a general consensus that there should be follow-up programmes designed to assist individual countries in developing national contingency plans and to discuss what could realistically be achieved at the regional and sub-regional levels in the field of contingency planning.

Objectives of the workshop

Effective oil spill response action requires suitable preparation and training in order to implement appropriate procedures as quickly as is necessary. One aspect of spill activities is the protection and clean-up of the shoreline. One of the primary objectives of this workshop was to develop an understanding of shoreline character and of the factors that control shoreline stability, so that the methods selected for protection or clean-up are appropriate to the local environment and do not cause more damage than that which results from the stranded oil.

The workshop was designed to present a working knowledge of the factors that control coastal processes so that response decisions can be made that are appropriate for specific sites. For example, it is not possible to deal with all sand beaches in exactly the same manner as sediment abundance, erosion or burial of oil, and backshore access to the shore varies from site to site. The flexibility to adapt to differing situations and environments can be developed with an understanding of the shore zone of the East African coast (table 1).

The workshop is only one of a range of preparatory or training elements that are necessary to develop a comprehensive response capability. The development of regional and local contingency plans is a fundamental aspect of oil spill response organisation. Boom handling and deployment, for example, require a "hand-on" approach and spill impact assessment studies involve field studies and map preparation. All of the various components are a necesary part of an adequate spill response programme.

Table 1: Eastern Africa - Coastal lengths

Comoros	350 km
France (Réunion)	250
Kenya	500
Madagascar	4000
Mauritius	200
Mozambique	2500
Seychellles	600
Somalia	3000
Tanzania	750

The elements of the workshop that are covered in this document relate to lectures on:

- coastal processes and coastal geology;
- shoreline types;
- oil and fate of spilled oil;
- shoreline protection;
- shoreline clean-up;
- potential clean-up damage; and
- response strategy.

An integral aspect of the workshop was the two field excursions that were designed to examine and discuss shore-zone characteristics at representative locations along the Kenya coast. The field excursions provided a realistic element to the classroom material through the discussion of coastal and spill-related problems.

Format

The workshop was a combination of lectures, field excursions, and an exercise discussion. The lecture format on shoreline factors and shoreline clean-up follows that which is given in the workshop notes. The notes are intended to be only a synopsis of these lectures and further information can be obtained by use of the references listed at the end of the document.

COASTAL PROCESSES, COASTAL GEOLOGY AND SHORELINE TYPES

Coastal processes

Waves

Winds generate waves that in turn expend their energy in the shore zone. The character of locally-generated waves is controlled by wind velocity, fetch, and by the duration of the wind. Waves that leave the generating area are no longer influenced by local winds and travel as long-period swell. The levels of wave energy at the shoreline are a function of the wave climate and of water depths in the nearshore zone. Reefs and shallow nearshore waters protect coasts from incoming waves. In regions of relatively unidirectional winds, such as the trade winds belt, there is a marked difference in energy levels between windward and leeward coasts. The mechanical energy of breaking waves at the shoreline causes the redistribution (or transportation) of sediments.

Tides and water-levels

Cyclical tidal water-level changes at the coast in the Western Indian Ocean are in the order of 1m or more. In "micro-tidal environments" (where the tidal range is 1m or less) wave action is concentrated in a narrow band at the shore. By contrast, in areas of high tidal ranges (range 3 m or more) wave energy is dissipated over a wide section of the shore. Storm surges, caused by winds piling water against the shore, raise the water level above the normal limit of wave action.

Winds

In addition to wave generation, winds may be important in the transportation of sand-sized sediments in the shore zone. Dunes are mobile sediment deposits that result from wind transport. They may be stablized by the growth of a surface vegetation cover.

Sediment transport and beach stability

Sediment sources for beaches include:

- the onshore transport of sediments from adjacent nearshore waters;
- the alongshore transport of sediments in the shore zone from adjacent coasts;
- coastal erosion of bedrock outcrops or exiting beach deposits by waves; and
- river sediments that are eroded from the interior and carried to the coast.

Sediments undergo redistribution on an almost continuous basis the exceptions being large-sized material (cobbles and boulders) that require substantial amounts of energy for transport, or low-energy environments that are sheltered from wave activity.

Beaches are in a state of dynamic equilibrium with the coastal processes. Changes are part of a normal process. Change may take place by the movement of sediment alongshore by waves that approach the beach at an angle. If the angle of wave approach varies, the transport direction may be reversed. Where this occurs within a pocket beach system, erosion in one section is counter-balanced by accretion in other parts. The interruption of alongshore transport, by construction of a groyne, can lead to accretion in updrift areas accompanied by erosion in the sediment-starved downdrift section (fig. 1).

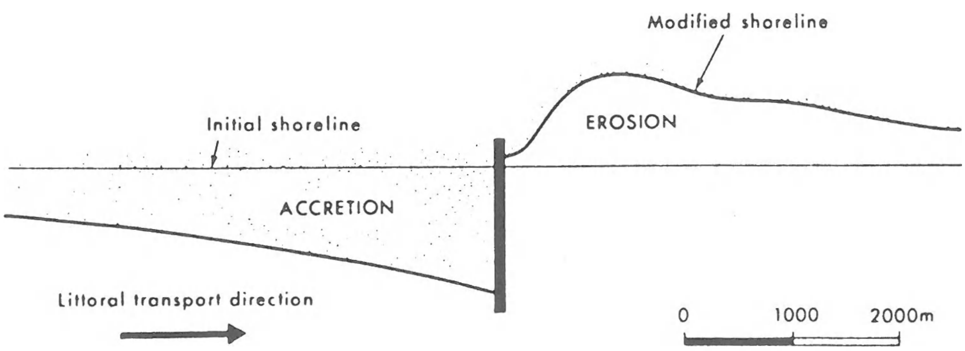


Figure 1: Initial shoreline and changes that result from construction of a groyne across the beach (from Komar, 1976)

During periods of high-energy wave activity (e.g. storms) beaches are usually eroded as sediments are transported from the intertidal zone in the adjacent nearshore (subtidal) zone. Beaches recover by post-storm constructive wave activity as sediments (in the form of ridges) are moved back into the intertidal zone (fig. 2). This on-offshore cycle of erosion and accretion can occur over short periods (days or weeks) or over seasonal periods. Beaches may undergo long-term retreat (erosion) if more sediments are lost from a section than are supplied to it. This may occur if sediments are removed and not replaced by man.

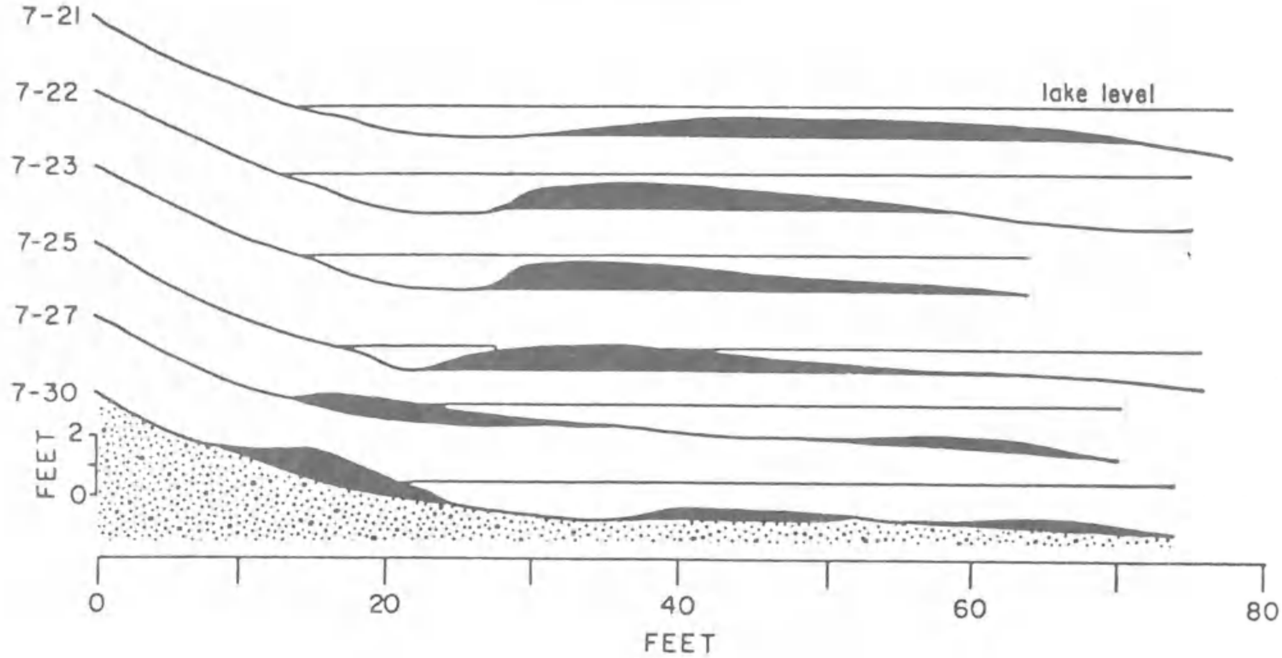


Figure 2: Sequence of onshore ridge migration following storm erosion of a beach, Lake Michigan (from Davis and Fox, 1971)

Shoreline types

Shoreline character is a function of the coastal processes and of the materials upon which those processes act. A primary distinction can be made between those coasts that have sediments in the shore zone and those that do not. These individual shoreline types (table 2) frequently exist in combination (for example: a sand beach with either beach rock or a rock platform in the lower intertidal zone). Further subdivision of shorelines with sediment is based primarily on the size of the material (table 3). Beach sediments vary in origin throughout the region. The primary sources are (i) bedrock and shore erosion (quartz or volcanic sands) and (ii) the breakdown of shells or corals (shell hash, carbonate sands, and coral rubble) (see fig. 3). This approach can be extended to include morphological parameters (vertical rock cliffs, bedrock ramps, rock platforms, sea stacks, washover fans, boulder ramparts, etc.) and, in the case of bedrock shores, the resistance of the material may be a factor (unresistant sandstone outcrops, or resistant volcanic outcrops).

Table 2: Shoreline types based on substrate

Without sediments	With sediments
Bedrock	Mud
Beachrock	Sand
Coral man-made structure	Pebble
Man-made structures	Cobble
- concrete	Boulder
- metal	Mixed (incl. gravel and rubble)
- wood	Vegetated
	- mangrove
	- marsh
	- backshore dunes

Table 3: Sediment size grades

Sediment	Particle diameter
Mud	<0.06 mm
Sand	0.06-4 mm
Pebble	4-64 mm
Cobble	64-256 mm
Boulder	>256 mm
Gravel	>2 mm

A summary of some of the features of the major shoreline types is given in table 4.

Table 4: Features of major shoreline types

Shore-zone Material	Grain Size (mm)	General Descriptive Features
MUD	≤0.06	• Low beach slope • Develop in areas where there is a source of fine material • Incised by a complex network of creeks and channels despite the generally flat surface • Saturated with water; the mud deposits are often covered with a thin film of water that cannot drain through the closely packed sediments • Low bearing capacities frequently incapable of supporting the weight of a person if sediments are wet; dry sediments may be able to support personnel and vehicles
SAND	0.06-4.0	• 1° -40° beach slope • Subjected to seasonal erosion and deposition cycles as a consequence of the varying levels of incoming wave energy • Closely packed substrate with a low water infiltration rate
PEBBLE	4.0-64	• Narrower and steeper beach slope than sand beaches • Storm ridges often present to the landward side of the berm; ridge height increases with exposure to wave energy
COBBLE	64-256	• Narrower and steeper beach slope than sand beaches • Storm ridge usually present to the landward side of the berm; ridge height increased with exposure to wave energy
BOULDER	≥256	• Detached rock masses that are somewhat rounded or otherwise distinctively shaped by abrasion in the course of transport • Typically located near the base of cliffs or rocky outcrops; often found on pocket beaches
MIXED SEDIMENT	all sizes	• Poor sediment sorting results from low wave-energy levels in many instances • Frequently the size of sediments increases on berm or storm ridge • Low water infiltration rate where sand packs spaces between pebbles and cobbles

Table 4 (continued)

VEGETATION:	
mangrove:	• a complex coastal swamp community of halophytic trees and shrubs; very productive habitat • common in most tropical regions between 25° N and 25° S • sediments are trapped in the root systems
marsh:	• Develop in sheltered environments which have a source of fine material • Marsh surface inundated during periods of high-water levels • Flat topography interrupted by muddy creeks or channels
dune:	• Wind-blown sand is trapped and stabilized by backshore vegetation • Removal of or damage to vegetation destabilizes dunes
ROCK:	
cliffs:	• Occur as a result of high relief in the coastal zone or because the unresistant rocks or unconsolidated material are rapidly eroded by littoral processes • Often little or no sediment accumulation at the cliff base, allowing erosional processes to act directly on the cliffs
platforms:	• Typically occur in shallow waters at the base of rock cliffs • Sediment cover, if it occurs, does not provide a protective cover; wave-induced processes act directly on the rock surfaces
beachrock:	• formed by the interstitial cementation of intertidal and sub-tidal sediments; results from physical precipitation or as a by-product of biologic activity • extends below the low-tide level; frequency occurs in a layered form
MAN-MADE	• Any structure found on a shoreline constructed by man; materials may be rock, concrete, metal or wood • Examples include piers, boat ramps, seawalls, groins, jetties

Sand beaches

Sand-sized sediments may be silica (quartz), volcanic, carbonate, or coralline (figs. 3 and 4) depending upon their origin. The beach morphology is a function of coastal relief, sediment abundance, and wave-energy levels. Sand beaches are subject to continuous change as sediments are redistributed by wave action. Rates of change and rates of sediment transport increase as wave-energy levels at the shoreline increase. On many exposed coasts the presence of offshore reefs protects the beaches by reducing incoming wave energy. Sand dunes occur in come backshore areas, (fig. 5) and overwash may occur during periods of high waves and/or high water levels on beaches that are backed by lagoons.

Pebble-cobble-boulder beaches

This type of material is not common on the coasts of the Eastern African region. Where present this material is derived from bedrock erosion (fig. 6), erosion of coral reefs or, as in Mauritius, from the breakdown of basalt columns (figs. 7 and 8).

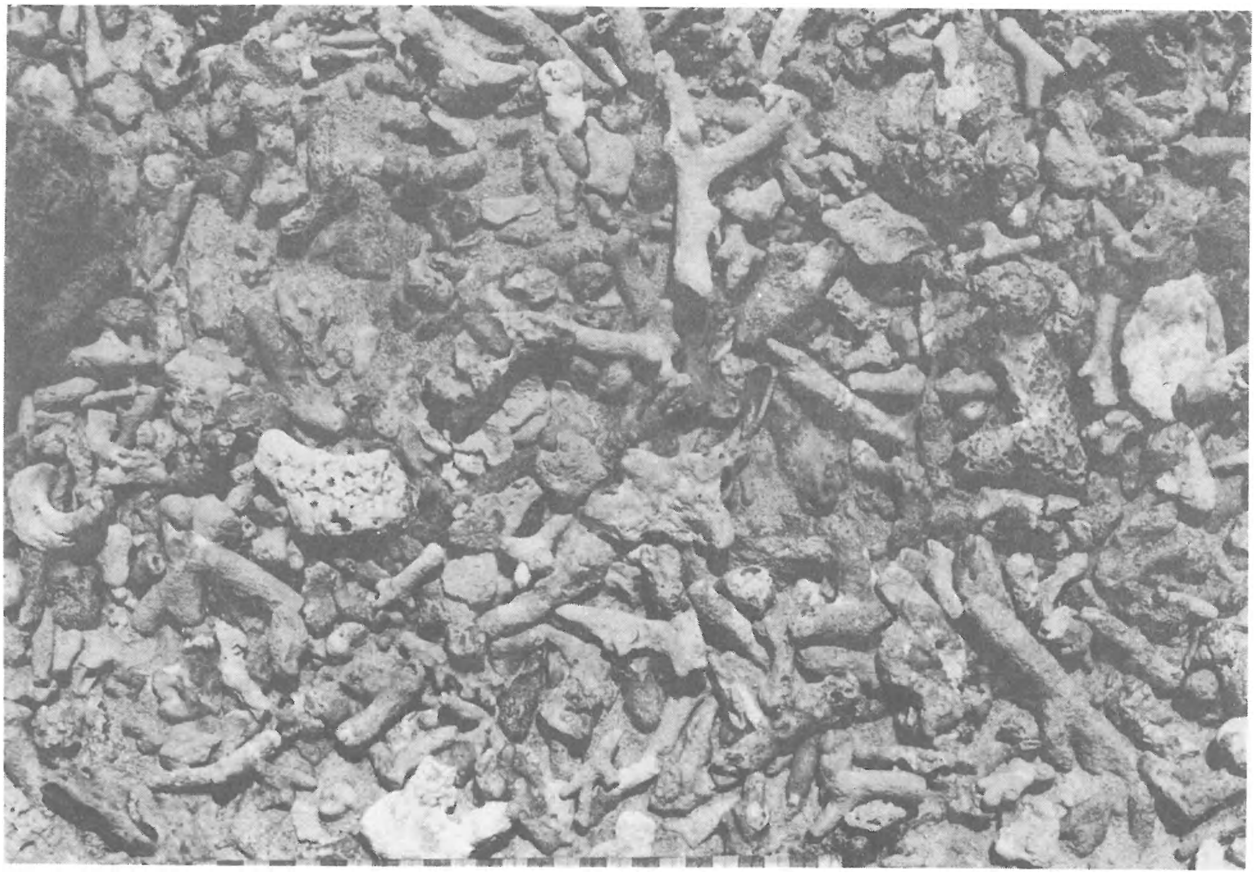


Figure 3: Closeup of coral fragments on beach adjacent to figure 4 (scale graduations are in centimetres)

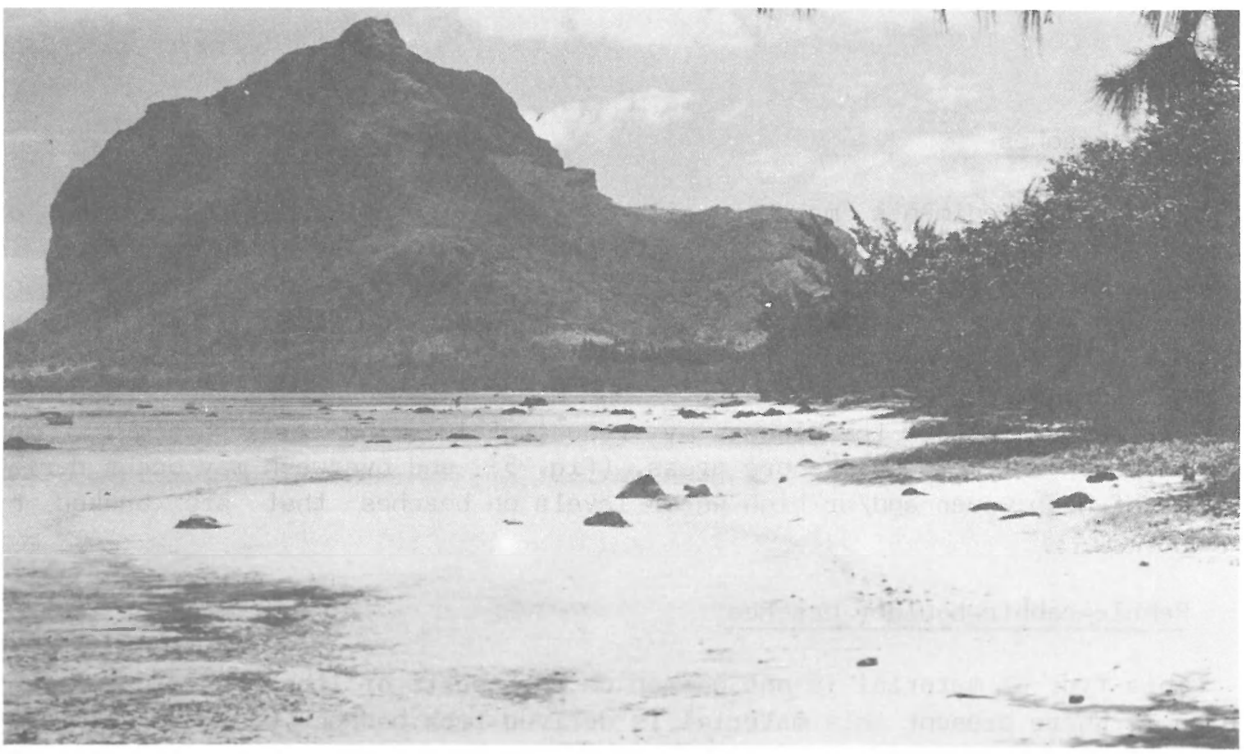


Figure 4: Wide, flat beach: L'Embrasure, near La Morne Brabant, Mauritius

Figure 5: Sand beach backed by dunes, near Malindi, Kenya

Figure 6: Low-energy beach, composed of sand, pebbles, cobbles and boulders; near Petite Rivière Noire, Mauritius

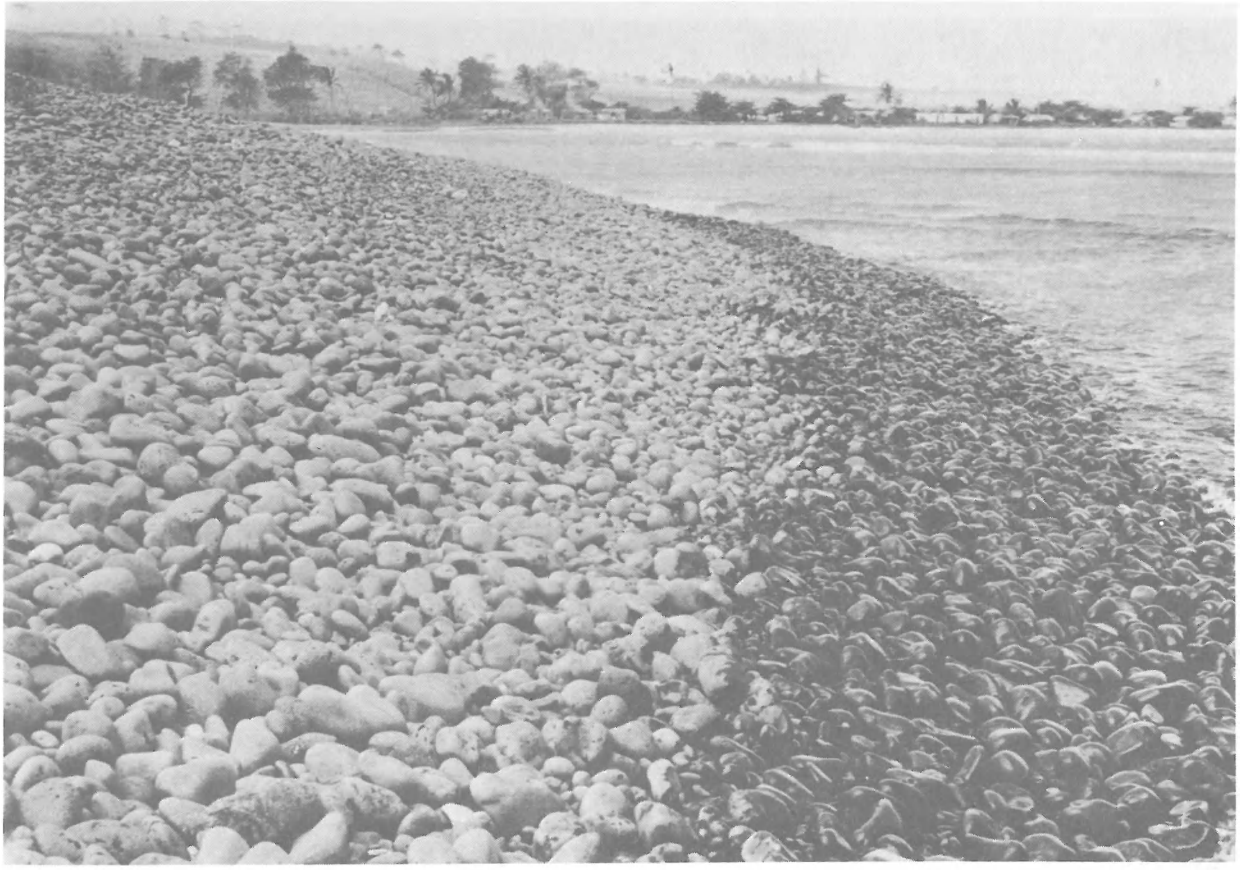


Figure 7: Pebble-cobble beach, Petite d'Araimbel, Mauritius

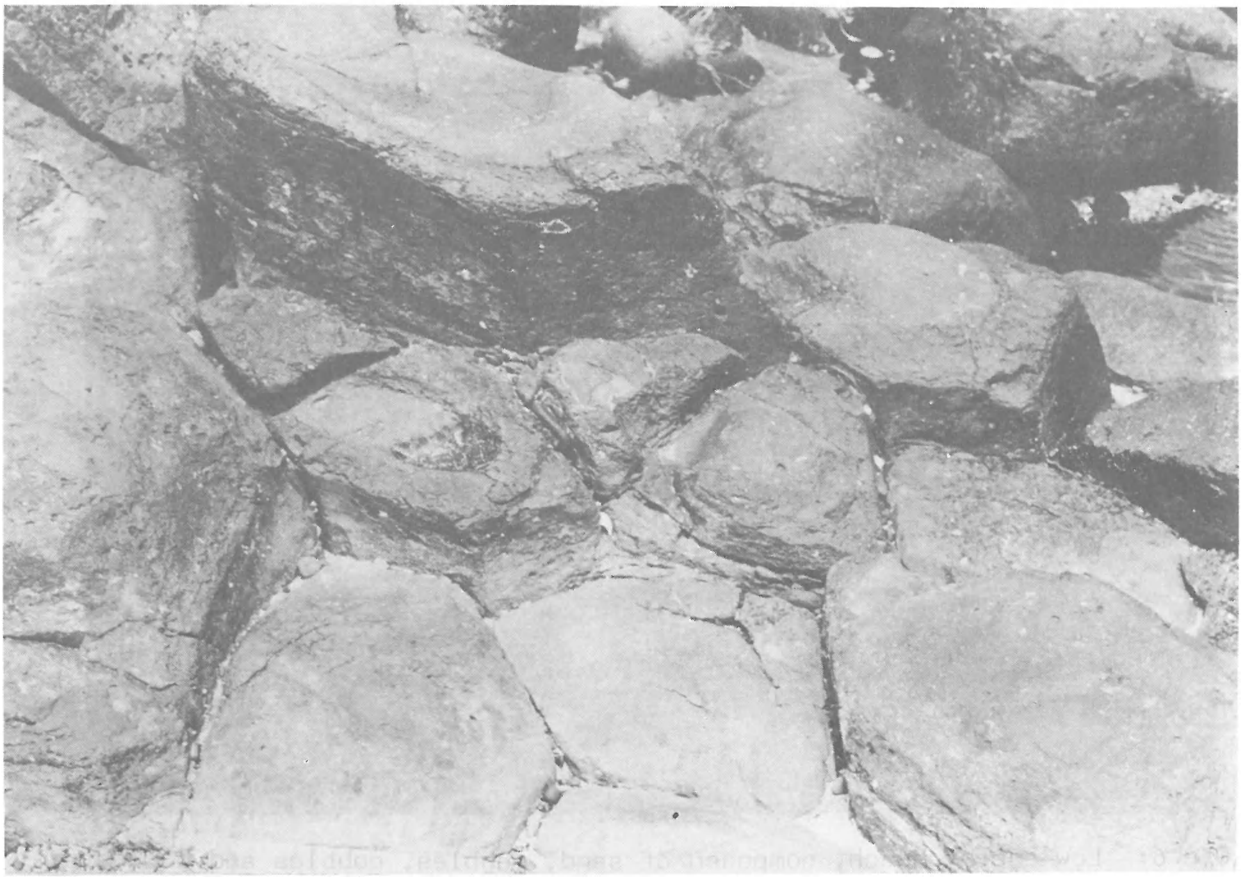


Figure 8: Columnar basalt-source for the sediments on the beach in figure 7

Bedrock coasts

Relief in the coastal zone throughout much of the Eastern African region is very low, although bedrock outcrops at the shore are common in many areas. In most regions on the continental coast the bedrock outcrops are uplifted coral formations (fig. 9). By contrast Mauritius is composed entirely of volcanic rock (fig. 8). Bedrock coasts can be distinguished initially in terms of high or low relief, and secondly in terms of resistance to erosion by coastal processes. On vertical cliff faces a wave-cut notch at the high-water mark, also known as a "visor", is a common feature (fig. 10). Wave-cut platforms are found in areas where coastal processes have been able to erode the cliffed sections of bedrock outcrops faster than the intertidal outcrops. This is further elaborated under the section on coastal environments and shoreline processes.

Mangroves

Coastal swamps that may occur in the tropics (fig. 11) in salt or brackish waters and that on the outer fringe, are characterized by the red mangrove Rhizophora mangle. They occur in low-energy environments that are sheltered from storm-wave activity. They are found on windward coasts, but only where shallow nearshore waters or reef systems provide sheltering from wave action. A complex system of arching prop roots characterize the outer fringes of a mangrove swamp (fig. 12). The roots extend through the intertidal zone to the low-water level. Inland, the red mangrove gives way to the black mangrove, Avicennia germinans, that occurs only in the upper intertidal zone. Tidal waters permeate through the root systems but the water circulation does not lead to the development of channels (fig. 13). Mangroves are extremely productive environments for many marine species (particularly fish, prawns and lobster: fig. 11).

Beachrock

Cementation of beach sediments in the intertidal zone results in a layered rock outcrop at many locations (figs. 14 and 15). Beachrock forms below the mean high tide level and often extends well below the low tide level. Beachrock formation is associated with the production of aragonite, calcium and/or magnesium cements in the interstitial beach groundwater sytems by physical precipitation or as a by-product of biologic activity (Roberts and Sneider, 1982); (see also section on coastal environments and shore line processes). The presence of beachrock produces a mixed shoreline type of sediments and rock.

Coastal reefs

A reef is composed of complex colonies of individual polyps that secrete limestone (calcium carbonate) skeletons. Reefs have the capacity to create rigid, wave-resisting structures that modify their physical environment. Coral growth is limited by low temperature (<16°C) and low salinity so that reefs are found only in the tropics, but each ocean basin has its own genera and species.

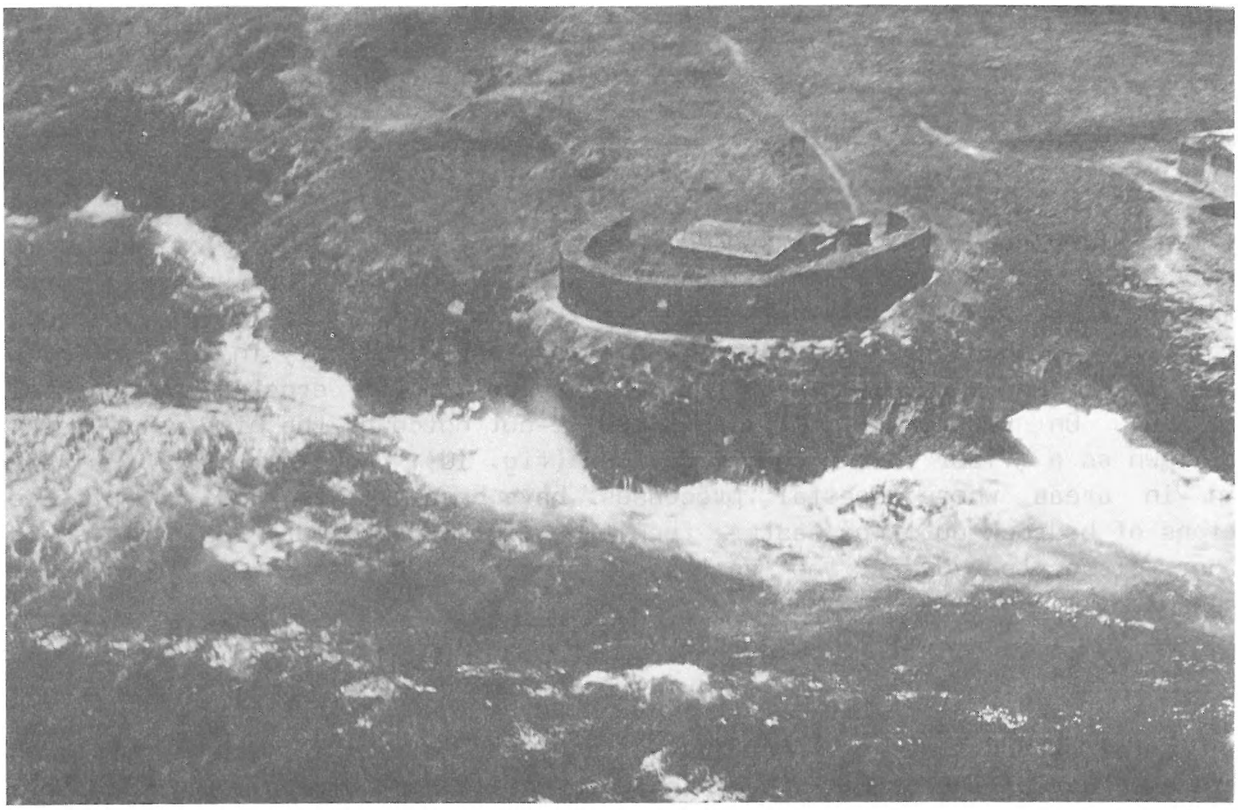


Figure 9: Exposed cliffed coast, Mombasa, Kenya

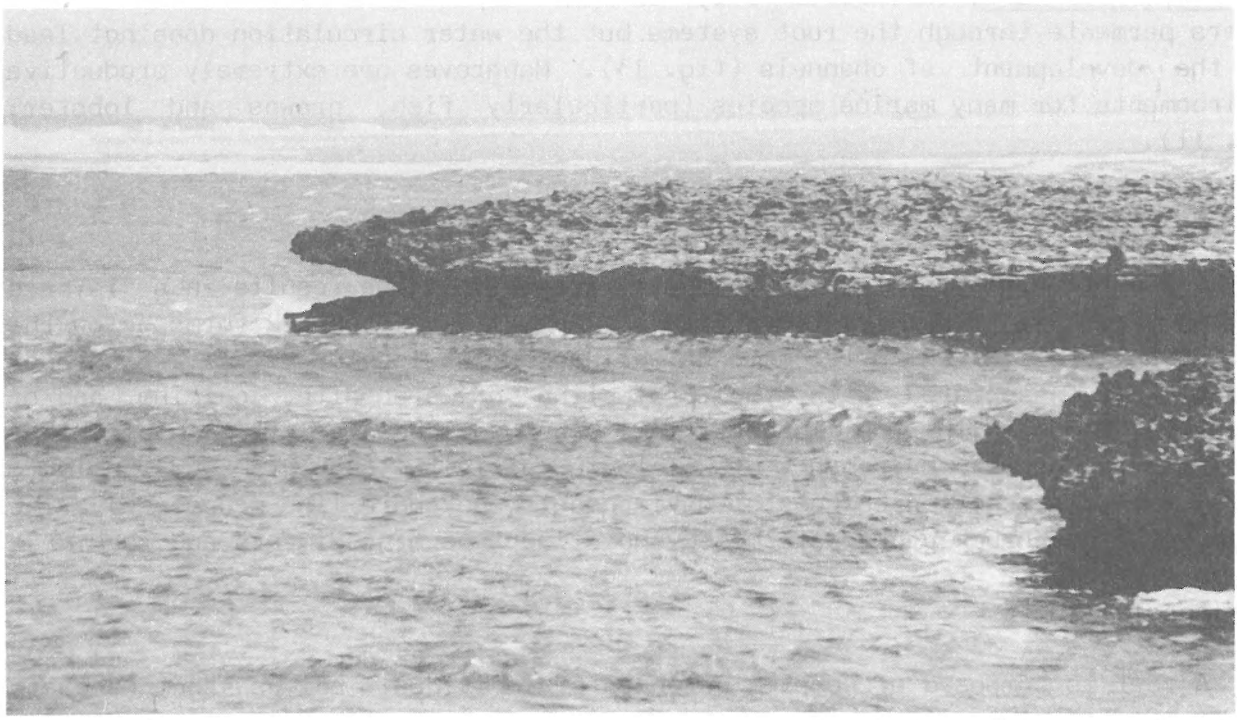


Figure 10: Wave-cut notches ("visors") in basalt outcrops, Ilot Sancho, Mauritius

