CHAPTER 6

OFFSHORE SPREAD AND TOXIC EFFECTS OF DETERGENTS SPRAYED ON SHORES

The shore surveys reported in the previous chapter have shown that detergent cleansing of rocks and sands causes extensive damage to, and often total destruction of, the populations of intertidal plants and animals in and immediately adjacent to areas of intensive spraying. There was also evidence that, as a result of movements of toxic water, organisms living a quarter of a mile or more from the area of spraying may be damaged or killed.

It seemed important therefore to investigate in greater detail the patterns of flow of shore-originating polluted water under different conditions of wind and tide; the concentration and persistence of the component detergent fractions; and their possible effects on organisms living in the offshore waters. The investigations were undertaken during the month of April by teams working mainly in the Porthleven (South Cornwall) area. The teams, comprising shore-based parties and underwater divers, were aided by a ship survey (R.V. 'Sarsia' inshore stations A–M of 13 April, see Fig. 19) which included Agassiz-trawl sampling of the offshore benthic fauna. Laboratory measurements were made of the concentration of the component fractions of detergents present in the area of long-shore and offshore spread of the detergent-charged water.

Oil reached PORTHLEVEN on 25 March in considerable quantities during a period of spring tides and onshore winds so that in some places it was distributed well above the high-water mark. Very large amounts of detergent were subsequently used to combat the oil. According to the figure supplied by the local authority a total of 34875 gallons were used between 25 March and 8 April at a rate of about 2500 gallons a day. Between 8 and 24 April another 10800 gallons were used and the total issued for use in the area up to 9 May was given as 45675 gallons. However, large amounts of detergents were used in the harbour on 26, 27 and 28 March, and these are not included in the daily totals provided by the local authority. In addition, the amounts of detergent used by the Army are not accurately known but usually seemed to equal or to exceed the local authority issue. A figure of 100000 gallons would therefore be a reasonable estimate of the total amount of detergent used in the Porthleven area during the last week of March, April and the first week of May. It cannot, however, be considered a final figure since detergent treatment was reported to be restarting on 10 May. The distribution of the detergent was probably as follows: 50000 gallons within the harbour itself, 35000 gallons on Porthleven Reef, to the west of the harbour, and 15000 gallons on the rocks and beach to the east.

In Porthleven Harbour spraying was carried out continuously from 25 March to 8 April and then again between 26 and 28 April. On the reef to the west and on the beach to the east of the harbour spraying began somewhat later, on 4 April. It was continued on the rocks of Porthleven Reef until 12 April and, after a break, was renewed for two days on 26 and 27 April. The maximum rate of application was 3000–4000 gallons a day, though these rates were not maintained throughout the period of cleansing. A similar intensity of treatment was for a time in operation at Halsfarren Cove, three miles south east of Porthleven, and some spraying was also reported at intermediate points (Figs. 15, 16, 17).

Shore surveys were made of the Porthleven Reef on 30 March before the cleansing operations on the reef had started and on subsequent occasions during the period of the detergent treatment (see page 57). Offshore dives, mainly off the Porthleven Reef and the harbour entrance, were undertaken during this period on 5, 7, 11, 13, 19 and 28 April, and water samples for chemical and biological assay were collected on 5, 7, 11, 13 and 19 April.

Observations relevant to the matters discussed in this chapter were also made on 23 April at the south end of Watergate Bay (North Cornwall).

The formation and behaviour of mixed oil and detergent patches

When oily shores are treated with detergent, clearly visible patches of detergent and oil emulsions develop in the sea. These patches are poisonous, for the solvents used in the detergents are toxic to marine organisms (Chapter 7). The development by the Laboratory, within a short time of the 'Torrey Canyon' stranding, of methods of biological assay for detergent toxicity thus enabled us to make quantitative determinations of the toxicity levels of the detergent/oil-polluted water. In this section, which deals with the formation, behaviour, and persistence of these areas of polluted water under different conditions of wind and tide, an important part of the observations was therefore to determine how far, both horizontally and vertically, the toxicity of the detergents would spread from treated shores.

In most of the cases to be described the detergent was sprayed after low water so that the oil could be emulsified as the tide rose and dispersed as the tide ebbed. Frequently fire hoses (Plates 5A, B, 10A), spraying either sea or fresh water, were used to help in emulsifying and dispersing the oil, particularly where it was near high-water mark. Milkiness due to detergent usually started to develop in the sea shortly before high water and grew rapidly as the tide ebbed (Plate 23A, B). Milky areas will be referred to as detergent patches. The oil in these patches, however, was often of three kinds: emulsified oil which stays in suspension (Plate 2), at least for some time; incompletely emulsified oil which soon floats to the surface; and oil which has been released from the shore by the cleansing operation but which is not emulsified (Plates 1A, B, C, 5A, B).

Methods

With the detergent patches concentrations of detergent (in ppm BP 1002) were measured by biological assay (p. 141), shrimps being used to cover the range 2–100 ppm and larvae of the barnacle *Elminius* to check concentrations over the range 2–10 ppm. A simple method for detecting kerosene (Gerade & Skiba, 1960) was also used successfully to check samples having low toxicities (p. 20). About 0·5 ppm of BP 1002 could be detected by this method, though interference was sometimes encountered from oil in the water. In many cases duplicate samples were analysed by British Petroleum Limited and by the Government Analyst, who used Method 1 (p. 19), which measured the concentration of the surfactant fraction rather than the more volatile toxic component.

Samples of water were collected in 200 ml glass clip-top bottles both from the shore and by the Laboratory's divers. At stations farther from the coast the samples were collected from R.V. 'Sarsia'.

By taking colour photographs of the detergent patches while surface samples were being collected it was possible to record the appearance of different concentrations of detergent. For instance, in calm water 25 ppm or greater usually gave the sea a milky appearance and 5 ppm was distinctly visible. The formation and development of detergent patches was therefore recorded on colour transparencies and these were sometimes used to estimate concentrations of detergent in inaccessible parts of patches.

Observations

The development and subsequent behaviour of these detergent patches is largely determined either directly, or indirectly, by the strength and direction of the wind. In presenting these results therefore the localities studied are grouped according to the wind direction relative to the shore.

The effect of cross-winds was observed at two places—Porthleven and Halsfarren Cove.

At PORTHLEVEN on 5 April (Fig. 15) an estimated 3600 gallons of detergent were used on a neap tide with a moderately fresh westerly wind blowing. There was brown oil on the rocks at either side of the harbour entrance and on the sands for 1–200 metres east of the pier. The surface of the outer harbour was also covered with brown oil and this surrounded a large patch of black oil. All three regions were treated with detergent.

Even before high water a detergent patch which developed to the east of the pier was extending eastwards along the shore, while later at about high water separate patches from different treated areas were fusing together

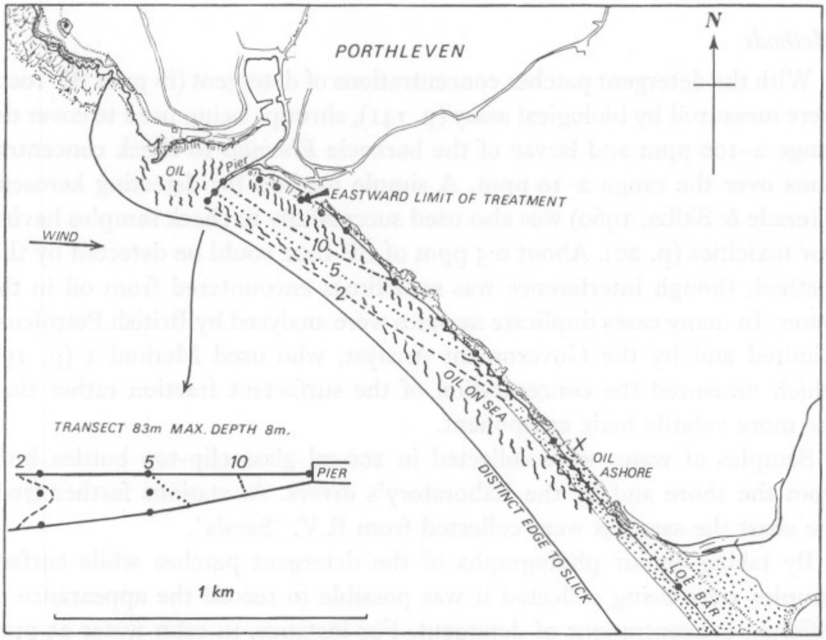


Fig. 15. The situation at Porthleven about 1 hour after high water on 5 April. Sampling stations along the shore and in the transect are shown by closed circles. Numbers show the concentrations of detergent in the water in ppm BP 1002. The scale refers to map, not transect.

near the end of the pier. A transect through this region is given in Fig. 15 and shows that the toxicity of the patch extended through the water column from top to bottom. The situation about 1 hour after high water is summarized in the same figure and also in Plate 22A. It will be seen that toxic concentrations of the detergent were moving rapidly south-eastwards along the shore and had already spread 1 kilometre from the nearest treated area. In addition, a layer of thin oil, or some constituent of the detergent, extended along the surface of the sea close to the shore for about 4 kilometres to the end of the bay. The movement of this detergent patch was mainly due to the strong wind, although it was probably assisted by inshore current. It was also noted that oil released from the rocks and harbour, but

