'Torrey Canyon' Pollution and Marine Life

A Report by the Plymouth Laboratory of the Marine Biological Association of the United Kingdom

Edited by J. E. SMITH

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For ten days, in March 1967, the 'Torrey Canyon' leaked its cargo of 117,000 tons of crude oil into the sea. The immediate fear was for the holiday beaches in Devon and Cornwall, but a less obvious and far more insidious effect was the poisoning of marine life by the detergents which were applied in enormous quantities in an effort to disperse the oil. Pollution on this scale was unprecedented and there was very little time for an organised study of the effects, but the Plymouth laboratory of the Marine Biological Association immediately took up the task.

This report descrbies the step-by-step development of their intensive ten-week survey and discusses the results of field observations and laboratory experiments. It also outlines methods developed for predicting and plotting the movement of oil at sea.

This book will be of interest to all who value the preservation of sea shores and coastal waters, including ecologists and marine biologists, government departments and local authorities. It is illustrated with many maps and an impressive selection of colour photographs.

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'TORREY CANYON' POLLUTION AND MARINE LIFE

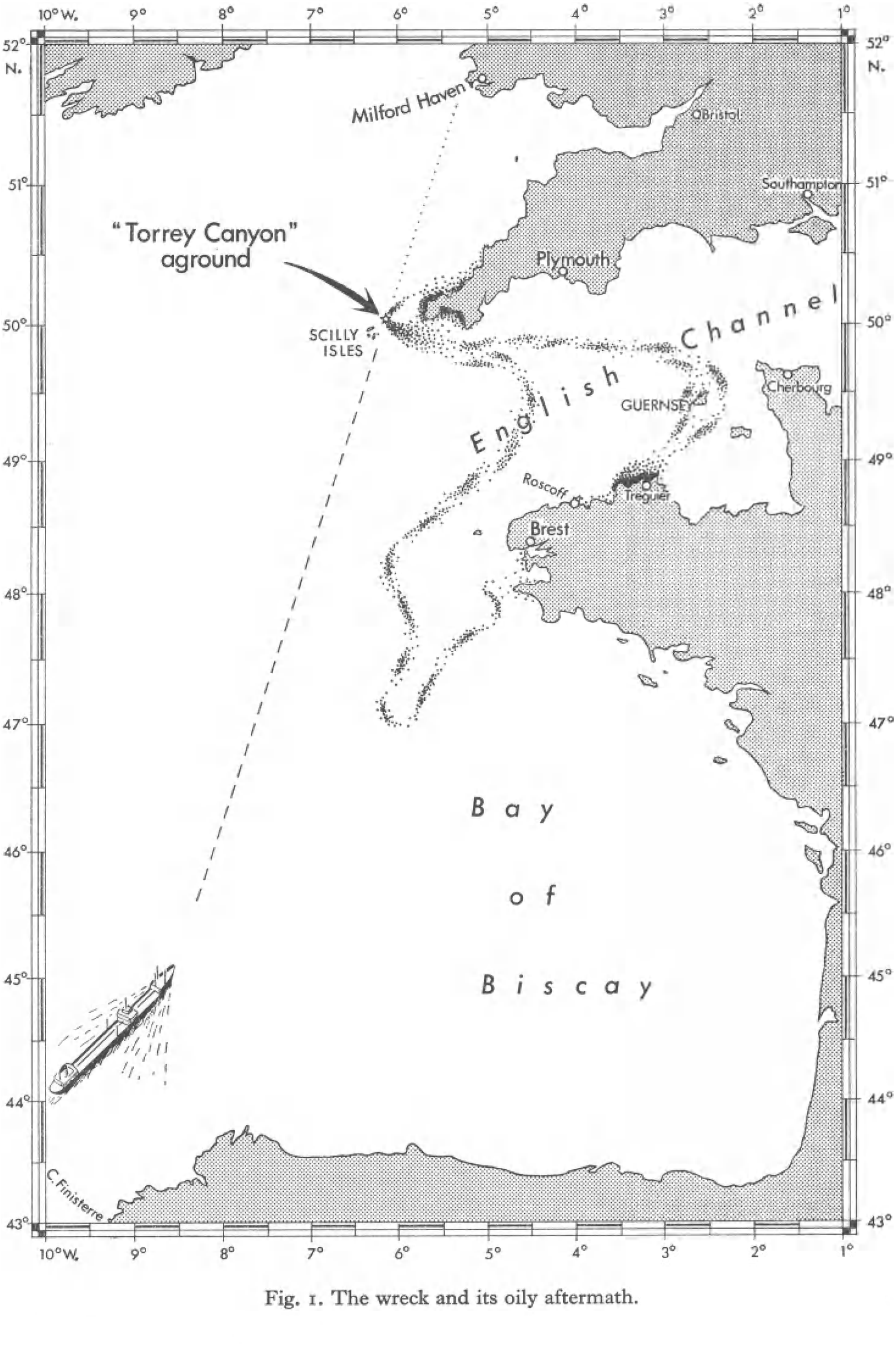

Fig. 1. The wreck and its oily aftermath.

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Under the general editorship of

J. E. SMITH, Sc.D., F.R.S.

Published for the

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CONTENTS

LIST OF PLATES

PREFACE

This report is based on an intensive ten-week survey and analysis by the scientific staff of the Plymouth Laboratory of some biological consequences resulting from the release of 117000 tons of crude oil from the tanker 'Torrey Canyon' which, on 18 March 1967, was wrecked on the Seven Stones reef 15 miles from the Land's End of Cornwall.

The measures adopted by British authorities in dispersing oil at sea, and in the cleansing of the rocks and beaches along the 140 miles or so of the Cornish coastline invaded by oil during the week-end of 26–28 March, relied almost entirely on the liberal application of oil solvent/oil emulsifier mixtures (detergents). Detergents are toxic to marine organisms, and some $2\frac{1}{2}$ million gallons (more than 10000 tons) of detergents were used during the 'Torrey Canyon' operations. The greater part of this report is therefore concerned with the effect of detergents on marine plants and animals as revealed by field observations and laboratory experiments.

It was not the intention initially to include non-biological aspects of the 'Torrey Canyon' spillage within the Plymouth programmes. But the need to know the day-to-day distribution of the masses of oil released from the tanker, and the speed and direction of their movements, led to the development of methods of plotting and predicting oil movements which were encouragingly accurate and which have a clear relevance in the report to pollution of the Brittany beaches.

A brief comment may be offered in explanation of the way in which the report is presented. It was rarely possible during the period of the 'Torrey Canyon' investigations to make an observation or do an experiment under the terms that the investigator would have chosen, and in many instances observations had to be made well knowing that the means of fully understanding them were not available, either for lack of some necessary information or the absence at that time of suitable techniques of analysis and measurement.

In writing the report it was therefore thought best to describe the investigations as nearly as possible in the order in which they were done. This may help to explain some of the more obvious imperfections in the work reported, and will enable the step-by-step development of the programme to be the more clearly recognized.

The production of this report has been a truly corporate effort, not only in the field and laboratory work, but also in the preparation of the manuscript and in the editing.

STAFF PARTICIPATION

Almost all the members of the Plymouth Laboratory staff, and some of the long-term visiting scientists, participated in one way or another in the 'Torrey Canyon' investigations. The work was organized under the following headings:

Scientific Programmes

(*a*) Sea surveys and plankton investigations
(*b*) Shore and near-shore (sublittoral) surveys
(*c*) Detergent toxicity testing
(*d*) Oil movements at sea
(*e*) Brittany surveys

Survey Samples and Records

External Liaison

General Organization

Report Preparation

The following took part: Pamela Ashton, Ann Baker, G. A. W. Battin, G. T. Boalch, Q. Bone, G. W. Bryan, E. I. Butler, L. H. N. Cooper, P. G. Corbin, E. D. S. Corner, A. G. Davies, E. J. Denton, G. R. Forster, J. Gage, P. E. Gibbs, J. B. Gilpin-Brown, J. E. Green, D. Harbour, Joan Hearn, Pamela Hobbs, N. A. Holme, J. V. Howarth, L. G. Hummerstone, Rosemary Jowett, Janet Kibble, R. G. Maddock, C. Manwell, A. D. Mattacola, B. J. Morgan, A. E. Nutty, Elizabeth Nybø, B. W. Osborne, Mary Parke, J. B. Pilkington, G. W. Potts, R.V. 'Sarsia' (Lt.-Cdr. C. H. White, R.N. (Retd.) in command), J. E. Smith, A. J. Southward, Eve Southward, G. M. Spooner, Molly Spooner, R. C. Swinfen, Susan Tibbits, A. Varley, F. J. Warren, D. P. Wilson, M. Alison Wilson.

COLLABORATIVE ORGANIZATIONS AND INDIVIDUAL CONTRIBUTORS

This record of indebtedness to the organizations and individuals who assisted the Plymouth Laboratory investigations by providing materials and information or by actively participating in surveys is by no means complete. The names attached to the organizations are often representative of a much wider indebtedness.

Collaborative Organizations

Ministry of Agriculture, Food and Fisheries (Mr A. C. Simpson)
Nature Conservancy (Mr W. O. Copland, Dr D. Ranwell, Mr F. R. Gomm)
BP Trading Company Limited (Mr G. C. Silsby)
Operations staff of Commander-in-Chief, Plymouth (Comdr. M. J. Garnett, R.N., O.B.E. and staff)
H.Q. 19 Group Coastal Command, R.A.F. Mount Batten, Plymouth (Sqdn.-Ldr. P. Halfacree, R.A.F.)
Meteorological Station, R.A.F. Mount Batten, Plymouth (all the staff)
Detergent Distribution Centre, Truro, Cornwall (Brigadier G. Lerwill, O.B.E., M.C.)
Admiralty Materials Laboratory (Superintendent)
Cornwall Naturalists' Trust (Mr J. K. Williams)

Toxicity Testing

Dr A. D. Boney (University College, Aberystwyth), Dr J. H. S. Blaxter (University of Aberdeen), Mr Norman Hendey (Admiralty Materials Laboratory), Dr Sheina Marshall (Millport Laboratory, Isle of Cumbrae), Mr B. W. Sparrow (International Paints Laboratory, Newton Ferrers), Mr P. R. Walne (Fisheries Experimental Station, Conway)

Bacteriology

Dr W. Gunkel (Biologische Anstalt, Helgoland)

Shore and Offshore Surveys

Dr J. N. Lythgoe (Institute of Ophthalmology, London), Mr G. Harwood (Kodak Limited, Harrow), Dr A. Nelson-Smith (University College, Swansea), Dr Gillian Matthews (Fowey), Dr Susan Vaidya (Marazion), Cornwall Sea Fisheries Committee with patrol boat 'Cornubia'

Brittany Survey

Prof. P. Courtot (Faculté des Sciences, Brest), M. Cabioch (Roscoff), Cdr. C. H. Brusson (Brest), M. Daniel (Morlaix)

Secretarial Assistance

Mrs S. E. Potts, Miss J. Penfold

Photographs illustrating this report have been kindly supplied by the following:

G. T. Boalch, Plate 7A
Q. Bone, Plate 21B
G. W. Bryan, Plates 2, 22A, 23A, 23B
G. R. Forster, Plate 27A
J. Gage, Plates 20B, 24A, 24B
P. E. Gibbs, Plates 4B, 5B, 14C, 18C, 21A
G. E. Harwood, Plates 6C, 26A, 26B
N. A. Holme, Plates 1C, 4A, 6A, 6B, 7B, 18A, 22B, 27B, 27C, 28A, 28B, 28C, 29A, 29B
G. W. Potts, Plates 5A, 17B, 18B, 25A, 25B, 26C
A. J. Southward, Plates 9C, 19A, 19B
F. G. M. Spooner, Plates 1B, 3A, 13A, 14A, 20A, 26D
G. M. Spooner, Plates 1A, 3B, 8A, 9A, 9B, 13B, 14B
R. Swinfen, Plates 7C, 8B
D. P. Wilson, Plates 10A, 10B, 11A, 11B, 12A, 12B, 15A, 16A, 17A
M. Alison Wilson, Plates 15B, 15C, 16B

CHAPTER I

INTRODUCTION

A BRIEF CHRONOLOGY OF 'TORREY CANYON' EVENTS

Close to 09.00 hours on the morning of Saturday 18 March 1967 the 970 foot long tanker 'Torrey Canyon', bound for Milford Haven from the Persian Gulf and carrying within her eighteen storage tanks some 117000 tons of Kuwait crude oil, ran aground on the Pollard Rock of the Seven Stones 15 miles west of Land's End and 7 miles north-east of the Isles of Scilly (see Frontispiece map). The tanker was travelling at about 17 knots when she struck the reef. Six of her tanks were reported as having been torn open by the impact and others were thought to be less severely damaged. Engines hard astern failed to move the ship and she was to remain on the reef in progressive stages of disintegration until six weeks later, a submerged and broken wreck, she was declared to contain no more oil.

Phase 1: 18–20 March

Oil began to escape from the ruptured tanks immediately after the stranding, and by nightfall a narrow slick some 8 miles long had thrust southwards from the Seven Stones to the east of the Isles of Scilly under the influence of the fresh northerly wind. By the Sunday evening (19 March) an estimated 20000 tons of oil had escaped from the tanker and 24 hours later it was thought that almost 30000 tons had been discharged on to the surface of the sea. The main oil mass was now 18–20 miles long and moving to the south. But, with the wind freshening and backing to the west, the escaping oil began to be blown eastward, more directly threatening the southern shores of Cornwall, and causing serious concern for an extensive contamination of more distant coastlines of the Channel.

It had thus become apparent within the first three days of the stranding of the 'Torrey Canyon' (i) that an oil release was developing on an unprecedented scale, (ii) that it was occurring in a geographical situation where, with the return of the prevailing south-westerly winds, there would be an inevitable and heavy contamination of long stretches of the coastlines of the English Channel and Bristol Channel, and (iii) that, in order to minimize the effects of the invasion, urgent and energetic measures would be needed to remove the oil at source or to disperse it from the surface of the sea.

The first efforts to disperse the oil at sea had been made within 12 hours of the grounding of the tanker. For some time past the Navy had been using mixtures of solvent and emulsifying chemicals (detergents) for cleaning up relatively small oil spills in harbours and coastal waters. It was therefore natural that they should use the detergent method of oil dispersal in dealing with the 'Torrey Canyon' efflux. Two naval vessels which began spraying on the evening of 18 March were joined by a progressively increasing number of large and small ships, and within three days some 15000 gallons of detergent had been discharged on to the oil.

Meanwhile, there had been set up at Maritime Headquarters, Mount Wise, Devonport, a control centre where the measures needed to cope with the more immediate problems were being organized and co-ordinated. The Minister of Defence, Mr Denis Healey, placed the operations under the overall control of the Under Secretary of State (Royal Navy), Mr Maurice Foley. Mr Foley's first discussions with officers of the three Services, scientific advisers and representatives of local authorities were held at regional headquarters on 19 and 20 March. Press reports of the meetings gave especial prominence to plans for increasing the production of detergents, and for mobilizing stocks for use in the cleansing of beaches should oil be cast ashore in quantity.

Phase 2: 21–23 March

On the Tuesday and Wednesday (21 and 22 March) following the grounding of the 'Torrey Canyon' the fresh 15-knot westerly breeze of the previous day persisted. More oil was driven up Channel but it remained sufficiently distant from the shore not to threaten immediate danger. Moreover, with the wind veering to the north-west on the following day there came renewed hope that the fouling of the coastline might be further postponed. It was of course realized that so long as the 'Torrey Canyon' remained on the reef and charged with oil the invasion must surely come. But, if compressed air could be injected into the damaged tanker to give her added buoyancy in time for the onset of the spring tides, there seemed to be a reasonable hope that the ship would lift sufficiently to be hauled off the reef. Nevertheless, since there was no guarantee that the vessel would be freed, an official Committee of Scientists was convened on 22 March under the chairmanship of the Chief Scientific Adviser to the Government, Sir Solly Zuckerman, to advise on the actions to be taken if the measures already being considered were to fail. By Thursday 23 March (the last day of this second phase of the operations) the tensions had so far eased that *The Times* front page reporting of the 'Torrey Canyon' news was limited to a paragraph of a few lines. Some weeks were to pass before the 'Torrey Canyon' again achieved a comparable level of obscurity.

Phase 3: 24–26 March

During Friday 24 March (Good Friday) the wind backed from north-west to south-west and freshened to 25 knots. Oil newly released from the tanker, and the oil of previous days' release thrusting out to the east of the Seven Stones, began to be pushed inexorably towards the Cornish coastline. By midnight on the Friday two large masses were standing off the Land's End peninsula, and the first thick oil came ashore near St Just on the morning tide of Saturday 25 March. The oil continued to come ashore in massive quantities throughout the day. Along the south coast heavy fouling affected the greater part of the coastline from Land's End to the base of the Lizard at the east end of Mount's Bay, the least affected being a stretch 12 miles westward of Penzance. To the north of Land's End oil was driven in a north-easterly direction parallel to the coast, and at some distance from the shoreline, as far east as Newquay.

During the following day, 26 March (Easter Sunday) the wind veered from south-west to west and increased to gale force. On the south coast the movement of oil into the eastern side of Mount's Bay and along the west coast of the Lizard was completed, while along the north coast of Cornwall the long-shore movement of the oil was continued almost to the entrance of the Camel estuary. This girdle of oil was driven ashore in quantity from St Ives to Trevone Bay two to three days later with the turning of the wind to the north-west. While few of the north- and east-facing bays were affected, shores open to the north-west and west received a heavy pollution.

By the late afternoon of Easter Sunday it was estimated that some 48000 tons of oil had issued from the 'Torrey Canyon'. Most of the early release (about 30000 tons) had, as we have seen, moved southwards, and was too distant from the mainland to be returned by the later-developing but short-lived south-westerly wind. Much of this oil was later (11 April onwards) to inflict upon parts of the coastline of Brittany a heavy and damaging pollution, the oil smearing in its passage across the Channel a part of the Guernsey coastline (7 April).

The south-westerly wind which blew throughout the Saturday and Sunday of the Easter week-end captured most of the remaining 18000 tons of oil that had, up to that time, been released from the tanker and drove it rapidly towards Land's End. This 15 per cent or so of the oil carried by the 'Torrey Canyon' (now reduced a little by the evaporation of its lighter fractions) comprised, save possibly for some relatively small amounts that came ashore later, virtually the whole of the oil deposited on the British shoreline.

Almost all came ashore within the short space of four to five days, thereafter to be withdrawn and redeposited for a while with the rise and fall of the tides.

Phase 4: 27–30 March

Around 19.00 hours on the evening of Sunday 26 March, the 'Torrey Canyon', pounded by the heavy seas, broke her back, releasing an estimated 40000–50000 tons of oil into the sea. This immense mass of oil, at first driven in a south-easterly direction, was then, for two days, blown by a south-westerly wind towards the English coastline. Then, almost at the last moment, it was deflected seawards by the backing of the wind to the north. Thereafter, from 3 April, a north or north-easterly air stream persisted most uncharacteristically for a full 30 days, and the British coastline was relieved from further serious threat. For some weeks, at least, the greater part of this later outspill remained at sea. When in the Biscayan area it was treated extensively with powdered chalk by ships of the French navy and a substantial part of it was reported as having been sunk. A very small proportion of this oil eventually landed on the west coast of Brittany (Chapter 9).

The 'Torrey Canyon', her back broken and now almost beyond hope of salvage, was bombed on 28, 29 and 30 March. Oil in the ship and on the surrounding water was set alight, but in spite of the feeding on to it of aviation fuel the fires were not for long maintained. Thereafter, some oil continued to escape from the three separated sections of the wrecked tanker, which only gradually became submerged. The ship disappeared from view towards the end of April, by which time she was probably empty of oil.

THE PLYMOUTH LABORATORY AND THE 'TORREY CANYON' INVESTIGATIONS

The Plymouth Laboratory is the research laboratory of the Marine Biological Association of the United Kingdom. The Association, founded in 1884, is supported by the subscriptions and donations of private members, universities, scientific societies, the Fishmongers' Company and other public bodies.

Nowadays the Laboratory, with an annual budget of about £250000, is financed almost entirely from government funds which since 1965 have been administered through the Natural Environment Research Council of the Department of Education and Science. As a grant-aided, independent institution the Plymouth Laboratory is thus in close liaison with the Research Council and its advisory committees, as well as with the Council of the

Marine Biological Association, and both bodies advise on the scientific programmes to be undertaken by the Laboratory.

The permanent staff at Plymouth includes some twenty-five scientists and an approximately equal number of supporting technical staff. Many visiting scientists from British and oversea universities and research laboratories work at Plymouth for longer or shorter periods, the visitors at times outnumbering the resident scientists. Two research vessels, 'Sarsia' and 'Sula', and a motor launch, 'Gammarus', are used to collect material for purposes of research and teaching, and to carry out, under the direction of the Laboratory's scientists, hydrographical and biological surveys and investigations of the sea and sea floor, mainly in the English Channel and the Atlantic approaches.

In broad terms the biological work of the Plymouth Laboratory includes ecological surveys of sea shores and of the sea floor; investigations of the floating populations of the (mainly minute) plants and animals of the phytoplankton and zooplankton; studies of the natural history, behaviour, development, physiology and biochemistry of many individual species, including important modern work on fishes, squids and cuttle fishes; and investigation of a variety of living processes and activities such as nerve conduction, muscle contraction and locomotion. On the physical side much work has and is being done on the cycling of nutrient salts in the sea; studies on the availability to and utilization by plants and animals of dissolved and suspended inorganic and organic substances; the identification and characterization of water masses of differing origins and properties; as well as many other types of study requiring the special expertise of chemists and physicists.

At the time of the stranding of the 'Torrey Canyon' none of the work of the Plymouth Laboratory was directly concerned with the effects on marine organisms of noxious substances discharged into the sea. The Laboratory nevertheless possessed in its facilities for scientific work on shore and at sea, and in its staff of scientists expert in a wide range of scientific disciplines and techniques, an organization which could usefully and without much difficulty turn its attention to the problems posed by the threat of the 'Torrey Canyon' oil.

The first steps in the involvement of the Laboratory in the 'Torrey Canyon' programme were taken on Thursday 23 March, five days after the stranding of the tanker, with a visit to regional headquarters at Mount Wise, Devonport. We were introduced to key personnel, learned of the essential arrangements for the control and co-ordination of operations, and declared our willingness to assist in any investigations that might be made of the biological consequences of the oil spill.

These opening inquiries were made towards the end of the second phase

(21–23 March) of the 'Torrey Canyon' events when the fear of an imminent flow of oil on to the Cornish beaches had in some measure abated, but when the continued use of detergents as a means of dispersing oil at sea had begun to raise publicly expressed fears about the damage they might cause to marine organisms and, in particular, to coastal fisheries. On Saturday 25 March it was reported that Scillonian fishermen were worried about the possible effects of detergents on their crab and lobster fisheries; and on the same day, in an article in the *Guardian*, Anthony Tucker severely criticized the view that had been expressed by Mr James Hoy, Parliamentary Secretary to the Ministry of Agriculture, Food and Fisheries, in a written answer to a parliamentary question, that detergents sprayed on to the surface of the sea would become so diluted that they would not be seriously harmful to marine life.

It was known from recent experience of three oil spillages in Milford Haven in which detergents had been used to clear the oil that crabs, barnacles, winkles, shore-living fishes and other animals, as well as some algae, were killed in considerable numbers. In the most recent of the spillages upwards of 250 tons of oil had issued from the damaged tanker 'Chrissi P. Goulandris', and 8000 gallons of detergent had been used to help clear it. The plants and animals which were affected by the detergent had, in this instance, previously been surveyed in detail by Dr Anthony Nelson-Smith of the University College of Swansea and, at the time of the 'Torrey Canyon' stranding, he was resurveying the shores for 'before and after' comparisons. The preliminary findings were kindly made known to us, and the full results are now being published (Nelson-Smith, 1968).

Very few quantitative data were available in March 1967 about the toxic effects of detergents. The main information came from some unpublished tests made by Mr A. C. Simpson, Director of the M.A.F.F. Laboratory, Burnham-on-Crouch, Essex. These showed that, over periods of 1–24 hours continuous exposure, solvent/emulsifying mixtures could be lethal to various commercially important shellfish in concentrations ranging from 3 to 250 parts per million (ppm). The tests had not, however, included the detergents mainly to be used on the Cornish beaches, nor were the commoner shore-living plants and animals among the organisms which had been tested. And among the many important questions which remained unanswered were the possible effects on animals of sublethal doses of detergent applied over a long period of time.

When a meeting of the staff scientists of the Plymouth Laboratory was held on Easter Monday, 27 March, to decide how far the Laboratory should be committed to the investigation of the biological consequences of the wrecking of the 'Torrey Canyon' and what its programmes should be, there were several matters which could be seen to be in urgent need of attention.

It was decided to divert the entire resources of the Laboratory to the 'Torrey Canyon' programmes for a period of six weeks, after which the position would be reviewed. Thoughts were turned to two aspects of planning. First, it would be necessary to decide on the scientific programmes of the Laboratory. Secondly, since the Laboratory would undoubtedly become, because of its situation, the regional centre for biological activities and information exchange, some sort of organization would be needed to cope with these requirements.

Scientific programmes

The Laboratory programmes were to be limited to the examination of oil/detergent pollution on the marine plants and animals living between tide-marks and in the offshore waters both in the open sea and on and within the sea floor. None of the investigations would be primarily concerned with commercially important species solely because of their commercial importance—this being the area of inquiry within the special competence of the Ministry of Agriculture, Fisheries and Food. Nor would the surveys overlap the special interests of the Nature Conservancy, the Cornwall Naturalists' Trust and the Cornwall Bird-Watching and Preservation Society in the effects of pollution on life in the border regions between sea and land and on sea birds.

Within our self-imposed terms of reference it seemed important to discover without delay whether the detergent-spraying of oil at sea had adversely affected the fish, crustaceans, molluscs and other animals living on the sea floor and the plants and animals living in the surface and intermediate waters in the neighbourhood of the oil cover. It was therefore decided that, on the following day, the laboratory's vessel 'Sarsia' should go to Mount's Bay and the Seven Stones to take plankton samples and trawl hauls both in areas uncontaminated with oil and in places where oil was present and detergent had been used. Samples of sea water were also to be taken for later laboratory testing of the concentration and toxic levels of the chemicals present at the various stations.

It was also decided to organize within the laboratory a programme of toxicity-testing of all the proprietary brands of detergent that were being used or would be used in dispersing oil at sea or on the beaches. The organisms to be tested were to include planktonic larvae of various kinds and as many as possible of the commoner plants and animals of the intertidal region and nearby offshore waters. During the course of these tests note would be taken of the varying sensitivities of the different organisms to known concentrations of detergents in order to select a few suitable examples to be used as indicators of the toxicity of sea-water samples collected during cruises or shore surveys. Many extensions and developments of this kind of analysis were to be made during the course of these experiments. Although it would not be appropriate at this stage to mention them in detail, they included, for example, measurements of the toxicity of components of the various proprietary detergents and of the conditions of their persistence or decay in the sea and during laboratory experiments.

The third type of work in which it was important that the Plymouth Laboratory, situated as it was within working distance of the polluted beaches, should take the *initiative* was the survey of the effects of oil and detergent pollution on the plants and animals living between tide-marks.

The shore surveys had two main aims. First it was intended to put on record, in however brief a form, and for as many localities as could be visited, the extent of the initial oil pollution, the varying intensities and conditions of the subsequent detergent treatment, and the effect of the treatment on their resident populations of intertidal plants and animals. Secondly, it was thought important to survey in detail the effects of initial oil cover and of the subsequent detergent treatment in two or three localities chosen because they were well known beforehand and were therefore useful for making 'before and after' comparisons.

Other programmes which had not been thought out fully at the first staff meeting on Monday 27 March were developed later. These included underwater surveys with the main laboratory effort concentrated on the examination of the offshore movements and toxic effects of detergent used in beach cleansing at Porthleven, the plotting of the movements at sea of oil derived from successive phases of discharge from the 'Torrey Canyon', and the prediction of these movements in relation to the day-to-day variations in the speed and direction of the winds acting on the sea surface. Finally, there is included a report on the methods adopted in France for coping with oil at sea and with the oil deposited on the Britanny beaches.

Most of the work referred to in the foregoing paragraphs was completed for the purposes of this Report by the end of May, some ten weeks after the stranding of the 'Torrey Canyon', but observations of polluted shores are being continued. The chapter on the French experiences is based on a seven-day visit to Brittany by two members of the Plymouth staff in mid-June, during which they had many helpful consultations with scientists and representatives of the civil and service departments engaged in the anti-pollution operations. They were also able to visit a number of oil-polluted beaches and to inspect the methods of shore cleansing which were being used.

A list of members of the staff and long-term visitors who participated is given on page xii.

Some aspects of collaboration and liaison

The investigations planned in outline on 27 March involved from the beginning close liaison and collaboration with a number of scientific organizations, administrative authorities, consultative bodies and private individuals. Some indication of the indebtedness of the Laboratory for the help it received in carrying out its programmes from these external sources will be evident from the list given above (p. xiii).

The total participation of the Plymouth Laboratory in the 'Torrey Canyon' investigations had, at the outset, been assured of the active support of the Council of the Marine Biological Association through a message received from its chairman, Professor A. L. Hodgkin, F.R.S. On this being made known to the Natural Environment Research Council, its secretary, Mr R. J. H. Beverton, put at the disposal of the Laboratory the funds needed to get the programmes under way. Meanwhile, on Tuesday 28 March, the Director of the Plymouth Laboratory, Dr J. E. Smith, F.R.S., had been co-opted as a member of the official Committee of Scientists on the Scientific and Technological Aspects of the 'Torrey Canyon' Disaster which, under the chairmanship of Sir Solly Zuckerman, K.C.B., F.R.S., was required to review the consequences of the disaster; and to make recommendations for any future research needed and on necessary safeguards. The establishment of these initial conditions of programme recognition and support thereafter ensured a ready access to the bodies most directly concerned with the progress of the research and with its practical implications.

By comparison with the well-defined and largely predetermined channels of approach to these central advisory bodies the regional network of operational communications was more complicated and, for a time at least to the biologists requiring them, unfamiliar.

There may have been some aspects of the 'Torrey Canyon' operations which made little demand on outside sources for help and information, but this was certainly not true of the biological work. Each facet of the inquiry into the biological consequences of the sea and shore pollution relied in very large measure on assistance and information known or thought to be available and which had to be actively gathered in for the service of the work. There was a need to know how much oil was escaping from the ship; the latest reported positions of the oil masses; the kinds of detergents that were being used, in what quantity, and in what places; the composition of the detergents; the kinds of help that might be available for undertaking experiments which, either because of pressure of work or insufficient knowledge of specialized techniques, the Laboratory was unable to do.

And, in addition to these and many other outgoing lines of inquiry, there was, in reverse, a daily stream of incoming offers of help and requests for information. Could a place be found in the programme for a team of underwater divers? Would it be helpful if naturalists living in Cornwall were to survey the shores with which they were familiar, and what methods of survey should be used? Could the laboratory give information to fishing interests, to the press or to broadcasting agencies on particular questions or on the general situation? And could discussions be arranged with scientists from overseas—for example, from France, Germany and the United States?

It is not easy, in retrospect, to say exactly how or with what degree of efficiency these and many other aspects of co-ordination and information exchange were dealt with, but the nature and functions of the main channels of communication may be conveniently described by referring to the information on staff participation and collaborative organizations set out above (pp. xii and xiii).

During the early stages of the 'Torrey Canyon' operations the first three of the collaborative organizations listed, namely the Ministry of Agriculture, Fisheries and Food, the Nature Conservancy, and BP Trading Company Limited, had representatives resident in the Laboratory. This made for easy day-to-day liaison at a time when frequent consultations were particularly necessary.

The two-way communication with all other collaborative organizations and individual contributors was made in the first place by staff concerned with 'external liaison'. Much of this was effected by telephone and correspondence but some members of the staff spent a good deal of time going in search of information when it could only be obtained effectively by talking with people on their home ground (e.g. at Maritime H.Q., Mount Wise; H.Q. 19 Group Coastal Command; and in connection with the Brittany survey). Most of the information passing through 'external liaison' was subsequently recorded and distributed on the initiative of the people in charge. But when further advice was needed or matters of general policy were implicit in the inquiries the questions were passed to the members of the 'general organization' group for a decision.

All survey collections, samples of oil, detergents and reports relating to field studies were accepted and dealt with by the group 'Survey Materials and Records' for distribution within the Laboratory or for indexing for general use.

A collection of photographs relating to the various aspects of the 'Torrey Canyon' investigations has been assembled. It will be kept in the library of the Plymouth Laboratory where it will be available for reference.

CHAPTER 2

OIL AND DETERGENTS

On the Cornish beaches about 10000 tons of detergent fluids were used to treat about 14000 tons of crude oil. What were the properties of these two major pollutants?

It might have been supposed that a cut-and-dried answer could be given at least with regard to the physical and chemical properties of the oil, and that, although information might not be made public for trade reasons, it would be available also for the properties of the detergent components. This was, however, far from true. Moreover, little was known of the probable biological effects either of crude oil or of detergents.

The brief account in this chapter depends partly on the information kindly supplied by British Petroleum (Trading) Ltd (BP) and detergent manufacturers, and partly on the results of simple and often empirical tests in the Laboratory, prompted by field observations.

THE OIL

Kuwait crude oil is a dark-brown liquid smelling like diesel fuel and having the consistency of heavy engine oil. It is a complex mixture of hydrocarbons containing appreciable quantities of sulphur and traces of metals such as nickel and vanadium.

After it is discharged on the sea, crude oil undergoes a series of changes over a period of months. At least this can be said, but it is not yet possible to give a confident account of what exactly happens to an oil-spill that remains at sea. In the absence of artificial treatments its probable fate may be assessed by reference to its physical properties.

Table 1 shows the composition of Kuwait oil (specific gravity 0·869) in terms of boiling-point fractions. From this it may be inferred that the oil will lose about 25 per cent of its volume by evaporation within the first few days. Evaporation continues at a progressively diminishing rate for some weeks, during which the oil is further eroded by photo-oxidation and bacterial degradation. If the oil stays at sea for three months or more there should theoretically remain persistent asphaltic residue representing perhaps 15 per cent of the original amount. Similar residues collect on the sides and bottoms of the storage tanks of tankers, and in the fuel tanks of oil-burning ships. The black tarry lumps, now all too familiar on British shores, are normally derived from the latter source, but occasionally they may

Table 1. *Composition of crude oil in terms of boiling point of fractions*

Fraction	°C	Loss of wt (%)	Loss of vol. (%)	Specific gravity at 15·5 °C of residue
1	Up to 100	9·0	11·8	0·895
2	Up to 200	13·0	27·7	0·9255
3	Up to 300	38·1	43·6	0·955
4	Up to 400	53·1	58·5	0·983

represent the end-product of weathered crude oil. Indeed, N. K. Adam (1935), in a pioneer investigation of the oil-pollution problem on our coasts, and to whose account we still have to turn for a picture of the fate of oil at sea, believed that refined fuel oil, if remaining at sea, would ultimately end as a residue of small aggregated asphaltic lumps. Adam, having conclusively shown that the world's oceans had not acquired a continuous molecular film of oil, gave a coherent explanation in physical–chemical terms of how oil was steadily disappearing. It is curious that he gave no consideration to the possible role of bacteria in helping this degradation, though Orton (1924) had already appreciated that the weathering of floating oil involved bacterial decay. The importance of bacteria is now, of course, well recognized (see ZoBell, 1963); but many aspects of the changes crude oil may be expected to undergo after release on the sea surface are still obscure. Research on this problem is urgently needed.

In practice the actual time course of the degradation processes must be influenced by several environmental factors including temperature, wind, wave action, thickness of the oil and its degree of dispersion; but perhaps the most important factor is the tendency of the oil to form emulsions with sea water. Such emulsion may be oil-in-water (as is milk) or water-in-oil (as is butter), and the emulsification so modifies the physical properties of the oil as to render unreliable most predictions of the life of oil at sea. The oil from the 'Torrey Canyon' certainly formed water-in-oil emulsions of variable composition, and it is this which accounts for the thick consistency and variable colour, quite unlike the original, of the oil masses observed at sea and on the Cornish beaches (Plates 3A, 6C, 7A, B, C, 13A, 14A, B). Attempts in the laboratory to reproduce these water-in-oil emulsions by shaking with sea water, or by exposing oil and sea water in open containers out of doors for several days, all failed. Oil vigorously shaken with sea water immediately settled out, re-forming a layer of the same thickness as at the start. It remained the original very dark colour in all experiments. However, the chocolate-coloured type of stranded oil could be imitated by adding a little detergent (BP 1002) to the mixture.

The water-in-oil emulsion may contain up to 80 per cent water. It follows that whereas the mass of oil may be appreciably reduced by evaporation after a period at sea the bulk of the emulsified material may yet exceed that of the original oil. It is also noteworthy that as evaporation proceeds the mass of oil not only diminishes but its density increases (Table 1). This has practical consequences when attempts are made to sink the oil by application of dense powdered material. A sample of emulsion taken from the Bay of Biscay on 18 May (some 50 days after release) by R.V. 'Sarsia' contained 50 per cent sea water and the specific gravity of the oil fraction was 0·97. This corresponds to a loss of about 50 per cent of the original oil, the specific gravity of which is 0·869 at 15·5 °C (cf. Table 1). The French navy were successful in sinking oil emulsions of this kind by applying powdered chalk (Chapter 9), but to have sunk the same oil soon after release would have required six times as much chalk.

In the seas around Cornwall and on the Cornish beaches the principle of the cleansing operation was, in essence, to convert the viscous water-in-oil emulsion to a milk-like oil-in-water emulsion (Plates 4 A, 5 A, 10 A, 22 A, B, 23 A, B, 28 C) and so allow it to disperse in the great bulk of the sea.* This was achievable by treating the water-in-oil emulsion with detergent (Plate 5 A) followed wherever possible by mechanical agitation. However, the emulsions were not readily formed under the conditions that obtained, and even when they were produced they were apt to be unstable (p. 21). Oil separated from unstable emulsions by floating upwards, just as the cream settles out on top of milk (Plate 1 A, B). This oil, as seen in shallow shore pools, or in laboratory vessels, was black and fluid, much as it originally had been in the tanker. When separation occurred in the sea just offshore under different conditions a paler colour was typical (Plate 6 A). Observations on the North Cornwall coast, in particular, showed that some of the oil very soon separated from detergent emulsions and that only a proportion could have been dispersed effectively. Aided by onshore winds the separated oil returned, either in a liquid condition or mixed with fine sand and fragments of seaweed, leading to secondary pollution (Plates 3 B, 6 A, B, 13 B). Even as early as April oil masses weighted with sand were observed on the sea bed (Plate 6 C).

Elsewhere in this report the water-in-oil emulsion which polluted the beaches is usually referred to as 'oil' and when reference is made to

* Dispersal in the sea, if effective, implies (1) that the small particles into which the oil is split are so scattered that they will not re-aggregate, and (2) that the oil is thus converted to the best possible state for attack by oil-consuming bacteria, which will eventually destroy any that has not evaporated. Thus the most ideal detergent cannot of itself destroy the oil.

emulsification it applies to the formation of a dispersible oil-in-water emulsion, unless otherwise stated.

Floating oil is not a serious hazard to marine life in the open sea save in the case of birds, thousands of which have died as a result of contact with oil from the 'Torrey Canyon'. Oil deposited on the coast is, however, severely damaging to coastal amenities and may affect shore animals by smothering them. Nevertheless, we were surprised how well such conditions could be tolerated and survived by many shore animals. Limpets, for example, were found to recover completely even after they had been left under an apparently continuous oil layer (Plate 9B). Indeed, limpets have been observed to be grazing on rocks coated with weathered oil, ingesting it without noticeable harm (Chapter 4; Plate 9C). No actual toxic effects of the oil have been noted either in shore or pelagic animals. Several intertidal algae survived after oil had settled on their fronds. In the splash-zone the lichen *Xanthoria* proved able to survive under a hardened oil layer (Plate 18C).

Stranded oil sticks all too readily to surfaces, offering considerable resistance to the force of waves and hoses. After settling, the oil layer becomes appreciably thinner, as it loses contained water and its own more volatile fractions. At the same time the oil becomes darker, whatever its original shade of brown, and eventually quite black. Typical examples of the blackened strand lines could be seen on granite boulders of the Land's End area, and around Hayle Estuary, where the oil had been left untreated. Plate 27 shows oil-blackened shores in Guernsey and Brittany.

DETERGENTS

Detergents are classified as ionic and non-ionic. Ionic detergents readily dissociate in solution and the effective portion may be positively (cationic) or negatively (anionic) charged. Non-ionic detergents, on the other hand, do not dissociate in solution to any significant degree.

The bulk of detergents used to deal with the 'Torrey Canyon' oil were non-ionic. When they were used no froth was produced, as so frequently with the more familiar household detergents. Household detergents release oil or grease from soiled articles by altering the surface tension of the oil so that it is no longer firmly held. Slight mechanical agitation will then dislodge the oil or grease, drops of which become dispersed in the form of an emulsion. It is not necessary for the emulsion to be stable, since it is normally quickly removed by rinsing.

However, for treatment of oil at sea, or on beaches, a stable emulsion is needed so that the oil may be more effectively dispersed. Some experiments on the stability of detergent–oil emulsions are described later in this section. The detergents used for this purpose are mixtures of two or more compounds, a surfactant, an organic solvent and a stabilizer. The surfactant, often an ethylene oxide condensate, is the primary oil emulsifier; the solvent enables the surfactant to mix with the oil and form an emulsion. Substances such as coconut oil diethanolamide, when present, stabilize the emulsion formed.

All the solvents contain a proportion of aromatics. The higher the proportion of aromatics, the more effective is the solvent, but at the same time the more toxic.

The surfactants used, unlike those employed in household detergents, are 'hard'; that is, they are not readily destroyed by micro-organisms.

The following proprietary detergents were reported as having been used:

Gamlen Oil Spill Remover	Dasic Slickgone
Atlas	Petrofina Unisolva
Snowdrift	TC 4 (Drew Chemicals)
Basol AD 6	Esso F. 6155
Gramosol	Houghtosafe 112
BP 1002	Whittakers G.P. Degreasant

Some examples of the composition of these, indicated by code numbers not related to the above list, are:

Detergent no. 1: 66% solvent containing 24% aromatics, remainder cetyl phenyl ethylene oxide condensate

Detergent no. 2: 70% solvent containing 43% aromatics
15% tall oil
15% nonyl phenyl ethylene oxide condensate

Detergent no. 3: 75% solvent containing 76% aromatics
25% mixture of ethylene oxide condensate and calcium petroleum sulphonate

Detergent no. 4: 85% kerosene extract with a high proportion of aromatics
12% nonyl phenol ethylene oxide
3% coconut diethanolamide

Detergent no. 5: 75% solvent containing 83% aromatics
7·5% tall oil
2·5% triethanolamine
10% dodecyl benzyl sulphonate as the ammonium salt
5% non-ionic detergent

Some physical properties of BP 1002 and methods of estimation

The Laboratory experiments described in this section examine certain physical properties of the detergent BP 1002. This detergent was used on a much greater scale than any other, especially on the shore. Samples of the detergent and its separate fractions were made available to us by BP Trading Limited, who also kindly undertook some of the analyses reported later.

Properties of solvent

(*a*) Density: 0·874 at 17 °C.

(*b*) Miscibility with sea water at 17 °C: 100–150 ppm (w/v) remain in the water phase some hours after shaking solvent with sea water.

(*c*) Boiling point: fractional distillation at atmospheric pressure yielded four fractions, of which the first two had a sulphurous smell.

Boiling point (°C)	% by volume of solvent	Toxicity compared with whole solvent as 100*
Below 120	1–2	45
Below 165	7	45
Below 185	18	80
Residue boiling above 185	74	78

* See page 143.

(*d*) The solvent has a characteristic smell, which can be detected at low concentrations. Sea-water solutions containing ½ ppm BP 1002 are easily distinguished from detergent-free sea water by smell.

Rate of loss of solvent from sea water

Large volumes of a 10 ppm (parts per million) solution of BP 1002 in sea water were placed in open containers and exposed in the open air. Solvent concentrations at different depths in the solution were determined at intervals by the third method given below. Similar results were obtained in two experiments, using 70 and 30 l. of solution (Fig. 2). After 35 hours the concentration of solvent had fallen to 5 ppm; after 95 hours it had fallen to ½ ppm. In the open sea evaporation would be more rapid. At concentrations around 10 ppm, the solvent tends to rise to the surface, as is seen by placing solutions in stoppered columns and determining solvent concentrations in upper and lower parts of the column after some hours. In one such experiment, where the initial concentration was 5 ppm, after

PLATE 1

Treatment of oil with detergent may give varying results and mixtures of varying colours. **A**, Watergate Bay, 15 April: heavily oiled sand adjacent to rocks that had recently been hosed with detergent/freshwater mixture. The pool of white emulsion had patches of re-separated oil (resembling the original Kuwait crude oil) which had not formed an emulsion with the detergent as shown in Plate 2. **B**, Booby's Bay, 8 April: orange-brown partially emulsified oil floating on detergent solution in a high-water rock pool. **C**, Kynance Cove, 20 April: orange-brown oil emulsion after detergent treatment oozing down from boulders near high-water mark.

PLATE I

A

B

C

(*Facing p.* 16)

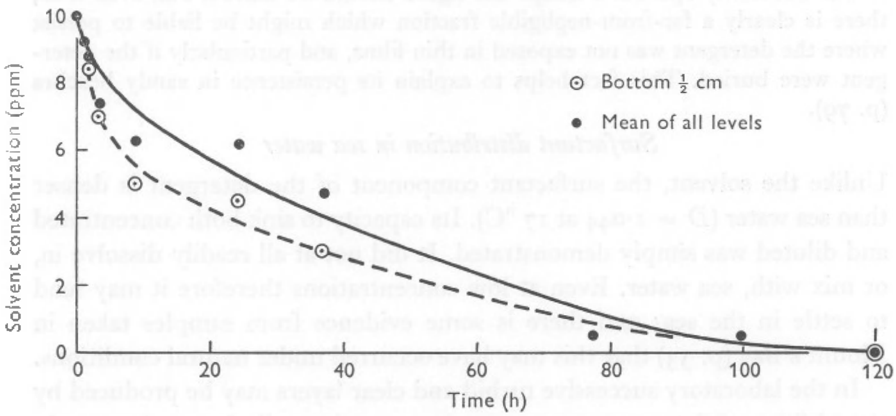


Fig. 2. Rate of loss of solvent fraction of BP 1002 from large volume of 10 ppm solution in sea water in open container.

3 hours a sample from the upper part of the column contained 6 ppm, lower down the concentration was 2½ ppm. Similar experiments with more concentrated solutions (e.g. 100 ppm) did not show layering.

Evaporation of detergent (BP 1002)

Some laboratory experiments were conducted on the undiluted detergent and its components to test their capacity to evaporate. The tests were carried out in a fume cupboard with air draught.

The whole mixture. Eighty ml (67·64 g by weight) was placed in an open Petri dish of 10 cm diameter. Half the weight was lost by evaporation in about 4 days, and 70 per cent in 11 days. The rate was continually becoming slower and in the next 11 days only an additional 5 per cent was lost. The graph was approaching exponentially a base-line representing 14 g (or 20·7 per cent by weight of the original sample).

The surfactant. This appeared not to evaporate at all.

The solvent ('*Kex*'). Eighty ml were placed in a Petri dish (experiment of 9 May). Sea water was used for comparison in a similar dish. It took 3¼ days for the sea water to evaporate to the point of leaving a deposit of moist salt crystals. In the same time the 'Kex' had lost barely half its volume; but it was steadily evaporating, and in 7 days had lost about three-quarters. From this point evaporation was hardly noticeable and at the end of the second week (23 May) the volume was measured at 17·5 ml (22 per cent of the original). This residue was found to be relatively persistent after transference to a small cylinder, which could be weighed easily. In this more confined vessel only 0·0176 g of the 'Kex' residue was lost between 31 May and 26 June, or 0·00068 g a day. It may be thought that 22 per cent was unduly high for the relatively persistent residue of a volatile solvent, and some allowance should perhaps be made for loss of the more volatile components from the can from which the sample was taken, since it was not newly opened. Perhaps the figure should be halved, but, even if so, there is clearly a far-from-negligible fraction which might be liable to persist where the detergent was not exposed in thin films, and particularly if the detergent were buried. This fact helps to explain its persistence in sandy beaches (p. 79).

Surfactant distribution in sea water

Unlike the solvent, the surfactant component of the detergent is denser than sea water ($D = 1{\cdot}044$ at 17 °C). Its capacity to sink both concentrated and diluted was simply demonstrated. It did not at all readily dissolve in, or mix with, sea water. Even at low concentrations therefore it may tend to settle in the sea; and there is some evidence from samples taken in Mount's Bay (p. 33) that this may have occurred under natural conditions.

In the laboratory successive turbid and clear layers may be produced by the addition of detergent to sea water in measuring cylinders under certain conditions, the differences between the layers presumably resulting from micelle formation.

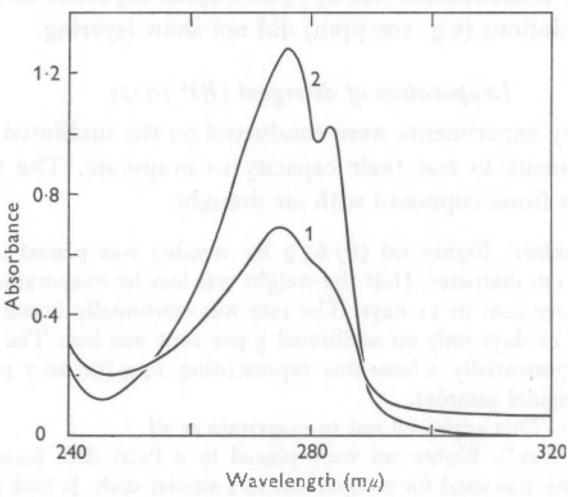


Fig. 3. Ultra-violet absorption spectrum of BP 1002 surfactant in sea water. 1, 50 ppm, 5 cm light path; 2, 500 ppm, 1 cm light path.

Micelle formation of surfactant

Determinations (by cryoscopic methods) of the molecular weight of the surfactant at concentrations above 1 per cent in sea water indicated an approximate molecular weight of above 10000. Since the molecular weight of the surfactant is around 650 it is evident that molecular aggregates, or micelles, are formed. At lower concentrations the method used was un-

Table 2. *The relationship between the surfactant concentration and the ultra-violet absorbance at 275 mμ*

Concentration (*C*) (ppm)	Light path (*L*) (cm)	Absorbance at 275 mμ (*A*) corrected for turbidity	*A*/*CL* (× 10⁻³)
5	10	0·108	2·2
10	10	0·226	2·3
50	10	1·23	2·5
50	1	0·127	2·5
100	1	0·2	2·0
500	1	1·25	2·5

suitable, but further evidence of micelle formation was obtained by the use of ultra-violet spectroscopy. Fig. 3 shows the ultra-violet absorption spectrum of the major surfactant component of BP 1002 in sea water. Measurements in the range 5–500 ppm have been made. At 50 ppm a slight turbidity of the solution was apparent and at 100 ppm the turbidity was very marked. At 500 ppm the solution was clear and its spectrum indicated the formation of a new species of micelle in solution. At all concentrations examined except 100 ppm the absorbance at 275 mμ has been found to obey Beer's law (that is, was proportional to concentration) reasonably well after allowance has been made for the turbidity as estimated from the absorbance at 320 mμ (Table 2). The discontinuity found at 100 ppm is indicative of the formation of insoluble micelles at 100 ppm with subsequent regrouping to give a new dissolved species at higher concentrations. On the shore, concentrations of 100 ppm or greater were frequently observed.

By reducing the effective concentration of surfactant, micelle formation would be expected to reduce the toxicity of surfactant solutions in sea water, as well as affecting such physical properties of the detergent as its adsorption on to sand (p. 77).

Methods used in the determination of detergent concentrations in sea water

Three chemical methods were used, in addition to the bioassay methods described later (p. 141). The first two actually determine the amount of surfactant present and the third the amount of solvent.

Method 1

All the analyses by this method have been kindly made for us by BP Trading Limited at their Pumpherston laboratory. The method, devised by Conoco (Continental Oil Company), estimates surfactant in sea water and gives an accuracy and repeatability of ±3 per cent relative at the 20 ppm level. The procedure is as follows.

Place 100 ml of sample solution into a separating funnel. Add 15 ml of ammonium cobaltothiocyanate reagent (prepared from 620 g reagent-grade NH_4SCN plus 280 g reagent grade $Co(NO_3)_2.6H_2O$ diluted to 1 l. and extracted twice with benzene) and 35–40 g of sodium chloride. Shake to dissolve the salt and allow to stand about 15 min. Accurately add 25·0 ml of benzene to the funnel. Shake for 1 min, then let stand to allow the layers to separate. Draw off and discard the lower aqueous layer. Transfer the benzene layer to a centrifuge tube, stopper, and spin at 500–700 rcf for 10 min. Read the peak absorbance at about 320 mμ against a reagent blank using a Beckman DB Ultraviolet Spectrophotometer with a deuterium lamp and 1 cm cells; 4 cm cells can be used to improve sensitivity. (The spectrophotometer connects to a 100 mV recorder through a Beckman Scale Expander accessory, to scan the region between 340 and 315 mμ.) Compare the absorbance with the reading obtained on a sample of known concentration.

Alternatively peak absorbance can be read at 625 mμ against a reagent blank using an infra-red tungsten light source and cell.

The instrument used at Pumpherston is a Cambridge SP 500. Present experience at Pumpherston indicates that in the range 0–10 ppm this procedure gives an accuracy within ± 20 per cent on samples obtained under practical working conditions.

This method determines only nonylphenol ethoxylate and is not effective at concentrations of 1 ppm or less.

Method 2

This simple method was developed in this laboratory at an early stage in the operation.

Add to 25 ml samples of the test solution in separating funnels 5 drops of an oil reagent ('3 in 1' oil saturated with Oil Red O and filtered through tissue). Shake vigorously for 15 sec. and stand for 3 min $\pm$ 10 sec. Separate and extract the aqueous layer with 4 ml chloroform. Read at 525 mμ in 1 cm cuvettes.

The calibration curves were linear over the range 0–5 ppm.

Method 3

This method was adapted from Gerade & Skiba (1960) and determines the amount of solvent present.

Using 50 ml test samples, extract into 3 ml of carbon tetrachloride. Shake the extract with 5 ml acid reagent (25 ml of 40 per cent formaldehyde in 500 ml concentrated sulphuric acid). Visual comparison with standards in the range 0–10 ppm gives values ± 5 per cent or better. The initial colour developed is pink, which after 30 min changes to orange brown.

The stability of detergent–oil emulsions

As already stated, the detergents act on the floating oil by producing a detergent–oil emulsion which is then supposed to be dispersed in the sea. The stability of such detergent–oil emulsions is important, for the more stable they are the better the dispersion. Some simple laboratory tests were made on this property.

Comparison between different detergents

A test was carried out on the stability of detergent/oil emulsions in sea water when there is no stirring; the results obtained give some indication of the relative efficiency of the different detergents tried.

Several detergents were used. In each case, 2 ml of detergent and 2 ml of Kuwait crude oil were mixed in a 100 ml measuring cylinder. Then 96 ml of sea water were added and the cylinder was sealed and shaken for 10 seconds. Oil started to settle out on the surface of the emulsion within a few minutes. As more oil settled out the emulsion column became lighter in colour and after about 2 hours there was considerable difference between the cylinders (Plate 2). In order of decreasing opacity of the emulsion the detergents were: Houghton, BP 1002, Gamlen, Gramosol, Whittaker, Slipclean, and Dasic.

These results suggest that Houghton detergent is best able to maintain an oil emulsion in sea water. It is also one of the most toxic detergents, as are BP 1002 and Gamlen. Dasic seems to be particularly poor in maintaining an oil emulsion in sea water and the water column cleared almost completely in a few hours. When the detergents only were added to sea water all except Dasic gave a milky emulsion. Dasic settled out on the surface of the water. It gave a perfectly good emulsion in fresh water and was extremely effective for washing off oil from all kinds of surfaces with warm tap water. The surfactant portion is largely anionic, and the preparation is presumably designed for use with fresh water.

Conductivity measurements made with 0·1 per cent solutions of detergent in distilled water verified that the surfactants of most of the detergents used are non-ionic; with the exception of Dasic and Teepol. These two detergents are least effective in sea water.

