*IPIECA REPORT SERIES*

*VOLUME NINE*

# BIOLOGICAL IMPACTS OF OIL POLLUTION: SEDIMENTARY SHORES

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International Petroleum Industry Environmental Conservation Association

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IPIECA

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# PREFACE

This report is part of a series commissioned by the International Petroleum Industry Environmental Conservation Association (IPIECA). The full series of reports represents the IPIECA members' collective contribution to the global discussion on oil spill preparedness and response.

In preparing these reports—which represent a consensus of membership views—IPIECA has been guided by a set of principles which it would encourage every organization associated with the transportation of oil products at sea to consider:

- It is of paramount importance to concentrate on preventing spills.
- Despite the best efforts of individual organizations, spills will continue to occur and will affect the local environment.
- Response to spills should seek to minimize the severity of the environmental damage and to hasten the recovery of any damaged ecosystem.
- The response should always seek to complement and make use of natural forces to the fullest extent practicable.

In practical terms, this requires that operating procedures for transportation, storage and handling of petroleum and petroleum products should stress the high priority that management gives to preventative controls to avoid spillages. Recognizing the inevitability of future spills, management responsibilities should also give high priority to developing contingency plans that will ensure prompt response to mitigate the adverse effect of any spills.

These plans should be sufficiently flexible to provide a response appropriate to the nature of the operation, the size of the spill, local geography and climate. The plans should be supported by established human resources, maintained to a high degree of readiness in terms of personnel and supporting equipment. Drills and exercises are required to train personnel in all spill management and mitigation techniques, and to provide the means of testing contingency plans which, for greatest effect, are carried out in conjunction with representatives from the public and private sectors.

The potential efficiencies of cooperative and joint venture arrangements between companies and contracted third parties for oil spill response should be recognized. Periodic reviews and assessments of such facilities are encouraged to ensure maintenance of capability and efficiency standards.

Close cooperation between industry and national administrations in contingency planning will ensure the maximum degree of coordination and understanding between industry and government plans. This cooperative effort should include endeavours to support the administrations' environmental conservation measures in the areas of industry operations.

Accepting that the media and the public at large have a direct interest in the conduct of oil industry operations, particularly in relation to oil spills, it is important to work constructively with the media and directly with the public to allay their fears. Reassurance that response to incidents will be swift and thorough—within the anticipated limitations of any defined response capability—is also desirable.

It is important that clean-up measures are conducted using techniques, including those for waste disposal, which minimize ecological and public amenity damage. Expanded research is accepted as an important component of managements' contribution to oil spill response, especially in relation to prevention, containment and mitigation methods, including mechanical and chemical means.

# INTRODUCTION

Sedimentary shores encompass a wide range of intertidal habitats including steep pebble beaches, sand and mud. Sandy beaches have obvious amenity value for activities such as sunbathing or swimming; and many sheltered sediments (such as estuarine mudflats) are highly productive. This is not immediately obvious, because most of the fauna remain buried beneath the surface when the tide is out and so hidden from view.

Sandy embayments are often important nursery grounds for commercial species of fish, and intertidal sandflats may support shrimp fisheries and provide sites for mariculture. To those interested in birdlife, mudflats provide a haven for large numbers of wading birds, ducks and other seabirds.

Because of their high amenity value and public profile, sedimentary shores feature high in press coverage of oil spills and often form the focus of public concern for damage of the marine environment. This report describes the main types of sedimentary shores, their vulnerability to oil spill damage, clean up after an incident and their capacity to recover.

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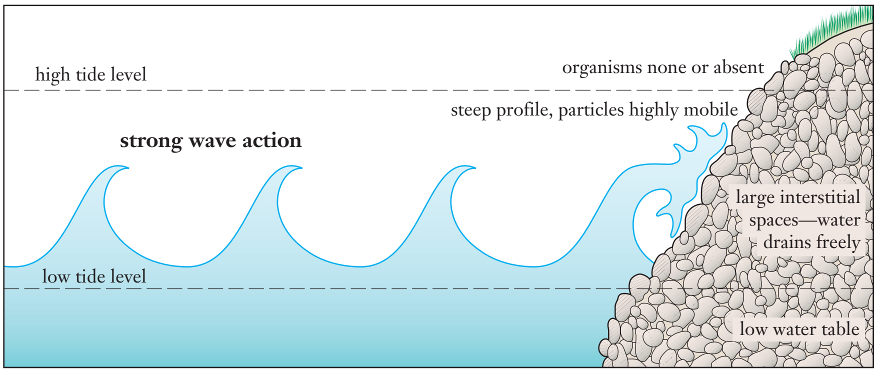
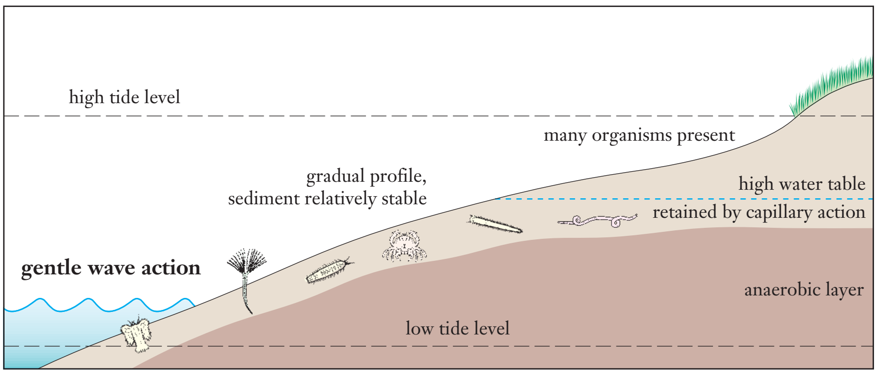
# THE VARIETY OF SEDIMENTARY SHORES

