THE ROYAL SOCIETY

INTERNATIONAL INDIAN OCEAN EXPEDITION

R. R. S. 'DISCOVERY'

Cruise 1. South East Arabian Upwelling Region

Cruise Report

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Introduction

The Royal Research Ship 'Discovery' is now taking part in the International Indian Ocean Expedition and this report gives an account of her first cruise in the Arabian Sea. At this stage it is clearly not possible to present any final treatment of the results of the Expedition as all the scientific data have to be recomputed and checked. For this reason the actual measurements and results of analyses have deliberately been excluded from this report, but the different scientists who took part have contributed preliminary comments on various findings so that other ships of the Expedition now working or about to work in the region will have this information at their disposal. It must be emphasized, however, that any conclusions drawn at this stage may well have to be reconsidered at a later date.

The first cruise of the R.R.S. 'Discovery' in the Indian Ocean was planned to survey the region off the South Arabian coast. During the period of the south-west monsoon, active upwelling occurs along this coast (Bobzin 1922) and the intention of the survey was initially to delimit the area of upwelling and then to investigate its mechanism and the ensuing cycle of chemical and biological events. It was hoped also in the course of this work, to collect as much information as possible which might be of use in the future to the development of any fisheries in this region.

Itinerary

The greater part of the scientific staff (table I) embarked at Plymouth from where the ship sailed on 1 June 1963. On the passage out to the Indian Ocean it was necessary to proceed with as much speed as possible since the ship was somewhat behind schedule and although this limited the amount of scientific work which could be done, it gave ample opportunity for the preparation of equipment. Continuous echo-soundings were taken and a number of stations were worked in the Mediterranean mainly to calibrate and test equipment and to ensure that everything was functioning properly before commencing the survey. A brief call was made at Malta to take on two additional seamen to bring the ship's complement up to strength and then a course was made to Port Said and through the Suez Canal to the Red Sea.

On 15 June near the middle of the Red Sea an extensive bloom of the blue-green alga Trichodesmium erythraeum (which is reputed to be the origin of the name of the Red Sea because of the reddish discolouration it produces) was encountered. The ship was stopped, samples were taken and this station (no. 5000) marked the beginning of the Discovery's work in Indian Ocean waters. Two stations were then worked in the deep in the centre of the Red Sea and the full routine of water sampling, current measurements and net work was carried out. Each of these stations was followed by an Isaacs-Kid Midwater Trawl intended to sample the deep water fauna; the temperature in the Red Sea at a depth of

1000 m is over 21°C and as might be expected the fauna at 800 m was most unusual in that there appeared to be a complete absence of the normal bathypelagic organisms found at comparable depths in the larger ocean basins.

After refuelling the ship sailed from Aden on 23 June to commence the survey and by midday on 24 June all underway observations were being made. The plan of the survey consisted of six lines of stations about 200 miles long running normal to the Arabian coast at intervals of about 120 miles (fig. 1). The first of these lines commenced at Ras Fartak (52°E), and this point was reached at 1600/25 June. The station routine consisted of the following:

1. Water sampling at standard depths: 0, 10, 20, 30, 50, 75, 100, 150, 200, 250, 300, 350, 400, 450, 500, 550, 600, 650, 700, 800, 900, 1000, 1200, 1400, 1600, 1800, 2000, 2500, 3000 m etc.

2. Bathythermograph lowering to 270 m.

3. Current profile to 100 m with attached temperature/salinity/depth probe.

4. * Chlorophyll measurements at fixed depths 0, 20, 40, 60, 80 and 100 m.

5. Vertical haul with 50 cm diameter phytoplankton net (N50V) from 100-0 m.

6. Vertical hauls with 70 cm diameter 200μ mesh zooplankton net, metered for depth and flow, in the layers 50-0. 100-50, 200-100, 500-200, 1000-500 m.

7. * Vertical haul with Indian Ocean Standard Net from 200-0 m.

8. * Bottom grab (0.1 m^2 spring grab).

9. On completion of station, a 15 min tow with a neuston net at 5 kt.

A line of 14 such stations was run across to Socotra at 10 mile spacings near the coasts and opening out to 30 mile intervals in between. Socotra was reached at 1842/28 June and then a northerly course was made towards the Arabian coast. Underway observations made between the stations and on the passage between lines of stations consisted of continuous echo-soundings, half-hourly bathythermograph lowerings and neuston net hauls in selected positions. Ras Risut (54°E) on the Arabian coast was reached at 0825/30 June and the second line of stations commenced. This was abbreviated as the first line had taken rather longer than expected and the nine stations were run out to only 100 miles from the coast. These observations were completed by 2 July and the ship returned along the same course to anchor a buoy for current measurements off the

* These observations were usually made only at alternate stations.

edge of the continental shelf. The current measurements continued until 1048/3 July and then a zig-zag route was followed along the coast to the Kuria Muria Islands. It had been intended to carry out some essential repairs involving a complete shut down of the main engines, at an anchorage there, but the wind was blowing about force 9 and the ship had to proceed offshore before the repairs could safely be made.