Deposited oil and BP 1002

The test reported above involved only 10 sec. shaking. Some other attempts were made to form a permanent emulsion with Kuwait crude oil and BP 1002, giving longer vigorous agitation and different amounts of sea water. With one mixture the emulsion, when left standing, showed no sign of separating until the next day, but the oil eventually layered out, and no better result was achieved than this.

With the oil collected on the shore, which, as has been explained, was already an emulsion of sea water in oil, the situation was appreciably worse. Though '*café-au-lait*' emulsions could be formed with different mixtures of oil, detergent, and sea water, these proved always to be very unstable and layering started at most within an hour or so. This was true even when the oil was first soaked with the optimum amount of detergent for about half-an-hour before sea water was applied.

Further comments

The formation of persistent emulsions in sea water does not take place readily, and detergents were often applied by methods that were largely ineffective, uneconomic, and wasteful of effort. This was particularly true of the methods used in dealing with the oil stranded on the shore. Thorough agitation by hosing, or by the natural agencies of wind, waves, and tide is essential for effective dispersal of oil, and these conditions were not always ensured.

As to spraying at sea, we have no information about its eventual effectiveness. It was genarally agreed by those taking part in the sea operations that dispersal was often achieved in the immediate neighbourhood of spraying. However, despite the large quantities of detergents used, large areas of undispersed oil persisted for weeks as extensive and discrete patches.

CHAPTER 3

SEA SURVEYS

On 27 March when the 'Torrey Canyon' programmes of the Plymouth Laboratory were first discussed at a staff meeting there was one question that required an immediate answer. The question was this: to what extent is the crude oil which is escaping from the tanker and the detergents which are being used to disperse it affecting the planktonic plants and animals and the stocks of pelagic and bottom-living fish in the area of the polluted water? And so, in order to find out what was happening, it was decided to send the Laboratory's research vessel 'Sarsia', with a party of scientists on board, to the area of the Seven Stones to collect samples of water and of plankton for analysis and investigation. Trawl and dredge hauls would also be made for the examination of bottom-living fish and other animals.

CRUISE I

For some time past the Marine Biological Association had carried out five or six times a year a survey of the hydrographical conditions and plankton production of the western English Channel. A survey was in fact due on 28 March and to meet the needs of the occasion the route of the 28–30 March cruise was modified to work the stations shown in Fig. 4A. These included stations 1–5 of the regular survey, where the water was thought to be uncontaminated, together with stations A–M which lay within the area of visible or suspected contamination. At stations A, B, C, D, G, H, I and L a thin film of oil dotted with occasional patches of thicker oil covered the surface of the sea. Stations E and F, which were sampled on the morning of 29 March, were characterized by broken patches of rust-red oil (similar to that shown in Plate 7A), some 1½–2 inches thick. Detergent was being sprayed at these stations and there was a strong smell of kerosene. Much more extensive areas of thick oil were found around stations J and K between 18.00 and 20.00 hours on 29 March. Because of the bombing of the 'Torrey Canyon' on this day the area north of a line from the Longships lighthouse to the Isles of Scilly had been closed to shipping. As the oil observed at stations J and K appeared from its direction of movement to have come from the closed area, it was thought at the time that this oil would have escaped treatment with detergent; but later calculations (as described in Chapter 8) show that the oil observed must have been released early on 27 March, and so would not necessarily have escaped spraying.

Distribution of detergent

At most of the stations water samples were taken in the normal way with hydrographic sampling bottles. At stations J and K, where samples were taken under the oil the open sampling bottle was lowered into the sea outside the oil area. The ship was then allowed to drift into the oil, and the bottle was closed. Finally the ship moved out of the oil and the bottle was raised.

Water samples taken on this cruise were sent to BP for chemical analysis of their detergent content. The analytical method used by BP measures the concentration of the *surface active* (*surfactant*) *component* of the detergent. It is important to bear this in mind in interpreting measurements given below since the two main components of the detergents, surfactant and solvent, may tend to separate at sea, the former sinking and the latter remaining near the surface and escaping by evaporation (Chapter 2). Samples were taken at seven depths between the surface and 70 m at station 2, at or near surface and at 50 m at stations A–D, at 1 m and 30 m at stations E–G and at the surface at stations H–M. With a single exception only, the results were completely negative, indicating that detergent was either absent or at most around 1 ppm. The only exception was station E at 1 m, where duplicated readings gave an equivalent of 1·2 and 6·0 ppm detergent (BP 1002).

This indicated that by 28–29 March the detergent might be accumulating locally to unwelcome concentrations, but it was not doing so at an alarming rate over a wide area.

Phytoplankton surveys

Tow-net samples of the small floating plants of the phytoplankton were taken at the surface, 5 m and 10 m at stations 2, 4 (uncontaminated water), A, B, C, D and M (under a thin oil film) and E (near to detergent-sprayed oil). They were examined on the ship under a microscope and were then stored at 5 °C for a more detailed examination in the laboratory on 30 March. Fig. 5 illustrates the appearance and size of some of the phytoplanktonic organisms referred to in this chapter.

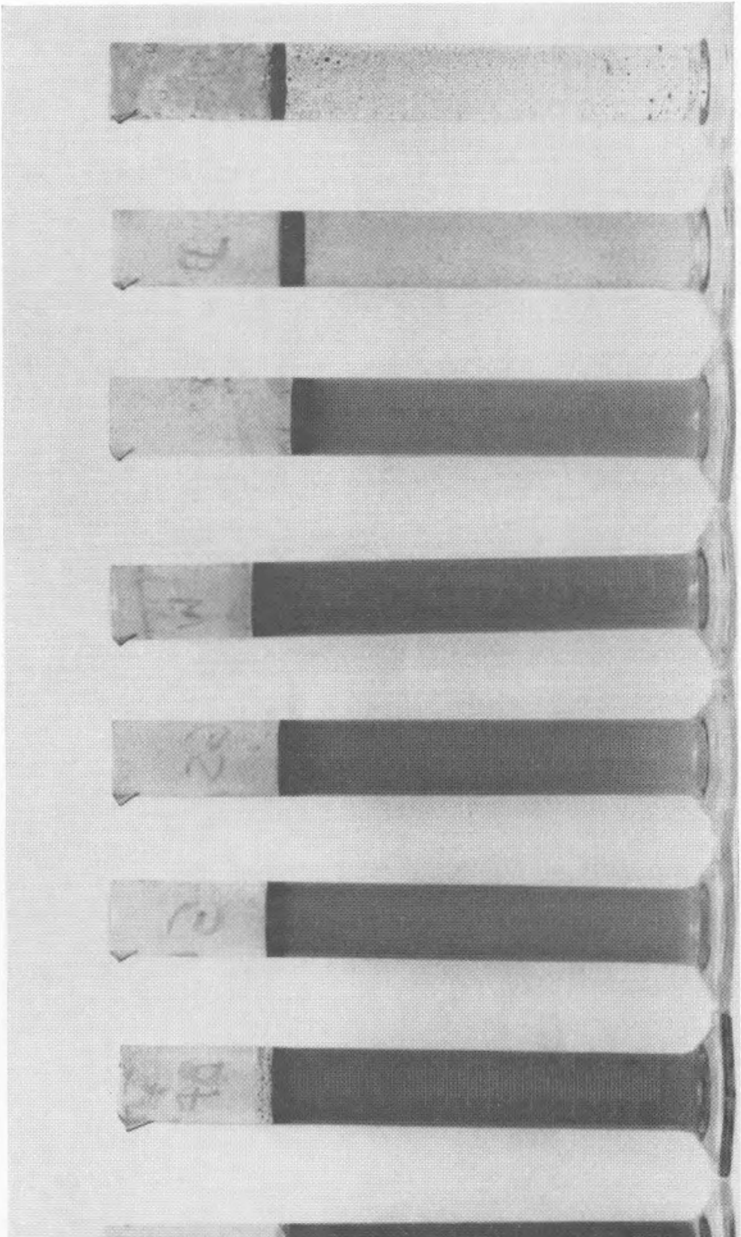
PLATE 2

A comparison of detergent–oil emulsions in sea water 36 hours after the cylinders were shaken. Left to right: Houghton, BP 1002, Gamlen, Gramosol, Whittaker, Slipclean, Dasic, and control.

PLATE 3

A, Newly arrived splodges of oil deposited on sand at Marazion, 1 April. **B**, Marazion looking west after a gale, 5 May: strand lines of re-deposited treated oil mixed with fragments of torn weed.

PLATE 2



(*Facing p.* 24)

A

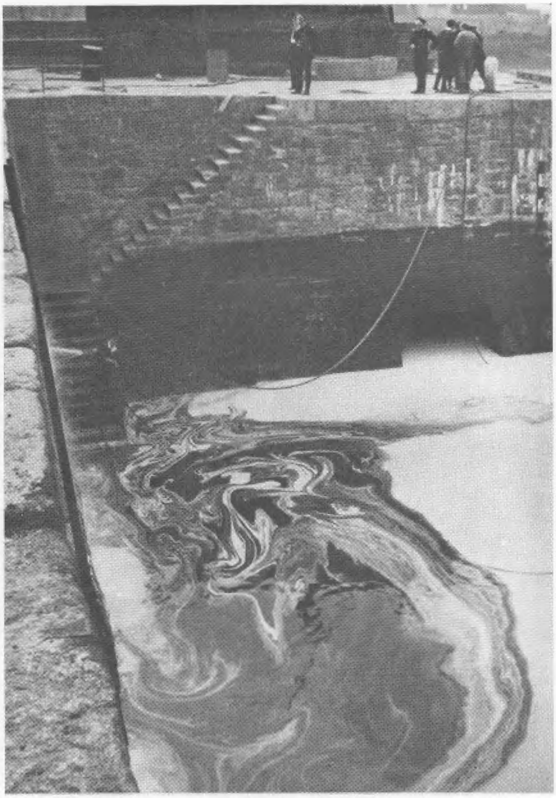
B

PLATE 4

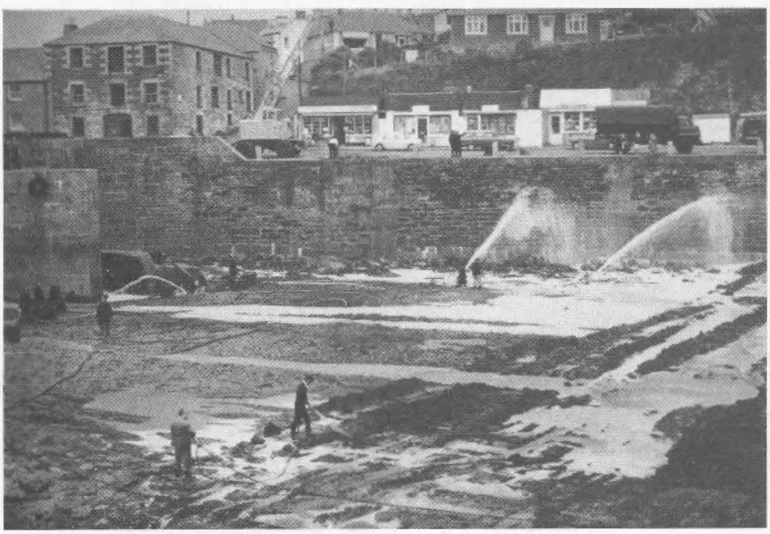
A

B

PLATE 5



A



B

(*Facing p. 25*)

When the samples were examined on the ship and later on 30 March in the laboratory, all of them contained plant populations of the type normally found in the Channel in early spring and both diatoms (Bacillariophyceae) and dinoflagellates (Dinophyceae), appeared to be healthy at all stations. Cysts of the very small Prasinophyceae were examined with especial care for it was thought that their habit of floating on or near the surface might make them especially vulnerable to surface-sprayed detergent. They appeared, however, to be healthy at all stations except M, where some individuals of all the species in the group showed shrinking of the cell contents from the cell wall.

Thus, on first inspection, the phytoplankton was surprisingly normal. But, in order to test whether there might be delayed effects, specimens from the tow-net samples were cultured in the laboratory for a further week.

The first cultures contained cysts of the Prasinophyceae which had been picked out from the samples and placed in a stock culture medium. After seven days many had released viable motile cells. Only a few of the remaining cysts, however, were in a healthy condition and many of the younger cysts had died. This does not normally happen.

Four other series of cultures were also set up and the results are briefly reported. They were not aerated.

Series 1. Tow-net samples from stations A, B, C, D, E and M were cultured in equal volumes of the sample and culture medium. In three of the cultures most of the diatoms became abnormal or died within seven days; in the other three they remained healthy. The Prasinophyceae remained healthy in only one culture. Small colourless flagellates, on the other hand, prospered in all six cultures.

Series 2. Tow-net samples from stations A, B, C, D, E, M and 2 were cultured in one part volume of the sample to nine parts of the culture medium, a mixture favoured at Plymouth for the culture of diatoms and dinoflagellates. Except in two instances when a few diatoms appeared to be abnormal, all the organisms were healthy after seven days.

Series 3. Water samples from station J (under thick oil) and station D (where

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PLATE 4

A, Detergent spraying in a remote cove near the Lizard, 22 April. Detergent drums are being ferried by helicopter to the cliff tops, from where it is piped down to the beach. Note the large patch of white emulsion in the sea. **B**, Fishing Cove, Gunwalloe, 28 April, showing ridges bulldozed in the shingle for detergent treatment of this heavily-oiled beach.

PLATE 5

Cleansing operations at Porthleven Harbour, 28 April. **A**, Operator spraying detergent on harbour wall. The detergent is forming a white emulsion in the sea, with which are mingled streaks of re-separated oil and oil–water emulsion. **B**, Spraying detergent on the harbour walls at low tide. The floor of the harbour has been bulldozed.

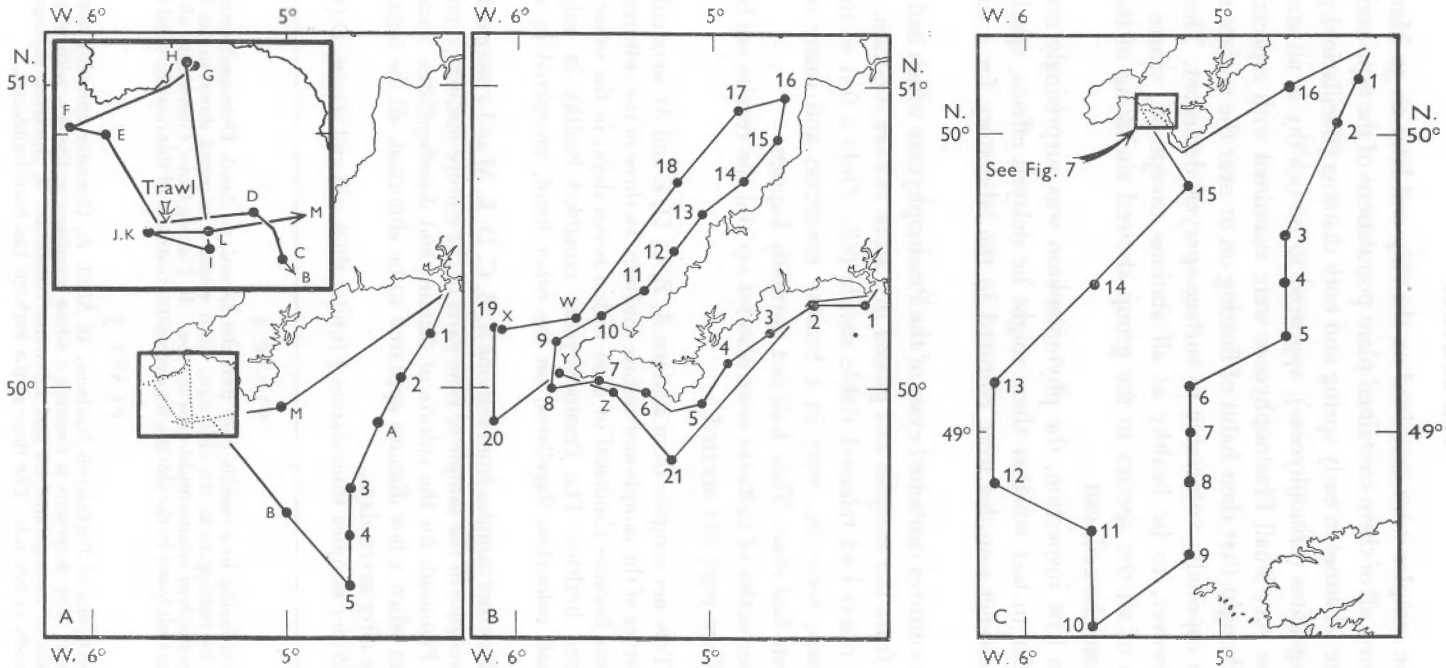


Fig. 4. Positions of stations on 'Sarsia' cruises. A, 28–30 March; B, 3–6 April; C, 11–14 April.

oil appeared to have been treated with detergent) were enriched with nutrients to encourage growth of the contained phytoplankton. All organisms were healthy after seven days.

Series 4. Water from stations J and D was filtered to remove the plankton and to the filtered water was added culture medium inoculated with planktonic algae grown in the Plymouth culture collection. Algae grown in an uncontaminated culture medium were used as controls.

The results of the series 4 tests span too many species to be set out in detail. A very brief summary of the results, however, is that, while the naked or scale-covered Prasinophyceae were killed in the stations J and D samples, the one species with a complete protective thecal covering that was tested grew better than in the controls. By and large all other forms prospered as well in the J and D water as in the controls.

The overall results and conclusions which follow from this phytoplankton survey may therefore be summarized as follows:

(1) There were deaths among the smallest flagellates (Prasinophyceae), often only after a period of some days in all the samples taken from areas of thin or thick oil cover, and there were no deaths at stations in the uncontaminated water. It is clear therefore that the Prasinophyceae can detect and respond to concentrations of toxic substances that are too low to be detectable by the method of chemical analysis that was available.

(2) Other phytoplanktonic algae (diatoms and dinoflagellates) were exposed at some stations to a lethal concentration of toxic substances; at others they were not. Those grown in the laboratory on a one-tenth concentration of the sea water in which they were taken survived. It may be concluded therefore that the concentrations of toxic materials in the water samples taken on cruise I were not much above the lethal level for the most delicate of the organisms examined.

(3) Most of the colourless flagellates were unaffected, and some of them grew rather better in the toxic sea water than in uncontaminated water.

Zooplankton surveys

Oblique tow-net hauls were taken at stations D and L (under thin oil) for the sampling of the plankton animals—mainly copepod crustaceans. The animals appeared to be of a normal abundance and all seemed healthy when examined immediately after capture.

Benthic organisms

Fish taken in the trawl at station D appeared to be healthy. No oil was found on the sea bed and there were no external signs of oil contamination

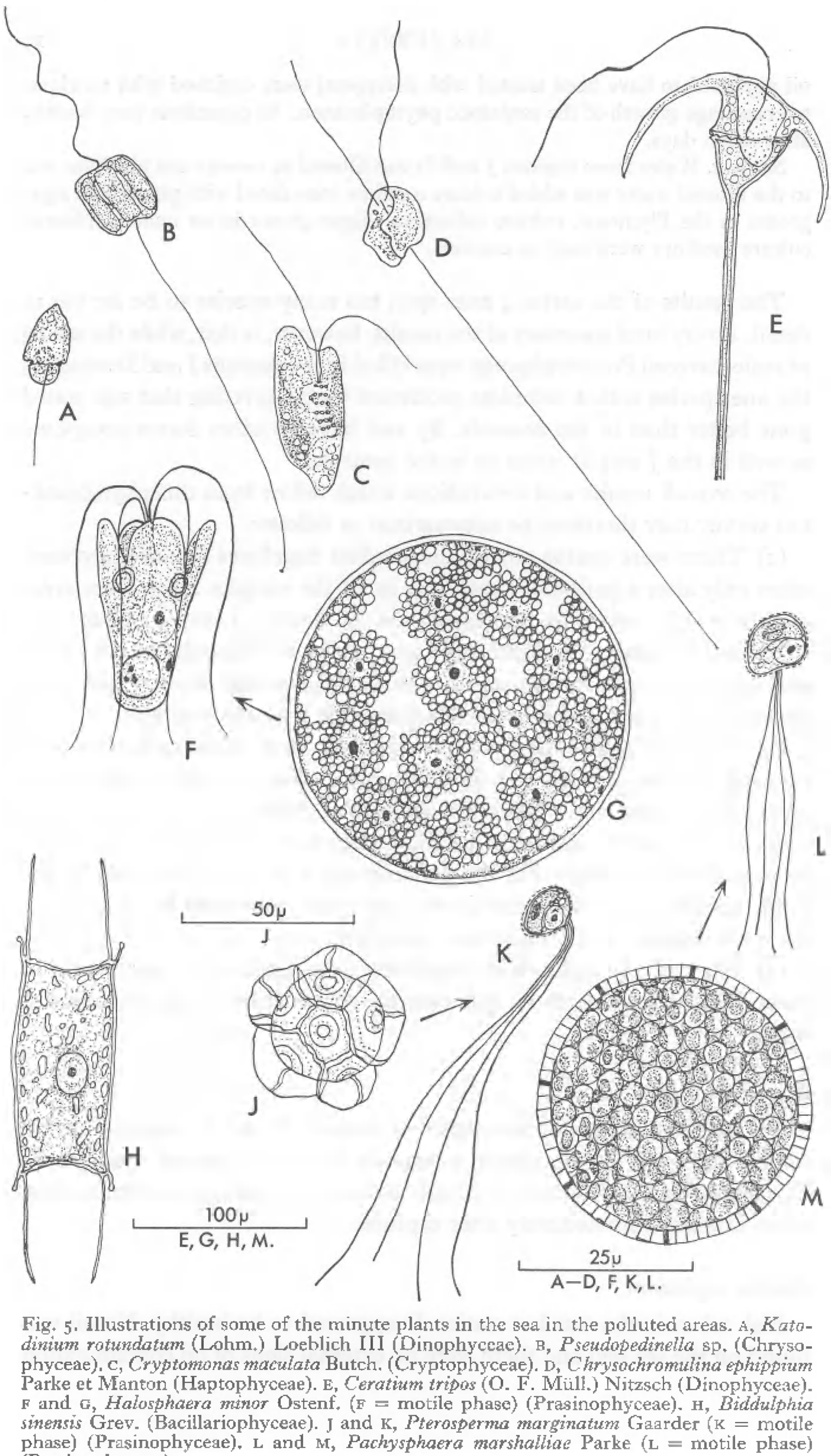


Fig. 5. Illustrations of some of the minute plants in the sea in the polluted areas. A, *Katodinium rotundatum* (Lohm.) Loeblich III (Dinophyceae). B, *Pseudopedinella* sp. (Chrysophyceae). C, *Cryptomonas maculata* Butch. (Cryptophyceae). D, *Chrysochromulina ephippium* Parke et Manton (Haptophyceae). E, *Ceratium tripos* (O. F. Müll.) Nitzsch (Dinophyceae). F and G, *Halosphaera minor* Ostenf. (F = motile phase) (Prasinophyceae). H, *Biddulphia sinensis* Grev. (Bacillariophyceae). J and K, *Pterosperma marginatum* Gaarder (K = motile phase) (Prasinophyceae). L and M, *Pachysphaera marshalliae* Parke (L = motile phase) (Prasinophyceae).

on any of the fish or visible traces of oil within the gut. Several different types were boiled and eaten. They were much appreciated and there were no subsequent ill effects.

Investigations consequent to the cruise I survey

The laboratory studies of the toxicity of oil and detergents reported in Chapter 7, none of which, however, had been undertaken at the time of the first exploratory cruise of R.V. 'Sarsia', show that many kinds of zooplanktonic organisms are in varying degrees susceptible to poisoning by detergents, the lethal doses depending on the detergent used, the concentration of the detergent, and the length of time the organisms are exposed to the toxic substances.

In addition, as is pointed out on page 145, laboratory experiments had shown that most of the very toxic organic solvent ingredient of the detergents tested is lost by evaporation within about two days. And so, although the first cruise of R.V. 'Sarsia' had demonstrated that the presence of oil on the sea and use of detergents had in the early stages produced little demonstrable adverse effect on any marine organisms, save for the smallest of the algae, it was not known how the continuation of spraying might alter the picture. It is possible also that seemingly healthy organisms might be harbouring deleterious effects which would only later become fully apparent. With these thoughts in mind it was decided to undertake further sea surveys and, at the same time, to carry out a series of laboratory experiments designed to examine the problem of possible long-term effects of detergents on planktonic organisms.

CRUISE II

On this cruise from 3 to 6 April twenty-one stations were worked with the Gulf III high-speed plankton sampler from Plymouth through the Seven Stones area round to Hartland Point on the north coast of Devon, and samples of water were collected. The stations at which samples were taken are shown in Fig. 4B.

Oil pollution was restricted to small patches, mainly of iridescent films containing a few small clots of thicker oil. They were present off the Lizard, near the Seven Stones, where surface and bottom 'drifters' were dropped, and off Trevose Head. Surface and bottom 'drifters' of plastic were dropped near the Seven Stones in the hope that they would drift with the oil and thus act as markers of the movements of the areas of contaminated water. These plastic 'drifters' are the modern version of the well-known drift bottles.

Table 3. *Detergent analyses*

Position	Station	Result
49° 56′N., 5° 02′W.	—	0
50° 10′N., 6° 04′W.	19 (W)	0
49° 56′N., 6° 01′W.	—	0
50° 03′N., 5° 47′W.	Y	+ ve (3·3 ppm) and 0*
49° 59′N., 5° 30′W.	Z	0

* These two samples may have been half a mile apart.

Samples of sea water collected from the polluted area were sent to BP for analysis. The results expressed as detergent concentrations (ppm) are shown in Table 3.

Four sets of phytoplankton tow-net samples (W, X, Y, Z) were brought back from the cruise and were examined in the laboratory on 6 April. The diatoms and dinoflagellates appeared to be healthy in all the samples, but cysts of members of the Prasinophyceae showed abnormalities. At stations W and Y there was an abnormally large number of empty outer walls of a size not consistent with their being from normal cysts. These were probably young *Halosphaera* cysts which had burst and exuded their contents. At station Y, in particular, there were many young cysts of *Pterosperma* spp. which were dead or in an unhealthy condition. One species of *Halosphaera* (a delicate one) also appeared to be adversely affected. The sample from station X, on the other hand, showed relatively fewer empty outer walls from abnormal releases of contents and all cysts appeared healthy. An abnormal contraction of cyst contents was more noticeable at station Z than at the other stations, but even so some individuals of both *Halosphaera* spp. and *Pterosperma* spp. released viable motile cells in the normal way after four days in the laboratory.

Thus, the observations made during the second cruise revealed abnormalities in one class of algae, the Prasinophyceae, especially at station Y where large quantities of detergents had been used. As mentioned already (p. 25), cysts of this class tend to float on or near the surface and this would make them particularly vulnerable to substances such as oil and detergents poured on to the surface.

Quantitative samples of the larger plankton animals were collected with a modified Gulf III high-speed plankton sampler (Southward, 1962) on 4 and 5 April, one or two days after the cessation of detergent spraying of oil patches at sea. These samples were examined for young fish, fish eggs and the larger zooplankton 'indicator' organisms (Fig. 6).

At two of the stations (7 and 8) nearly all the pilchard eggs (90 per cent) were dead, compared with a figure of about 50 per cent mortality at other stations where pilchard eggs were taken. Fish eggs tend to float near the surface of the sea and would thus be expected to show any deleterious effects of oil and detergent spraying. Young fish also tend to be found in the surface layers in the first few days after hatching. The numbers of young fish found in the samples taken on the second survey are shown in

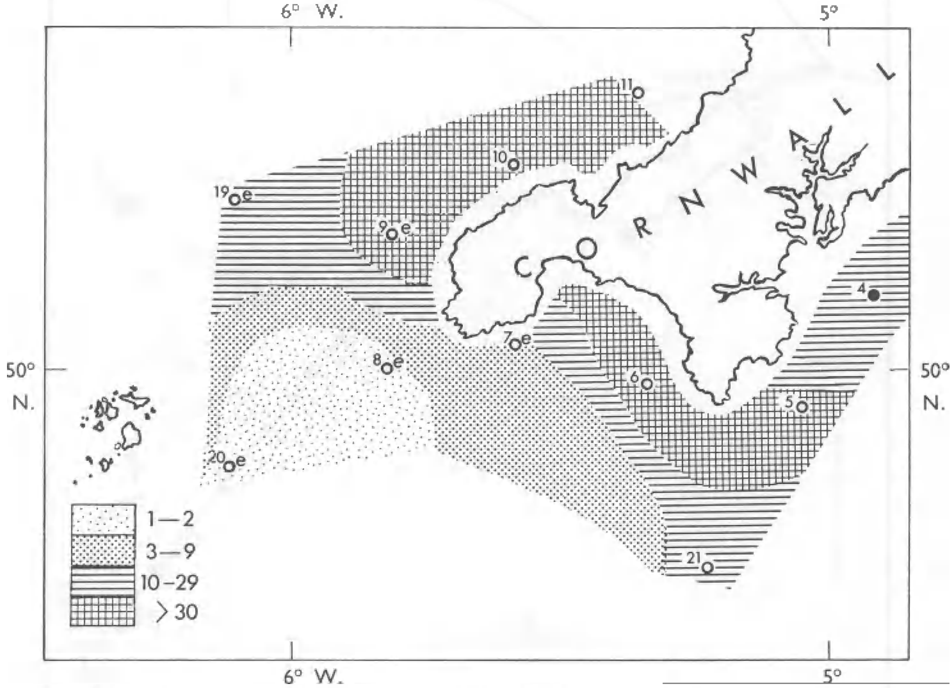


Fig. 6. Distribution of young fish (3–20 mm length) off West Cornwall, 4–5 April. Samples taken with modified Gulf III high-speed sampler, fitted with 40 m.p.i. net. Results are expressed as numbers per haul, corrected to a flowmeter reading corresponding to approximately 40 cubic metres of water filtered. All samples except one (solid black circle) were taken in daylight. The letter 'e' shows the occurrence of north-western type of plankton, a predominance of the arrow-worm *Sagitta elegans* and/or the presence of larvae of the starfish *Luidia sarsi*.

Fig. 6. It is obvious that young fish were scarce or absent in the area to the south and east of the Seven Stones, where detergent was used at sea. The lack of young fish in this area bears no obvious relationship to the type of plankton found and it seems an inescapable conclusion that the absence of young fish south of the Seven Stones and the observed mortalities of pilchard eggs at nearby stations was the effect of detergent spraying carried out one or two days before the planktonic samples were taken.

CRUISE III

On Cruise III (11–14 April) series of stations across the Channel and in the Mount's Bay area (Figs. 4C, 7) were worked. One series of observations was made as close inshore as practicable (stations A–M), to coincide with

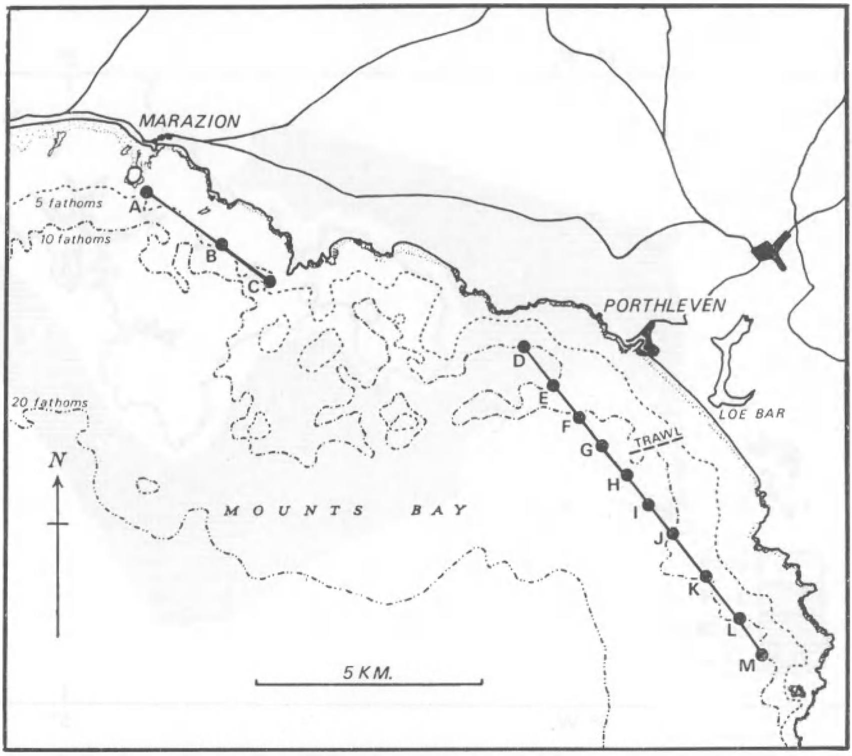
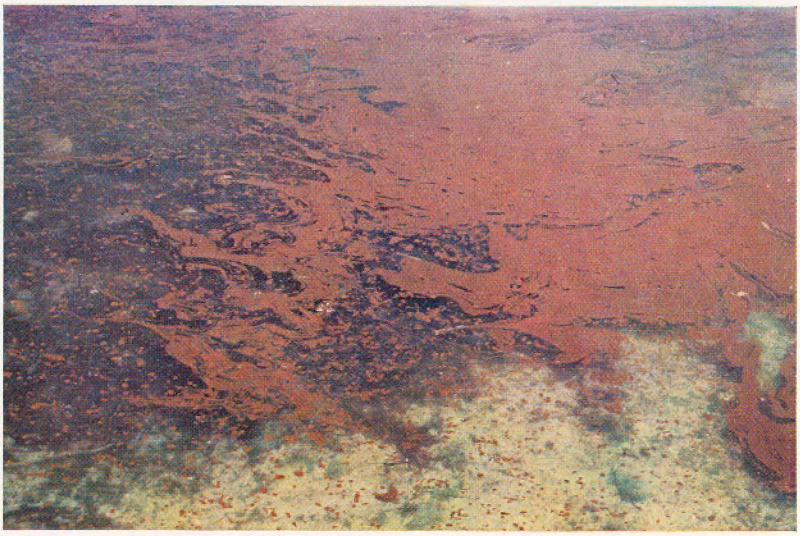


Fig. 7. Inshore stations worked by 'Sarsia' on 13 and 29 April. The area shown here is indicated on Fig. 4C.

the activities of a party of aqualung divers working from the shore (see Chapter 6). At this time heavy detergent treatment was being applied in the Porthleven area.

Water samples from the Mount's Bay transect were again sent to BP for analysis, with the results, given in Table 4, expressed as detergent concentrations in parts per million.

In interpreting these figures it must be remembered that it was only the surfactant component that was being measured and that separation of surfactant from the solvent component may already have occurred. It is likely, therefore, that the detergent will have been underestimated at the surface



A

B

C

(*Facing p.* 33)

Table 4. *Detergent estimations in Mount's Bay (ppm)*

Calculated from surfactant values

	Mount's Bay stations												
	A	B	C	D	E	F	G	H	I	J	K	L	M
Surface	7·8	6·7	5·1	5·1	2·4	2·4	0	0	0	0	0	0	0
Mid-water	6·7	2·4	0	0	0	0	0	0	0	0	0	0	0
Bottom	44·0	28·0	0	0	0	0	0	0	24	0	0	0	0

stations, and many times overestimated at some bottom stations where surfactant was detected. There is no doubt that the two most westerly stations at least (A and B) had been poisoned to a considerable degree. The high mortality of bottom-living animals recorded in Chapter 6 is readily understood. The toxic properties of the water in Mount's Bay clearly decreased eastwards, but zero readings should not necessarily be taken that no significant concentrations of the detergent (or some component of it) occurred.

Water samples from the same area were sent to Professor D. E. Hughes, of the Department of Microbiology, University College of South Wales and Monmouthshire, Cardiff, who reported that no oil-degrading bacteria were detectable. Such organisms are normally present in the sea in small numbers (ZoBell, 1963), and multiply as soon as any suitable substrate is provided. The present few results are too limited to be taken as indicating an effect of the detergent on oil-degrading bacteria in this area. The general subject of the effects of detergents on oil-degrading bacteria is being investigated by Gunkel (see p. 82).

On the cross-channel transect (Fig. 4C) no oil pollution was observed at stations 1 and 2. Stations 3–6 were worked during the hours of darkness, but no oil was observed during the stops on station. An oil film with occasional lumps—characteristic of oil treated at sea—was first observed at station 7 and this was found all the way along the route until just before station 12. Around station 8 there was an extensive area of thick oil (Plate 7A). This was of the same colour and general appearance as the oil observed on the first cruise, and once again it had a strong smell. Surface and bottom drifters were put down in this contaminated area.

PLATE 6

A, Trégastel-Plage (Côtes du Nord), 21 June. Oil–water emulsion which had re-separated after detergent spraying drifting on to the beach. **B**, Salt marsh near Trégastel (Côtes du Nord), 21 June. A line of dark brown patches of re-separated oil deposited on the beach already blackened by the initial pollution. **C**, Mullion Harbour, 6 April. Underwater photograph of an oil-water emulsion weighted with sand on the sea bed in the harbour mouth. Note the separated globule floating beside the main mass.

Phytoplankton tow-net samples were taken at stations 2, 4, 7 and 9–15, and examined immediately on return to the laboratory on 14/15 April. They contained organisms in varying quantities, but were all normal except that, as on previous cruises, there were some stations (2, 4 and 7) where the representatives of the Prasinophyceae were dead or abnormal.

SUBSEQUENT CRUISES

Later cruises by R.V. 'Sarsia' could not be diverted for long from normal oceanographic research work. However, some effort was devoted in three later cruises to a search for patches of oil that had disappeared to the south (see Chapters 8 and 9).

Water samples were taken on cruises on 28–30 April and in mid-May for oil content analysis of apparently clean water, at stations across the mouth of the English Channel. A closing water-bottle placed horizontally was used to sample the surface layer (top 10 cm at most). These samples contained crude oil at concentrations of 0·007–0·014 ppm at the end of April and 0·004–0·009 ppm in May. Subsurface samples contained negligible amounts of oil, no oil being detected in samples from 5 and 50 m depth (the lowest limit of detection being about 0·003 ppm).

We are indebted to the Superintendent, Admiralty Materials Laboratory for these analyses and also for the information that at a station 10 miles south of Portland Bill (*ca.* 280 kilometres up Channel from the Seven Stones) in surface samples taken weekly the concentration of crude oil was 0·003 ppm or less in March and April 1967, rising to 0·005 in June and returning to 0·003 in July, which is similar to the oil content of Channel waters sampled during recent years.

THE SEA SURVEY OBSERVATIONS IN RETROSPECT

The relatively little detected damage suffered by planktonic organisms in the western English Channel following the release of oil from the 'Torrey Canyon' and its treatment with detergent seemed, at the time of the surveys, to be rather surprising in view of the magnitude of the oil release and the large quantities of detergent used in an attempt to disperse the oil at sea. However, now that the circumstances of the pollution are better known it is possible to take a more informed view of its consequences.

Experiments reported in Chapter 7 show that many of the smaller planktonic organisms may be killed in a matter of a few hours in concentrations of detergent of 1–10 ppm. Zooplankton, however, are mostly active organisms which undergo marked vertical migrations and might well escape toxic surface water by swimming downwards. But the more passive members of the plankton may really not have been so harmfully affected as might at first appear. Let us consider.

About 500000 gallons of detergent were used during the fourteen days or so of the sea-spraying operations. If all the detergent that had been used were spread evenly through the top 5 m of water (where the damage was mainly done) at a concentration of 1–10 ppm, an area of water 20–200 square miles would have been contaminated. Damage of this extent, bad, but far from catastrophic, was visualized at first.

But this is a wholly unreal picture, for detergents in sea water rapidly lose much of their toxicity (Chapter 7) and the patches of high concentration formed in the areas of spraying remain, for a time at least, coherent and do not readily disperse (Chapter 6). In Chapter 7 it is reported that the toxicity of detergents is mainly due to their aromatic components and in open dishes these are largely lost by evaporation within a period of from two to five days. Since in the sea the maximum solubility of aromatic hydrocarbons is of the order of 30–800 ppm the dissolved aromatics could, it is true, persist as a highly toxic system. But winds of a strength sufficient to achieve sufficient vertical convection to bring about a mixing to 5 m would also evaporate the toxic aromatics very rapidly from the sea surface to the air.

The effect of spraying oil patches, therefore, is to produce patches or tongues of oil and water charged with detergent which could be driven 30 miles or more downwind by a steady fresh breeze (Beaufort 6) lasting for two to three days. During this time much of the toxicity due to aromatics would be lost, though there would be a small proportion of aromatics remaining in true solution. In detail, much will depend on the stratification, cellular structure, and dynamic stability of the water, and these are dependent in turn on the relative sea and air temperatures by night and by day, and on the strength of tidal and residual currents. Thus, after a very few days, planktonic organisms are subject in the main to the much-diluted non-volatile and much less toxic surfactant constituents of the detergents.

The subsequent history and possible effects on organisms of these more persistent substances have not been studied during the present investigations.

CHAPTER 4

SHORE SURVEYS—ROCKY SHORES

On the Cornish coast there are two main types of substratum: (1) the rock of cliff bases, platforms, reefs or boulders, and (2) beach deposits usually of clean sand, or sometimes of pebbles. Rock is essentially stable whereas sands shift with the tides. On sandy shores there are seasonal changes, in that parts of the beach build up during the spring and summer under relatively calm conditions and are removed again during stormier periods of autumn and winter. Such different types of substratum obviously demand different cleansing procedures. The initial amount of exposure to, and damage to life by, detergent differs widely on rock and sand as does the degree to which the detergent persists. As, however, the two types occur in close proximity at any one locality this chapter is to some extent geographical in its approach. Attention is focused first on the more rocky shores; observations on sandy shores being given in the following chapter. Estuaries form yet a third type of habitat with quite different cleansing problems. The 'Torrey Canyon' pollution fortunately did not affect any of our major estuaries, but such effects as were seen are mentioned in Chapter 5.

ARRIVAL OF THE OIL

An account by a resident at Marazion stated that there was a smell of oil for a day before any actually arrived on the shore on 25/26 March. Dark blobs were seen silhouetted in crashing waves, and close inshore there was so much oil on the sea that the waves were smoothed, while elsewhere it was choppy with tan-coloured instead of white breakers (cf. Plate 13B). The receding tide left a band about 5 metres wide of 'chocolate icing' (elsewhere described as 'chocolate mousse'). Some of this oil was washed off by the next tide, but some was left adhering to the seaweeds *Fucus* and *Porphyra*. Oil tended to be washed off barnacles but to be left in crevices on the rocks. Further landfalls of oil extended and thickened the coating, and then with gale-force winds behind a very high spring tide oil was flung right up the sea-walls and cliffs. But much of the oil brought into Marazion Bay did not settle, owing to a change of wind.

Along the coastline from the Lizard to Trevone pollution was general but far from continuous. A stretch of about ten miles of the coast on the west side of Mount's Bay, as well as many lesser areas, escaped. Winds concentrated the oil on to west-facing shores, or towards the eastern end of bays facing north or south, pushing it into localized areas on a beach or into small coves. Later changes of wind direction caused more general pollution of northward-facing shores. This ghastly mess of oil, like thick blankets of 'chocolate mousse', presented a very different problem from the black tarry lumps of oil previously familiar along the drift line. Plates 3A, 8, 13 and 14 convey the appearance of the oil on the shore soon after arrival better than could any description.

Sennen was seen seven tides after the first oil-fall, and while more oil was still arriving and before any use of detergent. The boulders at high water were completely smothered in oil: the layer was estimated as about 1 cm thick, less on slopes, more in hollows (Plates 13A, 14A). On the sand there were large areas of oil about ½–1 inch thick covering perhaps 50 per cent of the middle shore. At Gunwalloe Fishing Cove the oil was driven along the shore (Plate 4B), concentrated so that the breaking waves looked as if they were almost composed of oil, and their turbulence was markedly suppressed (Plate 8A). They swirled among the rocks, depositing a coating of oil on everything animate and inanimate. On the shingle they left a sticky blanket 1–2 inches thick which sank only slightly among the pebbles. But nowhere on the Cornish coast was oil nearly as thick as that which settled on parts of the Brittany coast (see Chapter 9, p. 160).

The 'chocolate mousse' was a mixture of oil, sea water and probably also detergent sprayed on at sea. Statements that this coating, usually referred to simply as oil, was up to 2–3 feet thick must have referred to very localized corners, or be erroneous. Oil floating on water in pools or, for example, in Porthleven harbour, could give a very misleading impression. Thicknesses and the area covered were very difficult to estimate and were subject to changes with each tide. Depths mentioned here were of oil seen after a few tides.

In most places the early deposits were mainly in the high-water zone and in the splash zone, but at Trevone where the oil was deposited on 29/30 March under calmer conditions the blanket of oil half an inch or more thick was spread over a wider tidal zone.

Treatment on the shore by detergents, usually hosed down with fresh water, produced milky streams running down the sands or retained in the rock pools (Plates 1B, 10A). It was this detergent mixture and neat detergent which proved so lethal to the fauna and flora.

As more oil arrived from the sea or was dispersed by detergents from one place to another pollution became more general. Even so there were stretches of shore and localized areas which escaped completely, providing a reservoir of organisms from which recolonization by the next generation of their larvae or spores can take place.

The zeal of the detergent users was such that even the most remote coves were often eventually tackled (Plate 4A), being incorrectly considered as the source from which 'new' oil was appearing. It is much more likely that the secondary deposit of oil on 'cleansed' beaches was in fact due to oil washed back by onshore winds or buried oil coming up from beneath the sands.

The map (Figs. 8–10) presents a synthesis of data from all reliable sources. It is based almost entirely on observations from Marine Biological Association workers, supplemented by records from the Nature Conservancy and from an Admiralty worker. The relative amounts of oil at different places are represented conventionally and were somewhat difficult to assess, but there seems little doubt that oil-falls were heaviest at Sennen Cove. The region of Cape Cornwall received a great deal and St Ives (Porthmeor Beach) had an exceptionally heavy plastering (Plate 8B), though the harbour and nearby beach escaped. Passing northwards along the coast there seemed to be rather less oil, but, owing to attempts to clean it during the long spell of northerly winds, relatively much more detergent was used, over a prolonged period. The degree of damage to life was much the same in all heavily treated areas. Two sharp spells of westerly wind caused heavy pollution along much of the eastern shore of Mount's Bay, but cleansing operations in this area were greatly helped by the long spell of northerly winds. The ten-mile stretch of coast from Penzance south-westwards escaped entirely and very little oil was deposited east of the Lizard. Only a few places, difficult of access, or lightly polluted, were left untreated by the end of the operation. Because detergent was distributed and used partly by the army and partly by local authorities (with frequent changes of personnel on the beaches) it has proved impossible to be exact about the amounts of detergent applied in the different areas and used on particular beaches. Figures are given (see page 42) for a few places where they seem to be reasonably reliable. For approximate totals of oil and detergent on Cornish beaches see Chapter 8. An essential contribution to the cleansing operations was made by the fire services using pressure hoses for delivering fresh water, or occasionally sea water, to wash the detergent and oil down the shore to meet the incoming tide. The methods of application varied widely as did the conditions and times relative to the tide. Local geography and weather were important. All these could make a great deal of difference to the effect on the flora and fauna as well as to the efficiency of oil removal.

AREAS STUDIED

Marine Biological Association workers between them visited sixty-five sites, many of them several times. Field work began on 28 March, and frequent journeys were made to West Cornwall until mid-May, since when studies have been continued by sporadic visits. The main sites studied are listed in Table 5.

The south coast is, in general, much the more sheltered from intensive wave action, has more localities with good weed cover, and is probably the richer in variety of species. The north coast is more open to powerful wave attack, tends to have on its rocky shores more barnacle and mussel coverage and less weed cover, and, while harbouring many plants and animals that are commoner there than on the south coast, is less rich in its variety of species.

On exposed shores the boulder zone near high water and also the intertidal sands have but a limited fauna. These were at first the hardest hit regions, but the spreading of the contamination, due largely to the use of detergent, meant that many rocky shores and sands became mildly contaminated over nearly the whole of their tidal range.

Some of the places, particularly those on the north coast, and especially Trevone, have been visited regularly for a number of years by scientists from the Plymouth Laboratory, while for others there are detailed records of some of the commoner plants and animals which go back to the late 1940s and early 1950s (Crisp & Southward, 1958; Southward & Crisp, 1954, 1956; Southward, 1967) and in some cases to the 1930s (Fischer-Piette, 1936; Moore & Kitching, 1939). There was therefore a good background of information available for detecting and assessing changes in the intertidal fauna and flora which could be attributed to the effects of oil pollution or of the cleansing operations.

From the field data currently available, a fourfold comparison has been attempted of shores or patches of them which (1) were completely untouched and unspoilt, (2) had oil pollution alone, (3) had both oil pollution and detergent treatment, and (4) were affected by detergent but had never had any oil contamination.

Detailed surveys are given of two areas, Marazion and Trevone. Apart from visits paid by members of the Plymouth staff to Marazion, regular surveys were made by a local resident, Mrs S. Vaidya. Her studies of the algae and the commoner shore animals gave valuable continuity to the observations which covered a period of 20 weeks from the arrival of the first oil. This shore provided a range of habitats and showed a gradation of the effects of moderate pollution. In this it contrasted sharply with

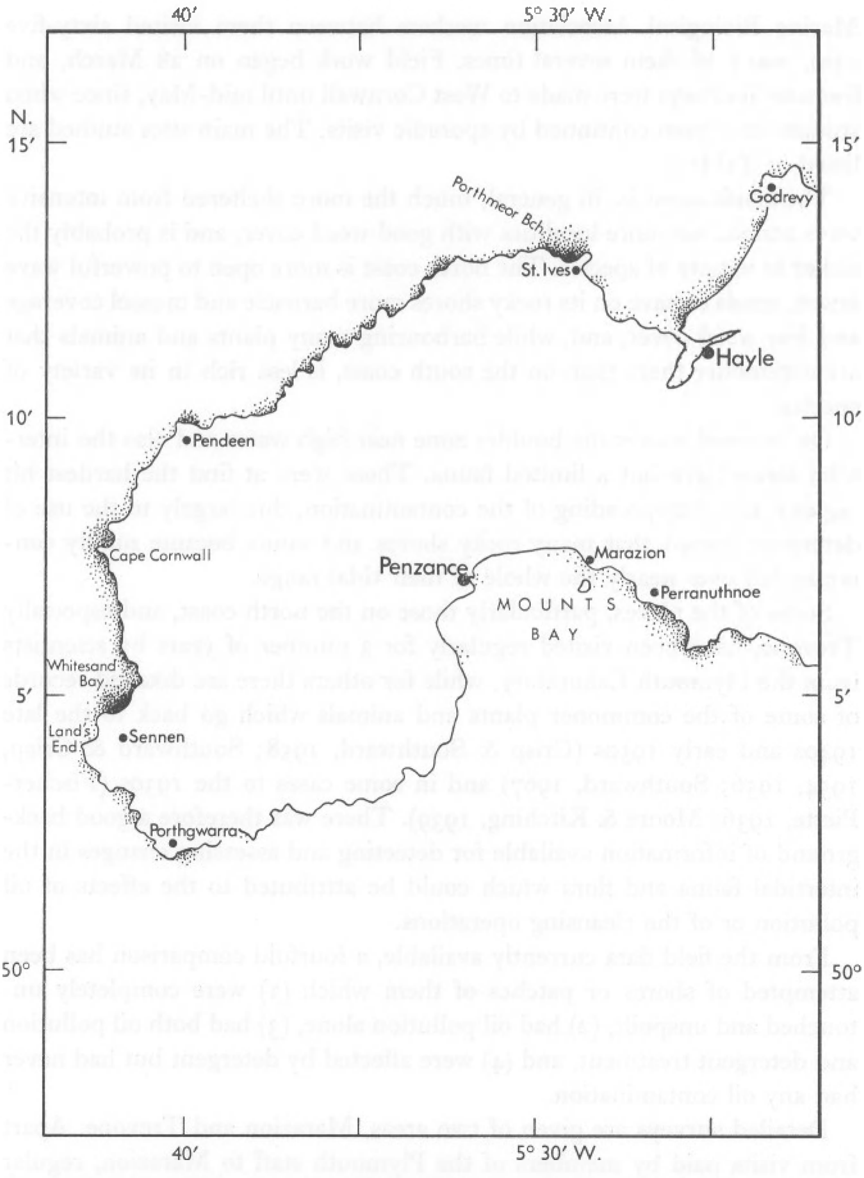


Fig. 8. The maps in Figs. 8–10 show the chief places studied by M.B.A. workers, and the amount of oil deposited on the beaches. The density of stipple indicates the relative degree of oil pollution. Scale, 2·5 kilometres to 1 cm. (approx. 4 miles to 1 inch).

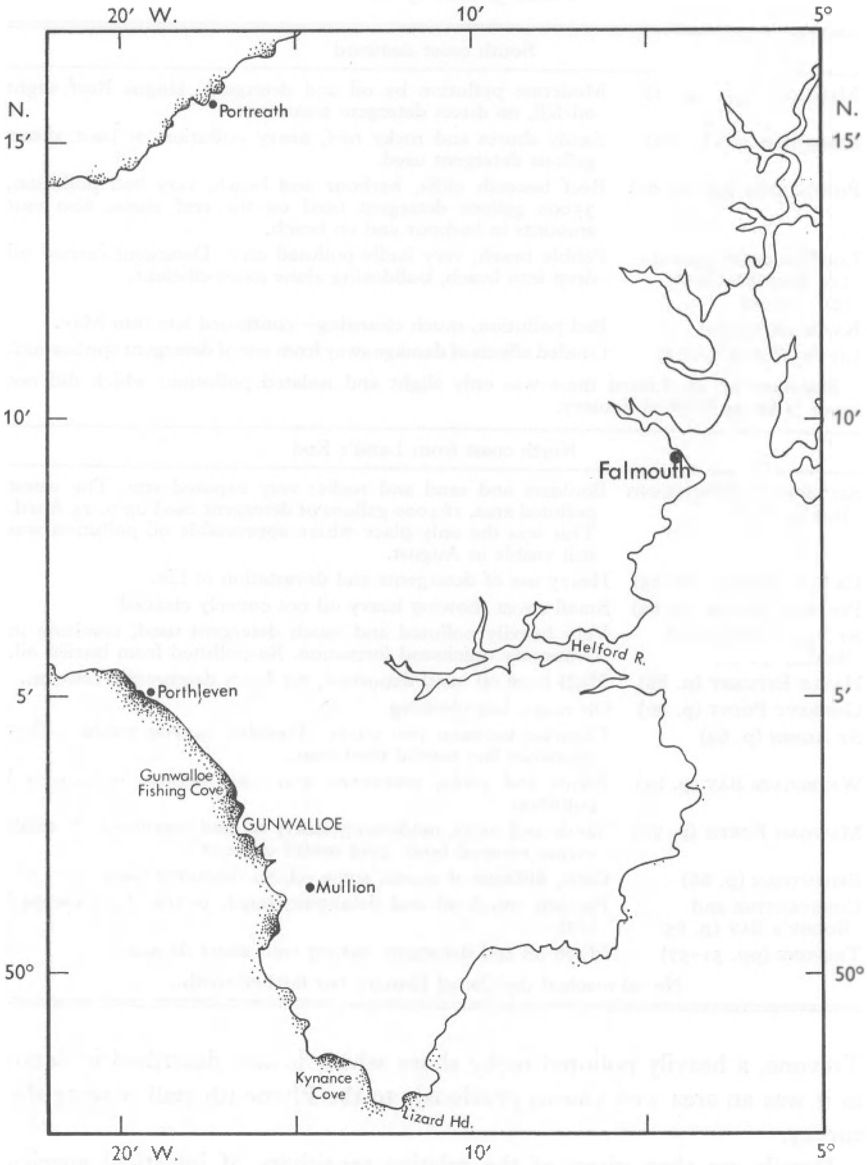

20′ W.
10′
5°
N.
15′
Portreath
N.
15′
10′
10′
Falmouth
Helford R.
5′
Porthleven
5′
Gunwalloe
Fishing Cove
GUNWALLOE
Mullion
50°
50°
Kynance
Cove
Lizard Hd.
20′ W.
10′
5°

Fig. 9

Table 5. *List of main sites*

South coast eastward	
MARAZION (pp. 44–51)	Moderate pollution by oil and detergent. Hogus Reef slight oil-fall, no direct detergent treatment.
PERRANUTHNOE (p. 82)	Sandy shores and rocky reef, heavy pollution, at least 38000 gallons detergent used.
PORTHLEVEN (pp. 57–61)	Reef beneath cliffs, harbour and beach, very bad pollution, 35000 gallons detergent used on the reef alone, also vast amounts in harbour and on beach.
LOE BAR and GUNWALLOE FISHING COVE (pp. 79, 90)	Pebble beach, very badly polluted area. Detergent carried oil deep into beach, bulldozing alone more efficient.
KYNANCE (p. 63)	Bad pollution, much cleansing—continued late into May.
LIZARD POINT (p. 62)	Graded effects of damage away from site of detergent application.
Eastward of the Lizard there was only slight and isolated pollution, which did not reach as far as Helford Estuary.	
North coast from Land's End	
SENNEN AND WHITESAND BAY (p. 81)	Boulders and sand and rocks; very exposed site. The worst polluted area, 164000 gallons of detergent used up to 24 April. This was the only place where appreciable oil pollution was still visible in August.
CAPE CORNWALL (p. 65)	Heavy use of detergents and devastation of life.
PENDEEN WATCH (p. 62)	Small coves showing heavy oil not entirely cleaned.
ST IVES (PORTHMEOR SANDS) (p. 81)	Very heavily polluted and much detergent used, resulting in temporary quicksand formation. Re-polluted from buried oil.
HAYLE ESTUARY (p. 88)	High-level oil band deposited, no direct detergent treatment.
GODREVY POINT (p. 66)	On rocks, late cleaning.
ST AGNES (p. 64)	Contrast between two coves, Trevallis heavily treated, Trevaunance late careful treatment.
WATERGATE BAY (p. 81)	Sands and rocks, treatment over long period; repeated oil pollution.
MAWGAN PORTH (p. 78)	Sands and rocks, moderately heavy oil and treatment. A small corner escaped both, gave useful contrast.
BEDRUTHAN (p. 66)	Cove, difficult of access, some oil, no detergent used.
CONSTANTINE and BOOBY'S BAY (p. 65)	Patchily much oil and detergent, much of the shore escaped both.
TREVONE (pp. 51–57)	Much oil and detergent, mainly mid-shore damage.
No oil reached the Camel Estuary nor farther north.	