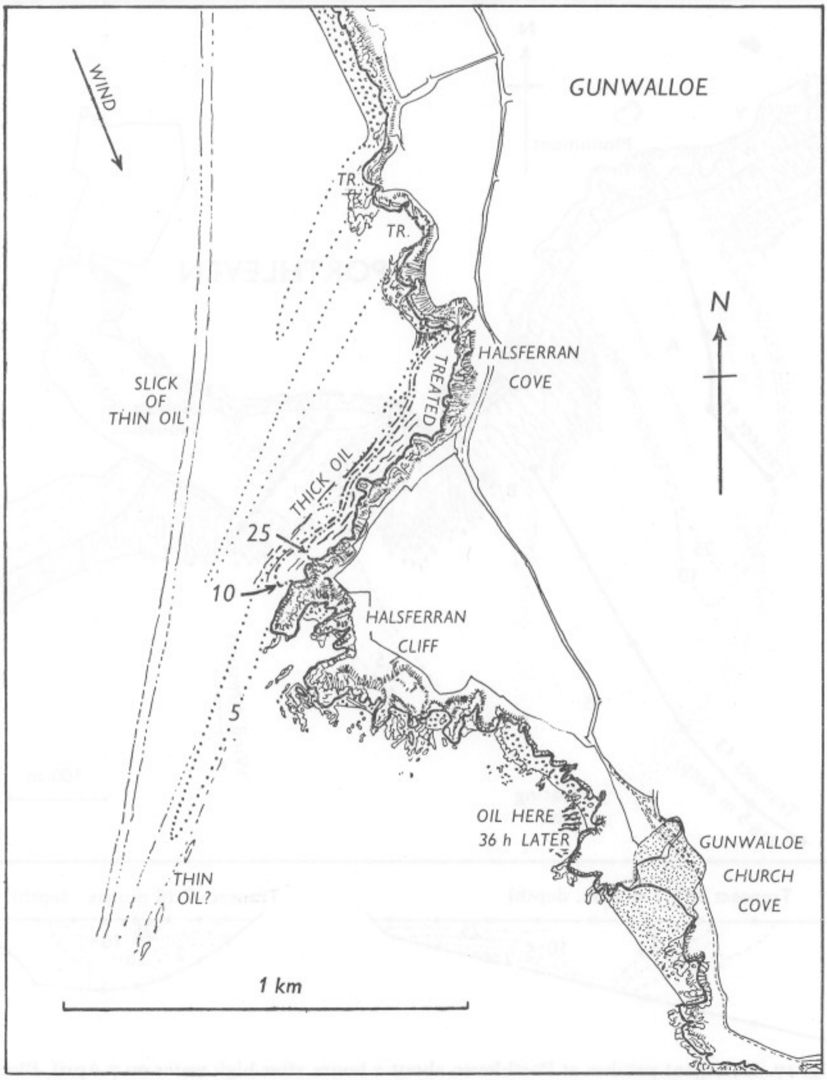


Fig. 16. The situation at Halsferran Cove about 2 hours after high water on 11 April. Numbers show the concentrations of detergent in the water in ppm BP 1002. Outlines of detergent patches from two other coves correspond roughly to concentrations of 5 ppm BP 1002. *TR.*, treated beaches.

not emulsified, was being blown rapidly along the surface of the sea and was already coming ashore on the sands to the east of the harbour (Fig. 15; Plate 22A).

At HALSFERRAN COVE on 11 April (Fig. 16) about 4000 gallons of detergent were used on a spring tide in the cove itself and more was used in the

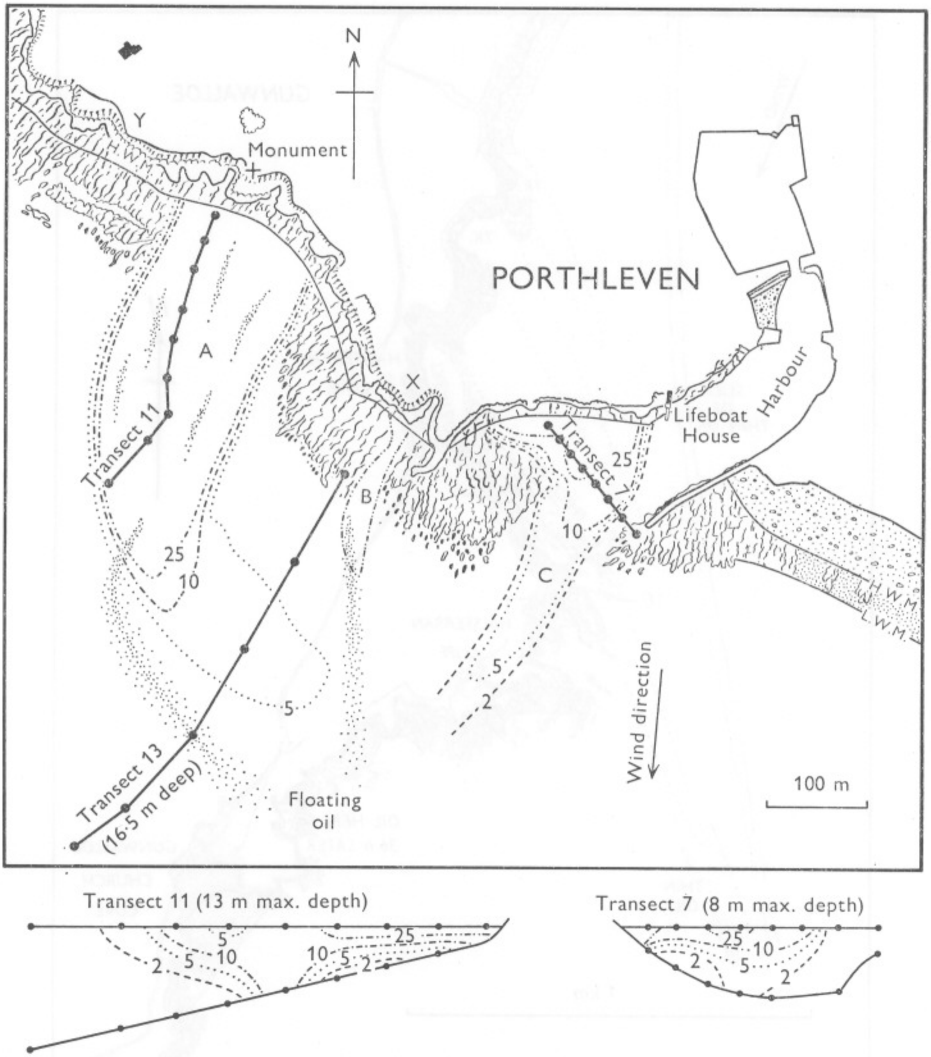


Fig. 17. Detergent patches at Porthleven about 2 hours after high water on 7 April. Black circles show the positions of sampling stations in a transect which was made on 7 April and also in transects made on 11 and 13 April. Results of transects made on 7 and 11 April are shown below the map. Numbers show the concentrations of detergent in the water in ppm BP 1002.

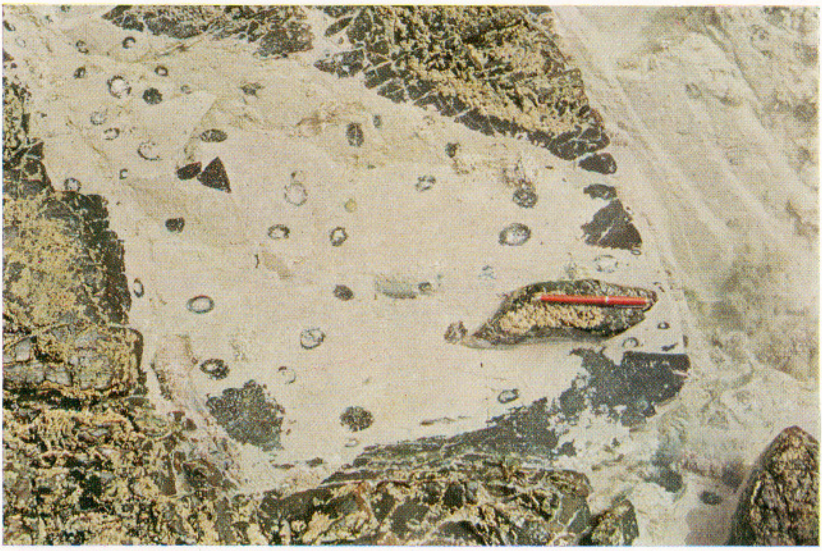
two coves to the north. The winds were light to moderate north-north-west. Brown oil up to 1 cm thick completely covered the intertidal and spray zones from Halsferran Cove to the base of Halsferran Cliff.