Sedimentary shores are a feature of the intertidal habitat in any part of the world. They range from coarse cobble beaches through sandy beaches to mudflats. The most important factors influencing particle size and slope of the shore are wave and current action. The more exposed the shore, the steeper it is and the coarser the material accumulated. Sheltered areas tend to have shallow gradients and are composed of finer particles. Mudflats in estuaries result not only from sheltered conditions but also from the flocculation of suspended material brought down by the river when it reaches the sea.

| Sediment particle sizes | (mm) |
|---|---|
| Cobble | 64–256 |
| Pebble, also called shingle | 4–64 |
| Granule, also called gravel | 2–4 |
| Sand | 0.06–2 |
| Mud (including silt and clay) | less than 0.06 |

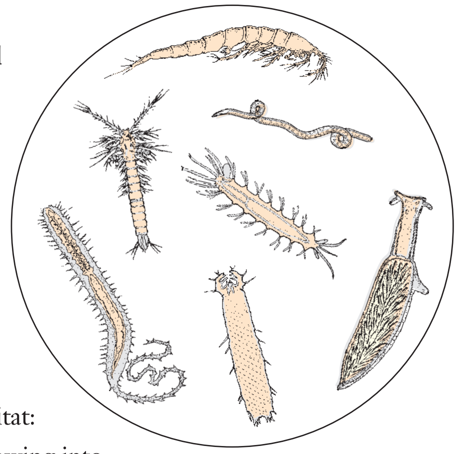
*The nature of a sedimentary shore is influenced by the degree of exposure to wave action.*



# SEDIMENTARY SHORE ECOLOGY

The type of sediment has important consequences for organisms. Cobble and pebbles are usually unstable and drain quickly. Such shores support very little life. With sand and mud, the capillary effect of the interstitial spaces between the particles holds water above the tide level after it has retreated, providing a suitable habitat for many burrowing species. Two basic sizes of marine organism are adapted to this habitat: large animals (>0.5 mm) capable of burrowing into the sediment and small species known as meiofauna (0.05–0.5 mm) that live between the particles in interstitial spaces. In addition there are micro-organisms such as diatoms and bacteria that adhere to the surface of the sediment particles.



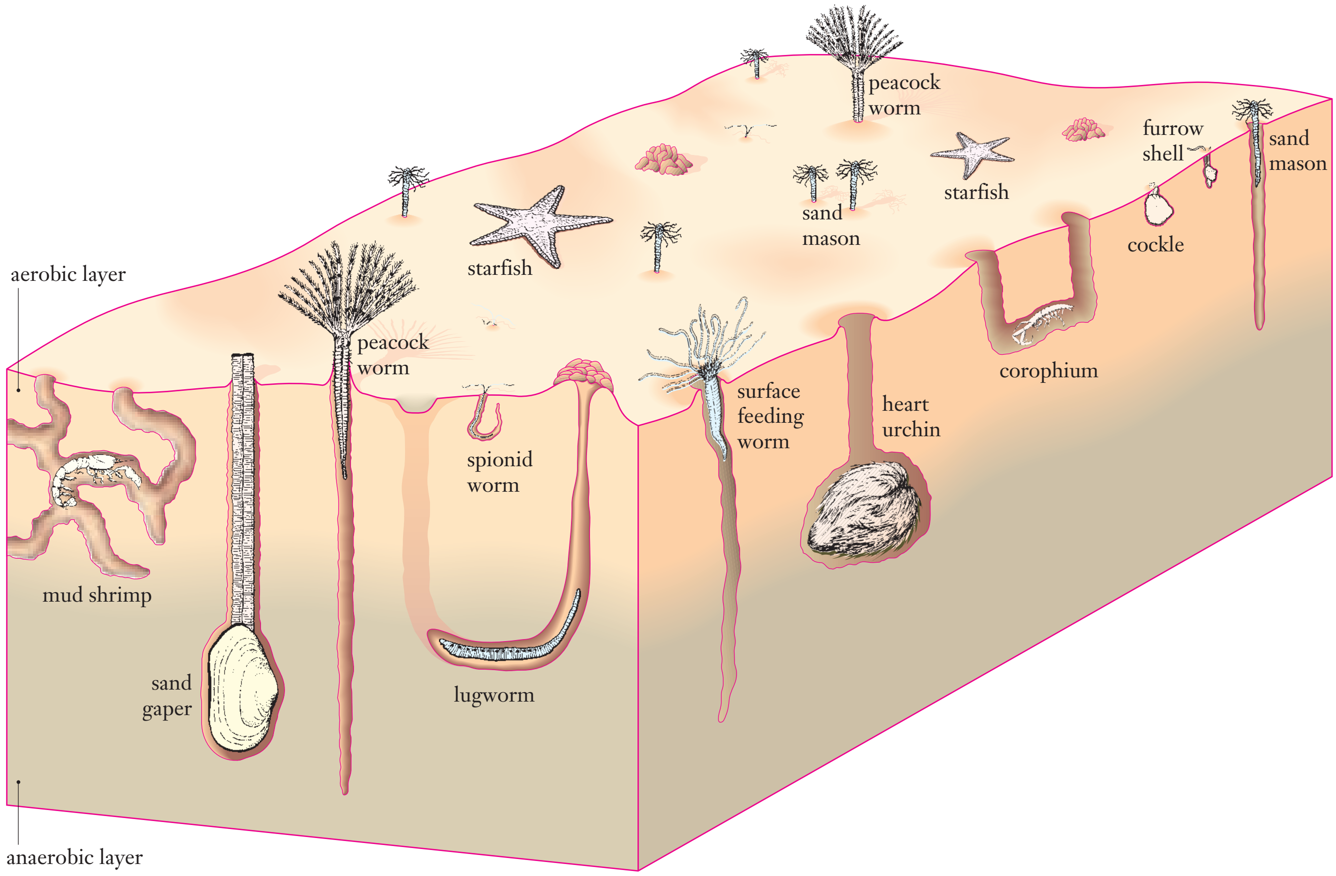
*Examples of meiofauna, tiny animals that live in the interstitial spaces between sediment particles.*