The third section was commenced from Ras Sauqara (54°41'E) at 0106/5 July and after ten stations the line was interrupted to give the analysts some time to meet arrears of chemical analysis. The ship returned to the continental shelf edge to make current measurements but the weather deteriorated to such an extent that these had to be abandoned. As there seemed little chance of immediate improvement the ship returned seawards to complete the section. The remaining stations were worked in heavy weather and the section was completed by 0206/9 July. A straight course was then made into Ras al Madraka (57°55'E) and the fourth section began at 0236/10 July. This section was completed at 0806/13 and the ship returned to the coast in the vicinity of Masira Island (59°E). A number of sharp fronts were crossed on this passage and to examine one more closely we recrossed it and made continuous BT dips as the ship drifted over it. After obtaining bearings on Masira Island, current measurements were made until 1430/15 July. The fifth section was then started in 59°E at 1714/15 July and completed at 0054/18 July. A course was then set in to Ras al Hadd and a series of current measurements were made off the edge of the shelf on 19 July. While tracking the neutrally buoyant float, an Isaacs-Kidd Trawl was taken. The current float was tracked until 0530/20 July and then a final line of BT observations and neuston net samples was worked from Ras al Hadd out to 64°E. This had to be interrupted to answer a distress call from a nearby ship but was completed some twelve hours later. Two final grab samples were taken on passage to Karachi which was reached at 1500/21 July.

In Karachi the Pakistan National Committee for Oceanic Research, the Naval Authorities, the Council for Scientific and Industrial Research and the Fisheries Department organized a most interesting series of visits for the scientific party, to meet local scientists and see laboratories and we were most grateful to the chairmen and heads of these departments for the trouble they took to make our visit so enjoyable.

The 'Discovery' left Karachi at 0930 on 27 July and proceeded back to the Arabian Coast. Shortly after leaving the continental shelf an extensive lane of discoloured water was seen and the ship was diverted to examine it. It proved once more to be Trichodesmium erythraeum.

The first survey had shown the general distribution of the upwelled water along the Arabian Coast and pointed to the presence of comparatively intense upwelling in the vicinity of Ras al Madraka and around the Kuria Muria Islands. To examine this in more detail and to select a position for current measurements and the chemical and biological work, a BT survey (fig. 2) was commenced at Ras Madraka on 30 July. A zig-zag course was followed along the coast from Ras al

Madraka ($57^{o}50'$E) westwards to Ras as Sauqara ($56^{o}30'$E), but the upwelling there was not so pronounced as expected and the survey was continued west to the Kuria Muria Islands and Ras Nus (55^{o}E) at the westernmost end of Kuria Muria Bay. Here, intense upwelling was in progress and at 1140/3 August the detailed chemical and biological observations were commenced. The first stations lay near a pronounced red discolouration of the sea which was sampled and found to be caused by a species of Gonyaulax.

The next few days were spent in making current measurements both at the surface and in the 200-300 metre layer while detailed chemical and biological observations were made at different distances from the centre of the upwelling. This continued in the area south of the Kuria Muria Islands until midnight on 7 August when it was found that one of the seamen who had been ill would have to be taken to hospital and the ship was diverted at full speed to Aden. No scientific work was possible on the passage, but radio contact was made with the United States Research Vessel 'Atlantis II' and a very profitable discussion of the respective work of the two ships was possible. Aden was reached on 10 August.

This unexpected visit to Aden inevitably meant some rearrangement of the programme and as time was running short it was clear that the remaining observations around the Kuria Muria Islands would have to be abandoned. It was decided instead to return to the vicinity of Ras Fartak and to continue the observations so far as possible in that area (fig. 3).

After leaving Aden at 2138/10 August a straight course was made to the Indian Ocean Reference Station No. 12 at which a full series of observations was made in position $13^{o}14{\cdot}0'$N, $50^{o}14{\cdot}4'$E. The ship then steamed to near Ras Fartak (ca. 52^{o}E) and commenced current observations and chemical work at various positions in the vicinity of this point. Some hauls were made with a large trawl in scattering layers here and while tracking the current floats various other projects were completed. On 13 August, a 24-hour series of vertical net hauls were taken; on 15 August a 27-hour series of neuston net hauls were made in the one position.

The work off Ras Fartak was completed at 1130/18 August and a course was set for Aden. On passage, a further series of repeated neuston net hauls was made over the period of the evening migration and some further chemical sampling and an Isaac-Kidd Midwater trawl in the Gulf of Aden brought Cruise 1 to an end. Aden was reached at 0800/20 August.

Meteorology

Throughout the cruise, continuous records were maintained of wet and dry bulb air temperature, total incident radiation and net radiation flux. Further instrumental and visual observations of barometric pressure, wind direction and velocity, cloud cover etc., were recorded at four-hourly intervals and at all station positions.

The period during which the ship was working in the Arabian Sea was the time of greatest intensity of the south-west monsoon and indeed clear of the Gulf of Aden the wind was remarkably constant in direction blowing from 210-220^{o}true with an average strength of force 5-6. In general the wind seemed to b stronger away from the coast and, on some lines of stations, gales of up to forc 9 were encountered in the region well offshore. Close to the coast the weather was generally fairly calm but winds up to force 9 were encountered around the Kuria Muria Islands. The coastal weather appeared to be characterized by mor variability and comparatively rapid changes occurred. This may to some extent be related to the actual position of the Intertropical Convergence which evidently runs along the south coast of Arabia.

Air temperatures were typically high in the offshore region, usually rangi between 25 and 27^{o}C whereas close to the coast temperatures of 22 to 23^{o}C wer regularly encountered. Humidity throughout the region was consistently high an frequently in the vicinity of the coast thick mist or even fog was encountered - a typical atmospheric characteristic of most upwelling regions.

It did not prove possible to make any successful radio-sonde ascents in the Arabian Sea as the weather was too heavy for the rather temporary provisior made for this work.

Waves

Wave recordings were taken daily by Mr Tucker.