Under the influence of the wind, and probably also of the tidal current, the detergent patch which originated in Halsferran Cove moved along the

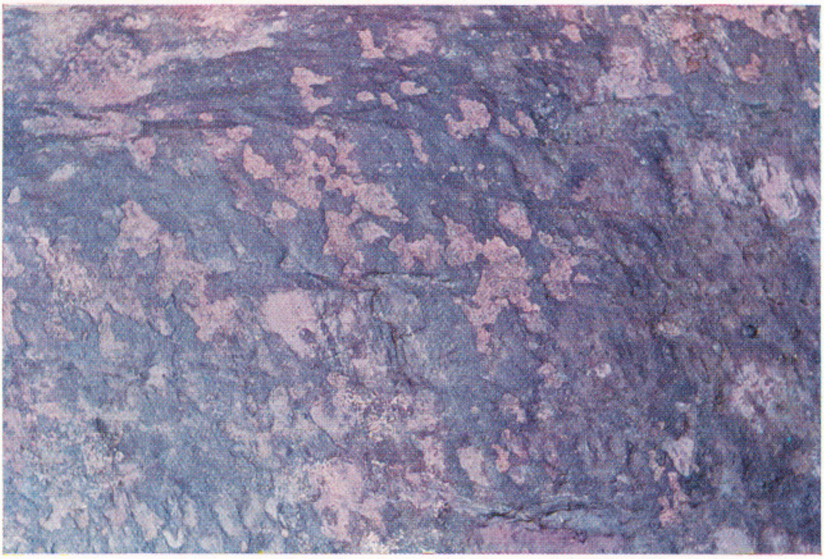
PLATE 17

A

B



A



B

C

(*Facing p.* 97)

coast close to the base of the cliffs. It had a very distinct seaward edge. Beneath the cliffs 2 hours after high water (Fig. 16) the patch was mainly concentrated in the intertidal zone and, although there was very little wave action, it would almost certainly be toxic from top to bottom. The patch then continued out to sea and was more than 1 kilometre long, with large amounts of brown oil which had been released from Halsferran Cove floating in it and nearby. This patch, or possibly one developed subsequently on 12 April, may well have given rise to the fresh oil which appeared farther down the coast on 13 April (Fig. 16). This figure also shows how patches extending from other coves ran parallel to the patch from Halsferran Cove, and the position of a narrow band of thin oil (which was seen on a number of occasions) is also shown.

These two examples clearly demonstrate that, when winds are blowing along the shore, oil and toxic levels of detergent may be carried for some considerable distance parallel to the shore to pollute adjacent areas of coast.

The effect of offshore winds was studied at Porthleven on two occasions.

On 7 April oil was still present on the rocks and in the gullies to the west of the harbour and about 3000–4000 gallons of detergent were used, the largest detergent patch (A in Fig. 17) representing perhaps half of this. A similar amount of detergent was used when a detergent patch almost identical with patch A was produced on 11 April.

On 7 April three distinct creamy white detergent patches developed, from west to east (A, B and C). About $1\frac{1}{2}$ hours before high water, patch B was well developed, and oil released from the shore and floating on the surface was being blown seawards (Plate 23A). A photograph of patch A (Plate 23B) also shows how, half an hour before high water, this released oil was being separated from the detergent patch by the wind. It also seems likely that,

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PLATE 17

A, Detergent-affected rock near sewer outfall, Trevone, 9 July. A surviving limpet and a top-shell (*Monodonta lineata*) keep a small area of rock free from algal growth. The barnacles and the mussels are alive. **B**, Bedruthan Steps, 10 August. Two limpets on an oil-covered rock. The limpets have cleaned away oil from the region immediately around them. The oil is seen to be impregnated with sand from the surrounding beach.

PLATE 18

A, Kynance Cove, 20 April. Mid-tide pool on reef which had been heavily sprayed with detergent. The pool is lined with encrusting coralline algae, normally pink, which have become bleached, as have the tufted corallines, several small clumps of which may be seen. Both of these algae showed heavy mortalities on this reef. Oval patches where limpets had been living show up clearly. At this time these pools contained the bodies of limpets which had separated both from their shells and from the rocks, and one such body may be just seen below a tuft of coralline toward the lower right-hand side of the picture. **B**, Bedruthan Steps, 7 August. Oil impregnated with sand flaking off rocks at high-water mark as a result of natural weathering processes. **C**, Hayle Estuary, 23 August. Oily sea-wall, which had not been treated with detergent, showing distinct tide-line. The orange lichen *Xanthoria* is seen still living beneath a covering of oil.

in addition to the oil released from the beach, some oil was separating from the emulsion. Thus, close inshore, where there was a little wave action, there was no floating oil and the detergent patch was the colour of milk chocolate, yet at about 20 m offshore floating oil was present. Under the offshore wind the sea was calm and conditions were not ideal for creating or maintaining detergent–oil emulsions.

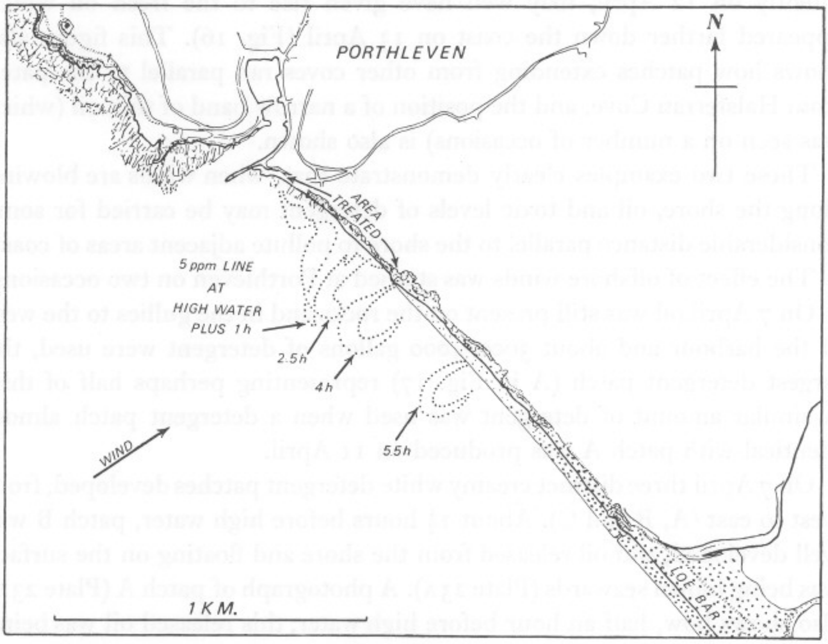

Fig. 18. Changes in the shape and position of a detergent–oil patch after high water at Porthleven on 19 April.

The situation at the surface of the sea 2 hours after high water on 7 April is summarized in Fig. 17. Each of the detergent patches had elongated, and all had very distinct edges, except at the seaward margin where some dilution and mixing seemed to occur. The largest patch (A) gradually turned eastwards and moved towards patch B, which was particularly well defined and was starting to constrict from the shore. Patches B and C did not turn eastwards because the wind blowing out through the harbour entrance was perhaps sufficient to counteract the eastward tendency of the tidal current.

A transect of patch C was made on 7 April, and on 11 April a transect was made of a patch which was almost identical with patch A as shown in Plate 23B. Results from both transects are illustrated in Fig. 17. Both show that most of the detergent–oil emulsion floats to the surface from the treated rocks. However, they also show that in the middle of each patch the toxic levels of detergent reached the bottom well seaward of the intertidal zone.

The effect of onshore winds was studied at two places—Porthleven Sands and Watergate Bay.

PORTHLEVEN SANDS were visited on 19 April on a neap tide with a light to moderate south-westerly wind blowing (Fig. 18). Detergent was being applied by pouring it on to the very coarse sand containing the oil and this was then covered by bulldozing on to it more oily sand. During this operation only about 300 gallons of detergent were used. Separate small detergent patches formed along the beach and later fused into larger patches which then moved out as the tide started to ebb. About $2\frac{1}{2}$ hours after high water these had fused into a single patch having a very distinct eastward edge and a tendency to curve to the east. After 4 hours the patch had moved eastward and had almost separated from the shore. It had also developed a hooked shape—possibly because the end of the patch near the surface was being blown back on to the shore. The patch was still clearly visible about 5 hours after high water and had started to move down the coast more rapidly. This movement was probably caused by the tidal current, although the wind was in a direction which might have slightly assisted the movement. In its later stages the patch was only attached to the shore by a toxic strip about 10 metres wide and seemed to be shrinking in size. However, it still retained a distinct shape and the mixing was not as rapid as might have been expected with an onshore wind.

The southern end of WATERGATE BAY (near Newquay) was studied during a spring tide on 23 April. The winds were light north-westerly. Here oil was present on the rocks and in the sand at the bottom of the high cliffs. About 400 metres of shore were treated with what was reputed to be some 4000 gallons of detergent.