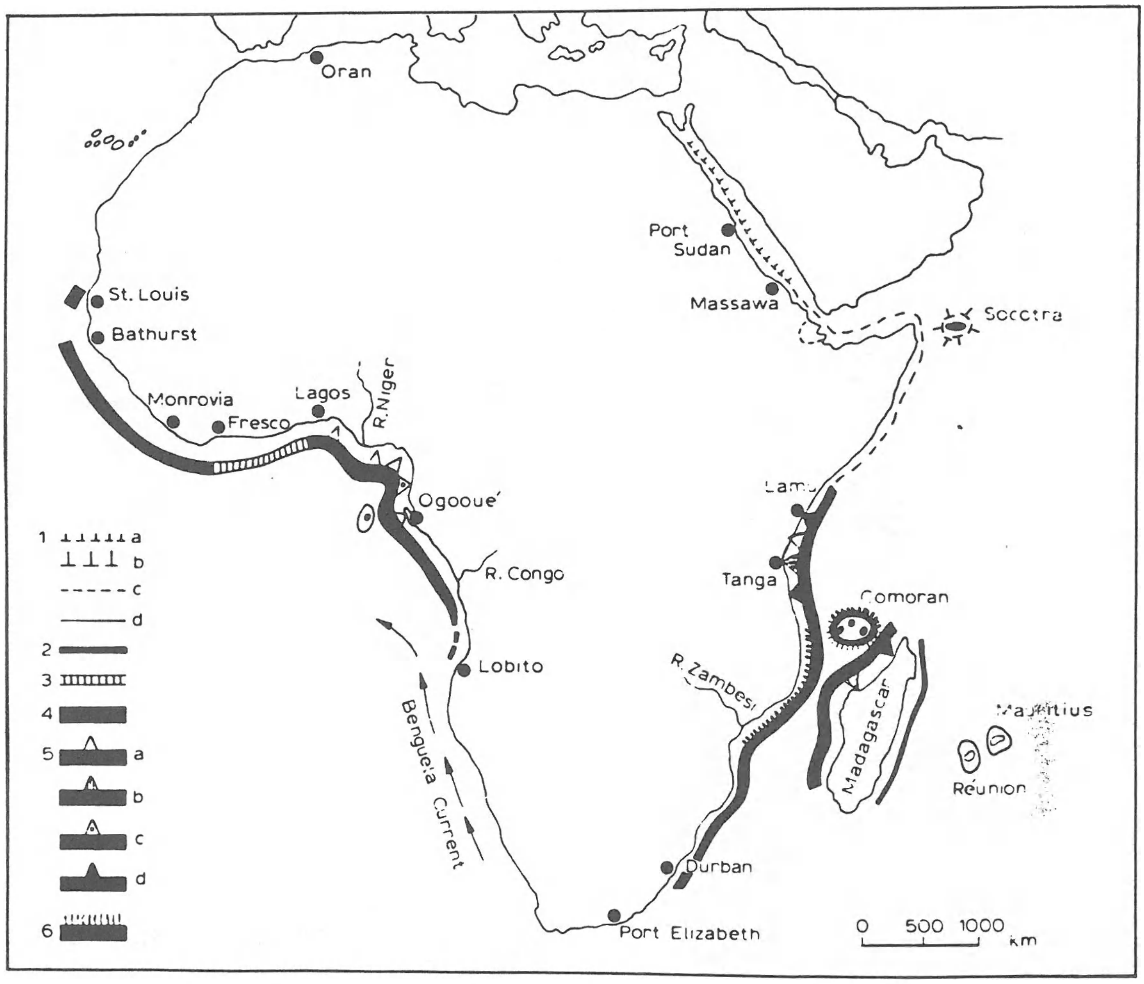


Figure 11: Mangal distribution in Africa (after Grewe, 1941) 1 = Avicennia: (a) single and very small groups, (b) closed community, (c) with sporadic Rhizophora, (d) with better developed Rhizophora; 2 = most species present, well developed; 3 = as 2, in lagoons; 4 = complete mangal, well developed ; 5 = forest used for commerce: (a) not for export, (b) bark for export, (c) wood for export, (d) wood and bark for export; 6 = well-developed forest, bark used for export (from Chapman, 1977)

Figure 12: Mangrove at low-tide; Makupa Causeway, Mombasa, Kenya

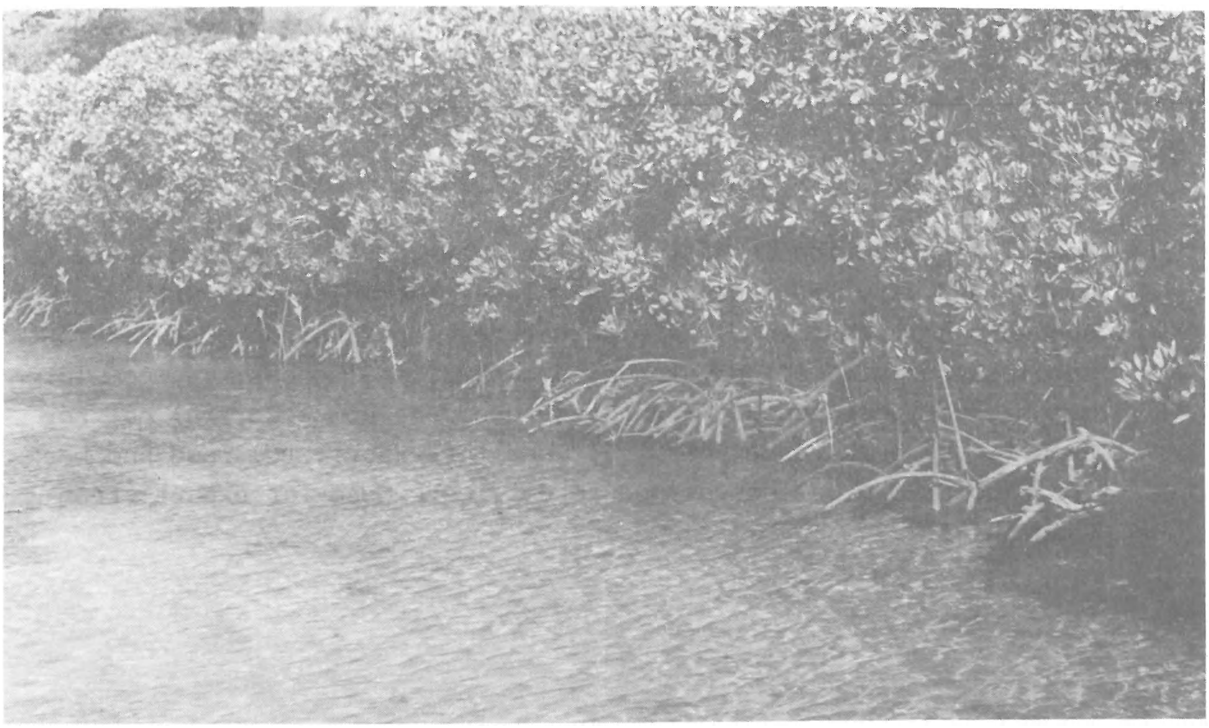


Figure 13: Edge of mangrove forest; Pointe aux Sables, Mauritius

Figure 14: Beachrock outcrops, near Mombasa Beach Hotel, Kenya

Figure 15: Layered beachrock outcrops near Cap Malheureux, Mauritius (see also figure 36)

Three major types of coral reefs occur:

- fringing reefs: parallel to the shoreline and separated from it by a shallow narrow lagoon (fig. 16);
- barrier reefs: larger system found offshore, on the shelf; and
- atolls: form around islands in the Pacific.

Reef form is largely controlled by circulation patterns and wave action (Roberts et al., 1977; Murray et al., 1977). Corals are found on exposed coasts and can withstand high levels of wave activity. The species zonation is a function of the relationship between waves and currents (Roberts et al., 1979). Because of this zonation a wide variety of shoreline environments occur within a reef system. On islands where sediments in the nearshore are swept from windward towards leeward coasts, reef development is limited in the leeward environments (Adams, 1968). Active reefs rarely are exposed above the sea surface as the reef corals can withstand only a few minutes of exposure, but water depths may be very shallow (<1 m) (fig. 17).

Coral reefs are the single most important coastal feature of the western Indian Ocean. Because they are complex and because they produce a wide range of shore-zone features a detailed description of reef systems is provided in a later section. Reefs are very diverse and productive biological environments. They are also important geologically as they build sea-floor topography and they are a renewable source of carbonate sediments.

Figure 16: Fringing reef; Le Morne Brabant, southwest Mauritius

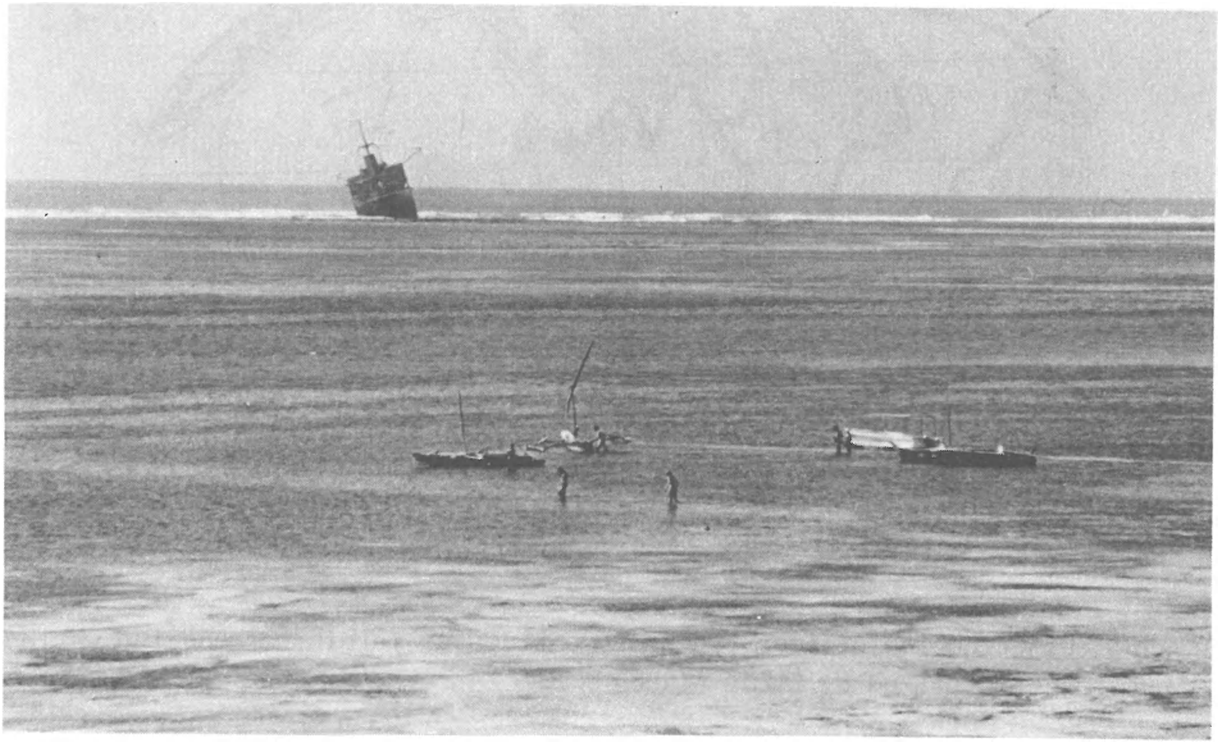


Figure 17: Reef that is exposed at low-tide off Nyali Beach Hotel, Kenya; the wreck is on the reef

Regional geology

The margins of continents and large isolated land masses, such as Madagascar, mark the transitions between thin oceanic crust and the thicker and chemically different continental rocks. Continental margin types are determined by plate tectonics. Complicated sea floor topography, is a reflection of the shifting of large plates of the earth's crust (UNESCO, 1971).

Most of the east coast of Africa and all of Madagascar display continental margins (which includes the coastal plain, continental shelf, slope, and rise) that are classified as "sediment starved" or "youthful" (figs. 18 and 19). The entire coast of Africa is part of a divergent margin or one that is not a plate boundary. These types of margins develop when continents are rifted apart to form new oceans, so that the continent and adjacent ocean floor are part of the same plate. Eventually they become sites of massive subsidence and thick accumulations of sediment. Africa's eastern margin, as well as that of Madagascar, is in a very youthful stage of development (figs. 18 and 19, and table 5).

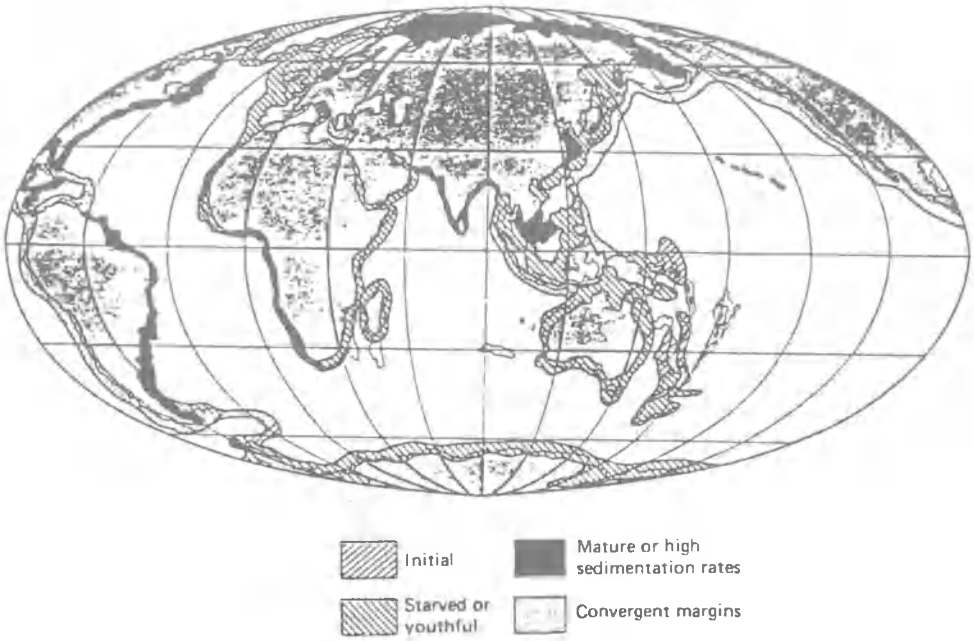


Figure 18: Distribution of four types of continental margins around the world as classified by Emery (1980)

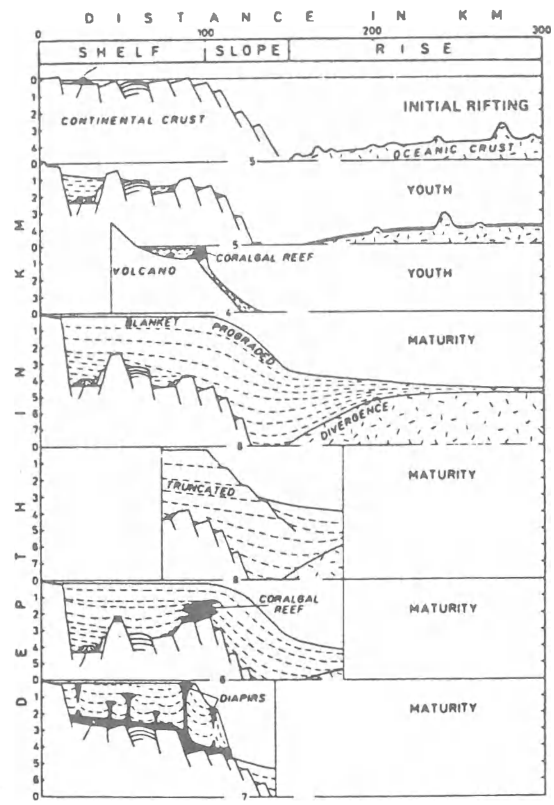


Figure 19: Evolutionary stages in the development of continental margins; vertical exaggeration about 10 x (after Emery, 1980)

Table 5: Stages of continental margins identifiable from continuous seismic reflection profiles (Emery, 1980)

	Continental shelf	Continental slope	Continental rise
Initial	Pretectonic, tectonic volcanic, or glacial rocks, exposed or thinly covered.	Pretectonic, tectonic, or volcanic rocks exposed or thinly covered.	None.
Youth	Thick sediment fills basins and troughs.	Pretectonic, tectonic, or volcanic rocks exposed or thinly covered.	None or small.
Mature	Thick sediment cover: 1. broad blanket 2. coralgal reef dam 3. post-rift diapirs	Thick sediments: 1. prograded 2. truncated 3. post-rift diapirs	1. Thick for divergent margins. 2. Thin for translation margins.

Youthful margins have not collected thick sedimentary wedges at the coast and on the continental shelf. Only continental rift basins have accumulated thick sedimentary sequences. Continental margins in an initial or youthful state have not had sufficient geologic time to develop a prograding or constructional continental shelf-slope-rise configuration. Therefore, outcrops of volcanic rocks are common on the thinly veneered continental slope. Continental rises are rarely present, and there is generally an abrupt transition with the deep ocean basin floor. Continental shelves along youthful divergent margins are typically narrow, with abrupt and structurally complicated shelf edges.

Regional climate and oceanography

Large-scale weather patterns

Planetary pressure fields determine the general circulation of the atmosphere. The rotation of the earth (Coriolis force) causes deflection of winds to the left in the southern hemisphere and to the right in the northern hemisphere. The southwest trade winds affecting the East African coast are a result of this (fig. 20). In the northern winter the pressure field over the Indian Ocean most resembles the planetary model (e.g., January, fig. 21). High pressure along 30°S latitude and low pressure south of India drive well-developed SE trade winds. In the northern summer the pressure field over the Indian Ocean (e.g. July, fig. 21) is dominated by the heat-induced monsoon low over the Indian sub-contient. There is a well-developed high-pressure ridge along 30°S latitude.

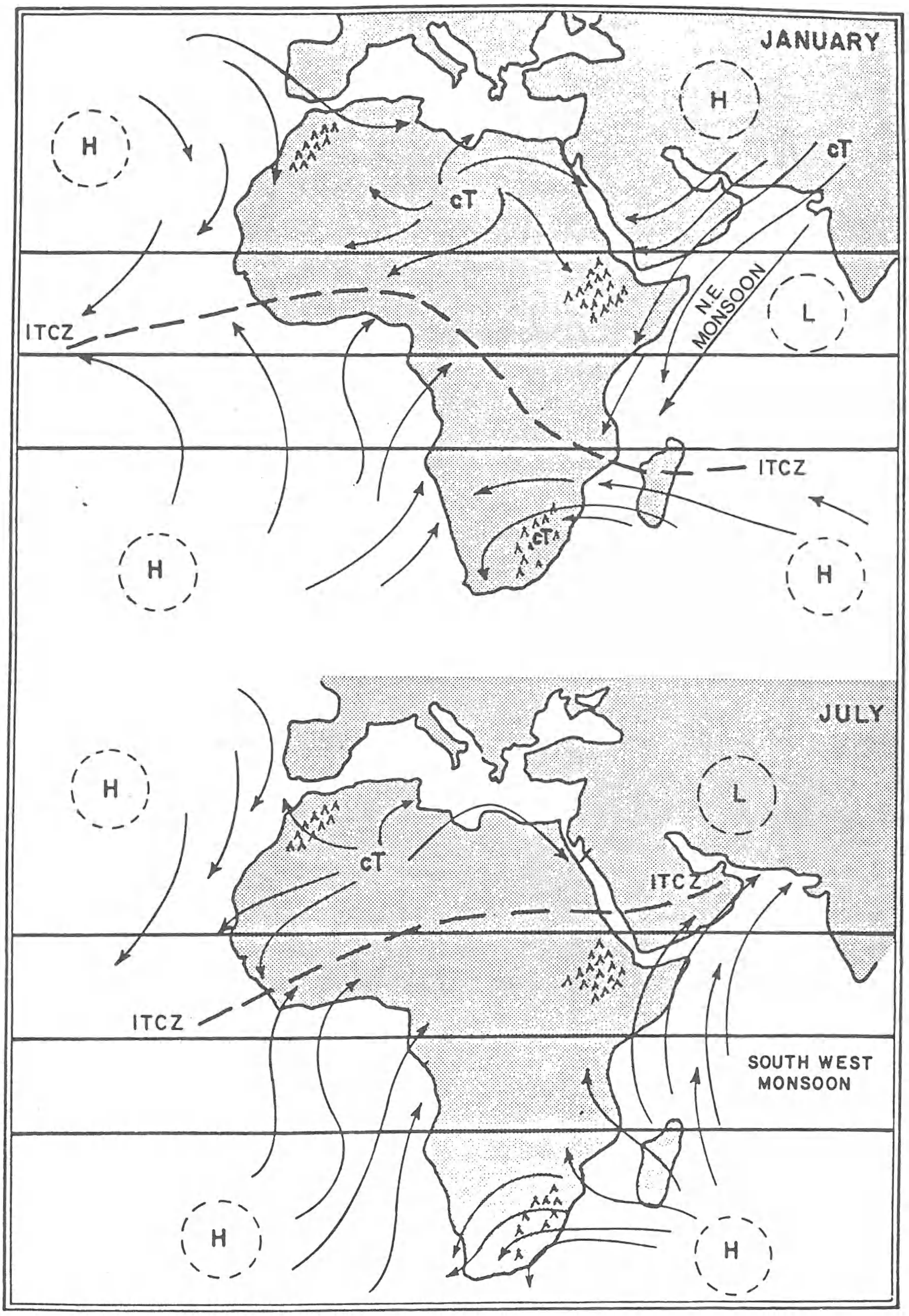


Figure 20: Pressure systems and resultant surface wind streamlines for the coasts of Africa (from Hayden et al., 1973)

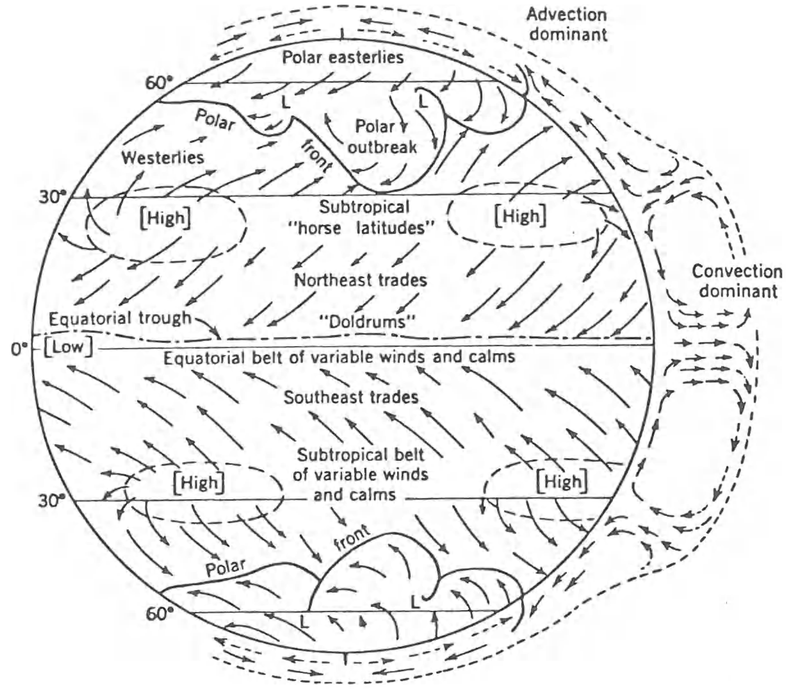


Figure 21: Schematic representation of the general circulation (from Strahler, 1965)

Surface winds follow the atmospheric pressure pattern. In the northern winter winds south of 100°S are SE trades; north of 10°S NE trades dominate. High wind speeds 60-70 per cent greater than 100 knots, occur off the coast of Somalia. Strong northerly winds dominate the East Africa coast north of Madagascar. In the northern summer, monsoon circulation dominates. SE trade winds reach the equator. Along the coast of Somalia strong SW winds blow towards low pressure on the Indian subcontinent (Ramage, 1971). At the coast, the frequency of onshore winds is low in the northern hemisphere winter and increasing in the northern hemisphere summer particularly on south-east facing shores (fig. 22).

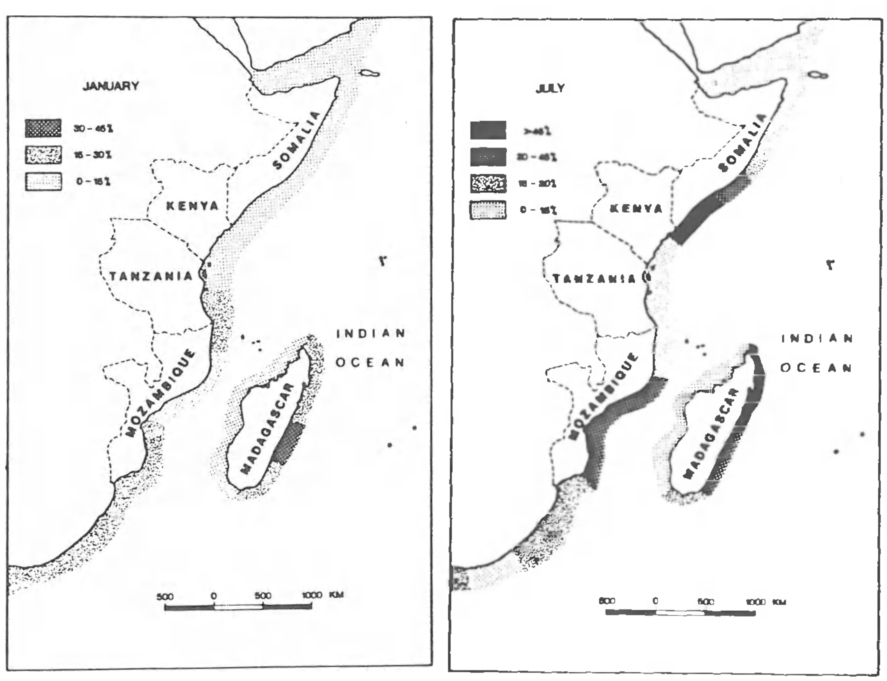


Figure 22: Frequency of onshore winds greater than 12 miles/hour (5.4 m/s) from Orme, 1982)

Rainfall off the Mozambique coast occurs during the wet season from December to April. The annual rainfall is 90 cm. North of Zanzibar this increases to 100-150 cm, mostly at monsoon turning periods. Off Somalia rainfall is 40-50 cm yearly on the coast. Numerous rivers in Mozambique and Tanzania distribute large volumes of fresh water to coastal seas, which will affect oil movements (Murray, 1975; 1982 a,b).

Tropical cyclones are compact intense storms with clockwise circulating winds which frequently impact the coastal seas from the Seychelles to south of Madagascar (fig. 23). About 75 per cent of these dangerous storms occur during January to April (table 6) (Ramage, 1971). Cyclones usually travel to the southwest at first and then recurve near 200°S towards the southeast (fig. 23). Sea-breeze-driven currents can be extremely important within the 10-15 km of coast in tropical latitudes (Sonu et al., 1973). Cyclones are significant in terms of wave generation, current generation and "storm tides". In particular, strong onshore winds can raise water levels at the shoreline well above the normal limit of high tides (fig. 24).

Table 6: Cyclones of the South Indian Ocean

Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	TOTAL
122	128	108	76	26	3	2	0	1	8	37	61	575

Currents

Wind-driven currents, generally 3-5 per cent of the wind speed in open waters are deflected to the left of the wind in the southern hemisphere and to the right in the northern hemisphere. This effect produces the Ekman spiral (fig. 25). Complex surface current patterns vary significantly with the season (see fig. 25). During winter the Northeast Monsoon Current feeds the strong Somali Current moving southerly along the Somali coast. The East African Coast Current moves northerly along the coast of Tanzania and Kenya. The Mozambique Channel has strong south-going currents on the west side and north-going currents on the east side. The east coast of Madagascar has very constant south-flowing currents. During summer the reversal of the monsoon winds toward India also reverses the Somali Current, making it a strong, deep, north-going current (Duing and Schott, 1978).

The Somali wind jet, a well-defined stream of high-speed air velocity, grazes the Somali coast in July, producing the well-known Ras Hafun upwelling area (fig. 26) (Brown and Schott, 1981). Wind roses, surface current patterns, and storm tracks are also presented for each month of the year in the Atlas of Pilot Charts (1966). Detailed maps of surface currents are presented in a new series of publications (U.S. Naval Oceanographic Office, 1977) for each 1° square off the East African coast.

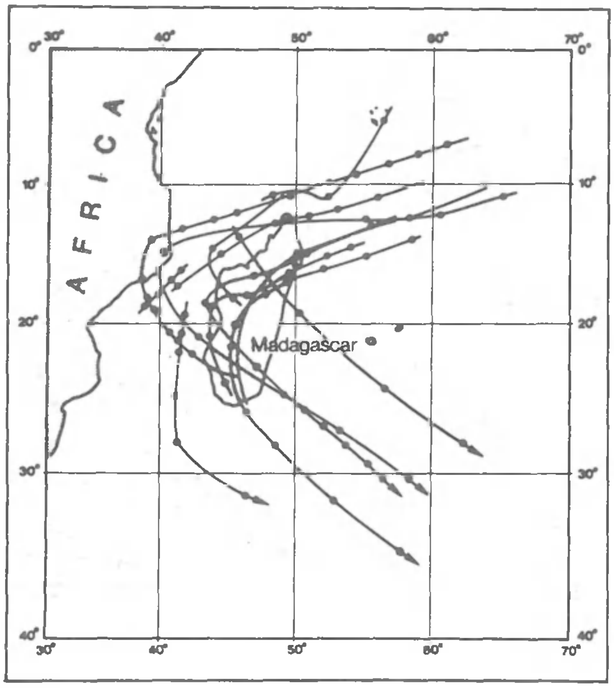


Figure 23: Typical tracks of tropical cyclones which have crossed Madagascar or the Mozambique Channel (after Sailing Directions, 1951)

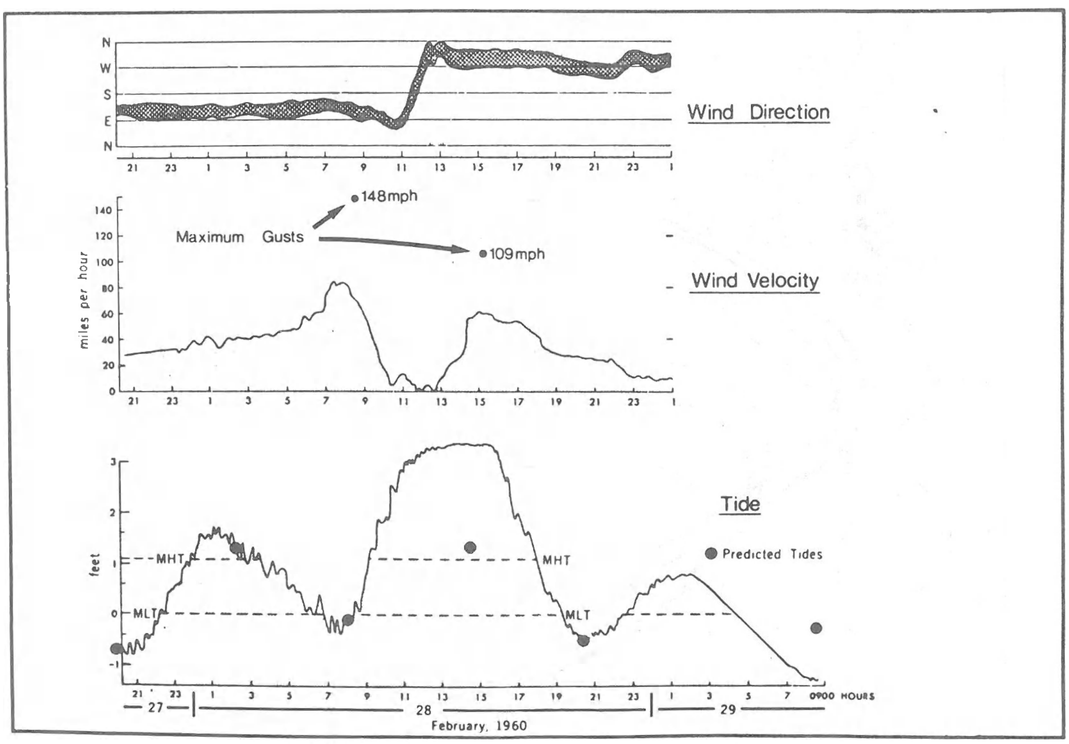


Figure 24: Wind direction, wind velocity, and tides associated with tropical cyclone Carol (1960) (from McIntire and Walker, 1964)

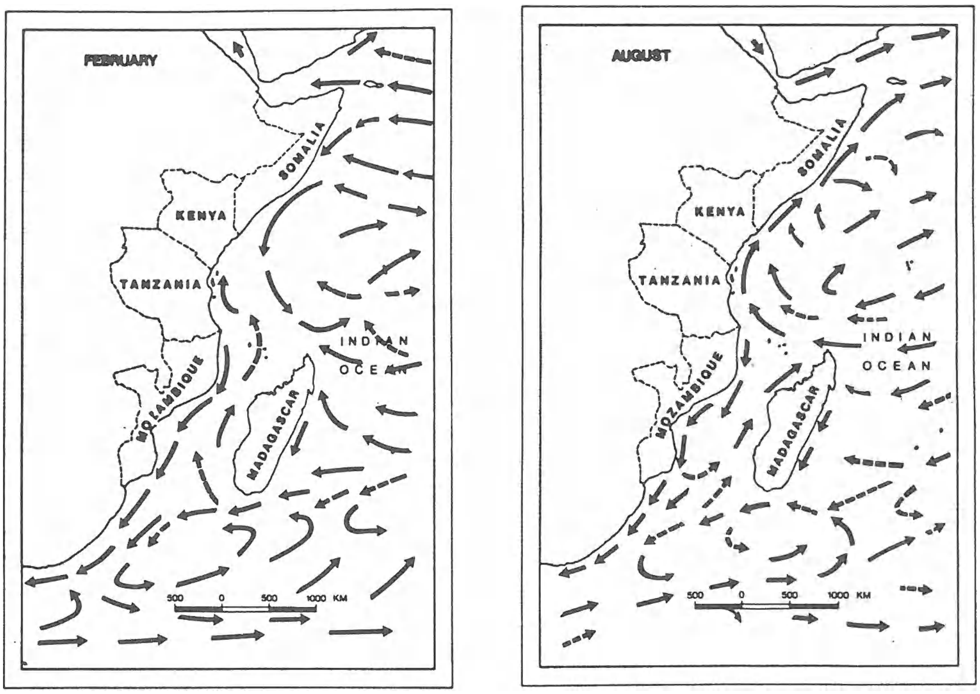


Figure 25: Schematic distribution of surface currents in the Western Indian Ocean during both Monsoon seasons (after Düing and Schott, 1978)

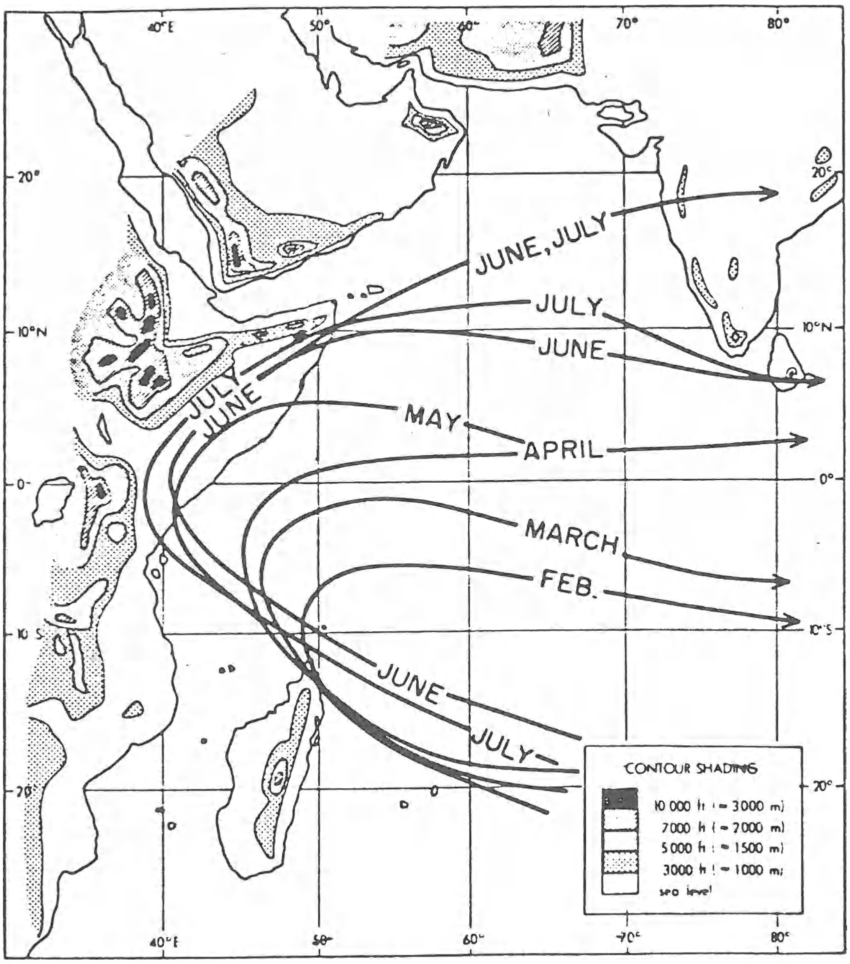


Figure 26: Month-by-month progression of the axis of the low-level jet (MONEX Panel, 1977)

Tides

Tides are caused primarily by the gravitational attraction of the moon and sun on the water and tidal waves progress in a systematic and very predictable manner around the globe. The three basic types of tides are semi-diurnal (SD), diurnal (D) and mixed (M). Tidal range varies through time and space owing to the alignment of the moon and sun to produce spring, neap, tropic and equatorial tides. Tide range along the East African coast varies between 0.3 and 5.7 m (table 7). Fig. 27 shows the magnification of the tidal range in the Mozambique Channel. The tide curves at Zanzibar and Beira (fig. 28) illustrate the effect of the alignment of the sun and moon on the range of tides. Tidal currents along open coasts are usually not too important. Tidal currents around the islands on the Seychelles Bank, Mauritius, and La Réunion can become extremely strong. Tidal jets and rips commonly form off the capes and points of these islands with speeds reaching up to 4 knots (Sailing Directions, 1952).