Echo-soundings

Soundings were obtained along most of the ship's track during the cruise. Some difficulty was experienced on occasion with the towed transducer which particularly at higher speeds and with a following sea tended to become unstable, but after adjustment it towed reasonably well at speeds not exceeding 11 knots. The hull-fitted transducers worked well in calm weather but their performance fell off badly when the weather worsened.

All soundings have been entered on plotting sheets which have already been given a limited circulation and bathymetric profiles have been drawn for each line of stations. There do not seem to be any major discrepancies between these soundings and the existing contoured sheets and, on occasions where tracks have crossed, the soundings have agreed satisfactorily. The last three sections reached or crossed the line of sea mounts extending south-west from the John Murray Ridge and relevant parts of the profiles were as follows.

Approximate position N	E	Depth (corrected, in fms)
15°16'	58°38'	1946
15°17'	58°41'	1681
17°23'	59°56'	1320
17°46'	60°06'	1755
19°55'	60°55'	1721
20°10'	61°00'	1292

In the vicinity of the Kuria Muria Islands some known discrepancies in the charted position of the islands and coastline were encountered and the detailed track of the ship, soundings and amendments to the coastline based on radar observations were plotted relative to the southern end of Hasikiya Island which was assumed to lie in latitude 17°26.6'N and longitude 55°36.4'E.

Currents

The following observations were made during the cruise:

70 vertical profiles of relative currents using direct-reading meters, in most cases to 100 m depth, some to 200 m. At 25 of these, radar fixing was sufficiently accurate to make allowance for the ship's movement thereby giving absolute currents.

81 surface-current vectors deduced from the discrepancies between dead reckoning and observed positions. Leeway due to the transverse component of wind has been allowed for, using a factor deduced from current-meter observations when lying-to.

6 surface drogues were followed for periods of 3 to 12 hours each.

6 neutrally-buoyant floats, at depths between 75 and 360 m, were tracking for periods of 14 to 65 hours.

The results are only partly worked up at present, and have not been related to the distributions of water properties, but some of them are shown in a preliminary form here, and some tentative conclusions can be drawn.

In fig. 4, the small arrows indicate the surface currents deduced from the navigation, with speeds shown in knots. They are scattered, but the tendency is north-east along the coast, turning towards south-east further offshore. There are indications of eddies near Kuria Muria Bay and off Ras Madraka. Speeds are generally of the order of a knot; some of the faster ones are uncertain, being averaged over short intervals of time.

Stations where currents were measured relative to an anchored buoy, or within accurate radar range of land, are shown as small circles, with selected

results tabulated near them. The currents down to 100 m depth were observed with the direct-reading meters, except at station 5083, where a neutrally-buoyant float at 75 m was followed for 24 hours. These observations in the 75-100 m depth range show considerable scatter in both speed and direction, sometimes differing widely when repeated measurements were made at a single station. In most cases, a movement towards the shore is indicated at these depths.

The observations shown at 170 m and deeper were made with neutrally-buoyant floats, except at station 5032 where a current-meter observation has been plotted.

At these depths, speeds were in the neighbourhood of 0.2 knot, and except at station 5091 the flow had a component towards south-west, opposite to the prevailing surface current.

Looking at the relative current profiles obtained with the direct-reading meters, at nearly all stations the surface current has an eastward component relative to 100 metres depth. Speeds rarely exceed 1 knot, the strongest relative currents being found generally about 50 miles offshore. Close to the coas currents change steadily with depth also. At the offshore stations, where a well-defined mixed layer is present, there is little or no shear down to a depth just above the base of the mixed layer. Below the depth and through the thermocline the relative current increases to about half a knot at 100 m relative to the surface.

Summarizing the current measurements, we have predominantly north-eastward flow at the surface close to the coast, turning more towards south-east farther offshore. At depths of the order of 100 metres, there appears to be movement in towards the coast at stations near the continental slope, with relatively weak currents farther out. At about 200 m depth, the currents are weak and tend to be opposed to the prevailing surface current. It is hoped that when the dynamic heights have been computed for the hydrographic stations, it will be possible to combine them with these direct measurements to construct a more complete model of the circulation in this area.

It may be of interest to mention one other observation of relative currents. Soon after leaving Karachi on 27 July, a Trichodesmium bloom was encountered, lying in a long lane downwind. Whilst samples were being collected, we tried to see whether there was any convergence of surface water into the lane, by putting in dye markers (fluorescein dissolved in sea water) from the rubber dinghy. Two marks were put in, across wind on either side of a patch of bloom. Their separation was estimated by comparison with the ship's length, while lying-to downwind of the dye marks. Their rate of approach was 43 m in 25 minutes, and the crosswind orientation was maintained, within about 10 degrees. This indicated a convergence of 3 cm/sec into the lane, with less than 1 cm/sec shear across it in the direction of the wind.

Temperature and Salinity

It will be clear from the chart (fig. 1) that the coldest surface waters were onfined to the immediate proximity of the coast and especially to the areas round the Kuria Muria Islands and eastwards to the Gulf of Masira. Away from he coast the temperature rose somewhat irregularly but there were clear ndications, particularly from the detailed survey made around the Kuria Muria slands (fig. 2), that fairly large eddies were present at some points along the coast. Extending east from the Gulf of Aden there seems to have been a tongue of varmer water, for at the southern end of section 3 there was a marked drop in emperature; it is not possible to say how continuous this tongue was, nor ow extensive the cold water to the south of it may have been.