At high water, when the sea was breaking against the base of the cliffs, the detergent patch started to move seawards as a discrete finger which was much narrower than the treated area. About $1\frac{1}{2}$ hours after high water the shape of the patch was similar to that shown in Fig. 19, although the advancing tip had not yet reached Trevelgue Head. Both changes in the direction of movement of the patch probably resulted from the effect of the current sweeping through the bay. The detergent patch was coloured brown, and obviously contained a large amount of oil. As the sea is very shallow here the toxic effects would almost certainly penetrate to the bottom. About 3 hours after high water the patch was no longer visible at its seaward end, although this may have been due to its dark colour and

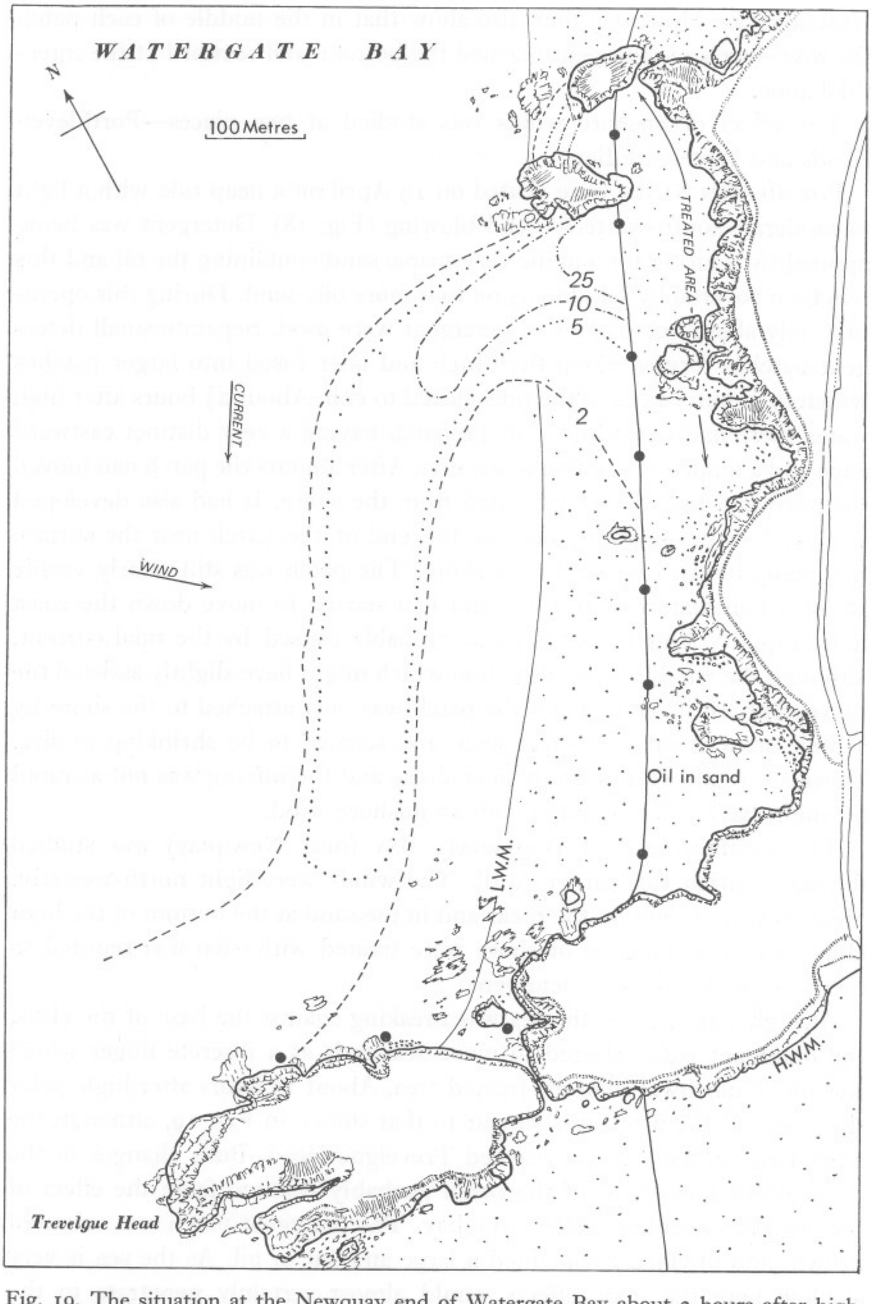

Fig. 19. The situation at the Newquay end of Watergate Bay about 3 hours after high water on 23 April. Black circles show the positions of sampling stations and numbers show the concentrations of detergent in the water in ppm BP 1002.

fading daylight. A series of samples was taken along the coastline as the tide ebbed. From the smell of detergent and the collecting of a toxic sample (greater than 2 ppm) near Trevelgue Head, it is almost certain that the patch was in the position illustrated in Fig. 19; but it was probably becoming progressively less easily defined as a result of mixing, evaporation and its movement out to sea. The figure clearly shows that the landward end of the patch did not spread farther along the shore but remained concentrated in the treated region. It seems almost certain that this part of the detergent patch would return on the following tide and that, in addition, detergent and oil were being left behind in the sand as the tide ebbed.

The persistence of detergent patches

Except where strong cross-winds were encountered (Fig. 15), the detergent patches have a fairly definite shape during their early history. It is difficult to discover just how long this shape lasts and what the ultimate fate of the patch is. Evidence from Figs. 17 and 18 shows that a constriction can eventually develop between a patch and the shore so that it could become detached and drift away. These patches are not visibly persistent, for no detergent patch was ever obvious on the day following its production. Presumably this is due to a combination of evaporation of the detergent and lateral and vertical mixing. However, mixing appears to be relatively slow, particularly in calm conditions, and individual patches may retain identity even when they are no longer visible.

There is some evidence to support this hypothesis. For instance, at low water on 7 April at Porthleven a transect was made by a team of divers with Dr Lythgoe with stations 120, 300 and 600 metres distant from the end of the pier. On the previous day the wind had been blowing off the shore and some detergent patches would have been expected to move through the region of this transect. Analyses by the Government Chemist of surfactant concentration gave equivalent total detergent concentrations at these stations of between 0·08 and 0·48 ppm. The results are summarized in Table 10 and show that the amount of detergent in the water decreases with depth. Concentrations of detergent of this order would probably not, however, be toxic to most species.

Further evidence for the persistence of an offshore detergent patch was obtained, again from Porthleven, on 13 April, on this occasion by a team of M.B.A. scientists. At low water a transect was taken from the reef to the west of the harbour along the line shown as transect 13 in Fig. 17. This extended 460 m from the tide line of low-water springs over a gently sloping rocky shelf to a sandy plane at approximately 16 metres depth. Toxicity equivalent to 2 ppm of BP 1002 detergent was detected along the

Table 10. *Concentrations of detergent (ppm) from a transect taken opposite Porthleven pier on 7 April*

(Concentrations were found by multiplying analyses for non-ionic surfactant by eight. At the most distant station the depth was about 20 m.)

Distance from pier (m) ...	120	300	600
Surface	0·4	0·48	0·4
1 m	0·24	0·40	0·32
½ depth	0·24	0·24	0·24
Bottom	0·16	0·16	0·08

shore, and at the surface stations 100, 300 and 400 metres, as well as at bottom stations at 300 and 460 metres distant from the shore. No detergent was used on 13 April. Detergent had, however, been used on 12 April, when it probably resulted in a detergent patch like A in Fig. 17, which passes through the region of this transect.

These two examples show that detergent patches may persist for at least 24 hours offshore. This may also be true for inshore patches. Thus, at high water at Mawgan Porth on 23 April the water at each end of the bay was toxic to the extent of about 4 ppm of detergent. This was at least 24 hours after the treatment of the sands with detergent. The detergent was probably still being leached from the treated sand and the onshore winds had probably prevented any seaward movement.

Evidence for a longer-term persistence of offshore patches is provided by R.V. 'Sarsia's' cruise III. On 13 April (p. 32) none of the samples collected off Marazion or Porthleven (Fig. 7) was toxic to shrimps. This suggests that there was very little detergent solvent in these regions and this was confirmed by using the test for it (p. 20). However, considerable amounts of the surfactant were found in some samples by the analysts of British Petroleum Limited. This was particularly evident in samples from the Marazion area (Table 4; Fig. 7). About 2 kilometres off Porthleven surfactant was only detectable at the surface, except in one instance where the equivalent of 24 ppm of detergent were found at the bottom. The only explanation which can be offered for this particular result is that it might be expected if the detergent moves in fairly discrete patches, as was suggested above.

Conclusions

From such a limited number of observations it would be dangerous to make any broad generalizations about the behaviour of detergent patches. As many different situations were examined as possible but in no cases, except that of 5 April at Porthleven, were strong winds encountered. For example, it is not certain what the effect of a directly onshore gale-force wind would be.

What is certain is that toxic concentrations of detergent are not simply confined to the section of shore which is treated, or to the surface of the sea where the detergent patches are most obvious. Most of the evidence shows that detergent patches do not disperse very rapidly. Consequently, patches of water with some toxicity extending to the bottom can influence distant areas of the sea-bed or shore, under the influence of the wind and tidal currents. With cross-winds, toxic concentrations of detergent can be spread along the shore, probably for several kilometres. With offshore winds, distinct patches with some toxicity extending to the bottom move seawards and influence regions below the intertidal zone.