*1. Cobble shores are characteristic of exposed conditions.*

*2. Pebble (shingle) shores develop where there are strong long-shore currents.*

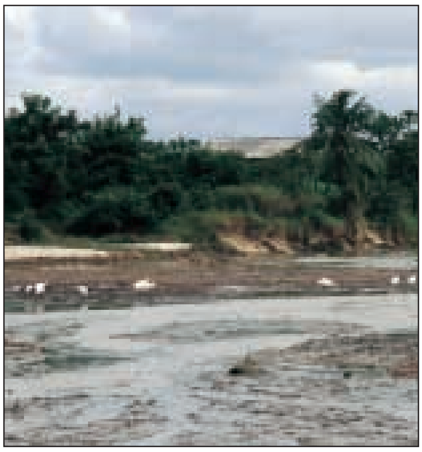
*3. Sand shores are characteristic of relatively sheltered embayments.*

*4. Mud shores are typical of very sheltered inlets and estuarine conditions.*




*Above: Animals living in the sediment may feed in three different ways:*
*i) they may filter the water when the tide is in, in which case the sediment simply acts as a support for the animal as it feeds and provides protection when the tide is out (e.g. peacock worm and sand gaper);*
*ii) they may use the substratum as a direct source of food, feeding on the organic matter that is incorporated into the sediment or the bacteria that adhere to the particles, (e.g. lugworm); or*
*iii) they may simply prey on other sediment dwellers (e.g. starfish).*

Because intertidal sediments are regularly exposed to air the animals and plants that inhabit them are subject to the rigours of both the terrestrial and aquatic environments. When the tide is in they may fall prey to a wide range of bottom feeding fishes and other predators; when the tide is out, not only do they have to withstand the onslaught of terrestrial foragers such as wading birds, but also the extremes of temperature and salinity that come with exposure to atmospheric conditions.