Trevone, a heavily polluted rocky shore which is also described in detail as it was an area well known previously to the Plymouth staff making the survey.

Details are then given of the relative sensitivity of intertidal species found damaged by heavy pollution, especially from Porthleven (p. 57). Further examples of graded effects of damage are given, and then follow data collected from places where there was oil but no use of detergent. A summary of the conspicuous effects of heavy pollution is based on many observations on these and other sites (p. 67). Observations connected with

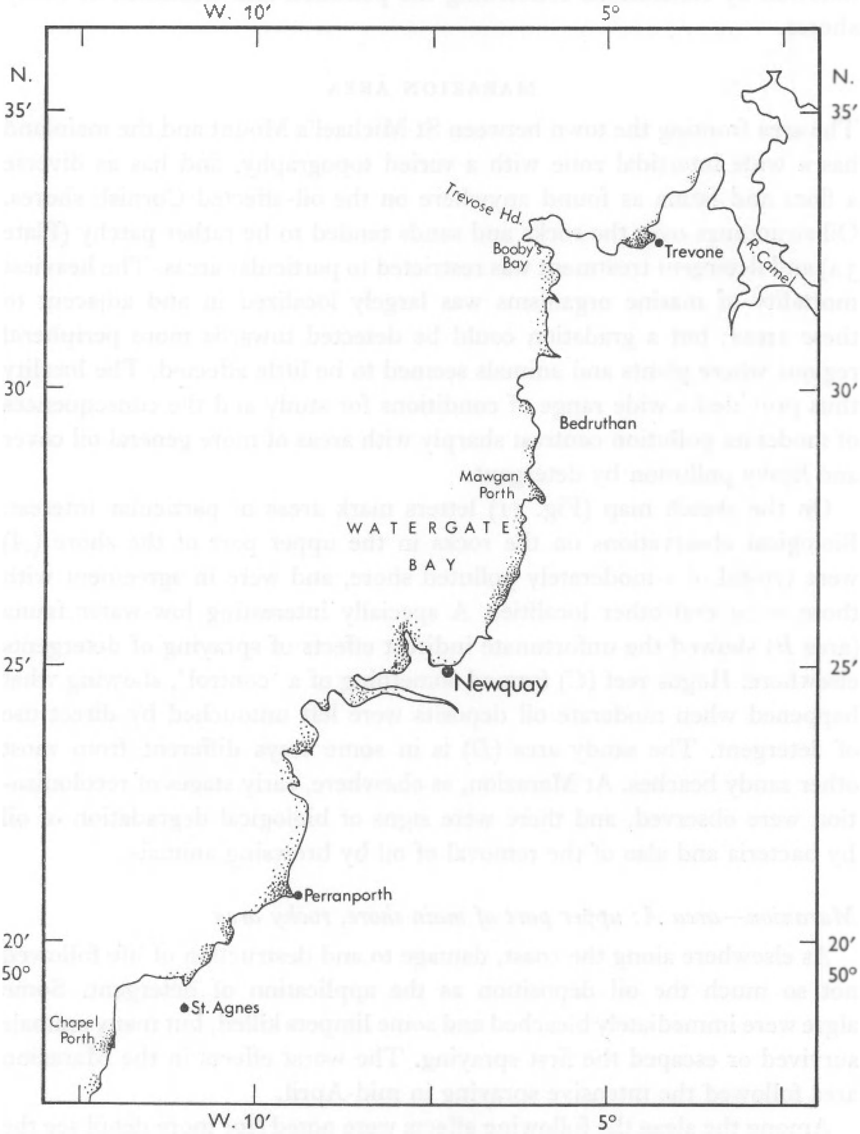


Fig. 10. The coast northward of that shown in Fig. 9.

the recovery and recolonization phase of rocky shores are summarized, followed by conclusions concerning the pollution and treatment of rocky shores.

MARAZION AREA

The area fronting the town between St Michael's Mount and the mainland has a wide intertidal zone with a varied topography, and has as diverse a flora and fauna as found anywhere on the oil-affected Cornish shores. Oil strandings over the rocks and sands tended to be rather patchy (Plate 3A) and detergent treatment was restricted to particular areas. The heaviest mortality of marine organisms was largely localized in and adjacent to these areas; but a gradation could be detected towards more peripheral regions where plants and animals seemed to be little affected. The locality thus provided a wide range of conditions for study and the consequences of moderate pollution contrast sharply with areas of more general oil cover and heavy pollution by detergent.

On the sketch map (Fig. 11) letters mark areas of particular interest. Biological observations on the rocks in the upper part of the shore (*A*) were typical of a moderately polluted shore, and were in agreement with those in several other localities. A specially interesting low-water fauna (area *B*) showed the unfortunate indirect effects of spraying of detergents elsewhere. Hogus reef (*C*) formed something of a 'control', showing what happened when moderate oil deposits were left untouched by direct use of detergent. The sandy area (*D*) is in some ways different from most other sandy beaches. At Marazion, as elsewhere, early stages of recolonization were observed, and there were signs of biological degradation of oil by bacteria and also of the removal of oil by browsing animals.

Marazion—area A: upper part of main shore, rocky area

As elsewhere along the coast, damage to and destruction of life followed not so much the oil deposition as the application of detergent. Some algae were immediately bleached and some limpets killed, but many animals survived or escaped the first spraying. The worst effects in the Marazion area followed the intensive spraying in mid-April.

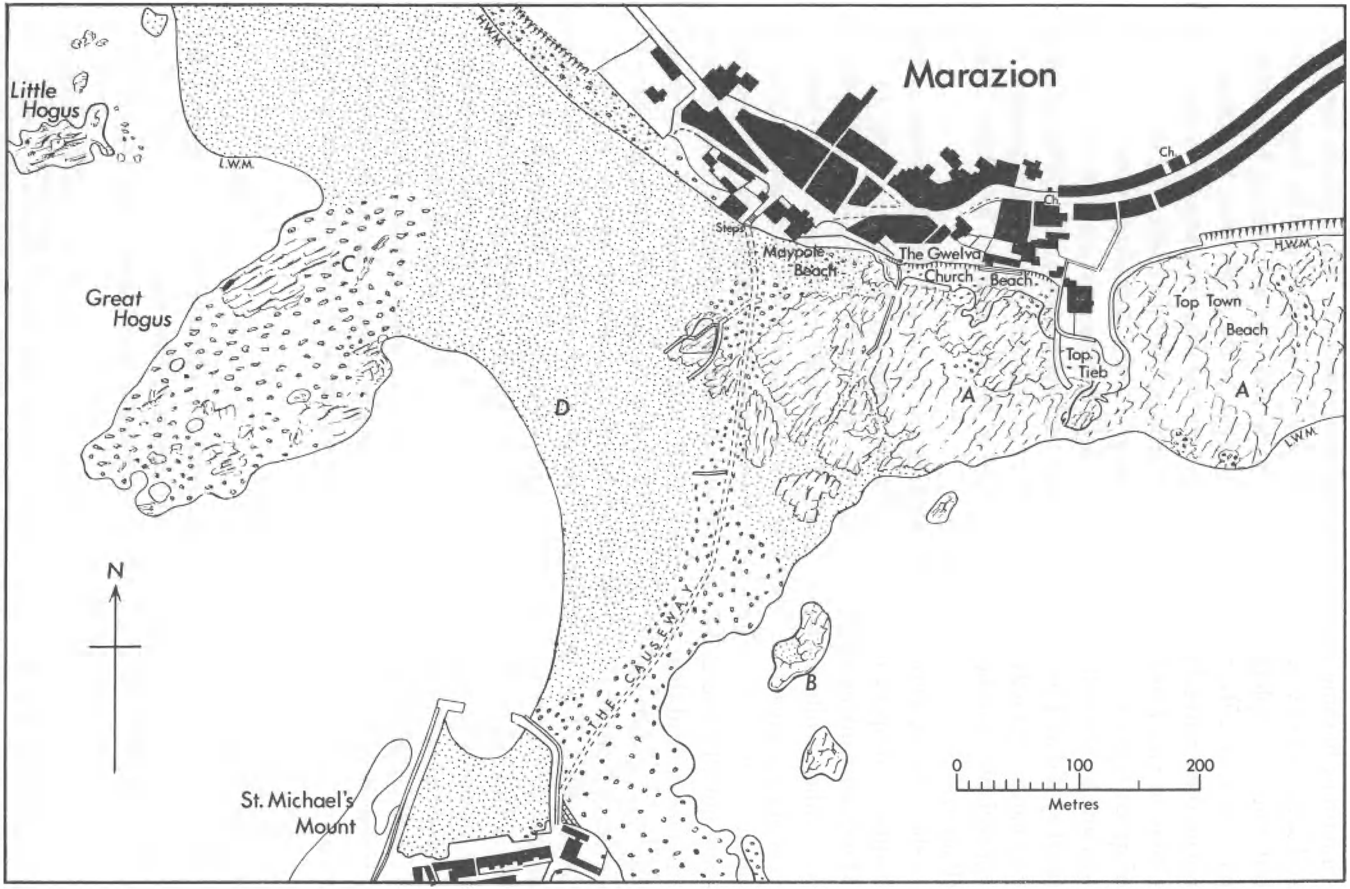
Among the algae the following effects were noted (for more detail see the account of algae at Porthleven, p. 58). Green filamentous algae were rapidly bleached as were encrusting coralline algae, particularly at the rims of pools where the detergent formed a toxic surface layer. Oil tended to cling to the thin fronds of laver (*Porphyra*), which after a few weeks became brittle and was washed away. The fucoids did not at once show the full extent of the damage; tips were soon discoloured (Plate 15C), later they often lost the blade of the frond, to be reduced to a midrib or stipe, and even this sometimes became readily detached from the rock; other plants survived and later put out new growth. There was considerable patchy loss of algae but not a complete devastation. There was also survival in the deeper parts of pools. By 23 April coralline algae in the pools were beginning to regain their normal pink colour. *Porphyra* and other red algae (for example *Chondrus* and *Dumontia*) were regenerating. Recolonization by sporelings of green filamentous algae (*Enteromorpha* and *Cladophora*) was beginning to show by the end of April but the rocks did not gain a heavy green cover (as they did at Trevone, for example), perhaps because some of the grazing population (chiefly the top-shells, *Monodonta*) were still present in appreciable numbers, although nearly all the limpets had been killed (Plate 9A).

Shore birds were observed pecking the upturned shell contents or the bodies of limpets occasionally left shell-less on the rocks (Plate 12A).* Many periwinkles and top-shells were also killed. Some mussels (*Mytilus*) were killed while others survived. The beadlet anemone (*Actinia equina*) gave sluggish reactions soon after use of detergent, but this resistant animal often survived when sited on the lower face of overhanging rocks. Barnacles were not all killed at Marazion, but crabs and shore fishes were much more often seen dead than alive. Some small crustaceans (gammarids etc.) which live in cracks in the rocks or under stones escaped the first application of detergent. Much later, in mid-July, what might be termed an indirect lethal effect of oil pollution was found. In the gullies between the rocks are flat stones under which oily drainage occurred. The deposit had become black and sulphurous and there was a complete dearth of animals due to the anaerobic conditions, that is oxygen lack. These were almost certainly brought about by bacterial degradation of the oil, some of which was still present, as indicated by vivid iridescence seen when stones were disturbed. By this date, the remains of paint-like oil patches on the rocks, except for those near and above high water, had mostly been worn off by wave action or other natural means.

Marazion—area B: low-water reef

The effects of detergent spread over the whole of the shore appreciably farther than the area where oil was deposited. This was apparent in the widespread effects mentioned above, and was also particularly well documented

* Dr Vera Fretter informs us that as a limpet dies the tonofibrillae—delicate structures which attach the columellar muscle to the shell—may be weakened whereas the mechanical suction and the secretion of the foot may still be effective in keeping the animal weakly attached. The loss of shells by limpets while still attached has been observed when they die in aquaria. It is not a specific effect of the detergent.



Marazion
Little Hogus
Great Hogus
L.W.M.
H.W.M.
Ch.
Steps
Maypole Beach
The Gwelva
Church Beach
Top Town Beach
Top Tieb
A
B
C
D
THE CAUSEWAY
St. Michael's Mount
N
0
100
200
Metres

Fig. 11

Table 6. *Summary of main events at Marazion*

(1) Oil deposited chiefly near high-water springs and in splash zone 25/26 March. Strong smell from volatile fraction of oil, which was ginger brown on arrival, gradually turning black on sea walls.

(2) First use of detergent 27 March chiefly at the town end of the Causeway, near the Top Tieb harbour, and between them, i.e. Maypole and Church beaches, also under the Mount.

(3) Lesser deposits of oil in splodges at high-water neaps during next few days (see Plate 6A, Maypole beach, 1 April). Subsequent tides (neaps) left thin layer of oil, which could be found over wider mid-tide zone.

(4) Widespread thin coating of oil on rock platform below the Gwelva and on Top Town Beach and in pools east of Causeway, 12 April. This oil was more viscous and mahogany-coloured. Probably some which had come out of emulsion after treatment elsewhere and was now redeposited.

(5) Moderate use of detergent on upper part of shore during mid-April; this moved most of the recent oil, some patches remained and there was still some buried in the sand (Maypole, Church and Top Town Beaches).

(6) Elements of oil–detergent mixtures were reappearing daily on the shore and on 26 April brown oil slicks with a detergent smell were close offshore.

(7) Secondary pollution after gale in early May (Plate 3B) on a long stretch of previously uncontaminated beach to west of area covered by map.

(8) Very heavy and extensive kelp (torn weed) deposited on sand (Maypole Beach to Great Hogus) by same gale, a normal seasonal occurrence.

(9) First faint signs of recovery, some return of pink colour to pools and of recolonization by very short green algae on rocks which lacked their normal browsing fauna, observed during last week of April.

(10) General greenness, especially on ungrazed rocks early July.

(11) Practically all oil removed by natural means from Hogus Rock by mid-July.

(12) Beach in full use by holiday makers, oblivious of such traces of oil as remain.

(13) Buried oil upshore being released by spring tides of larger amplitude, resulting in much stray oil and frothy oil seen in sea, 9 August.

(14) Abundant young fucoids replaced green weeds in early autumn in area *A*. Neither present in area *C*.

Caption for Fig. 11 opposite.

Fig. 11. Map of Marazion Beach showing places referred to in text. *A*, Upper and mid-tide rock platform with pools (see nos. 2, 4 and 5 of Table 6). *B*, Low-water reef, rich faunistically, no direct use of detergent, but showing serious indirect effects. *C*, Hogus Reef—patches of oil deposited 25/26 March, never any direct use of detergent, browsing fauna survived and helped in oil removal. *D*, Sand, some fauna affected temporarily at low level by detergent drifting with the tide. Buried oil at top of beach.

in the damage done to the low-water reef zone in the bay west of the Causeway, accessible only at very low tide. This area had been examined by M.B.A. scientists on 28 February and a rich and abundant fauna recorded. On 28 March it was free of oil. But by the time it was visited on 28 April, after the main period of detergent application upshore, a considerable change had occurred. Of the previously abundant snakelocks or opelet anemones (*Anemonia sulcata*) there were now very few and those present were only half expanded, with column and tentacle shrunken and not showing typical turgidity. The habitat had been especially interesting and rich in lucernarians, delicate little stalked jellyfish which live attached to weeds. Four species, one of them present in thousands, had been seen in February, but now they had all completely disappeared. Many of the algae, including the oarweed, a *Laminaria*, were unhealthy, with large irregular bleached patches of damaged tissue. The red weeds *Chondrus crispus* and *Calliblepharis jubata* were unusually pale or showed bleaching or abnormal red discoloration of the fronds. On this occasion a small colony of the very local hermit crab *Clibanarius misanthropus* was found in a pool. Among seven specimens there was a shell containing a dead individual. In natural conditions shells containing dead hermit crabs are never found. This example was probably a detergent victim.

Although there had been no oil deposited on this site and no direct application of detergent, polluted water could not have failed to have reached it, and direct visual evidence of this was obtained when it was noted on 28 April that an oily film had accumulated against all windward facing rock projections.

Marazion—area C: Hogus Reef

Great Hogus is a reef cut off from the shore at about half tide. The original oil-fall, in discontinuous patches, had been moderate (up to approximately ½ cm thick) and confined to the northern end of the reef (area *C*). During the succeeding weeks the rock received only insignificant

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PLATE 7

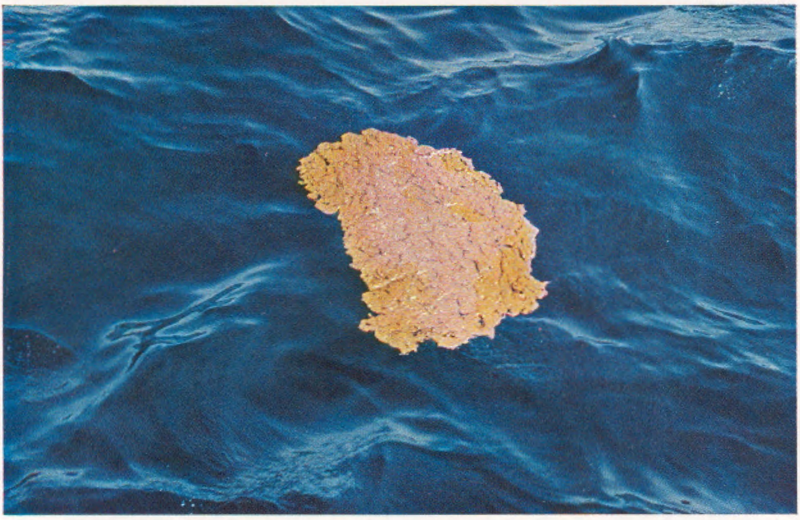
A, Oil emulsion on the sea surface about 20 miles north of Ushant, 12 April. **B**, Isolated patch of oil emulsion, about 1 metre across, floating a few miles south-west of Ushant at 48° 22·6′ N., 05° 16′ W., 18 May. **C**, Bay of Biscay, west of Pointe du Raz, 47° 22·6′ N., 05° 20·5′ W., 12 May. Part of a dense patch of untreated oil emulsion, some 100 square metres in area and perhaps 15 cm thick.

PLATE 8

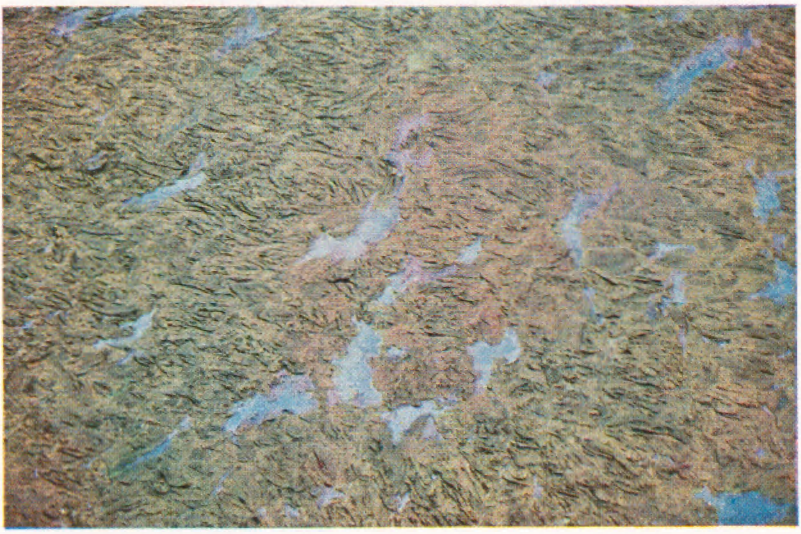
A, Gunwalloe Fishing Cove, 30 March. Breaking wave heavily loaded with oil emulsion. **B**, Porthmeor Beach, St Ives, 28 March. Beach polluted with untreated oil, deposited by receding tide, prior to any cleansing operations. In the foreground the reflection of the sky on the oil makes it appear blue.

PLATE 7

A



B

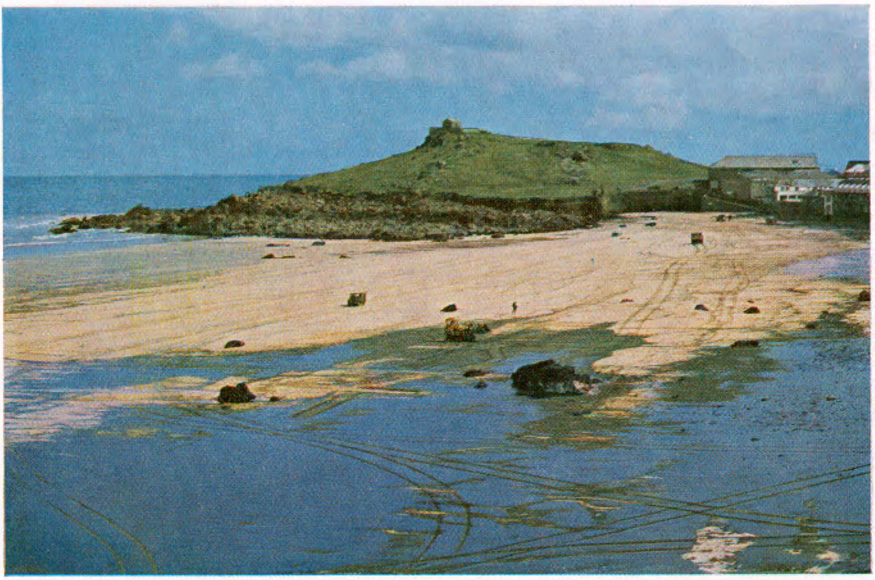


C

(*Facing p.* 48)

PLATE 8

A



B

additions of oil and detergents were never directly applied to it. It is probable, however, that the reef would on occasion have been washed by sea water containing detergent in low concentration when beach-cleaning operations were being carried out on the upper part of the tidal zone, some 300 metres distant.

Throughout the survey the absence of dead plants and animals in area *C* was in strong contrast to area *A*. On 28 March the flora and fauna seemed but little affected. Limpets which lay under a thin coating of oil were alive (Plate 9B) and reacted to touch, and some grazing tracks of top-shells through the oil were observed. Some of the limpets could be detached more easily than usual, and many of the top-shells (*Monodonta lineata*) had retracted within their shells and were remaining inactive at the bottom of pools.

Five days later the gastropod population of limpets, top-shells, periwinkles and dog-whelks, as well as small crustaceans, appeared to be entirely normal. Limpets gave their normal adhesion reaction, and *Monodonta* which had been taken to the laboratory on 28 March were now fully active. Oil patches were now somewhat thinner and darker. There was no evidence that any deaths of limpets or *Monodonta* had occurred as a result of the oil deposit. Indeed later in April limpets with their shells and the underlying rock still oil-coated had survived unscathed. Whatever indirect effects may have occurred temporarily during the height of the cleansing activities in mid-April, they had left no traces by 5 May, and limpets which had previously been photographed on a rock (Plate 9B) were all in their original seats. A hardened film of oil still covered shells and rocks seeming to offer inhospitable feeding conditions, for their usual food supply of algae and diatoms was smothered. If these could grow at all on the hardened surface of the oil, they were too scarce to be detected. That some of the limpets had in fact been grazing could be seen from the small partially cleaned areas around them (central limpet in Plate 9B; see also Plate 9C). A small boulder with four limpets attached was taken to the laboratory. These limpets had already cleaned a small area around themselves (cf. Plate 17B) and they continued to feed, browsing on the oily deposit and producing faeces containing oil. The presence of benzene-ring compounds in the faeces was demonstrated chemically. Similar observations were made on top-shells (*Monodonta*) and limpets (*Patella*) living on oily rocks at Perranuthnoe. They too produced oily faeces. The gut contents contained much brown-coloured matter, but the oily part could be distinguished by its solubility in benzene and by its taking up Oil Red O. The proportion of oil intake by these animals was estimated as about 20–30 per cent in *Patella* and 5–50 per cent in *Monodonta*.

When Hogus Reef was re-visited on 19 July the population of limpets and *Monodonta* was fully as abundant as before. It was very difficult to find an empty limpet seat (some always occur on normal shores). Practically the only traces of oil, now black, which could be found were on some of the *Monodonta* and limpet shells; the rocks and barnacles were clean. The oil may have been removed to some extent by wave action, but the distribution of the remaining traces is strongly suggestive that browsing played an important part in the cleaning, removing oil from the surfaces and binding it into small packages of faeces. As such, among other detritus, it would be readily accessible to bacterial oxidation. It is thus seen that the normal browsing fauna, left unkilled by detergent, can be effective cleaning agents, at least on rocks not too heavily oiled which are under water for some part (in this case about a third) of the tidal period. These observations confirm those made by George (1961) at Milford Haven.

Marazion—area D: sandy area

These sands differ in some ways from the usual Cornish sandy beaches which are of clean and often coarse sand (see Perranuthnoe fauna). A great deal of storm-torn seaweed is washed up here every year and much carted away by farmers; the 1967 kelp crop was normal and not considered by them to have been influenced by recent pollution. The sand here must receive much algal detritus and is greyish as a result; it also contains more silt than most beaches, thus making for stability. It is thus able to support an abundant polychaete worm population which was examined on 28 April. On this date there were only faint traces of detergent in the form of films on the surface of standing water near low-tide mark but no smell of detergent could be detected in the sand itself. The fauna within the medium-grade sand of which this beach is composed did not appear to have been affected. At about mid-tide level were bristle-worms, including lugworms (*Arenicola*), *Nerine* spp. and *Glycera convoluta*, all of which had survived such indirect effect of detergent as they may have encountered. *Arenicola* could have cut itself off from polluted water by ceasing to ventilate its burrow for a time. A single specimen of a sphaeromid crustacean and several of the bivalve mollusc *Venus striatula* were also found at this level. The *Venus*, though found on the surface, were apparently healthy.

At a low level on the same shore on 28 March, four specimens of the razor-shell *Ensis siliqua* had been found: three were protruding from their burrows and one was lying moribund on the sand (Plate 20A). This quite abnormal behaviour was attributed to effects of detergent spraying the previous day; two of the razor-shells recovered at least temporarily when put in clean sea water in the laboratory. As a result of the use of detergent there was considerable destruction of *Ensis siliqua* in Marazion Bay during April (see diving record, p. 113). Large numbers of recently dead razor-shells were found thrown up in the drift line—gulls and a pair of crows were seen feeding on them. The sensitivity of this species to detergent was borne out elsewhere (Porthleven, Watergate, etc., and see toxicity tests, p. 137). As well as *Ensis*, the bivalve *Mactra stultorum* was also involved to some degree, the greatest number of empty valves being observed under the Mount on 16 April.

Another animal showing the effects of detergent, as elsewhere, was the heart-urchin, *Echinocardium cordatum*. The fragile dead tests do not normally remain long on the shore. Occasional ones were found during April, but towards the end of the month they were quite unusually numerous. This evidence of sensitivity is in agreement with the findings in the sublittoral zone at Porthleven (p. 140, and Plate 24). The last three animals mentioned are essentially shallow-water species, and as such they are probably much more sensitive to adverse factors (such as detergents) than are strictly intertidal species. The reported survival of many of the shore-living species may therefore give a false impression of the tolerance of marine organisms as a whole to potential poisons.

Razor-shells would be unable to close up completely as, for example, can mussels, which are therefore able to survive moderate doses of detergent (see p. 69).

TREVONE

The value of the Trevone survey derives mainly from the detailed knowledge which we had beforehand of the shores of this region and from the reliance that could therefore be placed in making surveys within this locality on 'before and after' comparisons. Trevone (Newtrain Bay to Porthmissen Beach) received a heavy oil pollution on 29 and 30 March (Fig. 12). The oil was said to be more than half an inch deep over all the rocks, with some patches of similar depth on the sands of Porthmissen Beach. Elsewhere there was a thin layer, and at first none at high water. When the first brief survey was made on 10 April, the shore had been subjected to detergent treatment for four days. There was a film of oil on the rocks at high-water neaps, and mixture of sand and oil up to a foot thick between high water of neaps and springs where spraying was in progress. A thinner film of oil was still present at the mid-tide level and on the sea-ward reefs near the sewer outlet. Water samples from pools on the lower part of the shore were not toxic, but a sample from a pool at high-water neaps, close to spraying operations, contained oil, about 60 per cent fresh water and (by bioassay) 700–800 ppm of detergent.

The only organisms in the vicinity that seemed unaffected at the time were the two common barnacles (*Chthamalus stellatus* and *Balanus balanoides*), mussels and fucoid algae. Some red algae were dying, 50 per cent or more of all three species of limpets had been killed, while most, if not all, top-shells, periwinkles and dog-whelks were already dead. No anemones

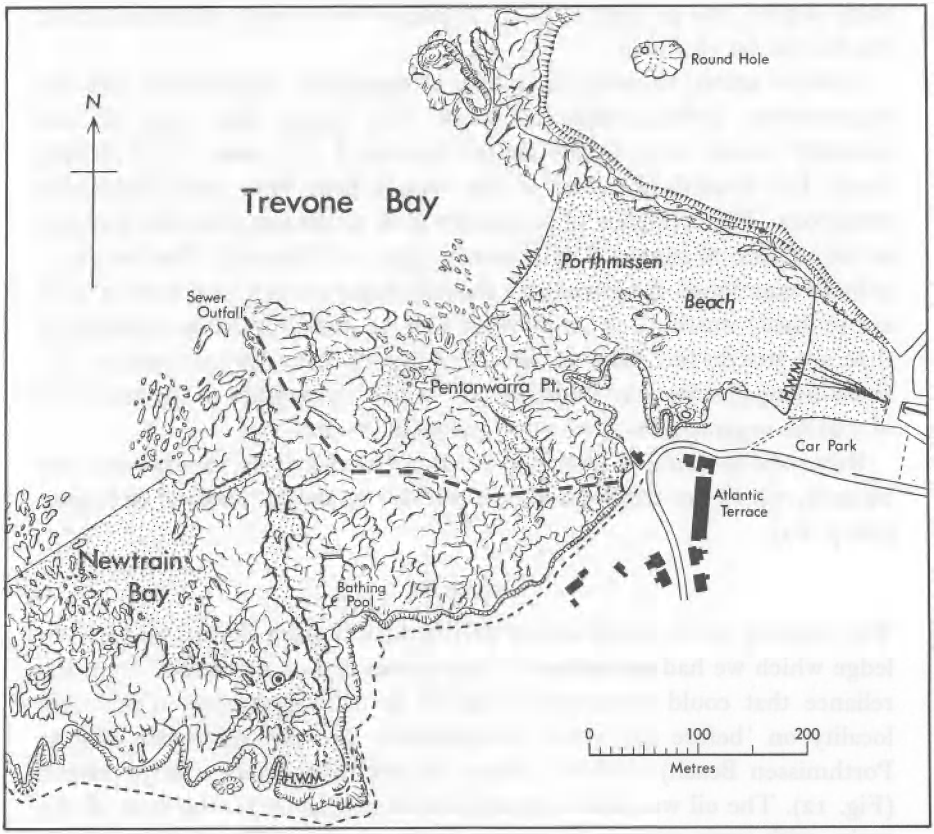


Fig. 12. Map of heavily oil-polluted and detergent-treated rocky and sandy shore at Trevone. – – –, Approximate line of sewer pipe. ⊙, Position of photographs reproduced in Plates 10B and 11 in Newtrain Bay.

were seen (alive or dead), nor intertidal fish, but among dead animals collected were the worm *Perinereis cultrifera*, the crabs *Carcinus maenas*, *Cancer pagurus*, *Porcellana platycheles* and the rare hermit crab *Clibanarius misanthropus*. Trevone was the only known locality for the latter on the north coast.

On 15 April firemen were still hosing detergent in fresh water over the rocks and sand of the rocky shore faced by Atlantic Terrace (Plate 10A), and the sand here was full of oil. Porthmissen Beach, the main sandy beach adjacent to the car park, which had also been affected badly in places, was still being treated. Streams of fresh water mixed with detergent were flowing down it and a few workers were turning over the sand. But the main work had been done and the sand looked clean, though smelling strongly. The rocks to the west around the bathing pool and in Newtrain Bay had already been treated, but over some areas a thin film of oil remained.

Much biological damage had obviously been done to the mid-tidal region extending roughly from high- to low-water neaps, the region where the most intensive spraying had taken place. Rocks were denuded of molluscs and detergent-filled pools had only dead algae in them. Drifts of limpet shells, with and without soft parts inside, and separated soft parts, were washed with other molluscs into gullies, also one or two dead fish, dead crabs and a dead *Nephthys* worm. *Patella aspera* with flesh inside, and large tufts of *Fucus serratus* growing on these limpet shells, had here been washed up from lower levels or from pools. Around the bathing pool and near the Newtrain gully, where the oily film on some rocks perhaps indicated that spraying had been less intense, the damage seemed to be less severe. Even so, most limpets were easily detached by hand and the shells often lifted cleanly away from the soft parts on the rock (Plate 12A) (see p. 45). Among the dead algae found on 21 April were the green *Ulva* and red *Gracilaria* and *Ceramium*.

On 23 April, some days after the cessation of spraying, all the loose limpets had gone (Plate 12B) and only a few seated in sheltered crevices and on rocks still thinly covered with oil remained firmly attached. Everywhere many thousands of fresh clean limpet seats were clearly visible. Some examples of each of the top-shells *Monodonta lineata* and *Gibbula umbilicalis* survived, a mere remnant of their former abundance. Beadlet anemones, *Actinia equina*, although reduced in number, were fairly plentiful in pools and on oiled rocks in the Newtrain and bathing-pool regions. Here also the deeper pools contained *Bifurcaria bifurcata*, *Corallina officinalis* and other algae in apparently normal condition. Only one snakelocks anemone, *Anemonia sulcata*, usually common, was seen, unattached and looking sickly. Mussels on rocks near the sewer outfall, where a little oil was present, were as abundant as usual and alive, but scarcely any specimens of the dog-whelk *Nucella lapillus*, which in this area feeds mainly on mussels and is normally very common, could be found. Inactivated dog-whelks were lying loose and empty shells were seen (Plate 15B). Almost all the limpets had gone, leaving clean seats everywhere on the rocks. This visit coincided with low water of a good spring tide, and it was encouraging to find all the plants and animals at the lowest levels more or less normal. Underneath stones at the lower end of Newtrain gully were good growths of the ascidian *Botryllus* and, among other animals sheltering beneath stones were the crabs *Portunus puber*, *Carcinus maenas* and young *Cancer pagurus*, and some shore fishes including blennies and several *Lepadogaster lepadogaster*. The starfish *Asterina gibbosa* was present but no living sea-urchins (*Psammechinus miliaris*) were seen, though dead ones were found washed up in the gully. Similarly at the highest shore levels on the east side of Newtrain Bay, where it seemed that oil and detergent had not penetrated, there was a normal fauna with *Patella vulgata*, *Littorina saxatilis*, *L. neritoides* and *Chthamalus stellatus* all alive.

The visit on 29 April confirmed this general picture of a devastated middle shore flanked by relatively unaffected upper and lower regions. Individual *Actinia* and *Monodonta* which had been specially noted previously were still in the same positions, and on the walls of the gully some patches of the sponges *Halichondria panicea* and *Hymeniacidon perlevis* survived. The floor of the Newtrain gully, however, contained moribund *Gibbula umbilicalis*, *Monodonta lineata* and *Patella vulgata* amid a drift of shells.

Certain shallow rock pools which had often been examined and photographed had been known to contain *Actinia equina*, *Anemonia sulcata*, *Gibbula*, *Patella*, *Littorina littorea*, *Nucella*, *Corallina*, *Lithophyllum*, tufts of *Enteromorpha* and other seaweed. Small crabs, occasional prawns and small blennies were also among the usual inhabitants. After the detergent treatment, these pools for several weeks contained only beadlet anemones, *Actinia*, tufts of young *Bifurcaria*, *Corallina* and one or two other small algae. A microscopic slimy brown alga and diatoms began to coat over the apparently dead encrusting calcareous algae (*Lithophyllum*) and limpet scars. By July very young fishes and tiny crabs were hiding in the weed and one fair-sized gemmed anemone (*Bunodactis verrucosa*), one adult *Gibbula umbilicalis* and one *Littorina littorea* were seen.

In August 1966 a small patch of rock in Newtrain Bay, situated at roughly mid-tidal level, had been photographed to show the fauna (Plates 10B, 11A). This patch approximately 45 × 35 cm. set within a sloping rock face of about 100 square metres area was readily identifiable by the rock structure and photographed again on 23 April 1967 (Plate 11B). The rock still had traces of oil on it but had undoubtedly been heavily sprayed, though tufts of coralline algae, such as that shown in the photographs, were still soaked in oil and were dead. The single *Monodonta* shown in the photograph of 23 April was alive and in the same place on 29 April. The detergent treatment had almost completely cleared the rock of living organ-

Table 7. *Animals in areas photographed at Trevone* (Plates 11 A, B)

Species	Number present August 1966	Number present 23 April 1967
Actinia equina	1	0
Chthamalus stellatus	Many	Few (dead?)
Mytilus sp.	2 or 3 very small	1
Patella vulgata	24 medium and small	0
Monodonta lineata	11	1
Gibbula umbilicalis	1	0
Littorina saxatilis	4	0

isms and the two photographs are typical of the whole area before and after the spraying. Table 7 lists the animals shown in the two photographs (Plate 11 A, B).

On a further visit on 14 May 1967 a count was made of the surviving organisms on this particular rock face of approximately 100 square metres. There were 41 *Actinia*, 34 *Monodonta*, 2 *Patella*, a few *Gibbula*, a few small *Mytilus*, no *Littorina*, and it was almost cleared of acorn barnacles. The whole rock face looked strangely bare compared with its normal appearance.

The mussel-covered rocks near the sewer outfall, once drab-coloured, had a greenish look, due to young growths of *Enteromorpha* and *Ulva*, which mingled with brown growths of *Ectocarpus* and diatoms. These growths covered rocks and mussels and were particularly well developed in pools and all wet places.

The rocks at Pentonwarra Point which had been intensively treated with detergent, but had not been examined previously, had many areas with freely hanging byssal threads showing where mussels had been killed and had fallen off (Plate 15 A). Acorn barnacles had also been extensively destroyed, and the rocks were almost bare of life.

On 14 May sandy patches opposite Atlantic Terrace were still extremely oily with a strong smell, in Newtrain gully there was only a slight smell, less than before, and similarly on Porthmissen beach. Here the sand looked clean on the surface, but digging in the cove on the west side revealed a dark grey oily layer of sand having a strong smell of detergent. For the significance of this see page 81.

The rocky shore at Trevone was reinvestigated on 9 June. A few patches of hardened oil were seen around mid-tide level, and some small (2 cm in diameter) spots of new, soft oil were present at high water. The smell of detergent appeared to come mainly from the grassy cliff top where detergent drums had stood, but there were distinct traces of it in the coarse sand opposite Atlantic Terrace at the highest level of the tides.

Most of the fucoid algae had survived the cleansing treatment, and some re-growth of *Corallina* had begun in the pools. The overall effect, however, was of greenness, due to the unprecedented growth of *Enteromorpha* which had developed freely in the absence of limpets and other grazing molluscs. The growth was heaviest at low-water and mid-tide level, with some scattered patches above this level.

The few surviving limpets (less than one per 10 square metres) could easily be recognized from a distance, as they each occupied 'clearings' in the growth of green weed (Plate 17A). *Monodonta* was the commonest surviving mollusc, but a few *Gibbula umbilicalis* and *Nucella* were present. The beadlet, *Actinia*, was the only anemone observed. Settlement of young of the barnacle *B. balanoides* was quite heavy, and had continued after the cleansing operations as shown by their occurrence on limpet seats.

A month later on 9 July *Enteromorpha*, and in the lower places *Ulva*, were much further developed. An unusual carpet of vivid green covered almost the whole of the rocky shore from about half-tide level downwards (Plate 16B). Nothing like this has been seen here before (Plate 16A). Surviving mussels on rocks near the sewer outfall had almost disappeared beneath the green weeds growing on their shells. On the tops of the reefs near the sewer outfall the green algae were replaced by purplish-brown *Porphyra*, growing just as abundantly on rocks and mussels. Here and there a few solitary limpets or *Monodonta* still kept clear little areas of rock (Plate 17A).

Many of the oil film patches which had remained on high-level rocks after cessation of spraying had now gone, destroyed by natural agencies. Others were breaking down; they contained tiny grains of sand and could readily be rubbed off, often without staining the finger.

On this sunny July day Porthmissen Beach was crowded with holiday-

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PLATE 9

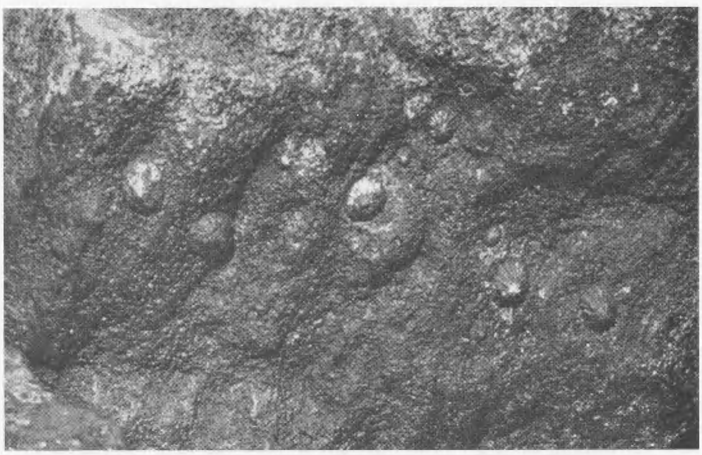
A, Marazion, Church Beach, 5 May. Treated rocks, on which all limpets had been killed, but top-shells (*Monodonta lineata*) had largely survived. Old limpet seats show as oval pale areas. **B**, Marazion, Church Beach, 5 May. Hogus Rock. Resident limpets surviving in oiled band, where the rock had not been treated with detergent. Note that the shells of the limpets are wholly or partly covered with oil. Oil has been grazed from the rock-face around the limpet in the centre of the picture. Others show it to a lesser extent. **C**, Limpet tooth-marks in a film of oil on a vertical rock-face at Trevone, 9 June. This photograph shows how the natural grazing activities of limpets will help to cleanse a rocky shore, providing the animals are not killed or damaged by detergents.

PLATE 10

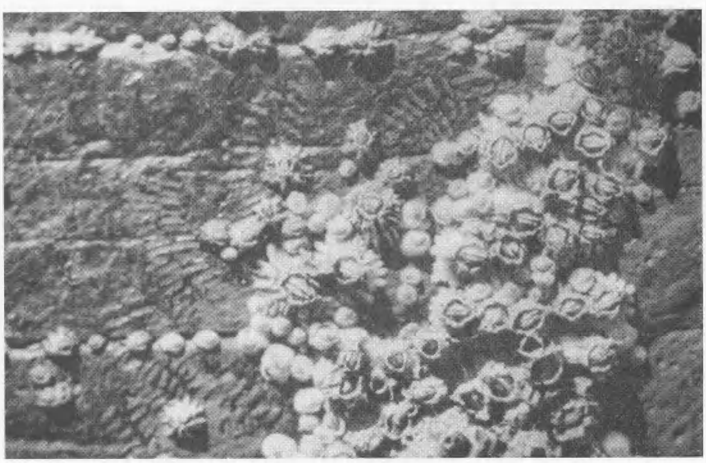
A, Spraying detergent on rocks and sandy patches opposite Atlantic Terrace, Trevone, 15 April. Note the white emulsion of detergent in the rock pools. At extreme top right men are spraying from Pentonwarra Point. **B**, Sloping rock-face in Newtrain Bay, Trevone, on which a count of surviving organisms was made on 14 May (p. 55). The white rectangle marks the site of the photographs reproduced in Plate 11.

PLATE 9

A



B



C

(*Facing p.* 56)

PLATE 10

A

B

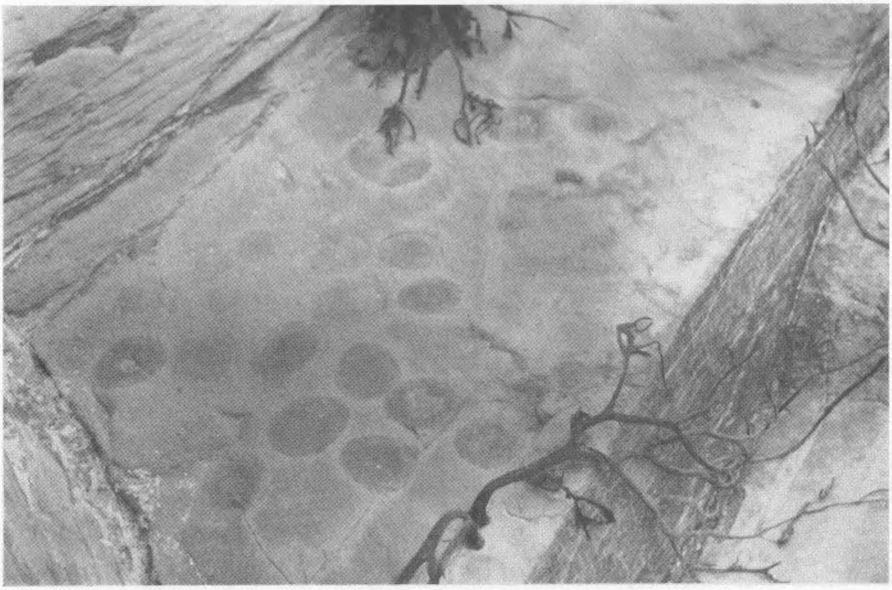
PLATE II

A

B

PLATE 12

A



B

(*Facing p.* 57)

makers and children were happily playing even in the still stained and still slightly smelly sandy patches opposite Atlantic Terrace. For them the shore was back to normal.

RELATIVE SENSITIVITY OF DIFFERENT SPECIES—PORTHLEVEN REEF

The field aspects of this problem were best studied at a place where the first visits could be paid while spraying was still in progress. The badly polluted area of Porthleven Reef (Fig. 17) was therefore chosen.

The first oil came in on 25/26 March on a high spring tide with a gale and was thus thrown about 20 feet up the cliffs to the thrift and turf. Lichens were largely smothered under this persistent blackening deposit. The bulk of the oil was near the base of the cliffs but on subsequent days much more oil was deposited—some of it probably being oil that had been washed out of the nearby harbour (see Plate 5 A, B)—so that nearly the whole reef had a slippery film of oil. Detergent was applied mainly in the higher regions of the shore, the most heavily treated area being between the monument on the cliffs and the harbour entrance (a distance of ½ km.) where it is estimated that a total of about 35 000 gallons of detergent were used in the eight days between 4 and 12 April and on 25 and 27 April. Sea water and not fresh water was used to hose down these rocks after spraying, thus simplifying the understanding of the cause of mortality. The shore here consists of a rock platform gently sloping from above mid-tide level to below low water. It is crossed by deep gullies running seawards from the base of the cliffs. Some of the gullies consist largely of a series of pot-holes but others contain loose rocks and patches of gravel. Between the gullies there are some rock pools and individual pot-holes. The gullies were very efficient in transmitting concentrated detergent from the upper part of the shore to the low-tide region.

PLATE 11

A, A small area of mid-tidal rock at Newtrain Bay, Trevone, photographed in August 1966 to show the typical fauna of limpets, top-shells, etc. **B**, The same area of rock photographed on 23 April 1967 after treatment with detergent to remove oil. One top-shell and one small mussel (indicated by arrow) survive (see Table 7, p. 55).

PLATE 12

A, Mid-tide limpets at Newtrain Bay killed by detergent. Shells have been lifted off two of them leaving their soft parts *in situ* on the rock. Photographed 15 April, some days after cessation of spraying and typical of innumerable neighbouring limpets at that time. **B**, Scars of the same limpets eight days later. Photographed 23 April and typical of many rocks of the mid-tidal region after the washing away by the sea of limpets killed by detergent. Limpets on oil-coated rocks not detergent treated survived not far away.

The algae were most seriously damaged by the detergent at the higher levels on the shores. A high proportion of the *Porphyra umbilicalis* plants growing on the higher rocks were killed; so also were the *Enteromorpha* plants in the high-level pools. *Corallina*, with its associated epiphytes, and the encrusting calcareous algae on the bottom of these high-level pools were also killed (Plates 15C, 18A), but at mid-tide only their tips and some of their epiphytes were killed, while near low water the *Corallina* and its epiphytes appeared healthy. In the mid-tide pools the *Bifurcaria* and *Cystoseira* plants were either killed or had the young growing apices destroyed.

The fucoid vegetation on the rocks and its associated algal undergrowth was also more seriously damaged or destroyed at the higher levels. *Fucus spiralis* appeared to be more easily killed by the detergent than either *F. vesiculosus* or *F. serratus*. Even so, dead plants of all three species were recorded and a high proportion of the remaining fucoids higher on the shore had their young growing apices destroyed. In other areas *Pelvetia canaliculata* reacted to the detergent in a similar way to *Fucus spiralis*. *Ascophyllum nodosum*, rather local on these exposed shores, appeared to show fewer ill effects. At the lower levels on the shore the *Fucus vesiculosus* and *F. serratus* appeared healthy and the receptacular tissue was apparently undamaged.

Some of the algal species growing on the rocks beneath the fucoids appeared to have suffered little except some plants of a few of the species growing at the higher levels which had received the concentrated detergents.

The species of algae least affected by the detergent were: *Ahnfeltia plicata*, *Chondrus crispus*, *Cladostephus spongiosus*, *Dilsea carnosa*, *Furcellaria fastigiata*, *Gigartina stellata*, *Kallymenia reniformis*, *Laurencia pinnatifida*, *Polyides rotundus*, *Pterosiphonia complanata*, *P. thuyoides*, *Rhodymenia palmata*, *Schizymenia dubyi*, *Scytosiphon lomentarius*.

On the other hand many of the plants belonging to the following species had either been killed (bleached or tips bleached) or appeared very unhealthy: *Acrosiphonia arcta*, *Acrosorium uncinatum*, *Apoglossum ruscifolium*, *Callithamnion* spp., particularly *C. tetricum* on rock-faces, *Ceramium* spp., *Cladophora rupestris*, *Cryptopleura ramosa*, *Delessaria sanguinea*, *Dictyota dichotoma*, *Ectocarpus* spp., *Gastroclonium ovatum*, *Gracilaria verrucosa*, *Halurus equisetifolius*, *Hypoglossum woodwardii*, *Jania rubens*, *Laurencia hybrida*, *Lomentaria articulata*, *Membranoptera alata*, *Plocamium vulgare*, *Plumaria elegans*, *Polysiphonia* spp., *Ulva lactuca*. Lower on the shore, however, apparently healthy plants of most of the above species could still be found.

At low water in the *Laminaria digitata* zone the fronds of many of the

Laminaria plants were completely bleached, or green in colour, and the reproductive parts of their fronds had been killed, but a large number of plants still appeared healthy and bore living reproductive tissue. The young *Himanthalia* plants, *Cladostephus verticellatus*, *Furcellaria fastigiata*, *Phyllophora crispa* and *P. brodiaei*, all appeared to be in healthy condition.

It will be seen from this short description that the damage sustained by the algae has been extensive. For any one species (for example, *Corallina*) there is a gradation of effect, damage being most severe at the higher levels of the shore where the toxic concentration was greatest. It can also be seen that not all the species are equally sensitive: thus the very delicate filamentous membranaceous red algae seem to be particularly susceptible and in some cases have been completely destroyed.

A gradation of effect and variation in sensitivity to the detergent is also exhibited by the animals of the reef. Although there was much oil on the shore when this reef was seen on 30 March, the animals did not appear to have been affected. However, when the reef was again visited on 7 April, three days after detergent treatment started, most of the animals were dead or moribund. On subsequent visits on 11, 26 and 28 April far fewer dead animals were found because many had been washed along the gullies into deeper water or had been eaten by birds. This removal of dead animals to deeper water was confirmed by the divers (p. 109). This has meant that much of the evidence rapidly disappeared and may explain the absence of some species, such as small crustaceans. From material which was collected, the following list of the more common dead animals was made.

ANEMONES. The beadlet *Actinia equina* and the dahlia anemone *Tealia felina* are possibly the most resistant animals on the shore, being commonly found alive, and on 26 April they were found in pools between the tidemarks which appeared to be devoid of all other animals. Some *Anemonia sulcata*, *Sagartia elegans* and *Cereus pedunculatus* were found dead; few survived.

POLYCHAETE WORMS. *Lepidonotus clava*, *Eulalia viridis*, *Nereis pelagica*, *Perinereis marioni*, *Eunice harassii*, *Lysidice ninetta*, *Marphysa sanguinea*, *Arabella iricolor*, *Dodecaceria concharum*, *Potamilla reniformis* and *Dasychone bombyx* were found moribund or dead on 11 April and one or more specimens of practically all species were found alive later. To some extent these are examples of animals which live in micro-habitats, in crevices or among weeds deep in pools, where they would have been able to stay away from the worst of the poisonous water, but laboratory experiments showed that these worms were fairly resistant to poisoning by detergent.

CRUSTACEA. Dead *Ligia oceanica* and *Orchestia* sp. were littered among the rocks at high water. The larger mobile crustaceans, the lobster *Homarus* *vulgaris*, and crabs *Porcellana platycheles*, *Cancer pagurus*, *Portunus puber*, *Xantho incisus*, *Pilumnus hirtellus* and *Carcinus maenas* were completely wiped out, only one living specimen of the last-mentioned and toughest crab being found. No shrimps or prawns were ever found nor were any gammarids seen. Barnacles appeared to have survived well on the main part of the reef, but near the old boat-house extensive patches of *Chthamalus stellatus* had been killed in this particularly bad area (Plate 19A).

MOLLUSCA. The limpet population that had been killed comprised the three species of *Patella* in about the following proportions: *P. vulgata* 70 per cent, *P. intermedia* 20 per cent, and *P. aspera* 10 per cent. Of these three species together about 10 per cent were still alive on 11 April between the zones of mean low water and mean high water, whereas on 28 April there were none left alive in this main stretch of shore, there being only a few survivors at low-water springs and in the spray zone. An idea of the original abundance of the gastropods may be gained from counts which were made of dead bodies in two pot-holes on 7 April; these were only about 20 cm in diameter and 20–30 cm deep. Their combined contents included 269 *Patella* spp., 21 *Nucella lapillus*, 15 *Nassarius incrassatus*, 13 *Gibbula umbilicalis*, 10 *Gibbula cineraria*, 2 *Ocenebra erinacea*, and 1 *Monodonta lineata*. Other species of gastropods found dead were *Patina pellucida*, *Calliostoma zizyphinum*, *Tricolia pullus*, *Littorina littorea*, rissoid sp., *Trivia monacha* and *Aplysia punctata*. The sea hare, *Aplysia*, which would have been coming up the shore to spawn, was found alive on each visit, and was also surprisingly resistant in laboratory tests. Though there was high mortality among the gastropods between tide-marks some may have been only inactivated and recovered later (see p. 49). By 28 April only a few *Patella*, *Nucella* and *Monodonta* remained. Elsewhere *Monodonta* was a conspicuously resistant mollusc, perhaps because it has a very efficient operculum and is able to close itself off from the environment, in marked contrast to *Patella* (Plate 9A). A limpet as soon as it ceases to hold its shell firmly against the rock would have all its delicate gills and the mantle edge—a large area—at once exposed to poisonous water, drawn in to its mantle cavity by ciliary activity. It is not therefore surprising that limpets are so vulnerable.The dog-whelk, *Nucella*,* has an operculum but does not seem to close it properly: despite this a few specimens were found alive on each visit, and at the end of April eggs were seen near low-water mark.