Residual toxicity can remain on shores, particularly in surface sand, for more than 24 hours. It has also been detected in offshore bottom samples 24 hours after treatment of the intertidal zone. Furthermore, when buried under fresh sand it can persist for many weeks.

Sometimes quite high concentrations of the non-volatile emulsifying agent (surfactant) from the detergent have been detected up to 2 kilometres offshore in the Porthleven and Mount's Bay areas. Emulsifying agents are not very toxic over short periods of time (p. 145) but we have no knowledge of their possible long-term effects.

It has been found that emulsification of oil is often incomplete and it further appears that, particularly in calm conditions, some oil separates from the emulsion—as it does in laboratory tests (p. 21). Whereas a detergent patch is influenced by tidal currents as well as the wind, the floating oil is moved solely under the influence of the wind (Chapter 8). As a result, floating oil can separate from the detergent patch and may then come ashore on another section of the coast (as seen in Plate 6A, B).

TOXICITY STUDIES ON OFFSHORE ORGANISMS

Our study of the initiation and subsequent fate of mixed oil and detergent patches has shown that relatively high concentrations of detergent can occur, not only at the point of application, but also some distance away. The question now arises: what will be the biological effects of the travelling patches of detergent? To examine this point further, toxicity experiments with representative offshore species were made in the laboratory (see Chapter 7, p. 137) in order to complement the offshore surveys made by various teams of divers which are reported later in this chapter.

BIOLOGICAL EFFECTS OF OFFSHORE DETERGENT PATCHES

One of the most significant results from our studies of the transport of detergent patches was to show that these patches may persist as discrete bodies of toxic water for at least 24 hours and may, under appropriate conditions of wind and sea, extend well offshore. Moreover, as will be shown below and on page 137, their detergent concentrations are toxic to some at least of the sublittoral species of plants and animals.

It was important therefore to get direct evidence of mortalities in the sublittoral flora and fauna by means of underwater surveys. It was decided to examine one underwater region (Porthleven) in considerable detail, and to supplement this study with more generalized surveys elsewhere.

To some extent the areas chosen were determined by the weather, since diving in shallow sublittoral regions cannot be usefully carried on in rough seas when visibility is greatly reduced and turbulence prevents easy manipulation of equipment. In addition to the Porthleven surveys dives were carried out off Gunwalloe, Loe Bar, Marazion, Sennen Cove and Porthmeor Beach, St Ives (for maps see Figs. 8 and 9).

Offshore surveys at Porthleven

During April a long period of northerly (offshore) winds was favourable for diving in the Porthleven area. A diary of the Porthleven dives with notes on the condition of some of the plants and animals noted during the dives is given in Table 11. (For dates of spraying here see p. 57.)

The most detailed observations were made during the dives (nos. 5–10 in the Table) of 13 April along a transect extending from the seaward edge of the Porthleven reef to a station 460 metres from the shore and at a depth of 8·5 fathoms (16·5 metres). Fig. 21 (p. 109) shows a diagram of the distribution of the affected and unaffected animals and algae off

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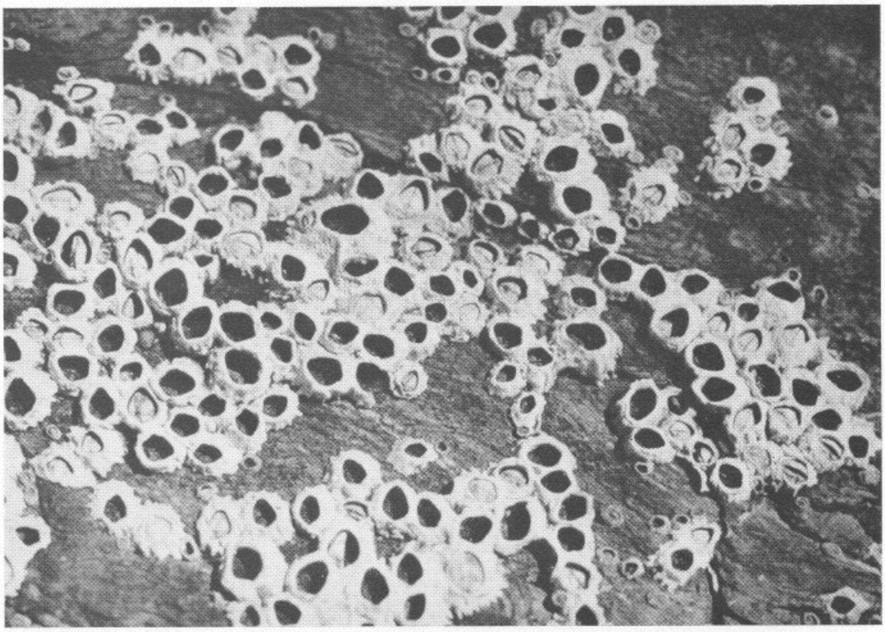
PLATE 19

A, Porthleven Reef, 8 May. Barnacles (*Chthamalus stellatus*) at high-water mark almost all killed by detergent-cleansing operations. **B**, Godrevy Point, 10 May. Barnacles (*Chthamalus stellatus*) at high-water mark almost completely covered by oil, but untouched by cleansing operations, still alive after six weeks exposure to pollution.

PLATE 20

A, Marazion, 28 March. Razor-shell (*Ensis siliqua*) showing effect of detergent, which has caused it to come up out of the sand. Low water of spring tides on sand beach west of the Causeway. **B**, Underwater photograph taken about 75 metres off Porthleven Sands at about 10 metres depth, 18 May. Dead shells of *Ensis siliqua*, *Mactra corallina* and one valve of *Lutraria* sp., together with fragments of tests of *Echinocardium cordatum*, which had accumulated in a gully between rocks.

PLATE 19

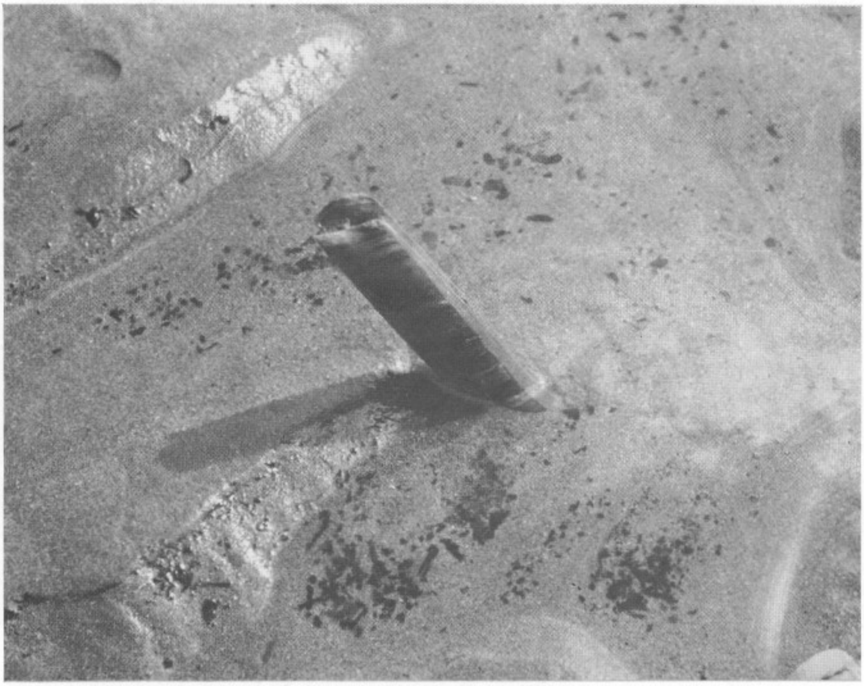


A

B

(*Facing p.* 104)

PLATE 20



A

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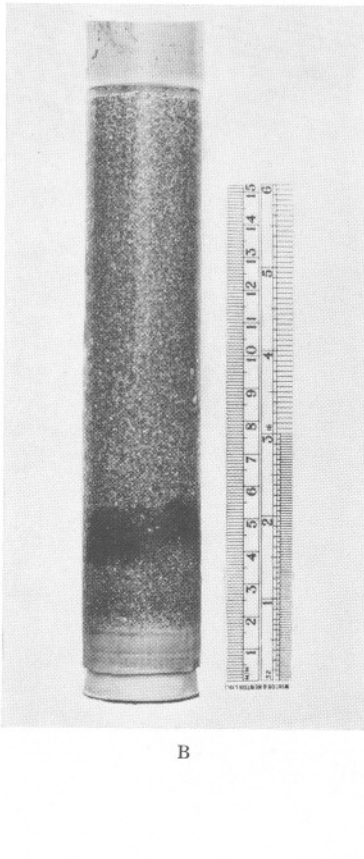
PLATE 21

A



B

A

B

(*Facing p.* 105)

Porthleven reef. The information is largely based on that gained from dives 5–10.

Dive no. 10 was made just below the low-water mark of spring tides at a station slightly to the north-west of the transect line.