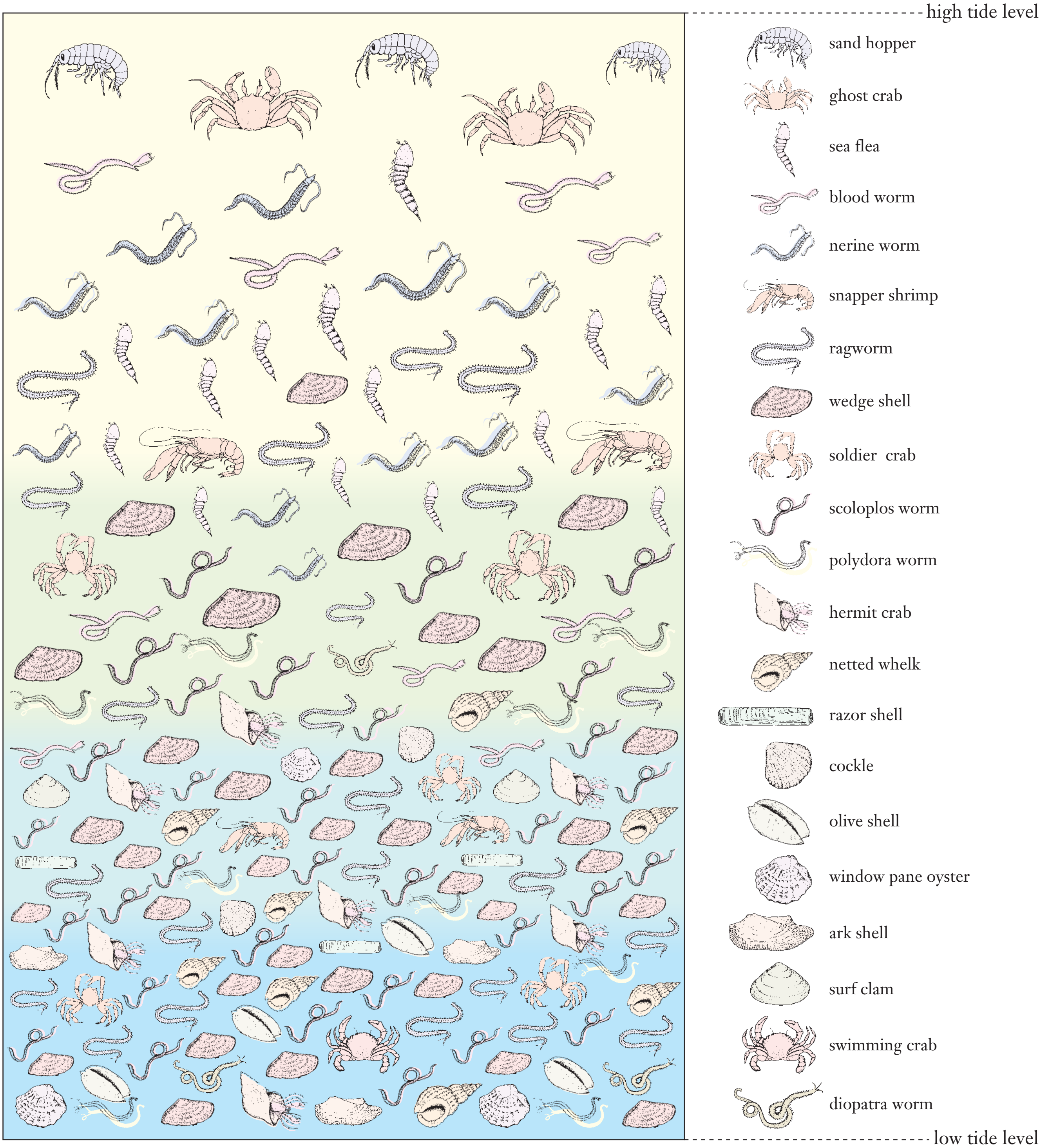


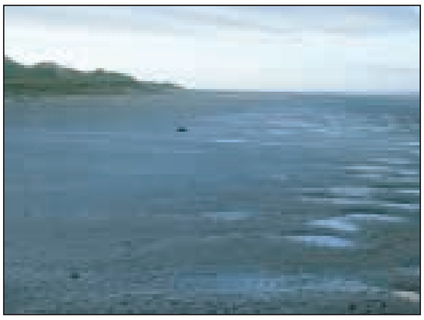
*Near right: wading birds are important predators of intertidal sand and mudflats when the tide is out.*

*Far right: when the tide is in, the animals in the sediments become the food of aquatic predators.*

Many of the problems associated with exposure to the air can be solved by simply burrowing into the sediment, which is one of the reasons why an intertidal sand or mudflat often appears bereft of life during low tide. The distribution of the organisms on the shore is influenced by their ability to tolerate the period when the tide is out. This results in zonation of species which, although less distinct than on rocky shores, is a feature of most intertidal sediments.

*Below: zonation of animals of a sandy shore: an example from Goa, India.*

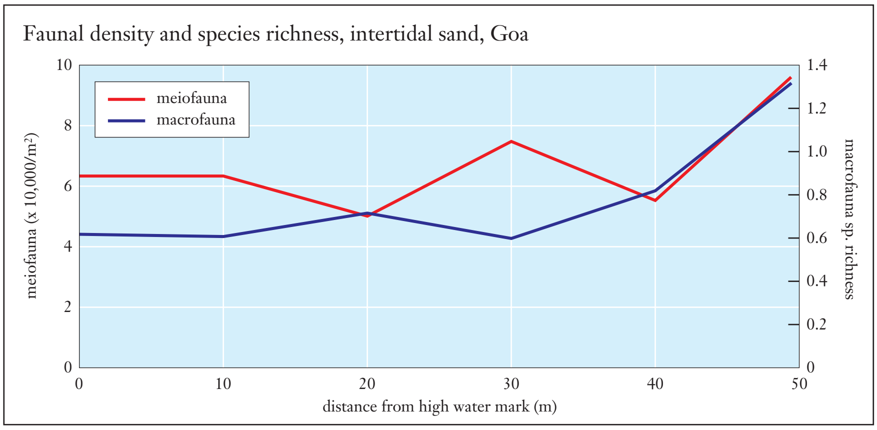




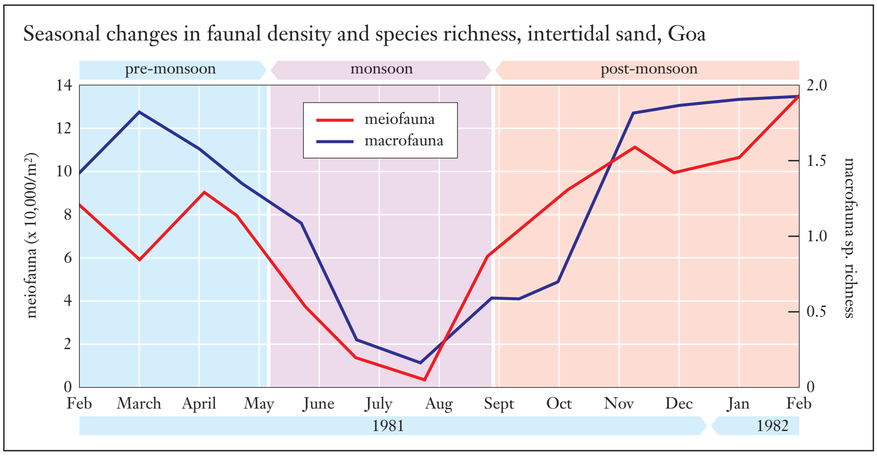
*The apparent absence of life on the surface belies the often teeming activity going on below the surface of the sediment.*

The longer the tide is out the greater the exposure of the intertidal organisms to atmospheric conditions and any material, such as oil, stranded by the retreating tide. Thus relatively few species are able to exist on the upper reaches of the shore, and numbers increase towards low water. In tropical areas, numbers of organisms are limited by exposure to strong sunlight and monsoon rains. This is demonstrated by the following example from Goa, India, where the numbers of animals are substantially reduced during the monsoons, but quickly increase in the following months. This illustrates the severe conditions under which all intertidal animals have to exist and their adaptation to recover quickly when more favourable conditions return. It is this adaptation that assists recovery after an oil spill.

*This diagram, based on data from intertidal sand in Goa, India, shows that fewer species are able to exist on the upper reaches of the shore due to their exposure to atmospheric conditions; numbers increase towards low water.*




*In tropical areas, the numbers of animals are reduced significantly during the monsoon season due to factors such as the substantial exposure to fresh water; numbers increase quickly in the following months.*



*Turtles drag themselves across sandy beaches to lay their eggs above the high tide mark.*

Sedimentary shores are important for the reproduction of a number of sub-tidal and offshore species, which are therefore vulnerable to adverse changes in beach use or pollution. Turtles are a notable example. They lay their eggs in the sand above the high tide line, and have to drag themselves across the beach since their flippers are not strong enough to support their body weight. Both their meat and eggs are highly sought after with the result that populations of most species of sea turtle have become seriously depleted and need to be protected from all threats including oil pollution.