* Far more specimens of *Nucella* were found on the reef in October–November than in April–June. Apart from mature specimens their shells nearly all showed a marked groove (usually with inner teeth formation) after which new growth had clearly been added. This is unusual in normal habitats (Moore, 1936) and would seem beyond doubt to indicate that these *Nucella* had passed through a period of inactivity. They were probably washed into the depths of gullies at the time of spraying and took some weeks to recover. Similar grooved specimens were found on other detergent-treated shores.

The chiton, *Acanthochitona crinita*, was found dead and one found alive in its habitat under stones.

Among bivalve molluscs, no living specimens of the saddle oyster *Anomia ephippium* were recorded. Several living specimens of the very small species *Lasaea rubra* and *Turtonia minuta* were found among *Corallina* in the low-water region. A few of the crevice-dwelling *Hiatella striata* were also found alive, in addition to dead specimens. No mussels (*Mytilus*) were recorded from this shore. They were sporadic in their occurrence and are much more characteristic of the exposed northern coast, where they were found to be quite resistant to oil alone and to moderate doses of detergent, but not to repeated intense treatment. They can close up efficiently for hours at a time, but when open they draw large quantities of water through their mantle cavity, and thus might be sensitive to low concentrations of poison.

ECHINODERMATA. Many fragments of the starfish *Marthasterias glacialis* were found, but neither it nor the cushion-star *Asterina gibbosa*, nor the little urchin *Psammechinus miliaris*, were ever seen alive on the reef.

FISHES. The common blenny, *Blennius pholis*, the Cornish sucker-fish *Lepadogaster lepadogaster* and *Conger conger* were found dead; only one living fish was seen, on 26 April, and on 28 April what appeared to be healthy eggs of a shore fish were collected. It seemed as if the occasional active animal visited the shore.

On 8 May all mobile crustaceans were still missing (see page 71 for recolonization by them). There were a few *Actinia* and a few *Monodonta* and one or two specimens of *Patella* surviving in favoured places. Barnacles appeared to have survived well and there was some settlement of young *Balanus balanoides* taking place on clean surfaces. Such oil as was still present was in the form of a surface-hardened film.

We can see therefore that, as a result of the large amounts of detergent used on the Porthleven Reef, there had been widespread mortality of intertidal animals and plants.

As was pointed out on page 59, there is difficulty in finding evidence of dead animals, as their bodies are quickly washed away or eaten. In the case of active forms it is not easy to tell if their absence may not in fact be due to escape rather than death. The following records are therefore included here.

At Gunwalloe Fishing Cove on 2 April while there was much spraying the following dead fish were found: *Blennius gattorugine*, *B. pholis*, *Cottus* sp., *Gaidropsaurus* sp., *Zeugopterus punctatus*, *Ammodytes immaculatus*. One small lobster, starfishes and crabs were also collected.

In Porthleven harbour abundant dead sand eels, *Ammodytes*, had been seen and on Sennen beach twenty sand eels were washed up.

OTHER ROCKY AREAS

Of the shores so far studied in detail Trevone and Porthleven have shown the effects of heavy detergent treatment. Marazion had only moderate damage and graded effects were seen, and there was an area on Hogus where the oil was never treated. Some further examples will amplify the observations already recorded.

Graded effects of spraying

Graded effects could be seen in the proportion of dead and of living members of one species, and in the extent to which the more or the less resistant species had been able to persist.

The first area, Polpeor Cove, close to LIZARD POINT, is one previously well known to the investigators. By 8 May this cove had received much oil and probably a generous amount of detergent, the effect of which had seemingly spread beyond the original limits of the oil. The rocks to the immediate east of Polpeor Cove (at the Lizard itself), are partly sheltered from wave action by numerous outer reefs exposed at low tide, and before the 'Torrey Canyon' pollution the fauna and flora were very rich. The outer most accessible reefs at the point seemed relatively unaffected and the best-known reef seemed absolutely unchanged, though there was a slight film of oil in places towards high water. However, as the survey progressed round the point into Polpeor Cove the influence of the detergent became apparent. At first only the green algae and hermit crabs were missing; then all the limpets in pools and most of the top-shells disappeared, though in these tide pools the encrusting calcareous red algae and *Corallina* were alive. Closer into the cove, however, all these algae were dead and the pools were coloured white, and there were signs of mortality among the barnacles. In the cove itself, particularly on the rocks close to the old lifeboat slip, it was difficult to find a single living animal. Here even the barnacles were killed and the fucoids were dying; and the especially rich flora of the iridescent alga *Cystoseira* in the pools was very much reduced, only the bare stipes being visible, and these apparently dying.

In the vicinity of PENDEEN WATCH on the north coast there are several small coves which became badly polluted with oil. Cleaning was first carried out on the east side towards Portheras Cove, Morvah. The cleaning operations were later extended and, by the time of the final visit on 9 May, rather light spraying had been carried out over most of the area but there were still some oil-covered rocks on the east side. These rocks supported a good population of mussels and barnacles even though other animals as well as the green algae had vanished. Nearer the more heavily cleaned areas, the barnacles began to show increasing mortality until close to the sandy coves even the hardiest of the barnacles, *Chthamalus stellatus*, were dead. In such places all the red algae had been killed and even *Fucus vesiculosus* (form *evesiculosus*) appeared to be dying.

In contrast to these barren shores to the east of Pendeen, Enys Cove to the west of the lighthouse showed hardly any deleterious effects, although there were traces suggesting that a small cleansing party had used a few drums of detergent where the small stream entered the cove. In spite of cleaning operations there was still a thick film of oil at high-water springs and a thinner layer extending down to mid-tide level. Most of the limpets and all of the barnacles seemed to be completely unharmed and patches of the green *Enteromorpha* were flourishing near high-water mark. Spat of *Balanus balanoides* were settling on oil-free patches of rock and periwinkles were present.

At FISTRAL BAY, NEWQUAY, the rocks of the Headland, as well as the sandy bay as a whole, had received much treatment and by 27 April most of the red and green algae were already dead, though some plants of the red alga *Gigartina* survived on vertical faces. On flat surfaces even the fucoid algae seemed to be dying. All the limpets had been killed. More than 50 per cent of the mussels had been removed from the rocks, leaving their byssus threads behind (cf. Plate 15A). On 22 April the empty shells had been conspicuous in the adjacent beach material. More than 50 per cent of the barnacles had died, including most of the *Balanus balanoides*, and all the purple-tinged *B. perforatus* of the more shaded and sheltered gullies. The settlement of young *B. balanoides* had begun on the seaward edges of reefs cleaned earlier. A few damaged anemones (*Actinia*) were still holding on.

On the south coast at POLDHU COVE there was still oil on the rocks on 7 April, though detergent had been used. The rocks on the north side of the bay showed a fairly good fauna, with limpets and anemones surviving in spite of a coating of oil, but the reefs on the south side were virtually denuded of animals. The oil fall and therefore the detergent treatment had probably been heavier on this side of the bay, while the direction of outflow of the tide and therefore of detergent drift may have affected this side more. The situation with regard to the organisms was relatively unchanged on 27 April. A similar state of affairs was seen at MULLION. It is thus seen that, although some areas were virtually stripped of living organisms, yet there are nearby regions which were relatively unaffected.

KYNANCE COVE suffered fairly heavy pollution during the first few days, and when examined on 20–22 April still showed much oil present on the rocks and in the sand (Plate 1C). Rocks at the centre and eastern end of the cove had been heavily sprayed and further spraying was carried out well into May. On the large central reef all of the limpets and most of the mussels had been killed. Barnacles (mainly *Chthamalus stellatus*) showed nearly 100 per cent mortality and even many of the *Balanus perforatus* near low water were killed. The few snakelocks anemones (*Anemonia sulcata*) seen were in poor condition and none at all were seen on subsequent visits. Only a few beadlet anemones (*Actinia equina*) survived on this reef, some of them in the depths of pools. In some pools the encrusting calcareous algae were killed, in others they survived. The *Corallina* had turned white and later disintegrated, and other algae were also lost; thus the denuded pools offered no cover for small active forms such as young fish and prawns, which would usually hide in these pools as the tide recedes. Some of the *Pelvetia* and *Fucus vesiculosus* (form *evesiculosus*) were a rusty brown colour, with fronds disintegrating (cf. Plate 15c). Some seem eventually to have died, others recovered. Not all these mortalities were observed until a later visit on 25 May.

In contrast to the heavily sprayed central and eastern reefs, on rocks to the north and west of the cove much of the flora and fauna remained untouched, though the rocks were still oily in places on the April visit. However, some 10 per cent of the mussels were gaping and probably dead.

Near St Agnes are two coves—Trevallis, which was heavily polluted and received intensive treatment, and Trevaunance, which had less oil, but where, owing to the private owner being averse to the use of detergent, the cove was at first not treated, and the common rocky fauna was reported to have survived well. Detergent was eventually used at Trevaunance, sparingly and with care, with little resulting damage to life. (For conditions later in the season see page 73)

Effects of oil without detergent

It had been amply demonstrated that treatment by detergent causes high mortality. It was therefore very interesting to try to observe what happened in the short term and in the long term if oil pollution were left untreated. In only a few sites was this possible because of the immense amount of detergent used even in remote places. However, in the first few days of pollution places were visited where oil was still untouched from the land.

The account by Richardson & O'Sullivan (1967) in which they compare the effects of pollution at Porthgwarra and Sennen before and after treatment was certainly borne out by our findings. The oil alone rarely seemed to have any ill effects during the first few days. At Cape Cornwall, however, moribund limpets under oil were observed; it is possible that they had been smothered very thickly with oil, or that the oil which

PLATE 13

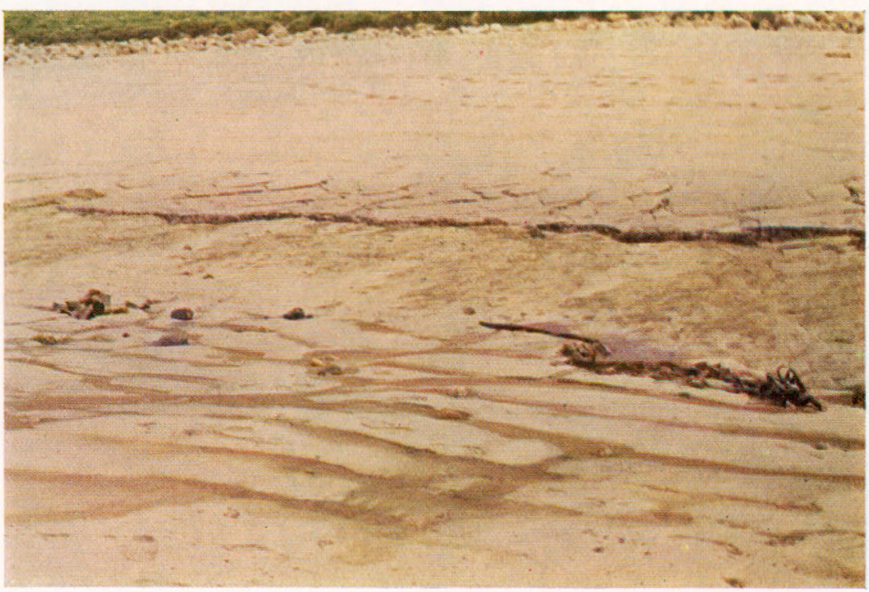
A

B

PLATE 14

A

B



b

a

c

C

(*Facing p.* 65)

enveloped them contained detergent sprayed at sea and retained in more than usual quantity. The volatile and more poisonous fraction of detergent sprayed at sea would probably usually have evaporated away, and the observations already quoted are in keeping with the opinion that oil alone as it arrived on the shore was not harmful. This is not to say that crude oil, before it has lost its own volatile and acrid-smelling fractions, would not be toxic. A very thick layer would interfere with respiration and spoil normal food supplies for browsing animals. On sloping rock surfaces the oil deposit was usually not more than about 1 cm thick and soon became thinner. So far as limpets are concerned, they are unable to remain closed off from their environment for very long: the adductor muscles relax occasionally, thus lifting the shell very slightly. The viscous oil would not readily be drawn in under the edge of the shell by the ciliary currents in the mantle cavity, whereas detergent, alone or diluted in sea water, would creep in much more readily and be liable to kill the limpet. That this type of oil alone is not toxic to limpets is seen by the fact that they ingest it and pass it through their guts. This had already been noted with limpets from Hogus Reef, Marazion (p. 49), where the persistence of the full population into at least July is clear proof of the harmless nature of the oil to them. Evidence of limpets eating oil was seen also at Godrevy, Trevone (see Plate 9C) and elsewhere. That they could derive any food value from the oil seems unlikely.

The survival of mussels under heavy oil was seen at BOOBY'S BAY, in the first few days of pollution. On many occasions it was noted that oil remained among small mussel shells on rocks from which it had obviously been present more generally and had been washed off. In the absence of heavy detergent treatment these mussels had survived. At PORTREATH, in

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PLATE 13

A, Whitesand Bay, Sennen, 28 March. Heavy oiling on boulders in the high-water region shortly after the initial deposition. Oily sand seen beyond. **B**, Whitesand Bay, north of Sennen, 20 April. Oil-laden breakers in the foreground depositing oil on the shore to form characteristic wave marks. Note the contrast in the colour of the oily breaker with those behind. The mass of oil already treated at least once is being carried back on the shore by the rising tide.

PLATE 14

A, Sennen, 28 March. Viscous oil emulsion settled between boulders in the upper part of the shore. **B**, Booby's Bay, Constantine, 29 March. Newly settled oil–emulsion dripping over rocks in the high-water region. Soldiers are seen in the background manhandling a detergent drum in readiness to start cleaning operations. **C**, Oil-impregnated sand exposed along the upper shore at Sennen Cove on 23 August. A layer of sand impregnated with thick brown oil to a depth of about 15 cm is shown (*a*); this layer probably represents the beach level at the time of the oil deposition in late March. Subsequent to the deposition of oil, sand has accumulated on the upper shore covering the oiled sand and boulders (*b*). Water draining from this sand above the impermeable oil layer is removing oil and redepositing it below as a thin layer on the sand surface (*c*).

pools which had a film of oil, mussels were found alive and behaving normally, even though the mantle cavity contained globules of oil.

It was difficult to find areas on which oil had been left untreated. Up to 10 May no detergent appeared to have been used at GODREVY POINT itself. Most of the oil was in the form of a partly dried black surface layer about 2 mm thick coating the sides of gullies from extreme high water to mid-tide. Beneath the surface layer the oil was still brown and semi-liquid, and care had to be taken when walking on it. Below mid-tide the oil film was much thinner and light brown in colour. It appeared to be eroding away, the erosion being helped by feeding activities of the limpets, the tooth marks of which could be clearly seen in places (Plate 9C).

As far as could be seen, the main deleterious effect of the oil on the fauna was physical rather than chemical. Where the layer was thick enough barnacles had been smothered, but more than 90 per cent of them had managed to clear an opening in the oil film. These were found to be in good condition when examined in the laboratory, and the gut did not appear to contain any oil. There were a few deaths among the *Balanus balanoides*, but *Chthamalus stellatus* seemed to be unaffected. Monterosso (1930) has shown that the latter is capable of surviving two months anaerobiosis under a film of petroleum jelly, and its survival in the present circumstances is not therefore surprising (Plate 19B). Some mortality had occurred among the limpets on one vertical rock-face that had received heavy contamination by oil, but otherwise there were no obvious differences in the fauna and flora of oily rocks and adjacent uncontaminated surfaces.

It was known that at BEDRUTHAN, although much oil had entered the cove, relatively little had been stranded. Two patches had been photographed from the cliff top on 15 April. No detergent was used in the cove, which is difficult of access. It was interesting to see what had happened on these rocks after several months, and on 11 August they were examined from the shore. The patches of rocks which had been oiled were still recognizable, but the oil was much reduced, probably chiefly by sand abrasion, though the activities of limpets had undoubtedly played a part. On this very exposed shore they were practically the only browsers. A few *Littorina saxatilis* were also present. Rocks on which there was still a nearly complete cover of oil (with sand embedded in it) were seen to have no limpets (Plate 18B). Rocks which were nearly clean had several limpets on them, there being markedly cleaner areas near the limpets and immediately round them (Plate 17B). Most of the limpet shells had some traces of oil on them, but the contrast of still-oily limpets on clean rocks was not as marked here as it had been on Hogus, probably because of the greater importance of physical abrasion in this sandy exposed habitat.

These examples of cleansing of oil-polluted rocky shores without the use of detergent strongly support the observations by George (1961) in Milford Haven. It is a great pity that more areas were not left to be cleansed by natural agencies, not only because much time, trouble, money and shore life would have been saved, but also because such areas would have provided better 'control areas' to contrast with sites lethally sprayed and cleansed. Moderately polluted areas and remote and inaccessible stretches of shoreline could well have been left untreated, as in fact were the coves below precipitous cliffs on National Trust property between Navax Point (near Godrevy) and Portreath.

Between PORTHTOWAN and St Agnes Head lies another stretch of coast which received appreciable oil, but where detergent spraying was strictly localized and applied with care. This also lies on National Trust land. In Chapel Porth Cove the oil was reported as up to 2 inches thick on 29 March. There would have been rather less on adjacent rocks along the open stretches which were left unsprayed. In early September barnacles and limpets were surviving on the oil-blackened rocks near high water, but very little oil was left at lower levels. The fauna in the cove itself had suffered, as indicated by the absence of limpets, and the rocks were still a little oily. To the south of Chapel Porth the boundary between the unsprayed National Trust land and the detergent-treated shore adjacent to Porthtowan was clearly marked. In July and August the boundary was shown by a change from rocks having normal fauna and flora to unusually green rocks where *Enteromorpha* had developed prodigiously in the absence of browsers (see page 71).

The effects of very heavy oil-cover left untreated by detergent can perhaps better be studied on polluted parts of the Brittany coast (p. 168).

SUMMARY OF EFFECTS OF HEAVY DETERGENT TREATMENT

This summary is based on the numerous sites visited by several observers from Plymouth. Where spraying had taken place, the beaches or coves were usually identifiable at a distance by the numerous empty brightly coloured drums, or, if these had been removed, by patches of dead grass killed by spilt detergent, the smell of which persisted for months, quite apart from the smell persisting in the sands for at least three months. Evidence of deaths of animals in sandy shores is not readily obtained, the macrofauna always being very scarce in typical clean sands. On rocky shores the effect could be assessed over wide areas by simple inspection, so the following account applies chiefly to the latter.

Even if the shores had not been known previously, the ecologists visiting them had a knowledge of what might reasonably be expected to be present. Where detergent had been used in any quantity the evidences of mortality could clearly be recognized and these signs were repeated all round the coast. The loss of limpets was at once obvious because of the many empty limpet seats, or 'scars', conspicuous in pools and detectable elsewhere (Plates 9A, 12B, 18A). Dead barnacle shells persisted for some time (Plate 19A), and, although it is usual to find a small number of dead and empty shells at times, a mortality of 50 per cent or more was clearly due to an unusual cause. Mussel shells gaped when dead. The rotting flesh did not take long to disappear, but, even when the shells had broken away, clumps of short straw-coloured byssus threads persisted for a few weeks, showing where mussels had died (Plate 15A). The absence of living winkles, top-shells and dog-whelks and the presence of many fresh shells of these and other species (Plate 15B) indicated the fate of such animals as have persistent hard parts. The absence of living crabs, shrimps, etc., and shore fishes might have been due in part to their quitting affected areas, but if killed their bodies would soon have been eaten by scavenging shore birds. Gulls were indeed seen feeding on dead limpets, even in water discoloured by detergent. In the early days of the disaster the presence of bleached weeds, particularly *Enteromorpha*, *Porphyra* and *Corallina*, and of discoloured wracks (fucoids), were sure signs of damage (Plates 15C, 18A). Later in the season an abnormal growth of the green weeds, developed in the absence of the normal browsing gastropods (Plate 16B), was seen on numerous polluted shores, but this evidence had to be examined carefully as it had in fact been an unusually good season in most localities for the growth of *Enteromorpha*. This greenness will probably not be a persistent feature, though the signs are that other algae will become unusually abundant before the browsing animals can recolonize the areas denuded of them (see Southward, 1964).

SUMMARY OF REASONS FOR SURVIVAL FROM DETERGENT POISONING

The occurrence of unharmed patches of shoreline with a full complement of species may be attributed to good fortune of geographical position. One side of a bay or even of a more localized rock formation often escaped both the oil and the subsequent effects of spraying. The drift of detergent from the upper part of a beach often affected one side of a cove and not the other because of the direction of tidal currents. The low-tide zone usually received no direct detergent treatment, and the mixtures which ran seawards while the tide was low were often channelled in gullies.

In moderately treated areas, differences of micro-habitat could be very important. The fauna on the undersurface of overhanging rocks quite often escaped, as did also some animals living in narrow crevices. In pools, the oil, detergent and fresh water all tended to stay on the surface, so that plants and animals in the depths of a pool stood a better chance of surviving. Animals, such as worms, burrowing in the depths of a fairly firm deposit (for example Marazion, area *D*) were probably below the level of influence of the poison.

The normal exigencies of shore life are such that only resistant species have been selected to live intertidally. Their adaptations often help, too, in their survival in poisonous water. The contrast between intertidal and sublittoral animals will later be apparent (Chapter 6). Animals which can close themselves off from their environment within resistant shells are at a great advantage, for example barnacles, mussels, and gastropods with well-fitting opercula. Limpets are at a disadvantage where poisonous water is involved, being dependent on maintaining a close adhesion to the rock during their period of exposure to the air. The beadlet anemone is normally able to survive long exposure to air, perhaps because of its mucoid cover: it was also a remarkably resistant animal to the unusual conditions of poisoned water. Some animals appear to be physiologically resistant; for example, the polychaete and oligochaete worms, despite their relatively unprotected bodies, were found to survive quite well. Such evidence as we possess suggests that nematodes also survived well, as would be expected from their known capacity to survive under difficult conditions.

This subject is discussed also on page 135 in relation to laboratory toxicity tests (Chapter 7) and with regard to sublittoral fauna (Chapter 6).

RECOVERY AND RECOLONIZATION

In most localities the existence of areas and pockets of surviving plants and animals gives hope of an eventual and perhaps an early recolonization and return to normal. How long this will be cannot be predicted, as natural balances have been upset even where there has not been complete destruction of life. These unharmed areas provide local sources for the spores of algae. Larvae of many shore animals often spend some weeks, if not months, in the plankton, in which case there is no question of immediate local recolonization. For mobile shore animals, such as fishes and crabs, and even for wandering gastropods, these local patches are important.

Where oil was left on rocks its fate was part of the recovery of the habitat. The very thin oily film which had often remained after cleansing was neither so persistent nor so continuous as to prevent some settlement of alage and barnacles by the end of April. Brown oil films between tide-marks on rocks and boulders were still occasionally present here and there after several months. They had either been missed by detergent or secondarily redeposited. The oil underwent a gradual change, developing a hardened skin, and the film decreased in thickness. Though dark on the surface it remained, for a time, light-coloured and fluid below, and it often had sand embedded in it. The decrease in quantity seemed to be due in part to some erosion by wave action, assisted by sand abrasion, and perhaps in part by evaporation, not to mention the action of browsing animals where these had survived. In the splash zone there was also a decrease in the blackened oil, so that by mid-summer it had become inconspicuous, looking not unlike the black lichen *Verrucaria*. This oil, too, was weathering away and the tiny winkles of this zone, *Littorina neritoides*, including (in August) some recently settled (under 2 mm), were found living on and among the black oil patches (see also page 72).

Flora

On the main part of the shore the algae will be considered first, because in addition to their own intrinsic interest they form an essential part of the habitat for the fauna, supplying cover and direct or indirect food supply for many animals. Most of the fucoids were not completely killed, commonly sprouting irregularly from distal parts. Thus in areas only moderately affected no great overall change was apparent.

On a completely denuded reef at SENNEN, where there had been repeated cleansings late into the summer, a very few fucoids were beginning to sprout in lateral clusters of tiny blades from the stipe. *Ascophyllum* was in a somewhat better condition, thus confirming a difference apparent elsewhere earlier in the season. Other reefs at Sennen, treated only lightly at an early stage were in marked contrast to this barren reef; on them recovery had brought the larger fucoid algae back to normal by mid-summer.

Where damage was more severe a distinction has to be made between recovery, often from basal parts very closely applied to or actually in the rock and recolonization by sporelings. An example taken from MAWGAN PORTH is typical of rocks in the mid-tide zone at many other places. Rocks which had lost their cover of *Porphyra* and *Enteromorpha* during April by mid-May had occasional strap-shaped fronds of the former, up to 6 inches long. These must have regenerated from basal parts of the *Porphyra* phase or from the filamentous 'concocelis' phase on the rocks. By mid-August these regenerated plants were common and well grown but darkly pigmented and reproductively immature. Besides the *Porphyra* there had developed a very thick coating of *Enteromorpha*, from growth already started by mid-May. This was one of the many places where there had been heavy loss of the browsing fauna with consequent rich development of the sporelings of green algae. A remarkable greenness was seen also, for example, at Porthleven, Cape Cornwall and Trevone. *Enteromorpha* and *Ulva* normally reproduce by frequent cyclical production of spores and they are prone to show very good growth in fine calm spells, so that reports of unusual greenness on the shores must be interpreted with care. Near Porthtowan a stretch of rocky coast which had been sprayed with detergent was markedly green in contrast to an adjacent unsprayed stretch with normal fauna and few green algae. As *Enteromorpha* dies soon after sporing and is soon reduced by storms the unusual greenness will not persist indefinitely. Sporeling fucoids (up to 3 cm) were becoming dominant in some affected areas (e.g. Trevone) by early September. The disturbance of balance, because of the lack of browsing fauna, may take a few years to redress. Elsewhere oil-spills have eliminated browsers and resulted in the abundant growth of the larger more persistent algae—for example, on the Californian coast (North, Neushul & Clendenning, 1965).

The recovery of algae in pools was very variable according to the degree of pollution. In mild cases there were early signs of recovery of calcareous encrusting algae, while it seems that *Corallina*, which grows relatively slowly, will take much longer to recover. Sporelings of *Ectocarpus* (a filamentous brown alga) were sometimes much in evidence, especially in the absence of browsers. The redevelopment of algae within tide-pools will be of importance to the life of the pools as a whole.

Fauna

There was evidence that some animals that suffered partial damage by detergent recovered in the field (gastropods on Hogus, p. 49, *Nucella*, p. 60). If there has been any cumulative poisoning to living animals it is not a phenomenon which could have been studied in the field in this present survey.

We have attempted to detect both the re-invasion of a denuded habitat by active adult animals and the recolonization by young stages—often, but not necessarily, of sedentary forms.

First there are the active swimmers, which may normally come and go with the tides. By 23 June some swimming crabs (*Portunus puber*) and shore fishes (*Blennius pholis*) had returned to Porthleven reef. Small fishes and active crustaceans need to have algal cover before they are likely to return. They were noticeably absent at Kynance from bare pools in July, while elsewhere (Trevone and Cape Cornwall) they were seen in August in pools previously barren and now surrounded by green algae. Animals which by their own efforts could crawl a short distance might also be washed from undamaged areas on to previously denuded patches, where grazing forms would find a new growth of algae. The more resistant gastropods (*Nucella*, *Gibbula*, *Ocenebra*, *Monodonta* and *Littorina*) had become more frequent again as early as 23 June on the reef at Porthleven. Some juvenile winkles (*Littorina littorea*) were found in pools at Kynance on 23 July from which they were certainly absent on 20 May, but these species had by no means regained their former abundance. Both at Porthleven and Mawgan Porth, a few limpets had apparently wandered a short distance into unoccupied territory.

The recolonization by a new generation is dependent on the presence of a suitably oil-free and unoccupied area of substratum, and on the availability of the larvae. So far no newly settled limpets have been seen, but their main time for settlement is in the early months of the year and therefore no recolonization is expected before 1968. Other shore species often have larvae in the plankton in the spring and summer months, and of these species newly settled *Littorina saxatilis* and *L. neritoides* have been found. Many recently metamorphosed crabs were seen in 23 June at Porthleven, and larger ones at Sennen and Cape Cornwall in August.

Special attention has been given to the settlement of barnacle spat, since its abundance can be compared with what we know from previous years (Southward, 1967). It is clear that in general the larvae were not killed by the concentrations of detergent that they encountered at sea (see p. 93 and experiments on toxicity in Chapter 7). Moreover, it is probable that the planktonic larvae had either been liberated into the sea before pollution occurred, or else had come from adjacent unpolluted areas. Any differences from previous years could well be accounted for by difference in the direction of winds between the time of liberation of nauplii (first-stage larvae) and of settlement. In Cornwall, the settlement of *Balanus balanoides* occurs once a year in April and sometimes early in May. Along the south coast, in Mount's Bay in particular, including Porthleven, it settled more heavily than in previous years, occurring equally well in localities which had suffered pollution and those which had escaped. Along the north coast, settlement was not quite so heavy this year. The larvae require an oil-free surface on which to settle. Some were found on the seaward end of reefs which had been cleaned, for example, at Fistral Bay, Newquay, at Trevone, and at Enys Cove, near Pendeen. Where groups were seen occupying empty limpet seats it was a sure sign that they had settled in an area which had at some stage been affected by detergent. At Mawgan Porth they were found developing well on 14 May, being especially numerous on an uncontaminated area, whereas at Watergate none were seen in suitable situations, but here cleaning had been delayed until nearly the end of April. For this species as a whole the pollution does not seem to have had any serious effect.

On 11 August a recent settlement of another species of barnacle, *Chthamalus stellatus*, was seen at Trevaunance in the mid-tide zone. Rocks at the same tidal level in the adjacent cove at Trevallis (where there had been heavy spraying) were smothered in green algae. In this part of the barnacles' tidal range its sites were therefore pre-occupied, but this may be only a very slight local effect as the species also settles abundantly higher on the shore later in the season.

SUMMARY AND CONCLUSIONS ON ROCKY SHORES

The lethal effects on the flora and fauna of heavy detergent treatment have been summarized above on page 67. Their seriousness for shore life is beyond dispute. Some of the reasons for escape or survival are set out on page 68. While in some places shore life escaped completely and serious damage was localized, yet the effects of detergent spread well beyond the extent of the original oil pollution. The second, man-applied pollutant was far more damaging than the accidental one. Recovery and recolonization is in progress but it may take some years before the normal balance of the population and the intricacies of the food chains are restored.

It has been seen that prolonged and repeated treatments do much harm even in a short space of time, and, while a region can recover gradually from one such onslaught, chronic oil pollution followed by repeated detergent treatment must do permanent damage. If large-scale and indiscriminate use of detergent were ever permitted as a standard method of treatment of oil-falls, shore life on one part of the coast after another could be disrupted and recovery would be far more prolonged and difficult. The risk of the loss of rare species and of species at the northern or southern limit of their geographical range would also be much greater.

We still do not know if there may be any long-term cumulative effects from the detergent persisting in the sands (see page 80).

Our survey shows that this type of *oil alone* has done little harm to shore life, and if the oil is left untouched there is clear evidence that browsing gastropods such as limpets and top-shells may remove and ingest oil without ill effects to themselves. The relative importance of the browsing fauna compared with physical agencies such as wave and sand abrasion, as well as evaporation, will depend on the locality and the tidal level. But left to themselves these physical and biological agencies have been able to effect the complete removal of moderate oil pollution in some places in three to four months. Above the tide level aerial weathering is the chief agent on rocks. In other places the covering growth of salt-marsh plants (see page 89) has been remarkably effective in rendering the untreated oil innocuous and inconspicuous by the end of the summer.

The use of detergent should be considered only on shores of high recreational value, and then only after mechanical removal of as much oil as possible has been attempted (see page 90). It should be used in limited amounts and with care. The time of application relative to the tide and wind is of importance both for the efficacy of the detergent in making emulsions and for minimizing damage to shore life. The problem would of course be simplified if non-toxic detergents could be developed for general use. On other shores much greater advantage should be taken of natural cleansing.

CHAPTER 5

SHORE SURVEYS—SANDY SHORES AND ESTUARIES

SANDY SHORES

On sandy bays the oil arrived at first in drifts of generally half an inch up to a few inches thick in the high-water zone, often localized on one side of the beach. Some sank into the sand, making layers like sticky coffee grounds, and as such it was not difficult to scoop up (see page 170). This treatment was applied in a few places, the sand being dumped inland. For example, at MAWGAN PORTH some was put on marshy hinterland whence any eventual slow exudation would ultimately reach the sea, but where decomposition of the concentrated buried oil will be extremely slow. At TREVAUNANCE the owner of the mineral rights shovelled it up, putting it in an old mineshaft near the sea, where there is presumably no risk of contaminating springs and inland water supplies.

By far the more usual method was to push the oil back into the sea, by hosing or by using earth-moving equipment (Plate 4B). Deep furrows were made and the oil mixed with detergent was hosed down the shore. Alternatively, sand was shifted to near low water or into a stream where it was sprayed or otherwise mixed with detergent. This resulted in some oil being carried away to the sea as a dirty emulsion, especially if there was an offshore wind, but it also spread unemulsified oil and detergent in various degrees of dilution and depth over the sands of the whole beach. In some places temporary quicksands were produced.

Wave action frequently buried untreated brown oily layers a few inches or even feet below the surface by depositing clean sand on top. There is a normal seasonal accumulation of sand at the top of beaches during the summer. This accumulation of clean sand helped greatly to give a 'cleansed' appearance to the shores. Offshore, water turbulence would occasionally mix oil and sand together so that the oil would be weighed down and has been seen resting on the bottom by divers (Plate 6C).

This movement of sand was clearly seen at SENNEN, where the whole of the boulder zone along the beach of Whitesand Bay had been exposed when the very heavy pollution of oil was deposited over the entire shore at the end of March (Plate 13A). By mid-summer sand had covered a great many of these boulders, but in July and August it was beginning to be eroded away and sticky oily layers were again appearing (Plate 14C).

This buried oil presented a considerable problem to the cleansers. Up to 24 April alone 164000 gallons of detergent had been used at Sennen and activities were continued at intervals during the early part of the summer as more oil drained out from among the boulders or otherwise reappeared.

The wisdom of the use of detergents on sandy beaches had been called in question, so, in addition to field observations, various laboratory experiments were set up to investigate the physical effects of oil and detergent in sands.

SOME PHYSICAL PROPERTIES OF SANDS CONTAINING OIL AND DETERGENT

Various experiments were devoted to the situation that might develop when oil, oil–detergent emulsions, and detergents themselves were in contact with sand.

The effect of oil alone on a sandy beach was examined by adding 5 ml Kuwait crude oil to the top of sand held in a glass column 3·75 cm in diameter. The sand was obtained from the shore at Duckpool (North Devon), an area free from the present oil pollution. The column was open at the top and the bottom, and was plugged with glass wool to prevent the sand flowing out. Tidal cycles were then simulated by mechanically raising and lowering the column in and out of sea water within a large measuring cylinder, the cycle time being 22 minutes. At the end of some 40 cycles, the oil had penetrated the top 3 cm of sand, but had not become further dispersed. Further cycling did not lead to more dispersion of the oil, and it seems likely that on the shore, in the absence of wave action, oil will not penetrate deep into sand and could therefore best be removed by mechanical means (see page 170; Plate 28C). A similar experiment was set up, with the addition of 2 ml of BP 1002, and in this case the oil–detergent emulsion spread throughout the column in a short time. On beaches treated with detergent, oil has been found dispersed through a considerable depth of sand (see page 81).

The effect of detergent alone on a beach sand was also examined. Simple experiments were carried out in which weighed amounts of sand were shaken up with solutions of detergent in sea water, and then allowed to settle. A significant amount of the solvent was adsorbed on to sand, whereas less surfactant was adsorbed.

Other experiments, where detergent was added to watch-glasses with and without sand and the rate of evaporation followed by weighing at intervals (Fig. 13), showed that the rate of evaporation was less in the presence of sand, a result which again indicates adsorption by the sand grains.

It seemed probable from these results that retention of the solvent by adsorption on to the sand particles would prolong the period during which the sand would be toxic to organisms living in it. Moreover, the adsorbed solvent is not readily washed out from sand, as the following experiment shows: 100 g of sand were placed in a 500 ml flask and 1 ml of detergent added before the flask was filled with sea water and shaken; repeated washing of the sand by fresh sea water was carried out at intervals and, after

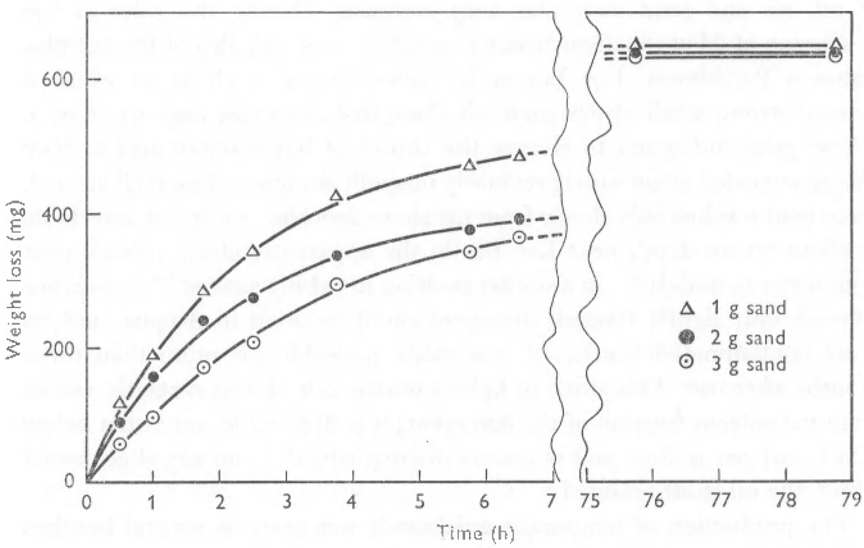

Fig. 13. Rate of loss of solvent from open watch-glasses containing different weights of sand.

nine changes over seven days, 10 ppm of solvent was still present in the supernatant water while, after eleven changes, 4 ppm was present. Such experiments indicate that a number of tidal cycles and frequent flushing would be required to remove the solvent from beaches where the sand has been impregnated by detergent.

In another experiment sand 'castles' were made from uncontaminated sand soaked in detergent solutions of various strengths and all equally well drained. The experiment showed that the cohesiveness of the sand was markedly reduced by detergent even at 10 ppm concentration, presumably by alteration of the surface tension of the interstitial water. To this lack of cohesion may be added the flotation of oil-covered sand grains to which air is readily attached. Together they could give rise to enhanced mobility of sand under wave action. This is a fortunate feature in that more oil and detergent would be washed out of the sand than if the physical properties had not been affected. Large movements of sand both up and down the shore have been noted, but whether or not these were abnormal is impossible to say without reliable long-term knowledge of the particular shores.

Some other field observations are especially relevant here. After the dispersal of detergent and oil through the sands quite unusual amounts of floating sand grains were noticed (similar to the little raft of sand grains seen in quiet corners soon after the turn of the tide) (see Plate 21 A). Scums of oil, air and sand were also very common. During the gales at the beginning of May the disturbance of sandy shores and also of the pebbles between Porthleven, Loe Bar and Gunwalloe was such as to cause a general strong smell of detergent all along that coast (see page 94 *et seq.*). These gales did much to cleanse the shores of both contaminants; they also redeposited oil on some previously unspoilt stretches of sand (Plate 3 B). Detergent was lost only slowly from the shore deposits: it was just detectable at about 30 cm depth near Loe Bar in the apparently clean pebbles near high water in mid-July; in a similar position in pebbly sand at Trevaunance (though only lightly treated) detergent could be smelt in August, and on more contaminated beaches it was easily traceable for more than three months after use. This smell of light aromatic oils almost certainly comes from the solvent fraction of the detergent; it is detectable somewhat below a half part per million and is readily distinguishable from any slight smell which the oil itself retained.

The production of temporary quicksands was seen on several beaches and was very pronounced at Porthmeor Beach, St Ives (see below). In Brittany quicksands were produced by oil alone.

The physical properties of sand deposits and some of their effects on the fauna have been studied by Chapman (1949). So far in our study only the purely physical effects of the use of detergent on sand have been considered, but there may be indirect biological effects in addition to the direct toxic effects on organisms living in the sand.

Oil content of sand

Rough estimates of the oil content of samples of oiled sand collected at various sites were made by weighing the sample, removing moisture by keeping at 37 °C until constant weight was attained, and removing oil by successive washing with solvents (petroleum ether and cyclohexanol). Very oily sand from Sennen contained 17 per cent by weight of water and 11 per cent by weight of oil; less heavily polluted sand from Porthmeor, St Ives, 8 per cent of water and 2–4 per cent of oil. Sand containing only 0·5 per cent oil was collected from an area where a quicksand had formed around rocks at Porthmeor. In general, where there is more than 2 per cent of oil by weight of sand, the sand appears very heavily oiled, and oil can be squeezed out. The sand above high water at Sennen contained 0·6 per cent of oil (13 June). It felt oily and discoloured the hand, as did the sand collected earlier from Porthmeor. The lowest oil content was found in the surface layers at low water at Perranuthnoe (0·1 per cent). Oil present in similar small amounts in sands at low water was seen on digging pits in several beaches, where oil globules and an iridescent surface to the water-table were often observed. Similar traces of oil were present well into the autumn.

FURTHER OBSERVATIONS ON SANDY SHORES

An intensive study of a particular beach could have given useful information, but, because of shifting and mixing of sands under natural shore conditions, reliable quantitative work would have been difficult. It was not undertaken in the early stages of the survey partly because of lack of time and partly because of the distance of these shores from the Plymouth Laboratory. To make such a programme worth while some control over spraying activities would also have been desirable. As these factors were lacking, data collected from various beaches give an idea of the influence

Table 8. *Improvement in sand conditions at Mawgan Porth*

Date	Oil in sand (% oil/dry wt. sand)	Condition of water-table	Detergent
22 April	Brown layers and bands left after oily sand removed (on other shores 1–5% oil in similar layers)	In area of quicksand and pools, oil floating on white detergent solution	Very strong smell in quicksand
14 May	Grey layers in above areas. Oily to touch. One sample 0·42% oil	Iridescence in all parts, some blobs of oil on water collecting in pits. Quicksand area still 'soft'	General smell, chiefly subsurface
11 June	Vague greyness in above areas could be due to mixing or addition of sand. No widespread grey layer down to 30 cm	Iridescence general but less marked in pits. Quicksand area recovered	General, below surface, less marked than earlier
11 August	Grey layers at 20–40 cm over practically whole beach, surface in wide deep ripples, stability during calm spell. One sample 0·67% oil	Ripple pools in firm sand with traces of oil on floating sand	Faint smell subsurface, not confined to grey layer

Eurydice: several seen near low water 14 May; general over whole beach 11 August.

of treatment of sands over a period of time. MAWGAN PORTH is given as an example of the use of various methods and their effects on a moderately polluted sandy shore. For details see key to map (Fig. 14).

Observations at MAWGAN PORTH were confirmed by some at WATERGATE, which had received repeated oil-falls and prolonged treatment, spraying and bulldozing of sand to low water. There was relatively more oil and detergent in the water-table in May and June, and no grey sand was seen in subsurface layers in some thirty pits on 14 May. The impression was that recovery was taking place but not so rapidly as at Mawgan Porth. The temporary quicksands gradually recovered. At ST IVES, PORTHMEOR BEACH had been heavily coated with oil from top to bottom (Plate 8B). From 28 March an enormous amount of detergent was used right through April into May, resulting in a temporary quicksand, and an immense amount of sand had been shifted mechanically. The beach was in full use by holiday-makers during the summer and only very slight traces of oil could be found by mid-August, but gales early in September disturbed much buried oil and the beach was again closed while oily sand was carted away. The very heavy pollution and prolonged cleaning at SENNEN and WHITESAND BAY has been mentioned above. In July and August there were widespread subsurface layers, often smelling distinctly of hydrogen sulphide, as well as brown oiliness in places, and oil was being redeposited on the surfaces of boulders, running out on to the sands (Plate 14C) or washing back as oily rims at wave edges. Despite this the beach was being used by holiday-makers.

At PERRANUTHNOE there is a long sandy stretch below low clay cliffs with flanking rocks. It was heavily polluted with oil: 34700 gallons of detergent

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PLATE 15

A, Trevone, 14 May. Byssal threads of mussels destroyed by direct spraying of detergent. Barnacles, *Chthamalus stellatus*, have also been killed. Some weeks later this rock was thickly covered with *Enteromorpha*, similar to the condition seen on Plate 16B. **B**, Trevone, 23 April. A few days after spraying with detergent dead and dying dog-whelks (*Nucella lapillus*), top-shells (*Gibbula umbilicalis*) and limpets (*Patella*) found in a rock corner near the sewer outfall. **C**, Trevone, 23 April. Damaged algae after spraying with detergent. Species of *Fucus* have been reddened and subsequently little but the midribs of the fronds survived. The coralline weed *Corallina officinalis* and the encrusting coralline *Lithothamnion* sp. have been killed and bleached.

PLATE 16

A, Sewer rocks, Trevone, summer 1955. Normal appearance in the summer with brown fucoids, limpets and top-shells, etc. **B**, Sewer rocks, Trevone, 9 July 1967. Intensive growths of *Enteromorpha*, *Ulva* and some *Porphyra* (at highest levels) on the rocks and mussels, consequent upon destruction of most limpets and top-shells (see also Plate 15B). A few limpets and top-shells survived and the occasional clean patches of rocks are mainly due to their grazing activities (see Plate 17A). (N.B. These rocks were most probably not actually sprayed with detergent. They were affected by detergent washed over them from spraying nearby. This diluted detergent killed limpets and top-shells but the mussels survived.)

PLATE 15

A

B

C

(*Facing p.* 80)

PLATE 16

A

B

were used up to 18 April, and a further 2555 gallons before 10 May, but by 20 May spraying had stopped completely. On 28 April there was a widespread thin layer of oil on the sands and in the water-table. Between this visit and one on 10 May the strong south-west gales had carried away much sand from the top of the beach, exposing previously buried rocks. It is not known if this would have been a normal occurrence after such a gale at this time of year or if it might more probably be associated with abnormal mobility of the sands due to detergent treatment. Much torn weed was heaped up and also deeply mixed in the sand. Sand cores were taken and pits dug along a transect from high- to low-water marks to examine the fauna (see page 86 and Plate 21 B). The water-table contained floating oil at all levels down the beach; thin iridescent layers of oil often with thicker brown blobs collected in the pits. There were also discontinuous patches of thicker oil below clean sand. No grey sand layers were seen on 10 May a week after the gales, and there was no sulphide layer down to a depth of 60 cm. Near the base of the cliffs the sand was saturated with detergent. On later visits to Perranuthnoe grey oily layers were found, indicating that here as elsewhere decomposition of the oil was progressing. On 8 August the water-table still contained oil blobs on an iridescent layer, but the sulphide layer was now at around 40–50 cm below the surface. It seemed to be less oily, and less conspicuous except near low water.

BIOLOGICAL DEGRADATION

When the grey layers in the sandy shores were first found it was strongly suspected that biological degradation had been proceeding, both of the oil and of the detergent. Evidence for this important microbiological activity was sought and is given below.

Specialized bacteriological work was not carried out at Plymouth in the present survey as there was no member of the staff qualified to undertake such work. We are therefore grateful to experienced workers from other laboratories for their co-operation.

Dr W. Gunkel, of the Biologische Anstalt Helgoland, kindly permits us to give a brief account of his yet unpublished results. He collected twenty-three samples from different places on Cornish beaches towards the end of May and examined them at once for their bacterial content. In most sand samples there was obvious oil present and a smell of detergent (the exact amounts in the samples have not yet been determined). The numbers of aerobic oil-decomposing bacteria were determined using a dilution method without agar and with no carbon source other than the oil. Most oil-decomposing bacteria were found in samples which were heavily

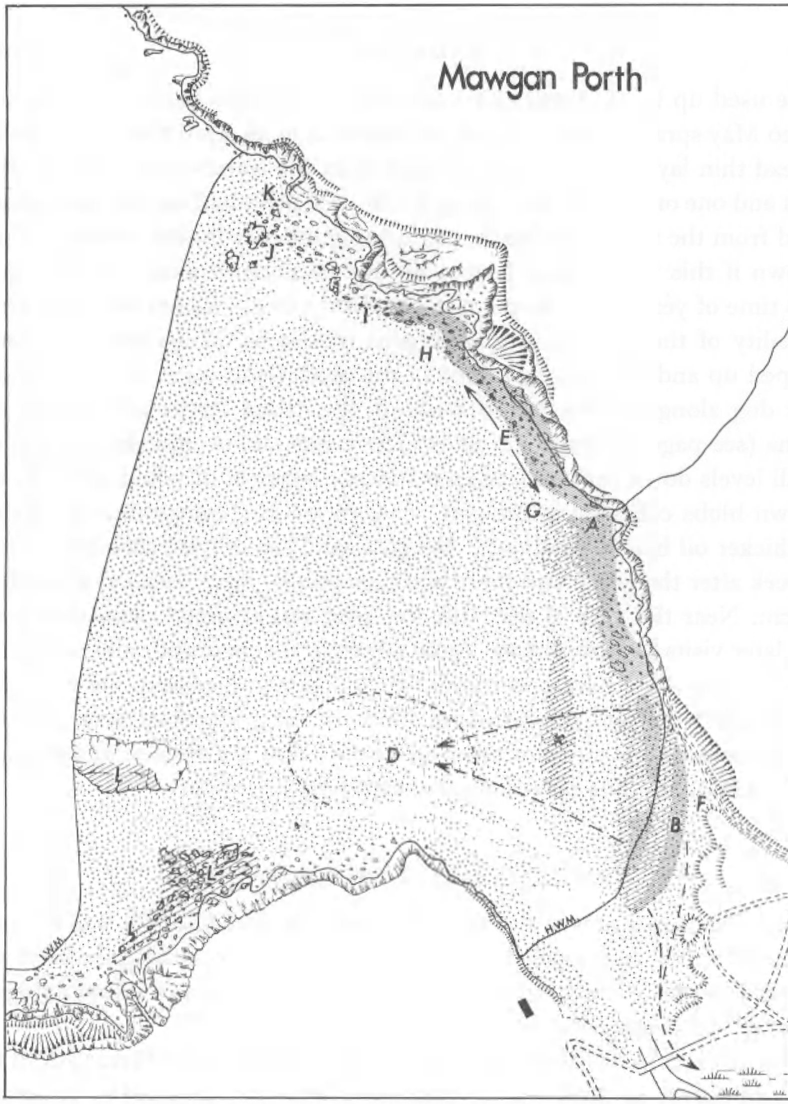


Fig. 14. Cleansing operations at Mawgan Porth. Scale 200 metres = 2·9 cm. The map shows low-tide conditions. High-water mark is above the boulder zone at the base of the cliffs except in the south-east part of the bay where there is sand rising into dunes. The main stream enters in the south-east corner and there is a side stream near *A*.

A Main area of contamination, $\frac{1}{2}$ inch of oil on rocks and boulders either side of *A*.
B, Patches of oil on sand $\frac{1}{8}$ inch thick, carted away and dumped on marshland in direction of *C*.
D, Sand pushed seawards, mixed with detergent and washed in stream.
E, Hosing with fresh water and detergent of main contaminated area. Boulders denuded of life, end of April.
F, Fires made of oil and drift-line weed (only a very small amount of oil destroyed).
G, Quicksand developed here, sand full of detergent and oil, April–May.
H, Milky stream at each low-tide period during hosing.
I to *J*, Boulders denuded by indirect detergent action. These, and those between *A* and *I* became very green with algae, June onwards.
K, Unspoilt 'control' area, not affected by detergent owing to direction of outflow.
L, Light spraying and some detergent damage.
x, Grey sand collected here, 14 May.

Sand over whole bay contained oil and detergent in May. Grey layer general in August after calm spell.

polluted or even consisted mainly of oil. The surprisingly high numbers found were much greater than ever experienced before elsewhere, the most numerous being over 400 million per 1 ml of wet sediment.

At Sennen: $1{\cdot}15 \times 10^8$, $6{\cdot}00 \times 10^6$, $2{\cdot}15 \times 10^6$, $4{\cdot}65 \times 10^6$;
Gunwalloe Fishing Cove: $3{\cdot}75 \times 10^7$, $4{\cdot}65 \times 10^6$, $9{\cdot}3 \times 10^6$;
Marazion Beach: $4{\cdot}65 \times 10^5$;
Pendeen: $8{\cdot}6 \times 10^6$;
Trenow Cove: $4{\cdot}2 \times 10^8$;
Prah Sands: $4{\cdot}65 \times 10^4$ (apparently no oil).

The so-called total number of other bacteria (heterotrophic-proteolitic types) was also determined. The average number of oil-decomposing bacteria ranged from about half to nearly three times as many as the other aerobes.

The only sample from which oil-decomposing bacteria were absent was of water from a rock pool which had much detergent in it. Subsequent experiments at Helgoland using bacteria from sea water (oil-free) showed that detergents, such as were commonly used against marine oil pollution, are capable of killing most oil-degrading bacteria even when used in fairly low concentration, e.g. 10 ppm. However, some bacteria survived even at 100 ppm and multiplied rapidly. At least some of them can use detergent as their only source of carbon. This must have happened on the shore except where detergent concentrations were very high as in the rock pool mentioned above. Because of the very high numbers of bacteria it is possible to assume that a fairly high rate of bio-degradation was taking place on the shores. In sand this process is not likely to be limited by the available nitrogen and phosphorus—as it may be in the sea (Gunkel, 1967). However, oxygen is likely to become a limiting factor. The presence of grey layers in the sand indicates an anaerobic condition subsequent to the activities of the main aerobic degraders. Aeration due to sand movement or water exchange would be important for the continuation of aerobic decomposition. Mechanical ploughing could help.

The development of grey layers was an abnormal and conspicuous feature of contaminated beaches from May and June onwards. The sands of a typical north Cornish beach are clean, i.e. with very low content of organic algal detritus, and, being generally devoid of silt, they are relatively mobile and well aerated. They do not normally develop grey sulphide layers because there is insufficient organic matter to provide sulphur for bacterial reduction. Such grey layers are characteristic of habitats rich in organic matter (Bruce, 1928).

In May sand-core samples and pits revealed only brown layers of buried oil, no grey layers being present on several beaches (Watergate, Sennen, Perranuthnoe). Later digging revealed grey layers in places where there was known to have been oil. On microscopic examination of grey sand no algal fragments could be found, but there was a film of oil around the sand grains. The deposits were oily to the touch and smelt distinctly of the solvent fraction of the detergent. From some of the darker samples—for example, from Sennen—there was an unmistakable smell of hydrogen sulphide, and from near Sennen harbour the deposit was quite black. Table 9 shows percentages of oil in dry wt of sand (estimated on 14 August).

Table 9. *Oil in grey sands*

Sand from	Collected	Oil (%)	Appearance
Trevone	14 May	1·08	Dark grey when collected, surface became light, wet part became darker
Mawgan Porth	14 May	0·42	Grey when collected, became paler
Mawgan Porth	11 August	0·67	Grey when collected, became paler overnight
Watergate	14 May	13·91	Rich brown when collected, grey speckles developed on keeping

These samples were used in some simple bacteriological tests at Plymouth. Greying caused by bacteria (unidentified) working on oil anaerobically was confirmed under laboratory conditions. This seemed to show that destruction of oil may continue to some extent after oxygen is depleted. The intensity of greyness is of course not directly related to the oil content but rather to the lack of oxygen developed in relatively stable or deep sand. Under aerobic conditions black iron sulphide is decolorized by simple chemical oxidation. Grey sand samples from Sennen were found to contain only 20–50 ppm of sulphur in wet sand. This was kindly assessed at the Marine Sciences Laboratories, Menai Bridge, for us through Dr G. D. Floodgate to whom we are indebted for discussing the following matter. Kuwait oil contains about 2·5 per cent sulphur in various organic combinations, some of which are likely to be attacked by appropriate bacteria. This combined sulphur is mostly divalent so that its liberation as hydrogen sulphide is neither an oxidation nor a reduction. As a further source of hydrogen sulphide there could be anaerobic sulphate reduction by other bacteria which derive energy from oxidation of organic matter, in this instance paraffins and aromatic compounds in the oil or detergent. Any destruction of the oil in these two ways is, however, likely to be of less importance than the far more efficient aerobic processes whose existence on the shores was established by Dr Gunkel.