Although the laminarians of wave-exposed shores, *Alaria esculenta* and *Laminaria hyperborea*, appeared healthy, the epiphytic red algae on the stipes of the latter, and also those on *Furcellaria* and *Cladostephus*, were either dead or had been seriously damaged. The only living species found as epiphytes were *Cryptopleura ramosa*, *Spermothamnium repens* and parts of some tufts of *Jania rubens*. Species which had been killed included the red algae *Apoglossum ruscifolium*, *Hypoglossum woodwardii*, *Polysiphonia* sp., *Ceramium rubrum*, *Plocamium vulgare*, *Delesseria sanguinea* and *Heterosiphonia plumosa*, and the brown alga *Dictyota dichotoma*. Species brought up from the sublittoral fringe zone in healthy condition included *Laurencia pinnatifida*, *Gigartina pistillata* and *Phyllophora crispa*.

In slightly deeper water (dive no. 9, 2 fathoms) the plants were by contrast not visibly affected. As with the plants, animals in the first few feet below low-water mark suffered severely. During a dive on 11 April in the same area many dead decapods including crabs (*Portunus*, *Cancer*) and squat-lobsters (*Galathea*), a lobster (*Homarus*), and a few prawns (*Palaemon*) were found. Numerous dead specimens of the starfish *Marthasterias* were also collected; and others were seen in a moribund state. Several dead rocklings were also taken. It would seem that the strong ground-swell of 11 and 12 April may have swept to sea most of the casualties recorded on 11 April, presumably accounting for the lack of dead animals observed on 13 April (dive no. 9).

At the two succeeding stations along the transect (no. 8 in 5 fathoms, and no. 7 in 6·5 fathoms), which like the first had a dense canopy of *Laminaria*, there were again no toxic effects apparent on 13 April. Indeed, only one dead top-shell (*Calliostoma*) was seen. However, at the next station this type of habitat abruptly gave way to a level sandy bottom, unprotected by

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PLATE 21

A, Sennen Cove, 23 August. Small rafts of floating sand grains on standing water in ripple 'troughs' at low tide. **B**, Sand core from low-water mark at Perranuthnoe, showing layer of oil under clean sand, 12 May.

PLATE 22

A, View of detergent–oil patch taken from point X in Fig. 15 looking towards Porthleven. The patch, which originated in the region of the harbour mouth, is being blown along the coast past the camera. A, Harbour mouth; B, seaward edge of detergent–oil patch; C, oil in the waves; D, lines of oil deposited on shore. **B**, Trégastel-Plage (Côtes du Nord), 21 June. Detergent emulsion spreading across the bay following spraying of oily rocks. This view is a little to the north of that shown in Plate 28C. The re-separated oil shown in Plate 6A was photographed an hour or two earlier beside the slipway seen in this view.

Table 11. *Summary of M.B.A. diving surveys—Porthleven*

Dive no.	Date: April	Position	Depth	Substratum	Results
2	7	(i) Off Porthleven reef	2 fm (4 m)	Rocks and gully	Collected dead crustaceans including one large lobster
3	7	(ii) Porthleven harbour entrance	2 fm (4 m)	Gravel	
4	11	Off Porthleven reef and harbour entrance	5 fm (9·5 m)	Rock shelf and gravel	Many dead decapods—*Portunus puber*, *Cancer pagurus*, *Galathea strigosa*, *Homarus vulgaris*, *Palaemon serratus*, *Xantho incisus*, also *Actinia equina*, *Marthasterias* sp. and *Onos* sp., *Delesseria sanguinea* affected, *Heterosiphonia plumosa* dead, *Hypoglossum woodwardii* bleached
		Porthleven reef			
5	13	(i) 460 m from shore	8·5 fm (16·5 m)	Sand	Dead and dying *Echinocardium cordatum*, *Mactra corallina*, *Ensis siliqua* (19), *Marthasterias*. Apparently unaffected *Asterias rubens*, *Acrocnida brachiata*
6	13	(ii) 400 m	8 fm (16 m)	Sand	As above—fewer *Ensis siliqua*
7	13	(iii) 300 m	6·5 fm (13 m)	Rock	One dead *Calliostoma zizyphinum*. Two *Echinus esculentus*, one *Archidoris pseudoargus* apparently unaffected
8	13	(iv) 200 m	5 fm (10 m)	Rock	None apparently affected. *Calliostoma zizyphinum*, *Maia squinado* healthy
9	13	(v) 100 m	2 fm (4 m)	Rock	No obviously affected animals, casualties probably removed by ground-swell

10	13	Porthleven reef	0–2 fm (0–4 m)	Rock	Collected algae—mainly *Furcellaria fastigilda* and *Cladostephus verticillatus* which appeared normal. Epiphytes dead. *Delesseria sanguinea*—dead, *Gigartina pistillata* normal, *Laurencia pinnatifida* colour not normal, *Alaria* sp., good condition. Epiphytes: *Hypoglossum*, *Apoglossum*, *Polysiphonia*, *Ceramium*, *Plocamium*, and *Dictyota* all dead or dying
16	15	S. Porthleven (700 m offshore)	10·5 fm (21 m)	Fine sand	As for dive no. 15 (see Table 12) but with fewer *Ensis*
17	15	Porthleven sands	11·5 fm (22 m)	Fine sand	Dead and dying *Echinocardium cordatum* (23 in 5 samples of 1 m^2), *Mactra corallina*, *Ensis siliqua*. *Acrocnida brachiata*, *Natica alderi*, *Corystes cassivelaunus* all appeared healthy
18	19	(i) Porthleven reef	7·5 fm (15 m)	Rock	*Echinus esculentus* on rocks—normal
19	19	(ii) Porthleven sands	7·5 fm (15 m)	Fine sand	Dead and dying *Echinocardium cordatum* (18 in 4 samples of 1 m^2), *Ensis siliqua*, *Mactra corallina*, *Corystes cassivelaunus*. Healthy *Asterias rubens*, *Marthasterias glacialis*, *Acrocnida brachiata*—photographs taken (see Plates 24 A, B)
21	28	Porthleven reef (i) 375 m offshore	8·5 fm (17 m)	Sand	Accumulations of dead and dying *Echinocardium cordatum*, *Ensis siliqua*, *Mactra corallina*. Healthy *Acrocnida brachiata* and on a rock two *Cancer pagurus* present. *Gobius* sp. seen
22	28	(ii) 325 m offshore	7·5 fm (15 m)	Rock	*Laminaria hyperborea* forest with normal encrusting species. Eight *Echinus esculentus* healthy

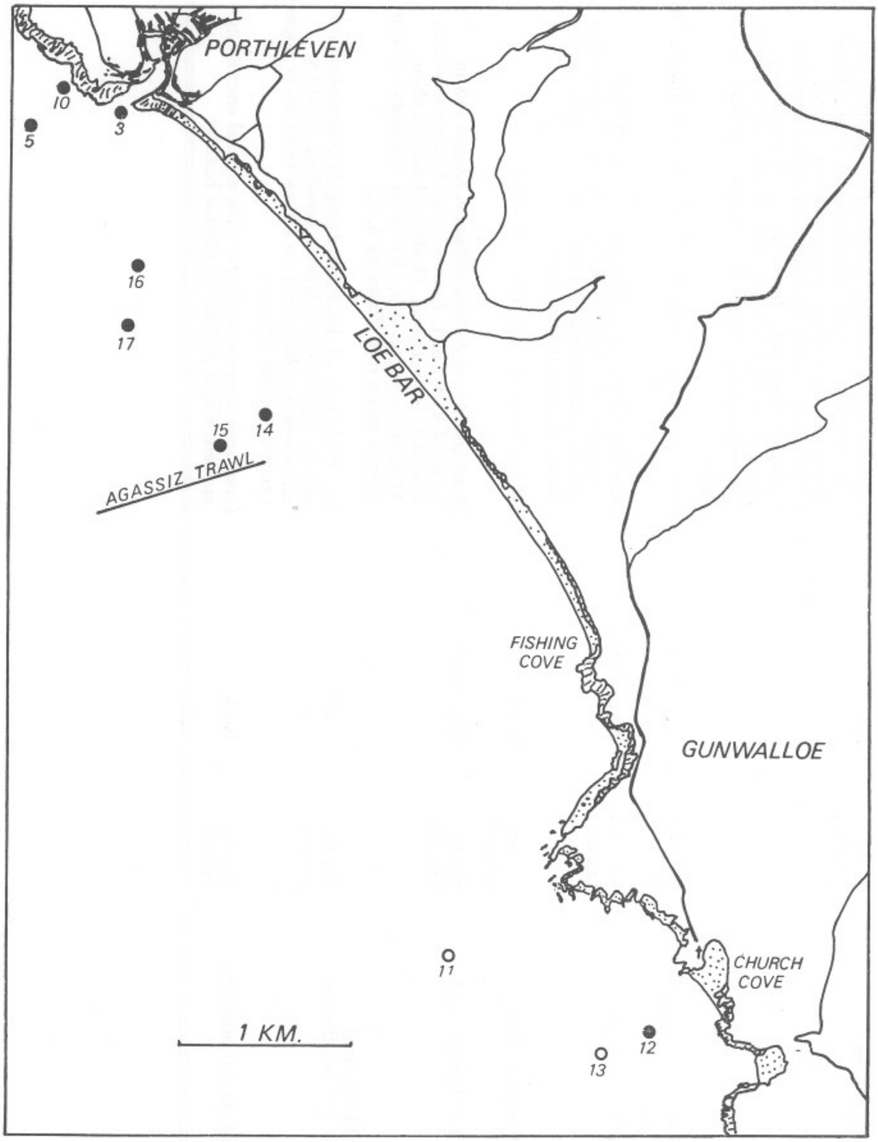


Fig. 20. Stations at which the bottom fauna were examined by divers between 7 and 15 April. Numbers correspond to those of the dives in the diving report (Tables 11, 12). Closed circles show that affected animals were found and open circles represent no effect or inconclusive evidence.