Although the surface temperature of the sea is subject to comparatively rapid hanges, it seems probable that in this region which had predominantly overcast onditions such changes would be minimized and that the pattern of distribution hown by the surface temperature would result mainly from the circulation in the pper layers. Indeed the bathythermograph sections also suggest that this is so nd two typical sections have been reproduced here (figs. 5 and 6) to show the ertical distribution of temperature in the upper 250 metres. Figure 5 depicting ection 3 shows clearly the upward trend of the isotherms above about 150 metres owards the coast, whereas below this depth the isotherms show only irregular ertical displacements. In figure 6 from the second survey, the upwelling vidently extended to a greater depth.

The observations of salinity are more widely spaced, as vertical profiles re available only at full stations, but even so the sections show a somewhat omplex picture. It appears that the lines of stations must have cut through a umber of horizontal eddies at different depths, thus creating a somewhat discon-inuous appearance in section. The dimensions of these eddies appear to be such hat they would probably not be traversed by more than one section and there is herefore some lack of continuity in detail from one section to another but the verall features are common to most of the sections - a highly saline surface ayer offshore (about 36.00‰) and separated from the coast by water of lower alinity (35.6-35.7‰) which (fig. 7) is characteristic of the sub-surface water nasses. At greater depths there was an irregular but pronounced salinity naximum at the level of outflow of water from the Red Sea and Gulf of Aden hich was particularly marked at depths of 500-600 m off the north coast of ocotra.

On a number of occasions during the passage of the ship, very sudden hanges of surface temperature accompanied by similar discontinuities in alinity occurred over short distances. Several of these fronts were encountered n the passage from the end of the fourth section to Masira Island and a close xamination of one shows something of their structure. On both sides there was fairly homogeneous surface layer about 70 metres thick. The temperature of his layer on the south side of the front was more than 3°C higher than on the orthern side but the underlying waters in both cases were at much the same

temperature; the warm layer was thus underlain by a strong discontinuity which was almost absent north of the front.

Densities, dynamic heights and other derived variables have not yet been checked. It is hoped that this will be completed within the next few weeks.

Chemistry

Besides estimations of salinity, routine analyses were made for dissolved oxygen, inorganic phosphate, nitrate and silicate. The nutrient analyses were done more intensely in the upper layers than in the deep water. Apart from the routine analysis, the chemical programme included many more specialized analyses which were made only at selected stations. These include estimations of ammonium nitrogen, albuminoid nitrogen, trace metals (samples for these will be examined at Liverpool University), and permanganate oxidizable material in filtered water. Measurements were made of ultra-violet absorption of filtered samples and of the volatile fraction of filtered water, and samples were taken for particulate carbon, nitrogen and phosphorus estimations (these will be analysed by Mr Armstrong at Plymouth). Samples of zooplankton were retained for similar analyses.

The phosphate determinations show high concentration in the deeper layers, reaching values of the order of 2.5μg ats P/litre. At a depth of about 100 metres, the concentration decreased rapidly and the over-lying surface layers offshore generally showed concentrations lower than 0.5μg ats P/1. Along the coast, however, the high concentrations extended into the surface layers where active upwelling was taking place (fig. 8). This was true on sections 3, 4 and 5 where values over 2.0μg ats P/1. were found at the surface close to the coast. On sections 1 and 2 high values were found near the surface inshore but not right at the surface where quantities were lower and had probably been reduced by the heavy phytoplank-ton crop at these stations.

Nitrate figures show a somewhat similar picture and indeed in the deep layers the N:P ratio seemed to be surprisingly constant. Silicate in the deep water was very high reaching concentrations in some places, greater that 150μg ats Si/1. and the quantities decreased fairly regularly towards the surface. A very high silicate content seems to be characteristic of the deep water of the Arabian Sea and, although its origin is uncertain, it may be associated with the abundance of diatoms in the algal flora of the region.

The estimations of dissolved oxygen confirmed the presence of a very extensive oxygen minimum layer between depths of about 150 and 1000 metres. Within this layer there appear to be one or two more intense minima but on no occasion was any hydrogen sulphide detected. This is interesting for the Russian Research Ship 'Vityaz' recorded the presence of hydrogen sulphide in the oxygen minimum layer during their cruise in November-December, 1960 (Ivannenkov & Rozanov 1961). At that time of year, however, the south-west monsoon is over and the appearance of hydrogen sulphide may well be associated with the cessation of upwelling on the Arabian coast.

Bacteria

A trial sampling at five selected depths was carried out to compare the efficiency of plastic water bottles with that of presterilized samplers in the collection of water samples for bacteriological analysis. The results indicated that the use of unsterilized water bottles was undoubtedly unsatisfactory as the percentage of obvious contaminants was very high. ZoBell samplers were used as a control in this instance. Only presterilized samplers were used, therefore, in the survey: ZoBell samplers for the shallower depths and Niskin samplers at greater depths.

In the upwelling area of the Arabian Sea samples were taken, first of all, at two shallow stations and one deep station with the intention of assessing the size of the bacterial population in this region, the technique employed being that of viable counts on membrane filters. The aerobic heterotropic population was established relatively rapidly on culturing but attempts to ascertain whether any anaerobic sulphate-reducing organisms were present in the oxygen minimum zone yielded negative results.

Samples were then taken at fifteen stations in the eastern region of the Arabian Sea where previous reports have been made of hydrogen sulphide being present in association with the oxygen minimum layer. All samples were subjected to culturing on two selective media for the growth of anaerobic sulphate reducers but it transpired that no hydrogen sulphide was evident in the water sampled. Results of the investigation for sulphate reducing organisms indicated that they were present at one inshore station only and at depths which bore no significant relationship to the oxygen minimum layer. An organism producing propionic acid was also found at this station.