That the beaches are becoming cleaner is beyond doubt. How much of this is due to bacterial degradation on the oil and how much to the washing out of oil from disturbed sands by wave action is unknown. The widespread presence of oiliness in the water-table and the smell of detergent suggests that a significant amount remained in the beaches below the normal level of disturbance in summer calm weather. During the autumn, until at least November, undegraded oil was still present on the very badly polluted beach at Sennen. Detergent treatment, by spreading oil thinly through a beach, may have aided bacterial oxidation of the oil.

The enrichment of the sand by oil and by all fractions of the detergent led to a great increase in the bacterial flora. This process may have been assisted by the poisoning of many or perhaps all of the smaller interstitial fauna which feed upon bacterial films on sand grains. As toxicity is lost and as oxygen becomes available again the way will be open for the re-entry of an interstitial fauna of microscopic predators.

FAUNA

In contrast with other shore environments mentioned in the previous chapter, it may be pointed out that these clean sandy beaches, being unstable and low in organic food content, do not support much animal life. The commonest detectable animal is a temporary inhabitant, the isopod crustacean *Eurydice pulchra* (about 3–6 mm long). When the tide is up it swims above the sand. As the water recedes it may be seen whizzing about in the ripple pools on sandy flats and leaving tracks before burying itself below the surface. Some specimens were seen on various visits to suitable sandy shores throughout the survey, but proper assessment of abundance would have been quite impracticable. It is, however, certain from the abundant tracks in pools at Mawgan Porth on 11 August that there was a numerous population over the whole of the lower part of the shore, in sand which still contained some oil and detergent, as indicated by discoloured floating sand grains and the faint smell. Toxicity tests on *Eurydice* (juveniles of *E. pulchra*) indicated that its survival after detergent treatment was above average for crustaceans (p. 134). All were killed at about 10 ppm after 24 hours exposure; at 5 ppm four out of five survived when transferred to clean sea water, while all survived at concentrations below this. In early days (23 April) a concentration of 4 ppm was found in sea water at either end of the bay on an incoming tide at least 24 hours after any spraying. Thus some individuals of the species would have been subjected to lethal conditions locally both in the sea water and in the sand, but some had survived (*Eurydice* were seen on 14 May near low water). The species had repopulated the whole beach by August. Although the sand still retained some detergent during the summer the animals would have spent twice daily periods in almost uncontaminated water. Single large individuals of *Eurydice* spp. were also found at Sennen on 23 August despite markedly grey layers in the sand below them.

We have only scattered records of other members of the sparse macro-fauna. Numerous sand eels were found dead at Sennen and Gunwalloe while detergent was being used. Empty carapaces of the small burrowing crab *Pirimela denticulata* were unusually common at Watergate soon after spraying as were also the empty tests of the heart-urchin, *Echinocardium cordatum*, and empty razor-shell (*Ensis siliqua*) and *Mactra* shells. All these animals are typical of clean sandy shores.

At Perranuthnoe, on 10 May, examination was made for fauna along a transect down a shore where there had been heavy treatment. Near high-water mark numerous small living oligochaetes and a few living nematodes were found where the water-table smelt strongly of detergent. At low-water mark similar fine sieving produced a live spionid worm. This suggests, as does evidence from Marazion and Porthleven and from toxicity tests, that worms can be fairly resistant to, as well as perhaps able to avoid, detergent damage. Animals under 1 mm in length, chiefly small crustaceans and nematodes, can be found by sieving many washings from normal sand through a fine net (see Delamare Deboutteville, 1960). At Perranuthnoe scarcely any fauna in this size-group was found, some dead foraminiferans and at one station live nematodes. At Sennen in August, similar washings produced a single nematode and three specimens of two species of *Eurydice* but no harpacticid copepods or cumaceans. It seems therefore that for the present at least there is a dearth of micro-fauna. At Sennen the production of hydrogen sulphide in subsurface layers might well be partly responsible.

THE INFLUENCE OF DETERGENT ON THE SETTLEMENT OF LARVAE AND THE RECOLONIZATION OF SANDS

Sabellaria is a polychaete worm whose behaviour at metamorphosis and settlement requirements had been previously investigated (D. P. Wilson, unpublished). It settles on rocky reefs protruding from sandy shores, building colonies of tubes of sand grains cemented together by an organic secretion. The crawling stage of the larva (about $\frac{1}{2}$ mm long) settles readily in the presence of sand containing this cement. Here, therefore, was a clear-cut reaction on which the influence of detergent could be tested on a polychaete living associated with sand—the most suitable organism available at the time, though not a species typical of the sparse macro-fauna living in open sandy shores.

Ground-up and well-washed fragments of *Sabellaria* tubes were soaked in solutions of BP 1002 at 1000 ppm and 10 ppm for 90 minutes, and then thoroughly and repeatedly washed in clean sea water so that it could reasonably be expected that only adsorbed traces of detergent would remain. This sand was put into glass dishes of filtered sea water, and thirty crawling-stage larvae added to each as well as to a control dish with untreated sand made from *Sabellaria* tubes. When examined the next day the sand from the strongest solution was found to have had a marked detrimental effect, causing both delay in settlement and abnormalities of form and behaviour from which there was no recovery. Sand which had originally been treated with 10 ppm had caused but little difference in behaviour from that seen in the control dish (where there had been about 50 per cent settlement), healthy larvae continuing normal activity.

Five days later the sand which had originally been treated with 1000 ppm BP 1002 and had proved to be toxic was compared with newly prepared sand from *Sabellaria* tubes freshly treated, as before, with 1000 ppm and with 100 ppm followed by washing, and with an untreated control, using a fresh batch of larvae. The formerly toxic sand was found to have lost its poisonous effect, being similar to the new control, while the larvae in the other two dishes showed some abnormal effects, presumably from adsorbed detergent.

Hence it would seem that the major part of the toxicity of adsorbed detergent could be dissipated fairly rapidly (see page 145). However, in this case a very small amount of sand was lying in a shallow dish of sea water and conditions for loss of toxicity were therefore very different from those on the shore, where the bulk of the deposit retained traces of detergent for months. These experiments with *Sabellaria* have shown that even a trace of detergent present in or adsorbed on sand may well interfere with settlement and hinder recolonization perhaps for a year, because larvae of a species normally settle during a limited period of a month or two at a particular season of the year.

For microscopic animals whose habitat should be thought of in terms of individual sand grains, detergent both in the interstitial water and adsorbed on the grains is of much more significance than for larger animals which draw in water supplied from above or only burrow in the sand while the tide is out. The re-establishment of the full normal population involves all sizes of organisms: microscopic bacteria, protozoans (including ciliates and foraminiferans), and small crustaceans (including harpacticids and cumaceans), as well as those visible to the naked eye such as the isopod *Eurydice* and small worms, and finally the more obvious macro-fauna such as the occasional bivalve mollusc, burrowing crab and heart-urchin. Studies on the recovery to normal physical and chemical conditions and on the recolonization of a sandy shore should include all these size-groups and work is in progress.

DRIFT LINE

The drift-line zone is evident on sandy shores where various small crustaceans and fly larvae play a useful part on the shore by acting as scavengers. Thick oil deposits at this level probably incapacitated and killed these small mobile creatures, but the sand hoppers (*Talitrus*) bury themselves in the sand, so some would probably be able to escape. Signs of damage from detergent were seen at Constantine where sand hoppers were found in a lethargic state at the base of the sand dunes soon after spraying. The same species was also found dead in quantity at Sennen.

It has already been reported that at Porthleven Reef *Ligia* and *Orchestia* were seen dead in quantities. They too are chiefly scavengers of the high-water zone.

In the Hayle Estuary the upper drift line was the only region badly affected by oil. It was left untouched by detergent and therefore formed an interesting 'control' area in which good recovery was observed in August (see below).

Very oily weed was sometimes thrown up. It is reported to have been collected and burnt at Mawgan Porth. This is a useful activity and practicable where quite small quantities of oil are concerned and dry weed is available, and providing burning is done well away from people as the fumes from partially burnt oil are considered noxious. It was not more widely attempted because of the trouble involved in the disposal of such a minute part of the oil stranded from the 'Torrey Canyon'.

ESTUARIES

The only estuaries to be polluted by oil were the small ones of the Gannel at Newquay and the Hayle Estuary. (Work on these is being carried out by the Nature Conservancy's Coastal Ecology Section.)

In the Hayle Estuary oil was carried in on one of the very high spring tides, 28/29 March, and left as a blackening rim chiefly on walls and to some extent on saltings. Owing to a special request from the power station and to representations from biologically interested bodies no detergent was used within the estuary though there was lavish use on the sands at the mouth of the river. Traces of this were probably carried up some gullies where, on 30 March, some dead and moribund rag-worms (*Nereis diversicolor*) and some small crustaceans (*Corophium volutator*, and *Gam-*

marus spp.) were collected. When examined on 10 April the rich worm fauna in the sandy flats seemed unharmed. These worms form an important food supply for birds, one branch of this estuary being preserved as a bird reserve. Animals scavenging in the drift line would have encountered a blackened sticky mess of limited width and therefore perhaps not of much consequence to the area as a whole. When inspected in mid-August the black oily rim was still visible on the vertical walls around the estuary and harbour but aerial weathering had reduced it considerably. In places the orange lichen *Xanthoria* was growing through the oil (Plate 18c). The sticky deposit in the drift line had become innocuous and inconspicuous. Perennial salt-marsh plants, sea-plantain, beet, sea-aster and grasses had grown through it and annuals such as sea-milkwort and spurry—though delayed in developing—were spreading over the oil residue. The normal drift-line fauna of small jumping amphipods (*Orchestia*) and woodlice (*Oniscus*) were common under stones. These scavengers had perhaps not recovered by reproduction to a full normal abundance but they did not now seem incommoded by the texture of the oil residue. Where this had been washed by recent spring tides the crumbly oil and sand was being carried away. These are good examples of recovery by natural means in the absence of the use of any detergent.

At Hayle a boom was erected but no further oil approached the area after the first high-level pollution. The problem might have been much more serious had oil been driven in on a lower tide, or had detergent been used on these stable sandy flats in this enclosed area of water. It is here further stressed that it would be far worse than the effects seen on open sandy shores where, in contradistinction to estuarine conditions, instability of deposit and frequent complete changes of water have meant that oil and detergents are being washed or oxidized away (p. 84).

Oil pollution along the north coast did not extend quite as far as the Camel Estuary nor enter it. On the south coast the Helford Estuary (with oyster beds) was also beyond the limits of pollution. Great attention had been given to preparing a boom and suction-clearing apparatus should any oil arrive. Mopping up with straw was also considered. No detergent would have been used, not only because of its direct lethal effect on the oysters but because the spreading of a thin film of oil over the mud would have interfered with the surface micro-flora living there as well as affecting the infauna, thus seriously upsetting the food-chains for a long period, both for the oysters and for the life of the estuaries as a whole.

Local authorities should be aware of the disastrous results which the use of detergents in estuaries could produce since two Ministries have already stressed the dangers of applying detergents in estuaries and harbours (as well as of applying neat detergent on rocks, etc.). Moreover, a general directive was issued that detergents should not be used in estuaries to combat 'Torrey Canyon' oil.

CONCLUSIONS ON THE USE OF DETERGENT AND OTHER METHODS OF TREATMENT OF SHORE AND ESTUARINE DEPOSITS

It may again be stressed that by good fortune the exposed conditions on the Cornish sandy shores were such as to lead to the ready flushing out of detergent and dispersed oil, providing the aeration necessary to aid bacterial decomposition without the production of much unpleasant smell of hydrogen sulphide. Had pollution occurred on more stable sheltered beaches and a similar enormous amount of detergent been used in dispersing the oil to depths (see experiment, page 76) the position would have been very different at the end of the summer. Likewise, if detergent had been used in estuaries and other enclosed waters, very long-term damage would have resulted.

We have seen evidence that oil left untouched as a black rim around Hayle Estuary at and above high tide has weathered and become innocuous in the absence of the use of detergent.

The removal of as much oil as possible *before* the use of detergent has proved worth while even on the few shores (Mawgan Porth and Trevaunance) where it was tried, and such procedure would have been an even more advisible method of dealing with oil on more stable sands or muds. On the shingle at Gunwalloe Fishing Cove it would have been possible to scrape up much oil from the surface if it had been attempted before detergent had been applied. The use of detergent caused the oil to sink very deeply into the beach so that very extensive mechanical shifting of shingle seawards was eventually necessary.

Some oil would be bound to remain, and, to aid its decomposition by bacteria, dispersal is desirable. This might well be accomplished much more cheaply by ploughing or otherwise mechanically mixing the oil and sand without the addition of detergents. There was no sandy beach on our Cornish coasts where detergents were not used which could be examined as a 'control'. Even if the cost of the procedure is ignored, the use of detergent is by no means the only and not necessarily the best way of treating oil on beaches. Other methods of treating sandy beaches were seen in Brittany (Chapter 9).

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

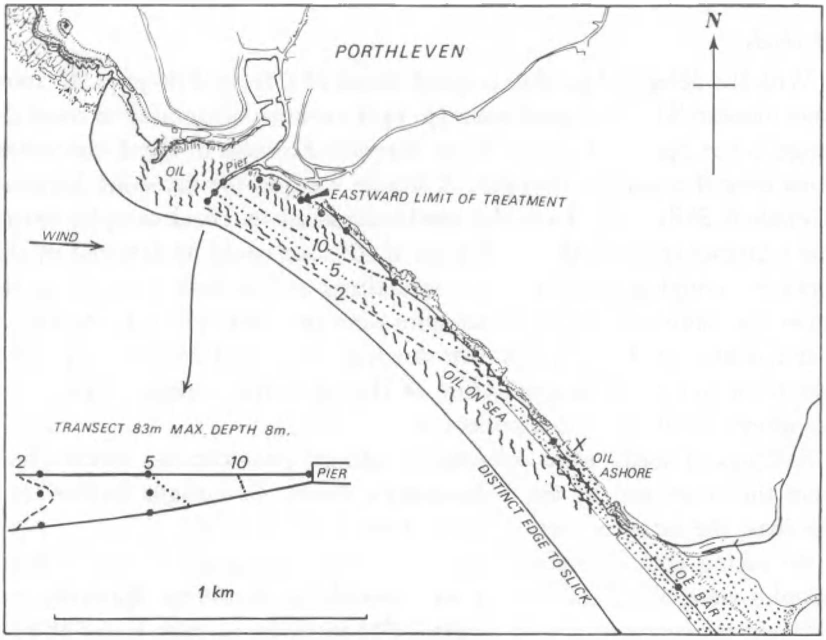


Fig. 15. The situation at Porthleven about 1 hour after high water on 5 April. Sampling stations along the shore and in the transect are shown by closed circles. Numbers show the concentrations of detergent in the water in ppm BP 1002. The scale refers to map, not transect.

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

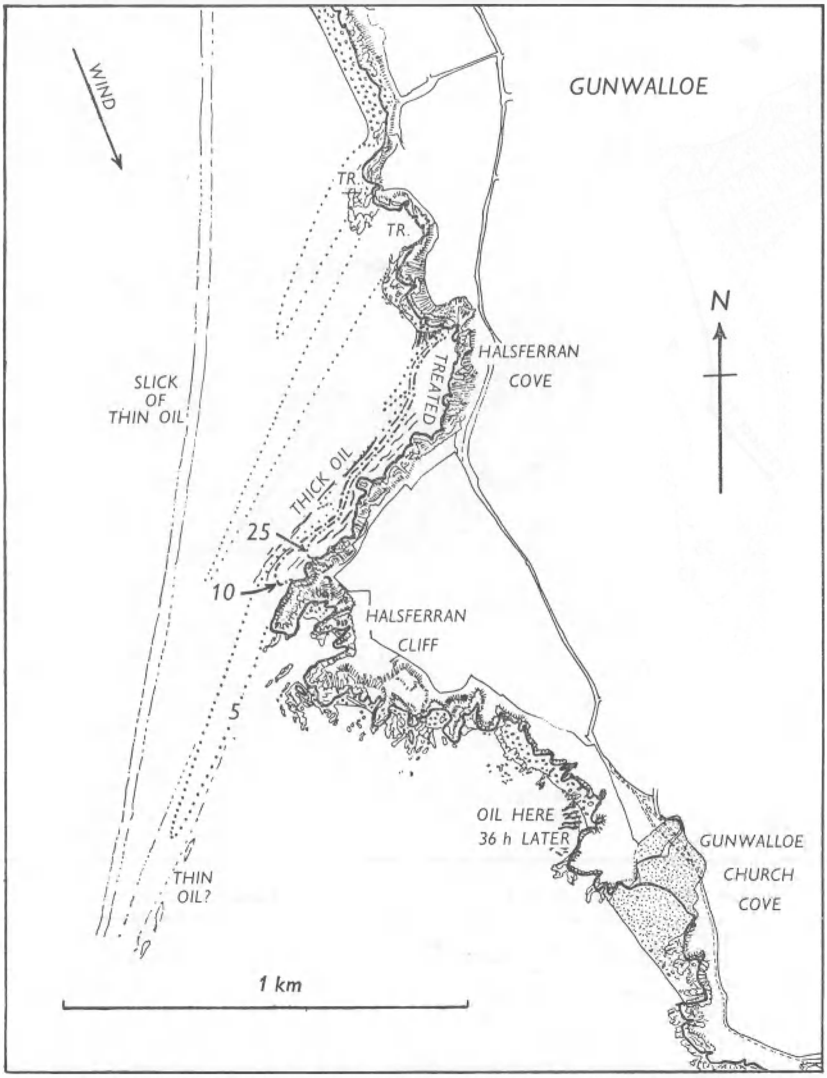


Fig. 16. The situation at Halsferran Cove about 2 hours after high water on 11 April. Numbers show the concentrations of detergent in the water in ppm BP 1002. Outlines of detergent patches from two other coves correspond roughly to concentrations of 5 ppm BP 1002. *TR.*, treated beaches.

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

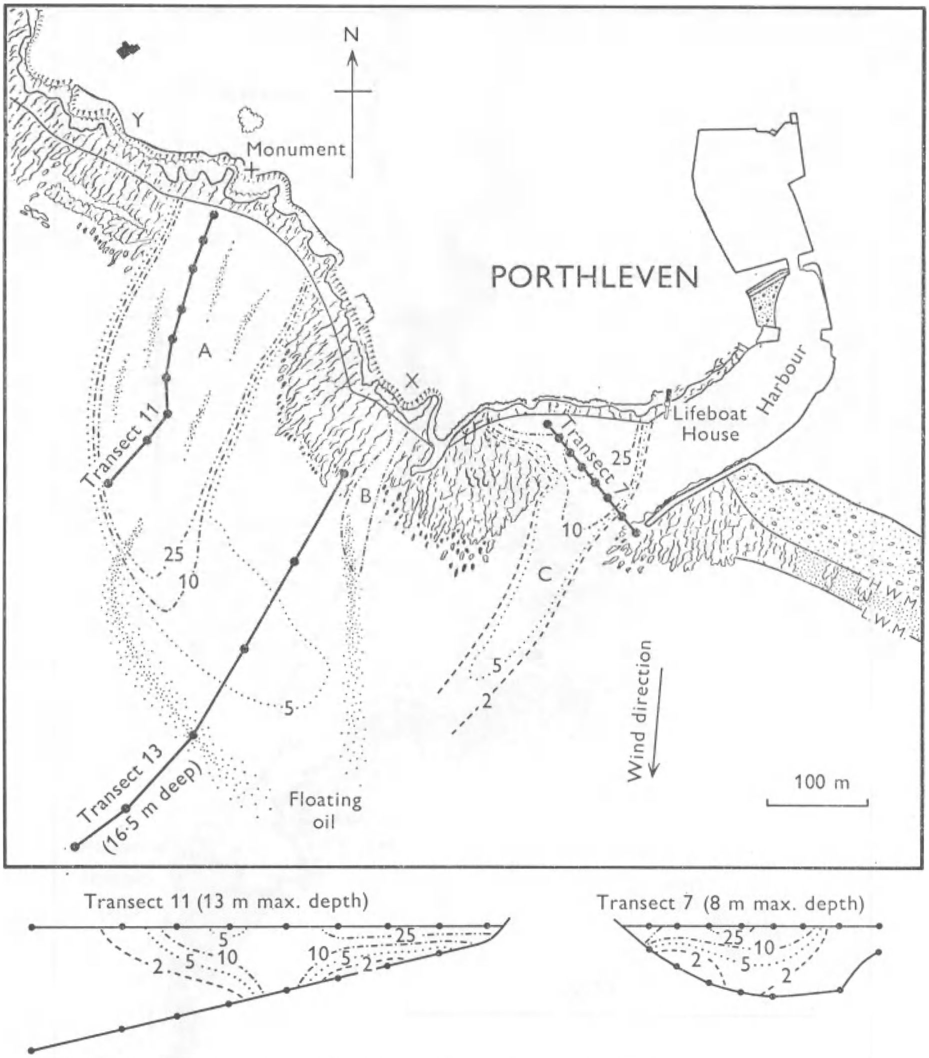


Fig. 17. Detergent patches at Porthleven about 2 hours after high water on 7 April. Black circles show the positions of sampling stations in a transect which was made on 7 April and also in transects made on 11 and 13 April. Results of transects made on 7 and 11 April are shown below the map. Numbers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

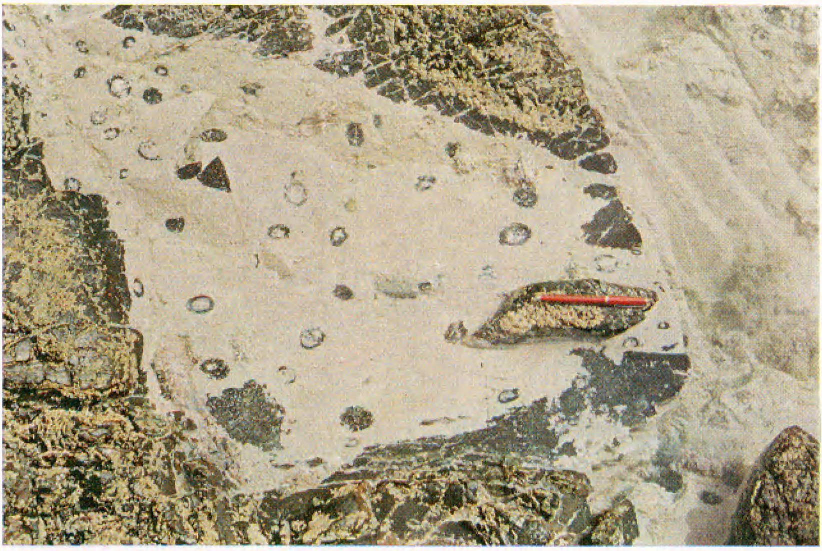
Under the influence of the wind, and probably also of the tidal current, the detergent patch which originated in Halsferran Cove moved along the

PLATE 17

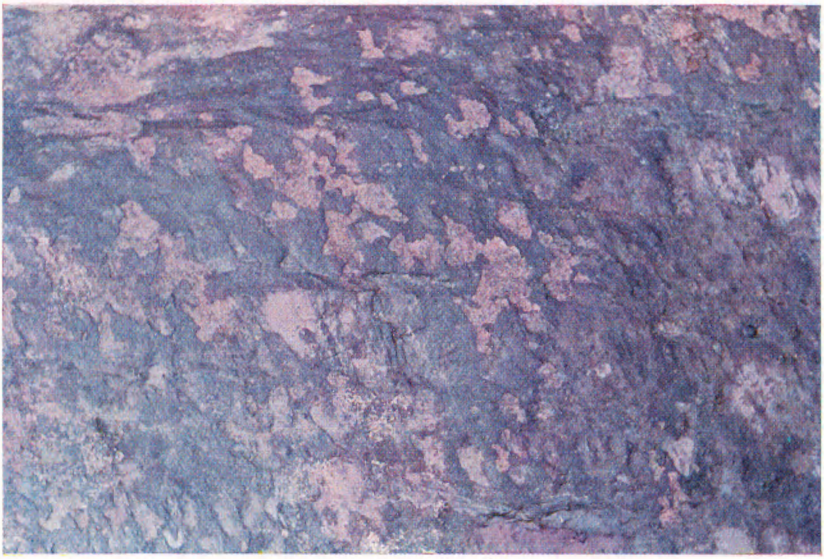
A

B

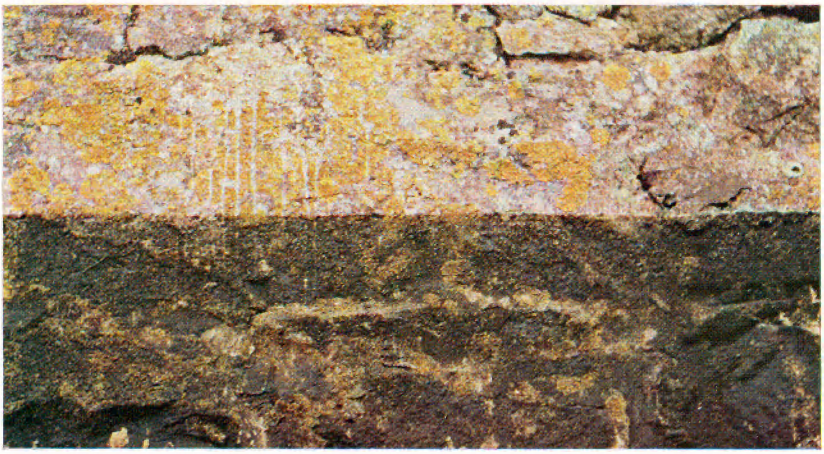
PLATE 18



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.

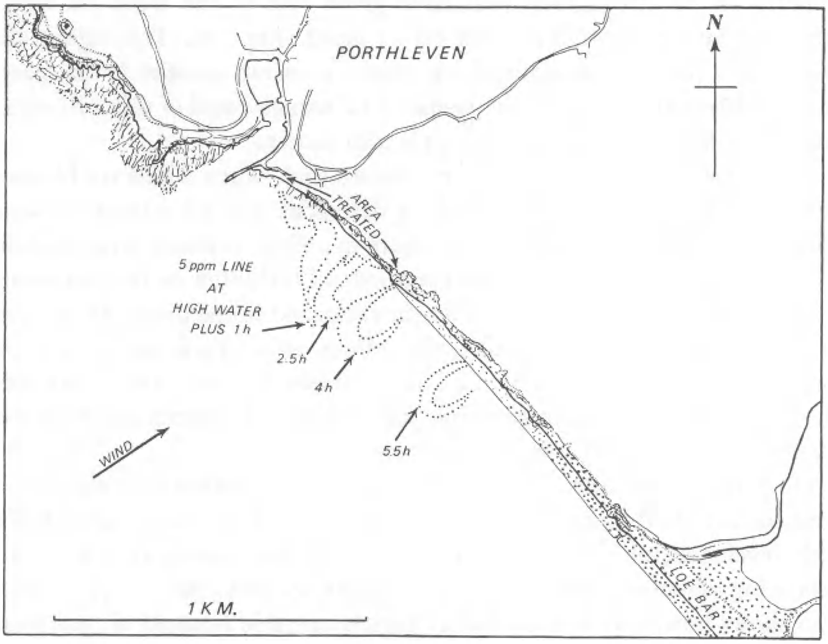

Fig. 18. Changes in the shape and position of a detergent–oil patch after high water at Porthleven on 19 April.

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

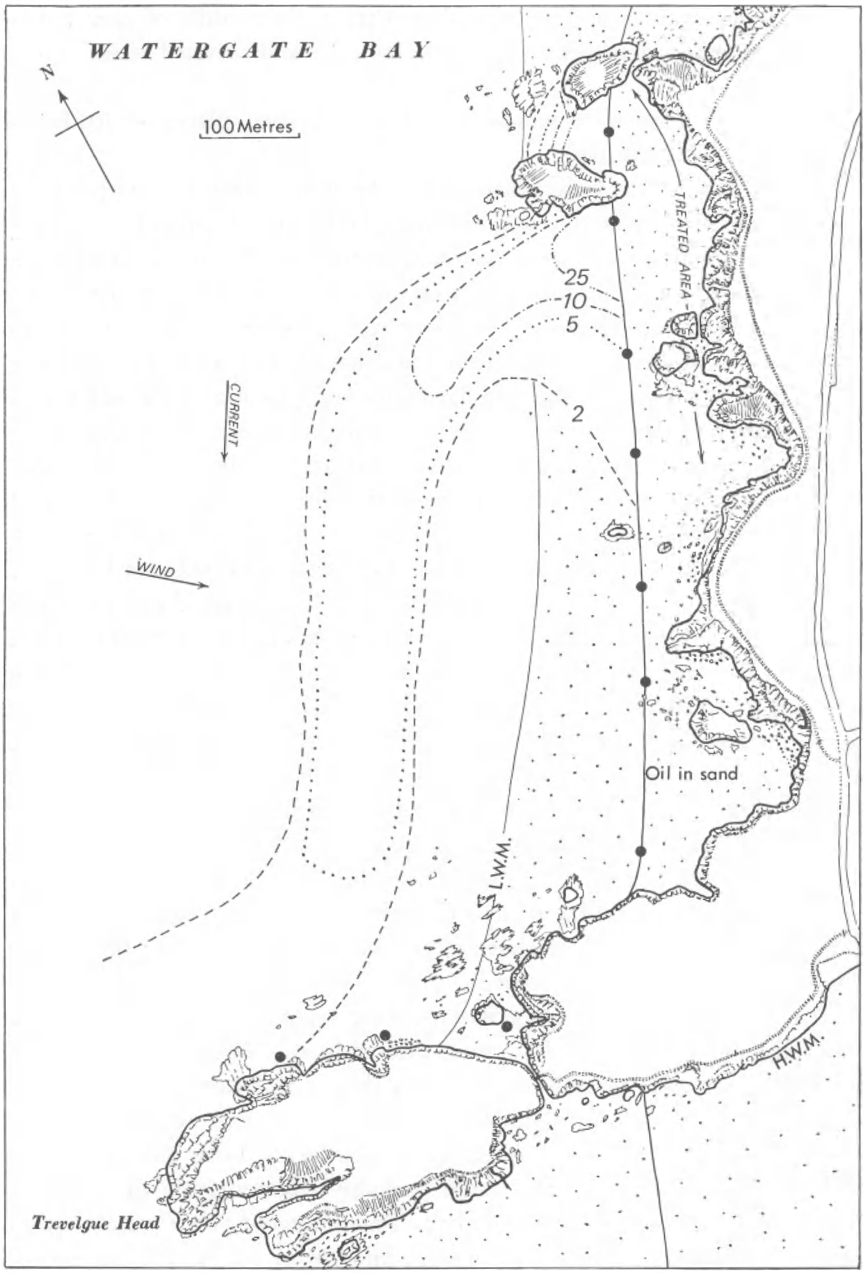

Fig. 19. The situation at the Newquay end of Watergate Bay about 3 hours after high water on 23 April. Black circles show the positions of sampling stations and numbers show the concentrations of detergent in the water in ppm BP 1002.

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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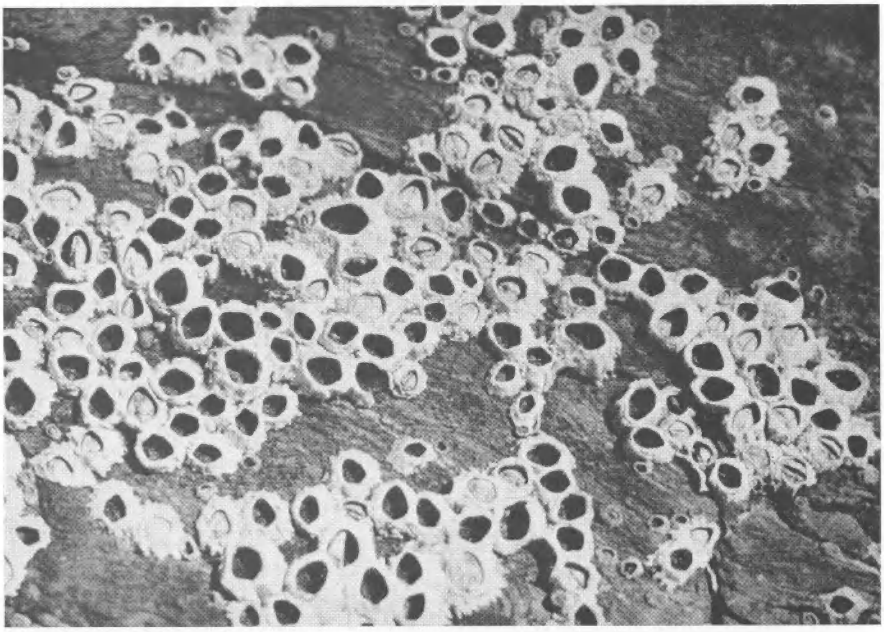
PLATE 19

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

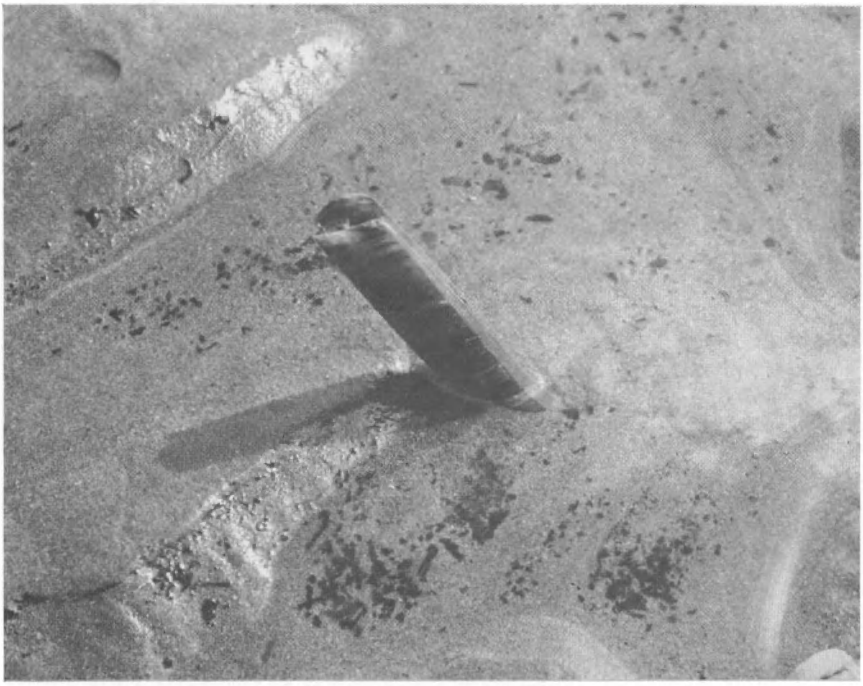


A

B

(*Facing p.* 104)

PLATE 20

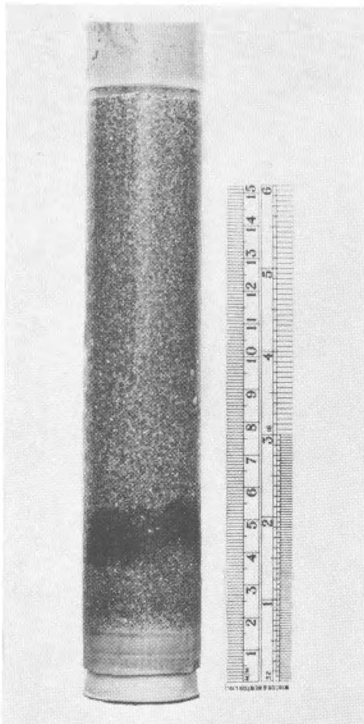


A

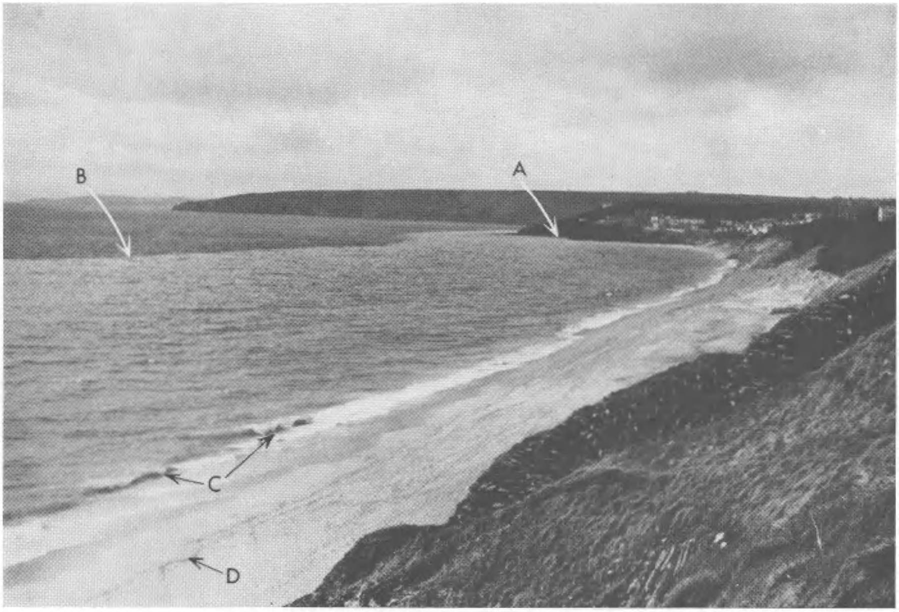
B

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

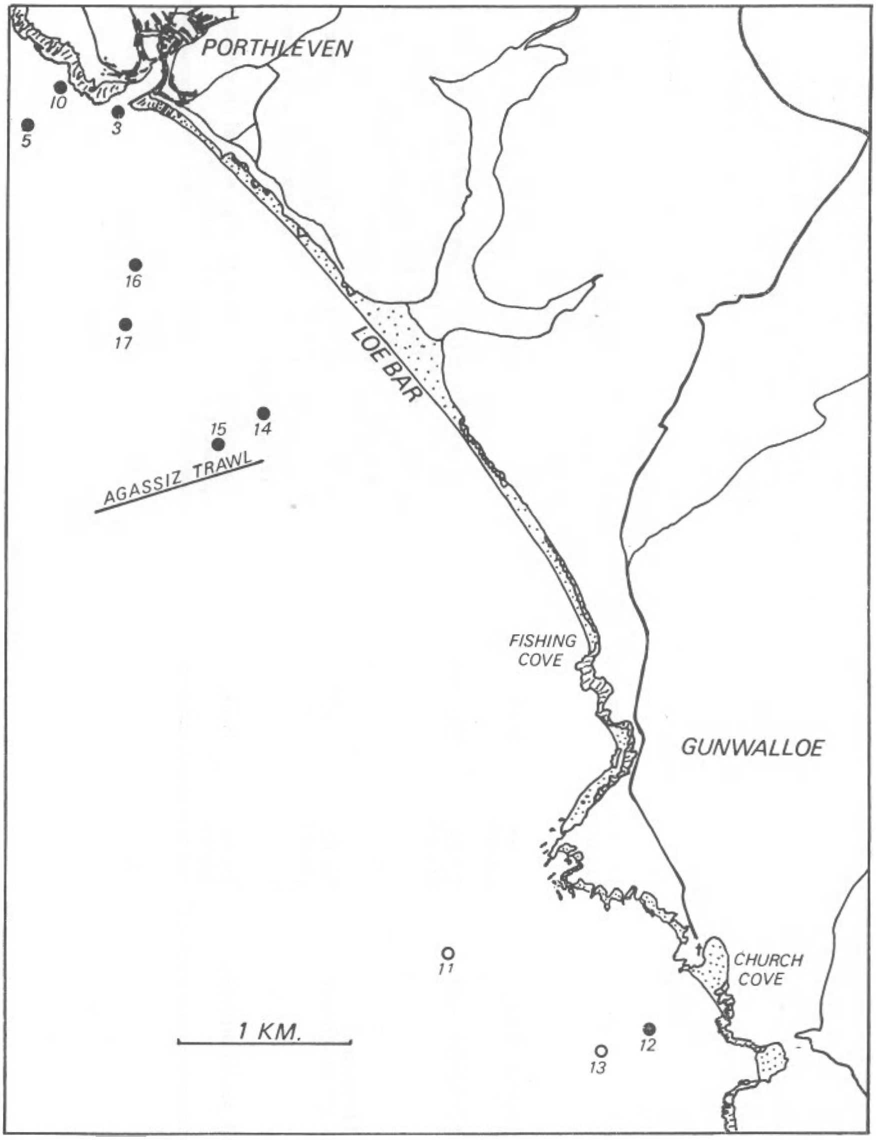


Fig. 20. Stations at which the bottom fauna were examined by divers between 7 and 15 April. Numbers correspond to those of the dives in the diving report (Tables 11, 12). Closed circles show that affected animals were found and open circles represent no effect or inconclusive evidence.

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.

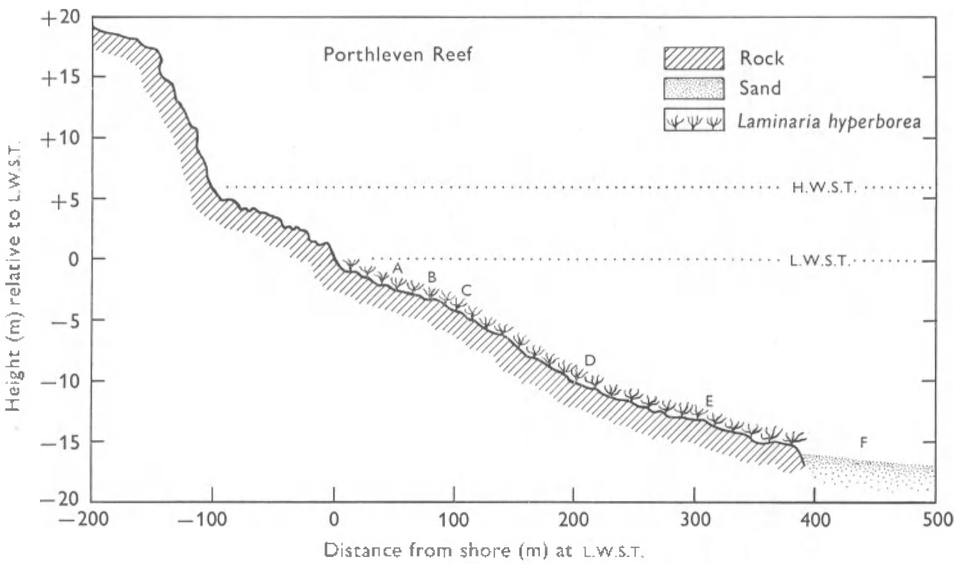


Fig. 21. Diagrammatic profile off Porthleven based on several dives carried out in the region. The nature of the bottom and distribution of organisms is shown. A, 0–2 metres depth: most crabs, starfish and other animals dead; many fine red seaweeds dead. B, 2–4 metres depth: some dead crabs, many others 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
		St Michael's Mount			
23	28	(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/m^2), *Echinocardium cordatum* (2–10/m^2), *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.

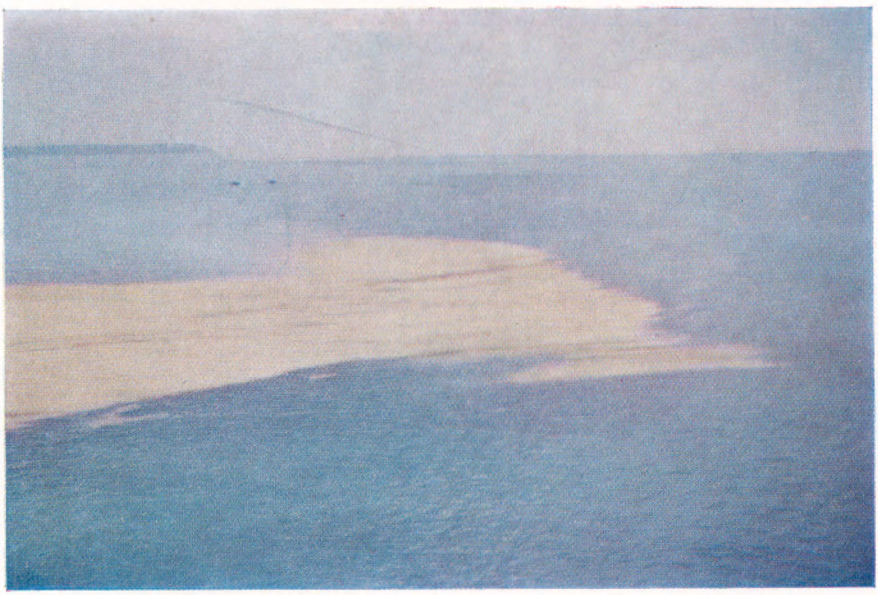
It can be concluded then that the effects of the treatment at Porthleven were felt on the sea-bed at least as far as 2 kilometres south-east of the harbour and 1 kilometre from the shore. This is the direction in which the detergent would be expected to move because there is a net eastward flow of water 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.

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 24A), 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 26C). 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 25B, 26B). 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 26A).

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.

CHAPTER 7

TOXICITY EXPERIMENTS

LABORATORY INVESTIGATIONS INTO THE TOXICITY OF OIL AND DETERGENTS

The spraying operations at sea and the detergent treatment of the beaches were mounted with one main objective in view, namely to preserve—or at least minimize the damage to—the amenity value of the coastal resorts. The amenity so seriously and blatantly threatened was the cleanliness of the beaches to which summer visitors flock for recreation. The removal of oil from the holiday beaches was an urgent objective, even at the risk of destroying or damaging other amenities, such as the incomparable wild life of the Cornish coast and shores. For even if the natural animal population around the treated beaches were largely destroyed, the effect on the tourist industry might be negligible compared with the prospect of an ever-oily beach. Few will have had serious doubts; to most only one course was right—to fight the oil with detergents regardless of the cost, in every sense.

But did these actions put at risk other and possibly greater interests? Was there a possible danger to public health? Was there a danger to off-shore and inshore fisheries? The answers to these and other vital and recurring questions had to wait upon the availability of accurate knowledge about the toxicity of the materials that were being applied, their persistence in the sea and the manner in which they spread.

We soon found that the scientific literature was deficient in relevant information and so a programme of toxicity tests was undertaken in the laboratory by several scientists whose previous experience enabled them to take up this work and develop it with the minimum delay. This work was carried out at the same time as the shore parties and the cruise personnel were making their observations on the beaches and at sea.

The urgency of the problem militated against the accurate refinement of the techniques employed, but in spite of this the experiments provided information of great value. In fact an answer to the all-important question of the persistence of the toxic qualities of the detergent emerged within the first few days.

From the toxicity experiments we were able to develop methods of bioassay which in turn made possible a more detailed investigation into the spread of the detergents.

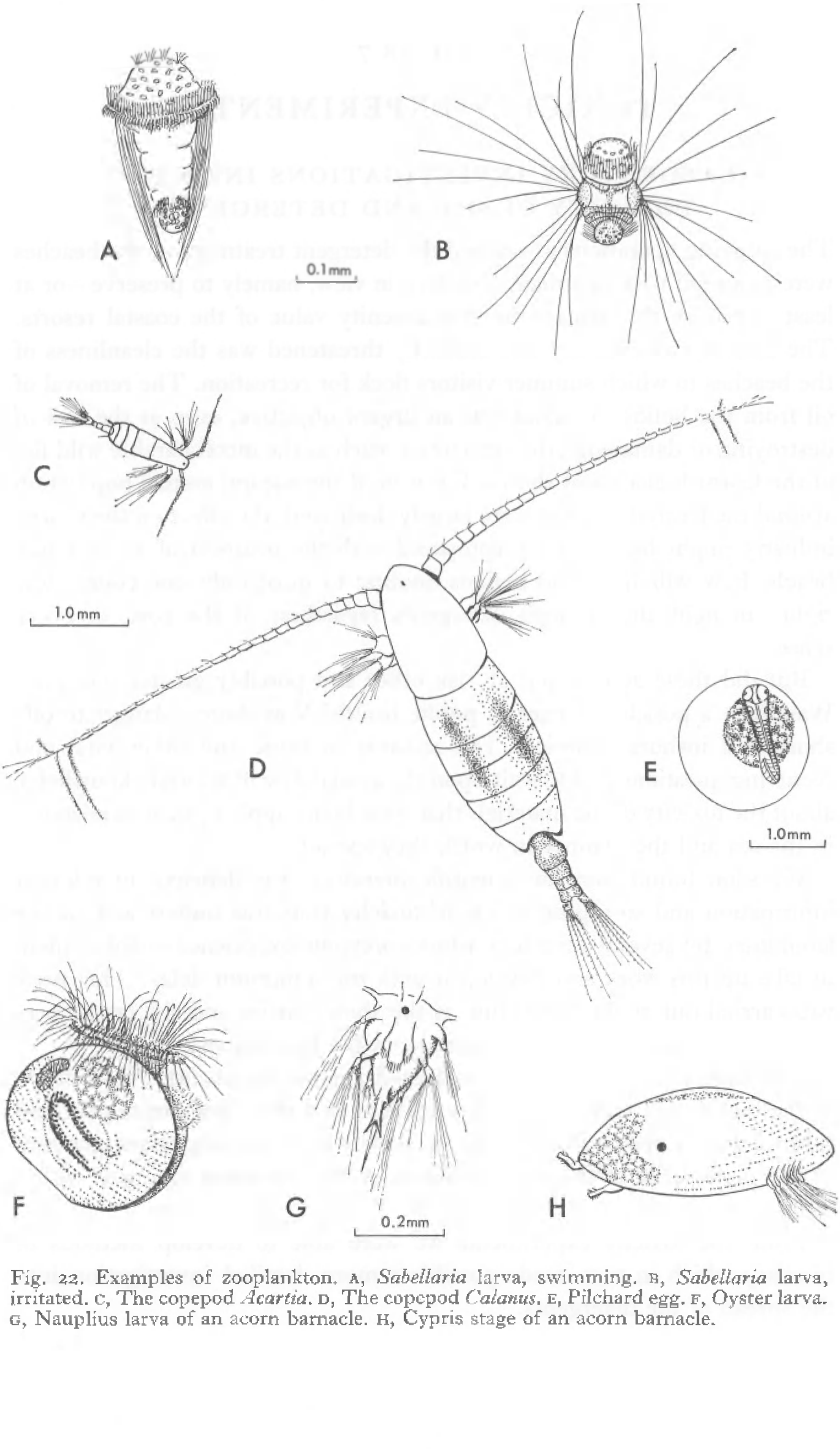


Fig. 22. Examples of zooplankton. A, *Sabellaria* larva, swimming. B, *Sabellaria* larva, irritated. C, The copepod *Acartia*. D, The copepod *Calanus*. E, Pilchard egg. F, Oyster larva. G, Nauplius larva of an acorn barnacle. H, Cypris stage of an acorn barnacle.

The results of the laboratory work are given in outline in the following pages; they represent much intensive effort. Where experiments are individually described they are examples of critical importance. It should perhaps be pointed out that when using living organisms as test material they are not necessarily continuously available; particularly is this true of larvae, which are of seasonal occurrence. Some zooplankton organisms tested are shown in Fig. 22 and phytoplankton in Fig. 5 (p. 28).

A survey of the contents of this chapter may help the reader to follow the somewhat complex subject-matter. The need for the analysis under section VI became obvious during early experiments in section I, and due care and allowance was made thereafter for the diversity of behaviour of the various ingredients of the detergents. At first several detergents were used and their toxicities compared. It became necessary to choose one detergent as a standard, and BP 1002 was chosen because it was one very widely used on the beaches, and with the willing co-operation of the BP Trading Co. Ltd its components could be separately investigated.

SUMMARY OF EXPERIMENTS

I. Toxicity studies on zooplankton
- Effects of detergents
  - *Elminius modestus* larvae, barnacles
  - *Calanus finmarchicus* and *Acartia clausi*, copepods
  - *Ostrea edulis* and *Crassostrea gigas* larvae, oysters
  - *Lacuna vincta* and *Nassarius reticulatus* larvae, shore gastropods
  - Young fish
- Notes on toxicity of crude oil and of oil with detergent
- Conclusions from early experiments

II. Longer-term effects on zooplankton species during rearing
- *Sabellaria* larvae, polychaete worm, showing immediate transitory effects and longer-term effects (for transitory effects on settlement see page 86)
- *Elminius* larvae to metamorphosis
- *Echinus esculentus* larvae

III. Toxicity studies on phytoplankton

IV. Toxicity studies on intertidal and sublittoral organisms
- Intertidal algae
- Intertidal animals—toxic effects of BP 1002
  - Various animals and in particular mussels, limpets, winkles and top-shells, barnacles (both recently metamorphosed and adult)
- Sublittoral animals—toxic effects of BP 1002
  - Various sublittoral organisms including *Echinocardium* (heart-urchin) and its commensals, and *Crangon* (shrimp)

V. Bioassay methods developed to enable water samples from the field to be assessed rapidly

VI. Toxicity and stability of components of BP 1002, etc.—solvent, surfactant and stabilizer
Elminius larvae
Sabellaria larvae
Crangon (shrimps)

I. TOXICITY STUDIES ON ZOOPLANKTON

Effects of detergents

Barnacle larvae

Stage II nauplius larvae of the barnacle *Elminius modestus* were used, being obtained by hatching out fully developed embryos from the adult barnacle. Preliminary tests showed that the detergents BP 1002, Gamlen and Slipclean all rendered the larvae completely motionless in under 2 h, at a concentration of 10 ppm. At high concentration (100 ppm) the animals were rendered quiescent in a few minutes. By contrast, Teepol L, chosen as an example of an ordinary domestic detergent, was found to be far less harmful, concentrations between 27 and 270 ppm of active ingredients being needed to stop swimming activity. Immobility was here taken to be an indication of toxicity. Although a larva may regain mobility if removed from dilute detergent solution and replaced in fresh sea water, it was generally found that the loss of swimming activity was irreversible.

These hastily contrived experiments led us to more detailed studies. The method followed that used by Corner & Sparrow (1956), but is here given in outline.

In these later experiments a series of concentrations of each of several detergents was prepared in sea water: about 100 nauplii were placed in 5 ml of sea water of each concentration contained in a corked tube. The percentages rendered motionless were recorded for increasing times of immersion. These data, when plotted as percentage motionless against time, gave a sigmoid curve from which the time at which 50 per cent of the test sample had lost all activity could be estimated. This time (i.e. TD 50) was then plotted against concentration of detergent (as ppm) on a logarithmic scale. The results obtained are shown in Fig. 23. It is obvious from this that Teepol L is far less toxic than any of the other detergents tested; also that Teepol L may have a separate mode of toxic action, as the shape of the dose/time curve is markedly different from those characterizing the other four detergents, each of which has a sharp inflection above which the concentration must be greatly increased in order to produce any sensible change in TD 50. As these inflections occur at different points in each of the four curves and as the slopes also vary, it is only possible to compare

Table 13. *Relative toxicities of detergents to* Elminius *nauplii*

	Number of times as toxic as active ingredients of Teepol L			
TD50 (min)	BP 1002	Slipclean	Gamlen	Dasic
10	60	30	17	13
30	28	12	25	7

toxicities by referring to a particular TD50 value. Thus, taking a TD50 of 10 minutes, the relative concentrations needed (as ppm) are 7 (BP 1002), 14 (Slipclean), 24 (Gamlen), 32 (Dasic) and 1550 (Teepol L). By contrast, if a TD50 of 30 minutes is used the concentrations are 3·5 (BP 1002), 3·9 (Gamlen), 7·8 (Slipclean), 15 (Dasic) and 370 (Teepol L). Relative toxicities based on these two TD50 values are therefore different (Table 13).