Waves

The height of offshore waves is dependent on the speed and duration of the wind and on the fetch. The orbital velocities are circular in deep water and elliptical in shallow water. Waves approaching the shore break and form surf when wave height is about 70 per cent of the water depth. Refraction of waves due to bottom topography causes waves to change direction and decrease in height. Waves will frequently refract completely around islands and cause a lee or low wave-energy area behind the island. Diffraction causes waves to lose energy as they pass through a gap in a harbour breakwater or in a fringing reef (see fig. 29).

Simple prediction schemes for wave height, direction, and period are available (e.g., in the U.S. Army Corps of Engineers, Shore Protection Manual - U.S. Army, 1973). The mean wave height values along the coast are highest off southern Mozambique and eastern Madagascar (fig. 30 and table 8). The wave climate off the East African coast (fig. 31) is a composite of locally-generated waves, storm-generated waves, and swell. The wind regimes associated with wave generation are the Trades, tropical storms (cyclones), and the monsoons.

Table 8: Seasonal Mean Wave Height (in meters)

	January-March	April-June	July-September	October-December
Somalia coastal area	0.52	0.97	0.52	0.61
Kenya coastal area	0.85	1.22	0.85	0.52
S. Mozambique coastal area	1.28	1.31	1.28	1.22

Table 7: Tides of the East African Coast

	Type	Neap Range	Spring Range
SOMALIA			
Zeila	D	1.1m	1.6m
Obbia	M	1.1	1.6
Mogadishu	M	1.4	1.9
KENYA			
Malindi	SD	2.0	2.9
Kalindini (Port Mombasa)	SD	2.3	3.2
TANZANIA			
Mkoani, Pemba Is.	SD	2.4	3.3
Zandibar	SD	2.6	3.7
Lindi	SD	2.1	2.9
MOZAMBIQUE			
Porto de Mozambique	SD	2.6	3.6
Beira	SD	4.0	5.7
Porto de Inhambane	SD	2.0	2.7
Maputo	SD	2.1	3.0
MADAGASCAR			
Hellville	SD	2.5	3.4
Cap Saint André	SD	1.2	3.9
Tulear	SD	1.8	2.6
Taolanaro	SD	0.4	0.6
Maronoantsetra	SD	0.9	1.3
COMOROS			
Ile Mayotte	SD	2.5	3.4
REUNION			
Pte des Galets		0.4	0.5
MAURITIUS			
Port Louis		0.3	0.5
SEYCHELLES			
Port Victoria		0.9	1.2

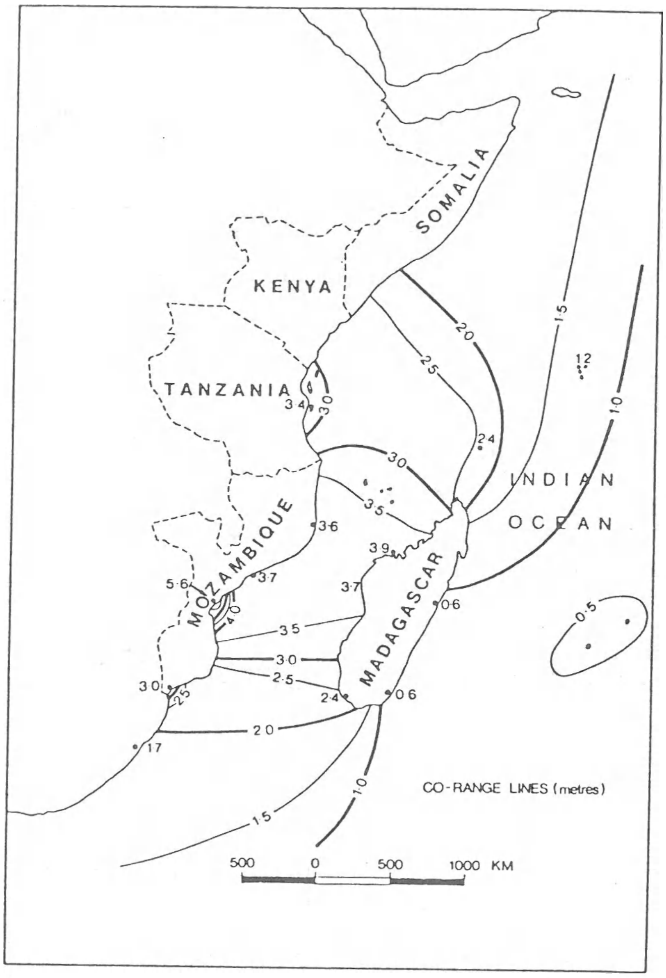


Figure 27: Lines that join locations of equal tidal range along the Western Indian Ocean coasts

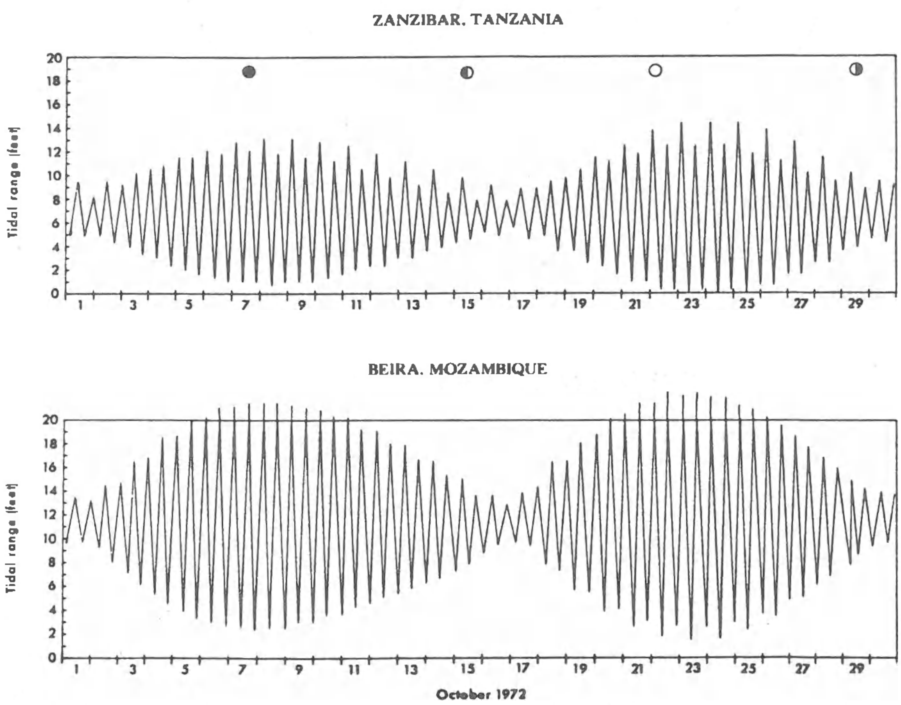


Figure 28: Examples of tidal range over a one-month cycle: solid circle indicates "New Moon"; open circle indicates "Full Moon"

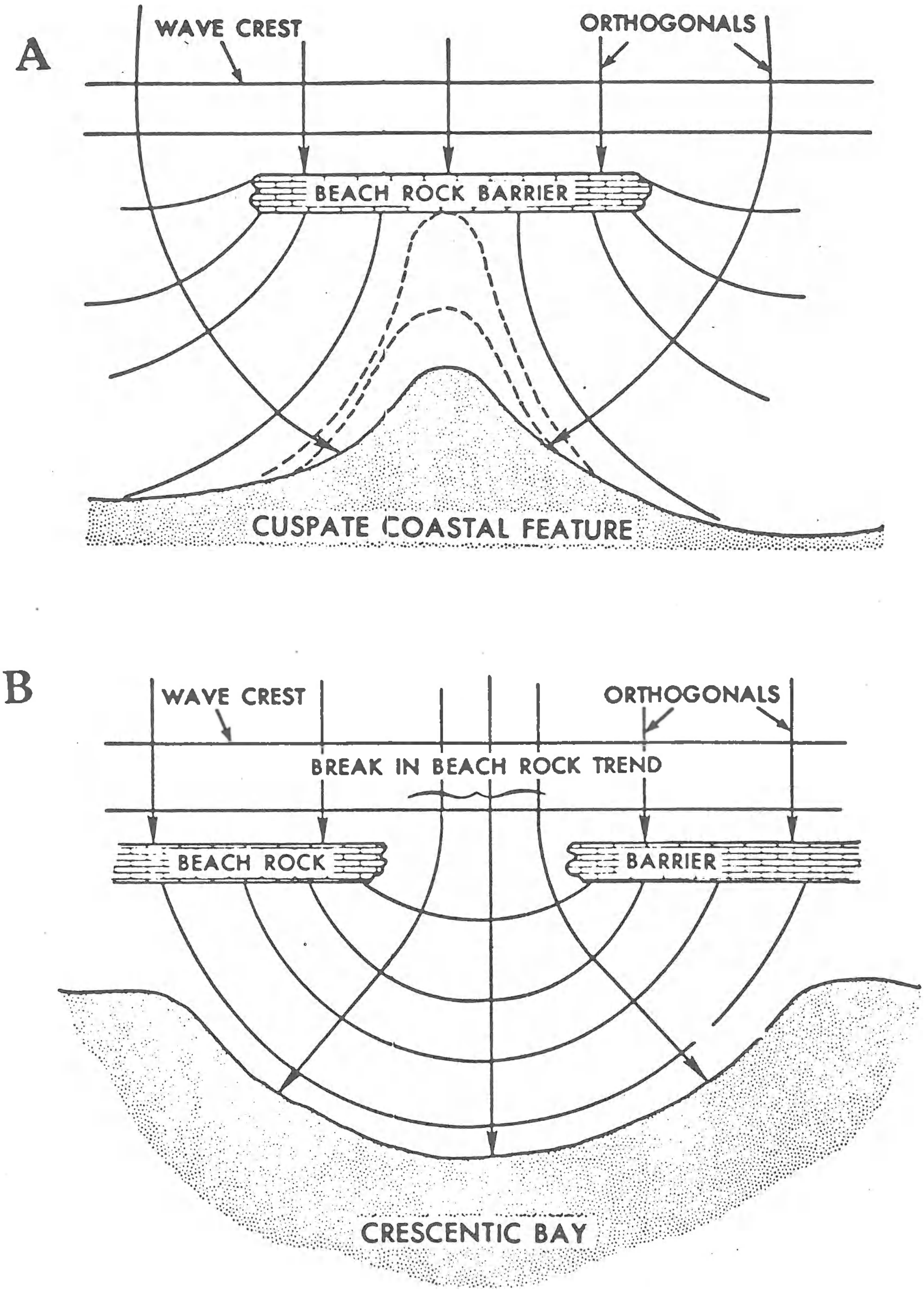


Figure 29: Schematic representation of the influence of offshore beach rock barriers on the response characteristics of the modern sandy shoreline. These changes occur through the combined effects of wave diffraction and refraction

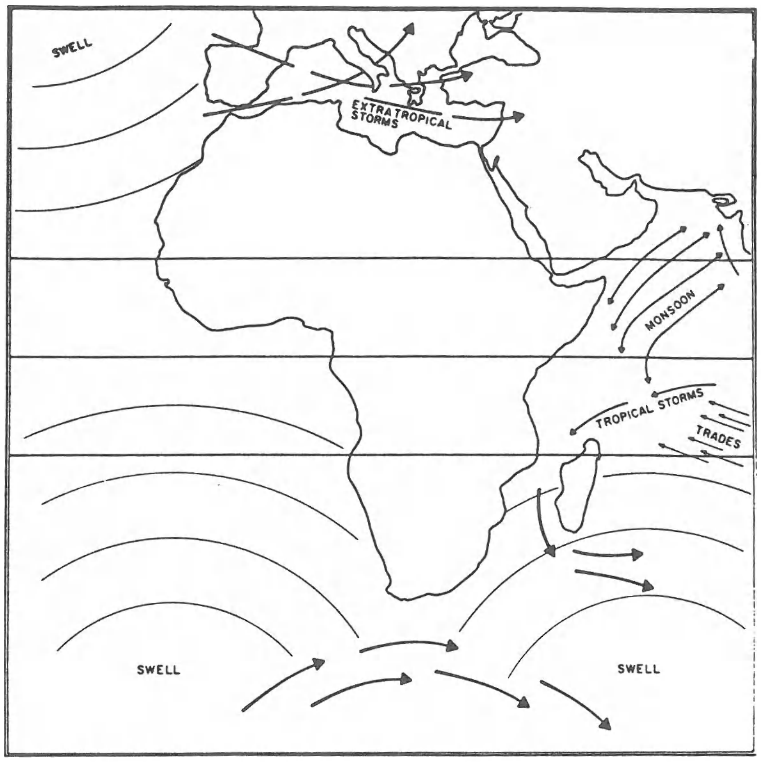


Figure 30: Major wave-generating forces (from Hayden et al., 1973)

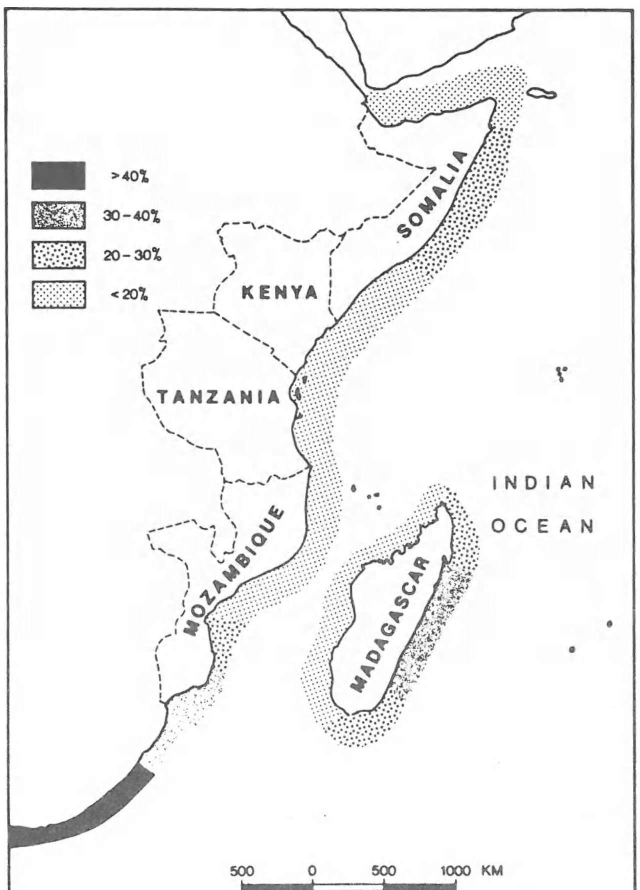


Figure 31: Annual percentage frequency of mean wave height greater than 1.5 m (from Orme, 1982)

Coastal environments and shoreline processes

Sandy coastal environments

The coastal zone throughout history has been traditionally a region of population concentration due to the resource potential, biological productivity, aesthetic appeal, and recreational value of this environment. On a global scale, it is estimated that up to two-thirds of the total world population is concentrated in the coastal zone. Sandy coasts represent approximately 45 per cent of this total shoreline area. This coastal class includes beaches, sandy barrier islands, and other accumulation forms such as spits. Sandy coasts are in a constant state of change and these changes may affect man's use of the environment, particularly if the rate of change is rapid compared to the lifespan of human beings and the structures they construct in a coastal zone.

Shoreline changes, which may be dramatic in some instances, in sandy coastal environments are generally related to changes in the levels of nearshore processes, such as wave activity, tidal range, and/or changes in sediment supply. Because of the dynamic nature of sandy coasts and the potential impact on human use of this environment, no other coastal class has received as much attention by scientists and engineers. Sandy coasts are extremely variable in space and time therefore each coastal sector has its own set of geological characteristics and physical processes. In order to understand the nature of this dynamic environment it is necessary to appreciate the association between nearshore processes and coastal geology.

A beach is defined as "the zone of unconsolidated material that extends landward from the low water line to the place where there is a marked change in material or physiographic form, or to the line of permanent vegetation (usually the effective limit of storm waves). The seaward limit of a beach - unless otherwise specified - is the mean low water line". (U.S. Army, 1973, vol. III). It is generally recognised that a beach, as defined above is part of a larger body of sediments that extends some distance offshore from the low-water line into what is generally referred to as the nearshore zone. Beach dynamics, which include the spatial and temporal variations of shoreline geometry, are reasonably well understood for sandy coasts. A knowledge of the sediment pathways and the forcing mechanisms for geologic changes enables us to predict, to a reasonable degree of accuracy, the frequency and magnitude of changes in particular coastal sections.

(a) Geomorphic variability of sandy coasts

In profile, a typical sand beach and the nearshore area, can be extremely variable (fig. 32). The part f the beach over which waves operate (through upwash and backwash) throughout a tidal cycle is commonly referred to as the "foreshore". This subdivision of the beach profile is limited by the low water mark of the backrush of wave swash at low tide, and at high tide by the crest of the berm. The berm is part of the backshore and is formed by the deposition of sediment by receding waves: some beaches may have more than one berm, where as others may have none at all.

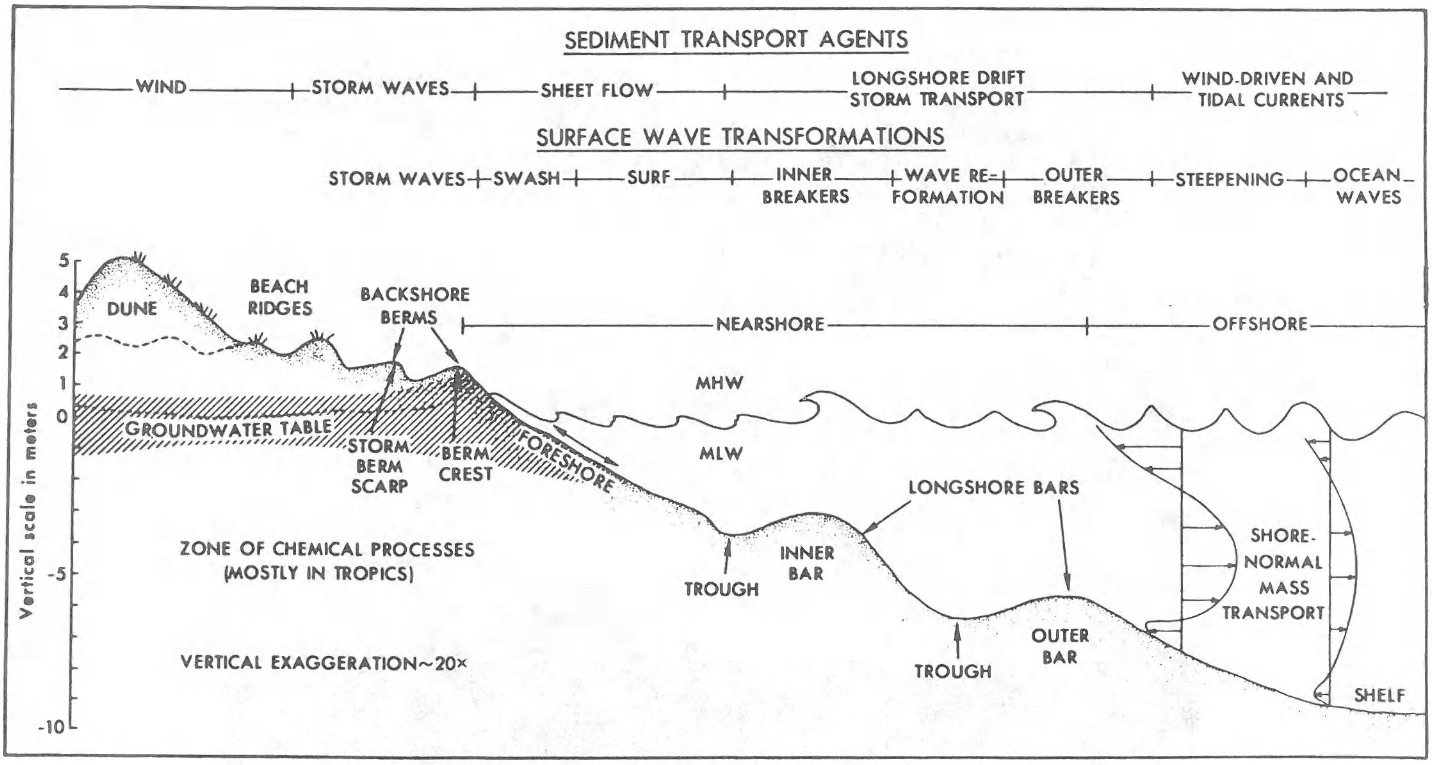


Figure 32: Sandy coast profile defining geomorphic components and physical processes

Seaward of the foreshore, one or more sand ridges that run parallel to the shoreline may be present in the sub-tidal zone. These longshore bars are accompanied by elongate depressions or troughs. Longshore bars are not usually exposed at low tide. Their positions can usually be identified because of waves breaking on the bar crests.

Inland from the active beach zone, ridges of abandoned beach sediments, that were shaped initially by wave activity, may be present due to the seaward progradation of the beach. These abandoned beach ridges are often capped with dunes that are constructed as sediment is transported landward by onshore winds (see fig. 5). Beaches may exist between rock headlands, these are referred to as "pocket beaches", and they are usually self-contained in the sense that sediment is neither transported into nor out of that pocket beach (fig. 33). Other forms of sand shorelines include barrier islands (and associated inlets), spits, tombolos, large coastal forelands and coastal dune fields.

This high degree of variability of sandy coastal types can be attributed primarily to three factors:

- sediment supply;
- the coastal history of the region; and
- the physical processes that operate on that section of coast.

Tidal range and wave action are the most important factors that control the form of a sand beach.

Figure 33: Sandy pocket beach (indicated by arrow) associated with the complex coast of Mahé, Seychelles

(b) Shore normal beach changes

Beaches are constantly going through cycles of erosion and deposition. These cyclic fluxes of sediment in the beach environment differ from one locality to another. Erosion occurs during periods of intensive wave activity, commonly in the winter (fig. 34). As a consequence of this energy expenditure,

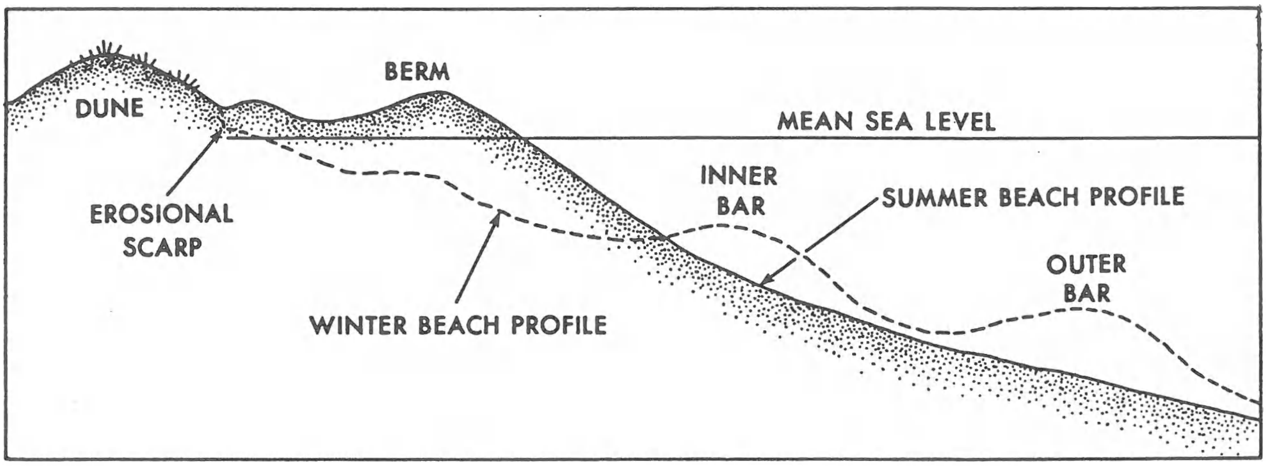


Figure 34: Typical shore-normal changes in beach morphology representing a winter storm beach with sediment stored offshore in bars and a summer moderate wave energy profile with onshore migration of sediment and berm formation

sediments are transferred from the beach to a storage area offshore. When wave activity diminishes and energy levels drop, commonly during the summer months, sediment once again migrates onto the beach. The time necessary to complete an erosion-deposition cycle varies from one sandy coast environment to another. The "storm-post-storm" cycle is another series of changes that beaches display. This cycle is related to relatively short periods of intensive wave activity (see fig. 2).

Beaches of the northwest coast of North America dominantly illustrate these kinds of profile changes. In this setting the seasonal variations are small compared to the more frequent and intense erosional cycles related to the passage of storms. Within a few weeks, unless interrupted by another storm, sediment displaced seaward by the activity of storm waves is reworked back to the beach to re-establish the totally or partially eroded berm. The length of the post-storm recovery period depends a great deal on the intensity and duration of the storm. Generally, the longest lived and most intense storms require the longest recovery periods.

(c) Alongshore changes

Wave action in the shore zone moves sediment particles in the direction of wave approach therefore net sediment transport is in the same direction as wave travel. These wave-generated processes attempt to produce a beach and a nearshore profile that is in equilibrium with the amount of wave energy at the shore. If the waves approach the coast at an angle, they produce currents that flow along the coast and therefore result in net alongshore sediment. A single particle of sediment usually meanders alongshore due to swash running up the beach at an angle, followed by backwash running straight back down the beach under the influence of gravity. The magnitude of this beach drift or longshore drift is dependant on many factors, such as, the energy of the incoming waves, the angle of wave approach to the coast, and the size of the sediment particles. The actual alongshore configuration of a sandy coast results from the interaction of nearshore processes and the sediment supply. Most of the energy for nearshore processes comes in the form of winds, currents and waves. Wind-generated waves transmit energy towards the coast. In shallow water near the shorelines, waves interact with the seabed, currents and with other waves to produce energy exchanges that control sediment transport.

(d) Chemical changes

In tropical latitudes it is common locally for beach sediments to become cemented into a form that is generally known as beach rock. Beaches composed of calcareous sediments are very active in a chemical sense. Biological and mechanical breakdown of calcium carbonate material, plant and animal skeletal parts supplies the sediments to beaches, which in turn are susceptible to intertidal cementation and subsequent beach rock formation. Quartz and other non-calcium carbonate beaches may also be cemented into beach rock. This type of formation is common along beaches in the Seychelles, Madagascar, and also in local areas along the East African continental coast (fig. 35; see also figs. 14 and 15).

Figure 35: Tropical beachrock that has formed in the intertidal zone of a sandy beach. Note the original accretion units of beach that are now preserved by the lithification process. This process takes place very rapidly (tens of years).

The cementation process can be either a direct physical-chemical precipitation from the seawater, in the pore spaces between grains, or a secondary by-product of biological activity within the beach (Moore, 1973). Cementation occurs very rapidly in beachrock formation. It is not uncommon to find bottles and other human artifacts incorporated into the cemented material (Russell and McIntire, 1965). The presence of beachrock and other offshore obstructions to wave activity can have a dramatic effect on coastal processes.

On high-energy coasts, with abundant sediments, the tendency is to build long straight beaches or barriers generally with one or more parallel alongshore bars. If these linear barriers and beaches are lithified they act as a semi-permeable filter for marine energy onto the active coast. Because of the localised focussing of wave energy due to the presence of beachrock and breaks in the beachrock trends, the active coast can be highly crenulated. Cuspate features, or tombolos, often form opposite isolated offshore obstructions, whereas crescentic bays tend to form opposite breaks in a continuous offshore barrier (fig. 29).

River deltas and tidal inlets

(a) River deltas

Deltas are formed by the deposition of river-borne sediments at the shoreline. These sediments are redistributed to various degrees by marine processes. The characteristics of any delta are a function of the interaction between the riverine processes and the coastal processes. Riverine processes include the hydraulic regime, sediment load, climate, tectonic stability, and the shape of the receiving basin. Oceanographic/coastal processes that are significant include tides, nearshore wave regime, nearshore slope, and coastal currents. The interaction of these processes in time and space controls the shape of the delta plain and of the delta deposit.

Major deltas occur along the East African coast, for example at the mouth of the Zambesi River, where a large sediment load has been deposited in the shore zone with a resultant progradation of the coast into the adjacent nearshore area. The Zambesi river owes its size to the volume of the river and to the large amount of sediments that is brought down to the coast. The actual shape of the delta is controlled by wave processes that have redistributed the delta sediments to form a smooth morphology of sandy beaches at the mouths of the river (fig. 36a). The Pungue River delta, by contrast, has a bell-shaped river mouth with elongate mid-channel bars. At this location the sediment load is much lower than that of the Zambesi River and the tidal range is greater. This delta is one that is dominated by tidal processes (fig. 36b).

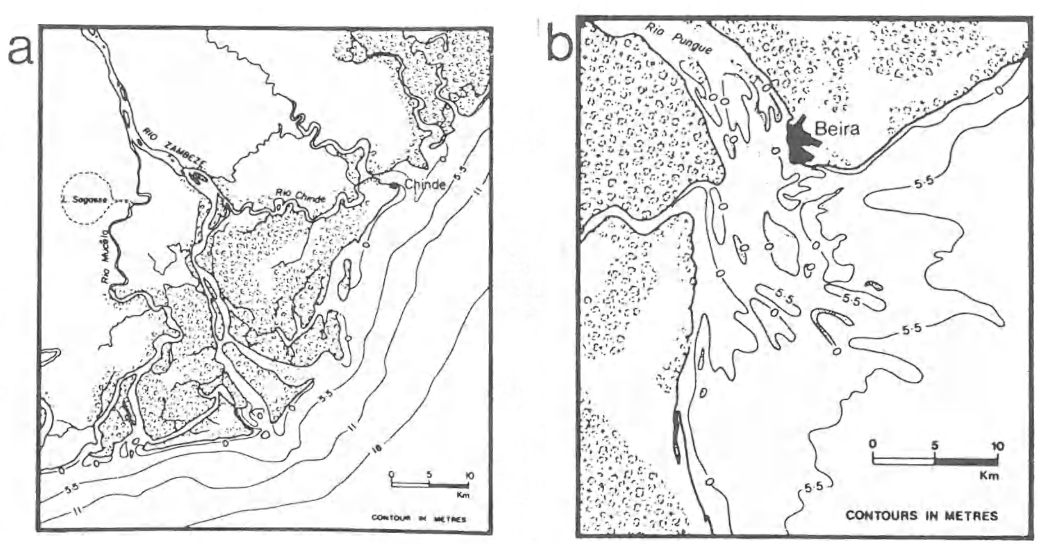


Figure 36a,b: (a) The Zambezi River delta, a smoothed but protruding morphology that is a product of strong river discharge, sediment input, high wave action at the coast; (b) the Pungue River delta has a bell-shaped river mouth with elongate mid-channel bars that indicate a tidally-dominated system

(b) Tidal inlets

Inlets form on sandy coasts where rivers or lagoons drain into the sea. In the East African region tidal inlets are particularly common along much of the coast of Mozambique and along the east coast of Madagascar (see fig. 37). The characteristic feature of inlets is that the flow through the inlet is reversed with the changing of the tides. Frequently small subaqueous deltas form on both the seaward and landward sides of the inlet. The actual form of these subaqueous deltas results from a combination of wave and tidal processes with the availability of sediments and the size of the river outflow. On coasts where there is a prevailing longshore sediment transport direction, due to the angle of wave approach, tidal inlets may migrate alongshore (fig. 38).

Tidal inlets are highly dynamic features, and are subject to both long term regular changes (such as alongshore migration) as well as to changes that result from storm events (particularly during the passage of cyclones across a coastal region).

Bedrock coasts

Bedrock outcrops occur in a wide range of morphological forms. They are common on all continental coasts and most islands. It is estimated that on a world-wide scale bedrock outcrops (including those with pocket beaches) account for approximately 39 per cent of the total coastline length. Cliffs are common along the SE African coast as well as in Madagascar, the Seychelles, La Réunion and Mauritius (fig. 39). The abundance of cliffed coasts around the world reflects the major changes that have taken place between relative levels of land and sea in recent geological times. Many cliff coasts that are active today have been in their present form since the last, and continuing, rise in the general level of the sea that has taken place over the past 20,000 years. Sea-level has risen approximately 100 m during that time.