The heterotrophic population was also investigated at these stations with the aim of discerning any changes, both qualitatively and quantitatively, in the transition off the continental shelf and also to assess the vertical distribution of bacterial organisms. The depth at which sampling was carried out were as follows:

10, 50, 100, 200, 500, 750, 1000, 2000, 3000 and 3500 metres.

A definite diminution in bacterial numbers was observed with increasing depths at all stations off the continental shelf (fig. 9) but no such characteristic pattern emerged in inshore waters.

Sampling procedures were carried out at 6 further stations, the majority being located in the western part of the Arabian Sea thus enabling comparison of the flora with that of the eastern region. At one of these stations the investigation was restricted to that of two autotrophs, Thiopedia and Thiobacillus, and at another merely to the isolation of Desulphovibrio. At two stations where the

main interest was in the heterotrophic population a statistical evaluation of the bacterial counts was made by repeating the filtration technique 20 times on the same sample of water and later comparing the resultant counts. Comparisons of growth in aerobic and anaerobic conditions yielded no significant differences.

In general there seems to be a reasonably good correlation between the concentration of the free heterotrophic bacteria and the concentration of zooplankton in the water (fig. 10). Since the latter figure only represents part of the organic material present a close correlation would be expected but the higher bacterial numbers are clearly associated with the greater abundance of planktonic animals.

The actual composition of the population appears to be relatively characteristic over the entire area investigated, about 10 different and highly distinctive forms of pigmentation recurring throughout. Luminescent organisms tended to proliferate in the inshore waters but also appear to be ubiquitous.

Phytoplankton

Both fine-mesh nets and water bottles were used to sample the phytoplanktor The net samples, taken primarily for the larger organisms, have been preserved with neutral formalin for later analysis. The water bottle samples from six depths within the euphotic zone have been used both for counts and for pigment estimations. Lugol's Iodine was used as preservative for the count samples.

The richest phytoplankton occurred close to the coast near Ras Farak (where values reached 64 x 10^3 cells/litre) and also in a bloom encountered in Kuria Muria Bay but generally speaking all the stations near the coast were comparative rich particularly in the surface and 20 m depth samples. Below this depth at the coastal stations quantities generally decreased. Beyond about 20-30 miles from the coast the phytoplankton became more sparse and the level of maximum abundance showed some tendency to lie deeper in the water, but even at the greatest distance from the coast the surface concentrations were still of the order of 3·5 x 10^3 cells/litre. Pigment values in the coastal waters reached concentrations of 4 to 5 mg chlorophyll a/m^3.

The phytoplankton concentration in the coastal waters usually imparted a green or brown discolouration to the sea but on one occasion near the Kuria Muria Islands the discolouration was a particularly intense brown, tinted in patches to a pronounced dark-red colour. Samples of this water showed that a species of the small dinoflagellate Gonyaulax was present in great profusion.

Although the colour of these patches of Gonyaulax depended to a great extent on the angle at which they were viewed relative to the sunlight, they appeared to lie across the direction of the wind and were scattered somewhat randomly with rather ill-defined limits. Nevertheless the general character of their distribution contrasted with the blooms of Trichodesmium erythraeum, the blue-green alga, which were encountered both in the Red Sea and in the

Arabian Sea. The *Trichodesmium* on both occasions occurred in clearly defined lanes running more or less downwind. The lanes, of the order of 2-3 km long and a similar distance apart, were about 50 metres wide. One edge of the discolouration was generally rather more sharply defined that the other and it seemed to extend some five to ten metres below the surface. On the surface, the organisms were streaked on the waves like foam in a gale and bucket samples gave the typical sea-sawdust appearance.

Detailed chemical observations were made on both filtered and unfiltered samples in these blooms and in the surrounding waters; on one occasion, fluorescein dye was liberated from a rubber dinghy in patches on either side of a *Trichodesmium* bloom to study the water movements in its vicinity. Final conclusions must await analyses of the particulate material but there are strong indications of active convergence within these lanes and the sinking of the convergence waters coupled with the buoyancy of the organisms may well be the basic mechanism of their formation.

A limited number of samples were taken by Mr Irwin for photosynthesis measurements at different light intensities, using radioactive carbon (^{14}C) as a tracer. The samples from these still have to be counted.

Dr Cushing conducted a number of algal growth rate experiments using a Coulter-counter technique.

Zooplankton

The displacement volume of all the 70 cm diameter vertical net hauls, excepting those containing a high volume of phytoplankton, was measured on board (fig. 11). The depth range fished and the volume of water filtered were metered and the results have been considered both in terms of the surface plankton concentration (in ml displacement volume/m^3 for the upper 50 metres) and the total quantity of plankton in the 1000-0 m layer (expressed as ml/m^2). The conclusions affect, of course, only the size of organisms taken effectively by this net.

The first station was too rich in phytoplankton to be volumed, but would probably have given the highest surface concentration for the first section. On the first section the total quantity of zooplankton (1000-0 m) was generally comparatively low but reached a maximum some 70 miles from the coast. On the second section phytoplankton was abundant in the surface samples but the total quantity of zooplankton was much lower than on the other lines of stations, the highest value occurring 23 miles from the coast and just off the edge of the continental shelf.

On the third section the inshore station had a very high surface plankton concentration but again the maximum total volume in the water column lay 33 miles from the coast on the continental slope. This position was remarkable for the high concentration of plankton in the deeper layers. The total quantity

of plankton decreased seawards from the maximum. On the fourth section the distribution was very similar, the shallow stations providing the highest surface concentrations and the total volume again reaching a maximum just off the continental slope but on the fifth section the offshore maximum in quantity was not so evident although again the inshore stations showed the highest surface volumes.