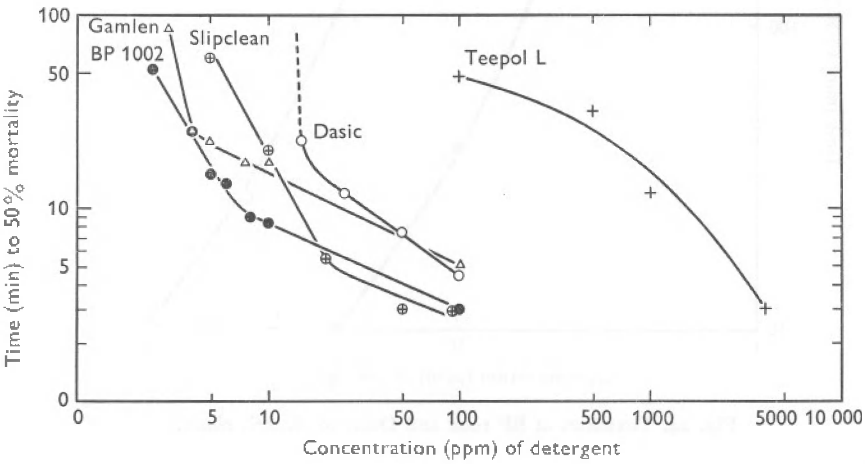


Fig. 23. Toxicities of various detergents to stage II *Elminius* nauplius larvae at 16–20 °C. Note: concentrations of Teepol L refer to the commercial preparation, which contains about 27 per cent active ingredients. The curve for pure Teepol L would be appropriately closer to those for the other detergents (as in Corner, Southward & Southward, 1968).

Copepods

These animals are important as food for pelagic fish and thus play a central role in the oceanic food-chain. Unlike *Elminius* their complete life-cycle is spent in the zooplankton: not just the young stages. The first experiments were 'rough and ready'. Samples of mixed zooplankton, mainly consisting of small copepods, were used in toxicity tests with BP 1002. Samples of the plankton were immersed in concentrations of 2·5 and 5·0 ppm of BP 1002 for 24 hours and then the fraction rendered inactive estimated by eye. The indications were that both these concentrations had a deleterious effect on the animals.

(*a*) *Calanus finmarchicus* (Fig. 22D). More detailed experiments were carried out at Millport by Dr S. M. Marshall, F.R.S., who has kindly allowed us to use her results. The test animal used was the copepod

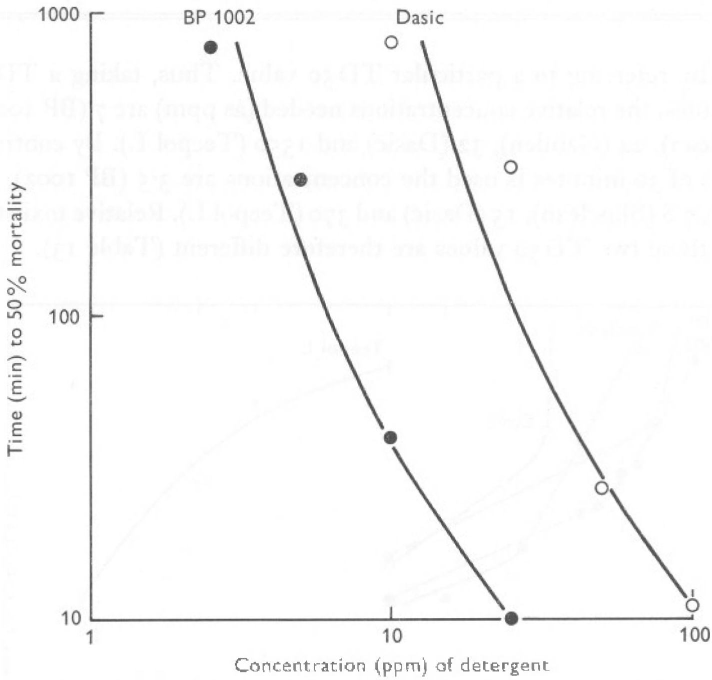


Fig. 24. Toxicities of BP 1002 and Dasic to *Acartia clausi*.

Calanus finmarchicus, and experiments with BP 1002, Gamlen, Dasic, Molyslip, and Houghton Solv. 112 showed that concentrations of 50 ppm were lethal in an hour; 5–10 ppm killed most specimens within two to three days, and 1 ppm, although not lethal, had some effect in that the

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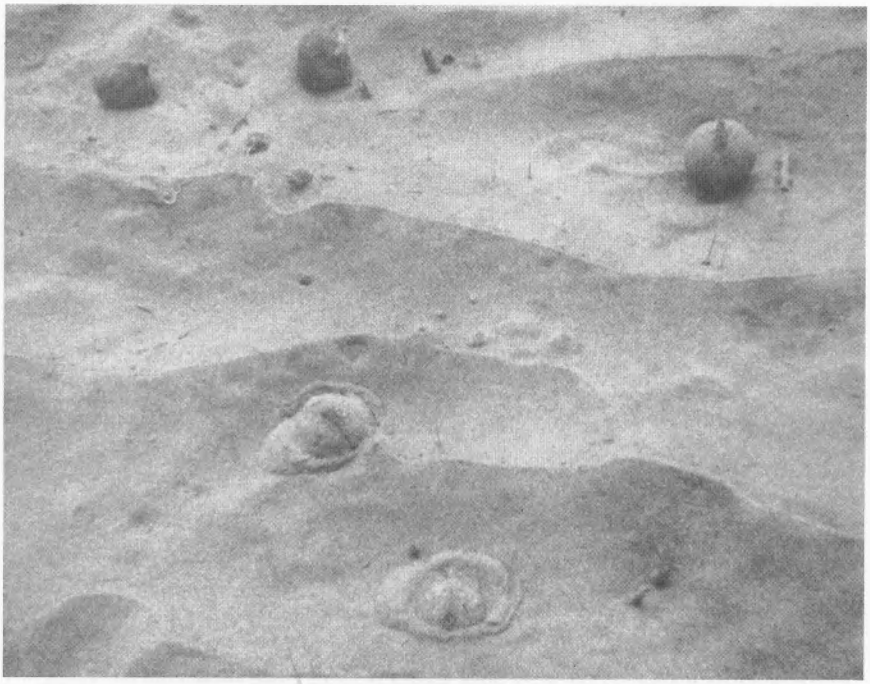
PLATE 24

Porthleven, depth 15 metres, 19 April. Photographs of the rippled sand bottom about half a mile offshore. **A**, *Echinocardium cordatum* on the sand surface. The sand humped up around the two urchins in the foreground suggests their recent emergence from the sand, these specimens being probably still alive. Those lying on the sand at the top had probably been there some time and were moribund or dead. **B**, Moribund *Echinocardium cordatum* and a razor-shell, *Ensis siliqua*, half projecting from the sand. In both photographs the slender arms of the brittle-star *Acrocnida brachiata*, which remained healthy, may be seen projecting above the sand surface.

PLATE 24



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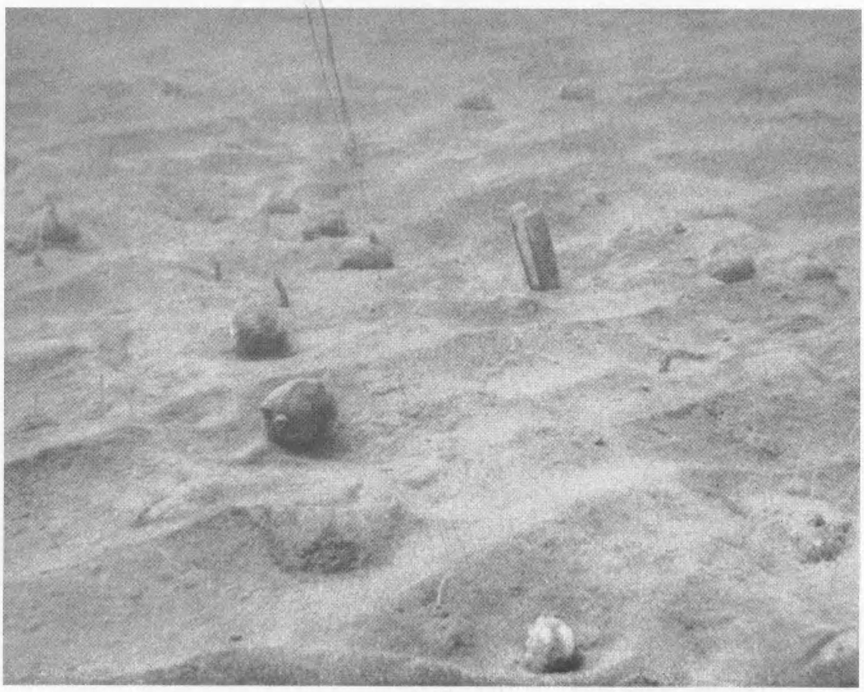
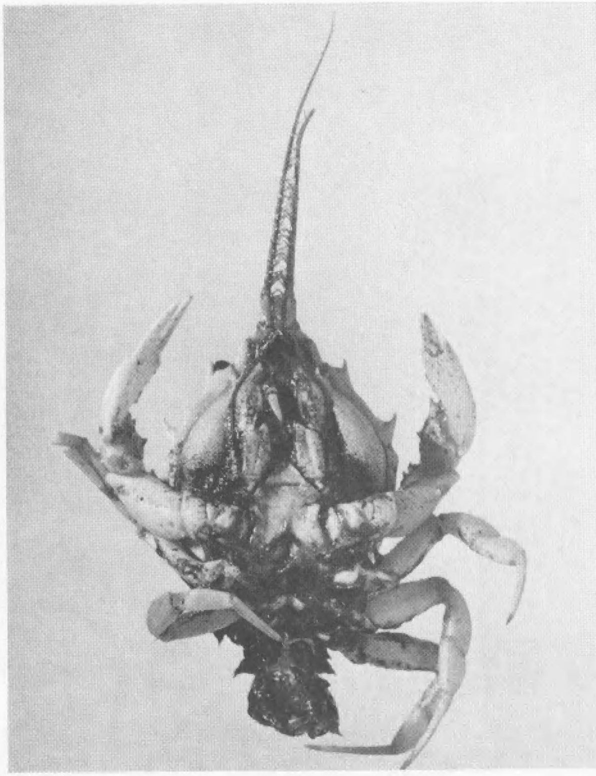


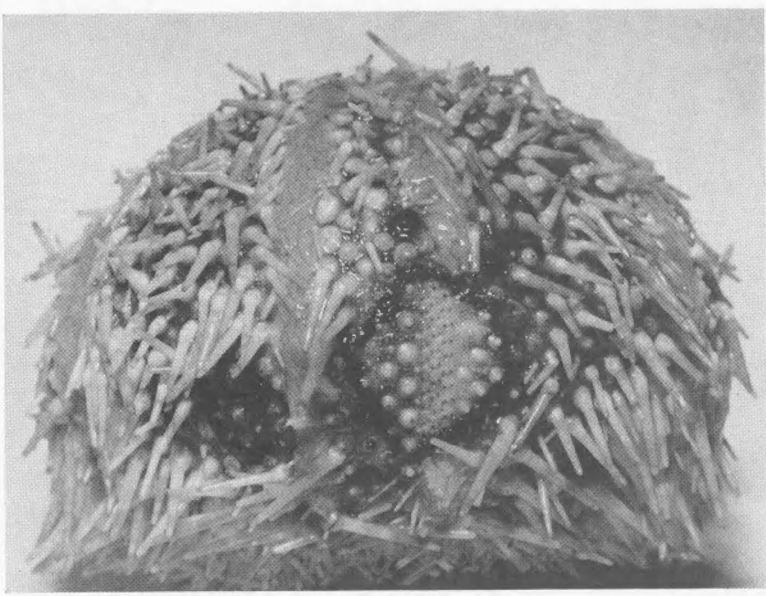
B

(*Facing p.* 120)

PLATE 25



A



B

(Facing p. 121)

treated copepods were not as active as those used as controls. These data indicate that *C. finmarchicus* is more resistant than *Elminius* nauplii to the various detergents used.

(*b*) *Acartia clausi*. Another species used as a food by fish, and one that spends its entire life-cycle as a member of the zooplankton, is the small copepod *Acartia clausi* (Fig. 22C). Experiments with this animal were carried out by Mr B. W. P. Sparrow (International Paints Laboratory, Newton Ferrers), who has kindly allowed us to quote his results, summarized in Fig. 24. It will be seen here that the dose/time curves for BP 1002 and Dasic are almost parallel, so that their toxicity ratio can be stated for a wide range of values for TD 50. As in earlier studies with other species, BP 1002 is more toxic than Dasic, the ratio being approximately 5:1. Moreover, the resistance of the very small copepod *Acartia clausi* to detergents is far less than that of the much larger species *Calanus finmarchicus*: thus a concentration of 50 ppm BP 1002 was lethal to *Calanus* in 1 hour, whereas half this concentration (25 ppm) killed *Acartia clausi* in only a few minutes.

There is a general indication that among similar animals the resistance to detergent poisoning is related to size in such a way that the bigger the animal the more resistant it is.

Oyster larvae (Fig. 22F)

Because of the possible effects of detergents on oysters, particularly when the animals might be spawning, experiments were carried out at the Fisheries Laboratory (Conway) by Dr P. R. Walne, who has kindly allowed us to quote his results. The animals used were embryos of the oyster *Crassostrea gigas*, a relatively warm-water Australian species. The developing eggs were placed in solutions of various detergents for 24 hours at 23 °C, and the proportion of swimming larvae that had developed to the so-called D-stage was then estimated. The results, shown in Table 14, demonstrate that all the detergents tested were toxic to oyster larvae at

PLATE 25

A, *Corystes cassivelaunus*, the masked crab. This specimen was alive when collected from Gunwalloe, 600 metres from the shore in 10 metres depth on 15 April (dive no. 12; see Table 12). It has an accumulation of black material on the setae of the ventral side which is not usual in healthy individuals. This material had collected along the region of the crab's respiratory currents. **B**, A living edible sea-urchin (*Echinus esculentus*) collected from Sennen Cove on 24 April (dive no. 20; see Table 12). The animal is enfeebled and shows scars in which the surface epidermis and spines are gone and which are surrounded by an area of black tissue. The tube feet adjacent to these scars are responsive to tactile stimulation. Toxicity tests showed that the coelomic fluid of these urchins contained traces (2–5 ppm) of the kerosene fraction from the detergent. It is concluded that the scars are the direct or indirect result of pollution since these marks have not been previously recorded from normal populations.

Table 14. *Effects of detergents on development of oyster larvae*

Concn. (ppm)	Proportions of swimming larvae developed to D-stage: Control	Polyclens	Houghton Solv. 112	BP 1002	Slip-clean	Dasic	Gamlen
0	+++	.	.	.	.	.	.
0·5	.	o	o	+++	+++	+++	+++
1·0	.	o	o	+++	++	+	++
3·0	.	o	o	+	+	o	+

+++ = all, ++ = some, + = a few, o = none developed.

a concentration of 3 ppm and that some, particularly Polyclens and Houghton Solv. 112, appeared to have effects at 1·0 and 0·5 ppm.

In earlier experiments, made with *Ostrea edulis*, six types of detergent were tested for their effects on the growth of larvae of *O. edulis*. The results are shown in Fig. 25, from which it is apparent that concentrations of detergent in the range 2·5–7·5 ppm can halve the normal rate of development over two days.

Lacuna vincta (*the banded chink shell*) *and* Nassarius reticulatus (*the netted dog-whelk*)

These are larvae of shore-living gastropod molluscs, but like the nauplii of the barnacle *Elminius* they spend their life in the plankton until they settle on the shore and turn into adults. They were hatched from egg capsules and maintained in filtered sea water at 10 °C. When treated with detergent the larvae became opaque and were invaded by ciliates, which removed the soft tissues to leave an empty shell. The results are shown in Table 15.

Nassarius is obviously the more resistant species. Further experiments showed that at a concentration of 1·0 ppm of detergent the larvae of *Nassarius* recovered their customary activity after 36 hours and, ten days later, were still swimming and feeding normally.

Table 15. *Effect of BP 1002 on week-old larvae of* Lacuna *and* Nassarius

Species	Concn. (ppm)	% dead after: 2 days	4 days	10 days
Lacuna vincta (banded chink shell)	20	100	.	.
	2	100	.	.
Nassarius reticulatus (netted dog-whelk)	20	.	100	.
	10	.	.	70

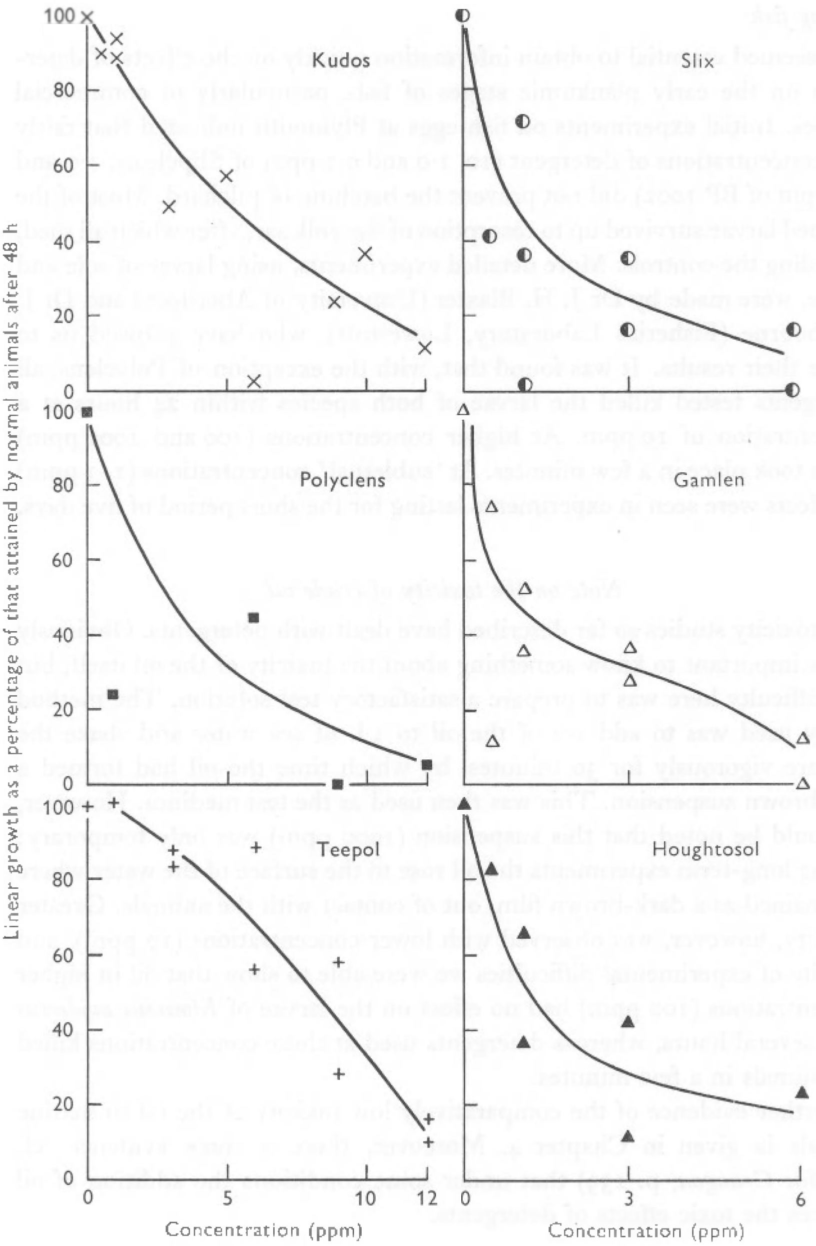


Fig. 25. Effect of various detergents on the growth of larvae of *Ostrea edulis*. Note the difference in the horizontal scale on the two sides of the figure, and the greater toxicity of the hard detergents on the right.

Young fish

It seemed essential to obtain information quickly on the effects of detergents on the early planktonic stages of fish, particularly of commercial species. Initial experiments on fish eggs at Plymouth indicated that fairly low concentrations of detergent (10, 1·0 and 0·1 ppm of Slipclean; 1·0 and 0·1 ppm of BP 1002) did not prevent the hatching of pilchard. Most of the hatched larvae survived up to resorption of the yolk sac, after which all died, including the controls. More detailed experiments, using larvae of sole and plaice, were made by Dr J. H. Blaxter (University of Aberdeen) and Dr J. Shelbourne (Fisheries Laboratory, Lowestoft), who have allowed us to quote their results. It was found that, with the exception of Polyclens, all detergents tested killed the larvae of both species within 24 hours at a concentration of 10 ppm. At higher concentrations (100 and 1000 ppm) death took place in a few minutes. At 'sublethal' concentrations (1–3 ppm) no effects were seen in experiments lasting for the short period of five days.

Note on the toxicity of crude oil

The toxicity studies so far described have dealt with detergents. Obviously it was important to know something about the toxicity of the oil itself, but the difficulty here was to prepare a satisfactory test solution. The method finally used was to add 1 g of the oil to 1 l. of sea water and shake the mixture vigorously for 30 minutes, by which time the oil had formed a pale-brown suspension. This was then used as the test medium. However, it should be noted that this suspension (1000 ppm) was only temporary: during long-term experiments the oil rose to the surface of the water where it remained as a dark-brown film, out of contact with the animals. Greater stability, however, was observed with lower concentrations (10 ppm), and in spite of experimental difficulties we were able to show that oil in higher concentrations (100 ppm) had no effect on the larvae of *Elminius modestus* after several hours, whereas detergents used at these concentrations killed the animals in a few minutes.

Further evidence of the comparatively low toxicity of the oil to marine animals is given in Chapter 4. Moreover, there is some evidence (cf. data for *Crangon*, p. 139) that under some conditions the addition of oil reduces the toxic effects of detergents.

Conclusions

The studies described in this section were of an exploratory nature, having been conducted over a period of ten weeks in response to a local disaster.

Nevertheless the results are unambiguous and the experiments left no doubt that the detergents used for emulsifying crude oil from the 'Torrey Canyon' were extremely toxic to marine planktonic animals. The experiments also showed that the very small members of the zooplankton are particularly susceptible to the toxic effects of detergents, and this could be serious in the sense that these animals—the microzooplankton—are now regarded as an extremely important part of the food-web in the sea (Johannes, 1961).

The overall biological effect of the detergents in the sea clearly depends on the persistence of the toxic principles. It was therefore desirable to know the relative toxicity of the several components of the detergents and their likely persistence. The experiments described in section V of this chapter are relevant to this question.

II. LONGER-TERM EFFECTS ON ZOOPLANKTON

In describing the experiments on the *Sabellaria* larvae (p. 145) the presence of a delayed effect was noted. To examine this further, and to see if it was evident in other species, some longer-term experiments were undertaken using sublethal concentrations of detergent. The species used for these experiments were *Sabellaria spinulosa*, *Elminius modestus* and *Echinus esculentus*. All are coastal animals having free-swimming planktonic larvae.

Sabellaria *larvae*

Larvae of *Sabellaria spinulosa* (Fig. 22A) were placed in Monax dishes, about a third to a half full, loosely covered with watch-glasses. Concentrations of 1 ppm and 0·5 ppm BP 1002 were tested with thirty larvae per dish. There was an immediate reaction to 1 ppm detergent, the animals flexing their bodies ventrally and erecting their provisional bristles to point in all directions (Fig. 22B). However, in the 0·5 ppm solution only about half the larvae reacted strongly: the remainder continued to swim but were irritable compared with the control animals. A little *Isochrysis* culture was added to all dishes after 2 hours, and overnight there was complete recovery of the larvae in 0·5 ppm, but not until two days had elapsed did those in 1 ppm appear to behave normally. At this time new larvae put into this dish showed no irritation, the irritant factor having disappeared. These two dishes and the control dish were kept supplied with *Isochrysis* for food, and all the larvae were apparently healthy and normal three weeks later. However, the experiment was continued, with the interesting result that after four weeks all the larvae in the solution which had originally contained 1 ppm of detergent were found to be lying motionless on the bottom of the dish, in very poor condition. They were still surviving after six weeks, but were then in an even worse state and had hardly grown. Meanwhile, those which had originally been in a solution of 0·5 ppm detergent had become sluggish—but were still growing—after five weeks; however, during the sixth week they lay motionless, apart from an occasional twitch of the bristles. During all this time the animals used as a control sample were healthy, active and growing well.

The experiment therefore showed that the toxicity of BP 1002 still persisted, even after the organic solvent had evaporated, for after a prolonged period of apparent normality the larvae eventually succumbed.

Elminius *larvae*

Freshly liberated stage II larvae of *Elminius* (cf. Fig. 22G) were reared in small vessels, with diatoms as food. The cultures were subsampled at intervals to estimate the percentage of mortality and the stage of development reached. All cultures were kept in loosely covered dishes and it is believed that the initial toxicity of those containing detergent was lost within the first few days. Thus, the experiments were equivalent to a short exposure to poison followed by a long period of recovery.

In the first series of experiments, using BP 1002, Gamlen and Slipclean at concentrations of 5·0, 1·0 and 0·5 ppm, and also 'Torrey Canyon' oil at 100 ppm, *Phaeodactylum tricornutum* was used as the main food. This diatom is known to be an indifferent food for *Elminius* (Moyse, 1963) and in addition the cultures were rather crowded. The final mortality was therefore high in all cultures, although initially much higher in those containing detergent at 5·0 and 1·0 ppm and oil at 100 ppm. The results are given in Table 16 and Fig. 26. At low concentrations of detergent (0·5 ppm) there was a slight delay in development compared with the controls, but after a week little difference was discernible. In the presence of oil and with medium concentrations of detergent (1 ppm) development was delayed by about two or three days throughout the experiment, the least effect being shown by Gamlen and Slipclean, and the most by BP 1002: all these cultures reached the cyprid stage, although those in BP 1002 failed to metamorphose and settle even when provided with suitably prepared surfaces—that is, cleaned shells of *Mytilus edulis* which had borne live *Elminius modestus* (see Knight-Jones, 1956). At the higher concentrations of detergent (5 ppm) more than 50 per cent of the larvae died the first day. Of the survivors, those in Gamlen failed to develop at all and died while at stage II. Most of the Slipclean survivors reached stage III four days behind the controls and then died, although a few individuals developed as far as stage VI. The survivors of BP 1002 recovered after seven days at stage II

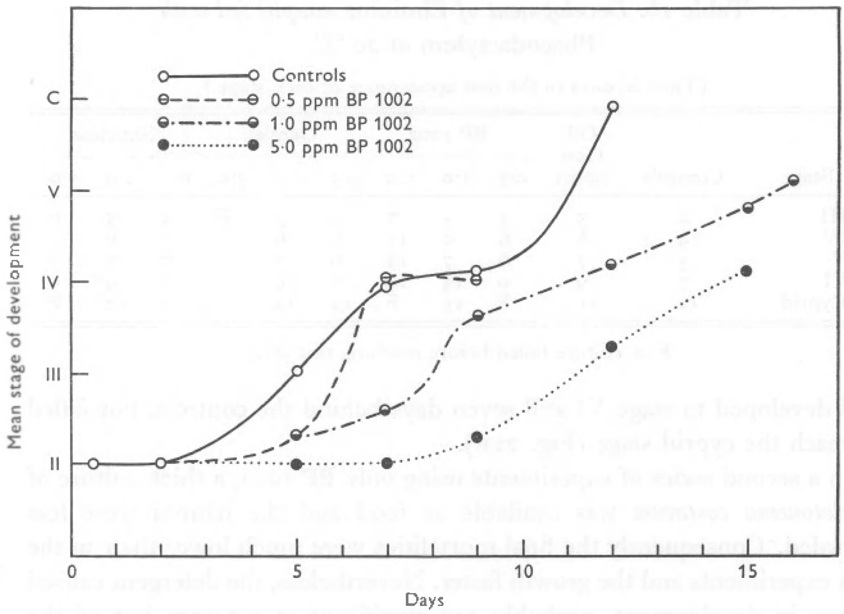


Fig. 26. Rate of development of larvae of *Elminius modestus* reared on *Phaeodactylum tricornutum* at 20 °C in the presence of different concentrations of BP 1002. Nauplius stages shown in Roman numerals; C, Cypris stage.

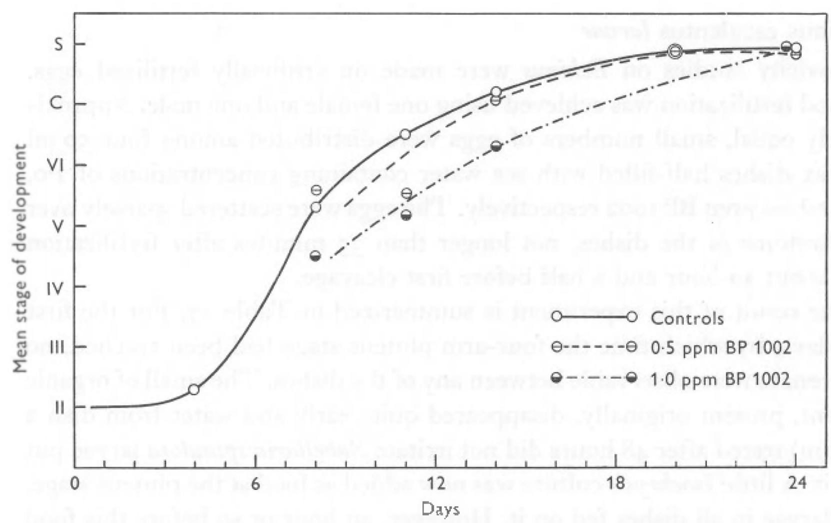


Fig. 27. Rate of development of larvae of *Elminius modestus* reared on *Skeletonema costatum* at 20 °C. Nauplius stages shown in Roman numerals. C, Cypris stage; S, settlement and metamorphosis.

Table 16. *Development of* Elminius *nauplii fed with* Phaeodactylum *at 20 °C*

(Time in days to the first appearance of each stage.)

Stage	Controls	Oil (100 ppm)	BP 1002			Gamlen			Slipclean		
			0·5	1·0	5·0	0·5	1·0	5·0	0·5	1·0	5·0
III	2	5	5	5	7	5	5	F	4	5	6
IV	4	6	6	6	11	6	6	.	5	6	7
V	5	7	6	7	12	6	7	.	7	7	7
VI	7	9	9	13	14	7	9	.	9	9	9
Cyprid	12	15	F	15	F	12	12	.	F	12	F

F = culture failed before reaching this stage.

and developed to stage VI still seven days behind the controls, but failed to reach the cyprid stage (Fig. 22H).

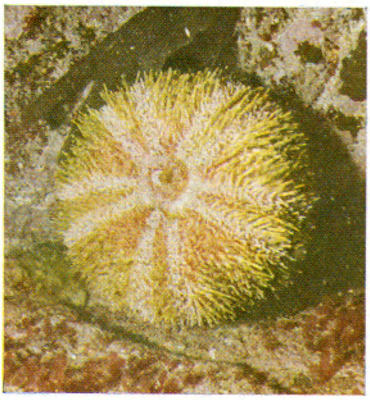
In a second series of experiments using only BP 1002, a thick culture of *Skeletonema costatum* was available as food and the nauplii were less crowded. Consequently the final mortalities were much lower than in the first experiments and the growth faster. Nevertheless, the detergent caused delays in development, probably not significant at 0·5 ppm but of the order of three days at 1 ppm (see Fig. 27). At the latter concentration only a few cyprids were produced and very few of them metamorphosed and settled (0·6 per cent of the original larvae) compared with the controls (10 per cent of the original larvae).

Echinus esculentus *larvae*

Toxicity studies on *Echinus* were made on artificially fertilized eggs. A good fertilization was achieved using one female and one male. Approximately equal, small numbers of eggs were distributed among four 50 ml Monax dishes half-filled with sea water containing concentrations of 1·0, 0·5 and 0·1 ppm BP 1002 respectively. The eggs were scattered sparsely over the bottoms of the dishes, not longer than 35 minutes after fertilization and about an hour and a half before first cleavage.

The result of this experiment is summarized in Table 17. For the first five days, by which time the four-arm pluteus stage had been reached, no differences were observable between any of the dishes. The smell of organic solvent, present originally, disappeared quite early and water from dish 2 (1 ppm) tested after 48 hours did not irritate *Sabellaria spinulosa* larvae put into it. A little *Isochrysis* culture was now added as food at the pluteus stage, and larvae in all dishes fed on it. However, an hour or so before this food was added, and some hours after assessment of their condition recorded in Table 17, some of the plutei in dish 2 began to 'reduce' the lengths of their

A



B

C

D

(*Facing p.* 129)

Table 17. *Development of* Echinus esculentus *in concentrations of BP 1002*

Date	Dish 1 (sea-water control)	Dish 2 (1 ppm)	Dish 3 (0·5 ppm)	Dish 4 (0·1 ppm)
5. iv. 67	Eggs distributed to all dishes half an hour after fertilization			
6. iv. 67	Normal blastulae	Normal blastulae	Normal blastulae	Normal blastulae
7. iv. 67	Normal gastrulae	Normal gastrulae	Normal gastrulae	Normal gastrulae
10. iv. 67	Normal plutei	Normal plutei	Normal plutei	Normal plutei
11. iv. 67	Majority normal, a few with reduced arms	All with much reduced arms	Majority with partially reduced arms	Majority normal, a few with reduced arms
12. iv. 67	Majority normal and growing	All poor, with stumpy arms	Majority with short arms, some normal	Majority normal and growing

arms; that is to say the flesh of the arms began to shrink down the skeletal rods, which, left protruding, broke off. This is always a sign of ill health. By next day all plutei in this dish had all their arms reduced to mere stumps, although their stomachs were well filled with food. In dish 3 (0·5 ppm) arm-reduction began later, not all plutei were affected and there was some recovery subsequently. But there was very little recovery in dish 2. Almost all the plutei in dish 1 (control) and dish 4 (0·1 ppm) continued to be in excellent growing condition, only a very few in both dishes having reduced arms (as almost invariably happens under even the best rearing conditions).

Too much should not be read into this single experiment. It is of interest only in that it confirms the earlier demonstration of a long-term toxic effect on other species of some component of BP 1002

III. TOXICITY STUDIES ON PHYTOPLANKTON

In order to grow phytoplankton organisms for experimental work it is necessary to keep the culture media well aerated by vigorous bubbling.

PLATE 26

A, 130–150 metres from the breakwater at Porthleven in 5 metres of water, 5 April. Fluorescent orange *Delesseria sanguinea* which has been affected by detergent and was found growing at the top of a gully on the sea-bed. The *Delesseria* is normally the same colour as the alga seen growing behind it. **B**, Sennen Cove, 7 April. Underwater photograph of a dead *Echinus esculentus* (edible sea-urchin) resting upside-down in a gully between rocks at a depth of 10–11 metres. Normally in healthy individuals the tube feet are conspicuously extended. **C**, Porthleven Reef, 28 April. Underwater photograph of the sea-bed at a depth of 17 metres (dive no. 21). Dead *Echinocardium cordatum* and *Mactra corallina* with healthy *Asterias rubens* and *Marthasterias glacialis* feeding on them. **D**, Constantine Bay, 8 April. Shells of recently killed molluscs in the drift line. Mussels, limpets, winkles and dog-whelks are all represented.

This greatly reduced the level of the organic solvent 'Kex' in BP 1002 (see page 145), and for this reason the following section deals in effect with only the surfactant components of the detergent.

The six following phytoplankton species were used: 64, *Phaeocystis pouchetii*; 81, *Dunaliella primolecta*; 85, *Chlorella stigmatophora*; 92, *Coccolithus huxleyi*; 205, *Halosphaera minor*; 207, *Gymnodinium* sp. The numbers are those used in the Plymouth culture collection.

The growth curves for each of these species were measured at 12 °C in sea water, initially filtered through an Oxoid membrane and autoclaved, and then enriched as follows: nitrate 10^{-4} g ions/l.; phosphate 10^{-5} g ions/l.; vitamin B_{12} 5·5 μg/l.; manganese 2 μg/l.; iron (as citrate) 50 μg/l. The cultures were subjected to alternating periods of 12 hours of darkness and 12 hours of light at about 600 foot-candles, and were vigorously aerated. One hour before inoculation, BP 1002 with known proportion of surfactant was added to the sea water at different concentrations. The aeration during the subsequent hour has been shown to cause the removal of most of the volatile kerosene solvent in the emulsifier. A fifth culture vessel containing no BP 1002 was used as a control.

Cell counts were made on each culture vessel 1 hour after inoculation and then daily for 12 days, using a Coulter Counter Model F; the inocula were obtained from Plymouth stock cultures.

From plots of the logarithm of cell numbers per ml against time, the length of the initial slow-growing phase (lag phase) and the mean generation time for each culture have been obtained. These are given in Tables 18 and 19.

Inhibition of growth is indicated by an increase in the length of the lag phase and the mean generation time in relation to the control. The two genera least affected by the surfactants were *Dunaliella* and *Chlorella*, both of which are characteristic of brackish-water plankton. At the highest concentration examined (1·2 ppm of surfactant) the lag phase for *Chlorella* was increased by a factor of three relative to the control, a result indicating some retardation in metabolism, but it grew at the same rate as in the other concentrations. At 1·2 ppm surfactant the other genera examined were destroyed in the hour between inoculation and the first cell count. The *Gymnodinium* proved to be the most vulnerable to the surfactant, with the growth rate almost halved at surfactant concentrations of $1{\cdot}2 \times 10^{-2}$ and $1{\cdot}2 \times 10^{-1}$ ppm, although, surprisingly, the length of the lag phase was about the same as in the control. An apparently paradoxical effect was noted at the lowest concentrations with certain species, notably *Coccolithus*. Here the mean generation time was shortened by about one-third, indicating a growth-promoting effect of the detergent. There are, however,

Table 18. *The length of the lag phase (in days) at various concentrations of the surfactant component of BP 1002*

Phytoplankton	Surfactant concentration (ppm) 0	$1 \cdot 2 \times 10^{-3}$	$1 \cdot 2 \times 10^{-2}$	$1 \cdot 2 \times 10^{-1}$	1·2
64 *Phaeocystis pouchetii*	—	1·4	0·4	0·4	Cells killed
81 *Dunaliella primolecta*	2·2	1·2	2·0	2·0	2·5
85 *Chlorella stigmatophora*	0·8	0·9	0·9	0·9	2·5
92 *Coccolithus huxleyi*	0·25	0·35	0·35	0·35	Cells killed
205 *Halosphaera minor*	0·2	0·3	0·5	0·3	Cells killed
207 *Gymnodinium* sp.	1·2	2·6	1·7	0·9	Cells killed

Table 19. *The mean generation time (in days) at various concentrations of the surfactant component of BP 1002*

Phytoplankton	Surfactant concentration (ppm) 0	$1 \cdot 2 \times 10^{-3}$	$1 \cdot 2 \times 10^{-2}$	$1 \cdot 2 \times 10^{-1}$	1·2
64 *Phaeocystis pouchetii*	—	1·0	1·0	1·0	Cells killed
81 *Dunaliella primolecta*	1·2	1·1	1·1	1·1	1·0
85 *Chlorella stigmatophora*	1·2	1·1	1·1	1·1	1·2
92 *Coccolithus huxleyi*	1·6	1·1	1·1	1·1	Cells killed
205 *Halosphaera minor*	1·6	1·5	1·2	1·6	Cells killed
207 *Gymnodinium* sp.	3·8	3·2	7·3	7·3	Cells killed

indications that cells grown under such artificial stimulatory conditions are abnormally fragile (Kidder, Dewey & Heinrich, 1954).

Non-ionic surfactants adsorb on to cell membranes by interaction of the hydrophobic portion of the surfactant with the lipoidal constituents of the membranes. This results in an increase in the permeability of the cell wall, facilitating the passage of dissolved substances both into and out of the cell. At sufficiently high surfactant concentrations the cell constituents are able to leak out from the cell, causing its death (Hotchkiss, 1946). The brackish-water *Dunaliella* and *Chlorella*, which proved the most resistant to the surfactant, are well adapted for ionic regulation (that is, controlling the passage of ions across their cell walls); they might therefore be expected to tolerate changes in the permeability of the cell wall more easily than the strictly marine species.

IV. TOXICITY STUDIES ON INTERTIDAL AND SUBLITTORAL ORGANISMS

Intertidal algae

The familiar seaweeds of the shore were often exposed to very high concentrations of detergent during the beach-cleaning operations. To investigate the effect on the shore vegetation, detailed tests were made by Dr A. D. Boney of Aberystwyth on four chosen intertidal species. These were the green filamentous alga *Cladophora rupestris*, the brown knotted wrack *Ascophyllum nodosum*, the red algae *Polysiphonia lanosa* (a filamentous form often epiphytic on *Ascophyllum*) and the thalloid *Porphyra umbilicalis* (sometimes known as laver).

The technique employed was to immerse the weed in detergent solutions of a wide range of strengths for varying periods, usually 3 or 6 hours, in some ways simulating conditions which might have been encountered on the shore, except that no freshwater mixtures were used. After immersion the weeds were rinsed with clean sea water and any gross damage could be seen at once. They were kept in clean sea water for 24 hours before being examined microscopically for signs of cell damage, such as shrinking of the protoplasm, loss of pigment, etc. The results are here given only in outline. On the whole, seaweeds are very much more tolerant of detergent than are intertidal animals. Indeed *Porphyra umbilicalis* and *Polysiphonia lanosa* showed no damage detectable by the microscope even after 6 hours immersion in the undiluted detergent. These short-term experiments suggested an unexpectedly strong resistance to detergent treatment not in accord with the bleaching of *Porphyra* and discoloration of other red algae often seen on the shore, although this could generally have been due to the action of fresh water with which the detergent was diluted. Tests carried out on the sublittoral red alga *Delesseria* (see page 137) perhaps suggest a further reason for the apparent discrepancy, in that this alga may take several days to show the effects of damage in sea water. The cell walls of *Porphyra* and *Polysiphonia* must presumably be very impermeable to the constituents of the detergents when uninfluenced by fresh water.

With *Ascophyllum nodosum* (one of the brown shore weeds) the investigation was confined to the reproductive cells which were active at the time of the investigation and were chosen as being likely to be the most sensitive indicators of toxicity. Six hours immersion in a 25 per cent solution of detergent caused irreversible cell damage to the reproductive cells themselves and also to the cells of the receptacle in which the reproductive cells lie before release. In detergent at 12 per cent concentration cell damage was very slight or absent, depending on the type of detergent used. In fact six proprietary brands of detergents were used for all the tests, but the difference in the degree of damage caused by the different brands was not significant.

After they were released from the parent plant the reproductive cells, the spermatozoids and the oospheres, were extremely sensitive, a brief exposure to 0·01 per cent solutions (that is, 100 ppm) being sufficient to kill them.

The green seaweed *Cladophora rupestris* was the most sensitive of the species tested. Here the reproductive cells were not accessible to study and the examination was concentrated on the apical cells of the filaments, which, being the growing points, were judged to be the most sensitive. Here, severe damage was noted after 6 hours immersion in 6 per cent solutions of all detergents (except BP 1002, which was apparently harmless at this concentration). There was less severe, but irreversible damage down to about 1 per cent concentration.

Intertidal animals—toxic effects of BP 1002

During shore-spraying operations the intertidal animals and plants were exposed to very high concentrations of detergent for periods of up to several hours and the expected mortalities described in Chapter 4 were soon evident to the shore observers. Nevertheless, the intertidal species are, as a group, constitutionally very tough, and many of them, the bivalves for example, are able to seal themselves off from a hostile environment for long periods, later to emerge unharmed. It therefore seemed profitable to examine some of these animals for their resistance to detergent poisoning.

The first experiments were only crude, and involved placing animals in sealed containers filled with sea water to which various amounts of detergent were added. The concentrations ranged from 0·2 to 100 ppm. The animals were left in the sealed containers for 24 hours before being removed to fresh sea water and their recovery observed. The containers were large enough to avoid any danger of oxygen deprivation. The results of these preliminary tests are summarized in Table 20.

A few species were selected for more careful study.

Mussels. Specimens of the common mussel, *Mytilus edulis*, 40–50 mm long collected from low-water neap-tide level were used in two sets of experiments. All survived 24 hours exposure to 5 ppm detergent (BP 1002), but 10 ppm and over was lethal within 24 hours. A good guide to the condition of *Mytilus* is its ability to reattach itself to the substratum after disturbance by the extrusion of new byssal threads. In 1 ppm detergent all the mussels had attached in 24 hours and in 5 ppm 60 per cent of the animals had attached, but there was no sign of new byssal threads in 10 ppm and over. Exposed to crude oil in 1000 ppm suspension the mussels all survived the 24-hour period but there was no attachment.

Experiments with *Mytilus galloprovincialis* in the Black Sea (Aljakrinskaya, 1966) reveal that high levels of oil in sea water (up to 2 per cent) can be tolerated by mussels, which remove it from suspension by means of their cleansing mechanisms. It should not be overlooked, however, that

Table 20. *Toxicity of BP 1002 to some intertidal species at 12 °C*

Species	Popular name	Conc. (ppm) needed to kill majority in 24 h	Notes
Coelenterata			
Actinia equina	Beadlet anemone	25	Some young animals survived 25 ppm
Anemonia sulcata	Snakelocks anemone	50	Some looked dead but later recovered
Annelida			
Nereis diversicolor	Rag-worm	25	A few survived this concentration
Crustacea			
Eurydice pulchra	Isopod	10	Some killed at 5 ppm
Carcinus maenas	Shore-crab	25	—
Cancer pagurus	Edible crab	10	—
Palaemon serratus	Prawn	5	—
Crangon vulgaris	Shrimp	2	—
Mollusca			
Nucella lapillus	Dog-whelk	100 +	Became detached at 10 ppm
Monodonta lineata	Top-shell	100	—
Littorina littorea	Winkle	100	Some could recover from 100 ppm
Calliostoma zizyphinum	Painted top-shell	10	Became detached at 2 ppm
Aplysia punctata	Sea hare	50	Became detached at 10 ppm
Patella vulgata	Limpet	5	Dying limpets frequently but not always release their attachment to the substrate

even low levels of detergent may inhibit the natural cleansing mechanism and thus reduce the mussel's tolerance to oil.

Limpets. The common limpet *Patella vulgata* was found in abundance dead and dying on the detergent-treated shores.

Experiments were made with small animals (about 25 mm length) carefully collected from an unpolluted beach, while they were actively moving. This avoids damage to the foot, as occurs if the animals are prised from their seats. The limpets were allowed to attach to glass plates kept in clean sea water overnight, and the water was then replaced by the test solutions shown in Table 21, which summarizes the results of the experiments.

The sensitivity to low concentrations of detergent is in accord with the high mortality of limpets noted in the field observations.

Top-shells and winkles. An experiment on the top-shells *Monodonta lineata* and *Gibbula umbilicalis*, and the winkle *Littorina littorea*, showed that the normal climbing response, observed when the animals are kept in

Table 21. *Toxicity of BP 1002 to* Patella

	Control	BP 1002 100 ppm	BP 1002 10 ppm	BP 1002 1 ppm
Behaviour of pallial tentacles	All expanded	All withdrawn	All withdrawn	Withdrawn at first but 75% recovered after 3 h
% attachment of foot after 18 h	100% living	All dead	All dead or dying	80% recovered

Table 22. *Effect of oil and BP 1002 on cirral (limb) beat of very young* Elminius modestus

	Control	BP 1002 100 ppm	BP 1002 10 ppm	Kuwait crude oil Film (1000 ppm)	Kuwait crude oil Suspension (100 ppm)
Initial Activity	60–80% fast beat	50% stopped cirral beat	50% normal beat	50% normal beat	50% normal beat
1 h	60–80% fast beat	50% stopped cirral beat	Pumping beat only	50% normal beat	50% normal beat
24 h	.	Dead	Few active	.	.
48 h	40% fast beat 40% normal beat	.	Dead	28% active	10% active

beakers of sea water, was inhibited by 10 ppm of BP 1002. The animals were partly withdrawn into the shell, and only the *Monodonta* survived three days immersion (by which time the toxicity was reduced by evaporation) and were able to climb out of the water. A detergent concentration of 1 ppm impaired activity in all three species but did not prove lethal.

The results of laboratory tests with the above species are again reflected in the observations on treated shores (Chapter 4) where there has been heavy mortality of winkles and top-shells. In places where the treatment has been light enough to give the animals a chance of survival *Monodonta* and *Nucella* have been the most tenacious.

Barnacles. Experiments made on *Elminius modestus* larvae (p. 118) were followed by others on the susceptibility of later stages to detergent poisoning. The effect on settlement and metamorphosis was first examined because this is a very critical stage in the life of a barnacle. Cleaned shells of *Mytilus* that had borne *Elminius* adults were placed in dilutions of BP 1002, and ten cyprids added to each. At 5 ppm and over the cyprids ceased swimming (see Fig. 30, page 141) and died in two days. At 3 ppm swimming stopped after 24 h and the cyprids died in four days without settling. At 1 ppm swimming was unaffected and many of the cyprids settled and metamorphosed. The newly settled adult form ('spat') is another critical stage on which experiments were also made. Shells bearing recently settled spat were exposed (1) to different concentrations of BP 1002, (2) to a film of Kuwait crude oil on the surface of sea water, and (3) to sea water that had been mechanically shaken for 5 minutes with the oil. The results are shown in Table 22, cirral activity (that is, limb movements) being assessed in the way described by Crisp & Southward (1961).

These data show that the young, recently metamorphosed barnacle is more resistant than the larval stages to poisoning by detergents. Nevertheless, BP 1002 at a concentration of 10 ppm was ultimately lethal. Moreover Kuwait oil had an obvious depressing effect on cirral activity, and hence on feeding, and would thus inhibit growth.

Fully grown specimens of *Elminius* attached to mussel shells collected from low water of neap tides were also tested. They were treated with various concentrations of BP 1002, and with water that had been mechanically shaken for 30 minutes with 'Torrey Canyon' oil collected from a beach at St Ives during the first few days contamination. The vessels were not covered and so it is probable that the detergent lost toxicity in 24 hours. At a concentration of 100 ppm the barnacles became inactive and some died; the rest showed some cirral activity after 24 hours.

Detergent at concentrations of 5 and 10 ppm and oil at concentrations of 100 ppm slowed the rate of cirral beating by 25–35 per cent.

Sublittoral organisms—toxic effects of BP 1002

The observations reported in Chapter 6 show how detergents sprayed on the shore can lead to an expanding front of toxic water spreading to appreciable distances along the coast, over the surface and down to the sea-bed. Divers exploring offshore reaches of the sea-bed found a variety of dead and moribund animals whose habits and habitat precluded any suggestion that they had been killed on the shore and subsequently washed seawards. To complete this picture toxicity experiments were made with a selection of sublittoral species. The results of these are reported below and are sufficient to verify that the divers with their restricted range of vision and coverage saw a typical, but only a small, sample of the offshore consequences of the beach-cleaning operations.

Tolerance of various sublittoral species. The method used was the same as that already described on page 133. Table 23 gives some results for a number of species that live below the low-water mark. As might be expected, they are more sensitive than the intertidal animals. However, for a crustacean,

Table 23. *Toxicity of BP 1002 to some sublittoral species at 12 °C*

Species	Common name	Concn. (ppm) needed to kill majority in 24 h	Notes
Coelenterata			
Calliactis parasitica	Sea anemone	25	Stayed closed at 5 ppm
Crustacea			
Corystes cassivelaunus	Masked-crab	10	·
Portunus holsatus	Swimming-crab	5	·
Diogenes pugilator	Hermit-crab	25	·
Mollusca			
Nassarius reticulatus	Netted whelk	2·5	Some survived 2·5 ppm
Chlamys opercularis	Queen scallop	1	Affected at 0·5 ppm (tended to gape)
Laevicardium crassum	Smooth cockle	1	Affected at 0·5 ppm (tended to gape)
Spisula subtruncata	Trough-shell	2	Affected at 1 ppm (tended to gape)
Ensis siliqua	Razor-shell	0·5	·
Echinodermata			
Asterias rubens	Common starfish	25	Climbing stopped at 10 ppm
Ophiocomina nigra	Brittle-star	5	Affected at 2 ppm
Algae			
Delesseria sanguinea	Red seaweed	10	Took several days to change colour

Diogenes (a hermit crab) is remarkably resistant. Another fairly resistant species was the common starfish, *Asterias rubens*, which during the diving programme (p. 113) was seen feeding on other animals killed by the detergent.

Although it is one of the most sensitive seaweeds and becomes 'fluorescent' orange when killed (Plate 26A), the red weed *Delesseria* when treated with 0·001 per cent detergent took several days to change colour.

Bivalve molluscs were the most sensitive of the animals which were examined. Of these the razor-shell *Ensis siliqua* is the most susceptible to poisoning and was killed by 0·5 ppm of detergent. Results of the diving programme (p. 113) show that *Ensis*, together with the clam, *Mactra stultorum*, was killed at a distance of at least 1 kilometre off Porthleven. It therefore seems likely that detergent–oil patches having concentrations of about 0·5 ppm at the level of the sea-bed had moved through these areas.

Shrimps. Details of the use of the shrimp *Crangon vulgaris* in toxicity experiments are given under 'Bioassay'. The same method was used in order to test the relative toxicity of several detergents and the results are

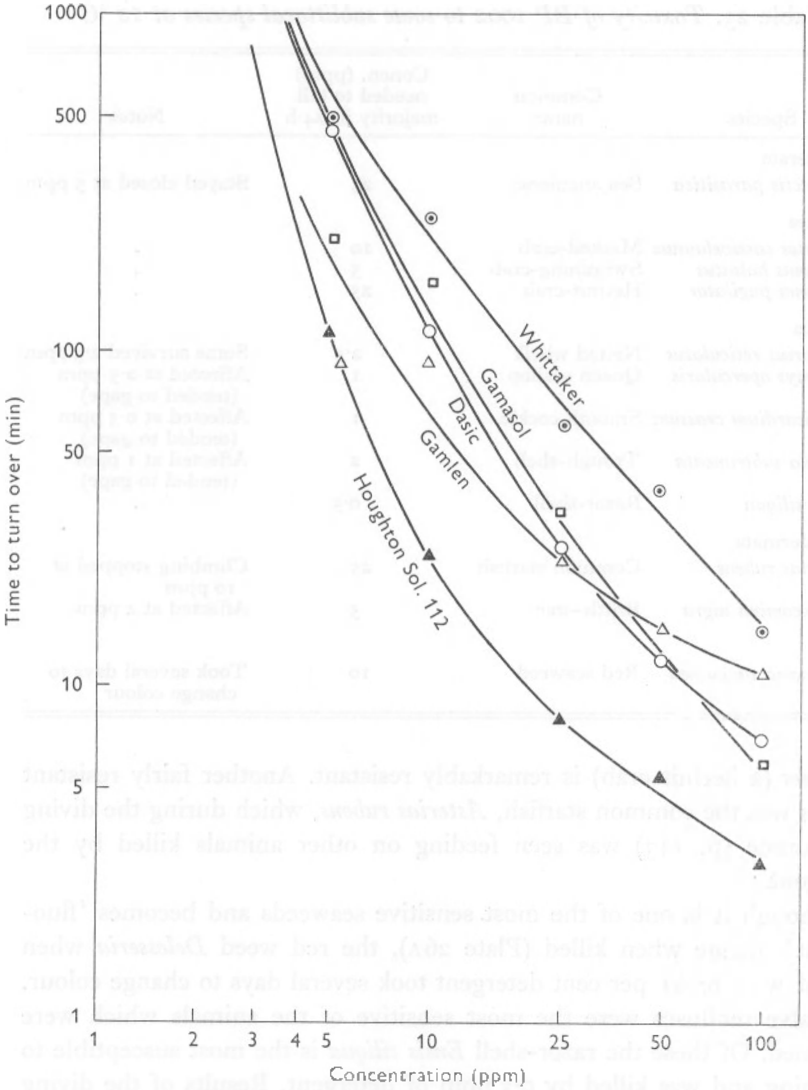


Fig. 28. Relationship between concentrations of different detergents and the mean times taken by *Crangon vulgaris* to turn over. (For 'Gamasol' read 'Gramosol'.)

shown in Fig. 28. As with similar experiments carried out on *Elminius*, the curves were not parallel: thus, whereas Gamlen was less toxic than Dasic and Gramosol at 100 ppm, it was more toxic at 5, 10 and 25 ppm. Comparison of these data with those for BP 1002 in Fig. 29 shows that at concentrations below 10 ppm BP 1002 was the most toxic detergent; this

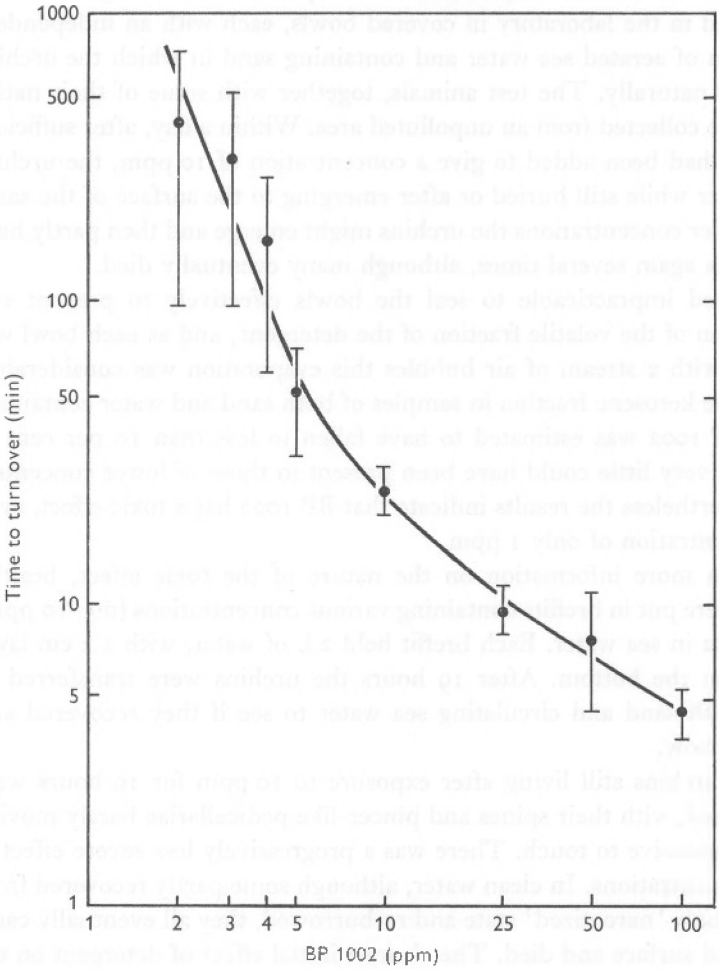


Fig. 29. Relationship between concentration of BP 1002 and the mean time for *Crangon vulgaris* to turn over. Vertical lines show the range of the standard deviation at each concentration.

again agrees in general with the *Elminius* results. In addition, it was found that a mixture of BP 1002 and Kuwait crude oil (equal volumes giving a concentration of 10 ppm detergent) was less toxic than the detergent used alone, the toxicity being reduced by some 30–40 per cent.