weed, and at the last two stations on the transect (6 in 8 fathoms and 5 in 8·5 fathoms) a totally different kind of fauna was found. Here there were found many dead and dying heart-urchins (*Echinocardium*), several bivalves including *Mactra* and the razor-shell (*Ensis*), and two species of starfish (*Marthasterias glacialis* and *Asterias rubens*). At station 5 even more *Ensis* were found moribund and dead; and during a later visit to this station on 28 April large numbers of dead animals were taken here. Both the affected *Echinocardium* and *Ensis* (which live in considerable numbers within this fine sand) had taken up characteristic and unusual postures which are more fully described below (p. 113), and illustrated in Plates 20B, 24A, B and 26C.

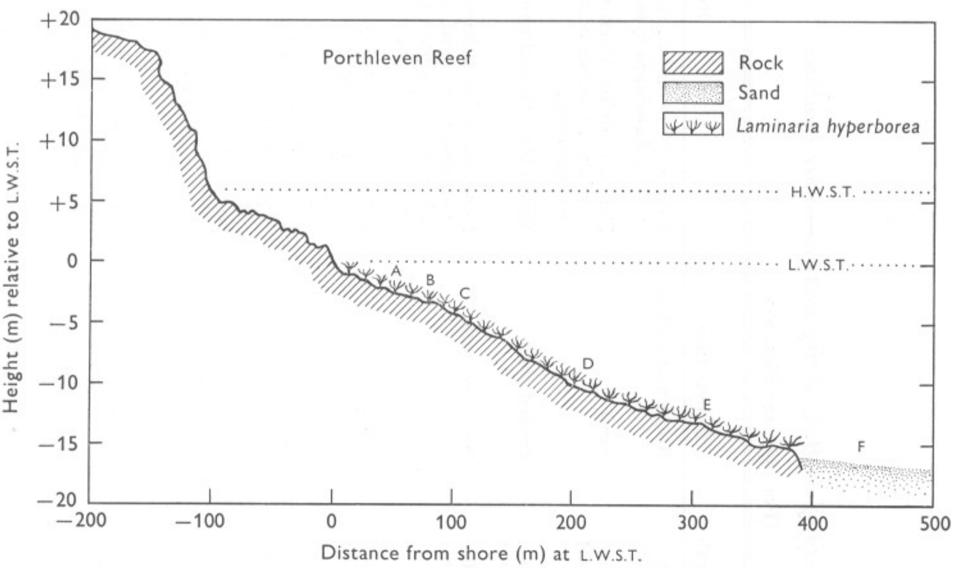


Fig. 21. Diagrammatic profile off Porthleven based on several dives carried out in the region. The nature of the bottom and distribution of organisms is shown. A, 0–2 metres depth: most crabs, starfish and other animals dead; many fine red seaweeds dead. B, 2–4 metres depth: some dead crabs, many others lacking limbs (?moribund); few dead rocklings; red seaweeds occasionally affected. C, 4–5 metres depth: some crabs lacking claws, others apparently unaffected; seaweeds also unaffected. D and E, 7–17 metres depth: no animals or seaweeds affected; edible sea-urchins present. F, 17–18 metres depth: many dead razor-shells and burrowing sea-urchins; brittle-stars and common starfish very little affected.

It will be seen that, in general, the immediate sublittoral fauna and flora of Porthleven Reef was markedly affected by the outflow of detergent—many animals being killed. However, the apparent diminution of effect close inshore (for example, at stations 7–9) is puzzling. The answer probably lies in the difference between the two habitats at the inshore and more distant stations—weed-covered rock inshore and open sand further to sea. In the first, many of the more obvious animals are free-ranging and when killed the carcases are probably washed to sea. In the second, much

Table 12. *Summary of M.B.A. diving surveys—other localities*

(For map, see Figs. 8–9.)

Dive no.	Date: April	Position	Depth	Substratum	Results
11	15	Gunwalloe (Church Reef)	6 fm (12 m)	Rocks and gullies	No sign of pollution, typical rocky bottom, fauna among *Laminaria hyperborea*. Fish present
12	15	Gunwalloe (600 m offshore)	5 fm (10 m)	Sand	Dead and dying *Mactra corallina*, *Echinocardium cordatum*, *Corystes cassivelaunus*. Healthy *Eupagurus* sp.
13	15	Gunwalloe (800 m offshore)	9 fm (18 m)	Packed sand	Worm burrows and one healthy *Cancer pagurus* seen
14	15	Loe Bar	6·5 fm (13 m)	Sand and rock	Dead and dying *Echinocardium cordatum*, *Mactra corallina*, many dead in gullies near rocks. Few *Acrocnida brachiata* which seemed healthy. Encrusting species on rock healthy
15	15	Loe Bar	9 fm (18 m)	Fine sand	*Echinocardium cordatum*, *Mactra corallina*, *Ensis siliqua* dead and dying on surface. Healthy *Asterias rubens* present
20	24	Sennen Cove	0–3 fm (0–6 m)	Sand and rocks (wreck)	Dead *Cancer pagurus*, *Portunus puber*, *Xantho* sp., *Patella vulgata*, *Echinus esculentus*, *Psammechinus miliaris*, *Actinia equina*. Healthy *Bunodactis verrucosa*, *Cancer pagurus*, *Labrus bergylta*, *Gadus pollachius*, *Marthasterias glacialis*, *Patella vulgata*, *Maia squinado* and worms. Red algae and *Corallina* sp. affected
23	28	St Michael's Mount (i) 250 m offshore	1 fm (2 m)	Coarse sand	Dead and dying *Ensis siliqua*, *Echinocardium cordatum*, *Mactra corallina*, *Venus striatula*, and *Portumnus* sp. *Acrocnida brachiata* appeared normal

24	28	(ii) 350 m offshore	2 fm (4 m)	Fine sand	Numerous dead and dying *Ensis siliqua* (90% dead, 1–2/m²), *Echinocardium cordatum* (2–10/m²), *Mactra corallina*, *Portumnus* sp., *Donax vittatus*. Apparently healthy *Marthasterias glacialis*, *Asterias rubens*, *Natica alderi*, *Acrocnida brachiata*, *Crangon* sp., and *Zostera* sp.
		Sennen			
25	29	(i) Lifeguard station	5·5 fm (11 m)	Rock reef and sand	Dead *Echinus esculentus*, *Marthasterias glacialis* abundant
26	29	(ii) Pedn-men-du	8 fm (16 m)	Rocks	Dead *Echinus esculentus*, *Homarus vulgaris* claw, *Alcyonium digitatum*. Healthy *Labrus bergylta* and two undersized *Cancer pagurus*
1	1	Porthmeor 'Browther Rocks'	4–5 fm (8–9 m)	Rocks on sand	Two dead *Cancer pagurus*, one without legs, everything else normal
	May				
		St Ives			
27	4	(i) 450 m off Porthminster Point	7 fm (13 m)	Fine sand	*Ensis siliqua*, *Echinocardium cordatum*—some dead, some on sand apparently unhealthy. *Dosinia lupinus* many dead shells, a few shells with dead tissues. One *Lutraria* sp. unhealthy. Hermit crabs healthy
28	4	(ii) About 350 m off Porthminster	7 fm (13 m)	Fine sand	Two *Echinocardium* within a 3 m radius, mollusc fauna as (i) but sparse. One young *Sepia* healthy
29	4	(iii) About 700 m south of Carrack Gladden	4·5 fm (8 m)	Clean sand	Fourteen *Echinocardium* covered with oil and sand. Two *Ensis* unhealthy. One *Corystes* healthy. One *Lutraria* possibly unhealthy, all in 3 m radius circle
30	4	(iv) About 500 m east of harbour light	9 fm (16·5 m)	Clean sand	One *Echinocardium cordatum* dead, one possibly unhealthy, two unhealthy *Ensis siliqua*, partly dead colony of *Hydractinia echinata*; whereas two hermit crabs, one *Corystes cassivelaunus*, two *Gari fervensis*, four *Dosinia lupinus* all apparently healthy. One shell with living goby eggs attached collected

of the fauna is less mobile and, moreover, contains mainly suspension and detritus feeders which sample considerable quantities of water.