Some marine mammals also use sedimentary shores. For example, seal haul-outs and pupping sites sometimes occur on pebble or cobble beaches. Favoured sites tend to be in remote areas where access for spill response teams may be difficult.

# HUMAN USES

Human uses of sedimentary shores may be divided into exploitation of physical and biological resources. A particularly important physical use is for recreation. To many, sandy beaches conjure up images of holidays by the sea, and there is no doubt that they are valuable both aesthetically and economically. Other physical uses include aggregate extraction and reclamation.

The biological resources of sedimentary shores have been exploited since the dawn of history. They include shellfish beds, bait species such as worms, and fish or prawns that come in with the tide and are caught in traps or with hand nets. Such fishing may be for both adults and larvae, the latter sometimes being used for mariculture. Mariculture also includes intertidal culture of shellfish such as oysters and cockles.

*1. Aggregate extraction from beaches is common all over the world.*

*2. Sandy shores are often important because of their amenity value.*

*3. The remains of shellfish are often found at prehistoric sites by the sea, showing how important this food was to early human beings.*

*4. Harvesting of natural beds of intertidal shellfish still goes on.*

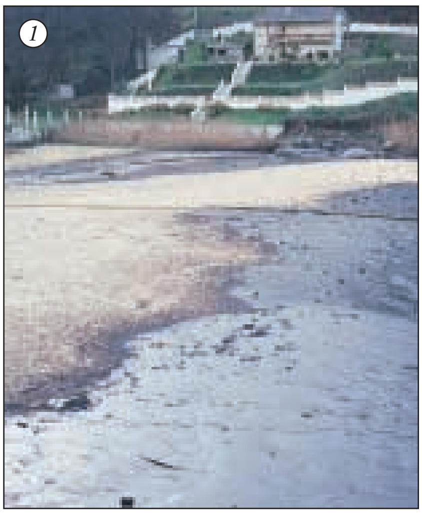
# FATE AND EFFECTS OF OIL

Oil may be cleaned from the shore surface by natural processes, particularly wave action. Self cleaning is usually faster on relatively exposed coarse sediment beaches than on sheltered mud. Clay-oil flocculation (a process first recognized following the 1989 *Exxon Valdez* spill in Alaska) promotes self cleaning in some cases by reducing the adherence of oil to pebbles or cobbles. Oil may persist for relatively long periods if it is buried by wind-blown or water-moved sediments, if it penetrates deeply into the sediments, or if it forms asphalt pavements.

Depth of penetration is influenced by:

- Particle size. Penetration is not generally as great on mud as on coarser sediments.
- Oil viscosity. Viscous oils and mousse (water-in-oil emulsion) tend to penetrate less deeply than low-viscosity oils such as light crudes or diesel oil.
- Drainage. If sediments are poorly drained (as is often the case with tidal flats remote from creeks or channels), the water content may prevent the oil from penetrating into the sediment. In contrast, oil may reach depths greater than one metre in coarse well-drained sediments.
- Animal burrows and root pores. Penetration into fine sediments is increased if there are burrows of animals such as worms, or pores left where plant roots have decayed.

1. *A North Sea crude covering a beach in NW Spain during the* Aegean Sea *spill, 1992.*
2. *Lugworm* (Arenicola) *burrows and casts.*
3. *Light crude oil in sand ripples.*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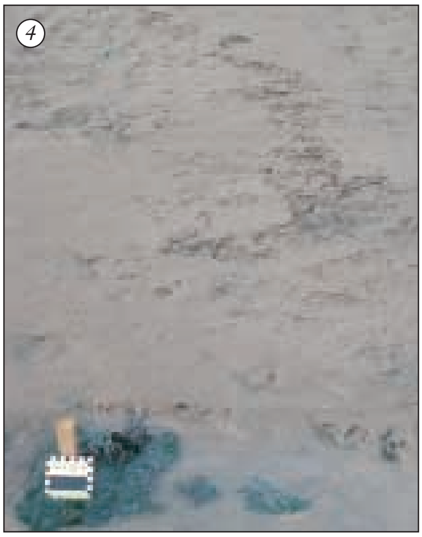
Asphalt pavements (on coarse sediments) or oil crusts (on sand and mud) form when relatively large quantities of oil or mousse consolidate the surface sediment layer. The oil and incorporated sediment form a hardened layer as the oil weathers. Such pavements can be persistent, though wave action eventually undercuts the edges and they break up.





*Serial photographs showing changes in appearance of an experimentally oiled sheltered sandflat over time:*

1. *immediately after experimental application of 1 litre/m² of Nigerian crude oil;*
2. *four days after oiling, having been covered by one high tide, the sediment oil concentration was over 90,000 mg/kg;*
3. *seven days after oiling, clean sand ripples migrated over the oiled surface;*
4. *44 days after oiling, the oil crust was being undercut from the left, but average oil content was still almost 20,000 mg/kg;*
5. *388 days after oiling, oil concentration was about 5,000 mg/kg. The green algae are transient features of the sandflat and not related necessarily to the oil.*

*Scale: the square in the bottom left corner of each photograph is 10 cm x 10 cm*

Breakdown of oil by microorganisms (biodegradation) is not likely to be significant until physical processes have removed much of the oil. Biodegradation can then make a greater contribution, particularly to reducing oil toxicity. However, biodegradation is relatively slow where oxygen is limited—for example in poorly-drained fine sediments, or in the interior of thick oil layers.