Sand-urchins and their 'commensals'. In view of the extensive mortalities of the heart-urchin, *Echinocardium cordatum*, off beaches cleaned with toxic chemicals, the effect of the detergent BP 1002 on it was tested in the laboratory.

The sand-urchin normally burrows to a depth of about 10–15 cm. It was maintained in the laboratory in covered bowls, each with an independent circulation of aerated sea water and containing sand in which the urchins burrowed naturally. The test animals, together with some of their native sand, were collected from an unpolluted area. Within a day, after sufficient detergent had been added to give a concentration of 10 ppm, the urchins died, either while still buried or after emerging to the surface of the sand. But at lower concentrations the urchins might emerge and then partly bury themselves again several times, although many eventually died.

It proved impracticable to seal the bowls effectively to prevent any evaporation of the volatile fraction of the detergent; and as each bowl was supplied with a stream of air bubbles this evaporation was considerable. In fact, the kerosene fraction in samples of both sand and water containing 5 ppm BP 1002 was estimated to have fallen to less than 10 per cent in five days; very little could have been present in those of lower concentration. Nevertheless the results indicate that BP 1002 has a toxic effect, even at a concentration of only 1 ppm.

To gain more information on the nature of the toxic effect, healthy urchins were put in breffits containing various concentrations (0·5–10 ppm) of BP 1002 in sea water. Each breffit held 2 l. of water, with a 2 cm layer of sand on the bottom. After 19 hours the urchins were transferred to a bowl with sand and circulating sea water to see if they recovered and would burrow.

Those urchins still living after exposure to 10 ppm for 19 hours were immobilized, with their spines and pincer-like pedicellariae barely moving and unresponsive to touch. There was a progressively less severe effect at lower concentrations. In clean water, although some partly recovered from the seemingly 'narcotized' state and re-burrowed, they all eventually came to the sand surface and died. The clearest initial effect of detergent on the activities of burrowed urchins was an arrested forward movement. A toxic effect was found above about 0·5 ppm. A small bivalve, *Montacuta ferruginosa*, and an amphipod crustacean, *Urothoë grimaldi*, both under 1 cm long, are common 'commensals' with the sand-urchin. Animals were tested in small, sealed bottles (150 ml capacity) holding various concentrations (0·1–50 ppm) of BP 1002, at least two specimens of each species being placed in each bottle for 12 hours. The *Urothoë* died when the detergent was above 5 ppm and appeared unaffected by lower concentrations. *Montacuta*, on the other hand, showed a graded effect: the bivalves died quickly in 50 ppm, but recovered in clean sea water from a 'narcotized' state with their valves gaping after exposure to lower concentrations. Concentrations below 1 ppm did not seem to have any effect.

V. BIOASSAY

The chemical methods of analysis described in Chapter 2 (p. 19) are potentially very accurate for estimating detergent concentration under well-controlled conditions, but they are attended by several defects which make them unsuitable for the testing of water samples, collected at sea or from the shore. The worst of these defects is that they estimate only

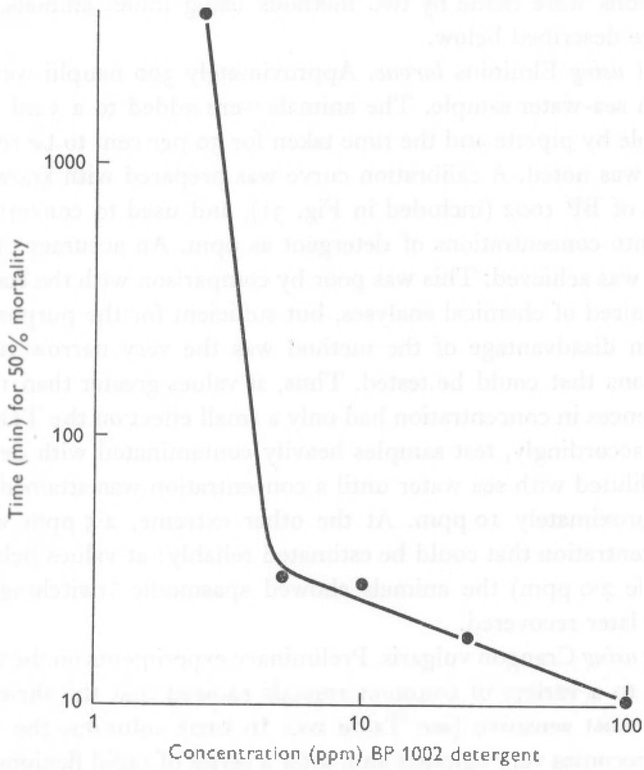


Fig. 30. Effect of different concentrations of BP 1002 on swimming activity of cyprids of *Elminius modestus* at 20 °C. See page 135.

one component of the detergent mixture; in two of the three methods this is the surfactant component which differs in density, persistence and toxicity from the main solvent component. Thus the concentration measured does not necessarily reflect the toxicity of the sea-water sample.

From the experience gained in the many toxicity tests earlier described we were able to devise simple methods of bioassay which, although they may fall short of the standards required in the analytical laboratory, are easy to perform, are reliable, and directly measure the toxicity of the water sample. It was these methods which made possible the important series of observations on detergent drift reported in Chapter 6.

Several methods were tried. One which showed promise involved observing the effect of detergent solutions on the ciliary beat of isolated strips of the gill membranes of the mussel *Mytilus edulis*. However, the little time available in the early stages of the 'Torrey Canyon' operations prevented us from developing this method and, in the end, bioassay determinations were made by two methods using intact animals. These methods are described below.

Method 1 using Elminius *larvae*. Approximately 300 nauplii were used to test each sea-water sample. The animals were added to a 5 ml portion of the sample by pipette and the time taken for 50 per cent to be rendered motionless was noted. A calibration curve was prepared with known concentrations of BP 1002 (included in Fig. 31), and used to convert values of TD 50 into concentrations of detergent as ppm. An accuracy of about 10 per cent was achieved. This was poor by comparison with the standards usually required of chemical analyses, but sufficient for the purpose.

The main disadvantage of the method was the very narrow range of concentrations that could be tested. Thus, at values greater than 10 ppm, large differences in concentration had only a small effect on the TD 50 (see page 118): accordingly, test samples heavily contaminated with detergent had to be diluted with sea water until a concentration was attained representing approximately 10 ppm. At the other extreme, 2·5 ppm was the lowest concentration that could be estimated reliably: at values below this (for example 2·0 ppm) the animals showed spasmodic 'twitching' from which they later recovered.

Method 2 using Crangon vulgaris. Preliminary experiments on the toxicity of BP 1002 to a variety of common animals showed that the shrimp was one of the most sensitive (see Table 20). In toxic solutions the shrimp eventually becomes very agitated and, after a series of rapid flexions of the abdomen, turns over. Turning over is a fairly sharp end-point and the time taken for this to occur can be related to the concentration of detergent in the water. Occasionally, shrimps that have turned over in the presence of low concentrations of detergent subsequently recover if returned to fresh sea water. However, if at 25 ppm this recovery has not taken place after 5 minutes the toxic effect may be assumed to be irreversible.

Water samples for testing were collected in 200 ml clip-top glass bottles. The top 50 ml was removed for other tests and a shrimp weighing 1–2 g then placed in each bottle, which was subsequently sealed. Times for animals to turn over at 12 °C were recorded and converted into concentrations of BP 1002 as ppm using the calibration curve shown in Fig. 29. The method is not very accurate but seems to be reliable within its limits of accuracy. Thus, within 24 hours, 2 ppm of BP 1002 was always toxic but 1 ppm was not. Beyond this time, control shrimps died through lack of oxygen. The detergent does not seem to act on the respiratory system.

This second method has the same drawback as that using *Elminius* larvae, namely that the range of good sensitivity is restricted. In addition, as only one animal is used to test the sample the results are more variable; moreover, the volume of sea water needed to accommodate the test animal is much greater than the sample used in tests with *Elminius* (5 ml). However, a more serious criticism applying to both methods, when relating them to field observations, is that results are expressed as ppm BP 1002. In the field, toxic effects were often caused by some other detergent, or even by fresh water used in hosing down the beaches.

To sum up—in spite of their recognized limitations, two methods of bioassay were usefully applied in testing water polluted by detergents.

VI. TOXICITY AND STABILITY OF THE COMPONENTS OF DETERGENTS

Details have already been given in Chapter 2 of the chemical composition of various detergents, and it will have been noted that the largest constituent is the *organic solvent* (e.g. kerosene extract or 'Kex'). In addition there is a *surfactant* (or emulsifying agent); and a *stabilizer*.

None of the three components dissolves easily in sea water and stock suspensions were therefore prepared by mechanically shaking 1·0 ml with 1 l. of sea water for 30 minutes. These suspensions were then quickly diluted to provide test media representing an appropriate range of toxic concentrations. The organic solvent, 'Kex', was obviously unstable and evaporated continuously from the sea-water suspensions. Accordingly, all tests of the toxicity of the 'Kex' fraction were carried out in sealed vessels (the same precaution having been taken when tests were made with the whole detergent).

Studies with Elminius *larvae*

Toxicity. Stage II animals were used, as in the previous toxicity experiments. Data for the solvent 'Kex' are compared with those for BP 1002 in Fig. 31, from which it will be seen that 'Kex' used alone has a toxicity very close to that of BP 1002. By comparison, the stabilizer was notably less toxic than 'Kex' and the surfactant notably less toxic than the stabilizer (see Table 24). Figure 31 also includes data for Shellsol R, the organic solvent used to prepare the Dasic detergent. Compared with BP 1002,

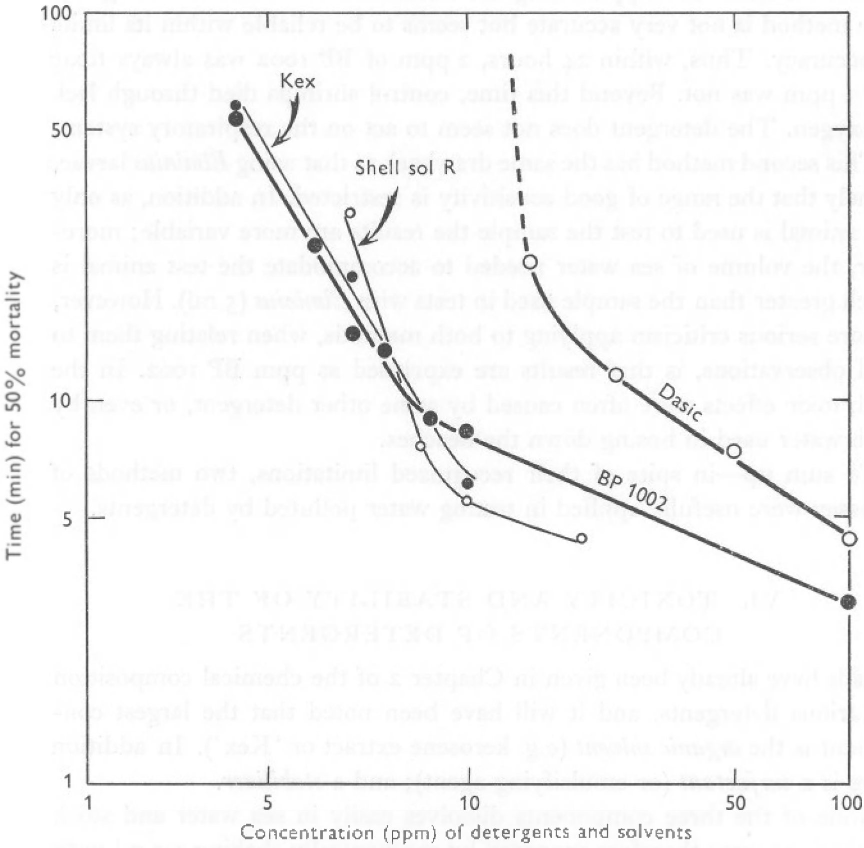


Fig. 31. Toxicities of detergents and their components to stage II *Elminius* nauplius larvae at 16–20 °C.

Dasic is much less toxic, but somewhat surprisingly, its organic fraction Shellsol R has almost the same toxicity as 'Kex'. The proportion of Shellsol R used in Dasic is slightly less than the proportion of 'Kex' in BP 1002. However, this difference is too small to account for Dasic being much less toxic than BP 1002. Possibly the other ingredients in Dasic may reduce the toxicity of Shellsol R.

Thus, in the case of BP 1002 and Dasic, and probably Gamlen and

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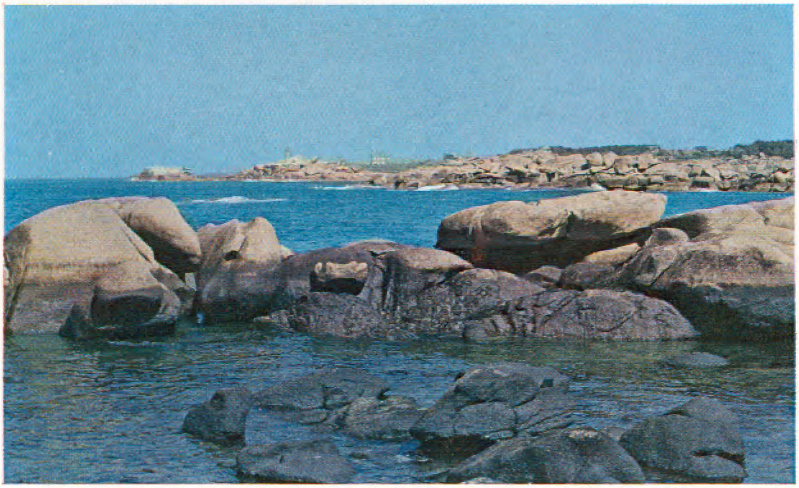
PLATE 27

A, Oil residue on rocks west of Fort Le Crocq, Guernsey, 10 July. Shingle beach in distance mainly clear but with some residues above high-water springs. Rocky reefs were also oil covered at high-water neaps level. **B**, Oiled rocks on Ile Renot (Côtes du Nord), 21 June. The oil darkened to this colour after two neap tides. Mean Ruz lighthouse in background. **C**, Oiled salt marsh and sand near Trégastel (Côtes du Nord), 21 June. Note that the rushes, although presumably oiled nearly two months earlier, appear healthy.

A



B

C

(*Facing p.* 144)

Table 24. *Toxicity data for the components of BP 1002*

Concentration (ppm)	TD50 (min)			
	Surfactant	Stabilizer	'Kex'	Total Mixture
500	50	—	—	—
50	120	18	2	4
25	200	38	4	5½
5	Non-toxic	212	21	17

Slipclean, the high toxicity of the 'detergent' is due mainly to the organic solvent on which it is based: in BP 1002, for example, the surfactant used is ten times less toxic (25 ppm) than the solvent (2·5 ppm). This finding appears to contrast with results obtained in fresh water, where some pure non-ionic surfactants, including the nonylphenyl-ethylene oxide condensate used in BP 1002, are toxic at concentrations below 10 ppm (see Marchetti, 1965). Possibly the cell membrane mechanisms are more sensitive in the fish that were used in Marchetti's freshwater experiments.

Stability. The stability of BP 1002, and of its three constituents, were also tested. Sea-water solutions were aerated for various periods of time in open vessels, and it was found that all the test solutions lost toxicity. The most marked effect was with 'Kex', a solution of 10 ppm (which originally killed 50 per cent of the test animals in 8 minutes) possessing no detectable toxicity after 2 hours aeration. The experiment was repeated using wide-mouthed dishes open to the atmosphere, but no aeration. The half-life of 'Kex' used at concentrations of 1–100 ppm was less than 24 hours in these conditions. The detergents Gamlen and Dasic also lost toxicity when similarly treated.

Solutions of the three components of BP 1002 were prepared with a heavy bacterial contamination by using sea water which had contained decaying barnacles. The stabilizer was found to have lost toxicity overnight, but the other components seemed unaffected.

Studies with Sabellaria *larvae*

Tests were made with *Sabellaria spinulosa* larvae that varied in the stage of their development from that figured by Wilson (1929, plate v, fig. 6) to the later stage drawn in fig. 7 on the same plate. The larvae had been reared in the laboratory from an artificial fertilization. The concentrations of BP 1002, and later of its constituents, were prepared in the same unfiltered sea water as used for the controls. All experiments were carried out under north-window illumination at a controlled temperature of about 15 °C.

To prevent loss of the toxic solvent during the course of the experiment, the sea water control and a solution of 1 ppm BP 1002 were each put into 100 ml glass-stoppered conical flasks, completely filled to leave no air-spaces under the stoppers. There were ten larvae in each flask, but no food was added. The larvae in the control were healthy and active three weeks later, although their flask was still well stoppered. But those in the detergent solution never recovered, remaining motionless on the bottom, bodies flexed ventrally and bristles erect. When the flask was unstoppered after 48 hours they were found to be dead. Moreover, water from the flask, shortly after unstoppering, was still extremely toxic to new larvae, quickly rendering them motionless with erect bristles. Air was now bubbled through the flask for several hours, the smell of the organic solvent disappeared and the water no longer had any toxic effect on fresh larvae immersed in it.

Tests were next made with sea-water solutions of the surfactant (10 and 1 ppm) and the stabilizer (10 ppm) prepared in open dishes. At 10 ppm both substances killed the larvae within a few hours, after first slowing their speed of swimming. There was no sudden raising of the bristles characteristic of treatment with the detergent. The larvae died with straight bodies, and with the bristle bundles only partly raised. In fact, in the solution of stabilizer, the bristles were barely lifted away from the sides of the body, the posture in death being almost as in life. In the 1 ppm concentration of surfactant, larvae showed no immediate reaction, but gradually their rate of swimming slowed and they became increasingly irritable. After 12 days, in spite of *Isochrysis* added for food, they were in poor condition and a few days later most were dead, the rest dying. All this time larvae used as a control were healthy, active and growing, and remained so five weeks after the experiment began.

A more extensive series of tests of the ingredients of BP 1002 was next made. These are listed in Table 25 and the results briefly summarized. 'Kex' at 2 ppm and 1 ppm had at first very little effect on the larvae: it merely made them slightly irritable. Overnight the slight smell of the solvent disappeared and from then on the larvae behaved normally for nearly four weeks; however, after this they lost activity until they lay motionless with only an occasional twitching of their bristles. The surfactant at 5 ppm and 2·5 ppm killed the animals, and the same concentrations of the stabilizer gradually slowed the swimming and killed within 20 hours. When treated with these components the larvae died as before with bodies straight and bristles scarcely raised. In another dish, containing 1 ppm of BP 1002, the immediate reaction was the usual ventral flexure of the body with well-raised bristles, the animals then remaining

Table 25. *Toxicity tests with BP 1002 and its components.*

(Ten larvae of *Sabellaria spinulosa* 29 days old were put into each dish.)

Date	Time	Dish 1: Control	Dish 2: 2 ppm 'Kex'	Dish 3: 1 ppm 'Kex'	Dish 4: 5 ppm surfactant	Dish 5: 2·5 ppm surfactant	Dish 6: 5 ppm stabilizer	Dish 7: 2·5 ppm stabilizer	Dish 8: 1 ppm BP 1002
14. iv. 67	3.00 p.m.	Put in	.	.	Put in	Put in	Put in	Put in	.
14. iv. 67	3.05 p.m.	Normal	.	.	Motionless	Normal	Normal	Normal	.
14. iv. 67	3.40 p.m.	Normal	.	.	Motionless	Slow	Slow	Slightly slow	.
14. iv. 67	3.45 p.m.	.	Put in	Put in	.	.	.	.	.
14. iv. 67	4.07 p.m.	.	.	.	.	.	.	.	Put in
14. iv. 67	4.25 p.m.	Normal	Irritable	Irritable	.	.	.	.	Motionless
15. iv. 67	10.08 a.m.	Normal	Almost normal	Normal	Dead	Poor	Dead	Dead	Slight recovery
17. iv. 67	2.30 p.m.	Normal	Normal	Normal	.	Dead	.	.	Poor
25. iv. 67	10.30 a.m.	Normal	Normal	Normal	.	.	.	.	Very poor
28. iv. 67	5.00 p.m.	Normal	Normal	Normal	——Ten new larvae put into dishes 4–7——				Three dead
29. iv. 67	10.40 a.m.	Normal	Normal	Normal	Poor	Slow	Poor	Almost normal	Bad
1. v. 67	10.10 a.m.	Normal	Normal	Normal	Dead	Very slow	Dead	Slightly slow	Bad
2. v. 67	12.20 p.m.	Normal	Normal	Normal	.	Almost motionless	.	Slow	Bad
4. v. 67	10.50 a.m.	Normal	Normal	Normal	.	Five dead	.	Slow	Another dead
11. v. 67	12.15 p.m.	Normal	Less active	Less active	.	Eight dead	.	Slow	All dead
17. v. 67	11.45 a.m.	Normal	Motionless	Motionless	.	All dead	.	Almost normal	.

motionless for some considerable time. There followed a period of apparent partial recovery but progressive deterioration soon set in.

The animals were not fed for two weeks after the beginning of the experiment. Some *Isochrysis* culture was then added to all dishes. On the same day, healthy larvae were put into the dishes of surfactant and stabilizer (Table 25, dishes 4–7) where the original larvae lay dead and decayed. In both these components at 5 ppm the larvae soon died with straight bodies and bristles held almost normally. In dishes containing these components at a concentration of 2·5 ppm there was a more gradual slowing of the swimming speed and the larvae survived longer than did those originally put into these same dishes. In fact, although they eventually died in this surfactant concentration, the larvae in the 2·5 ppm stabilizer showed distinct signs of recovery by the end of the experiment. The stabilizer was evidently no longer present in toxic concentration.

These experiments, like those conducted with *Elminius*, demonstrate that the solvent fraction of BP 1002 is quickly lost from sea water exposed to air. But there is evidence of chronic poisoning resulting from fairly brief exposure. These open-dish experiments differ from those with *Elminius* larvae in that the effect of the whole detergent is considerably more severe than that of the 'Kex' alone.

Studies with Crangon

Methods described in an earlier section (see page 142) for estimating the toxicities of detergents to shrimps were used in further experiments concerned with testing the relative toxicities of the components of BP 1002 and the stabilities of these components in sea water. Experiments with shrimps showed that the organic solvent 'Kex' is the most toxic fraction; and that aeration of sea-water solutions of BP 1002 causes loss of toxicity.

CONCLUSIONS AND SIGNIFICANCE OF THE TOXICITY EXPERIMENTS

The account of the results of the range of toxicity experiments is already in a much summarized form. The results as a whole may be drawn together in a few comments.

They exhibit the expected variation of tolerance as between one species and another, and it would be impossible to define a generally 'safe level' of detergent concentration in sea water. All that can be said is that acute effects in some animals are detectable at less than 1 ppm of detergent and that as the concentration increases so the effects mount progressively and extend over a wider variety of species. At 10 ppm exposure for 1 hour is lethal to most planktonic and sublittoral animals and, whereas the intertidal animals are more tolerant, they were exposed to much higher levels of detergent concentration in the type of beach-cleaning operation employed in the situation under study.

The experiments were conducted under conditions of great urgency, for the detergent spraying was begun in the absence of any detailed and reliable information on its likely biological effects.

There is, it is true, abundant information in the scientific literature on the toxicity of detergents. However, this is largely concerned with ionic detergents and with a freshwater environment. There are good physiological reasons for supposing that the action of non-ionic detergents in sea water could be very different.

The assumed toxicity was quickly verified in the first experiments and the effect of the operation hinged upon two interwoven questions. How far will the poison spread? And how long will it last?

The many experiments performed to establish toxic levels together with the observations reported in Chapter 6 throw light on the first question, and the experiments described under 'Toxicities and stabilities of the components of detergents' were undertaken to help answer the second.

The various reports in the literature describing toxicity experiments with detergents are almost wholly concerned with the surfactant fraction of the oil-spill detergents or their equivalent. It was therefore natural to suppose that the toxicity of the oil-spill detergents was largely in the surfactant fraction. The toxicity of this fraction to some species, at least, has been demonstrated, and the possibility of accumulation in food-chains, though perhaps slight in open waters, should not be forgotten. The surfactants used in the manufacture of oil-spill detergents are 'hard'; that is, only slowly degraded, so that it seemed that the toxicity was likely to persist in the coastal waters of the Channel, and the prognosis was indeed gloomy.

Hence it is of crucial significance that our experiments show that the toxicity of the oil-spill detergents in sea water is almost entirely in the organic solvent fraction and, moreover, that this fraction rapidly disappears by evaporation, at least when in low concentration. This result is of central importance for the whole of the spraying operation, for had it not been for this previously unknown and unsuspected fact the biological consequences in the English Channel would have been vastly worse than they were.

Nevertheless, it should be noted that besides this important demonstration of the severe but transient toxicity of the detergents used there is also a longer-term effect on the organisms tested.

CHAPTER 8

THE PATTERN OF OIL DISCHARGE AND OIL MOVEMENTS FOLLOWING THE WRECK

The oil which escaped from the 'Torrey Canyon' was driven by the tidal movements of the water on which it lay and by the wind. Although, as is indicated later, tidal movements alone can give an appreciable to-and-fro movement of the oil with sometimes a residual movement remaining at the end of a tidal cycle, the movements of the oil over periods of several days will usually be determined mainly by the wind. In Fig. 32 are shown, from the excellent observations* made by R.A.F. Coastal Command based at St Mawgan, Cornwall, successive positions, for times between 20 March and 8 April 1967, of the very large patch of oil which was released from the 'Torrey Canyon' between the time when the tanker struck the Seven Stones Reef on 18 March and the evening of 20 March. By measuring the distances and directions between points marking the approximate centres of this patch on different occasions, the resultant oil movements between known times were determined. Over the same periods of time, vectors, giving wind distance (velocity of wind × time) and direction, were added geometrically to give resultant wind distances and directions with which the corresponding distances and directions of oil movement could be compared. For this purpose the wind velocities and directions were taken for 6-hourly intervals from the observations made at the land meteorological station nearest to the oil patch. The results of such comparisons are given in Table 26 (p. 161), which shows that the oil movement could have been very well predicted by assuming that the oil always moved in the same direction as the wind but with about 3·4 per cent of its velocity. This agrees well with the measurements made by Hughes (1956) on plastic envelopes floating close to the surface of the Atlantic Ocean. He found that the drift of such plastic envelopes was parallel to the surface winds, and that the velocity of drift was about 3·3 per cent of the velocity of these winds. The small difference between the factors 3·4 and 3·3 per cent indicates that the oil moves with almost, if not exactly, the velocity with which

* Different observers gave very consistent results for the positions of the heavier concentrations of oil. The observers themselves noted, however, that there was great difficulty in defining the areas of lighter pollution. Weather conditions, the state of the sea, and the criteria adopted by different observers all greatly affected the answers given.

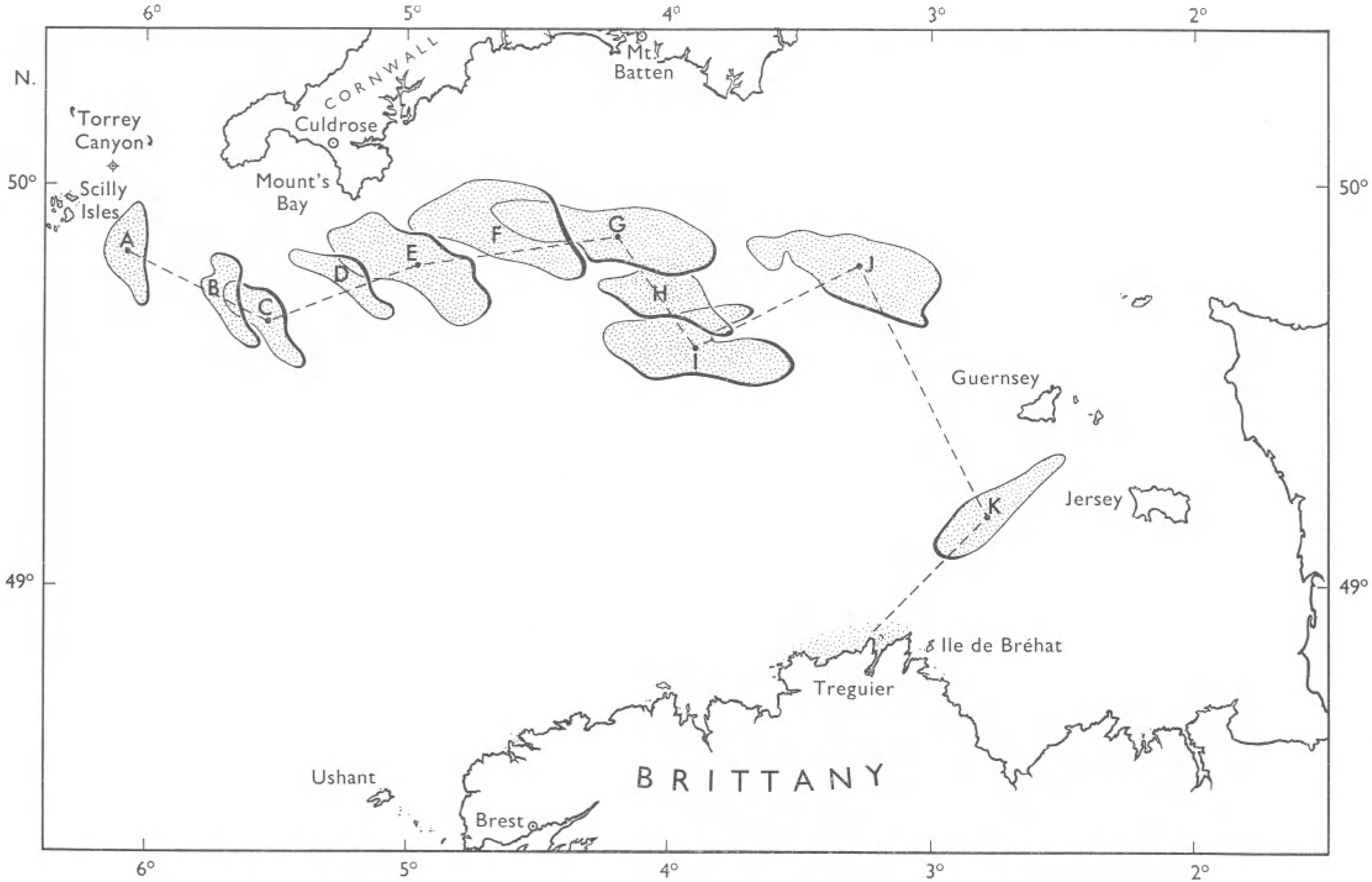


Fig. 32. This diagram, which is based on observations made by R.A.F. Coastal Command, shows successive positions of a single patch of oil as it drifted under the influence of wind and tide up the English Channel. The times were: A, 20 March, 07.00 h; B, 22 March between 06.00 and 08.00 h; C, 23 March, between 06.00 and 07.00 h; D, 25 March between 06.00 and 07.00 h; E, 26 March, 13.00 h; F, 27 March between 06.00 and 09.00 h; G, 28 March between 05.45 and 11.00 h; H, 30 March between 06.00 and 11.30 h; I, 1 April, 09.00 h; J, 4 April between 08.45 and 11.50 h; K, 8 April about midday.

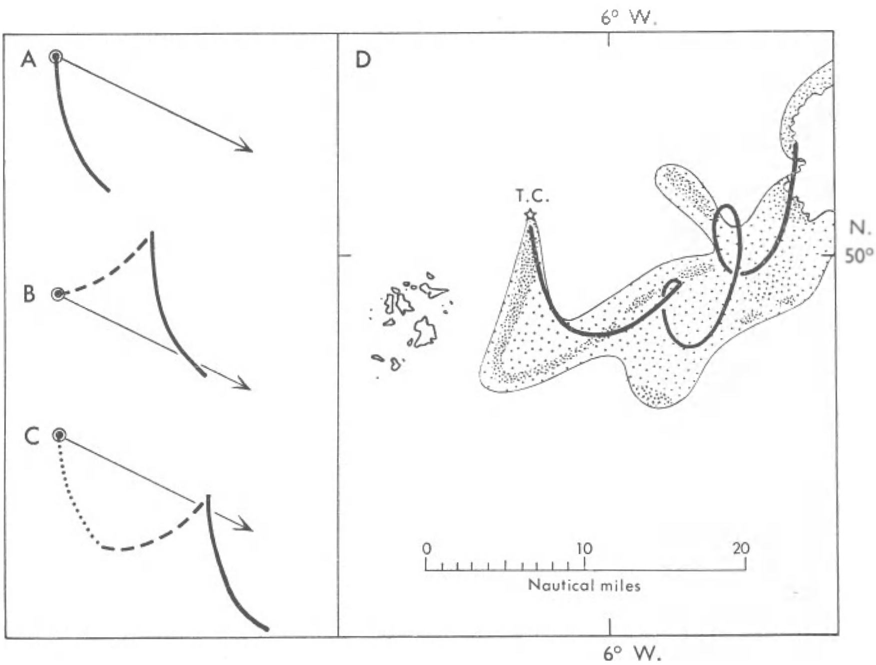


Fig. 33. A–C. If oil had leaked out of the ship at a steady *low* rate after 18.00 hours on 25 March and the wind had remained constant in direction and of strength 25 knots (in fact the wind was less strong and south-west over the first 6-hour period) the oil patch would be expected to have the shape shown: in A at about 00.00 h on 26 March, in B at about 06.00 h on 26 March, in C at about 12.00 h on 26 March. The patch of oil released in the first half tidal period is shown by the heavy black line; it is unchanged in shape in successive periods of time but pushed by the tide first to the north and then to the south of a line in the direction of the wind and passing through the wreck.

Fig. 33 D. Here we compare an actual R.A.F. plot of oil distribution close to the 'Torrey Canyon' made at 13.00 hours on 26 March with a line, calculated like those of A, B and C, but covering three full tidal periods before 13.00 hours on the 26th. We have taken account of the fact that over roughly the first two-thirds of this period the wind was south-westerly and of a force about 13 knots and later rose to 24 knots and became west-north-west. We have *not* allowed for the fact that the tidal streams closer to Land's End are stronger and have a set generally in a more westerly and easterly direction than those close to the wreck; if we had corrected for this, the calculated curve would certainly give a better fit to the actual observations. The oil was discharged in great quantities and has of course spread out after leaving the wreck.

surface water would move. There is therefore no reason to suppose that any change in the condition of oil as it becomes older would affect its velocity.*

Figures 33 A–C use these calculations to show the kind of effects which

* Following damage to the tanker 'Gerd Maersk' in 1955 8000 tons of crude oil were pumped into the North Sea. The German Hydrographic Institute of Hamburg followed the movement of the oil in the shallow coastal waters off Germany and Denmark and came to the conclusion that the oil moved with the wind at about 4·2 per cent of its velocity (Tomczak, 1964). It is hoped to discuss the differences between their results and those of this report in a later communication.

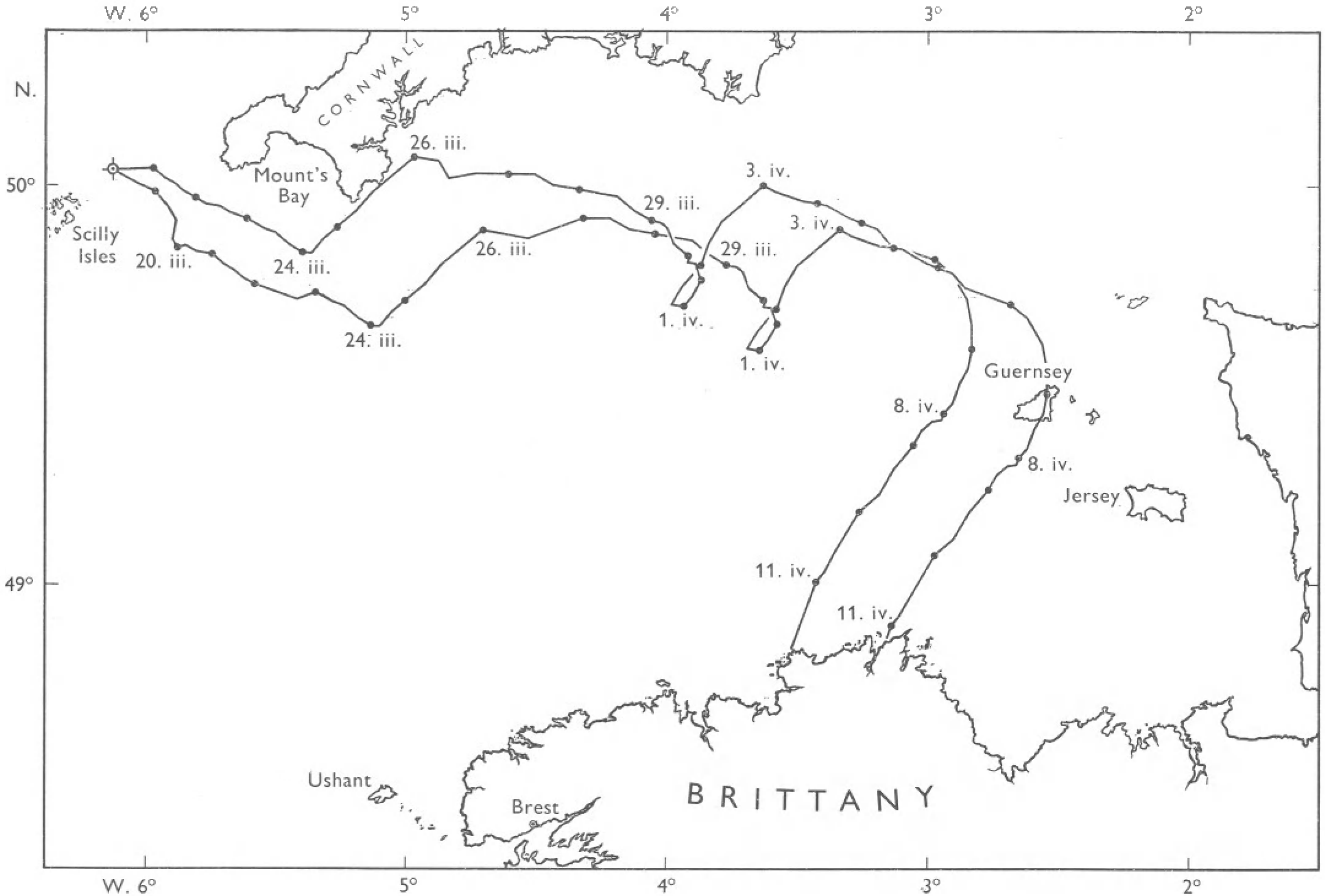


Fig. 34. These two tracks bracket the estimated movements of the oil which was released from the 'Torrey Canyon' between 09 00 h on 18 March and 12.00 h on 20 March. It has been assumed that the oil moved in the direction of the wind with 3·3 per cent of the wind's velocity. The dots on the lines mark 00.00 hours on successive days.

combined wind and tidal movements will have on oil movements, and Fig. 33D shows a plot of oil distribution made by Coastal Command on the afternoon of 26 March together with an estimated pattern of oil movement. It will be seen that the agreement is good except that the oil patch widened considerably as it moved away from the ship. A great part of this widening must certainly be due to the spreading of oil under its own weight. The effect of tidal movements and spreading of oil meant that the patches were often several miles wide and this should be borne in mind in the discussion which follows.

Figure 34 shows how the oil released from the 'Torrey Canyon' between 18 and 20 March would have moved if it had been drifting under the influence of wind alone with a velocity equal to 3·3 per cent of the wind velocity. The plot shows that this oil, the first great volume released from the ship, would have failed to reach the English shoreline but that part would have fetched up on the Channel Islands and the rest around Treguier in Brittany on about 11 April, three weeks after release. (The oil did in fact land in Brittany around Treguier at this time, see Chapter 9).

Figure 35 plots, in a similar way, estimated oil movements for oil released between 21 and 25 March. This shows, for example, that oil released at the beginning of this period would have been blown on to the shores around Mount's Bay on 25 March while oil released later in this period would have been driven first along the north Cornish coast and then ashore on 26 March. There would, of course, be a great deal of oil driven on to the beaches around Land's End over this time. These estimates reflect very well the actual course of oil pollution over this period.

The two available official estimates of oil release agreed that the largest single loss followed the breaking of the 'Torrey Canyon' by storm on the evening of 26 March. This volume was given as 30000 tons in one estimate and 48000 tons in the other, and the later figure of about 48000 tons will be assumed below. Figure 36 shows how this oil would have moved under the winds which prevailed between 26 March and 12 April. For most of this time, since the oil was in the open sea, we have followed Hughes (1956) in taking our winds as two-thirds of the appropriate geostrophic winds calculated from the isobaric plots.* As the figure shows, this enormous volume of oil would have entered Mount's Bay, skirted the Lizard and then, during a long period of north-westerly, northerly and finally north-easterly winds, would have been pushed past Ushant well into the Bay of Biscay without touching land at all.

* The wind speeds calculated from isobaric plots agreed very well with the observations of neighbouring meteorological stations except for the sea area around Ushant, where the calculated speeds were consistently lower than those reported by the meteorological station at Ushant.

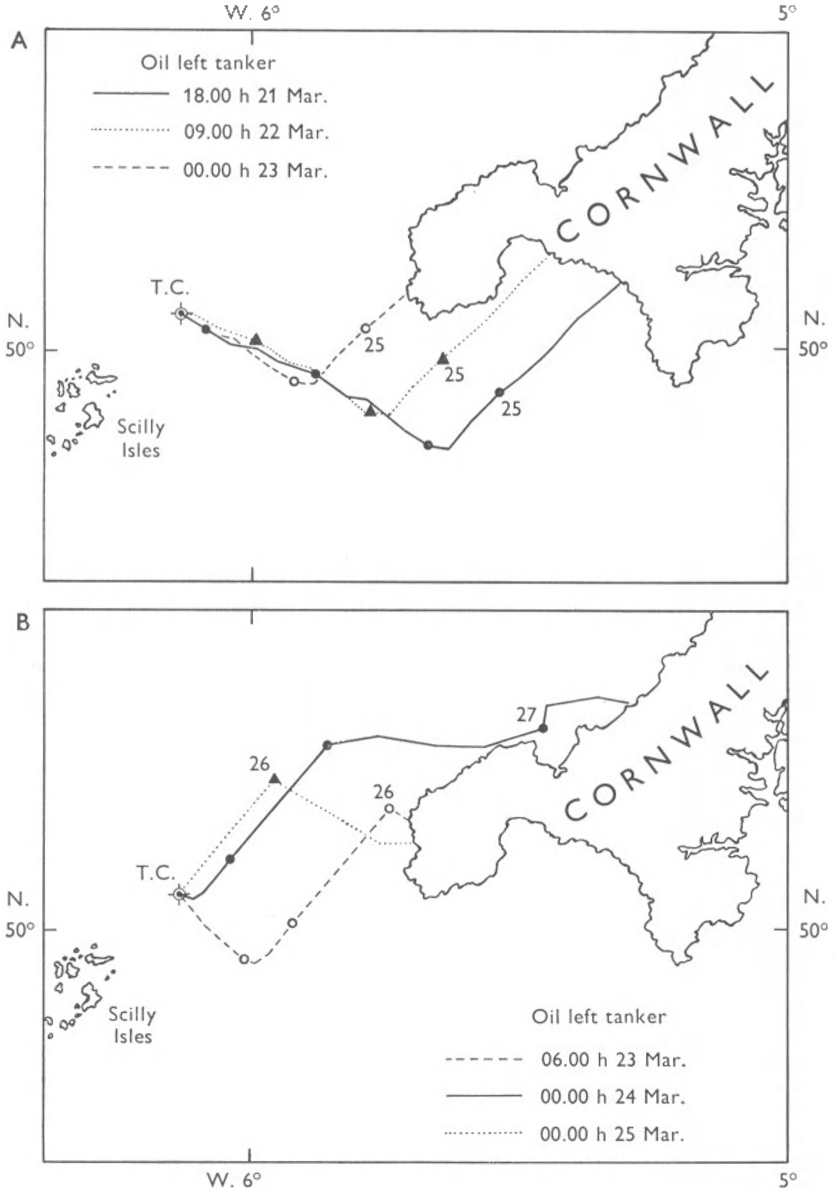


Fig. 35. A and B. This shows how oil leaving the 'Torrey Canyon', at various times in the period between 21 and 25 March, would have moved if it had travelled in the direction of the wind with 3·3 per cent of the wind's velocity. For an idea of how tides and the spreading of oil can affect such movements see Fig. 33D. The symbols on the lines mark 00.00 hours on successive days.

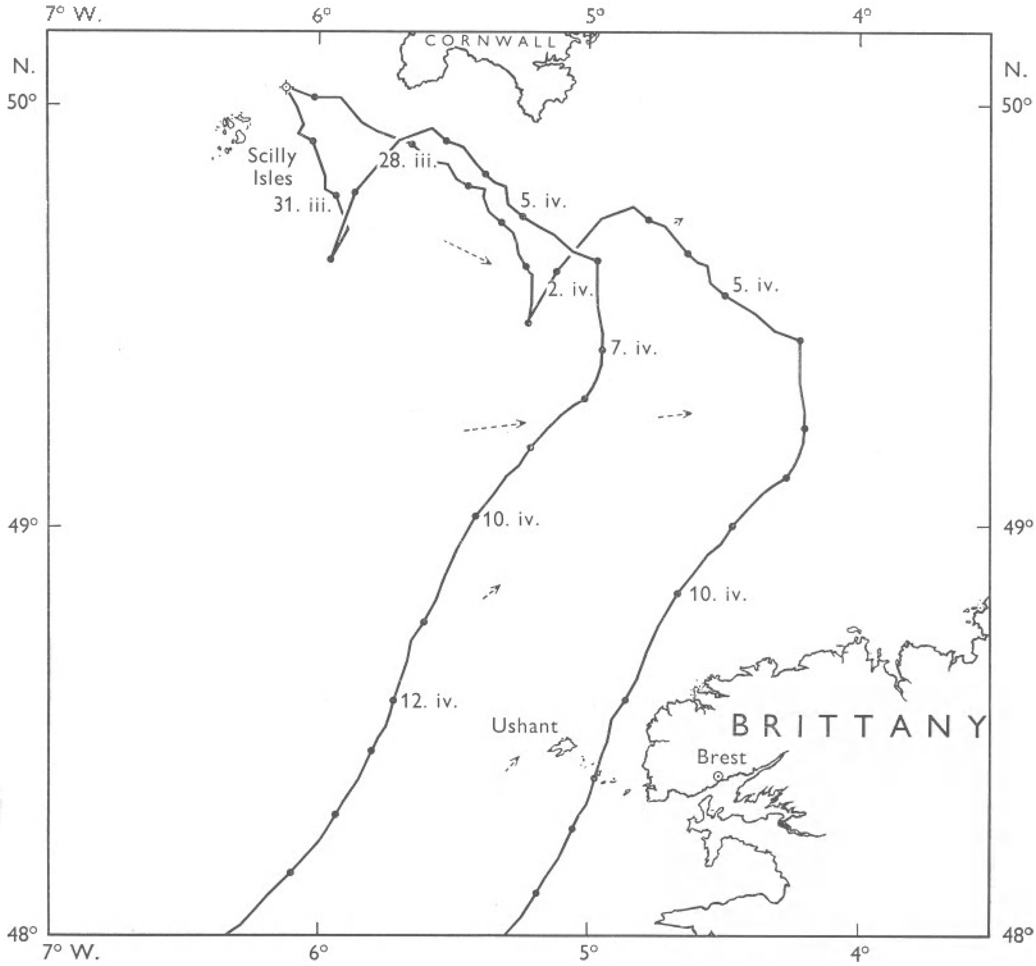


Fig. 36. This gives the estimated movements of the oil which was released from the 'Torrey Canyon' between 18.00 hours on 26 March and 00.00 hours on 29 March. This includes the oil released on the ship breaking up and most of the oil which was released (but not burnt) when the ship was bombed. It may be seen that this oil would not have reached any shore before passing Ushant. It has been assumed that the oil moved in the direction of the wind with 3·3 per cent of its velocity. The arrows give the directions of the tidal residuals at various places along the predicted path of the oil. The lengths of the arrows give the approximate distance by which the tides would have affected the oil movements. The dots on the lines mark 00.00 hours on successive days.

The air surveys showing oil distribution were mostly directed to finding the positions of patches of oil close to shore so that oil which had moved away from the shore is often not shown on the plots given by Coastal Command. It would have been almost impossible to interpret these surveys without some theory as to how the oil moved, and in no circumstance was

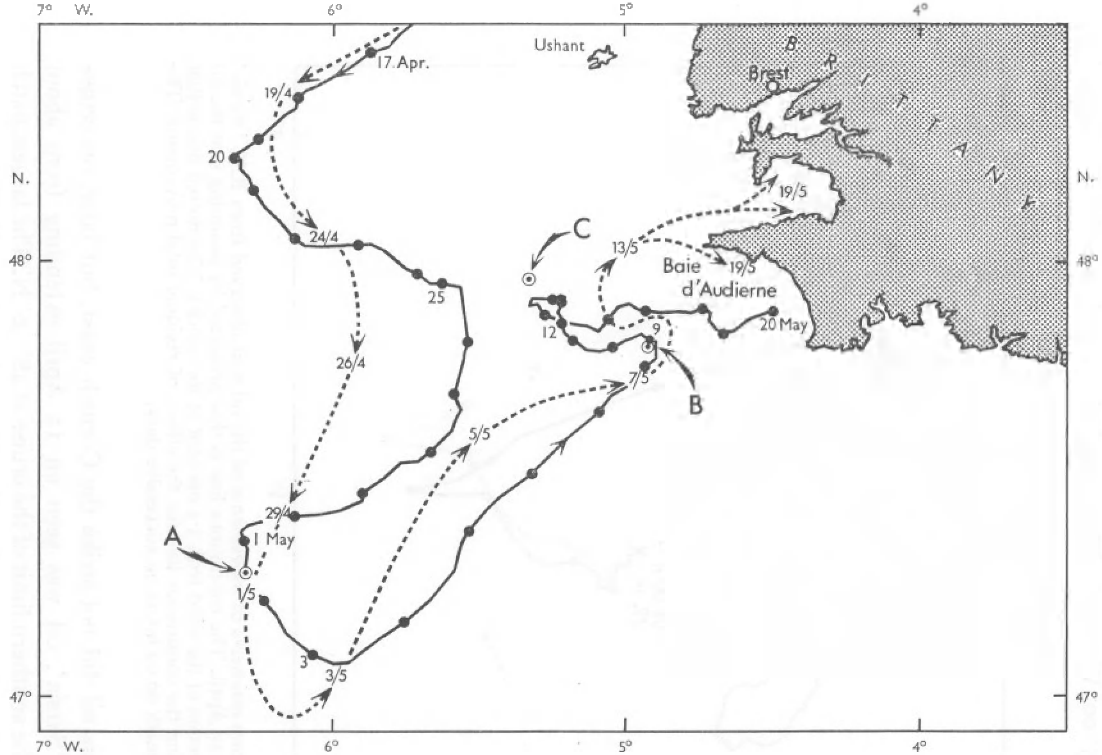


Fig. 37. This shows estimated movements of a large patch of oil which was observed in position A on 1 May by the French. It has been assumed that oil would move in the direction of the wind with 3·3 per cent of the wind's velocity. Estimates have been made working forwards to 20 May and backwards from 1 May to 17 April. B is the position of this oil on 9 May (given by French Navy). C is the position, on 12 May, of the largest 'patch' of oil seen from R.V. 'Sarsia' during a survey of oil in this region. The observed positions B and C are close to those predicted and the oil is shown as having come from the direction expected (see Fig. 36) of oil released from the "Torrey Canyon" between 26 and 30 March. The dots on the lines mark 00.00 hours on successive days. The pecked line shows an actual track of oil movement as plotted by the French Navy and supplied to us after our own report had been completed.

this more true than in attempting to follow the oil released from the 'Torrey Canyon' during the period between 26 and 30 March. The air surveys do show, however, a very large patch of oil in Mount's Bay on 29 March and, at the same time, a large area covered with oil was seen in the same position (49° 35′ N., 05° 00′ W.) by the Plymouth Laboratory's vessel R.V. 'Sarsia'

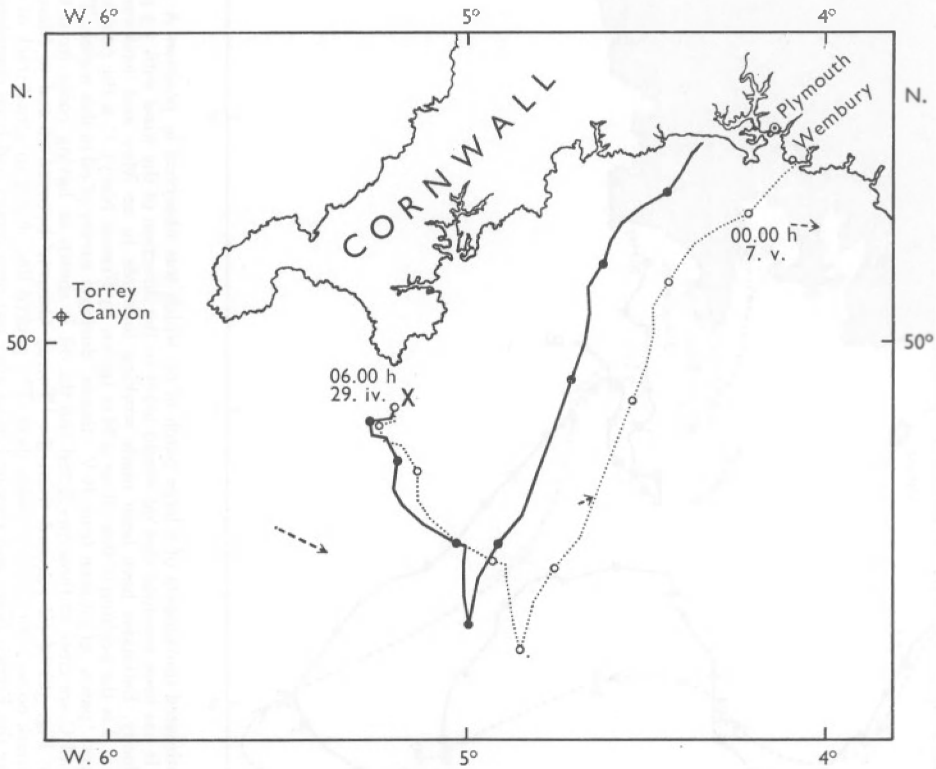


Fig. 38. This shows estimates of movements of the oil first observed from R.V. 'Sarsia' at position X on 29 April. The continuous line is that predicted by assuming that the oil moves in the direction of the wind with 3·3 per cent of its velocity. The dotted line is that given by correcting the continuous line for the effects of residual tidal movements. The dots on the line mark 00.00 hours on successive days.