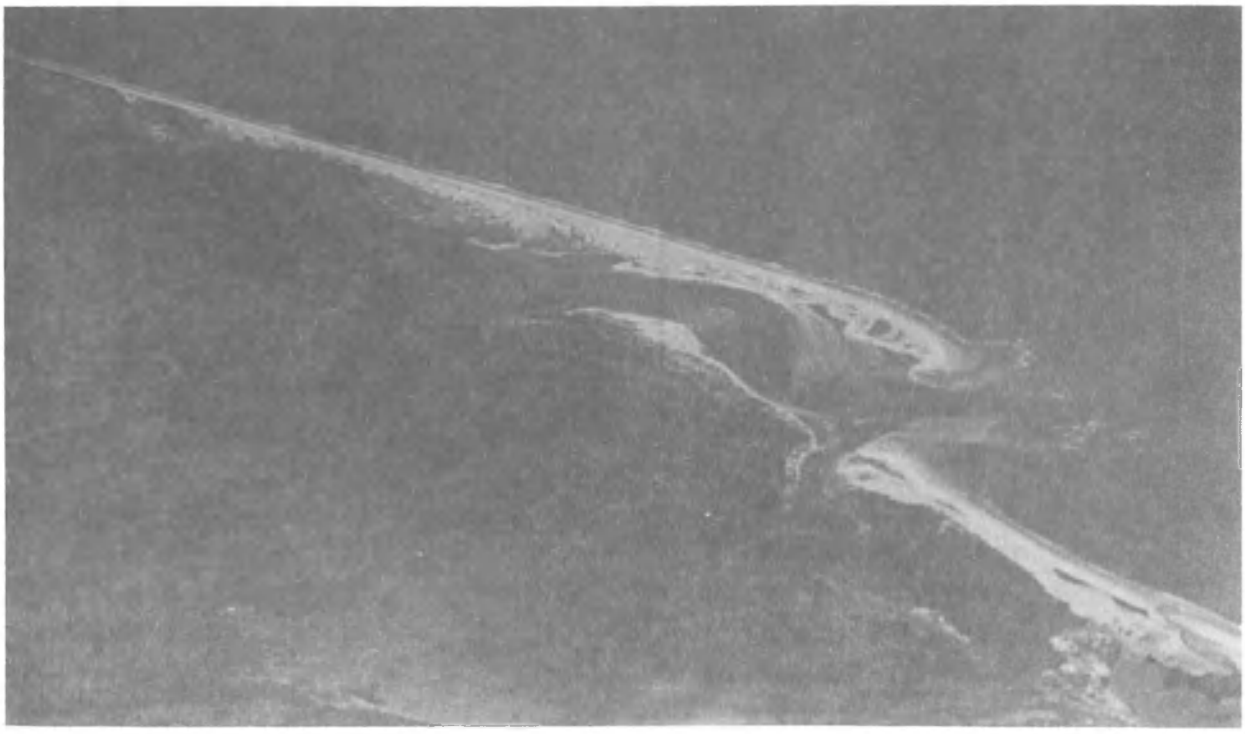


Figure 37: Deflected inlet, west coast of Madagascar, to the north of Mainterano; spit growth is to the north

Figure 38: Complex barrier island, inlet and tidal delta systems on the Mozambique coast at Angoche

Figure 39: The south cliffy coast of Mauritius showing volcanic rocks exposed to wave attack. The retreating weathered basalts leave a wave-cut platform that commonly is inhabited by reef-building organisms.

Wave action, particularly storm waves, is the most important agent of marine erosion in the formation of bedrock platforms or cliffs. Small waves, such as those associated with normal surf conditions, may cause attrition of material and minor amounts of abrasion. But it is storm waves that affect more change during a short period than average waves will affect over several months. Wave action against bedrock accomplishes erosion by:

- the force applied by the volume of water that impacts the bedrock with each wave;
- the hydraulic compression and release of air in pockets associated with cracks and joints in the bedrock; and
- the abrasive action of sand and gravel or rock debris that is moved along the bedrock by wave action.

(a) Bedrock platforms

Platforms (often called wave-cut platforms) are formed generally where coastal processes are sufficiently strong to erode a backshore bedrock outcrop.

Platforms are most commonly formed at or near the low tide level but may also occur at mid or high tide elevations. The width of a wave-cut platform is a function of the difference between the rate of cliff retreat versus the rate of platform retreat. Platform retreat is primarily a function of wave energy whereas cliff retreat is dependant on atmospheric parameters as well as wave parameters. Only if cliff retreat rates exceeds platform retreat rates will a platform form - for this reason some cliffed coasts do not have rock platforms.

(b) Cliffed coasts

The simplest form of a cliff is found where the sea erodes a steep coastal slope in an area of relatively deep water offshore (fig. 40). Under these conditions waves lose little energy before breaking at the bedrock surface. On resistant bedrock outcrops, such as granites or basalts, the rate of erosion is extremely slow, whereas where less resistant outcrops occur, such as sandstones or limestones, a small cliff or notch may be eroded rapidly. These erosive processes result in the formation of two shoreline features: (i) a steep wave-cut marine cliff, and (ii) a sloping wave-cut or abrasion platform. The material that results from the erosion commonly accumulates at the base of the cliff or on the seaward margin of the platform. This debris or sediment provides an abrasive tool for wave action to further enlarge the notch and abrade the platform. If the supply of sediment and debris from the coastal erosion is at a rate greater than that which can be removed by wave activity, then that sediment acts to protect the cliff or platform from further erosion.

(c) Feed-back relationship

Marine processes (waves and currents) work on the steep coastal slope and eroded materials act as abrasives, thus intensifying the erosive force of incoming waves (fig. 41). Initial stages of erosion are rapid, producing notches, platforms, and a pad of sediment seaward of the cliff. Sediment accumulates most rapidly and is most stable when waves approach nearly normal to the cliff. Otherwise, longshore transport can result in nearshore sediment erosion. As the sediment thickens ("n" increases, see fig. 41) and extends seaward, incoming waves are attenuated by bottom friction, the notch-cutting vortex breaks down, and cliff erosion is slowed. Along many cliff coasts in tropical latitude, reef-building corals quickly colonise wave-cut platforms and extend them seaward as well as build them vertically. This process also slows the rate of cliff retreat and slows the rate of contribution of cliff derived sediment to nearshore waters.

(d) Variations in cliff coast morphology

Variations in cliff coast morphology are associated with numerous factors:

- lithologic differences and structural complexity of the coastal rock formations;
- degree of exposure to wave attack (openess of a coast to wave approach, characteristics of the waves themselves, and depth of water offshore);
- intensity of biological erosion (especially in tropical settings such as the east-central African coast);
- the relative effectiveness of subaerial versus marine processes of coastal denudation; and

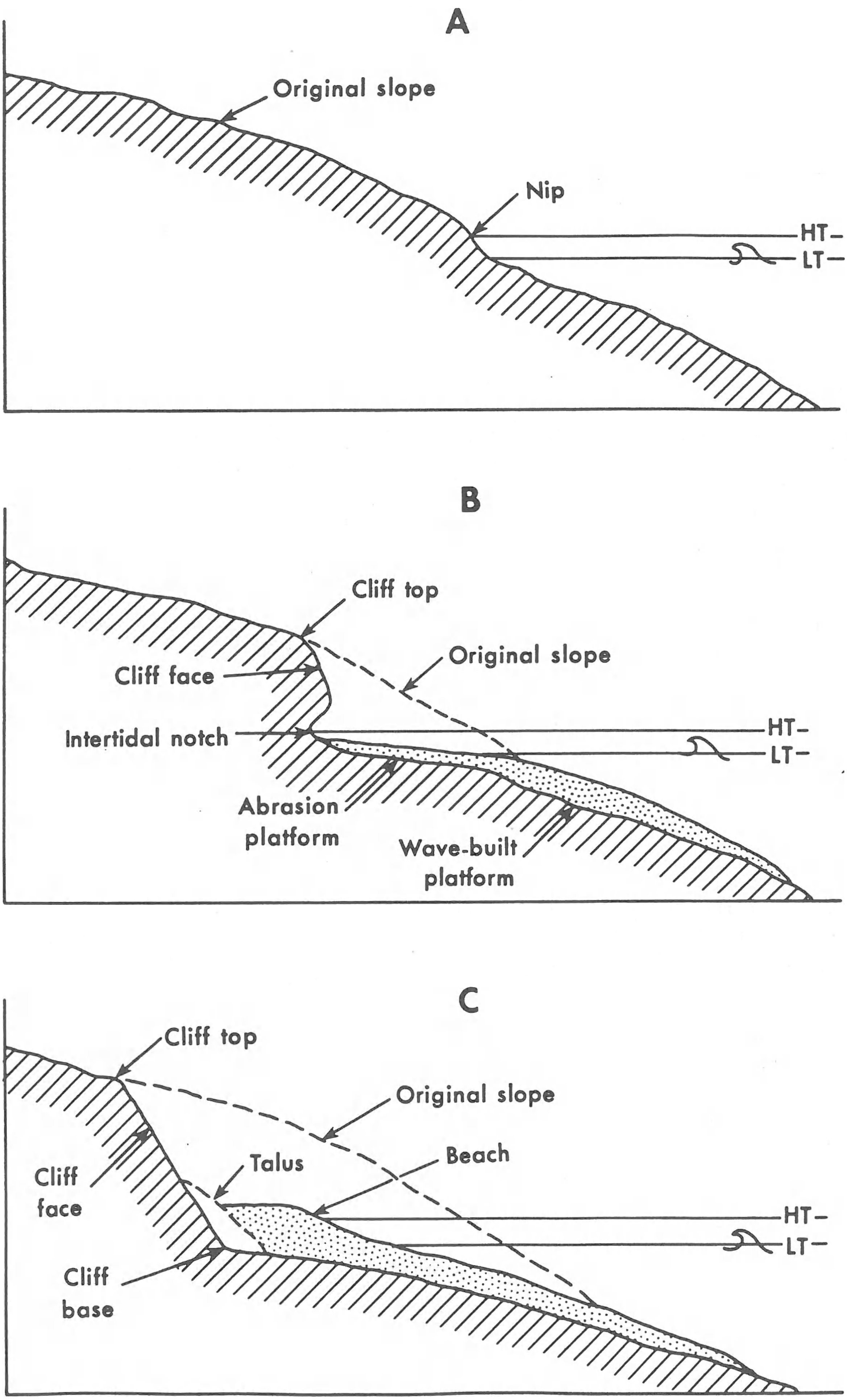


Figure 40: A simplified model showing the evolution of a marine cliff coast and accompanying topographic elements

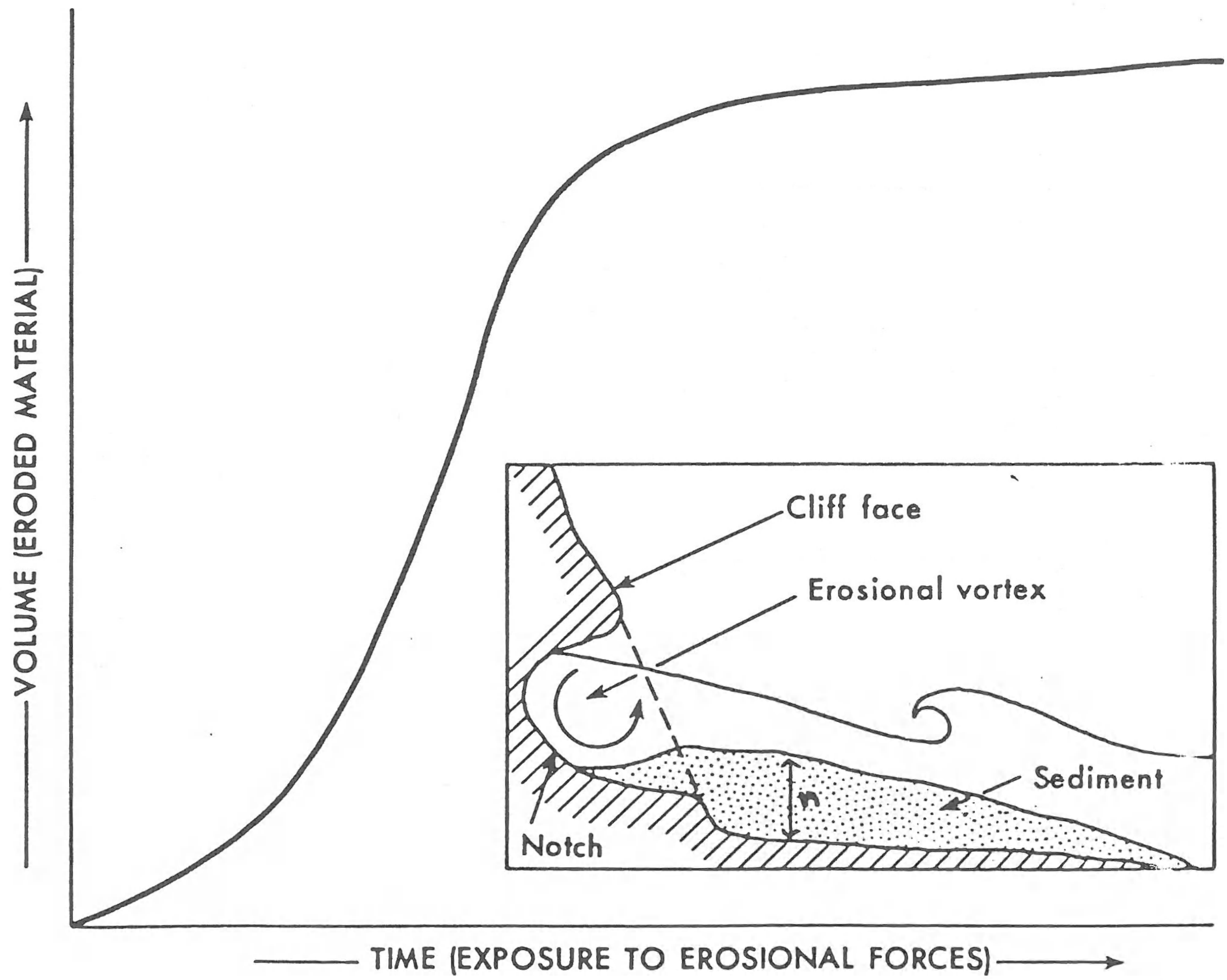


Figure 41: Schematic representation of temporal variation of volume of material eroded from a given cliff (adapted from work of Sunamura and Horikawa, 1971)

- stability of the shoreline position with regard to relative land- and sea-level changes.

Rapid changes occur along cliff coasts because of various processes of mass movement (fig. 42). Landslides and other mass-movement phenomena occur primarily in response to gravitational forces. However, seismic activity occasionally initiates these features. In tropical and subtropical climates coastal mass-movement occurs mostly as creep (slow movement) or landslides (rapid movement). Sediment size and geomorphology can change rapidly along a cliff coast that displays various forms of mass movement.

Reefs and associated environments

Coral reef systems are the single most important coastal feature of most tropical regions (for example, the southwestern coast of Madagascar, fig. 43). The growth and presence of reefs has a marked effect on the biological and physical character of the adjacent nearshore and foreshore environments. In nearshore areas consistently bathed by warm tropical ocean water and free of large inputs of terrigenous sediment, coral reefs commonly develop and may front other shoreline types such as rocky or mangrove coasts.

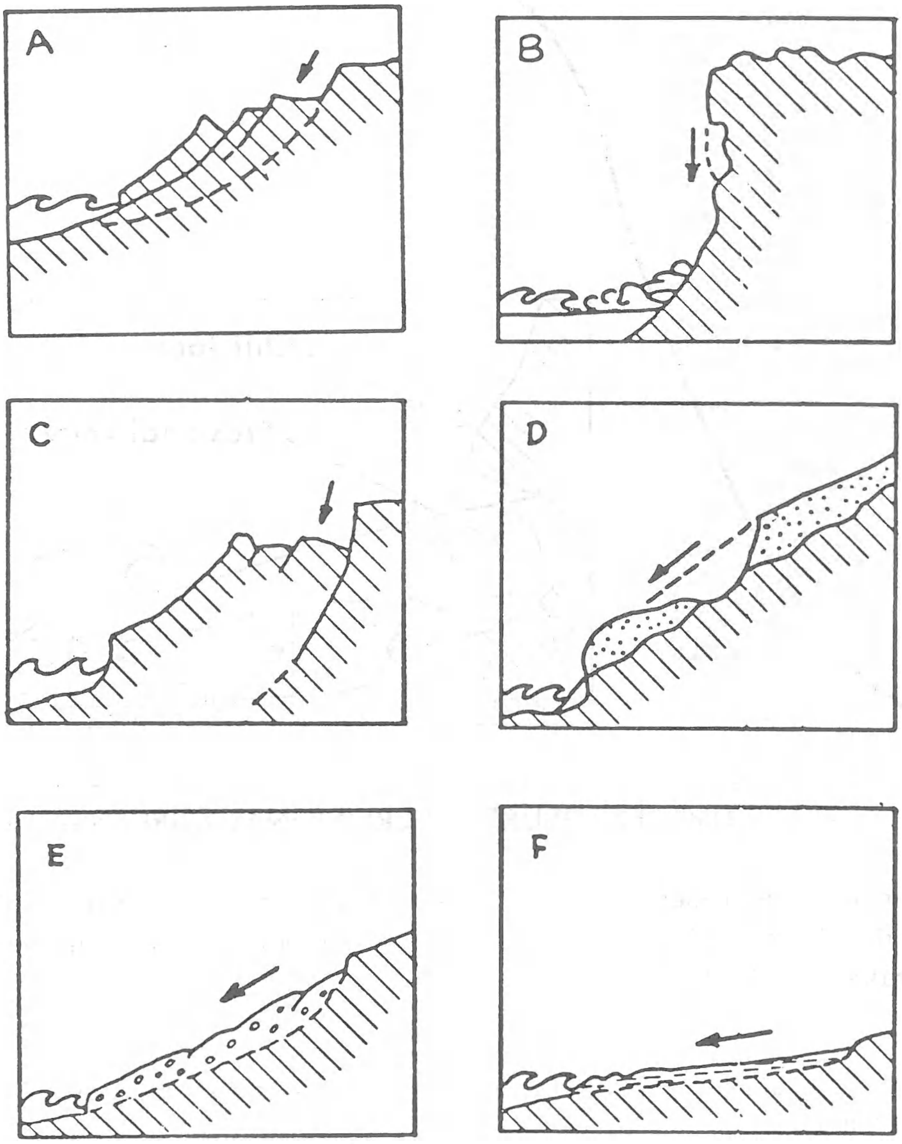


Figure 42: Landslide types commonly found in coastal areas: (a) rotational slide, (b) rock fall, (c) compound slide, (d) translational slide, (e) earth flow, and (f) mudflow

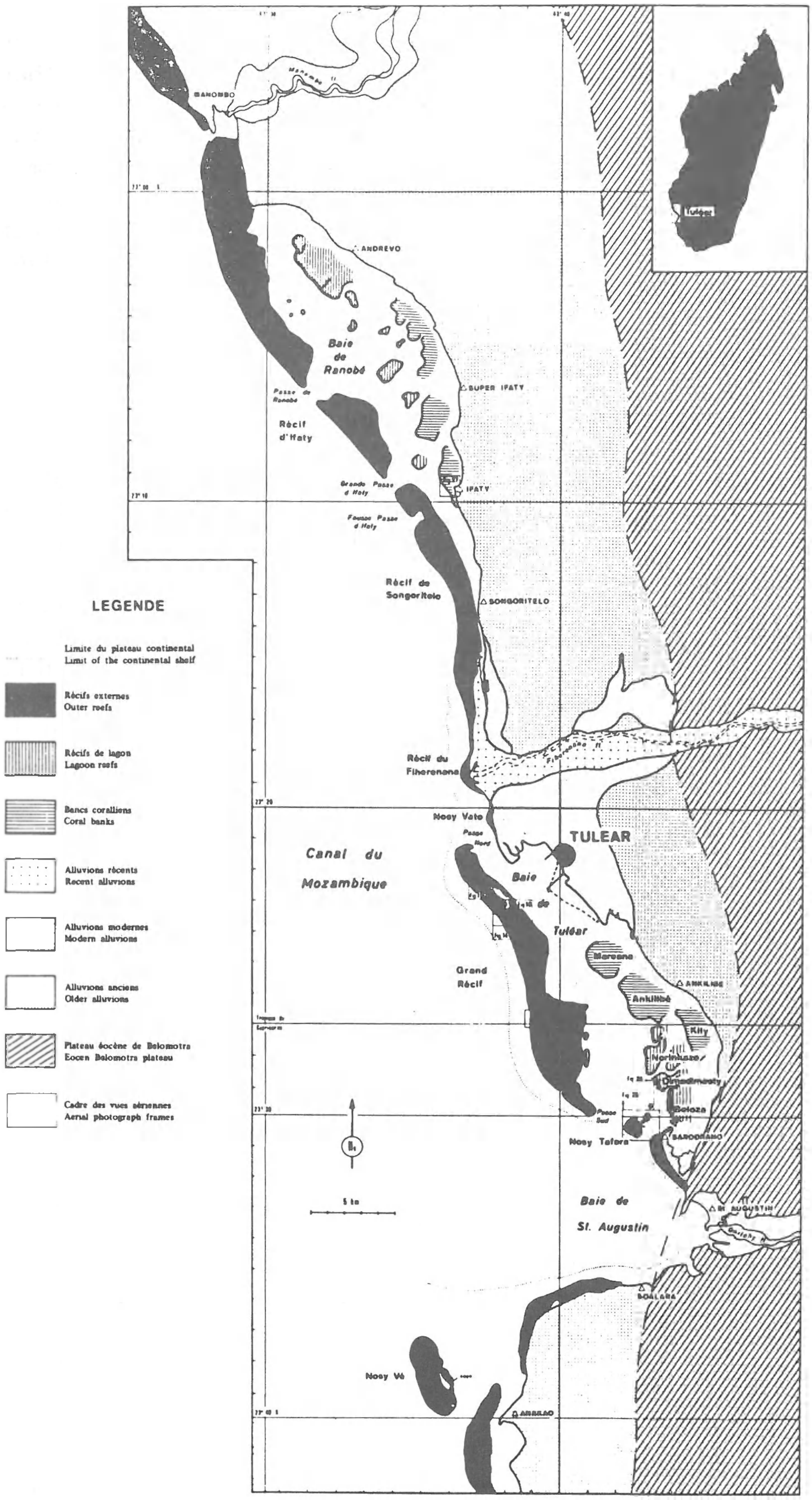


Figure 43: Coral reefs along the southwest coast of Madagascar

Brief descriptions of the shoreline types that occur in the study region are given in the section on shoreline types and regional factors that affect the coastal character are presented further in the document. In order to bring together these varied components, this section describes systematically the primary features of a reef system. A typical cross-section from the shore to the shelf is given in fig. 44 to indicate the relative location of the component features. Although considerable detail is provided in this section, further information can be found in various other reports (e.g., Lewis, 1969; Roberts, 1977; Roberts and Sneider, 1982).

(a) Environmental conditions: reefs as ecosystems

(1) Reefs and reef-associated environments

Reefs have the capacity to create rigid, wave-resisting structures that modify their physical environment, thus creating a wide variety of associated depositional environments. Most backreef shorelines are therefore characterised by low energy conditions. Reef zonation and high-energy reef to low-energy backreef environmental distinctions are a product of this ability to modify the current and wave regime (Roberts et al., 1975). Most corals that are capable of building viable reefs are found in tropical waters, and each ocean basin has its own genera and species. Biologically, coral reefs are the most diverse and productive environments in modern seas. They are also important in a geologic framework because they build sea floor topography and are renewable resources of carbonate sediments.

(2) Reefs depend on the growth and development of colonial corals

These reef-building genera have definite ecological controls:

Depth - the limiting depth for reef-building coral growth in most major oceans is about 100 m. This depth varies with the amount of suspended sediment in the water column. Since reef corals have symbiotic algae in their tissues, which aid in metabolic processes, decreasing light intensity with depth limits photosynthesis, and thus coral viability. Therefore, depth is a limiting factor only because light intensity is decreased drastically as depth increases.

Temperature - reef corals thrive in warm tropical waters. They grow best in waters between 25°C and 29°C. At water temperatures below 16°C most reef-building corals become unable to feed. Prolonged exposure below this critical stress threshold will cause coral mortalities. Tolerance to cold water is species dependent, but most Indian Ocean reef corals will die after only a few hours of exposure to waters below 10°C. Maximum temperatures on reef flats may reach 39°C. Most shallow-water species can survive to this limit.

Salinity - tolerance to salinity change is variable. Most corals survive best at normal oceanic salinities. However, a wide variety of species seem to be able to survive between extremes of 17.5 and 48 parts per thousand.

Emersion - coral that are typical of reef flat environments have developed a tolerance for being exposed to the atmosphere during low-water periods of the tidal cycle. Most reef corals can take only a few minutes of emersion.

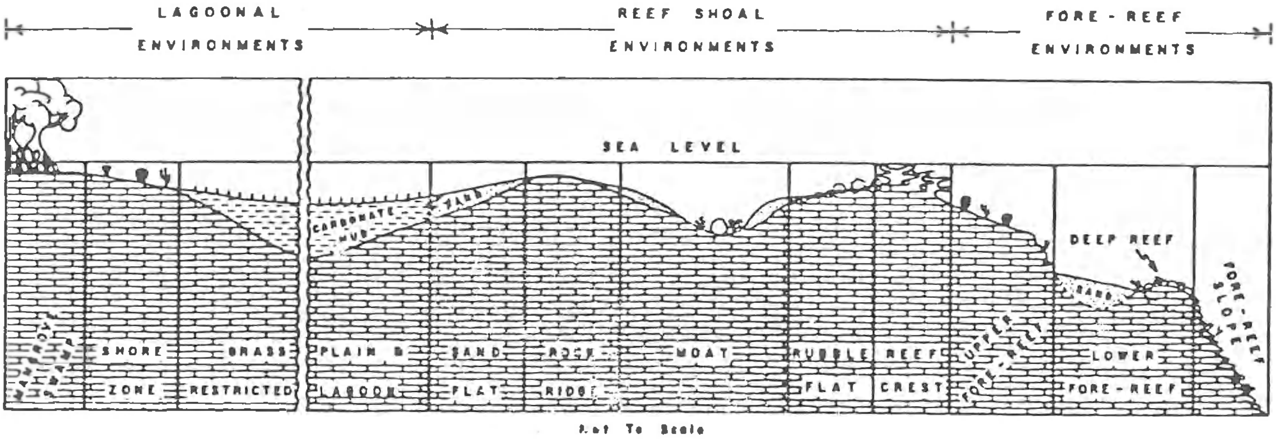


Figure 44: Schematic profile across a typical carbonate coastal platform that includes a low-energy backreef shoreline, shallow lagoon, and high-energy reef and reef associated environments

<u>Sedimentation</u> - sedimentation is a control of reef growth. Rates of sedimentation on corals may be high after storm events, for example. Many corals, however, have the ability to clean themselves. These species can therefore tolerate settling sediment. Recent research suggests that corals can withstand much more sedimentation than was originally thought.

<u>Water turbulence</u> - wave- and current-induced turbulence is important in that the direct physical effect influences coral and reef morphology. Biologically, turbulence is responsible for bringing supplies of fresh seawater to the reef coral. It also removes the byproducts of metabolism.

(3) Climate controls on reefs and reef-associated environments

Reefs develop in both humid tropical and arid tropical settings where interfingering with siliciclastics is common. However, sediments are delivered to these carbonate environments from terrigenous sources in quite different modes, depending on climatic setting. More or less continous input of terrigenous sediments from rivers and streams is typical of the humid tropics. Pulses of sediment associated with flash flood events is typical of arid settings. Chemical precipitation of evaporite minerals such as salt, gypsum, and anhydrite is typical of hot coastal environments in arid climates. These evaporites are not commonly part of the facies suite found in the humid tropics.

(b) Depositional environments of a reef complex

<u>Back-reef environments</u>

The kind of back-reef shoreline depends on continuity of the reef, width of the backreef lagoon, architecture of substrate for Holocene sediments, relief of adjacent land mass, and climate.

Low-energy shorelines

Tidal flats - these muddy shorelines characteristically develop on the sheltered sides of islands on broad carbonate platforms or along coastlines of low relief. Fine-grained carbonate muds are derived from the broad, shallow platform fronting the flats. Reefs are commonly located far offshore or are patchlike in construction. Sometimes tidal flats composed of terrigenous sediments are formed in a backreef setting as a product of sediment introduction to the system by small streams and rivers.

Mangrove swamps - in the humid tropics, salt-tolerant vegetation, dominantly mangrove trees, may occupy the low-energy shoreline reserved for tidal flats in arid settings. Many of the low-lying coastal areas of Eastern Africa and other adjacent sites such as protected coasts of Tanzania (figs. 11 and 45) and Mahé, Seychelles, have thriving mangrove swamps (figs. 46 and 47). Coastal mangrove swamps are biologically important because they function as

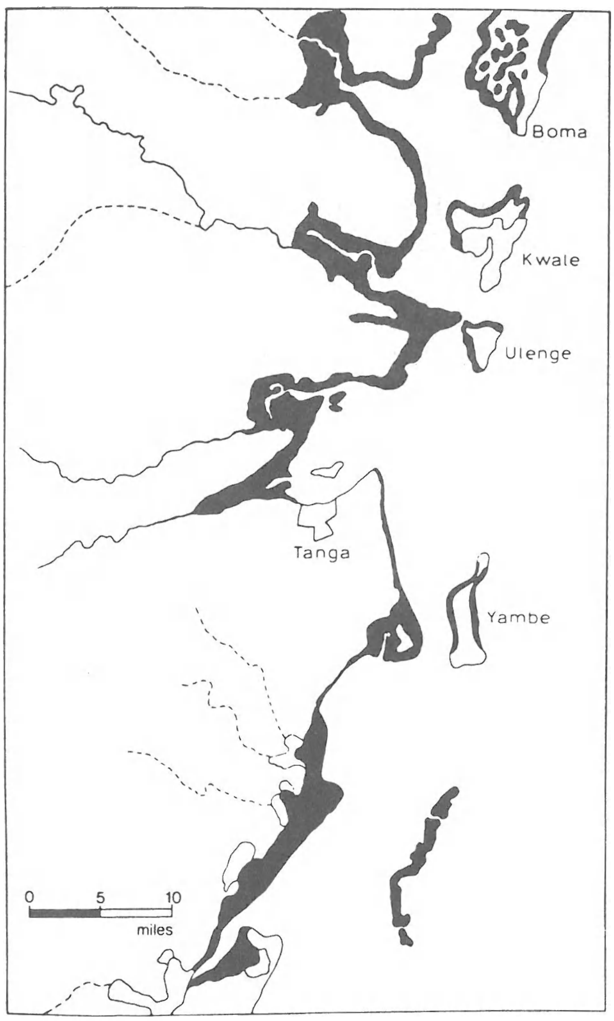


Figure 45: Distribution of mangrove forest in vicinity of Tanga, (Tanzania) (after Walter and Steiner, 1936)

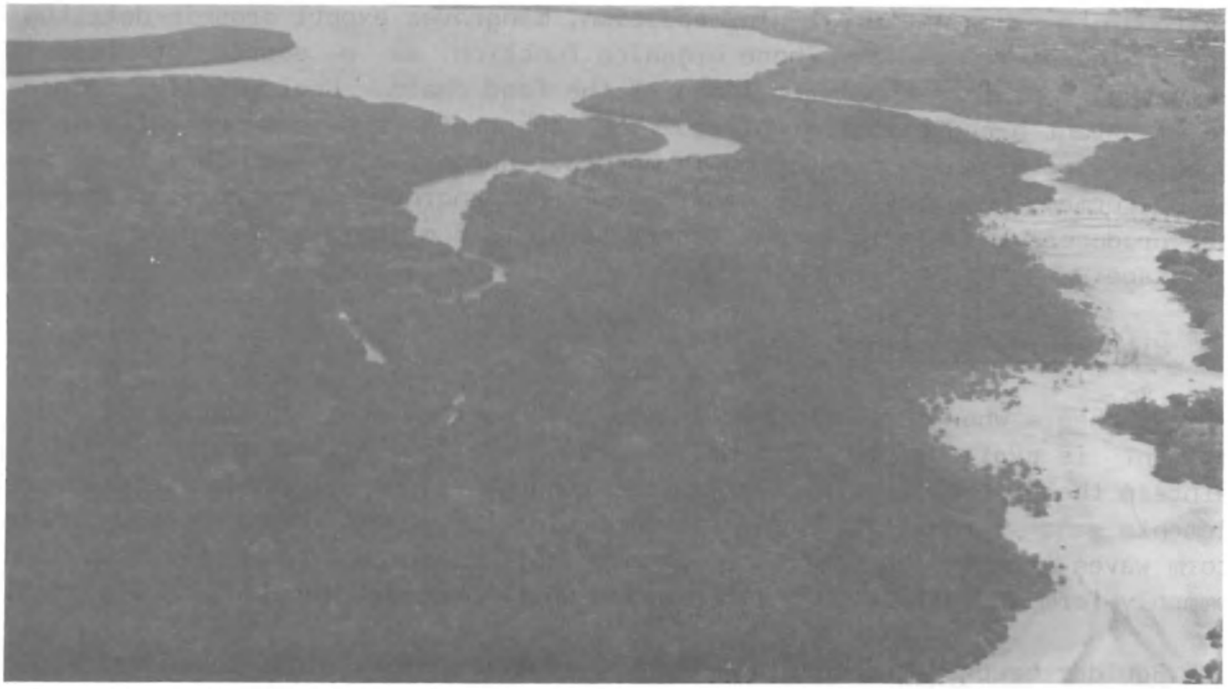


Figure 46: Mangroves in Port Tudor, Mombasa. Note vegetation-less strandflat at high-water level (see figure 47 below)

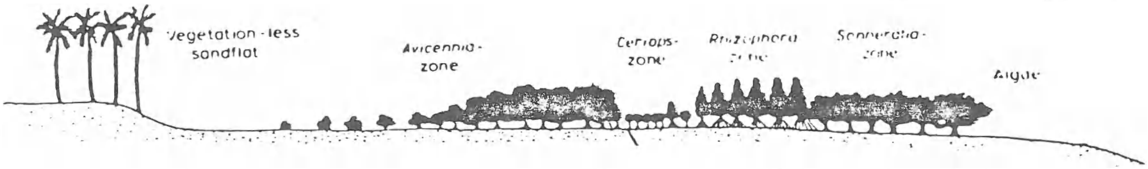


Figure 47: Mangrove zonation at Tanga (after Walter and Steiner, 1936)

nursery grounds for numerous forms of marine life that inhabit other environments when mature. In addition, mangroves export organic detritus to surrounding environments. These organics function as a source of food for organisms that form the lower links of the food chain. Geologically, mangroves are important because they stabilize the substrate and can actually create topography. Organic production in mangrove swamps is so high that thick peats may be formed. Mangroves with prop roots (red mangroves) are the most important peat producers. Their roots may penetrate up to 5 m below the sediment-water interface.

High-energy shorelines

Beaches - when the backreef lagoon is narrow and a supply of coarse sediment is available to the coast, beaches develop. Normal waves necessary to maintain these beaches enter the lagoon through tidal channels between reef elements and across the reef at high tide (if reef geometry is favourable). Storm waves transit the reef as a product of elevated water levels. Dunes commonly form in association with beaches where sediment supply is sufficient.

Boulder beaches and coastal ridges - if the reef is close to shore, boulder beaches and coastal ridges composed of coarse coral rubble form on the storm sides of islands and reef systems. Studies have shown that living corals have been transported to these subaerial settings from depths of 15 m on the forereef shelf.

Lagoon

Currents and waves typically found in this environment are insufficient to transport sand-sized particles. Ocean waves are filtered by the reef, leaving local low-energy wind waves in the backreef. Circulation is forced by tidal pumping, wave-driven water movement over the reef, and by local wind drift (Roberts, 1980).

As a product of low physical energy in the environment, backreef lagoons are generally the sites of fine-grained carbonate sediment accumulation. Although fine sediments derived from the breakdown of the reef are contributed to this setting, most sedimentary particles are produced in situ. The end result is a bimodal sediment composed of coarse particles floating in a carbonate mud matrix. Coarse particles result from the breakdown of mollusc shells, calcareous green algae (Halimeda), and large forams. The fine-grained fraction is contributed primarily by calcareous green algae. Because of intense bioturbation, primary sedimentary structures are quickly obliterated and sediments appear mottled.

Biologically, backreef lagoons can be very productive areas. A dense carpet of various marine grasses (fig. 48), which serves to stabilize these bottom sediments, is typical of this setting. Epiphytic growth of carbonate-producing biota on the leaves of marine plants significantly contributes to the mud fraction of the sediments.

Figure 48: Marine grasses common to the quiet-water backreef lagoon

Reef-shoal environments

Sand sheet - behind each linear reef is a coarse deposit composed of dominantly sand-sized sediment. This material has been derived from the reef and spread into the backreef during major storm events. Although surge currents generated from normal wave breaking on the reef crest can transport sand-sized and larger particles short distances, the formation of a broad sand sheet in the backreef requires storm waves and currents. This sand sheet and its associated shoals, which commonly develop opposite tidal passes, can extend several kilometers into the lagoon. The entire sand belt parallels the reef. As a rule, this sand apron is composed of reasonably well sorted particles with a very low content of silt- and clay-sized carbonates. Tidal currents and over-the-reef flow in conjuction with wave and biological activity winnow these deposits (fig. 49).