From an ecological point of view, the greatest concern is likely to be about the effects of oil on relatively sheltered sediments. This is because they are more likely to retain oil and because they are more productive, supporting a variety of worms, molluscs and crustaceans. Such animals may be killed if oil penetrates into the sediments. For example, following the *Sea Empress* spill (in west Wales, 1996) many amphipods (sandhoppers), cockles and razor shells were killed. There were mass strandings on many beaches of both intertidal species (such as cockles) and shallow subtidal species. Similar mass strandings occurred after the *Amoco Cadiz* spill (in Brittany, France, 1978). Most spills are smaller than these two examples and the effects on sediment fauna not so spectacular.

Recovery from oiling depends partly upon the sensitivity of the species concerned. For example, following the *Sea Empress* spill, populations of mud snails recovered within a few months but some amphipod populations had not returned to normal after one year. Opportunists such as some species of worm may actually show a dramatic short-term increase following an oil spill.

Recovery from oiling also is related to the persistence of oil in the sediments. For example, after the *Florida* spill (Buzzards Bay, USA, 1969), fiddler crab populations took more than seven years to recover and this was correlated with the persistence of toxic hydrocarbons in sub-surface mud. In contrast, recovery after the *Arco Anchorage* spill (Port Angeles, USA, 1985) was well under way after one year, helped by an effective spill response in which oil had been removed from sediments using agitation techniques.

Long-term depletion of sediment fauna could have an adverse effect on birds or fish that use tidal flats as feeding grounds; and in some countries persistent oil on sandy beaches could affect turtle breeding. There have been some cases of oil killing seal pups, and adult seals may fail to breed in oiled areas.

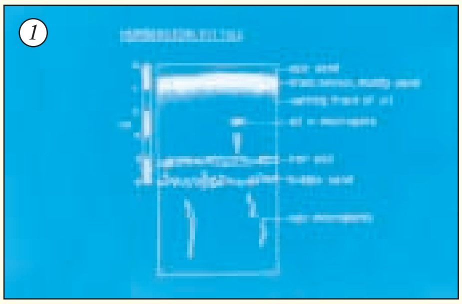
## AN EXAMPLE OF AN OIL SPILL ON MUD AND SAND SHORES

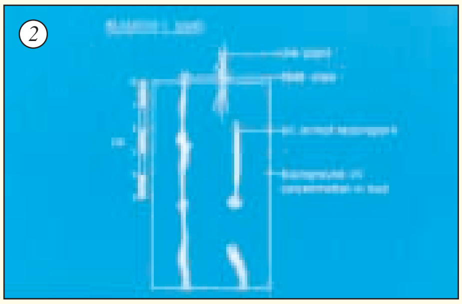
The *Sivand* spill in 1983 resulted in 6,000 tonnes of crude oil entering the turbid estuary of the Humber, UK. A study of the fate of the oil was concentrated on two sedimentologically different shorelines; one a mudflat and the other a sandflat. Soon after the spill, the sands had oil concentrations of 50,000 mg/kg. Over one year, this reduced to about 3,000 mg/kg. This was expected since coarser sediments generally promote oil degradation. The muddy sediments showed lower levels of contamination initially (about 2,000 mg/kg) followed by only a slight reduction over one year.

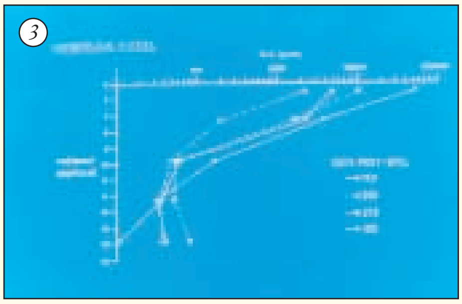
Good drainage at both sites permitted initial oil penetration. The steep gradients in oil concentration and composition with depth at the sandy site contrasted with the muddy site, where 'free' oil penetrated as a coherent mass via the channels in the sediment made by plant roots. Sediment mobility at the muddy site probably helped natural cleaning. Interstitial water movements promoted degradation of the oil at the sandy site, but no dramatic sediment turnover or erosion occurred which might have removed the oil.

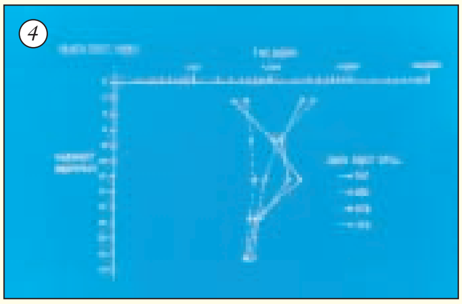
These studies illustrate the importance of sedimentological factors in determining the fate of spilled oil.

*Cross section of core at 10 cm depth from mudflat showing penetration of oil*









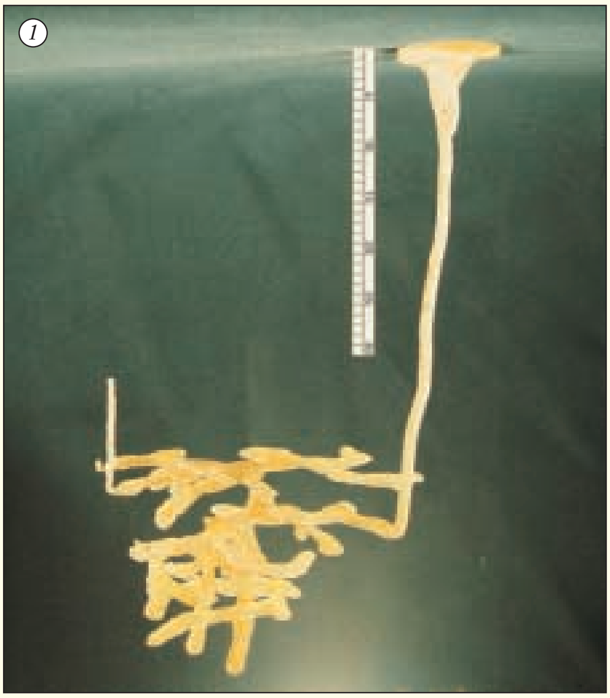
1. *Core sketch showing sediment structure and oil distribution at sandflat*
2. *Similar core sketch at mudflat*
3. *Sandflat sediment hydrocarbons measured on four visits*
4. *Mudflat sediment hydrocarbons measured on four visits*

## PENETRATION OF OIL INTO SEDIMENTS THROUGH ANIMAL BURROWS

Oil can penetrate fine sediments through animal burrows. It has been demonstrated experimentally that infaunal burrows allow the penetration of surface layers of oil into subsurface sediments to a greater depth and at higher concentrations than in similar sediments where burrows are absent.