It appears, therefore, that while the highest surface concentrations of plankton occurred at the stations in shallow water on the continental shelf, the total amount of plankton in the water column (100-0 m) was at a maximum just off the edge of the continental shelf and seawards of this the quantity generally decreased although secondary maxima occurred on the first, fourth and fifth sections at greater distances from the coast. At the deep water stations the surface concentrations were generally proportional to the total plankton volume.

On some lines of stations there is some evidence of vertical migration but it is improbable that this would affect these general conclusions.

Indian Ocean Standard Net

Altogether 44 hauls were made with the Indian Ocean Standard Net and these have been presented to the Indian Ocean Biological Centre at Cochin, South India, where they will be brought together with material from other parts of the Indian Ocean to serve as a comprehensive collection for distributional studies.

Neuston

The neuston net was used 113 times during the survey. This net is of 60 mesh/in. nylon and has a rectangular mouth 30 x 15 cm so mounted between boards that when it travels along the surface it fishes through the upper 10 cm of water. The apparatus is towed from a boom projecting from the port side of the ship at the level of the foremast and it is so designed that like an otter board it rides out abeam of the ship and tows alongside some 11 m clear of the vessel. The present model of the net has been used in winds of force 9, but in this weather it jumps out of the water a good deal. It has been towed at up to 8 knots but at 5-6 knots the contents of the catch were far less damaged and this speed was used for all the 15-minute routine hauls.

In the Mediterranean the catches were spoilt by the presence of large quantities of fuel oil on the surface but in the Red Sea and Arabian Sea very little fuel oil was encountered.

In the Arabian Sea the catches have been interesting and often very large. Flying fish up to 14 cm in length have been caught and on one occasion 43 were taken in a 15-minute haul, ranging in size from 4 to 14 cm; on another occasion 33 were taken. At one station 740 post larval Carangiid fish were taken ranging in size from 12 to 40 mm, and at another station substantial numbers of larvae very similar to the published descriptions of tuna larvae have been caught (fig. 12).

At station 5039, 886 larval Clupeoids, possibly sardines, were taken and smaller numbers occurred frequently (fig. 13). On several occasions, Myctophids up to 6 cm in length were caught.

The hauls have consisted mainly of Copepods, Euphausiids and, in inshore waters, larval crabs, but frequently occurring organisms have been Ianthina, Velella, Porpita, Physalia, Halobates spp, Stomatopod larvae, Decapod larvae, Pteropods, very small larval fish and Ostracods.

Night hauls have been much larger than day hauls and to find out more about the diurnal migratory cycle a close series of repeated hauls were made over a period of 27 hours at a position south-east of Ras Fartak and a further series was made during the dusk to dark period at a position near the mouth of the Gulf of Aden. These have not yet been analysed.

Experimental work

In connexion with vertical migration studies, Mr Herring and Mr Angel conducted some trial experiments. These will be continued next year. Mr Baker made a number of observations on the feeding of Euphausiids which were kept alive in the constant temperature laboratory.

Sonic scattering layers and fish shoals

Both the precision echo-sounder and a higher frequency narrow beam sonar were used to record sonic scattering layers, discrete echoes from fish and fish shoals. Only a cursory examination of the records has, as yet, been possible; but the regions where distinct fish echoes were recorded are set out in figure 14. This figure shows only positive records along the ship's track and where there is no record it does not necessarily mean there were no fish echoes. Some of the recordings have not yet been examined while on other occasions the gain settings of the instruments, which were at the same time being used for bottom sounding, may not have been suitable for locating fish. The fish occurred both in tightly packed shoals in the layer around 300 metres and as individuals (probably fairly large individuals) in the waters nearer the surface.

At the time these fish echoes were recorded it was not possible to interrupt the survey to sample them. Later in the cruise, the mid-water trawl was rigged and fished, but in the region where it was used near Ras Fartak very few fish echoes were recorded and no sizeable fish were taken.

Benthos

The object of the benthos sampling was to estimate the ratio of macrobenthos (metazoans retained on an 0.5 mm sieve) to meiobenthos (metazoans passing this sieve) in a series of samples and to determine how the ratio varied with depth and type of bottom. This is of interest since recent work suggests that meiobenthos (a previously neglected size group of animals) may play a much more significant

part in benthic ecology than has been thought. The Arabian Sea cruise offered a good opportunity for this work since a wide range of depths could be covered and since such information is not available for tropical waters.

The spring-loaded grab used to collect the samples was designed for use in bad weather on hard sand on the shelf, but since one of its main features is that it cannot release in mid-water it seemed a suitable type of instrument to use in great depths. It was therefore modified to make its release more sensitive for soft muddy ground, and provision was made for adding weights. On the initial operations the grab failed to close on three occasions in water of about 1000 m, but when larger trigger plates were added and the weight increased to a total (in air) of about 100 kg the instrument worked well and its impact on the bottom could be detected from the movement of the accumulator spring even at depths of 3500 m. On soft bottoms the grab filled completely, digging to about 15 cm and producing about 14 litres of deposit.

A total of 18 samples were obtained from depths between 48 and 3500 m. From each grab a sub-sample core of 6-7 cm length was taken for meiobenthos and soil analysis, while the remainder of the sample was sieved usually through a mesh of 0.5 mm.

Preliminary sorting of some of the macrobenthos collections shows moderately rich population of Crustacea and Polychaetes at intermediate depths (600-1300m) near the shore. However, final sorting of the samples and the meiobenthos analysis must await return to the shore laboratory, but even at this stage it is felt that a good series of samples has been obtained which should produce useful results.