Topographic highs such as tidal bars and shoals are especially clean and well sorted. Unlike the coarse debris in the lagoon, the sand sheet is composed primarily of coral and coralline algae fragments. Generally, the facies change from sands of this depositional environment to muddy sands and muds of the lagoon is very sharp.

Moat - in the immediate lee of many linear reefs is a channel-like feature that functions as a conduit for the exchange of tidally driven waters between the lagoon and open shelf. These channels, which are commonly referred to as moats, connect with well-defined breaks through the linear reef, which are exchange points between the backreef and forereef. Moats have a typical coral community that consists of large coral heads and thickets of delicately branching types. Both coral colony types prefer wave-sheltered conditions but can survive quite well in a strong current regime. The moat floor is composed of coral-rich sand derived from the reef. Under high ebb flow conditions these sediments are transported out of tidal passes to the forereef shelf.

Figure 49: Sand sheets in lagoon adjacent to La Morne, southwest Mauritius

Rubble flat - directly behind the living linear reef is a deposit of coarse material derived from breakdown of coral colonies at the reef crest. Numerous boring organisms, including sponges, bivalves, worms, and algae, weaken the coral colonies, especially the branching varieties that function as the main reef frame builders. Storm waves break the weakened colonies and transport the pieces in a logoonward direction by strong lagoonward-directed surge currents that develop from the process of waves breaking on the reef crest. This apron of coral rubble parallels the reef and is transitional lagoonward with the sand sheet. Biological and chemical cementation quickly stabilizes the debris into a consolidated part of the "geologic reef".

Reef - a living coral reef is one of the most diverse and productive biological environments in modern seas (fig. 50). Geologically, this community of corals, coralline algae, and other accessory organisms functions as a renewable resource of sedimentary particles for other depositional environments.

Shallow, linear reefs act as wave and current energy filters between the oceanic forereef environment and the quiescent backreef setting. This modification of shoreward-directed energy results in rather abrupt transitions from "high energy" to "low energy" deposits (facies changes). Experiments show that under normal trade wind wave conditions most fringing and bank barrier reefs filter out 70-98 per cent of the incoming wave energy before it reaches the backreef (Roberts, 1980). In the process, strong but short-duration surge currents capable of transporting sand-sized and larger particles are developed. In areas of significant tidal variations, large areas of reef flat are exposed at low tide (fig. 51).

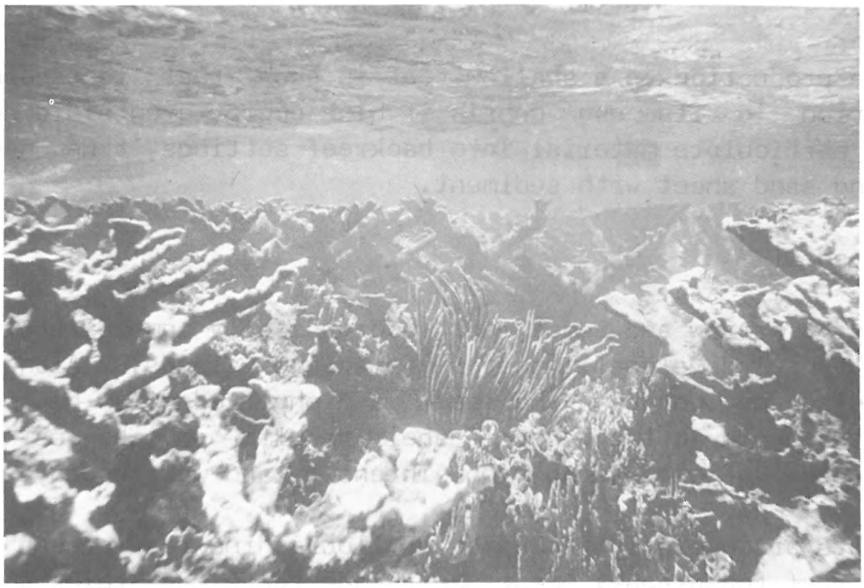


Figure 50: The reef crest is one of the most densely populated and diverse environments in modern oceans

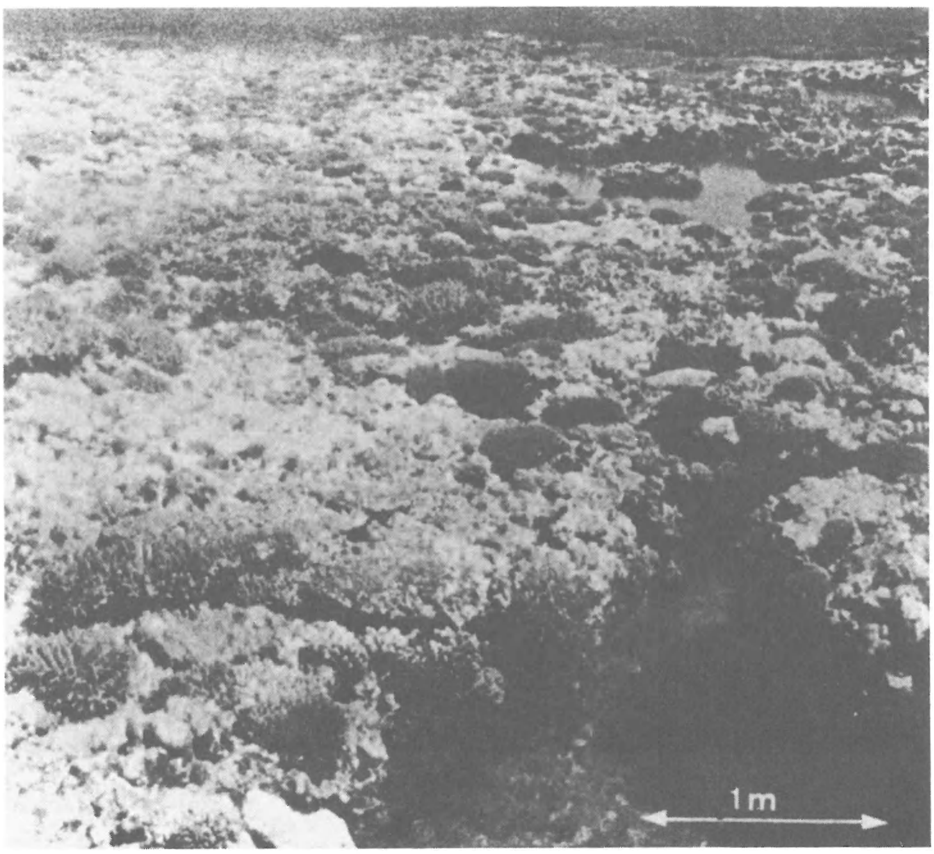


Figure 51: Where there is a significant tidal variation, as along the western Madagascar coast and along parts of the Kenya coast, vast reef flats develop and are exposed at low tide (see also figure 17)

Carbonate production on a shallow reef is such that the coral framework would be buried in its own debris if high-energy events did not push large quantities of particulate material into backreef settings, thus nourishing the rubble flat and sand sheet with sediment.

Forereef shelf

Generally, a narrow and sometimes topographically complex shelf lies on the seaward side of well-developed linear reefs around islands. Along continental coasts the distance between the reef and shelf edge can be great. Rapidly increasing water depth on the forereef shelf results in changes in the reef communities because of decreasing light intensity and wave energy.

Shelf edges are commonly the sites of flourishing reef growth (fig. 52) and extraordinary reef topography. Most shelf-edge reefs have thick sediment wedges trapped behind them. Well-defined grooves through shelf-edge reefs function as pathways for offshelf sediment transport. The edge of the forereef shelf is generally defined by a steep to vertical slope into very deep water.

Reefs of the western Indian Ocean have diverse morphologies with intricate subenvironments, as indicated by the block diagram of fig. 53. Many of the reef-dominated carbonate platforms, as shown in the coastal profile from Mahé in the Seychelles (Lewis, 1968), simply have accreted from a steep igneous rock coastline (figs. 54 and 55).

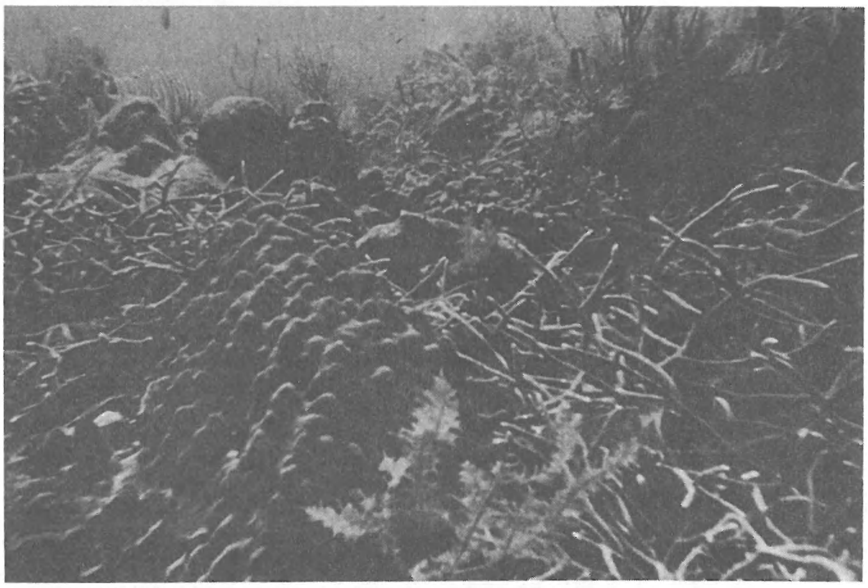


Figure 52: Flourishing reefs develop at shelf edges and on the upper forereef slopes

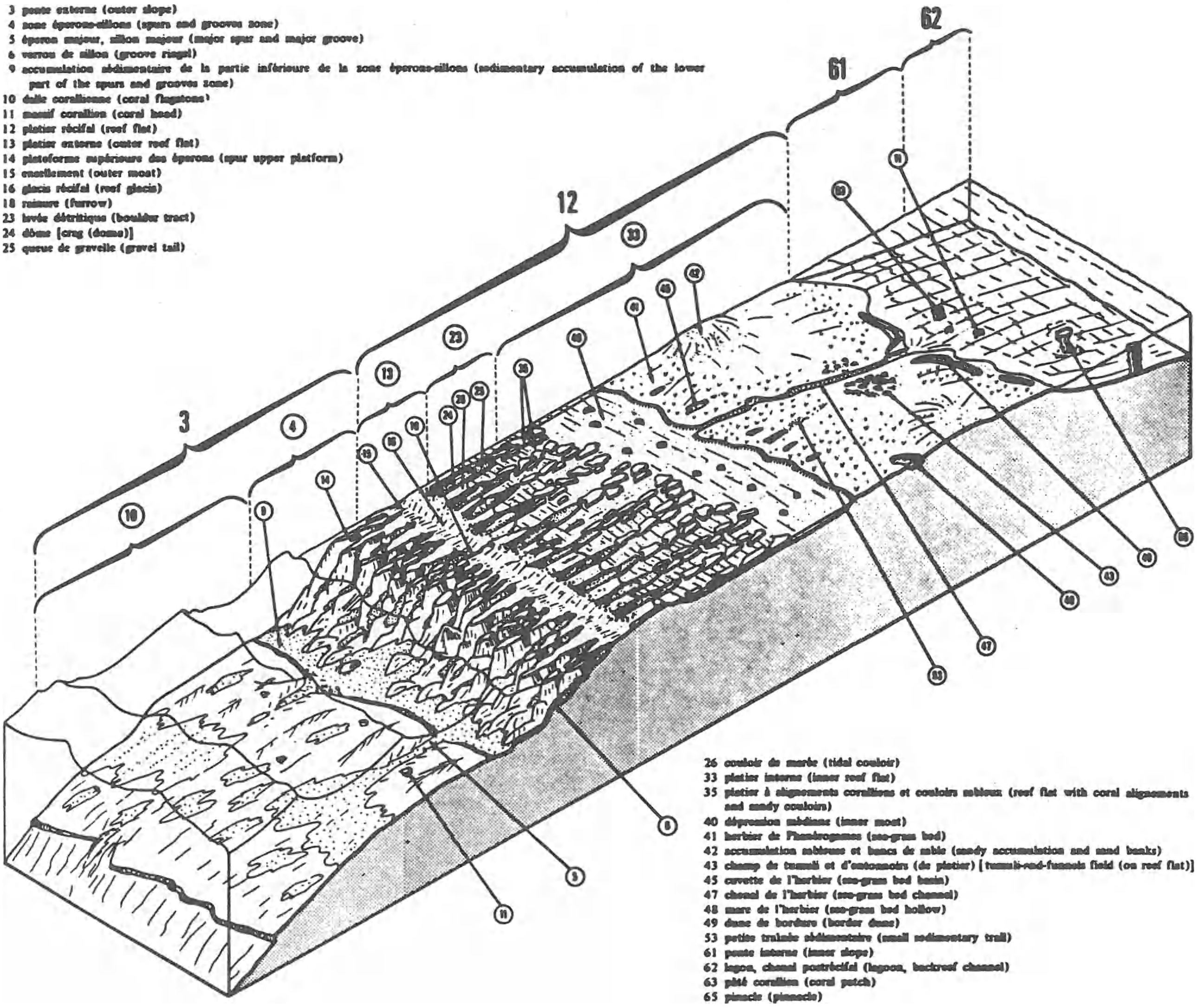


Figure 53: A block diagram of the coral reef in Tulear Bay, Madagascar

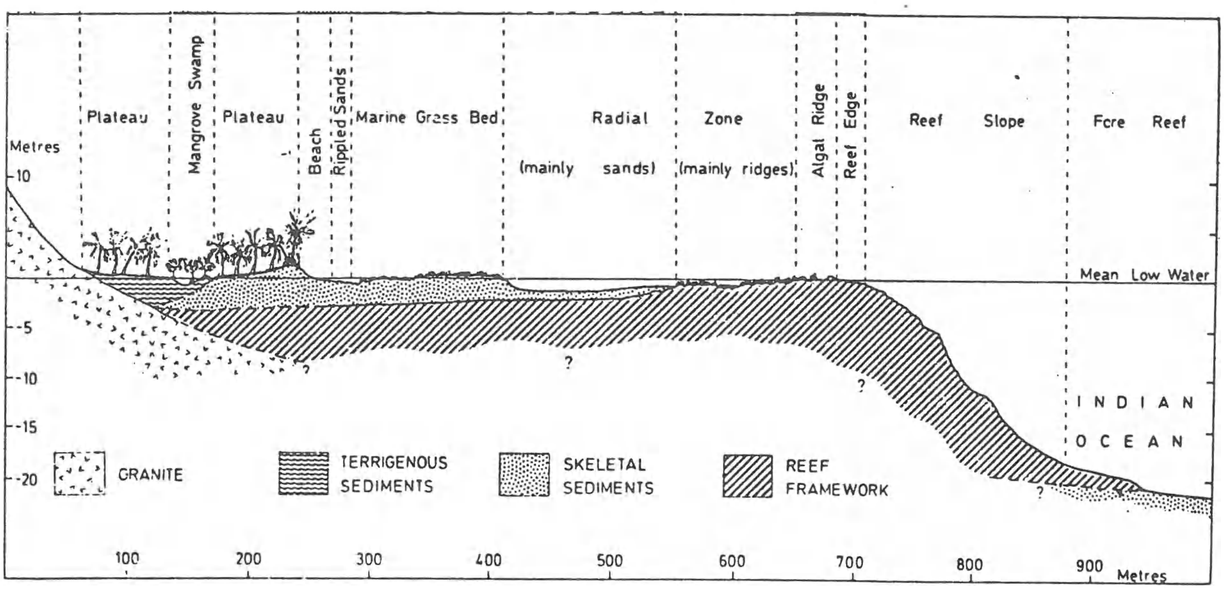


Figure 54: Cross section of a reef flat on the windward side of Mahé, Seychelles (Lewis, 1968)

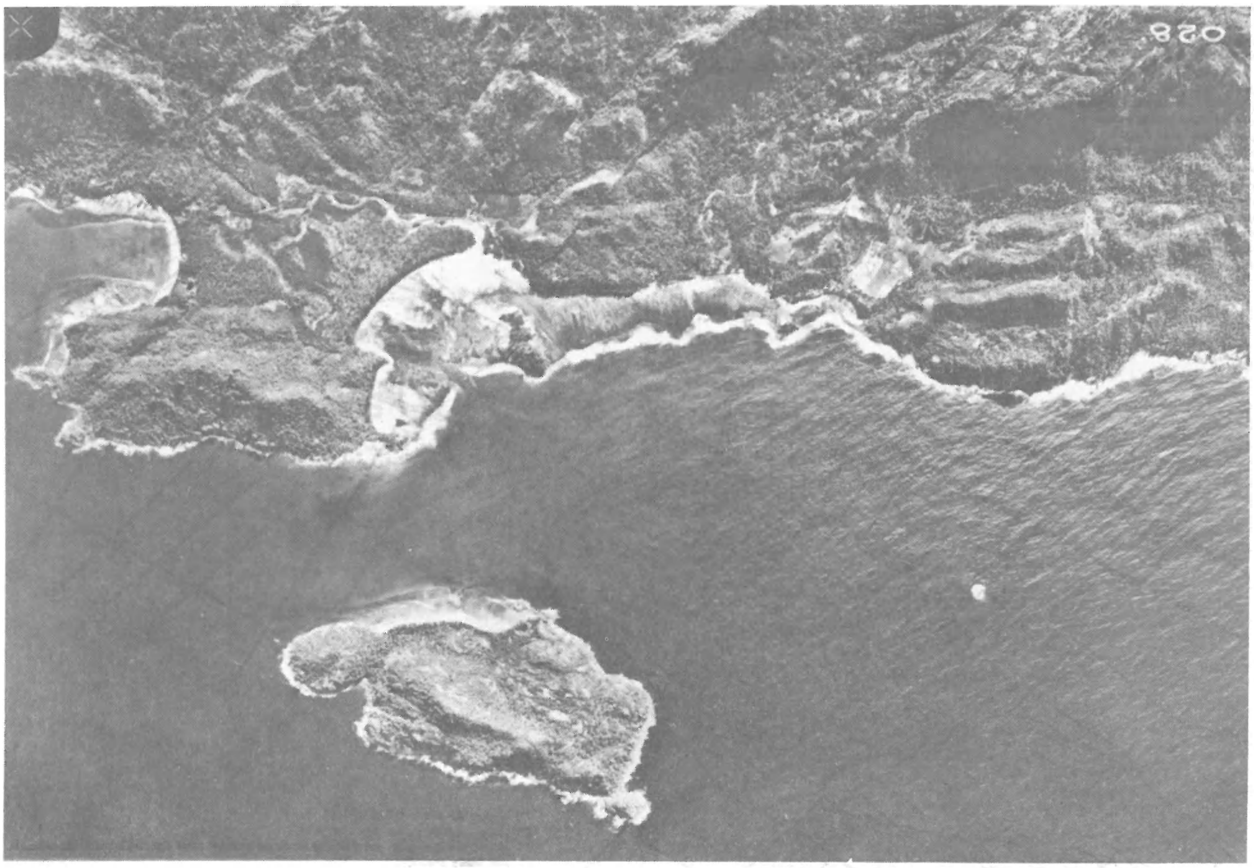


Figure 55: Air photograph of the western coast of Mahé, Seychelles, showing the cliffy igneous coast fronted by an actively growing reef and reef flat

OIL AND THE ENVIRONMENT

Sources of marine oil pollution

Oil that reaches the coast may be derived from:

- natural seeps;
- accidental discharges (during on- or off-loading operations);
- operational discharges (e.g. washing tanks, dirty ballast or machinery space); and
- marine accidents (grounding, collision).

The western Indian Ocean is a major marine crude oil transportation artery so that the risk of oil spills at sea is high. Crude oil is shipped through the area from the Middle East. Kenya, Tanzania, Somalia, and Madagascar have coastal refineries and import crude oil by sea; Comoros, Mauritius and Seychelles import refined oil (fig. 56).

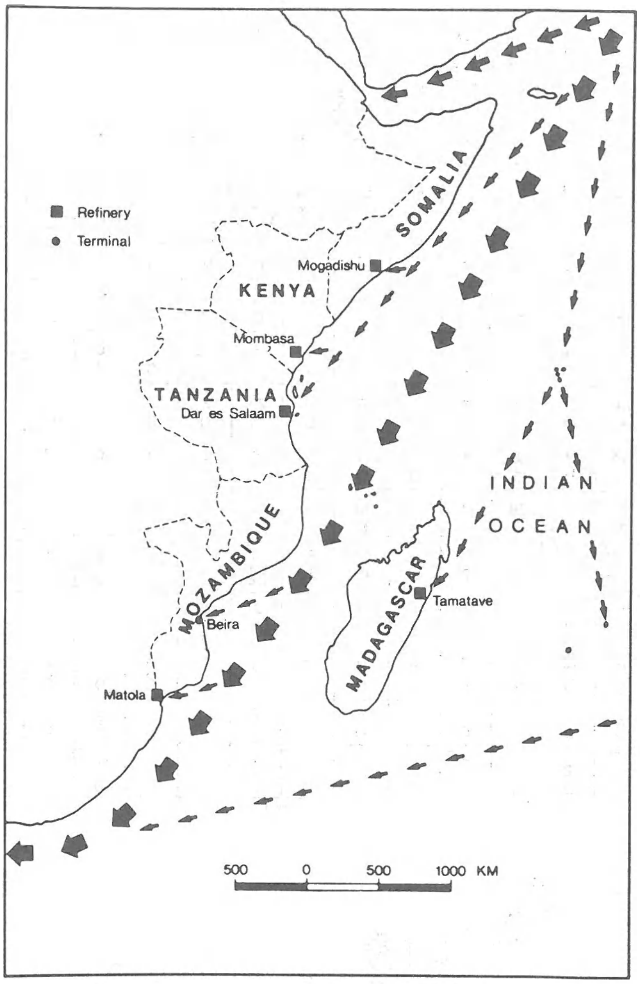


Figure 56: Tanker routes of the western Indian Ocean

An estimated 450 million tonnes oil/year goes from the Middle East around Cape Horn; an additional 22 million tonnes is imported into East and South Africa (UNEP, 1982). This transport involves approximately 1200 VLCC tanker (200,000 tons) voyages and 4000 medium-size tanker (average 60,000 tons) voyages each year through the region. At any one time an estimated 24 loaded VLCC's, 24 empty (in ballast) VLCC's plus 88 loaded and 88 in-ballast medium-sized tankers are in transit through the Eastern African region. The Mozambique Channel is a high-risk area because of traffic routing through this area. With the known traffic patterns and the high volume of oil in transit through the region, accidental (large) spills or operational spills and stranded tar balls must be expected to occur at any time throughout the area. The geographical distribution of oil slicks observed off the East African coast (fig. 57) indicates that knowledge of the offshore winds and currents is of paramount importance.

The nature of oil

Oil and oil products exist in a wide variety of forms, with very different physical and chemical properties (e.g. aviation fuel, bunker fuel, asphalt). The most important physical properties of oil are:

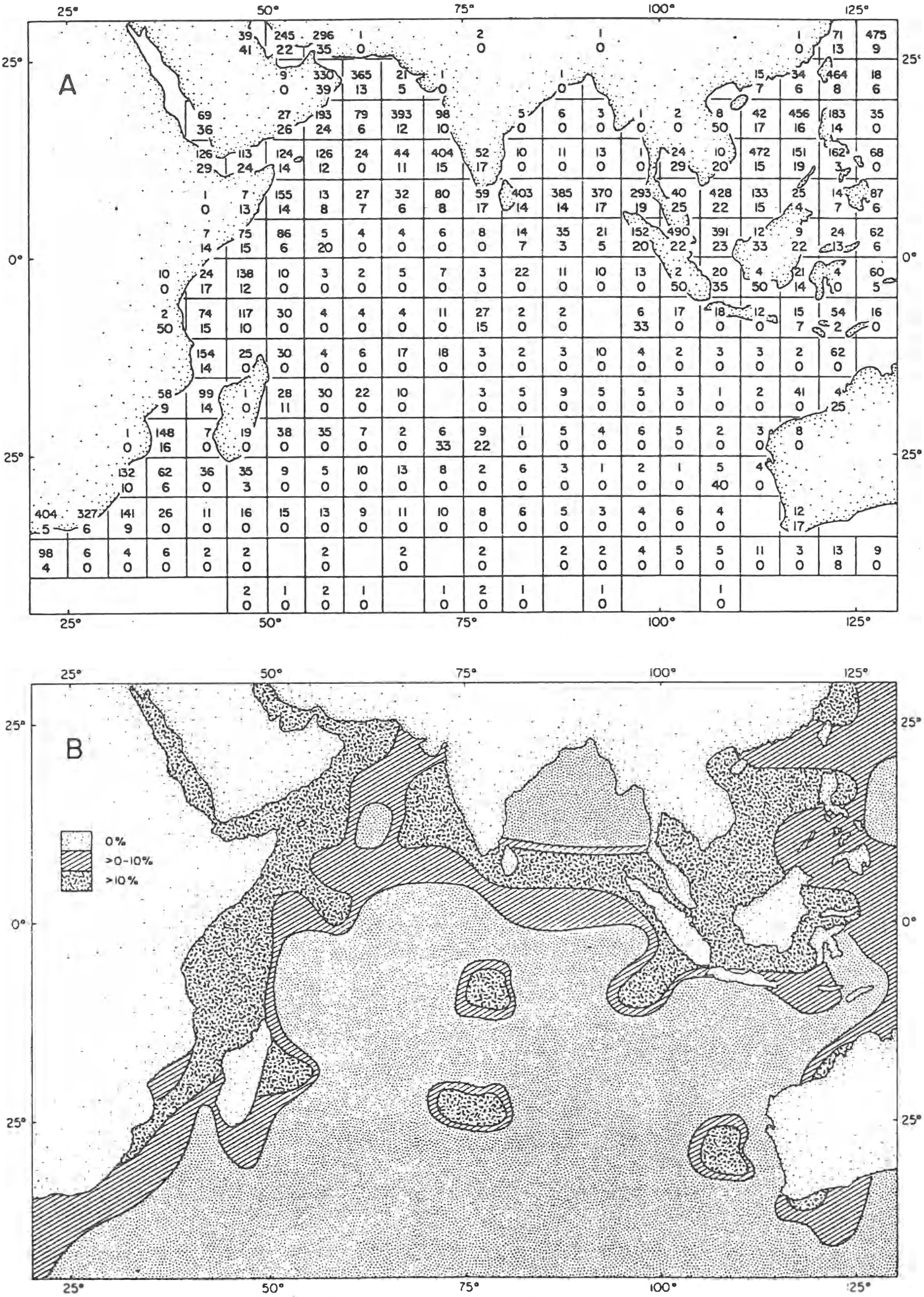


Figure 57: The geographical distribution of oil slicks on the Indian Ocean as indicated by the percentage of positive reports. A. Total number of reports of visual observations of oil slicks for 5*x5* squares of latitude and longitude of the Indian Ocean and the percentage that indicated the presence of oil (upper value, total number of observations; lower value, percentage of positive reports). B. Pictorial presentation of data (from Levy et al., 1981)

- boiling point: the temperature at which fractions of the oil evaporate;
- flash point: the lowest temperature at which the fractions will ignite;
- pour point: the temperature below which the oil will not flow;
- surface tension: the spreading character of low viscosity oils;
- viscosity: the resistance of oils to flow; and
- specific gravity: the relative density of the oil.

Following a spill, the physical and chemical properties of oil change continously as the oil undergoes transport and weathering (or degradation) by natural processes. These changes are most rapid immediately following a spill as the light ends are removed, primarily by evaporation (fig. 58). As a result of the loss of the light fractions, oil weathers to become a more resistant and less fluid substance. An emulsion may be formed by the mixing action of waves ("chocolate mousse").

Oil can spread to become a very thin layer on the water surface, only to reform into a thicker slick as the oil accumulates near the shore or against a barrier. The movement of oil on the water surface is controlled primarily by winds, but surface water currents can also influence the direction and speed of movement (see section on spill movement at sea). Oil degradation is a function of the effects of inputs of thermal, mechanical, and biochemical energy. The degradation or weathering processes occur on different time scales. Initial spreading (under the influence of gravity and surface chemical effects) is rapid and immediate. Evaporation of light fractions is usually a dominant process only during the first day or two days following exposure of the oil (fig. 59).

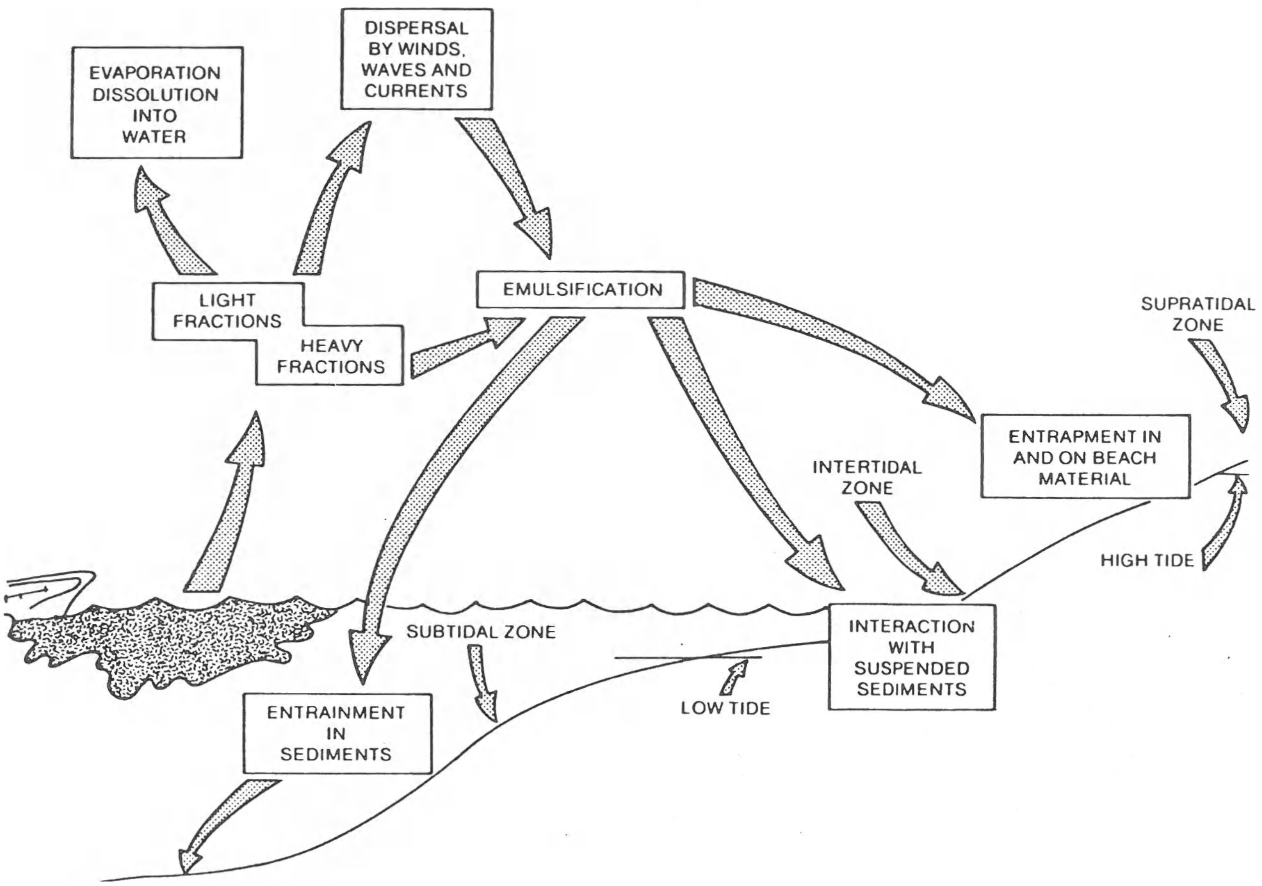


Figure 58: Mass balance components of spilled oil (from Wheeler, 1978)

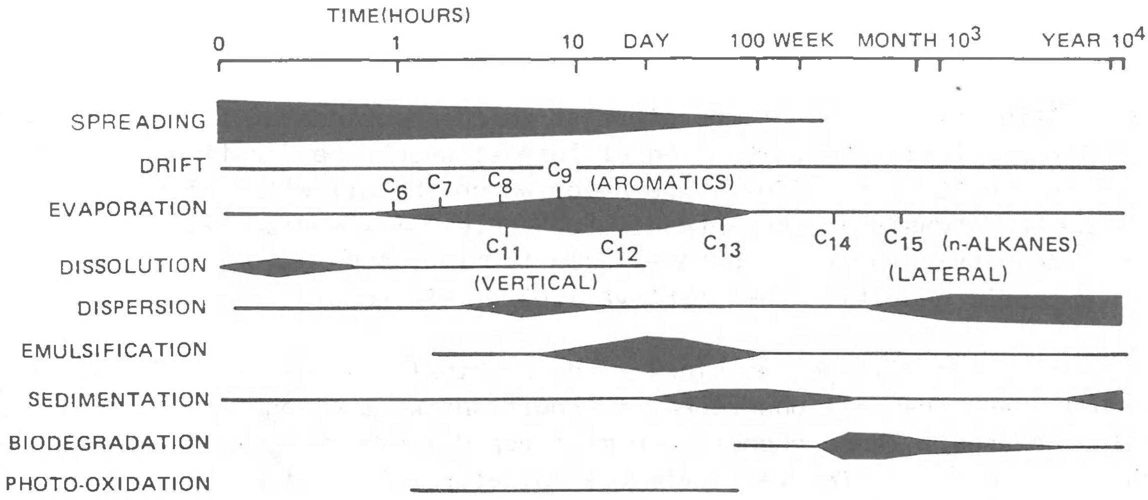


Figure 59: Time span (in hours) of the physical-chemical processes of oil degradation (from Wheeler, 1978)

Spill movements at sea

The movement of oil slicks on the water surface is controlled primarily by surface currents or by local winds if these exceed the current speed. Changes in wind direction or the movement of oil into a different current system result in a change in the direction of movement of the oil. Slick movement is usually in the order of 3 to 5 per cent of the wind velocity and slicks usually move at an angle between 10-40 to the right of the wind. Oil that is spilled in a coastal area (50 km from shore) will likely be driven onshore by the sea breeze as the onshore winds are stronger and longer than those offshore (Hsu, 1970), except where regional winds counteract the local circulation patterns. Weather systems that are smaller than an oil slick will tend to disperse it, whereas weather systems larger than the slick will act to advect it. Therefore the larger the slick the greater potential for dispersion (Murray, 1982). Oil spilled in the Trade Wind belt is likely to produce a large slick due to the characteristic relatively constant wind directions (Murray, 1982).

A general model of slick behaviour and slick growth in relation to physical oceanographic and meteorologic processes is shown in fig. 60. Slick behaviour must be considered in terms of both weathering processes and the forces that transport the oil. For example, a light volatile oil may totally evaporate within a few hours, whereas tar balls, which are a residual product of weathering, may persist for months or years (some tar balls have been found with marine growth). Wave action in the shore zone acts to break down the slick and may result in the formation of an emulsion.

Coastal (nearshore) water movements associated with wave action play an important role in the local distribution and movement of oil (for example: on steep rocky coasts reflected waves from cliffs may prevent oil becoming stranded). Large freshwater influxes into the sea from heavy rainfall or from a river source can serve as barriers to spill migration toward the coast. Extreme varibility in local physical processes can exist even within one region, such as the Eastern African area. Exploratory studies should be conducted in sensitive areas that are vulnerable to spill movement.