Observations made during experimental oil spills have suggested that greater oil penetration into sediments, both in terms of depth and volume, takes place where the overlying oil is in a relatively thick layer (but is not highly viscous), and where infaunal mixing of sediments (bioturbation), plant root channels or large established animal burrows are present. The giant ragworm *Nereis virens* has been seen to burrow in the presence of oiled sediments, and field experiments with the burrowing shrimp *(Callianassa californiensis)* have shown that infauna are capable of introducing measurable amounts of oil into the subsurface where it may be retained for some months.

1. *Resin cast of the burrow of the mud shrimp* Callianassa *showing the depth of penetration and the ramifications of the galleries.*
2. *Surface view of the entrance to the gallery of a burrowing crab exuding oil.*
3. *Worm burrows like these provide channels by which oil can penetrate the surface of the sand.*



# OIL SPILL RESPONSE

Response techniques are either for protection (stopping oil from reaching the shore) or for cleanup (dealing with oil once it is on the shore). Protection is of particular importance for mudflats because of the problems of access for cleanup once oil is on the mud, and because such areas usually have high biological productivity. Shores which are important for birds or as nesting areas for turtles, or which are amenity, tourist or fishing beaches should receive high priority for protection and cleanup. However, seasonal variation in the importance of the shores for these various functions should be taken into account.

## Protection techniques

The main approaches are to tackle the oil on the water as it moves towards the shore, or to provide a barrier to stop oil becoming stranded. Considerations for individual techniques for sedimentary shores are as follows:

- Booms can be used at sea to contain oil for recovery using skimmers, or along shorelines to divert oil to areas which are less sensitive ('sacrificial' beaches) where it can be collected. Protective booms can, in some cases, be deployed to

1. *No clean-up took place in this part of Chedabucto Bay, Nova Scotia after the* Arrow *spill in 1970. Asphalt pavements have survived more than 25 years in these remote locations.*
2. *Mixed cobble and fine sediment shore six months after* El Omar *(1988) spill in Milford Haven, Wales. The surface layer was mechanically removed but some oil remained.*
3. *One of the few extremely sheltered shores in Prince William Sound, still heavily oiled in June 1990, more than a year after the* Exxon Valdez *spill. Clean-up of the sediments was entirely manual.*
4. *Dried oil crust covering a sandflat in Saudi Arabia, two years after the Gulf War oil spill of 1991.*

stop oil from stranding on shorelines or to prevent it from entering channels in mudflat systems. However, in all cases booms only work effectively in the absence of waves and strong currents, and effective anchoring can sometimes be difficult along shorelines, especially if long lengths need to be used.
- Dispersants can in some cases offer a net environmental benefit if used offshore from a sedimentary shore. However, water close to muddy shores may be rich in sediment particles and, in such circumstances, use of dispersants nearshore could increase oil incorporation into bottom sediments through sedimentation processes.
- Sand barriers are a possible protective measure on sandy shores. They may be built on the upper shore (above significant wave action) for the purpose of protecting sensitive backshore areas which may otherwise have oil washed into them during extreme high tides.

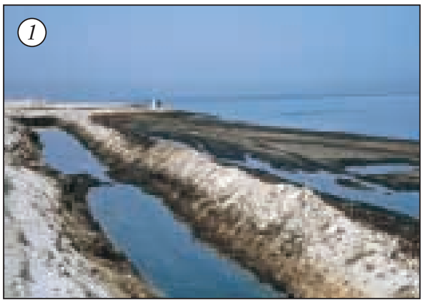
## Cleanup techniques

The intention of cleanup is to minimize adverse environmental impacts and to restore the ecological functions and human use of the shore. The choice of techniques is influenced by the amount and type of oil, the environmental and socio-economic importance of the affected areas, and physical characteristics such as wave energy.

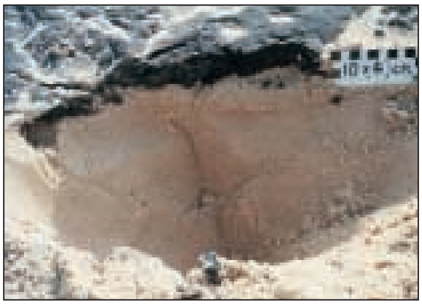
Natural cleaning is suitable for exposed shores where wave action is sufficient to remove oil. It is particularly appropriate for remote beaches where there are no overriding considerations such as imminent turtle nesting. It is also appropriate for more sheltered shores where other techniques would cause unacceptable damage, though oil residence times may be longer than for exposed beaches. On sheltered shores it is more effective where waterlogging of the sediments reduces subsurface penetration of oil.

When natural cleaning is deemed inappropriate, the following options may be considered. It should be borne in mind that accessibility of the shore and the maximum load that the sediment can accommodate may limit the use of any type of machinery. Vehicles should not be driven over oil as they may force it further into the sediments.