Ornithology

The ornithological work of the cruise was aimed at defining so far as possible, both the qualitative and quantitative distribution of birds in the area of investigation and where possible studying this in relation to the available food in the surface waters. This has involved both collecting the surface plankton and observing the feeding habits of the birds and also the examination of the stomach contents of as many specimens as could be obtained.

Numbers were assessed by making counts at least three times daily for a period of at least one hour (0530-0800, 1100-1230 and 1530-1800). The results have been recorded as numbers seen per hour, but details of flight, wind etc., have been noted in the hope that it may be possible to obtain some estimate of the actual densities over the sea surface. A total of about 140 counts were made and, although rather more time was spent within 50 miles of the coast than outside that limit, the coverage is quite good. Various means of collecting birds were tried but in fact all of the specimens taken flew on board, mostly at night.

In general, the total number of birds, irrespective of species, was greater close to the coast; they decreased rapidly in abundance some fifty miles or so from the coast. An exception to this was the third section where there was no apparent diminution in numbers until over 100 miles from the coast. The total number seen per hour varied from none, on only four occasions, to well over a thousand per hour on two occasions. Very large concentrations were recorded at the mouth of the Gulf of Aden, off Ras Fartak, off the Kuria Muria Islands and off Ras al Hadd and these seem in general to correspond with the areas of particularly cold water.

Altogether, at least twenty species of sea birds were recorded but only eleven of these were seen with any regularity or in any numbers; these included three shearwaters, two storm petrels, one tropic-bird, one booby, a phalarope, a gull and two species of terns. Several species of typically tropical birds were missing, including frigate birds, noddies and sooty terns.

One specimen of the pale-footed shearwater (Puffinus carneipes) was collected. There are few authenticated records for the area but it seems to be common close to the coast in coldwater areas. The wedge-tail shearwater, P. pacificus, which has frequently been recorded in the past from the Arabian Sea was represented by only a few sightings and as even these are somewhat doubtful it may be that Jouanin's petrel has often been mistaken for this species. The Persian shearwater (P. l'herminieri persicus) seemed to be restricted to the area from the Kuria Muria Islands to Ras al Madraka and the vicinity of Socotra and Ras Fartak, evidently associated with the upwelling areas. It was seen in largest numbers near the Kuria Muria Islands where it was feeding in flocks of several hundred. The breeding area and breeding season of this species is not known but the concentration around the Islands and the fact that one specimen taken off Ras Fartak had a brood spot on its abdomen suggests that it may have been breeding around these Islands.

Bulweria fallax (Jouanin's petrel) was only described in 1955 from a specimen taken in the Arabian Sea and yet it proved to be one of the commonest birds along the coast and still occurred 200 miles offshore. Seven specimens were collected and the presence of brood patches on them suggests that they also breed in the south-west monsoon and similar areas to the Persian shearwater.

Of the storm petrels, one specimen of Oceanodroma leucorhoa monorhis came on board but none were seen at sea and it was probably a stray from farther east; two specimens of Wilson's Petrel (Oceanites oceanicus) were collevted; the species was very common in some areas but seemed to avoid areas where other species congregated. Pelagodroma marina was widespread in small numbers outside the upwelling region.

The red billed tropic-bird (Phaethon aethereus) was commonly seen in small numbers throughout the area but again concentrations were seen around the Kuria Muria Islands. The blue-faced booby (Sula dactylatra) was nowhere abundant but occurred in the area out to 100 miles from the coast. The brown

booby (S. leucogaster), although common in the southern Red Sea where six specimens were collected, was only recorded twice in the Arabian Sea but it ma be present closer to the coast.

The Socotra cormorant (Phalacrocorax nigrogularis) was seen only in one place, at the Kuria Muria Islands, but there it was probably the commonest bir flocks running into several thousands were seen flying towards Hasikiya Island and it may well be that this island is a new breeding locality right at the centre of the upwelling.

The red-necked phalarope (Phalaropus lobatus) was commonest off headla but extended some 60 miles out to sea. Since the time of the survey probably coincided with the arrival of this species from its migration, however, it would premature to comment on its distribution.

Both the Antarctic great skua (Catharacta skua) and the pomarine skua (Stercorarius pomarinus) were recorded, the former well spread within 30 or 4 miles of the coast. The sooty gull (Larus hempwichi) was common along the whole coast up to 70 miles out to sea. The terns (Sterna anaethetus, S. albifro S. bergii and S. bengalensis) were generally seen close to the coast but S. anae thetus extended some 70 miles offshore, south-east of the Kuria Muria Islands. S. bengalensis was recorded only once off Ras al Hadd.

Perhaps one of the most interesting features of the observations is the concentration of several species around the Kuria Muria Islands and the strong indication that several were breeding there during the south-west monsoon - the Persian shearwater, Jouanin's petrel, the red-billed tropic-bird, the blue-faced booby, the Socotra cormorant, the sooty gull and the crested tern. More generally, however, the observations when they are brought together with the other biological data should tell us much about the ecological factors which affec the distribution of the sea birds in this area.

Entomology

A collection of about four or five hundred insects of various different orders was made during the survey, largely through the efforts of Mr Angel who catalogued and mounted the specimens. These were collected in a systematic manner by patrolling the ship's decks at intervals during the day and to some extent at night. Members of the crew and the scientific staff collected insects whenever they saw them. A number of these specimens were taken in harbour, but most were taken while the ship was at sea at varying distances from the coa and besides the strong flying insects such as dragon-flies, hawk moths and locusts, numerous very small insects, mainly moths were collected. At one place in the Gulf of Aden a number of large beetles were caught.