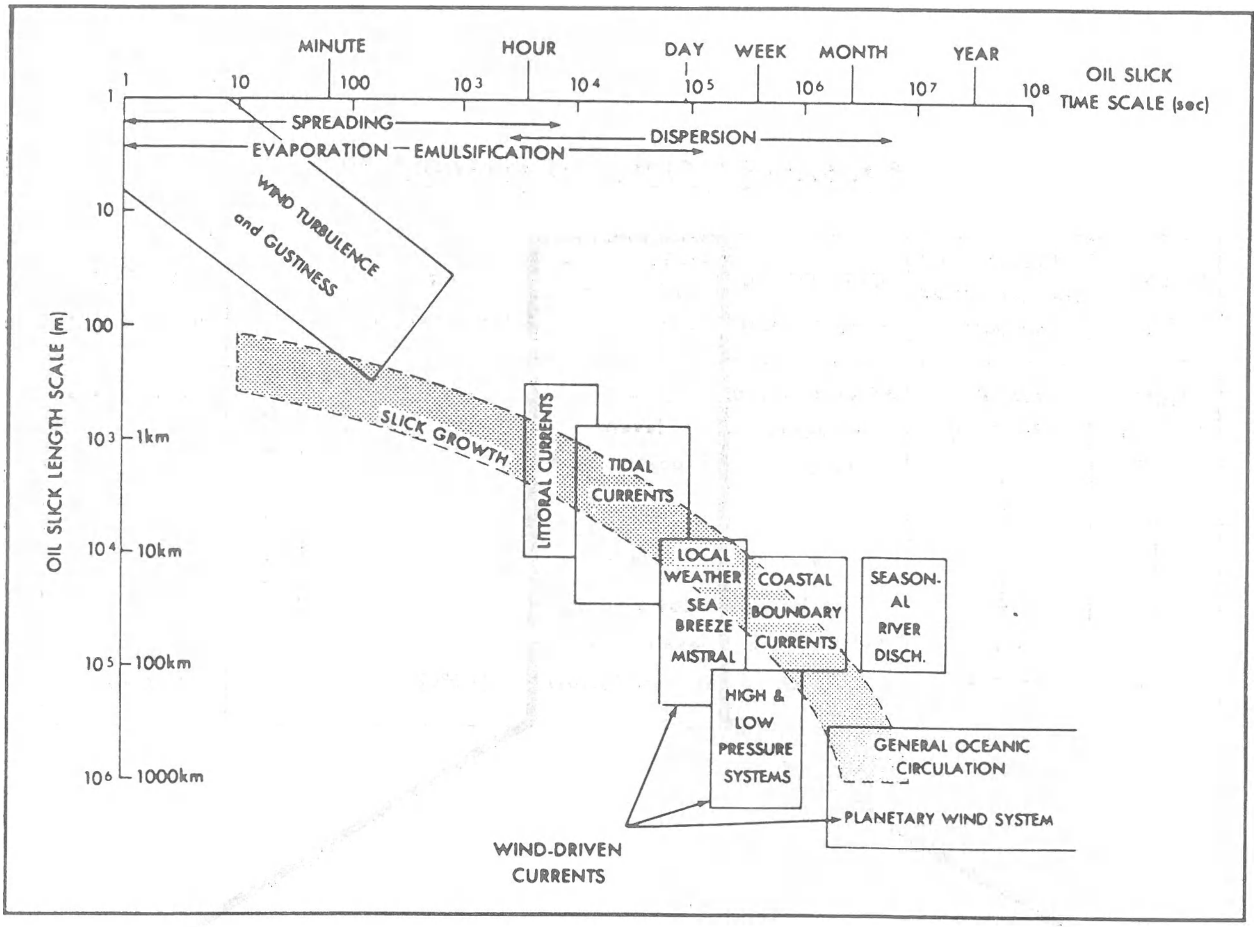


Figure 60: The growth of oil slicks in relation to physical oceanographic-meteorological processes (from Murray, 1982)

Oil persistence

The residence time of stranded oil depends primarily upon:

- physical and chemical properties of the oil;
- volume of the oil;
- thickness of the oil layer;
- depth of penetration or burial in sediments;
- ambient air temperatures;
- location of the deposited oil; and
- wave-energy levels at the shoreline.

The single most important factor for persistence of oil in the shore zone is the level of mechanical (wave) energy that can act upon the oil. As this increases, so the residence time (or persistence) of the stranded oil decreases (fig. 61). Biological degradation of stranded oil is a slow process, and is only significant in cases where oil is deposited above the limit of wave action (e.g., during a period of a storm surge). On island coasts, the levels of wave energy vary considerably depending upon exposure to the dominant wave approach direction and upon the presence of reefs in the adjacent nearshore waters. Oil tends to collect on sheltered sections of coast, areas where mechanical energy levels are usually lowest.

PERSISTENCE FACTORS FOR STRANDED OIL

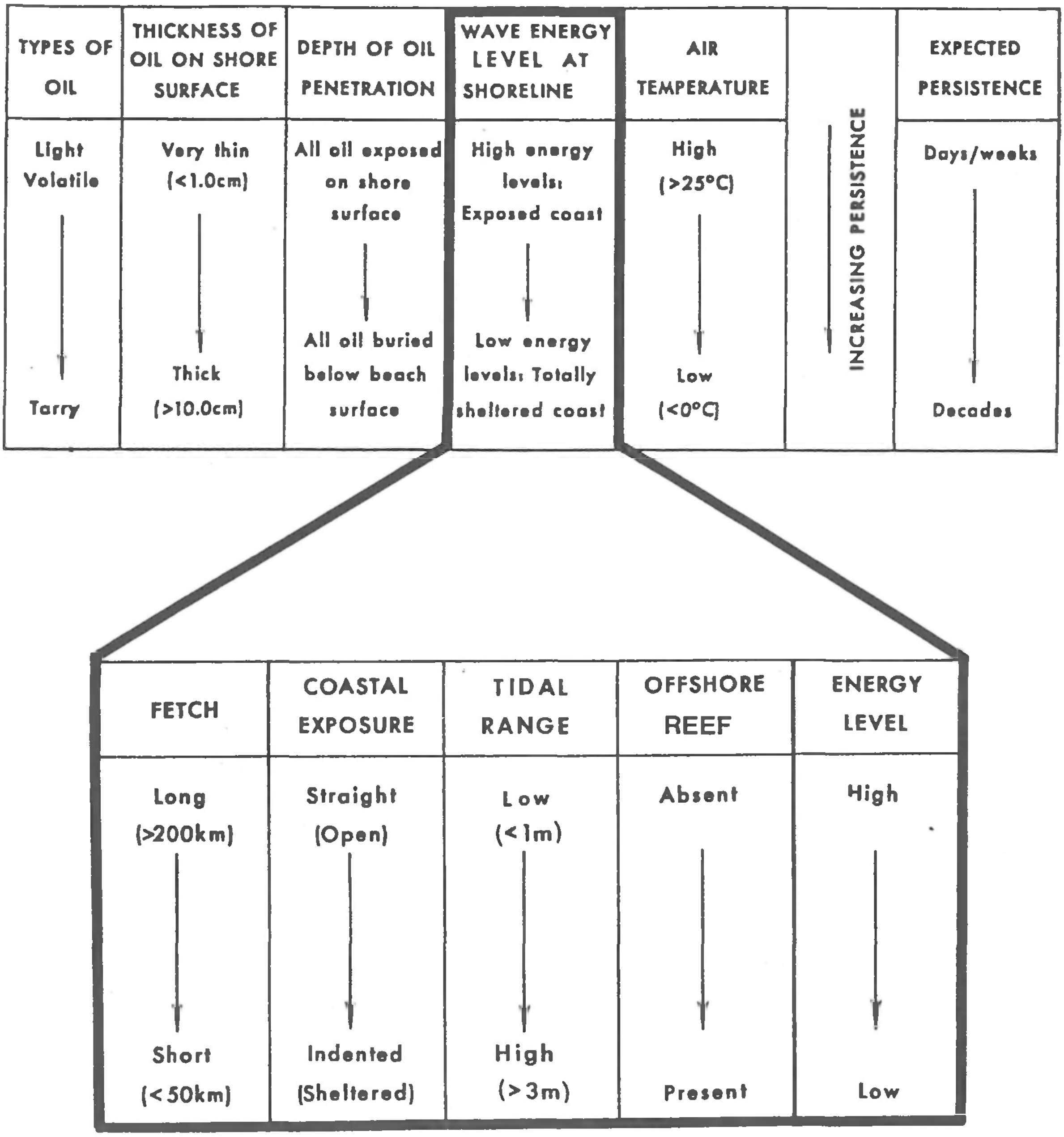


Figure 61: Shoreline energy level and persistence of stranded oil (adapted from Owens, 1977)

The reworking of stranded oil is also affected by rates of shoreline change (e.g., the normal reworking of beach sediments by waves, or coastal retreat). Oil burial or erosion can occur during periods of storm-wave activity. if oil is buried, it is unlikely to undergo further degradation until re-exposed by subsequent sediment reworking. The ambient temperatures and sunlight have been known to cause the leaching of water from a stranded emulsion as the tide ebbs. This destabilizes the emulsion and can result in the oil then penetrating into the sediments.

If oil is stranded at times of high water levels (storm surges or spring tides) it may be deposited above the normal limit of wave activity. Oil that reaches a shore during a period of "normal" water levels will have a different impact on mangroves and marshes than oil which is stranded at times of high water levels.

Oil may be buried by sediments that move onshore following a period of storm-wave erosion (fig. 62) or by the alongshore transport of sediment. Oil tends to accumulate in sheltered environments, where the biological impact is more severe and where natural weathering processes are slowest. On gravel beaches oil frequently mixes with the sediments to form a resistant asphalt pavement.

Shore-zone "sensitivity"

The effects (or the impact) of stranded oil are usually considered in terms of the degree to which the natural environment is altered. The degree to which oil affects the environment depends upon a wide range of factors (see fig. 63). Oil that resides in the shore zone for long time periods will have a greater impact than oil that is rapidly dispersed by natural processes (tables 9 and 10). The recovery time of a species or of human activities is an important factor in impact assessment studies. The timing of a spill is usually important, as the impact on the biological environment or upon activities often depends upon the season.

The definition of physical coastal habitats alone is an insufficient basis for impact evaluation, as this assumes that impacts are similar for similar shoreline types. Sensitivity may vary depending upon the practicality and effectiveness of clean-up operations. If the shore area can be restored, the impact of the oil may be greatly reduced. The single most important factor in coastal impact evaluation is related to human activities and to those parameters that are related to man's subsistence, commercial or recreational use of the shore zone.

Although a large body of relevant information on potential threats and potential impacts can be obtained prior to a spill incident, it is still necessary to determine, by surveillance and field checking, if in fact that threat is real at the actual time of the spill (e.g., the presence or anticipated movements of migratory species).

In the Eastern African area the coastal zone is of critical importance to local subsistence, commercial, and recreational activities. In addition to the direct effects of oil upon the shore for recreational use, the potential secondary effects of oil in spawning habitats such as mangroves must be carefully reviewed to ensure that the most critical (and long-term) factors are considered. The effects of oil on recreational activities would be obvious in

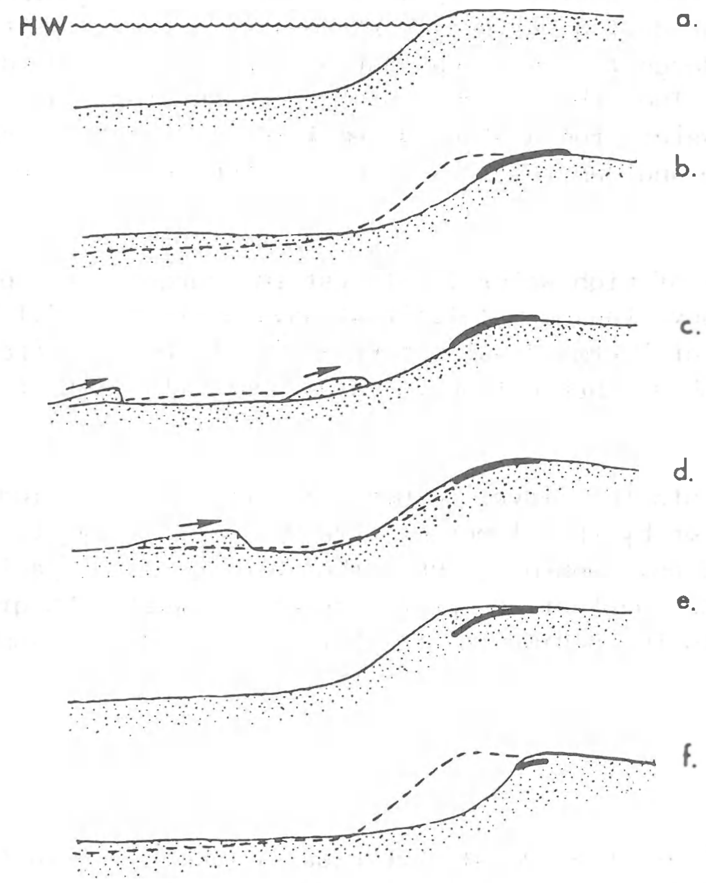


Figure 62: Sequence of storm erosion and oil deposition (b); burial (d), (e); and exposure following a second storm (f) on a sand beach (from Owens 1977), see also figure 2

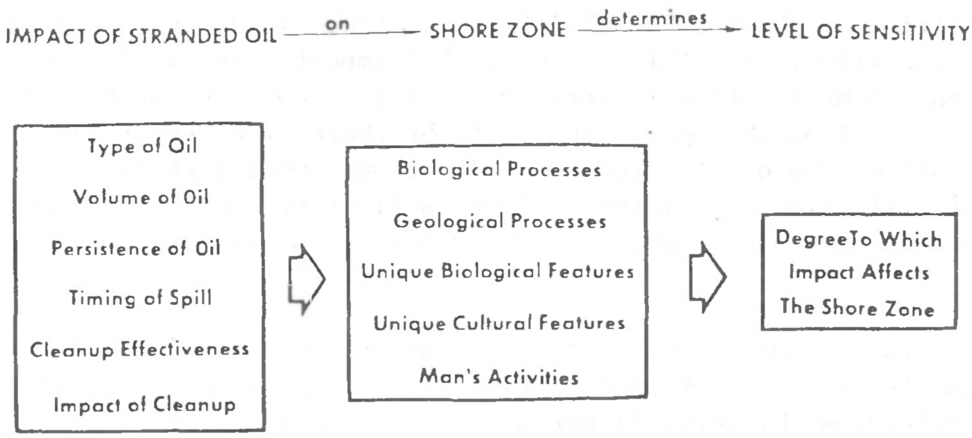


Figure 63: Factors that affect the level of shoreline sensitivity

Table 9: Factors that alter the residence time (persistence of stranded oil)

Factors that REDUCE impact and INCREASE rates of physical breakdown and degradation of oil	Factors that INCREASE impact and REDUCE rates of physical breakdown and degradation of oil
Waves • increasing wave-energy levels • mix or breakdown oil in breaker, surf and swash zones • use sediments as abrasive tools • redistribute or erode oil on the shore • reflected waves mix or break down oil and may prevent oil reaching the shoreline	Waves • decreasing wave-energy levels • bury oil by beach accretion or by long-shore migration of sediments • reduce temperature of oil • throw oil above the normal level of wave activity by the splashing action of breakers
Tides • low water levels cause deposition of oil in sections that would later be subject to wave or current action	Tides • high water levels cause deposition of oil above normal limits of wave or current action • oil can be carried onto marsh surface
Winds • increase rates of evaporation • increase dispersion and spreading of surface slicks	Winds • redistribute sediments and bury oil on the backshore • generate storm surges and oil is deposited in lagoons (by overwash) or in the back-shore • onshore winds trap oil on coast during surge, deposition then occurs above level of normal wave activity when water level lowers
Currents • increase dispersion of oil in water • transport oil offshore	Currents • concentrate oil in eddies and other areas of low currents • transport oil to previously non-impacted areas

the event of a large spill, whereas tar ball pollution is very common and has a relatively low impact on recreation, so that the type and quantity of pollution is an important factor in any sensitivity analysis.

Definitions:

- shoreline sensitivity is the effect of oil upon a resource (human or biological) and the recovery potential of that resource;
- shoreline vulnerability is the adverse effect that might occur if oil contacts a resource;
- shoreline oilspill risk is the probability that a spill will occur and that it will contact a resource; and
- oil persistence is the residence time of oil at a particular location.

ONSHORE OILSPILL COUNTER-MEASURES

Nearshore-onshore protection priorities

Consideration of a protection operation involves evaluation of the potential threat to a section of coast from oil. If an area is likely to be severely impacted and if a protection operation is feasible (in terms of time and available resources) then implementation of protective measures can be considered. If more than one area is threatened by a spill (and these threats

Table 10: The impact and persistence of stranded oil

SHORELINE TYPE	IMPACT OF OIL	PERSISTENCE
Coasts Without Sediment		
ROCK MAN-MADE	• oil may be reflected • coats exposed dry surfaces • wave splash can throw oil above normal limits of wave action • oil does not easily adhere to wet surfaces • thickness of oil cover decreases as steepnesss increases • oil collects in rock pools	• oil readily abraded if it is stranded below normal limit of wave activity, except in sheltered sites
Coasts With Sediment		
MUD	• mud has very small spaces between particles and these are usually filled with water, therefore, only very light grades of oil penetrate	• muds are easily transported by waves, therefore, oil can be buried • buried oil degrades very slowly in muds • surface oil may be easily removed by waves because water usually separates the oil from the mud
SAND	• only light oils can penetrate sand • heavy oils rarely penetrate more than 2 to 3 cm • penetration depths are greater during periods of high temperatures • oil is usually deposited at upper limit of wave action	• oil can be easily abraded if it is not buried and if it is within the zone of wave action • possibility of burial is high if beach is subject to wave action during storms • oil/sediment may form an "asphalt pavement", thereby increasing persistence
PEBBLE COBBLE BOULDER	• as the size of the sediments increases, the depth of penetration of all oils increases • penetration of medium and heavy oils can be as much as 1.0 m • light grades of oil may be washed through the beach and flushed by waves	• buried oil and "asphalt pavements" are very persistent • surface oil is easily abraded by waves and moving sediments
MIXED SEDIMENTS	• spaces between larger particles are filled with smaller-sized sediments, therefore, oils rarely penetrate (except light grades)	• usually low energy environments, therefore, even surface oil persists • "asphalt pavements" are common
MARSHES	• oil is usually restricted to the marsh edges • light oils are more toxic to the vegetation and can penetrate the marsh sediments • impact is less severe in autumn and winter months	• mechanical energy levels are low, but biochemical degradation is rapid if oil is not buried • marshes usually recover naturally unless the oil is very toxic or very large volumes of oil carpet the vegetation

have been verified by field checks) then a decision is necessary to determine how the available manpower and equipment resources will be deployed. This establishment of priorities can only be made at the time of a spill incident in most cases. Highest priority areas would normally be those where human life or safety is endangered. Second priority areas may be, for example, sections of coast (a) actively in use by rare, threatened or endangered species, or (b) where there exist threatened human subsistence activities.

Nearshore protection methods

The prevention of oil reaching the coast or a particular sections(s) of coast involves the use of resources to contain and remove oil from the water surface, or to divert oil.

The primary tools for containment are floating booms and for removal are skimmers. Booms are affected by high current velocities and by high waves. Different booming methods (see table 11) are more or less applicable for different conditions. Figures 64 to 70 provide illustrations of these booming techniques. There exist many different types and sizes of boom: the principal types are fence booms, curtains booms (regular or compactable) and sorbent booms. Boom failure (in terms of oil containment) usually occurs due to high winds or water currents, and oil is either entrained or splashes over the boom.

Skimmers can be used to remove contained or free-floating oil from the water surface. The skimmers may be self-propelled or floating. The primary skimmer types are shown in fig. 71. These include:

- oleophilic disc skimmers;
- absorbant (oleophilic belt or ropes);
- weir skimmers;
- filter belt or non-absorbent belt skimmers;
- centrifugal or vortex skimmers; and
- vacuum systems.

Onshore protection methods

On beaches, the construction of dykes (artificial berms) or of a dyke/ditch combination, can prevent oil from being carried into backshore areas (fig. 72). This may be desirable if (a) there is a sensitive backshore marsh or lagoon, or (b) clean-up using machinery would be made easier. In the latter case, the bearing capacity for vehicles is usually better on the lower beach (below the normal high-water level) than on the back beach, so that it may be preferable to prevent oil from reaching areas where clean-up operations may be more difficult and also less effective.

Dykes can be constructed rapidly by machinery. A ditch on the seaward side of the dyke can act as a collector for the oil, which would then be removed using buckets or pumps (fig. 72). Dams can be constructed across channels or inlets to prevent oil from reaching backshore lagoons or ponds. In some cases (e.g., where there is a tidal exchange of water) it may be necessary to install an underwater culvert so that this exchange is not impeded, while at the same time preventing oil from passing through the channel (see fig. 73).

Onshore clean-up priorities

Resource limitations (equipment and manpower) require that some order of action or set of priorities be developed for the clean-up of stranded oil where natural recovery is not acceptable. The selection of appropriate techniques can only be carried out at the time of a spill when the character, volume, and distribution of the oil, and the environmental conditions, are known. Consideration must also be given to the potential success of a clean-up operation. If a clean-up programme on one section of coast cannot meet the objectives for that operation because of resource limitations or environmental constraints, then the priority for that action should be re-evaluated.

Table 11: Nearshore protection techniques

Protection Technique	Description of Technique	Primary Use of Protection Technique	Environmental Effect of Use
1. Exclusion Booming	Boom is deployed across or around sensitive areas and anchored in place. Approaching oil is deflected or contained by boom.	Used across small bays, harbour entrances, inlets, river or creek mouths where currents are less than 1 kt and breaking waves are less than 25 cm in height.	Minor disturbance to shore or to bottom at anchor points.
2. Diversion Booming	Boom is deployed at an angle to the approaching slick. Oil is diverted away from the sensitive area or to a less sensitive area for recovery.	Used on inland streams where currents are greater than 1 kt; across small bays, harbour entrances, inlets, river or creek mouths where currents exceed 1 kt and breaking waves are less than 25 cm, and on straight coastline areas to protect specific sites, where breaking waves are less than 25 cm.	Minor disturbances to substrate at shoreline anchor points; cause heavy shoreline oil contamination on downstream side.
3. Containment Booming	Boom is deployed in a "U" shape in front of the oncoming slick. The ends of the boom are anchored by drogues or work boats. The oil is contained within the "U" and prevented from reaching the shore.	Used on open water to surround an approaching oil slick to protect shoreline areas where surf is present and oil slick does not cover a large area; also on inland waters where currents are less than 1 kt.	No effect on open water; minor disturbance to substrate at anchor points.
4. Sorbent Booming	Boom is anchored along a shoreline or used in one of the manners described above to protect sensitive areas and absorb oil.	Used on quiet waters with minor oil contamination.	Minor disturbance at anchor points.
5. Sorbent Barrier	Barriers are constructed across a waterway and constructed of wire mesh and stakes which contain loose sorbents. The barrier allows water to flow, but retains and absorbs oil on the surface.	Used in small, low-velocity streams, tidal inlets or channels, or any narrow waterway with low current velocities.	Minor disturbance to stream or channel substrate.