- Flushing is particularly suitable for firm sediments with gentle slopes. Use of low-pressure ambient-temperature water minimizes damage to sediment



1. *Traps made by digging trenches in the sand are a way of temporarily containing spilled oil. These traps, which are exceptionally large, were constructed in Marduma Bay, Saudi Arabia following the Gulf War oil spill in 1991.*
2. *In some circumstances tilling the oiled sand surface can prevent the formation of an asphalt pavement and aid the natural breakdown of the oil. Dawhat ad-Dafi, Saudi Arabia following the Gulf War oil spill in 1991.*
3. *Hand scraping oil off the sand surface in West Angle Bay, Milford Haven, following the* Sea Empress *oil spill in 1996.*




*Exposed sand beach oiled during the* Katina P *fuel oil spill in Mozambique, 1992 showing the formation of a surface oily crust.*

*Above: Tenby, an important amenity beach in south west Wales, was heavily oiled after the* Sea Empress *spill in February 1996. Below: Four months later, after a careful clean up operation, the shore was restored.*

structure and organisms; nevertheless erosion of sediment is a possible problem that should be monitored so that flushing can be stopped if necessary. Flushed oil should be contained and recovered at the bottom of the shore. If trenches are dug for this purpose, there is a need to avoid burial of oil (which may, for example, occur if the incoming tide overwhelms the trench).

- Manual removal, for example using rakes and spades, is suitable for small areas of oil contamination where oil has not significantly penetrated the sediments. It is a useful technique for cleaning patchy oil, and in cases where use of machinery is limited because of access or because it would damage the beach structure. Care must be taken to remove as little as possible of the clean sediments and surviving animals and plants. If the beach is accessible to vehicles then the oily debris can be collected into piles and removed using front-end loaders. If this is not possible then the oiled material should be put into heavy duty bags for subsequent disposal.
- Mechanical removal is a method most commonly used on sandy shores where the oil contamination may be extensive but has not penetrated deeply. Graders are used to skim the surface layer of oiled sand, no deeper than the oil penetration depth. Oily sand may be collected using front-end loaders. Front-end loaders can also be used alone but this may result in more sand being removed, which increases the disposal problem. Sediment removal is best justified when there are overriding short-term considerations, e.g. the need to clean a fishing or tourist beach where activities of socio-economic importance need to continue.
- Mechanical relocation involves moving oily sediments lower down the shore where they are exposed to greater cleaning action by the waves, or moving buried oil to the surface for the same reason. This technique is most appropriate for badly oiled coarse sediments on relatively exposed shores, where wave action will eventually restore the normal shore profile.
- Sorbents may be used for removing small pools of oil which may collect in depressions in the sediments.
- Tilling involves mixing oil into the sediment to prevent the formation of asphalt pavements and to encourage oxygenation and interstitial water flow. This promotes natural degradation by microorganisms.
- Vacuum pumping is suitable for thick layers of oil, for example deposits concentrated in depressions on the shore. Care should be taken to minimize the removal of sediments and any organisms living on or in them.
- Bioremediation (degradation of oil by microorganisms enhanced by nutrient application) works best when the oil concentration in the sediment is no more than about 10,000 mg/kg. Other necessary conditions include abundant oxygen supply and interstitial water. Repeated and slow-release applications of appropriate fertilizers appear in some cases to speed up oil biodegradation by enhancing the activity of naturally occurring microorganisms. There is no conclusive evidence that introducing specially selected microorganisms is advantageous.

# CONCLUSIONS

Sedimentary shores range from steep coarse cobble beaches, through sandy beaches to mudflats. Shore characteristics are particularly influenced by wave action.

Biological productivity is low on coarse wave-exposed sediments, but fine sheltered sediments usually support large numbers of animals, mainly different species of worm, mollusc and crustacean. Such shores are used as feeding grounds by birds at low tide and fish at high tide. Some sedimentary shores provide breeding grounds for sea turtles, or marine mammal haul-outs.

Human beings exploit both physical and biological resources. A particularly important physical use is recreation on sandy beaches; biological resources include edible shellfish.

Oil may be cleaned from sedimentary shores by natural processes, particularly wave action. Oil may persist for relatively long periods (many years in some cases) on very sheltered shores, or if it forms asphalt pavements, becomes buried or penetrates deeply.

Ecological effects and recovery times depend upon the sensitivity of the species concerned and upon the persistence of oil in the sediments. Long-term depletion of sediment fauna could have an adverse effect on birds or fish that use tidal flats as feeding grounds.

Priority shores for cleanup are those that are important for birds, turtles or marine mammals, or which are amenity, tourist or fishing beaches. Protection is of particular importance for mudflats because of the problems of access for cleanup once oil is on the mud.

Protection techniques involve dealing with the oil while it is still on the water, and deployment of booms as barriers. Cleanup techniques for oiled sediments include flushing, manual and mechanical removal, mechanical relocation, sorbents, tilling, vacuum pumping and bioremediation. Different techniques are suitable for different sediment conditions and oil characteristics.

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**Further Reading**

Fusey, P. and Oudot, J. (1984) Relative influence of physical removal and biodegradation in the depuration of petroleum contaminated seashore sediments. *Marine Pollution Bulletin*, 15 pp. 136–141.

Howard, S. and Little, D. I. (1987) Effect of infaunal burrow structure on oil penetration into sediments. In *Proceedings of the 1987 Oil Spill Conference*, American Petroleum Institute, Washington, D.C. pp. 553–559.

ITOPF (1987) *Response to Marine Oil Spills*. International Tanker Owners Pollution Federation Ltd., London. Published by Witherby and Co. Ltd., London.

Price, A. R. G. and Robinson, J. H. (eds) (1993) The 1991 Gulf War: coastal and marine environmental consequences. *Marine Pollution Bulletin*, Special Issue, 27, 380 pp.

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