(cruise I). This oil did not strike the Cornish coast, but later, on cruise III of R. V. 'Sarsia', oil was seen on 12 April extending from about 48° 50′ N. to the southern limit of the cruise at 48° 30′ N. The largest patch of oil seen was found at approximately 48° 50′ N., 05° 10′ W. This is most easily explained by its being 'Torrey Canyon' oil which had moved in the direction predicted by the plots shown on Fig. 36 but about 20 miles less far to the south. Beyond Ushant oil patches were followed by the French Navy and Air Force, and Dr P. Courtot of the Faculté des Sciences de

Brest has very kindly sent us some of their observations. On 1 May the French reported a main 'patch' of oil at 47° 17′ N., 06° 17′ W. (25 km by 1 km, with its long axis orientated at 260° and said later to consist of spots of oil 300 square metres in surface area and 3 cm thick) and secondary patches at 47° 35′ N., 06° 05′ W.; 47° 25′ N., 06° 35′ W.; and 47° 18′ N., 06° 48′ W. Starting from the position of the main patch of oil on 1 May, estimated positions of this oil, before and after this date, are shown on Fig. 37, where these estimates may be seen to agree well with observations of the oil patches.

On 29 April oil patches were observed off the Lizard and surface drifters were placed in the sea close to this oil. Figure 38 shows estimates of how this oil would have moved driven by wind alone (continuous line) and by wind and tide together (dotted line). These predicted that this oil would reach shores close to Plymouth on 7 May, and a little oil did in fact come ashore at Wembury three miles east of Plymouth Sound on 8 May. Several surface drifters were found close by in the days that followed but it is not known when these first came ashore.*

The observations and predictions shown on Figs. 32–38 and summarized in Table 27 are thus in good agreement with one another. If the main patch of oil reported by the French on 1 May (position A of Fig. 37) is identified as part of that found over a month earlier, on 29 March, in Mount's Bay, reliance on estimates based on the oil being driven by the wind alone at 3·3 per cent of its velocity would have indicated the direction in which the oil moved very well. It would, however, have overestimated the distance moved by about 20 per cent. Two likely explanations of this possible discrepancy are:

(1) A generally northerly current of the surface water opposing the southerly movement of the oil past Ushant. This current would have to have an average velocity of about $\frac{1}{20}$ knot to account for the whole discrepancy.

(2) A reduction in the ratio of oil velocity/wind velocity in conditions of sustained wind and high seas such as obtained in the seas around Ushant over the period following 6 April.

The Nature Conservancy report and our own observations show that, although the pollution was more extensive in Cornwall, the pollution was much heavier in Brittany. It was officially estimated that about 48 500 tons of oil were released between 18 and 26 March. Our estimates are that some 18 500 tons of this oil drifted towards the Cornish coast and that about 30 000 tons drifted up the Channel. Both of these masses oil were sprayed

* The first of them was found by a member of the general public at Wembury on 12 May, and the fact that a member of the Plymouth staff who looked for drifters a few days later found two more suggests that such drifters are not always quickly found by the general public.

at sea with large quantities of detergent. Even if we assume that detergent spraying at sea did not substantially reduce the oil mass, evaporation and detergent dispersal together would have reduced the weight of oil by some 30 per cent. Consequently, the maximum amount of oil which landed on the Cornish beaches can be estimated at some 13 000 tons, and the quantities reaching France and the Channel Islands at about 21 000 tons.

These estimates of the quantities of oil may be compared with the amounts of detergent used in Cornwall. Up to about 5 May about 2½ million gallons of detergent were used—that is, about 10 000 tons—and a rough balance sheet would therefore read 13 000 tons of oil landing on our beaches with about 10000 tons of detergent being used to disperse it. Now it seems that if the detergent is used to best advantage it can disperse about four times its volume of oil. We know, however, from our own and from other people's observations that ideal ratios of this kind would be impossible to achieve in practice and that detergent was often not used in the best conditions and was sometimes used in excess. The balance found between volumes of detergent and oil is therefore not a surprising one.

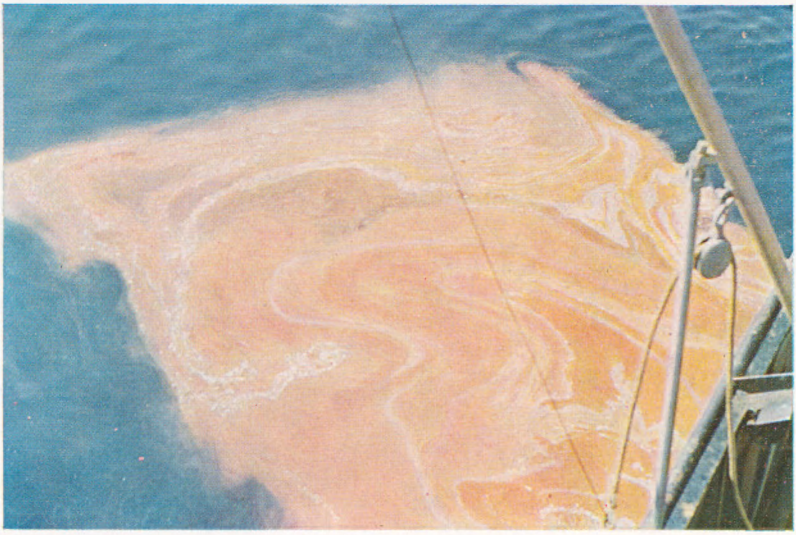
Thirteen thousand tons of oil may seem rather a small amount to cause so much damage but, when it reached the beaches, the oil was often in an emulsion whose composition was approximately 70 per cent sea water and 30 per cent oil, so that 13 000 tons of oil could give, for example, a continuous strip of oil-and-water emulsion 10 metres wide, 2 cm thick along a continuous length of over 200 kilometres of shore (cf. Figs. 8–10).

Although the pollution of our coasts was very serious we were greatly favoured by the fact that for most of the two months following the stranding of the ship the winds were northerly or north-easterly. If, for example, south-westerly winds had blown from 1 to 5 April the pollution along our shores would certainly have been three or four times heavier.

Conclusions

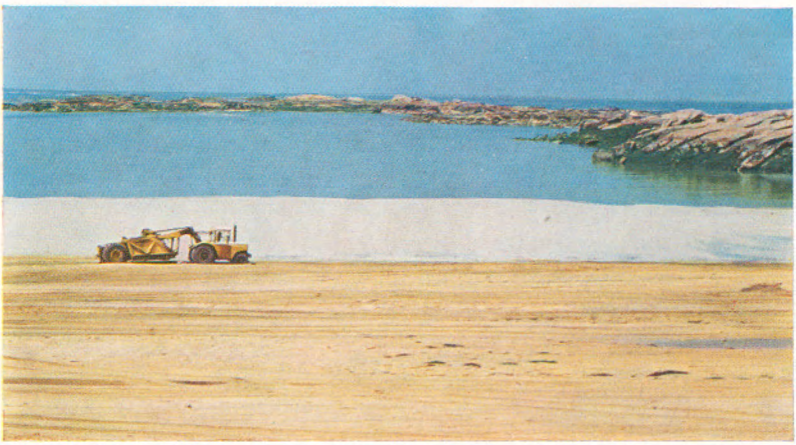
(1) Once a large patch of oil has been identified at sea its position subsequently can be predicted with fair accuracy by assuming that it moves in the direction of the wind at about 3·3 per cent of the wind's velocity. This means that very expensive blanket aerial surveys are not necessary since aircraft can be directed by predictions of the wind drift of oil. These predictions are simple to make and merely require wind speeds and directions which can be found either by calculation from the isobars on the meteorological charts or from the observations of wind by local weather stations. Allowance should, of course, be made for ocean currents and tidal streams where these are very strong.

(2) Patches of oil remain as patches for long periods. This is shown in



A

B



C

(*Facing p.* 161)

Table 26. *Assessment of oil movement in terms of wind movement (see page 150)*

Change in position of oil patch (Fig. 32)	Vector distance in nautical miles		$\frac{\text{Oil velocity}}{\text{Wind velocity}} \times 100$	Direction of movement	
	Oil	Wind		Oil	Wind
A to B	23·3	834	2·79	116°	120°
B to E	23·8	911	2·61	69°	73°
E to G	29·9	633	4·72	81°	98°
G to I	20·3	556	3·65	145°	152°
I to J	27·1	849	3·19	63°	70°
J to K	41·7	1081	3·86	153°	123°
A to J	227	6687	3·39	91°	95°

the successive observations such as those described on Figs. 32 and 37. It is certainly not safe to assume, as many people have done, that oil patches become very rapidly dispersed at sea.

(3) Even with moderate winds the position of a patch of oil can change greatly in a relatively short time. Thus the patch shown in Fig. 32 moved about 90 nautical miles eastward between observations A and I in about 10 days and the patch whose movements are shown in Fig. 26 moved southwards from the Lizard to Ushant in about 14 days. This means that, if coastal authorities are to be given reasonable warning of threatened pollution, aerial observations should not be confined to waters close to shore but that the main patches of oil should be followed at intervals decided from estimates based on wind velocities and directions.

(4) Boom defences are very worthwhile for, if pollution can be held at bay even for a short time, a change of wind direction may remove the threat entirely.

(5) If pumping of oil on to the sea ('Gerd Maersk'), or the bombing of a wrecked tanker ('Torrey Canyon'), or any other process which would release oil at sea is contemplated, the time at which this is done should be chosen in the light of the forecasts of winds. If for example, the 'Torrey Canyon' had been broken by bombing on 24 March and the oil contained in the ship released, then several times more oil would have polluted the English coastline.

PLATE 28

A, Biscay, west of Pointe du Raz, 47° 55′ N., 05° 12′ W., 12 May. Dense swarm of the planktonic dinoflagellate *Noctiluca*, as seen from R.V. 'Sarsia's' bridge. The white powder is craie de Champagne. **B**, 47° 55·2′ N., 05° 19′ W., 12 May. Similar view of *Noctiluca* swarm, with small lumps of oil. **C**, Trégastel-Plage (Côtes du Nord), 21 June. Machine skimming off surface layers of oily sand. In the sea is a milk-white detergent/oil emulsion formed after recent spraying of rocks to left of photograph. This drifted across the beach on the rising tide.

Table 27. *History of oil releases from the ship, and their subsequent fate*

Date of oil release	How oil was released	Where oil was blown ashore	When first blown ashore	When wind set offshore	Where oil was on 8 May	Rough quantities of oil based on official estimates
18 March 19 March 20 March	Ship aground 09.00 h 18 March; some oil tanks breaking and then ship subject to wave action and losing oil	Channel Islands and N. coast of Brittany	7 April 11 April	3 May	Mostly ashore in Channel Islands or France	30000 tons (about 21000 tons after loss of more volatile fractions)
21 March 22 March 23 March 24 March 25 March		Land's End S. Cornish Coast N. Cornish coast	25 March 25 March 26 March	29 March 29 March 8 or 9 April	Some ashore on Cornish coast (largely mixed with detergent and washed into sand) or dispersed at sea and widely spread	18500 tons (about 13000 after loss of the more volatile fractions)
26 March 27 March 28 March	Ship broken by storm approx. 19.00 h 26 March	Not ashore on 8 May	·	·	In Bay of Biscay	48500 tons (loss by evaporation was probably over 50% before this oil was dealt with by the French)
29 March 30 March	Ship bombed at 16.00 h 28 March and again on 29 and 30 March	A little on S. Cornish coast	2 April	13 April		20000 tons said to be mostly burnt by bombing

CHAPTER 9

OIL POLLUTION IN FRANCE AND GUERNSEY

From 18 to 25 June two members of the M.B.A. scientific staff visited Brittany and met many of those concerned both scientifically and administratively with oil pollution in France. They also visited polluted beaches on the north and west coasts of Brittany.

OIL POLLUTION AT SEA

The French coast was threatened at different times by two separate bodies of oil (Fig. 1). The first emerged after the original stranding of the 'Torrey Canyon' and drifted up-Channel in the manner shown in Fig. 32, where it was thought to be threatening the Channel Islands and Cotentin peninsula. Its course was tracked by sea and air reconnaissance from England, and it was also treated at sea with detergent. By 5 April when the oil mass lay close to Guernsey the British ships treating it were withdrawn and it was signalled to the French that they had emulsified all the oil they could, and that in consequence spraying operations had ceased.

Aerial observations by the French showed much oil remaining and, with the wind veering to the north-east, the coast of Brittany was threatened. Emergency precautions were begun by the French on 8 April, but owing to bad weather on 9 April, which prevented aerial reconnaissance, the first oil reached the Côtes du Nord almost without warning, between Les Heaux and the Bay of Lannion, on 10 April. Although hurried attempts were made to treat the oil at sea with sawdust and with powdered chalk, there was insufficient time to prevent the bulk of the oil (estimated at 15000 tons by the French), from coming on the shore.

The second mass of oil to threaten the French coast almost certainly issued from the 'Torrey Canyon' between 26 and 30 March. Its estimated course is shown in Fig. 36. This oil does not seem to have been reported to the French by the British, as the first warning received in France was from a French fishing boat which reported dense patches of floating oil in mid-Channel north of Ushant on 4 April.

First accounts were that it stretched over tens of miles and estimates of its quantity varied between 'over 50000' and 80000 tons, several times as much as was at that time drifting on to the Côtes du Nord. This oil would comprise all that released from the 'Torrey Canyon' after she broke up.

The most recent British estimate of the oil released immediately after the ship broke apart on 26 March was 48500 tons (p. 162) and to this must be added any oil which was later released, but not burnt, when the ship was bombed on 28, 29 and 30 March.

The patches of oil were reported to be so dense and compact that vessels steaming into them were checked. The same oil was observed from R.V. 'Sarsia' on 12 April, about 20 miles north of Ushant (p. 33; Plate 7A).

From 11 April on the oil patches were reconnoitred and charted by the French Navy, with headquarters at Brest. The oil stayed at sea for a further five weeks (Fig. 37), during which it drifted to and fro off the west coast of Brittany. It was first treated by the French with sawdust, but from 18 April it was sprinkled with powdered craie de Champagne. This is natural chalk ($CaCO_3$) with about 1 per cent sodium stearate, which is normally added in the manufacture of blackboard chalk. In this instance the stearate seems to have made the chalk hydrophobic and oleophilic so that it was attracted to the surface of the oil, binding it into particles which sank after a few hours. The breaking up of the solid oil masses was facilitated by ships steaming through it, stirring up the mixture with their propellers. The French informed us that the 3000 tons used, if correctly applied, would sink 20000 tons of oil.

Because of the tendency of the dry chalk to choke the delicate machinery of the radar-operating gear and missile launchers of the larger warships it was found necessary to employ small but robust ships such as minesweepers and fishing trawlers to spread the powder on the oil.

In addition a 3000-ton coaster, the 'Petrobourg', was hastily adapted for pumping oil from the sea, and this came into service on 27 April. This ship had a hose with a special floating attachment for sucking oil from the sea surface. It was capable of collecting 1200–1500 tons daily, and operated by coming alongside an oil patch and allowing the wind to drift the oil against the side of the ship (causing the thickness of the oil to be increased to 60 cm), where it was held by a floating boom until sucked up. This method proved very effective when the layer of oil was sufficiently thick, but owing to the dispersion of the oil by the time the 'Petrobourg' was brought into use only 1200 tons in all were collected on the two days on which she was employed.

On 12 May R.V. 'Sarsia' steamed through the oil mass, which was centred at about 47° 58′ N., 05° 22′ W. The mass consisted of floating pieces of oil of varying sizes up to 'rafts' of some 100 square metres with a thickness of perhaps 10–15 cm and of the consistency of heavy grease (Plate 7C). It was estimated that at least 1000 tons of untreated oil was present in the area on that day.

The oil came ashore around the Pointe du Raz and the Crozon peninsula, south of Brest, on 19 and 20 May (Fig. 39), but the extent of beach contamination was small. One estimate was 300 tons in all, but the M.B.A. staff who visited certain of these beaches thought it might be much less.

It would therefore seem that the French were successful in preventing the bulk of this very large oil mass from coming ashore. This was possible because they had several weeks in which to apply the chalk and adapt a ship

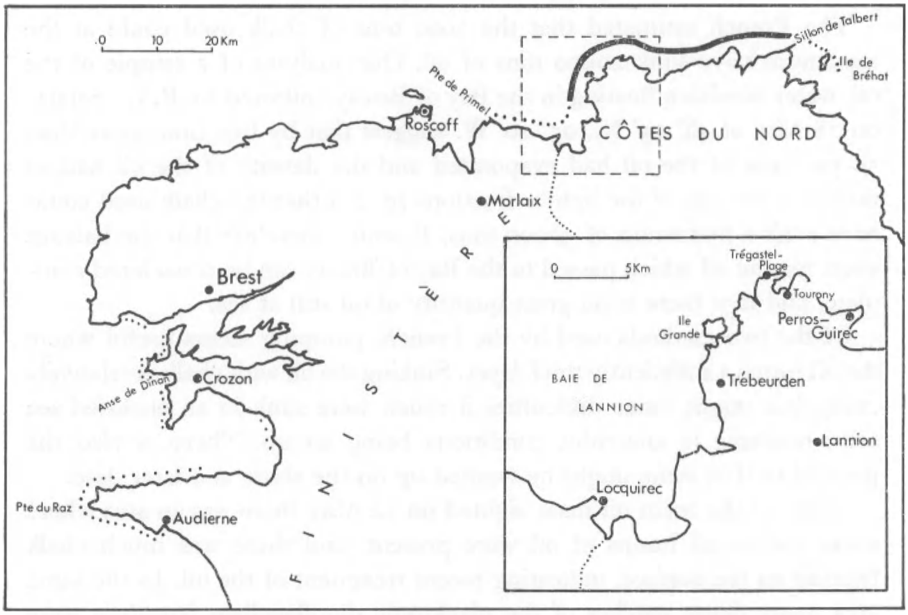


Fig. 39. Map showing oil pollution in Brittany, and some of the places visited by M.B.A. workers. The thick line shows the heavily polluted area on the Côtes du Nord. The dotted lines along the coast indicate slight or moderate pollution.

for pumping. Although the chalk would have sunk most of the oil it seems likely that in addition the remaining floating oil was broken up into small pieces which would soon become spread over a wide area and which, from the greater total surface area, would be more easily attacked by bacteria. An isolated patch of oil, still at sea on 18 May, is shown in Plate 7B.

Observations from 'Sarsia' in mid-May indicated that there was a large area where the surface of the sea was very slightly oily, resulting in smooth slicks, but not opalescence. This area stretched westward from the Ushant–Penmarc'h area to the continental slope south of La Chapelle bank. It seems likely that a lot of the remaining oil had by this time become dispersed in this region.

Taking an estimate of 50000 tons of crude oil initially released and passing to the west of Ushant, the 'balance sheet' seems to have been:

Lost by volatilization (and perhaps by biodegradation) of lighter components	25 000 tons
Pumped by 'Petrobourg'	1 200 tons
Stranded on coast	300 tons
	26 500 tons

Leaving 23 500 tons to be accounted for.

The French estimated that the 3000 tons of chalk used could at the maximum have sunk 20000 tons of oil. Our analyses of a sample of the oil–water emulsion floating in the Bay of Biscay collected by R.V. 'Sarsia' on 18 May at 48° 05′ N., 05° 20′ W. suggest that by this time more than 50 per cent of the oil had evaporated and the density of the oil had so increased by loss of the lighter fractions (p. 13) that the chalk used could have sunk a maximum of 30000 tons. It seems therefore that the balance sheet for the oil which passed to the Bay of Biscay can be considered complete, and that there is no great quantity of oil still at sea.

Of the two methods used by the French, pumping seems useful where the oil forms a sufficiently thick layer. Sinking the oil with chalk is relatively cheap but might cause difficulties if much were sunk in an enclosed sea area, resulting in anaerobic conditions being set up. There is also the possibility that some might be washed up on the shore at a later date.

South of the main oil mass sighted on 12 May there was an area where slicks and small lumps of oil were present, and there was much chalk floating on the surface, indicating recent treatment of the oil. In the same area many dense patches of the planktonic dinoflagellate *Noctiluca* were seen, producing a 'red tide'. It is not known if the appearance of *Noctiluca* in the same area as the treated oil is anything more than a coincidence, but it is possible that conditions favourable to the rapid multiplication of *Noctiluca* were created by the presence of oil or by its treatment with chalk.

Details of the red tide were as follows. Red tide was first seen as R.V. 'Sarsia' was steaming towards the polluted area, at 15.15 hours G.M.T. on 12 May. The first patches seen were right at the surface, but from 17.57 hours on they were described as submerged just below the surface. Only one patch was seen after 18.57 hours, suggesting downward migration or dispersion in the evening.

Meteorological details at 15.00 hours were: wind S., force 1–2; bright; 6/10 cloud; smooth sea, very slight swell; barometer 1007; shade air temperature 17 °C.

At a hydrographic station at the edge of the polluted area sea temperatures were: at 5 m, 13 °C; at 50 m, 11 °C; depth 124 m.

The patches of *Noctiluca* occurred over an area estimated as eight miles from west to east and three miles from north to south, with centre at 57° 55′ N., 05° 16′ W. (about 22 miles off Pointe du Raz).

Individual patches of *Noctiluca* tended to be elongated, with long axis south-west to north-east. A typical fairly large patch was estimated as 3 × 30 metres, but some formed elongated streaks 100 metres or more long and a metre or two wide. Patches were orange-red in colour (Plate 28A, B) thinning to white at the edges, and were often associated with small pieces of floating oil or chalk. The *Noctiluca* was concentrated near the surface of the sea, except in the evening, when it submerged. The association between *Noctiluca* and floating oil or chalk is probably due to 'convection cells' as described for plankton patches by Bary (1953). These would tend to concentrate plankton and floating particles into bands or streaks at the surface during calm weather. This red tide was evidently non-toxic, as no dead marine animals were seen.

Information on the outbursts of dinoflagellates and other organisms causing red tides has been summarized by Rounsefell & Nelson (1966). Outbursts occur in calm weather, mainly in warm waters, and after diatom blooms have impoverished the water of nutrients. They often occur in coastal regions subject to run-off from the land. Surprisingly enough the level of phosphorus in sea water within the red tide area may be very high, as much as ten times the normal level, but whether this is a cause or an effect is not clear.

Without further information it is difficult to speculate about possible causes of the red tide observed around the treated oil. The chalk or the oil might be a source of substances favourable to *Noctiluca*; partially anaerobic conditions may have been produced through bacterial action on the oil masses (aided perhaps by the breaking up of the oil by the chalk, so increasing its surface area); or the *Noctiluca* may have been feeding on micro-organisms which were themselves attacking the oil.

One possibility seemed to be that the chalk was a source of phosphate, but an analysis showed a content of only 300 ppm.

Some laboratory experiments were carried out, oil and chalk being added to *Noctiluca* cultures. These failed to show that these substances appreciably affected the rate of multiplication of *Noctiluca* in culture.

BARRAGES AND BOOMS

The French had some success with booms, and the M.B.A. scientists had an account from M. Cabioch, sous-Directeur at Roscoff, of the booms set up to defend the harbour and laboratory foreshore at Roscoff. Some of the oil from the Côtes du Nord, some 20 miles to the east, later drifted towards the Gulf of Morlaix and Roscoff, where it was under constant surveillance by local boats. The first boom was constructed in a great hurry, using straw covered with jute fibres buoyed up at intervals with tractor inner tyre tubes. The second boom had an expanded polyurethane core, surrounded by straw tied on, and a final covering of jute fibres. This boom was heavier, and according to M. Cabioch, less successful as a protection against oil. By means of these booms Roscoff was kept free of the oil, which for a time drifted in between the Ile de Batz and the mainland. The Biological Station at Roscoff is publishing an account of their experiences in a forthcoming number of the *Cahiers de Biologie Marine*.

CONDITION OF THE BEACHES

North coast

The beaches of the north coast of Brittany received about 15–18000 tons of oil, which arrived on 10–12 April over about 60 miles of coast on the Côtes du Nord, between Trébeurden and the Sillon de Talbert (Fig. 39). Lesser amounts came ashore west of Trébeurden, and in Finistère as far west as Roscoff. There was a significant quantity on the shores of Finistère between Locquirec and the Pte de Primel, but very much less than in Côtes du Nord. Scientists from Roscoff were familiar with the beaches in Finistère both before and after the arrival of the oil, but had scarcely visited the polluted areas of Côtes du Nord, where the fauna was considered to be less rich.

From Trébeurden north and eastward to Perros-Guirec the M.B.A. scientists visited a number of beaches which were uniformly polluted, showing a dark brown-black band of oil about a metre wide on the rocks at high water for many miles. The oil had arrived in calm weather, so this band was quite level. The coast in this region is mainly rocky with large pink granite boulders, up to 15 metres or more across, and unlike Cornwall is readily accessible as there are no high cliffs. There are also stretches of sand or gravel between the rocks.

Little or no attempt had been made to clean most of the shoreline, so that its condition contrasted with that of Cornwall which had mostly been sprayed with detergent. In mid-June the oil on the rocks was almost black (Plate 27B). We were informed by M. Cabioch that it came ashore

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PLATE 29

A, Steam-cleaning of oily rocks at Locquirec, Finistère, 20 June. **B**, North end of Trégastel-Plage (Côtes du Nord), 21 June. Troops wearing gasmasks spraying oily rocks with detergent.

PLATE 29

A

B

(*Facing p.* 168)

reddish brown in colour but after two days' exposure to the sun during neap tides it became blackened. The sandy regions had been to some extent treated with detergent and by mechanical means, but where they had not been so treated the surface of the sand was a dark blackish brown, sometimes with a thin hard crust of oil, with lighter brown oil in the top 10 cm of the sand (Plate 27C).

At Ile Grande such an untouched beach of coarse sand showed some evidence of biodegradation of the oil in the sand (p. 81), as under some patches of oil a thin grey layer was present. Farther east near Trégastel, in a similar coarse sand beach, the layer of sticky brown oil showed no evidence of biodegradation at the time.

In general the impression was that pollution had been overall heavier than in Cornwall, although at some places, such as Sennen and Porthleven, worse conditions had been observed. It is likely that an earlier visit, when conditions would have been comparable to those first seen in Cornwall, would have suggested that pollution in Brittany was everywhere worse than in Cornwall, where a rather smaller quantity of oil was spread over a much longer coastline.

West coast

South of Brest, beaches polluted by oil which came ashore about 20 May were visited on 23 June. Beaches on the west coast of the Crozon peninsula were inspected, but not those around the Pte du Raz, where pollution on a similar scale has been reported. Estimates of 300 tons as the total for the western beaches suggested that pollution was light, and the oil which was found was more or less confined to the northern end of the beaches. Oiled rocks were black, and at one or two places were covered by up to 5 cm of thick viscous oil. At the north end of the Anse de Dinan, in addition to this type of pollution, there were small lumps of brownish oil on the strand line evidently drifted in at a later date than the main pollution. None of these beaches had been treated with detergent, but one beach had been treated mechanically by bulldozing, and at another some troops were collecting and burning small lumps of oil and driftwood.

The quantity of oil on each of these beaches appeared to be less than a ton, so that 100 tons may be a more realistic figure for the total drifted ashore from an original mass of over 48000 tons.

METHODS OF TREATMENT

The following notes apply mainly to the north coast of Brittany.

Gorse and straw

Some sandy beaches had been cleansed of oil by laying a line of gorse or straw on the beach at low water. As the tide rose, these materials rolled up the beach and collected oily sand. They were then picked up and burned, and the process repeated. Repetition of this process over a month was said to be most effective, and the sandy part of the beach at Locquirec, for example, where this method had been used, was clean. Sawdust (of which there were traces on many beaches) was also tried in this way, but was not found to be effective.

Removal of upper layers of sand

When the oil arrived on sandy beaches it was reported to have sunk to about 15 cm below the surface. Cores taken at Ile Grande showed oil (in an untreated beach) in the top 10 cm. Since the beaches are mainly accessible to vehicles it had been feasible to bulldoze off the upper layers, repeating the process until all the oiled sand had been removed. In addition to bulldozers, two large machines flailing sand into a hopper were seen at Trégastel, the sand being carried away and dumped to aid land reclamation nearby (Plate 28C).

Steam cleaning

On 20 June the M.B.A. scientists attended an experimental cleaning of oiled rocks at Locquirec (Finistère) under the direction of M. Daniel (head of Civil Defence for the department). Troops were using small trailer-mounted steam-cleaning equipment of the same kind as is used to clean the underside of vehicles (Plate 29A). Steam at 140 °C and 8 kg/cm^2 was being delivered from small nozzles at the end of pipes held by the operators, who were equipped with oilskins and gasmasks (the latter not in use). A small quantity of Teepol (1 l. Teepol to 300 l. water) was added to the cold water used for rinsing the rocks after the steam treatment, and this produced a white foam around the treated areas. By this method 30 square meters of rock surface could be cleaned per hour per machine. An ample supply of fresh water, around 2000 l. per machine, was required.

The treated area was at high-water mark with few animals on it, and the steam treatment seemed to clean the rocks effectively. Below the treated reef, streams of water ran down through the sand, and in places the black sulphide layer in the fine sand had been washed up to the surface. It is possible that this may have resulted from previous mechanical removal of sand, which had begun on 10 April, as soon as the beach had been polluted.

There was no evidence of plant or animal mortalities on this beach, although anything subjected directly to steam treatment would naturally be killed. The ultimate fate of the oil removed by steam treatment and washed down the beach is not known.

No detergents were being used for beach cleaning in the department of Finistère. Because of the important inshore oyster beds and shellfish industry of the area the civil defence authorities had been strongly advised against the use of detergents by scientists at the Roscoff Marine Biological station. A few miles to the east, however, in Côtes du Nord, detergents were being used for beach cleaning.

Detergents

Detergents were being used to clean rocky shores at various places on the coast of Côtes du Nord, the coast being much more heavily polluted than in Finistère. Detergent treatment began on 24 May and continued until the beginning of July. During this period some 2300 tons of detergent were reported to have been used. At the time of our visit detergents were being used more or less on an experimental basis under the direction of two experts from the Institut National de Recherche Chimique Appliquée, seconded to Roscoff from the Laboratory of the Ecole Polytechnique.

The chief detergents used were Oxane and Fina-sol, the latter being a dark red liquid, non-ionic, with a much less pronounced smell than BP 1002. The chemists from I.R.C.A. had been sent more than sixty types of detergent, of which Fina-sol had proved to be the least toxic. Toxicity tests carried out by M. Audouin of the Fisheries Laboratory at Roscoff confirmed the opinion earlier put forward in this report that the more efficacious the detergent the more toxic it is. Some experiments had been carried out upon emulsion stability, the conclusion being that few brands were capable of forming a stable emulsion of oil in sea water.

Drums of detergent were pumped into small trailers at the army camps, and these small trailer tankers were then moved by lorry to different sites, where spraying was carried out (Plate 29B). A number of commercial tanker lorries were also employed. Operations were on a smaller scale than in Cornwall, spraying being from small nozzles by operators dressed in oilskins and wearing gasmasks. Only a limited area was treated at one time, the operators then moving elsewhere. On the badly polluted beach of Trégastel, spraying on the rocks produced sufficient detergent to form a white patch in the water which gradually filled the harbour (Plates 22B, 28C). The sand became impregnated with detergent from the water: it was not sprayed directly. On this beach, dead limpets, other gastropods and crabs were found. Spraying had been carried on there for some time prior to the visit. At this site alone of those visited, oil layers were found buried below clean sand.

Despite the fact that the oil being treated by detergent was some two months old and had become black, the spraying seemed to be efficient at removing it. Fresh brown patches of oil (Plate 6A) some metres across were observed at Trégastel on the water in the harbour perhaps resulting from de-emulsified oil returning. Similar small patches were observed on the strand line near Ile Grande (Plate 6B). At other beaches, such as Perros-Guirec, detergent had been used, and a sulphide layer, 1 cm below the sand surface, smelt of detergent. An iridescent oil film was present on the water-table. In the harbours of Ploumenac'h and Tourony nearby the water was milky white and the sand smelt of detergent. Dead crabs were floating there, and a local resident reported that dead congers had been found. Although the lagoon of Tourony dries out at low tide, and although detergent-spraying had stopped there five days prior to our visit, the water was still milky with detergent at high tide. Spraying had been carried out here for the past month.

The general impression gained was that at Trégastel and certain other beaches much detergent had been used, and that similar effects to those observed in Cornwall were either observed or could be expected. It seemed probable that more detergent would be used.

No evidence was obtained of any effects of detergent upon the important lobster fisheries of the Côtes du Nord, but, if spraying were carried out elsewhere in the same manner as at Trégastel, it seemed likely that toxic effects would be observed.

OIL POLLUTION IN GUERNSEY

The following notes on oil pollution in Guernsey were made by a member of the M.B.A. scientific staff who visited the island on 10 and 11 July. He is indebted to Mr Guillaumette (States Supervisor), Mr Bichard (Department of Public Works) and Capt. Walker (Fishery Officer) for information and assistance.

Guernsey, the only one of the Channel Islands to suffer pollution, received a severe but localized shore fouling on 6 April. Shortly afterwards the very large mass of oil which later went ashore on the Côtes du Nord of Brittany (Fig. 34) passed very close to the Channel Islands and much of it was blown southwards through the channel between Guernsey and Sark.

The only badly affected area was a two-mile stretch of the west coast of

Guernsey from Saumarez Fort to the south end of Vazon Bay (Plate 27A). The intertidal reefs in this area are very extensive, up to half a mile wide in places, forming small north-facing bays and fortunately one of the least popular spots for holiday visitors. While the wind stayed onshore the most effective means of disposal was found to be the direct pumping of oil from the sea surface at high water and just after. Up to seventeen sewage tankers of 800–1000 gallon capacity were available and, fortunately, good access to the shore was possible from several slipways. A minimum thickness of oil of about 2 inches was necessary for successful pumping; so long as the wind stayed fresh the depth of oil built up at times to 4 inches. If the wind dropped or changed, pumping had to stop. Pumping was carried on until 24 April when the wind changed to south-east for less than a day, but the remaining floating oil was carried away to the south.

Some of the oil pumped from the sea was delivered through a large (4 inch) suction pump into a pit or tank from which the tankers filled up later, and small amounts of oil were pumped from pools with portable pumps. The total quantity of oil removed directly was 866000 gallons (*ca.* 3000 tons).

Steam-cleaning plant was tested on oil-covered walls but was found to be very slow compared to light detergent spraying coupled with pressure jets of water from a fire-hose.

The use of detergent was very strictly limited (it had to be paid for at 6*s*. per gallon) and was generally confined to slipways and sea-walls. Very extensive rock areas around the level of high-water neaps were still blackened on 10 July and will be left. The oil residues on the rock surfaces were dry to a light touch and slightly powdery. The oil took many days to adhere to the rock and did not affect lower parts of the shore.

Natural banks of broken kelp above high water absorbed the oil and cut weed was used deliberately to a small extent to absorb it.

Rock pools in the most heavily polluted reefs contained a normal fauna, including blennies, sea anemones, winkles, limpets, etc. Nearby several live ormers (*Haliotis*) were found during a short search just below low-water springs at Le Jaune Pont.

The total cost of the oil clearance work in Guernsey was estimated to be about £30000 (working out at roughly £10 a ton).

CHAPTER 10

SOME LESSONS LEARNT

SUMMARY OF MAIN RESULTS

The investigations reported in the previous chapters of this book have provided us with new information about the movement of oil at sea, about the properties of detergents and their dispersal in the sea, and about the effects that these two pollutants have had upon the animals and plants with which they have come into contact both at sea and on the shore. How can we profit from this information; what advice can we give for dealing with similar problems that arise in the future; and what can we suggest for further lines of research which ought to be put in hand?

Perhaps first it is convenient to refer to some of the more important points which have been discussed and emphasized in earlier chapters.

As regards the oil itself, the formation of emulsions of variable composition with sea water makes it difficult to predict the rate of loss of oil by evaporation. In connection with the drift of oil at sea a simple formula has been given which allows the movement of oil on the sea to be predicted. Pollution by the 'Torrey Canyon' oil was found to have little biological effect apart from the tragic destruction of sea birds.

The detergent used to treat the oil away from the coast was not noticeably injurious to marine life except in the extreme surface layers, where pilchard eggs and some phytoplankton were affected. The direct treatment of polluted shores, however, resulted in the death of a large number of shore organisms of many different kinds, and effects were also observed in the sublittoral zone.

On shores left untreated, evidence has been obtained of removal of the oil by the fauna as well as by other natural agencies. In addition, on sandy beaches microbiological degradation has been occurring unhindered by detergent treatment.

Studies in the laboratory showed that, in addition to the immediate effects observed, longer-term consequences might be expected. It was found that the immediate toxicity of the detergent largely resides in the solvent fraction of the detergents, which is fortunately readily lost by evaporation from sea water, although it is adsorbed on to sand, and may have temporary physical effects upon sandy beaches. In general, treatment has been found to be most successful upon rocky shores; on sandy beaches the use of detergent has been less successful. On both types of shore, however, treatment has led to some degree of secondary pollution owing to instability of oil–detergent emulsions which allow the oil to re-separate from the emulsion. Methods have been devised for the bioassay of detergents in sea water, and these have been used to follow the dispersion of detergents in the sea after use on the shore. These show that dispersion is largely dependent upon local weather conditions.

POLLUTION

These results have emerged from a study of some of the effects of a major instance of pollution. To be quite clear what we mean, pollution may be defined as 'an event or a continuing circumstance whereby there are introduced into the environments of air, land and water substances that may adversely affect the balance of nature and human well-being'. Pollution of the environment affects everybody. It may carry with it an actual or a potential danger to man's health and to his economy, and it may be damaging to or destructive of features of the natural environment that provide the means of recreation and aesthetic enjoyment. In a modern industrialized society the problems of pollution apply with especial force. They are, moreover, complicated by the fact that some forms of pollution are often permitted in the interest of one requirement but to the detriment of others.

The 'Torrey Canyon' disaster presented these aspects and problems of pollution in such an acute and severe form that it evoked two immediate and significant reactions.

In the first place the unexpected drama of the event, and the magnitude and variety of its possible consequences, showed that when the dangers of pollution are evident there is a widespread public concern for the formulation and development of a nationally conceived policy for dealing with pollution hazards. Secondly, the disaster necessitated the setting up at short notice of administrative arrangements, technological procedures and scientific programmes to asssess and, where possible, to counteract the consequences of the large-scale oil pollution. The 'Torrey Canyon' campaign has thus shown up the strength and weaknesses of a complicated collaborative exercise in ways which, if the lessons are properly learnt, will be of the greatest value in the framing of future procedures and policy for dealing with pollution problems generally.

THE BIOLOGICAL ASPECT

The Plymouth Laboratory was directly concerned with only a small sector of the 'Torrey Canyon' programmes. In association with scientists of the Ministry of Agriculture, Fisheries and Food and of the Nature Conservancy, our primary purpose was to assess the damage done by oil and detergents to marine life and to make recommendations on the measures needed to reduce and alleviate such damage.

We soon found, however, that the need to obtain information on matters essential to our investigations—for example, the composition of detergents, the quantities used in different localities, the movements of oil at sea and its influx on to beaches—involved us intimately in all aspects of the remedial measures. And, in addition, we extended our investigations to the examination of some physical phenomena such as the movements of oil at sea and the stability of detergent-treated beaches which were not originally in our programmes. This has enabled us to view the problems of pollution in a broader perspective than at first we had thought possible. It is therefore thought appropriate to draw on these experiences, as well as on the results of our biological investigations, in commenting on the 'Torrey Canyon' procedures, to make suggestions which may be helpful in the planning of future programmes of work on marine pollution. We omit from our comments, however, reference to matters which are outside our scientific competence; for example, questions bearing on the salvage of the 'Torrey Canyon', the disposal of oil contained within the ship, and the efficacy of mechanical devices designed to prevent the spread of oil and to provide the means of collecting it. These matters are dealt with fully in the Report of the Committee of Scientists on the Scientific and Technological Aspects of the 'Torrey Canyon' Disaster (1967). Our comments are arranged under the following headings: 'Torrey Canyon' programmes and procedures in retrospect; organizational requirements for future emergencies; a final comment.

'Torrey Canyon' programmes and procedures in retrospect

The 'Torrey Canyon' marine pollution was caused by crude oil released on to the surface of the sea and by non-ionic detergents used in the dispersal of the oil. Oil, although it killed several thousand sea birds, was recognized from the outset of the 'Torrey Canyon' operations to be a pollutant mainly destructive of the amenities of shores and beaches; detergents, on the other hand, were known to be destructive of life.

There was therefore built into the operations, from the beginning, a division of effort and of purpose. Almost the entire complex machinery of policy-making, administration and technological procedures were focused on the problem of disposing of the oil, either by getting rid of it at source, by preventing it reaching shores, or if these methods failed by removing it from rocks and beaches. With the preservation of one kind of amenity the primary and most urgent objective of the operations, the biologists' role was thus essentially to assess the effects of the oil pollution and of the use of detergents. A situation of this kind inevitably means, in a crisis, that the many bodies engaged in the preservation of 'amenity' have this purpose wholly in view and have little occasion to consult biologists for information which could assist them in their purpose. Biologists, on the other hand, must continually seek for information as to what is being done if they are to measure the effects of the pollutants and to recommend (as we were required to do) the measures needed to reduce and to alleviate the damage which they cause.

During the 'Torrey Canyon' operations we were fortunate in finding at Maritime H.Q. liaison personnel who were sympathetic and helpful in answering inquiries. Our work, however, would have been made easier, if from the beginning of the operations, there could have been established an interchange of personnel on a recognized basis between the Plymouth Laboratory, as the centre of biological operations, and Maritime H.Q. This would have needed one or two additional staff at H.Q. who could have spent some time each day at the Laboratory to see at first hand the nature and progress of the research going on and to discuss its implications with members of the staff. A direct contact of this kind would have been of particular value in assessing: the movements of oil at sea; the determination of its quantity in the travelling patches; in advising H.Q. on the routing of air reconnaissance flights; and in alerting authorities in France of the magnitude, rate of travel and direction of approach of oil patches threatening the French coastline.

Within the Laboratory itself our main need, once the programmes of investigation had been formulated, was to ensure (*a*) that we had expert advice available on all matters relevant to the study of pollution problems and (*b*) that the teams of workers in each field should be large enough to cover, in the limited time available, the work that had to be done. Pollution problems required the participation of organic and physical chemists, hydrographers, physiologists, pharmacologists and bacteriologists; and they involve the expertise of ecologists with a special knowledge of planktonic or of benthic organisms. So far as possible it is most important that all should work in a laboratory near the scene of operations. Only in this way can a problem which overlaps many scientific disciplines be fully probed, and the expert in each field be assured of the means of seeing the opportunities offered for study and for developing his investigations in his own way. During the 'Torrey Canyon' investigations we often felt the need for assistance in particular fields (e.g. bacteriology) and we should perhaps have been more active in recruiting it had we always known where to make the approaches.

We may now turn to some of the problems which had to be tackled in examining the biological consequences of the 'Torrey Canyon' pollution, and, in particular, to the effects of the use of detergents.

As has already been made clear in this report, the decision to use detergents for the dispersal of oil was taken on the view—with which there will be general agreement—that the preservation of coastal recreational amenities was of first priority, and in the hope that the effects of detergents on marine life would not be catastrophic. Let it be said straightway that the effects have not been catastrophic. But it would be wise not to take comfort from the outcome of an action taken largely in ignorance of its possible consequences. It is all the more necessary therefore in the light of our new-found knowledge of the nature and effects of detergents to examine (*a*) by comparison with other possible methods of oil clearance, the efficiency of the detergent method of dispersal, and (*b*) the possibility of the modification of detergents to reduce their toxicity.

Non-ionic detergents have been used for some years by the Navy and by harbour authorities for clearing small oil spills. Though detrimental to marine life if used repeatedly, they have been found to be convenient, efficient when properly applied, and relatively inexpensive to use when only small quantities of detergent (used in an approximate proportion of 1 part by volume of detergent to 2–4 parts of oil) were needed.

The decision to spray at sea the large oil masses which were escaping from the 'Torrey Canyon' was taken on the basis of these experiences. It has been argued that, if complete emulsification of the oil was, in fact, achieved, the 700000 gallons of detergent employed in the sea-spraying operations would have effectively dispersed up to 15000 tons of oil which might otherwise have been carried on to the neighbouring coastline (Committee of Scientists Report, 1967). However, the total cost of the sea operations was probably of the order of £400000 and the question arises as to whether the operation could have been done more cheaply and more effectively.

An alternative method of disposing of oil from the surface of the sea that was tried during the 'Torrey Canyon' operation was the French practice of sprinkling powdered natural chalk (with 1 per cent sodium stearate added) on to the oil. Our information was that 3000 tons of chalk were applied, and we estimate that up to 30000 tons of oil may have been sunk by this method (Chapter 9). Evidently, much more chalk would have been required to sink the same amount of freshly released oil, for the amount of chalk required depends directly upon the density of the oil to be treated; the longer that oil remains at sea the denser it becomes by evaporation of the lighter fractions. The cost of the materials has not been ascertained but it would undoubtedly have been but a small fraction of the estimated £200000 spent on sea-sprayed detergents alone in the area of the Seven Stones. Possible disadvantages of the chalk-sinking procedure are that (1) the sunk oil may foul fishing grounds, and (2) the oil may subsequently be washed ashore. All that can be said at present is that there have been no reports that either has happened. There is at least a prima facie case for believing that oil patches moving into the open sea and away from the coast are best dealt with by sprinkling with chalk, or better still, a heavier material rendered unwettable by suitable pretreatment (for example, silicone-treated sand). Such methods might also be as effective as any other in dealing with oil patches driven towards the shore, though under these conditions the danger of sea-bed fouling, adverse to inshore fisheries, might render the chalk treatment undesirable. Nor might it be altogether suitable in shallow areas such as the Thames Estuary or off the Rhine delta. Much depends on how quickly the sunk oil is destroyed by bacteria.

In commenting on the use of detergents for the cleansing of rocky shores and sandy beaches, we fully agree with the point made in the Committee of Scientists Report that every attempt should be made to remove oil from shores and their approaches by mechanical devices and trapping materials, wherever they can be effectively used. It cannot be emphasized too strongly that detergents, at best, can only *disperse*—they do not *destroy* the oil. But where there is a need for the rapid cleansing of a shore the 'Torrey Canyon' operations have shown that detergent treatment can be very effective. There is, however, both for reasons of economy and the preservation of shore life, a need to employ detergents with discrimination.

We were told, at the beginning of the operations, that detergents are only effective in clearing oil from rock surfaces if applied quickly, and before the oil has undergone changes. This has been shown, in the course of 'Torrey Canyon' operations, not to be true. Oil can be cleared effectively from rocks weeks after deposition, provided always that the detergent is applied in a proper manner, and adequate agitation given to the oil–detergent mixture. As therefore a delay in spraying is permissible, the most favourable conditions of wind and tide can and should be selected. It would then not only be possible to consider the optimal conditions for dispersal of the oil, but also to give due regard to the effects of the spraying on the flora and fauna of the affected area. Some places, notably, inaccessible coves should be left undisturbed for, as shown in this report, natural processes including removal of oil by browsing intertidal animals and bacterial decomposition will in the course of a few months bring about a considerable recovery. The nature and time scale of these processes need further investigation. Where rocky shores are needed for holiday recreation there seems, however, to be a case for employing detergent treatment to the point that they are again acceptable, although this may result in secondary pollution of adjacent sandy areas.

Oil on sandy beaches indeed presents an intractable problem. The difficulty here is that detergent-treated oil sinks into sand and may remain there for a considerable time to be uncovered at intervals by wave removal of the cleaner surface deposits. Moreover, oil mixed with sand may sink below low-tide mark and be subsequently washed back on the shore by gales.

The method of bulldozing oil-covered sand to the lower levels of the beach and there treating it with detergents met with some success, but owing to the instability of the oil-detergent emulsion the oil was apt to reappear and be redeposited elsewhere. An alternative method, if places for disposal are readily accessible, would be to remove the oily surface sand mechanically. Open coast beaches often have a sufficient cover to make this practicable without dangerously exposing the backing cliff to erosion, but the method would need to be used only when the conditions for sand removal are favourable.

We now consider the toxicity of detergents, with its attendant problems of (1) when, in their present form, their use would not be desirable, and (2) whether they could be modified to make them less toxic.

It may be supposed that the use of detergents for shore-cleansing becomes undesirable when the preservation of amenities is outweighed by other considerations of which the economic value of fisheries is probably the most important. The more cautious use of detergents by the French reflects the greater economic importance and the more open-shore siting of their shellfish industry. At the outset of the 'Torrey Canyon' operations it was very wisely decided, on the advice of Ministry of Agriculture, Fisheries and Food scientists that detergents should not be used in estuaries where there are commercially important shellfish beds. This should be a continuing directive to which greater point is given by the experiences gained from the 'Torrey Canyon' disaster. If they are protected by booms, estuaries are not likely to be polluted. Should oil enter, in small quantity, our evidence is that it would not kill shellfish, though it would probably make it undesirable for them to be eaten until the oil had been dissipated by natural processes of change and degradation.

The beaches and sea-beds affected by the 'Torrey Canyon' oil, and subjected to detergent treatment, were almost all of the clean, silt-free sand type characteristic of wave-exposed shores. The sand of these beaches is mobile and contains few animals other than minute interstitially living organisms. If, however, the pollution had occurred in a region of more heavily populated sandy muds and muds the high toxicity of the detergents would have had a catastrophic effect. Oil deposited on the muddy sands and muds of quiet water regions might be very difficult to remove, but use of detergent is not likely to improve the situation.

Our investigations have shown that the toxicity of detergents resides mainly in their volatile aromatic components and we would advise that research is urgently needed to discover whether less toxic materials can be found as substitutes for the presently used solvent fractions. The surfactant components of detergents are much less toxic, but, since they are more persistent in sea water, further biological investigations are required in order to test their possible long-term effects on organisms and their concentration within the terminal organisms of food-chains.

We now comment on our organization of onshore and offshore surveys.

An essential requirement for a scientific analysis of an artificial change of environment on the populations of marine organisms is that the means shall be available for comparing the population changes with any alterations which would have occurred in the course of normal seasonal and other natural changes of the environment. In order to assess the effects of detergents on the populations of intertidal animals it is therefore necessary to have available for collateral study a nearby shore that has not been subject to detergent cleansing. It was a feature of the 'Torrey Canyon' shore-cleansing operations that they left hardly a single locality free from the suspicion of some measure of detergent treatment. If biologists are to report adequately on the effects of a pollution they must be left in possession of a control, and must be consulted before the operations have gone too far on the localities which are to be left untouched. From the few moderately oil-polluted sites that were in fact left untreated, the natural cleansing action of wave, sand, and fauna has become obvious.

A programme of regular surveys will be a continuing requirement if pollution effects are to be adequately assessed in the future. They will also be necessary in the immediate task of assessing the patterns of recolonization of shores following their treatment by detergent. There is therefore, in our opinion, an immediate need to provide by appropriate directives for the reservation of selected localities as 'protected' areas free from avoidable unnatural disturbance.

In carrying out our shore and offshore surveys we had two main purposes in mind: to report, in essentially qualitative terms, on the developing destruction in as many localities as could be visited by our few scientists in the limited time available to them; and to survey more continuously and in greater detail one or two localities which we had examined regularly for many years. The latter aim was only partly achieved because the oil did not reach our home grounds. The detailed survey of the progress of the destruction of a rich and varied fauna and flora requires a concentrated and sustained attention, which can only be given by large teams working day by day on a shore and with well-prepared objectives, and where detergent-spraying or other treatment is carried out by authorities in collaboration with the scientists. This is a further example of the need for early discussion and collaboration of personnel at Operations H.Q. with the scientists involved in the biological surveys.

Our offshore surveys were limited in scope by the fact that only a single suitable research vessel was available; the cruise programme had therefore to be devised to cover as many different lines of investigation as possible, and this led to insufficient coverage of some important aspects.

Had our surveys been co-ordinated with other programmes including the aerial surveys, such important tasks as the collection of oil samples at sea to determine the progress of the ageing of the oil and its increase in density (relevant to decisions about the best method of treatment) could have been carried out more efficiently. We also think it important subsequently to follow not only movements of visible oil patches, but also the fate of very finely dispersed oil over the general sea surface.

Finally, some mention should be made of the observations and predictions made by scientists at the Plymouth Laboratory on the movements of oil at sea, the results of which are reported in Chapter 8.

As the laboratory nearest the scene of the wreck we began immediately to collect all the data relating to oil movements that we could lay hands on and we continued to collect records and to study them as a research project. By mid-April we had become seriously concerned that a very large amount of oil had disappeared from the scene, apparently without trace. The predictions shown in Figs. 32–38 were based on calculations from wind velocities and were intended as directives to further observation. Coastal Command of the Royal Air Force gave us most willingly all the assistance that it was in their power to give but their programmes did not allow them to fly the sorties which we needed. Our calculations remained therefore largely theoretical until at a later date oil stranded on the coast of Brittany and we established contact with the French Navy through Professor Courtot of the Faculté des Sciences, Brest.

We feel that the National Institute of Oceanography would have been admirably fitted not only to plot events but actively to advise the British and neighbouring governments on the air reconnaissance necessary for advising on the coasts which were at hazard.

It is, of course, easy to comment after all the facts have been collated and tested, but in any future incident of this kind we strongly urge the National Institute of Oceanography should at once be consulted as expert advisers on the probable course of events. The Institute is well able to co-ordinate effort with its sister laboratories in neighbouring countries with which it has close contacts. Such international co-ordination was needed but was only slowly achieved.

Organizational requirements for future emergencies

Our commentaries on the lessons learnt from the 'Torrey Canyon' disaster and from the investigation of its biological consequences have included some suggestions and recommendations that may be of value in future emergencies of a similar kind. Oil pollution and the measures necessary to counteract it could, however, occur over any part of the British coastline, and it is appropriate to consider the means by which the investigation of the biological consequences might most effectively be organized on a regional basis.

We have given our reasons for believing that complex investigations of this kind, involving a wide range of scientific disciplines, need to be based on a laboratory with staff and facilities adequate to service these various requirements. It would seem desirable therefore in anticipation of future emergencies to prepare a list of regional centres upon which pollution investigations could be based. Such a centre would ideally be not more than 30–40 miles from the field operations, and would need to be of a size and scientific coverage such as is provided in Britain mainly by marine laboratories and universities. If the co-operation of suitably located universities could be sought in the provision of facilities for the conduct of emergency programmes a substantial part of the British coastline could be covered by a chain of regional centres. Within the framework of the present organization of civil science in the United Kingdom, the Natural Environment Research Council might well be thought to be the body best able to organize the regional arrangements and to provide such advice and assistance as would be needed in preparation for future emergencies.

A final comment

The 'Torrey Canyon' disaster highlighted with an exceptional clarity the unpleasantness (to put its consequences in the least emotive terms) that can arise when materials essential to man's industrialized society escape from the confines of their intended use to foul the environment.

The escape through human error or by unavoidable accident of dangerous or unpleasant pollutant materials are hazards which must be accepted and dealt with as the occasion arises and as best we can. Other forms of pollution are intentional and many are thought to be necessary. If we ask why they are thought to be necessary there can be but one answer: it is because the easiest and cheapest way of disposing of unwanted materials is to throw them away. If materials so disposed of are harmless and unenduring no one minds very much. But, if they are injurious and persistent, acceptable means of disposing of them must be found even though it may be expensive to find the answer.

We are progressively making a slum of nature and may eventually find that we are enjoying the benefit of science and industry under conditions which no civilized society should tolerate.

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INDEX

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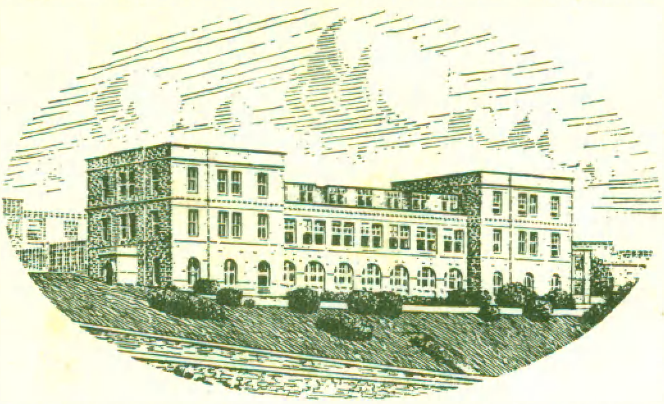

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