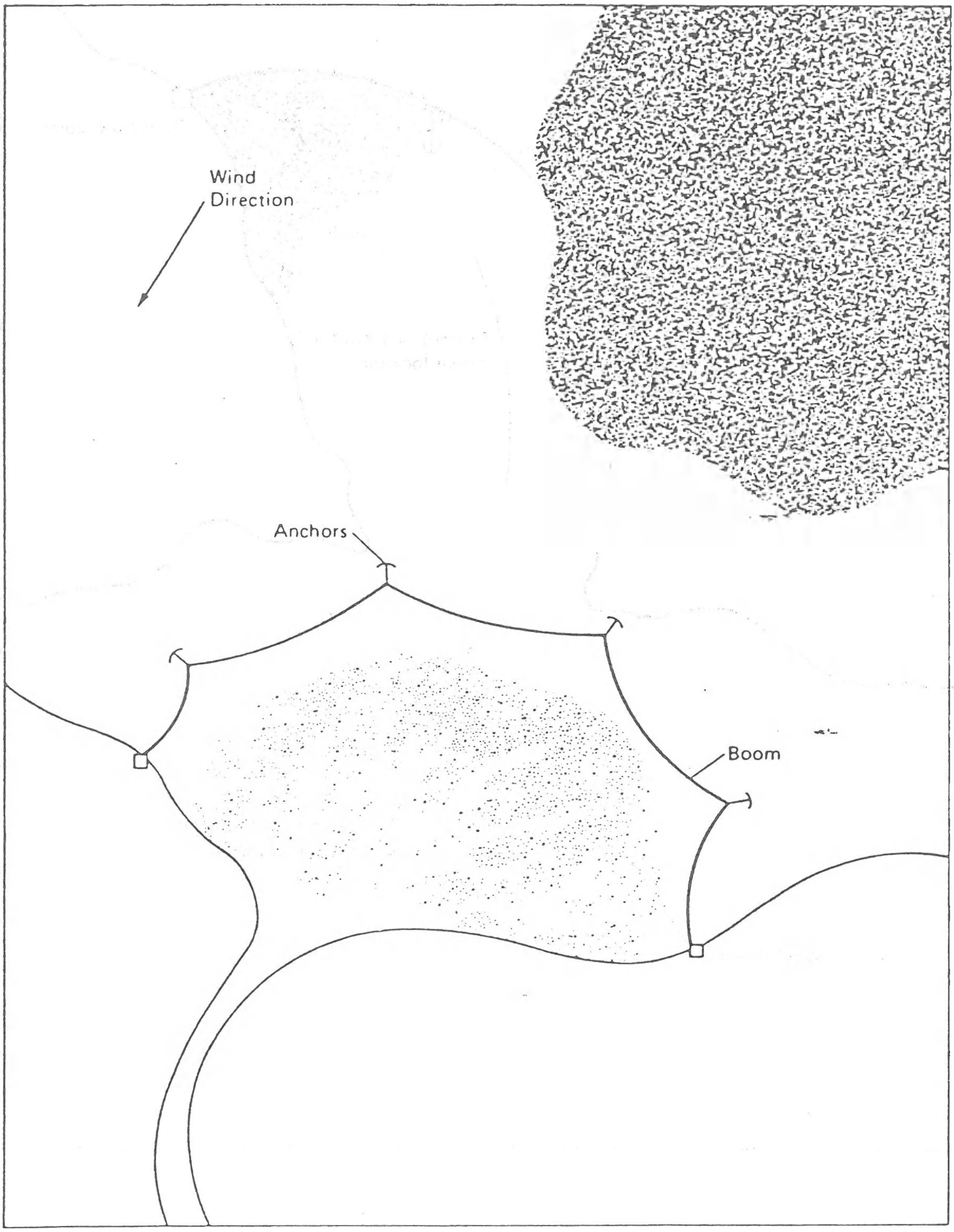


Figure 64: Exclusion booming of a stream delta

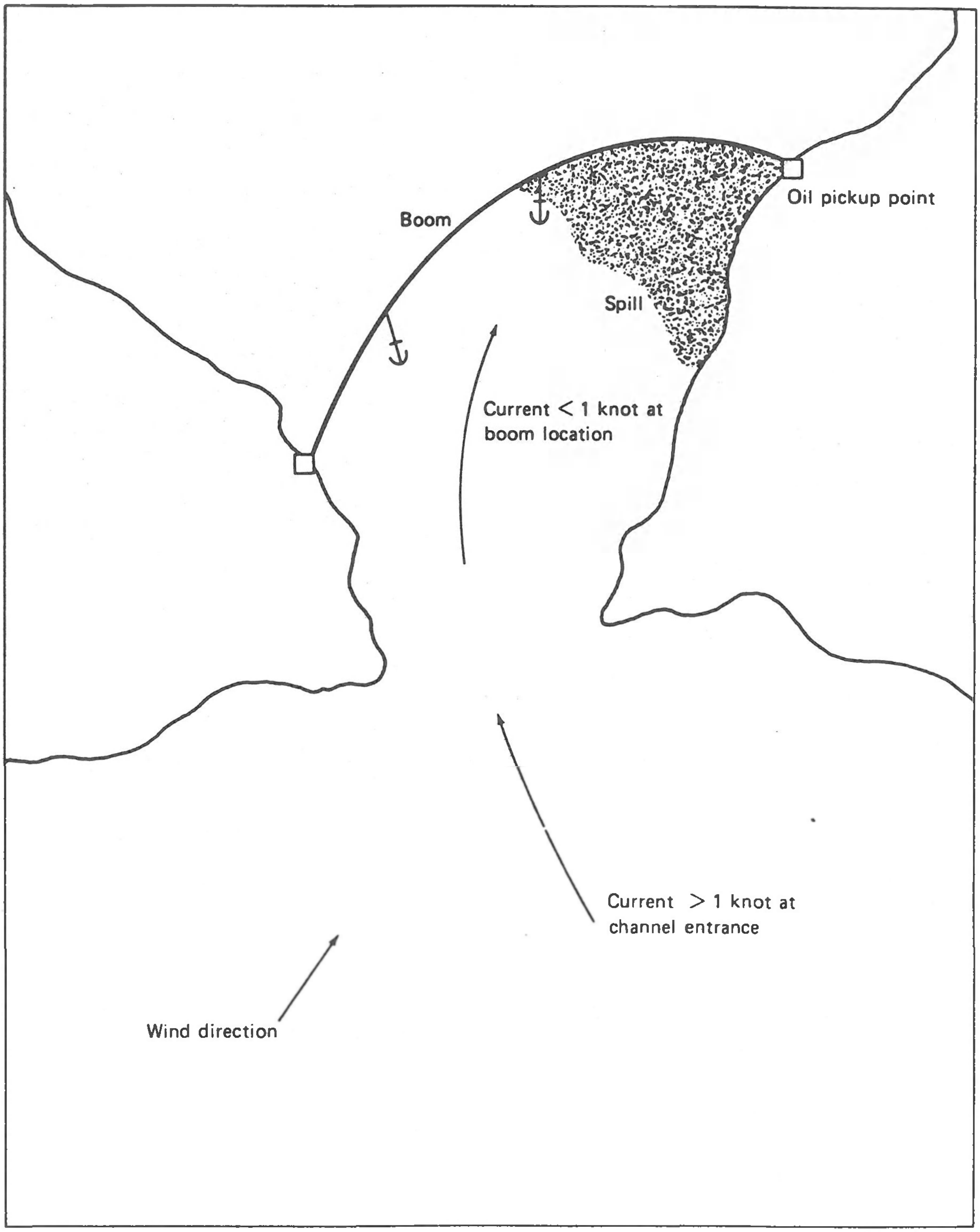


Figure 65: Exclusion booming at inlet with high channel currents

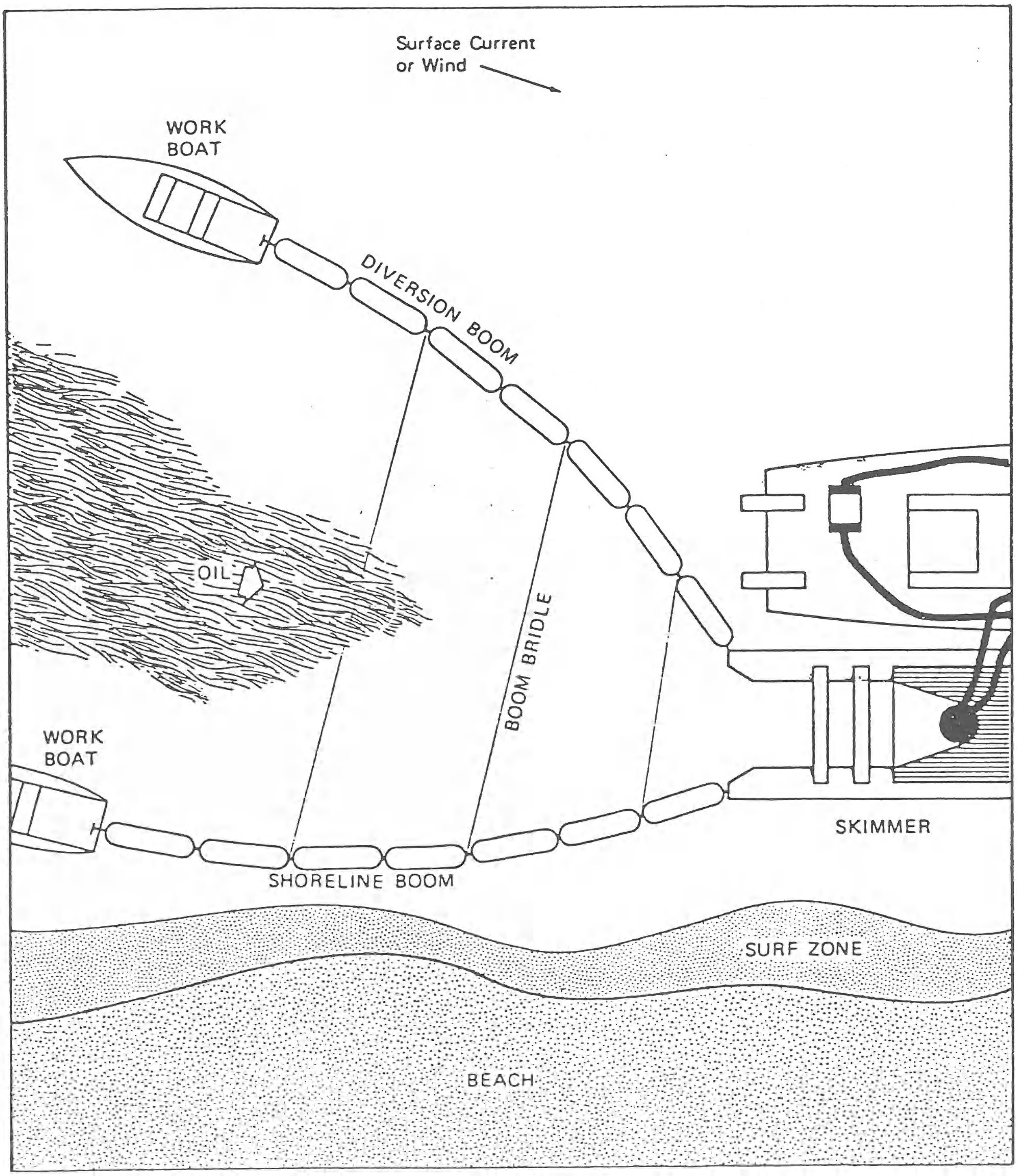


Figure 66: Protecting sensitive shoreline with two booms

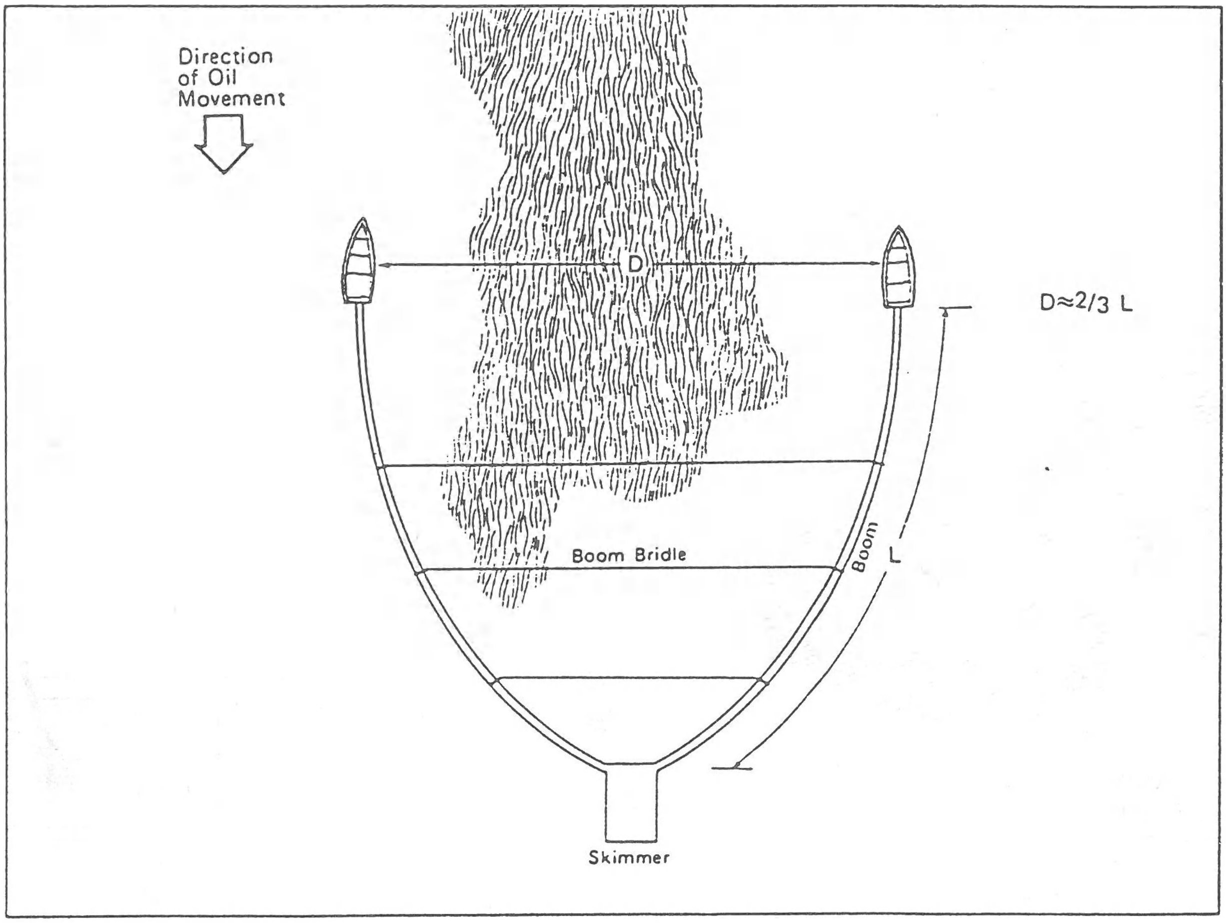


Figure 67: Boat, boom, and skimmer relationship

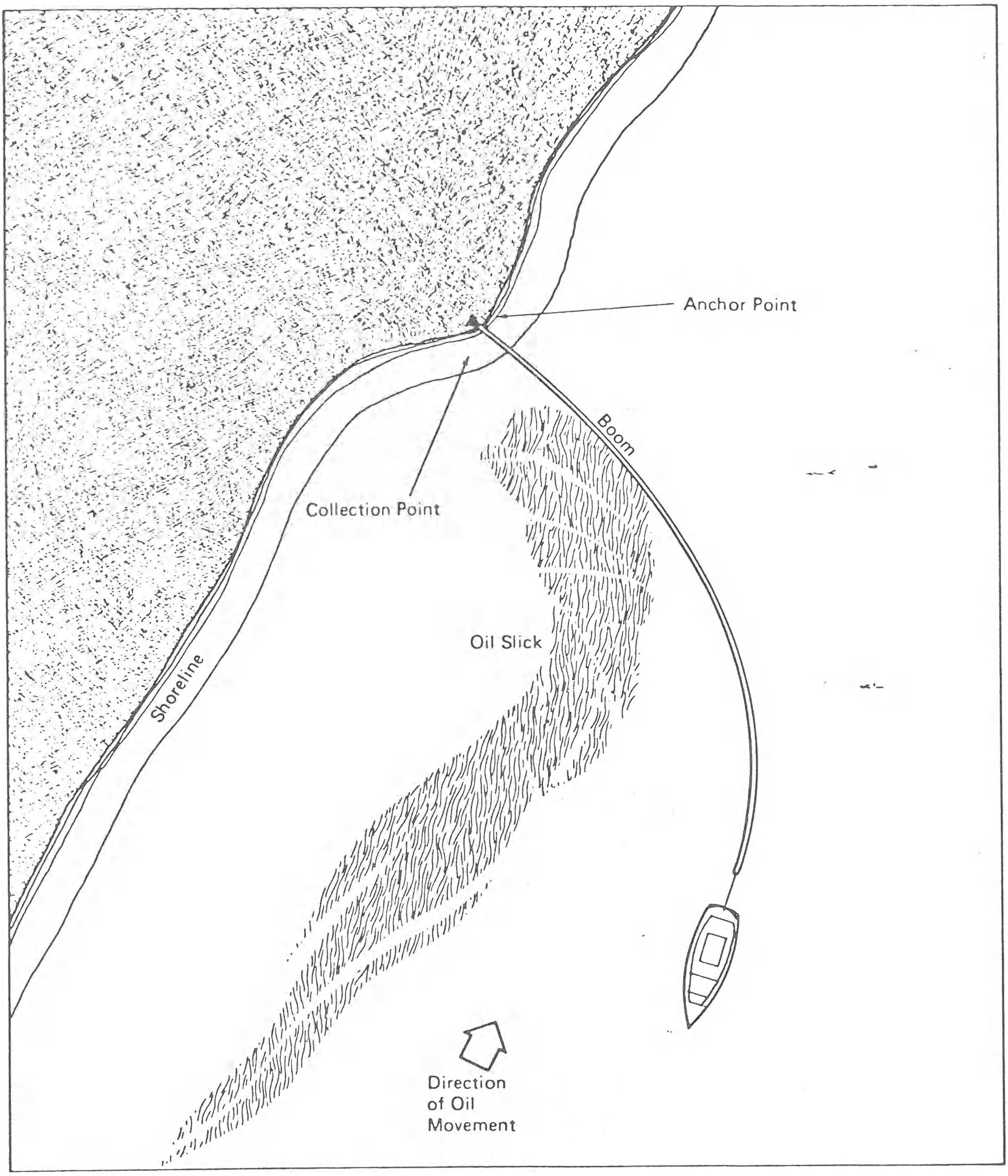


Figure 68: Diversion booming along shoreline

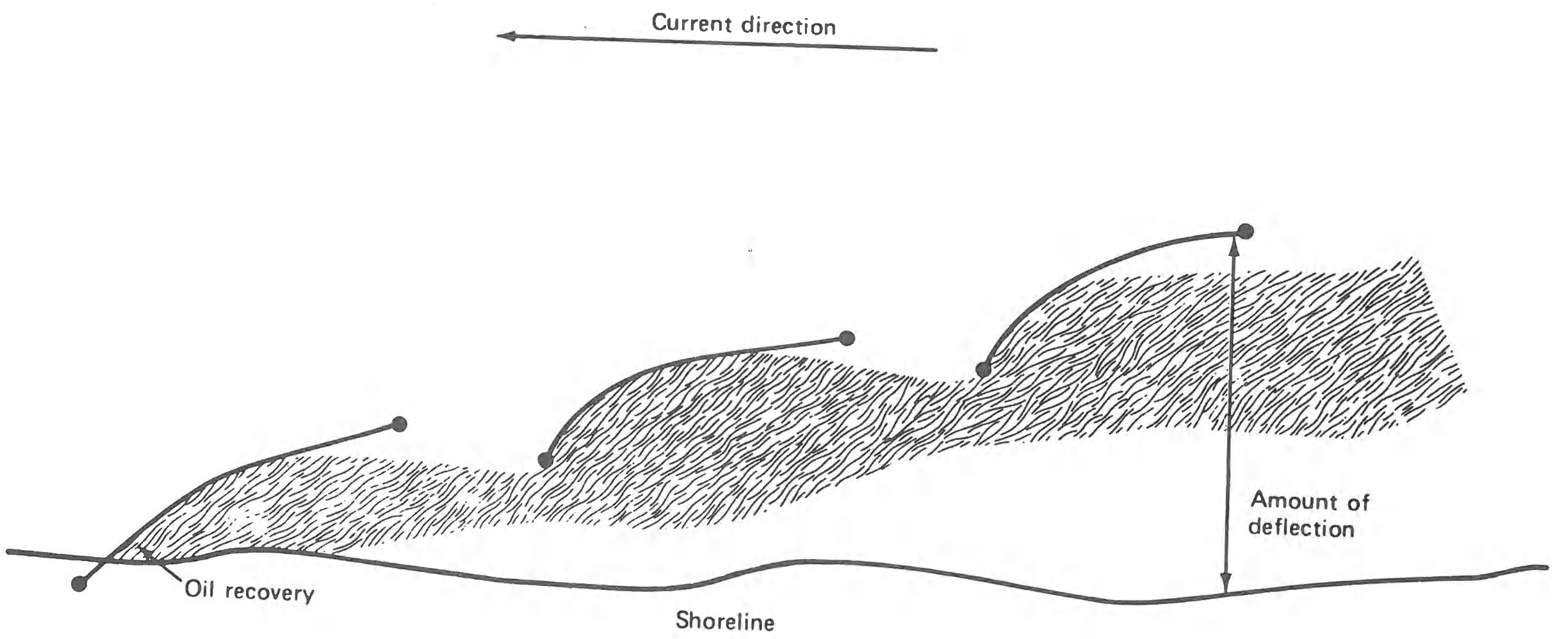


Figure 69: Placement configuration of 3 lengths of boom (cascading deflection booms)

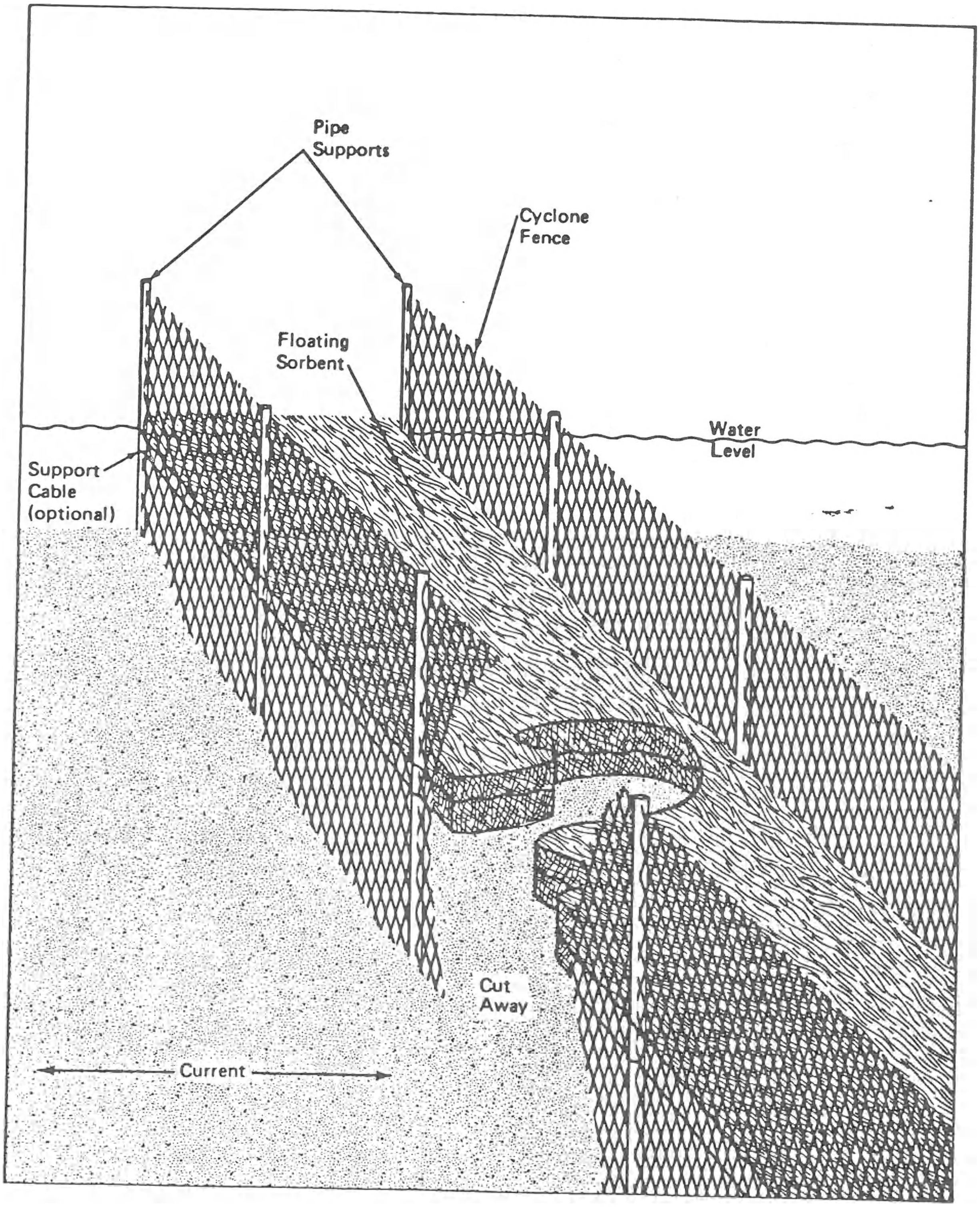


Figure 70: Typical permeable barrier

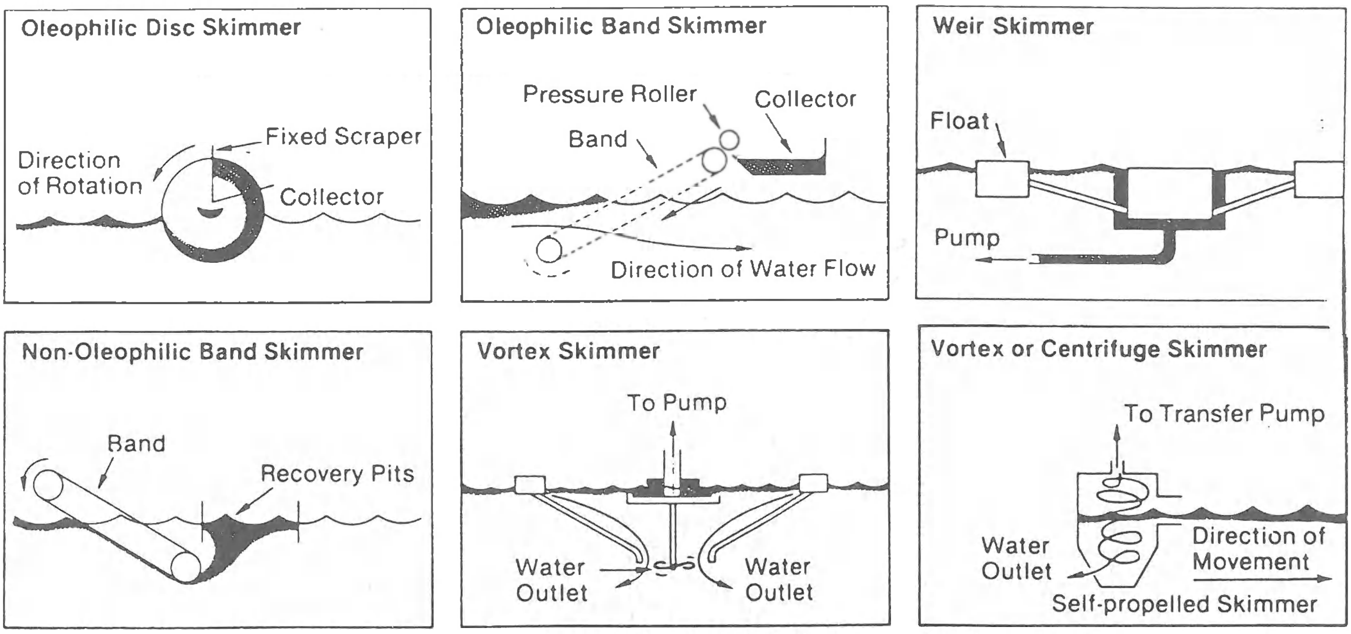


Figure 71: Examples of different types of skimmers (from CONCAWE, 1981)

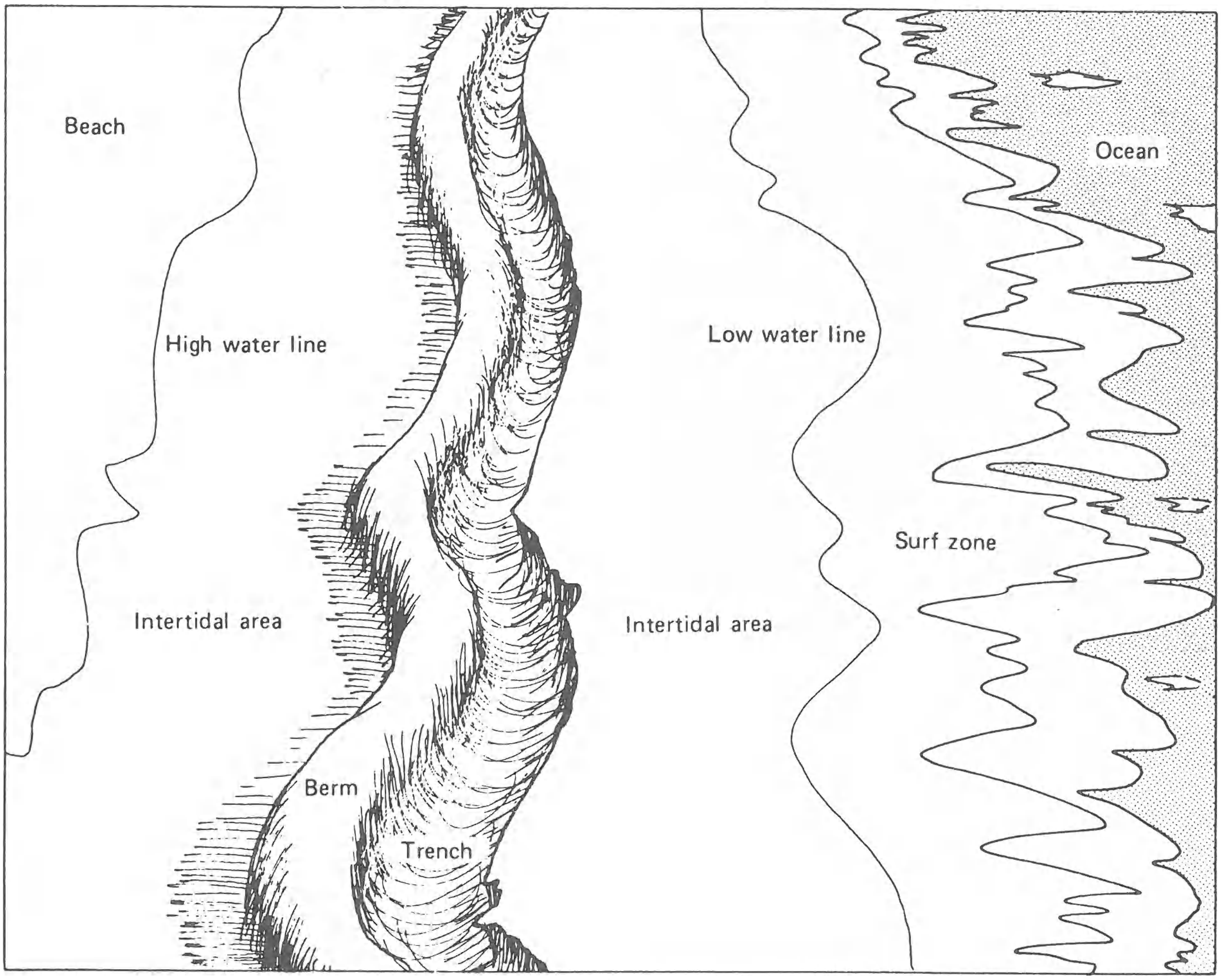
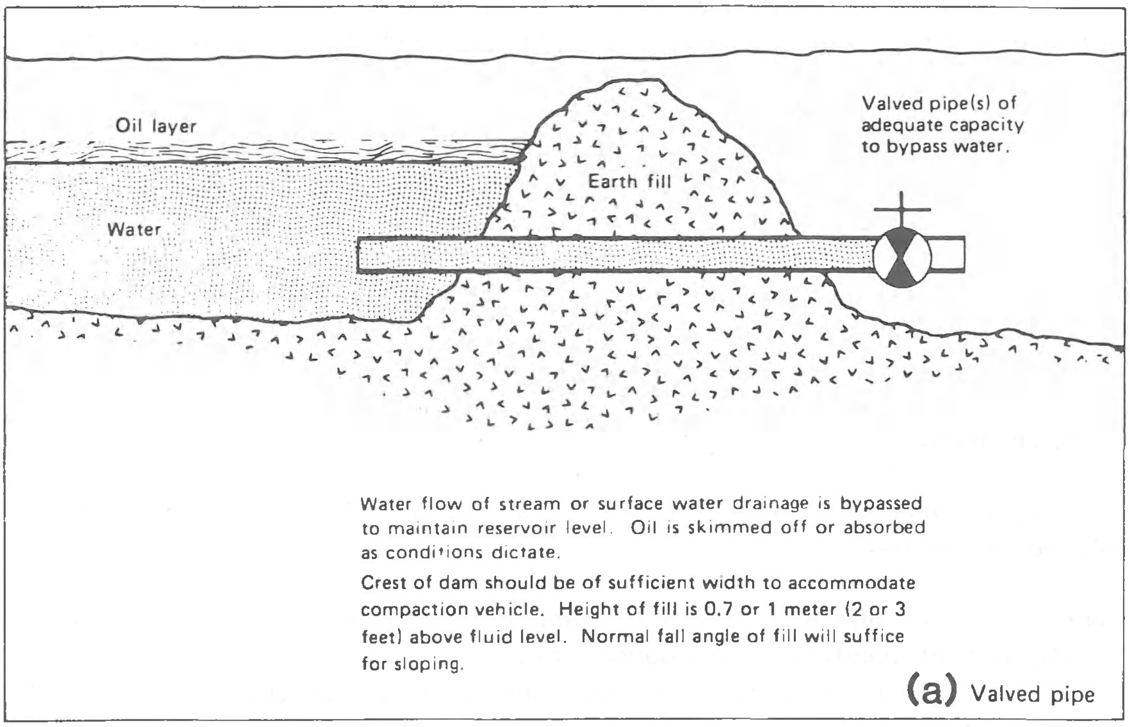


Figure 72: Ditch-dyke system



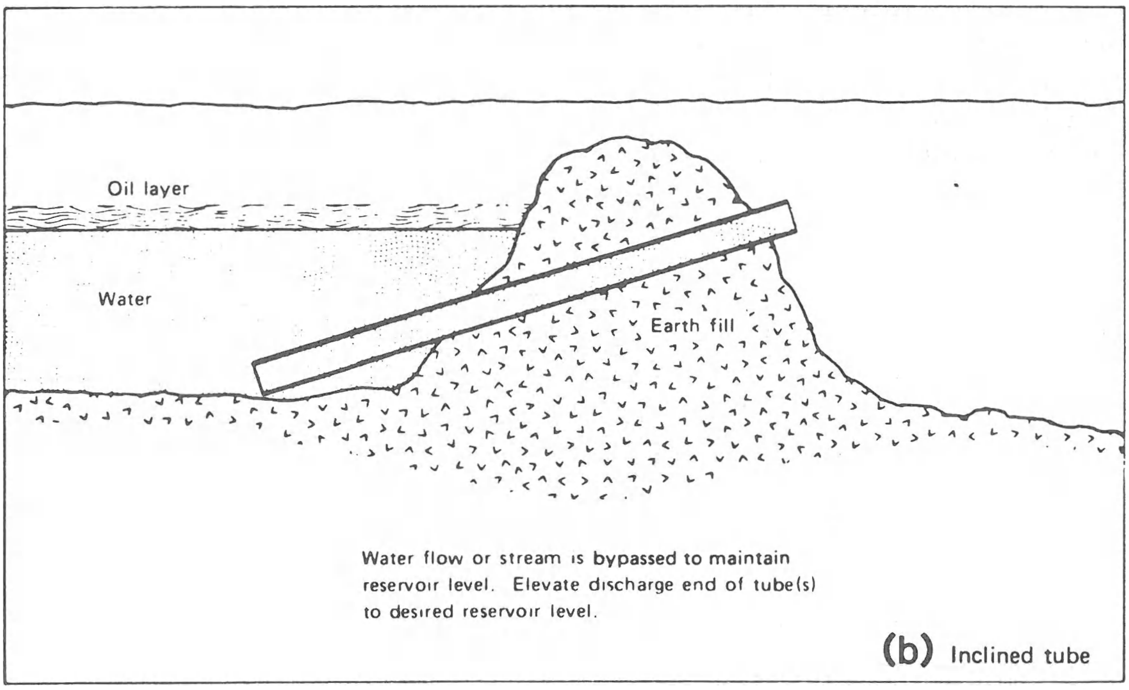


Figure 73: Water bypass dams; (a) valved pipe; (b) inclined tube

Onshore clean-up methods

A wide range of methods and techniques have been developed for the removal of contaminated sediments or oil from different substrates. In the development of parameters for shoreline operations the most fundamental distinction is between mechanical methods in which a machine is operated in a non-labour intensive manner and is motorised so that the equipment physically moves along the shoreline. Manual techniques are those in which the physical removal or dispersion or oil is undertaken by hand or by the operation of small machines (e.g. a pump or hose etc.) in a labour-intensive operation. Table 12 summarizes the different methods of shoreline clean-up and indicated the requirements for labour and also for the disposal of contaminated material. In this table effectiveness relates to the degree to which the oil is removed from the shoreline, whereas efficiency relates to the speed with which the operation can be undertaken.

The major categories of shoreline clean-up techniques presented in table 13 are defined as follows:

- manual removal and disposal - by hand or using shovels, rakes, solvents, or by the use of hand-operated machinery;
- manual dispersion - using hoses or back-pack sprays (hydraulic or chemical dispersion);
- motorised removal and disposal - by the use of machinery to lift oil and contaminated material from the shore zone for disposal at another location;
- motorised dispersal - involving the use of hydraulic or chemical dispersion techniques (e.g. by the use of motorised spray machinery, helicopters, or fixed-wing aircraft);
- sediment cleaning - removal of contaminated material is removed, either manually or mechanically, for cleaning by the use of hydraulic or washing techniques or by incineration. The cleaned material is then replaced in the shore-zone;
- motorised in situ removal - the use of machinery to remove oil from the beach by either sifting, shaking, or by adhesion of the oil to an oleophilic material; and
- motorised mixing - the use of heavy equipment to break up the oil cover and either push the material into the surf zone or to mix the surface layers.

The actual techniques are summarized in table 12 (see Foget et al., 1979 for a more detailed analysis of the techniques and their application). Mixing techniques (items 20, 21 and 22 on table 12) might be used to promote natural degradation by either exposing a larger surface area of the oil, by using machinery as a form of mechanical energy, or by moving the oil and contaminated sediments into the zone of wave action. These techniques could be used if actual removal of the oil and oil-contaminated sediments is not required.

A discussion of the use of beach cleaning machines (item 15 on table 12) is given further in the document. If oil contamination of beaches is extensive, the use of heavy equipment is more efficient and effective than manual removal. Manual clean-up is effective if (a) the oiling is light or patchy, (b) heavy equipment cannot be used, or (c) to remove residual oil after a mechanical clean-up operation. The clean-up of marshes requires a different approach to that used for other shoreline types. Applicable techniques are indicated in table 14 and further information is given for marsh and mangrove clean-up by Maiero et al. (1978).

Table 12: Shoreline clean-up methods

Cleanup Technique	Description	Primary Use of Cleanup Technique	Technique Requirements	Physical Effect of Use	Biological Effect of Use
1. Motor grader/ elevating scraper	Motor grader forms windrows for pickup by elevating scraper	Used primarily on sand and gravel beaches where oil penetration is 0 to 3 cm, and trafficability of beach is good. Can also be used on mudflats.	Good trafficability. Heavy equipment access.	Removes only upper 3 cm of beach.	Removes shallow burrowing polychaetes, bivalves, and amphipods. Recolonization likely to rapidly follow natural replenishment of the substrate.
2. Elevating scraper	Elevating scraper picks up contaminated material directly off beach.	Used on sand and gravel beaches where oil penetration is 0 to 3 cm. Can also be used on mudflats. Also used to remove tar balls or flat patties from the surface of a beach.	Fair to good trafficability. Heavy equipment access.	Removes upper 3 to 10 cm of beach. Minor reduction of beach stability. Erosion and beach retreat.	Removes shallow and deeper burrowing polychaetes, bivalves, and amphipods. Restabilization of substrate probably slow; recolonization likely to follow natural replenishment of substrate; reestablishment of long-lived indigenous fauna may take several years.
3. Motor grader/ front-end loader.	Motor grader forms windrows for pickup by front-end loader.	Used on gravel and sand beaches where oil penetration is less than 2 to 3 cm. This method is slower than using a motor grader and elevating scraper but can be used when elevating scrapers are not available. Can also be used on mudflats.	Good trafficability. Heavy equipment access.	Removes only upper 3 cm of beach.	Removes shallow burrowing polychaetes, bivalves, and amphipods. Recolonization likely to rapidly follow natural replenishment of the substrate.
4. Front-end loader; rubber-tired or tracked	Front-end loader picks up material directly off beach and hauls it to unloading area.	Used on mud, sand, or gravel beaches when oil penetration is moderate and oil contamination is light to moderate. Rubber-tired front-end loaders are preferred because they are faster and minimize the disturbance of the surface. Front-end loaders are the preferred choice for removing cobble sediments. If rubber-tired loaders cannot operate, tracked loaders are the next choice. Can also be used to remove extensively oil-contaminated vegetation.	Fair to good trafficability for rubber-tired loader. Heavy equipment access.	Removes 10 to 25 cm of beach. Reduction of beach stability. Erosion and beach retreat.	Removes almost all shallow and deep burrowing organisms. Restabilization of the physical environment slow; new faunal community could develop.
5. Bulldozer; rubber-tired front-end loader	Bulldozer pushes contaminated substrate into piles for pickup by front-end loader.	Used on coarse sand, gravel, or cobble beaches where oil penetration is deep, oil contamination extensive, and trafficability of the beach poor. Can also be used to remove heavily oil-contaminated vegetation.	Heavy equipment access. Fair to good trafficability for front-end loader.	Removes 15 to 50 cm of beach. Loss of beach stability. Severe erosion and cliff or beach retreat. Inundation of backshores.	Removes all organisms. Restabilization of substrate and repopulation of indigenous fauna is extremely slow; new faunal community could develop in the interim.

Table 12: Shoreline clean-up methods (cont'd)

6. Backhoe	Operates from top of a bank or beach to remove contaminated sediments and loads into trucks.	Used to remove oil contaminated sediment (primarily mud or silt) on steep banks.	Heavy equipment access. Stable substrate at top of bank.	Removes 25 to 50 cm of beach or bank. Severe reduction of beach stability and beach retreat.	Removes all organisms. Restabilization of substrate and repopulation of organisms is extremely slow; new faunal community could develop in the interim.
7. Dragline or Clamshell	Operates from top of contaminated area to remove oiled sediments.	Used on sand, gravel, or cobble beaches where trafficability is very poor (i.e., tracked equipment cannot operate) and oil contamination is extensive.	Heavy equipment access to operating area. Equipment reach covers contaminated area.	Removes 25 to 50 cm of beach. Severe reduction of beach stability. Erosion and beach retreat.	Removes all organisms. Restabilization of substrate and repopulation of indigenous fauna is extremely slow; new faunal community could develop in the interim.
8. High pressure flushing (hydro-blasting)	High pressure water streams remove oil from substrate where it is channeled to recovery area.	Used to remove oil coatings from boulders, rock, and man-made structures; preferred method of removing oil from these surfaces.	Light vehicular access. Recovery equipment.	Can disturb surface of substrate.	Removes some organisms and shells from the substrace, damage to remaining organisms variable. Oil not recovered can be toxic to organisms downslope of cleanup activities.
9. Steam cleaning	Steam removes oil from substrate where it is channeled to recovery area.	Used to remove oil coatings from boulders, rock, and man-made structures.	Light vehicular access. Recovery equipment. Fresh water supply.	Adds heat (> 100°C) to surface.	Removes some organisms from substrate but mortality due to the heat is more likely. Empty shells remaining may enhance repopulation. Oil not recovered can be toxic to organisms downslope of cleanup activities.
10. Sandblasting	Sand moving at high velocity removes oil from substrate.	Used to remove thin accumulations of oil residue from man-made structures.	Light vehicular access. Oil must be semi-solid. Supply of clean sand.	Adds material to the environment. Potential recontamination, erosion, and deeper penetration into substrate.	Removes all organisms and shells from the substrate. Oil not recovered can be toxic to organisms downslope of cleanup activities.
11. Manual scraping	Oil is scraped from substrate manually using hand tools.	Used to remove oil from lightly contaminated boulders, rocks, and man-made structures or heavy oil accumulation when other techniques are not allowed.	Foot access. Scraping tools and disposal containers.	Selective removal of material. Labour-intensive activity can disturb sediments.	Removes some organisms from the substrate, crushes others. Oil not removed or recovered can be toxic to organisms repopulating the rocky substrate or inhabiting sediment downslope of cleanup activities.

Table 12: Shoreline clean-up methods (cont'd)

Cleanup Technique	Description	Primary Use of Cleanup Technique	Technique Requirements	Physical Effect of Use	Biological Effect of Use
12. Sump and pump/ vacuum	Oil collects in sump as it moves down the beach and is removed by pump or vacuum truck.	Used on firm sand or mud beaches in the event of continuing oil contamination where sufficient longshore currents exist, and on streams and rivers in conjunction with diversion booming.	Heavy equipment access. A long-shore current present.	Requires excavation of a sump 60 to 120 cm deep on shoreline. Some oil will probably remain on beach.	Removes organisms at sump location. Potentially toxic effects from oil left on the shoreline. Recovery depends on persistence of oil at the sump.
13. Manual removal of oiled materials	Oiled sediments and debris are removed by hand, shovels, rakes, wheelbarrows, etc.	Used on mud, sand, gravel, and cobble beaches when oil contamination is light or sporadic and oil penetration is slight, or on beaches where access for heavy equipment is not available.	Foot or light-vehicular access.	Removes 3 cm or less of beach. Selective. Sediment disturbance and erosion potential.	Removes and disturbs shallow burrowing organisms. Rapid recovery.
14. Low-pressure flushing	Low pressure water spray flushes oil from substrate where it is channeled to recovery points.	Used to flush light oils that are non-sticky from lightly contaminated mud substrates, cobbles, boulders, rocks, man-made structures, and vegetation.	Light vehicular access. Recovery equipment	Does not disturb surface to any great extent. Potential for recontamination.	Leaves most organisms alive and in place. Oil not recovered can be toxic to organisms downslope of cleanup.
15. Beach cleaner	Pulled by tractor or self-propelled across beach, picking up tar balls or patties.	Used on sand or gravel beaches, lightly contaminated with oil in the form of hard patties or tar balls.	Moderate to heavy vehicular access. Good trafficability.	Disturbs upper 5 to 10 cm of beach.	Disturbs shallow burrowing organisms.
16. Manual sorbent application	Sorbents are applied manually to contaminated areas to soak up oil.	Used to remove pools of light, nonsticky oil from mud, boulders, rock, and man-made structures.	Foot or boat access. Disposal containers for sorbents.	Selective removal of material. Labour intensive activity can disturb sediments.	Foot traffic may crush organisms. Possible ingestion of sorbents by birds and small animals.
17. Manual cutting	Oiled vegetation is cut by hand, collected, and stuffed into bags or containers for disposal.	Used on oil-contaminated vegetation.	Foot or boat access. Cutting tools.	Disturbs sediments because of extensive use of labour; can cause erosion.	Removes and crushes some organisms. Rapid recovery. Heavy foot traffic can cause root damage and subsequent slow recovery.