The animals living in the fine sands off Porthleven demonstrated very clearly the toxic effects of the detergent patches at places far distant from the shore. Thus, affected animals (dead and dying *Echinocardium*, *Mactra* and *Ensis*) were found at all four of the diving stations off Loe Bar (Table 12, nos. 14–17; Fig. 20), two of which (15, 17) were more than a kilometre from the shore at about the 10-fathom line. Experiments (pp. 137, 140) have shown that these species are sensitive to only 0·5 ppm of detergent so that concentrations of this order presumably reached these offshore stations. Later dives on 28 April (Table 12, nos. 23, 24) showed that there had been a nearly complete mortality of *Ensis*. The numbers involved must be very great for there was often at least one dead animal to each square metre. It was also noted in the dives that fish were rare within a kilometre of the shore, yet when, on two occasions, the Agassiz trawl was used by R.V. 'Sarsia' 1–2 kilometres off Loe Bar (Fig. 20) living fish, such as plaice and dabs, were caught in normal numbers although one dead *Ensis* was seen. This would seem to indicate that for large animals the limit to which the toxic effects of the detergent had spread in this area was of the order of 1 kilometre from the shore.

It can be concluded then that the effects of the treatment at Porthleven were felt on the sea-bed at least as far as 2 kilometres south-east of the harbour and 1 kilometre from the shore. This is the direction in which the detergent would be expected to move because there is a net eastward flow of water in this region. At the end of the bay no effects were found at station 11 on 15 April. The detergents issuing from Porthleven had evidently not reached this area, and patches from Halsferran Cove (Fig. 16) may have passed between stations 11 and 13. Toxic effects found at station 12 were probably the result of treatment of Gunwalloe Church Cove.

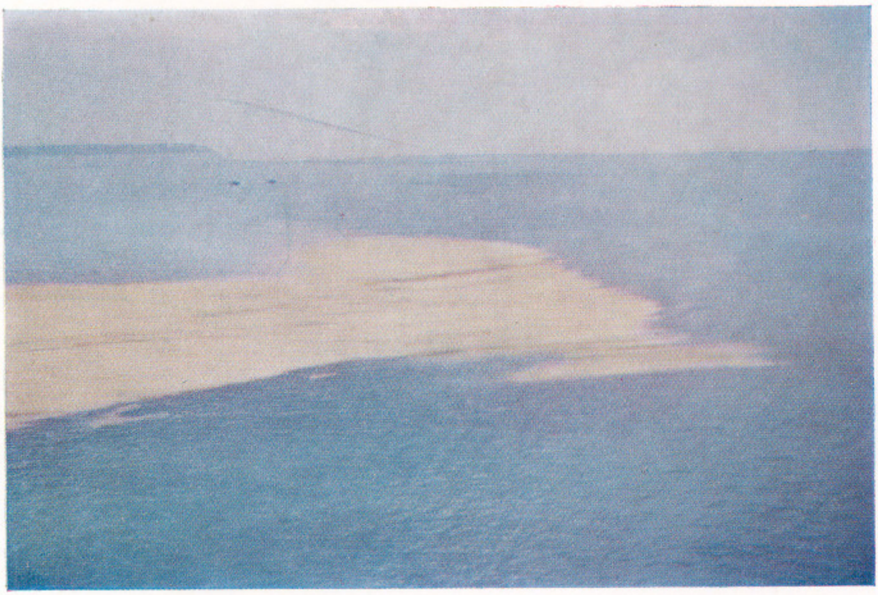
In concluding this section of the report dealing with the offshore spread and toxic effects of shore-originating detergent patches, it may be of interest briefly to survey the consequences of the passage of the detergent patches, with some notes made at the time of the dives, on a few of the commoner animals of the sublittoral region.

PLATE 23

A, Shows detergent–oil patch B from Fig. 17 taken from point X on the cliffs about 1·5 hours before high water. Released oil is being blown rapidly seawards. **B**, Detergent–oil patch A from Fig. 17 taken from point Y on cliffs about 0·5 hours before high water. Oil, which probably came out of emulsion, is being blown seawards as the detergent–oil patch swings to the east.

PLATE 23

A



B

(*Facing p.* 112)

Decapod Crustacea

Considerable mortality was noted in the squat-lobster, *Galathea strigosa*, and the swimming-crab, *Portunus puber*, as well as among young edible crabs (*Cancer pagurus*) during one dive from rocks 350 metres west of the harbour entrance at Porthleven on 11 April (dive 4, Table 11). Just below the lowest shore level down to about 1·5 fathoms (3 metres) virtually all crustaceans were dead, including one small lobster. At 1·5–2 fathoms (2·5–3·5 metres) some crabs were alive but incapacitated by loss of claws and legs, while at 2½ fathoms (4·5 metres) some *Portunus puber* and young *Cancer* were apparently unaffected. During a further search of nearby rocks on 13 April (dive 10) some more dead crabs were obtained but a ground-swell had swept away most of the casualties. A few dead *Cancer* and *Portunus puber* were found also at Sennen and two dead lobsters off Porthleven. Dead specimens of the burrowing *Corystes cassivelaunus* were collected from Gunwalloe and Porthleven (Plate 25 A).

Bivalve molluscs

Observations at four different positions showed that *Ensis siliqua* and *Mactra corallina* had been seriously affected along much of Mount's Bay (dive 23), and also in St Ives Bay (dives 5, 27, 28, 29, 30), down to depths of 8 fathoms (14·5 metres). During the first few dives many specimens were still alive but in an apparently moribund state, the *Ensis* often protruding up to 5 cm above the sand and *Mactra* lying on the surface. Later dives on 28 April (dives 23 and 24) showed that there had been a nearly complete mortality among the *Ensis*. Many of the unhealthy *Mactra* were being attacked by small starfish (*Asterias rubens*) and it seemed probable that many, if not eaten by predators, might die from the effects of detergent poisoning. Off Marazion, in water containing up to 6 ppm of the surfactant fraction of the detergent, some dead *Ensis* were found. Tests had shown that *Ensis* were unaffected by exposure to 10 ppm surfactant for more than 24 hours. It seems likely therefore that the animals were killed by low levels of the solvent rather than by the surfactant component of the detergent. Follow-up dives in July and August established that at least a few *Ensis siliqua* and *Mactra* survived both off Porthleven and St Michael's Mount.

Echinoderms

Many dead specimens of the starfish *Marthasterias glacialis* were collected just below the low-water mark near Porthleven (dive 4), from 1–3 fathoms (2–7 metres) depth, and many more were observed in a moribund state. A few on the sandy ground at 6 fathoms (13·5 metres) were not healthy, whereas animals on rocks at 5–6 fathoms (12·5–13·5 metres) were normal. At Sennen, however, moribund starfish were found in rocky areas from 3 to 6 fathoms (11–13·5 metres) depth (dive 25).

The burrowing heart-urchin, *Echinocardium cordatum*, was abundant (about six per square metre) on the fine-sand areas off Loe Bar, Porthleven, Long Rock and St Ives—most of the urchins were observed to have come out of the sand (Plate 24 A), in which they would normally bury themselves to a depth of several centimetres; only a very few were collected in their burrows. Those on the surface were moribund; with a slow-moving animal such as the heart-urchin it is sometimes difficult to know its condition. There were, however, numerous recently dead tests, often aggregated by the ground-swell at the edge of rocks (Plate 26 C). These and freshly dead animals washed ashore indicated widespread mortality. But dives later in the year showed many had survived.

Many recently dead tests of the large sea-urchin, *Echinus esculentus*, were seen off Sennen (dives 20, 25, 26) in depths of 3–8 fathoms (5·5–14·5 metres) together with live but moribund specimens (Plates 25 B, 26 B). Off Porthleven and near Gunwalloe, however, *Echinus* were common and apparently unaffected at 6–7 fathoms (13·5 metres) depth in the *Laminaria* zone. This would indicate a greater depth-penetration of the toxic concentration at Sennen than off Porthleven, perhaps because of the generally rougher sea on the west-facing coast during April, and also, no doubt, because of the extremely heavy spraying programme carried out at Sennen.

Algae

Apart from many of the delicate red algae at or near the shore margin the only species which seemed to be affected was *Delesseria sanguinea* in depths of less than 3 fathoms (6 metres) (Plate 26 A).

In listing the offshore species which were adversely affected by detergents it should not be forgotten that many species were apparently quite resistant. Thus the spider-crab *Maia squinado* was found on several occasions in rocky areas apparently unaffected by the toxic chemicals which were killing *Cancer pagurus* and *Portunus puber* in the same region. Some spider-crabs were, however, found dead in heavily polluted regions. Among the echinoderms the common starfish *Asterias rubens* was very little affected, and healthy specimens were taken from sandy regions off Porthleven (dives 4 and 5) with dead spiny starfishes *Marthasterias glacialis* next to them. Mention should also be made of the brittle-star *Acrocnida brachiata*, which was found burrowing in an apparently healthy state in all the sandy areas examined. With the exception of *Delesseria sanguinea* and the smaller epiphytic algae almost all offshore seaweeds seemed to be unharmed.