Table 12: Shoreline clean-up methods (cont'd)

18. Burning	Upwind end of contaminated area is ignited and allowed to burn to down-wind end.	Used on any substrate or vegetation where sufficient oil has collected to sustain ignition; if oil is a type that will support ignition, and air pollution regulations so allow.	Light vehicular or boat access. Fire control equipment.	Causes heavy air pollution; adds heat to substrate, can cause erosion if root system damaged.	Kills surface organisms caught in burn area. Residual matter may be somewhat toxic (heavy metals).
19. Vacuum trucks	Truck is backed up to oil pool or recovery site where oil is picked up via the vacuum hose.	Used to pick up oil on shorelines where pools of oil have formed in natural depressions, or in the absence of skimming equipment to recover floating oil from the water surface.	Heavy equipment access. Large enough pools on land or thick enough oil on water for technique to be effective.	Some oil may be left on shoreline or in water.	Removes some organisms. Potential for longer-term toxic effects associated with oil left on the shoreline. Recovery depends on persistence of oil left in the pools.
20. Push contaminated substrate into surf	Bulldozer pushes contaminated substrate into surf zone to accelerate natural cleaning.	Used on contaminated cobble and lightly contaminated gravel beaches where removal of sediments may cause erosion of the beach or backshore area.	Heavy equipment access. High energy shoreline.	Disruption of top layer of substrate; leaves some oil in intertidal area. Potential recontamination.	Kills most of the organisms inhabiting the uncontaminated substrate. Recovery of organisms usually more rapid than with removing substrate.
21. Breaking up pavement	Tractor fitted with a ripper is operated up and down beach.	Used on low amenity cobble, gravel or sand beaches or beaches where substrate removal will cause erosion; or where thick layers of oil have created a pavement on the beach surface.	Heavy equipment access. High energy shoreline.	Disruption of sediments. Leaves oil on beach.	Disturbs shallow and deep burrowing organisms.
22. Disc into substrate	Tractor pulls discing equipment along contaminated area.	Used on nonrecreational sand or gravel beaches that are lightly contaminated.	Heavy equipment access. Fair to good trafficability. High energy environment.	Leaves oil buried in sand. Disrupts surface layer of substrate.	Disturbs shallow burrowing organisms. Possible toxicity effects from buried oil.
23. Natural recovery	No action taken. Oil left to degrade naturally.	Used for oil contamination on high energy beaches (primarily cobble, boulder, and rock) where wave action will remove most oil contamination in a short period of time.	Exposed high energy environment.	Some oil may remain on beach and could contaminate clean areas.	Potential toxicity effects and smothering by the oil. Potential incorporation of oil into the food web. Potential elimination of habitat if organisms will not settle on residual oil.

Table 13: Basic categorisation of shoreline cleanup methods

METHOD	PERSONNEL REQUIREMENTS	DISPOSAL REQUIREMENTS	EFFECTIVENESS/EFFICIENCY
1. Manual Removal and Disposal	labour intensive	disposal facilities necessary	effective but generally a slow method
2. Manual Dispersion	labour intensive	some disposal if non-chemical techniques employed	usually effective but generally a slow method
3. Motorized Removal and Disposal	not labour intensive	large volume disposal problem	effective and rapid
4. Motorized Dispersal	not labour intensive	no disposal requirement	usually effective and rapid
5. Sediment Cleaning	not labour intensive if removal motorized	minor disposal requirement	efficient but moderately slow
6. Motorized In-situ Removal	not labour intensive	minor disposal requirement	efficient but moderately slow
7. Motorized Mixing	not labour intensive	no disposal requirement	rapid; but does not clean sediments

Table 14: Summary of Marsh cleaning techniques

Marsh Cleaning Techniques	Situations for Use of Technique	Equipment Required	Environmental Impact of Technique
Low-pressure water flushing	Preferred method: Use in small channels; around clumps of plants and trees; on vegetation, along channel banks and shoreline	Small boat Small gasoline-driven pump Intake and outlet hoses* Small floating skimmer Portable storage tanks Light curtain boom	Minimal impact: Some crushing of marsh plants if flushing is done from land
Sorbents: loose, pads or rolls	Loose sorbents: Use in small channels, or pools with low currents Pads or rolls: Use in open shallow pools and on shorelines without debris accumulations	Empty barrels for storing recovered sorbent Industrial vacuum cleaner or nets for picking up loose-sorbent - can be herded with water spray	Loose sorbents are difficult to retrieve and can crush marsh grasses
Oleophilic endless-rope skimmers	Preferred method: Use in open channels or pools with free-floating oil; upstream from containment boom; and along marsh shorelines	Oleophilic rope system Portable storage tanks for recovered oil Pulleys	Minimal impact
Vegetation cutting and removal (use only when flushing - will not remove oil from plants)*	Hand cutting: On vegetation in small channels Mechanical cutting: Along banks of channels or shoreline	Hand cutting: Shears, power brush cutters, or sickles Mechanical cutting: Weed harvester	Damages marsh surface Foot traffic damages plants
Burning*	Use in large contaminated areas. Can use if oil will burn. Probably suitable when marsh is in die-back stage	Portable propane flame throwers or weed burners	Considerable air pollution from smoke Can burn uncontaminated areas
Soil and vegetation removal	Use when toxic and persistent oils have deeply contaminated substrate	Dragline, dredge, clamshell, front-end loader, backhoe bulldozer	Major impact: Destroys marsh areas. Requires complete subsequent restoration

* For use on spartina-type (grass-like) marshes only

Factors that must be considered in developing a shoreline clean-up response include:

- volume and type of oil;
- physical shoreline character (sediment type, etc.);
- expected persistence of oil;
- oil burial or penetration;
- access to the oiled area;
- trafficability of sediments;
- availability of personnel and equipment; and
- location of temporary and permanent disposal sites.

The use of dispersants is not recommended, primarily because the dispersed oil, while not affecting the biota of the shore zone itself, can adversely impact the flora and fauna of the adjacent nearshore seabed.

Manual removal of oiled materials

Manual removal is used on mud, sand, gravel and cobble beaches when oil contamination is light or sporadic and penetration is slight, or where heavy equipment access is not possible. Manual removal may also be used when heavy equipment use is deemed harmful to the environment.

The equipment required for this work incudes rakes, shovels, hand scrapers, plastic and burlap bags, buckets, and barrels. Oiled vegetation, debris, and sediments are collected by manual labourers and placed in bags for removal and disposal (see fig. 74). Supervisors shold be placed in charge of groups of workers with a foreman for each group. The procedures for manual removal are:

- wear protective gloves, boots and hand cream;
- cut and/or collect contaminated material into small piles;
- do not rake vegetation;
- fill plastic 1/ or burlap bags half full with material from piles;
- place filled bags on plastic sheets above high-water line; and
- remove bags manually, by vehicle or helicopter or by loading onto small boats or barges from shoreline or makeshift docks.

The rate for manually cleaning a shoreline area depends on the number of workers used, their productivity, and the method of removal of contaminated materials, and the degree of contamination. If a shoreline area has sporadic contamination it can be cleaned much faster than if it is heavily contaminated. The more workers used, the faster an area can be cleaned. Helicopter, vessel, or vehicle removal of collected materials is fast and effective, whereas manual removal of collected materials is very slow and labour-intensive.

Tar balls and beach cleaning machines

Tar balls are common on many beaches of the Eastern African region (fig. 75). Several machines have been developed and tested for the removal of tar balls from sand beaches. The Massey-Ferguson Brighton Beach Cleaner uses a tractor-drawn rotating conical screen, with inter-changeable screens of differing mesh sizes (Nightingale, 1973). The Beemer Beach Cleaner is a tractor-drawn system that consists of a bar conveyor and a vibrating bar screen, with two interchangeable bar screen sizes (Nightingale, 1974). A third method, developed at the Warren Spring Laboratory in the U.K., uses coarsely-toothed discs to pick up the tar balls (Wardley-Smith, 1976, p. 188).

More recent equipment developments includes tests on (i) a spined wheel (the Caltrop device), (ii) an endless chain, and (iii) a disc (Russel et al., 1979). One machine in use at the present time to remove tar balls and litter from recreational beaches in Bermuda uses a sieving principal. For small numbers of tar balls fine-toothed rakes may be adequate to clean short sections of a beach manually.

1/ preferred bag thickness: 0.0254 mm (opaque material)
preferred bag size: 91 cm high: 46 - 61 cm wide.

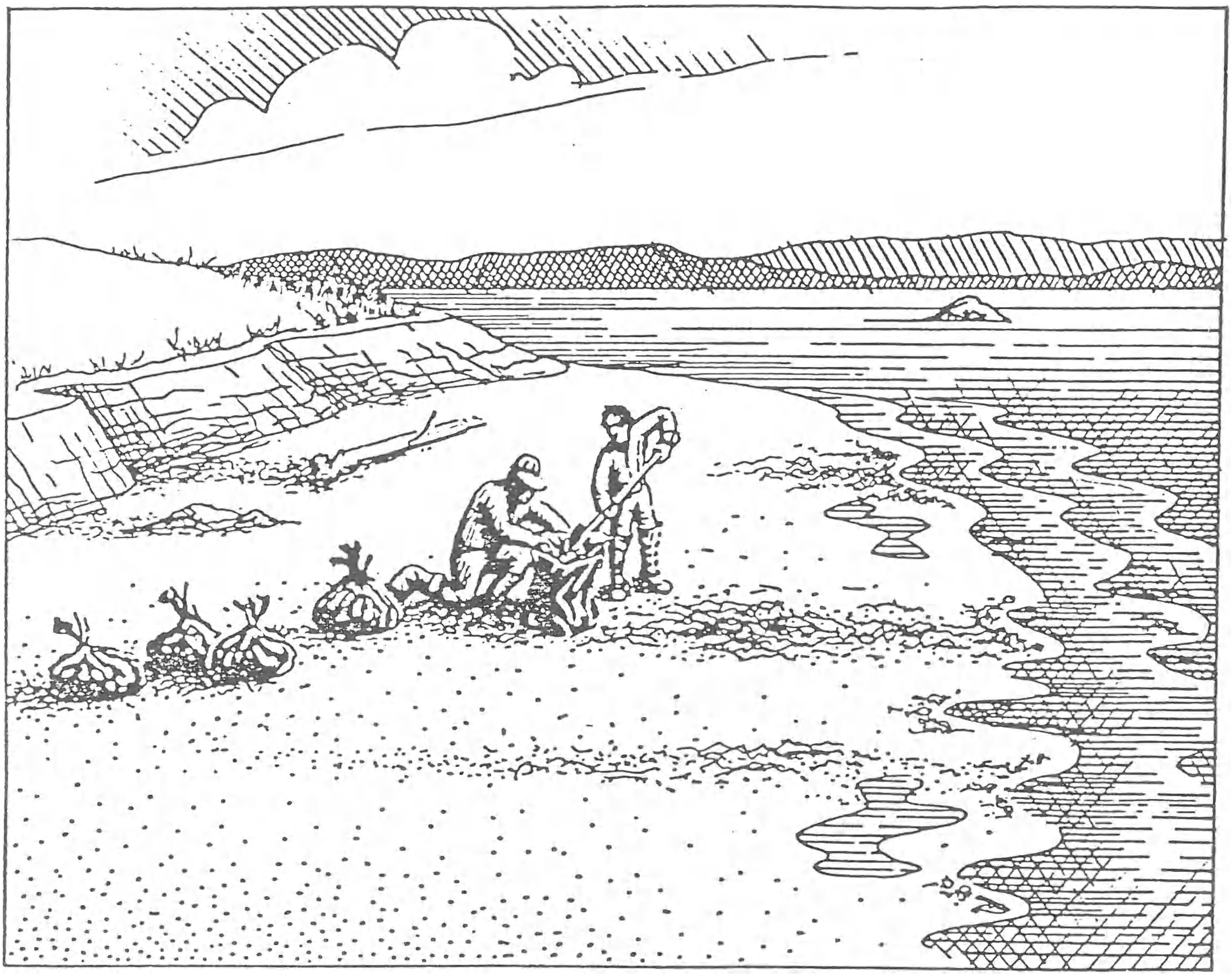


Figure 74: The removal of oil and contaminated sediments using shovels and plastic bags

Figure 75: Tarball lines, Long Bay (Chancery Lane), Barbados

Disposal methods

Temporary storage areas should be nearby to the area of clean-up operations. Lined pits are an inexpensive and simple method for liquid storage. Long, narrow pits are easier to construct and are more practical than large open pits. If pits are not practical, berms or dykes may be constructed - these sites should also be lined. Solid materials may be stored on the surface, but where possible the areas should be lined and be surrounded by a low dyke (fig. 76). Oil and water separation can be performed on-site using 55 gallon drums or sumps (fig. 77), for relatively small volumes of oil, to reduce the volume of material that is transported for final separation. Permanent disposal may be affected by:

(a) oil recovery techniques
- oil/water separation;
- emulsion breaking;
- solid washing;
- thermal processing; and
- refinery processing.

(b) stabilization
- used for roadmaking; and
- landfill or burial.

(c) destruction
- incineration (either on-site (e.g., Wayment, 1977) or following temporary storage); and
- biological degradation (by farming or composting).

The effectiveness of a clean-up operation frequently depends upon the removal of oil, oiled sediments, or oiled debris to temporary or permanent disposal sites. This activity requires the availability of suitable transport equipment (barges, tank trucks, etc.) and the implementation of a well-organized logistics system.

Potential clean-up damage

Removal of sediment from the shore zone reduces the volume of beach material which, if natural replacement rates by sediment transport are slow, can result in beach retreat (Owens and Drapeau, 1973). To avoid this effect, the clean-up operation should aim to remove as little beach sediment as possible. A knowledge of natural sediment replacement rates is necessary for decisions regarding sediment removal in cases where removal involves more than the surface contaminated layer. This procedure will usually involve advice from a coastal geologist or engineer. Replacement rates of pebble and cobble size sediments are usually extremely slow so that natural recovery of this beach type is unlikely to occur if sediments are removed. Damage (erosion) from sediment removal is of particular concern to the islands of the study region as in almost all areas the sources for sediment replenishment are limited.

At the local level, identification of sediment transport directions and of transport end-points ("sinks" or sections of accumulation) will greatly assist in developing clean-up strategies, for example, in the use of diversion booms to move oil onto beaches where sediment removal may not result in beach erosion (see fig. 69).

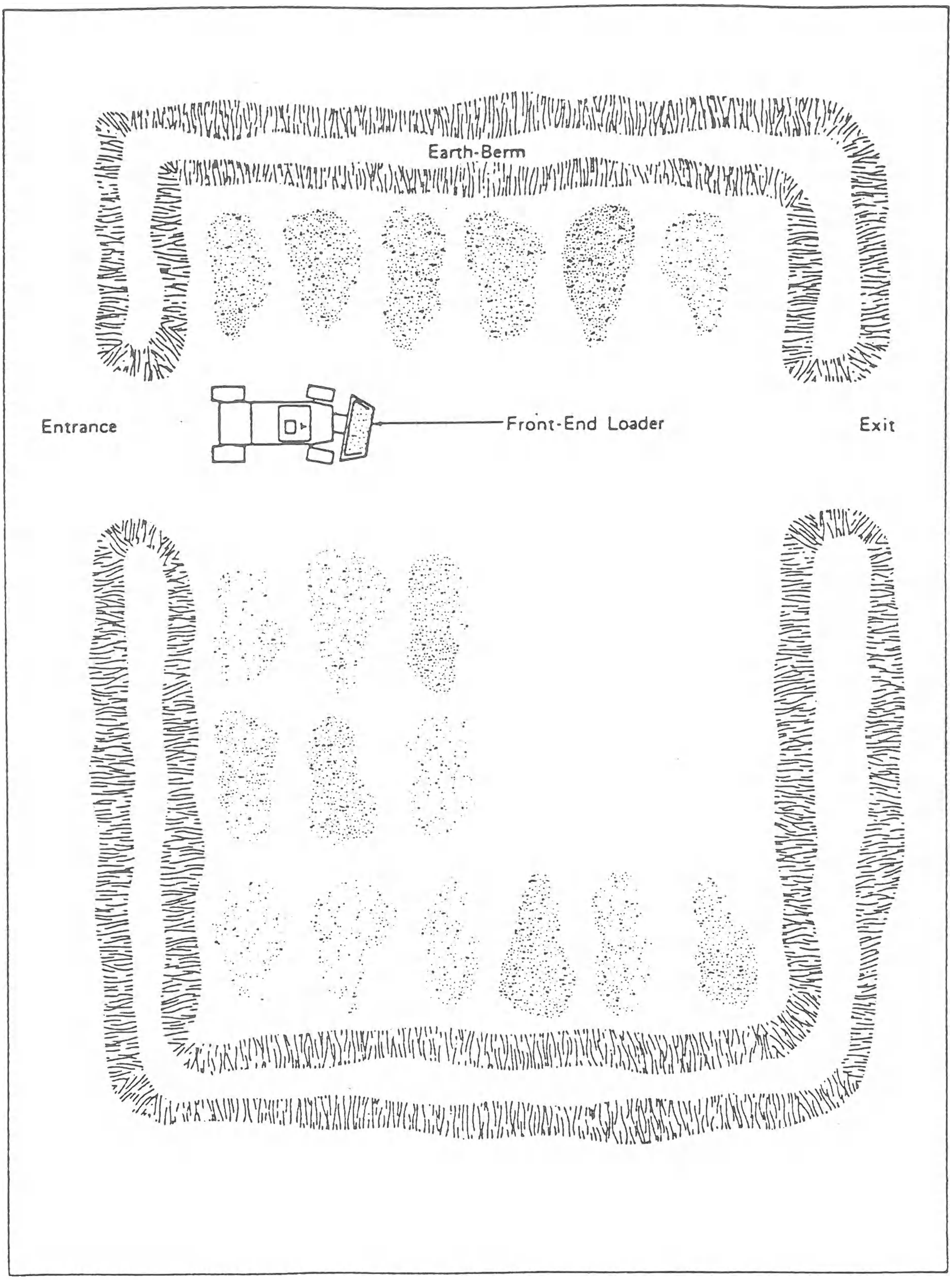
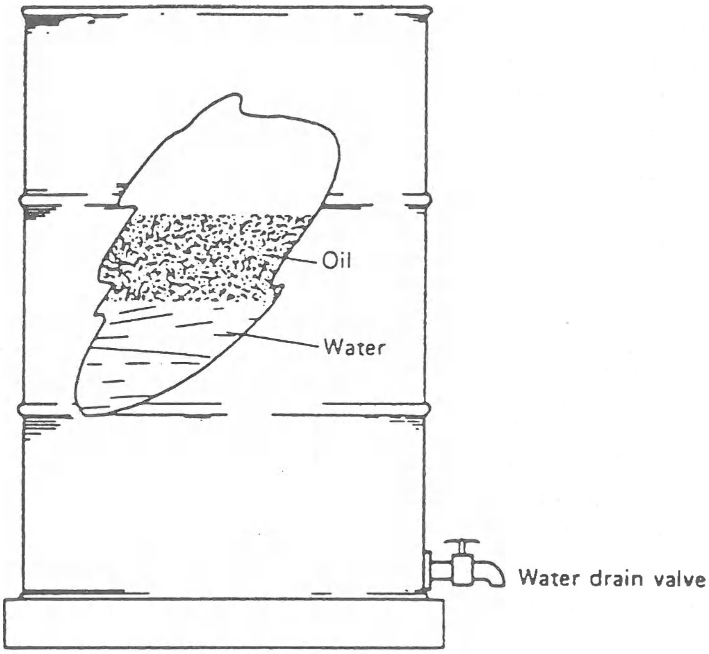
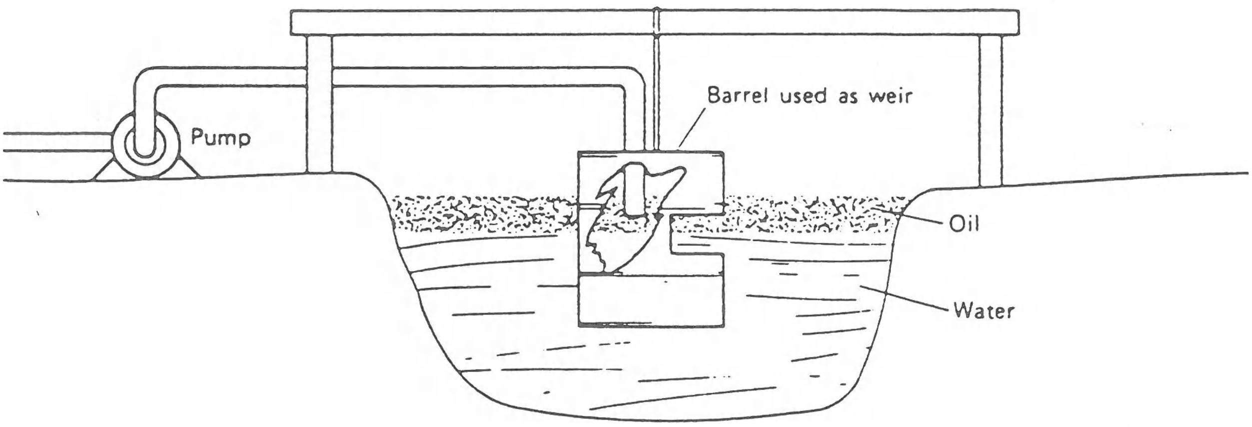


Figure 76: Suggested configuration for a temporary waste storage site



A. 55-gal drum oil/water separator.



B. 55-gal drum and sump oil/water separator.

Figure 77: Field oil-water separation technique

Surface vegetation (dunes, mangroves and marshes) can be severely disturbed by the uncontrolled movement of equipment or personnel. If access to the shore is necessary across vegetated areas, this should be restricted to a few routes and, if possible, a surface cover such as mats should be used, both to improve traction and to reduce the amount of damage. In dune and marsh systems, the damage is most severe when the root systems of the plants are disturbed. Further information on clean-up by different response techniques is given for (a) beaches and rocky coasts by Foget et al. (1979), and (b) mangroves and marshes by Maiero et al. (1978).

Accessibility and logistics

The movement of equipment, personnel, and oil or contaminated material presents a major logistic constraint in all but a few locations. In the selection of clean-up techniques, consideration must be given to the storage, transportation, and ultimate disposal of material that is collected. Large-scale removal operations would probably be restricted to those locations adjacent to roads where vehicle access to the shore is possible. The categories for accessibility listed in table 15 identify the primary factors that must be considered in planning the logistics of a clean-up response for a given site. In the case of land access, consideration can be given to the construction of access routes for heavy equipment or light vehicles.

Table 15: Shoreline accessibility

LAND

A.1 Existing direct access for heavy equipment (including trucks) by roads or tracks to the shore zone.
A.2 Suitable conditions for construction of A1 access.
A.3 Existing direct access for light vehicles (pick-up trucks) by tracks or trails.
A.4 Pedestrian access by tracks or trails.
A.5 Shore zone not accessible by land.

WATER

B.1 Unobstructed beach or shoreline access for boats or barge to deploy light or heavy equipment.
B.2 Shallow-water access for small boats only; pedestrian access.
B.3 Obstructed access, not accessible by water.

AIR

C.1 Flat back-shore suitable for STOL aircraft.
C.2 Flat ground available for helicopter access.
C.3 Inaccessible by air.

(Note: In some cases for remote sites, a combination of access parameters may be considered e.g., C.1 and A.2)

Operational constraints

(NOTE: PERSONNEL SAFETY IS A PREREQUISITE FOR ALL SPILL COUNTER-MEASURE OPERATIONS)

Climate

Hot temperatures, high wind velocities, or storm conditions place constraints on both equipment and personnel.

Accessibility

The lack of suitable staging areas near operational sites may constrain the deployment of equipment or personnel. Uncharted nearshore waters may limit movement by sea. Out-of-date maps or charts of coastal areas may be a concern in areas of rapid shoreline changes.

Resources

Manpower and equipment availability may limit the scale of counter-measure operations. Transport facilities for equipment and personnel (either by land or sea) may limit the movement of resources between and within operational areas.

Spill response strategies

Contingency planning for spill response involves:

- recognition of potential pollution sources;
- identification of damage that might be caused;
- identification of environmental factors that characterize the area; and
- organization of a response team in terms of coordination, assignments, and responsibility.

The implementation of a clean-up strategy requires initially:

- a knowledge of the location, movement, volume, and type of oil;
- an evaluation of the potential impact (on human activities and biological resources) of the oil; and
- an infrastructure of communications and logistics support that is designed to deal with oil spills.

Immediate definition of sites where the potential impact from oil would be high allows mobilization of protection resources. In most cases these decisions cannot be made until the spill occurs and until reconnaissance surveys have been conducted. Pre-spill studies or inventories can provide valuable information for use in the decision-making process. Usually at the time of the spill itself there are insufficient resources and insufficient time to undertake such data collection.

In most cases there is little value in cleaning a section of coast until all danger of oiling or recontamination is past. Otherwise it may be necessary to clean the same section of coast more than once. On beaches it is preferable to remove surface oil or oiled sediments if there exists a possibility that the oil may be buried by normal beach processes or may be refloated to contaminated adjacent coasts.

Most oil is recovered during the early stages of a response operation (fig. 78). As time passes so clean-up difficulty and costs increase (fig. 79). The selection of appropriate techniques and the careful supervision of the implementation of a response activity are essential to avoid greater damage than that which is caused by the oil alone.

On beaches the objective of the operation should be to remove as little uncontaminated sediment as possible. Greatest care must be exercised in mangrove and marsh environments. Clean-up operations can easily cause major habitat damage, whereas the oil alone may have a lower impact and the habitat may have a high recovery potential. In marsh and mangrove environments, traffic through the habitat should be avoided wherever possible. Backshore access to the clean-up area should be controlled to avoid damage to vegetation (e.g., in dune environments). Temporary disposal or storage site should be near to the clean-up area and be suitably constructed to prevent leaks or spillage.

No set of rules of pre-planned responses can be developed as decisions must be made for protection and clean-up that are appropriate at the time of the spill. A spill response operation requires a series of sequential decisions to determine the most appropriate course of action for a section of coast (fig. 80). The objective of pre-spill planning is to (a) develop a response organization, (b) locate response resources, (c) train personnel, and (d) obtain and organize relevant data and information.

FIELD EXCURSION

An integral component of the workshop involved the examination of representative shoreline sections that illustrate features or characteristics described in the lecture sections.

At each location the group discussed a series of questions that were designed to develop an understanding of the physical (geological and oceanographic) character of the site. On the second field trip the questions involved consideration of factors that affect response requirements and priorities.

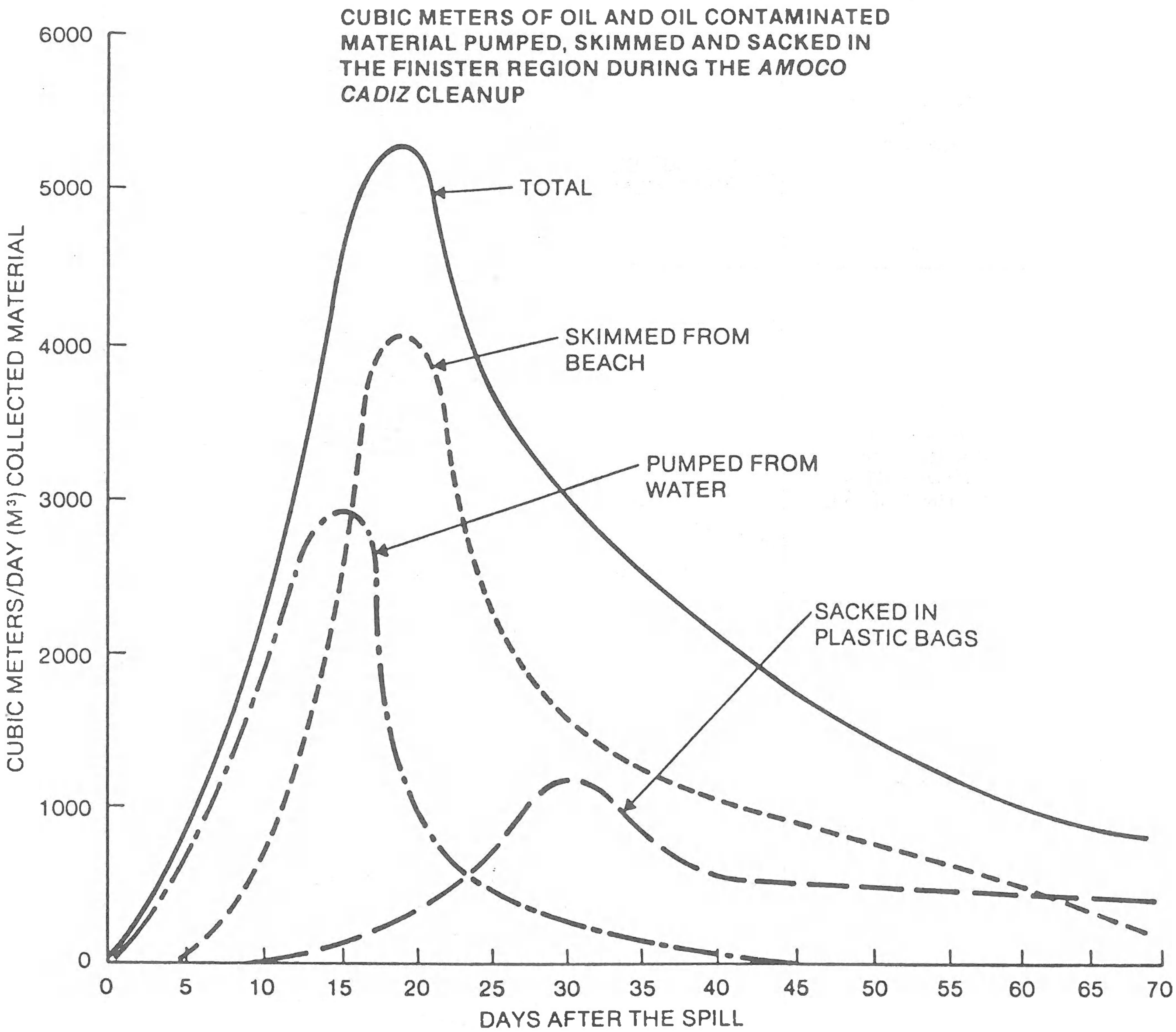


Figure 78: AMOCO CADIZ cleanup (from Exxon, 1979)

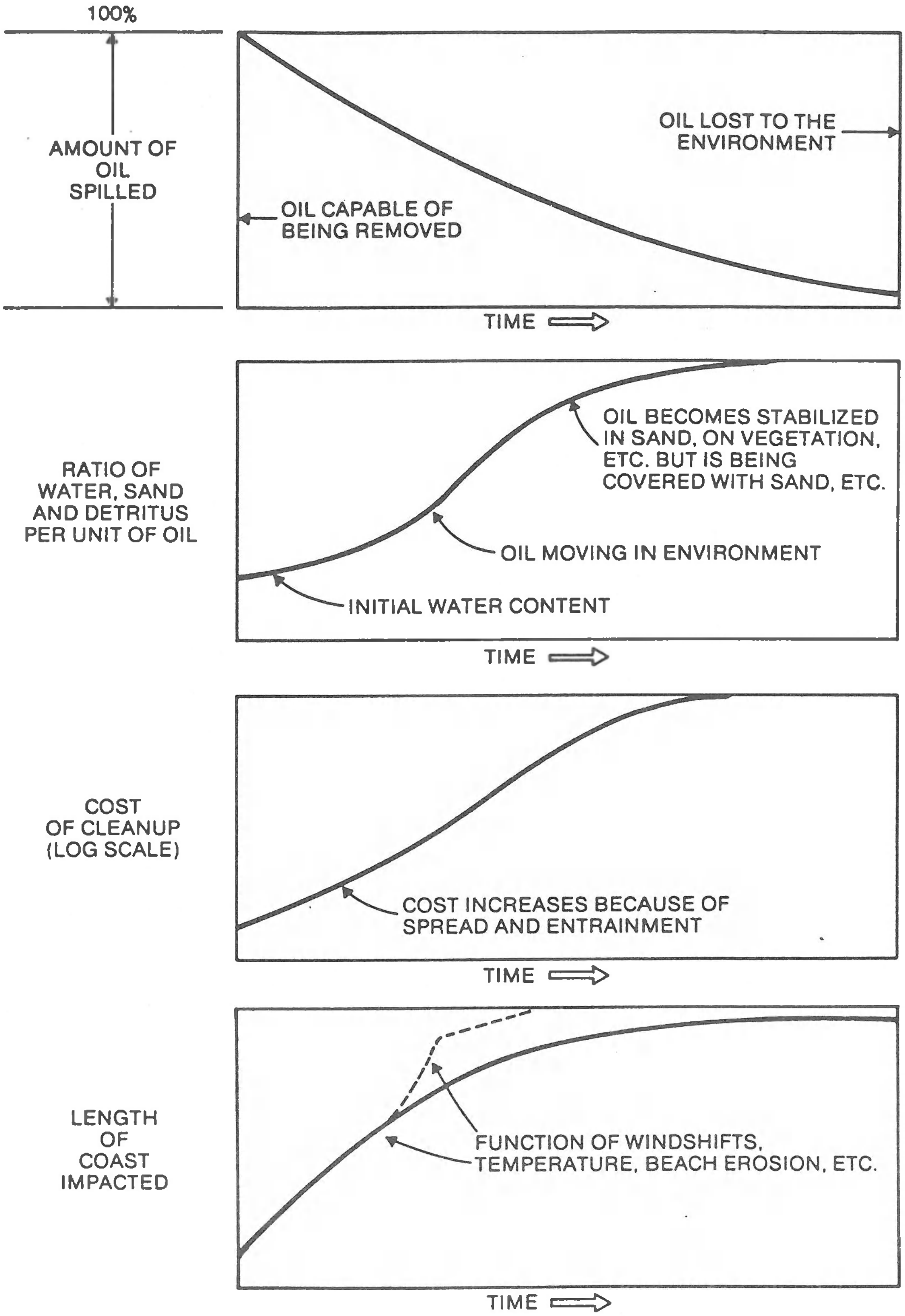


Figure 79: Effect of delayed cleanup response (from Exxon, 1979)

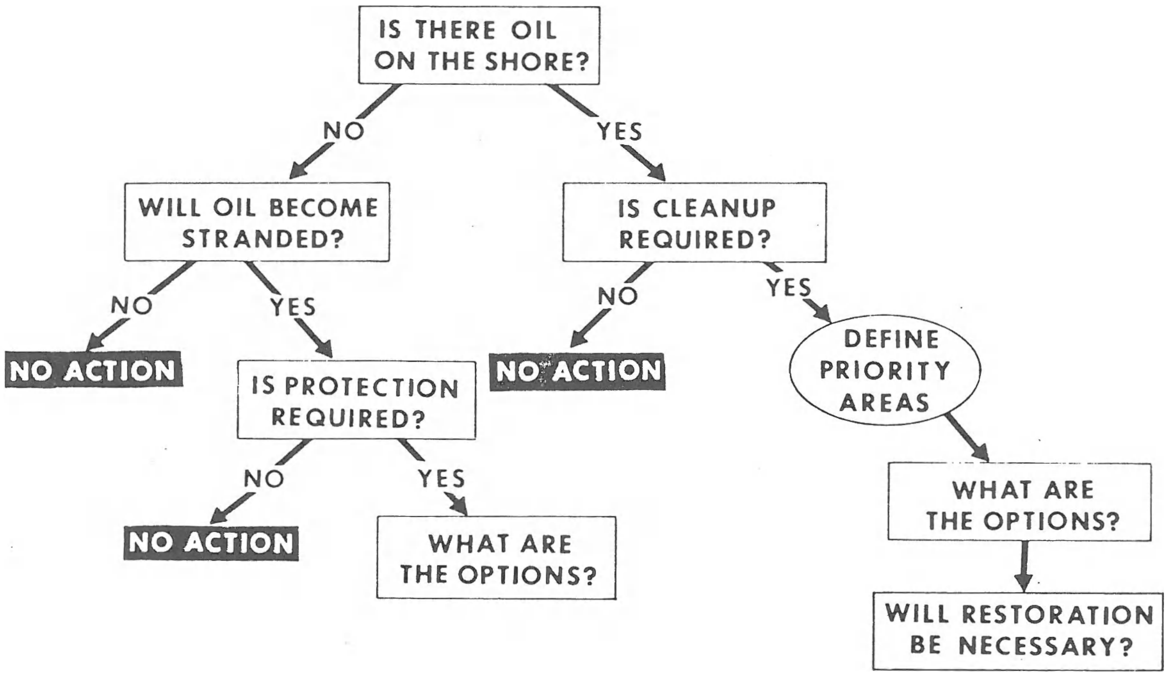


Figure 80: Decision tree for spill response strategy

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