In the conditions of persistent winds from the south-west, it seems probab that most of the smaller weak flying insects may have come from the African coast some hundreds of miles away and the collection may be of considerable interest to an entomologist studying migration.

The only truly pelagic insect, Halobates, was well represented in the collections of the neuston net and this material should provide some useful distributional information.

Acknowledgements

The success of a cruise such as this depends very much on co-operation between the scientists, the ship's officers and the crew and I would like to thank them all for the willing and enthusiastic manner in which they took part. They all worked long hours in unpleasant weather conditions and performed numerous tasks in addition to their normal duties. In particular, I would like to mention Captain C. Alexander whose understanding and help did much to make the voyage so enjoyable and Mr T. Humphrey, the Chief Engineer, who dealt calmly with all the troubles of a new ship and yet found time to manufacture and repair a miscellany of scientific equipment. To those who were less fortunate and did not accompany the ship but helped in preparations for the cruise, I would like to express my gratitude.

References

Bobzin, E. 1922 Dtsch. ubers Met. Beob., 23, H1-H18.

Ivannenkov, V.N. & Rozanov, A.G. 1961 Okeanologia, 1 (3), 443-449.

Table I. Scientific Staff

R.I. Currie	Biologist (in charge)	National Institute of Oceanography.
J.C. Swallow	Currents, Physical Oceanography	"
P.M. David	Zooplankton, Neuston	"
M.J. Tucker	Acoustics, Waves	"
R.A.G. Nesbitt	Hydrographic Liaison Officer Currents, Soundings	Hydrographic Department Admiralty
F.A.J. Armstrong	Chemistry	Marine Biological Association, Plymouth
D.H. Cushing	Phytoplankton	Fisheries Laboratory, Lowestoft
A.D. Mackintyre	Benthos	Marine Laboratory, Aberdeen
A. de C. Baker	Zooplankton	National Institute of Oceanography
Miss B. Kirtley	Bacteriology	"
N.D. Smith	Electronics	"
A.R. Stubbs	Acoustics	"
T. Boxell	Technician	"
B. Irwin	Phytoplankton	Marine Laboratory, Aberdeen
R. Bailey	Ornithology	Edward Grey Institute of Field Ornithology, Oxford
P.G. Brewer	Chemistry	University of Liverpool
G. Topping	Chemistry	"
A. Prakash	Phytoplankton	Biological Station, St. Andrews, Canada
P. Herring M.V. Angel	Zooplankton	U. of Cambridge

Table II. Station Positions

Station	Latitude North	Longitude East
5006	15°38·4'	52°19·7'
5007	15°28·8'	52°23·8'
5008	15°21·0'	52°30·0'
5009	15°10·7'	52°32·8'
5010	15°01·1'	52°36·0'
5011	14°52·3'	52°43·8'
5012	14°45·6'	52°47.5'
5013	14°38·0'	52°53·0'
5014	14°15·6'	53°12·2'
5015	13°43·6'	53°27·5'
5016	13°16·0'	53°30·6'
5017	12°56·4'	53°44·8'
5018	12°50·5'	53°52·3'
5019	12°43·5'	53°54·5'
5020	14°18·0'	53°56·3'
5021	14°52·6'	53°56·9'
5022	15°21·3'	54°02·1'
5023	15°50·4'	54°05·3'
5024	16°47·9'	53°56·7'
5025	16°41·0'	54°00·6'
5026	16°31·9'	54°08.3'
5027	16°20·1'	54°13·2'
~~5038~~ 5028	16°10·4'	54°23·0'
5029	16°01·3'	54°32·3'
5030	15°54·1'	54°31·5'
5031	15°26·7'	54°46·5'
5032	16°44·0'	54°04·8'
5033	18°05·1'	56°38·2'
5034	17°57·0'	56°44·2'
5035	17°47·8'	56 ~~65~~°50·5'
5036	17°32·8'	57°00·0'
5037	17°28·0'	57°03·4'
5038	17°18·8'	57°09·5'
5039	17°09·3'	57°15·0'
5040	16°56·9'	57°21·7'
5041	16°45·0'	57°30·1'
5042	16°40·6'	57°41·7'
5043	17°56·7'	57°46·0'
5044	16°11·8'	57°54·4'
5045	15°46·2'	58°17·0'
5046	15°09·0'	58°42·4'
5047	19°11·0'	57°55·5'
5048	19°03·2'	58°04·7'

Table II. Station Positions (Continued)

Station	Latitude North	Longitude East
5049	18°55·8'	58°12·0'
5050	18°51·0'	58°19·2'
5051	18°46·1'	58°23·0'
5052	18°39·1'	58°31·5'
5053	18°20·0'	58°59·9'
5054	17°51·5'	59°20·6'
5055	17°33·8'	59°45·3'
5056	17°12·6'	60°05·0'
5057	16°45·1'	60°31·2'
5058	19°47·0'	59°14·0'
5059	20°34·0'	59°12·8'
5060	21°03·5'	59°04·1'
5061	20°59·5'	59°14·5'
5062	20°52·0'	59°25·9'
5063	20°~~43·7'~~ 45.7'	59°36·0'
5064	20°38·6'	59°45·8'
5065	20°32·9'	59°55·5'
5066	20°26·2'	60°03·4'
5067	20°13·2'	60°20·9'
5068	19°58·0'	60°48·9'
5069	19°34·0'	61°14·9'
5070	19°02·9'	61°45·0'
5071	22°12·9'	59°54·3'
5072	23°26·0'	65°21·0'
5073	23°42·0'	65°45·0'
5074	23°57·0'	66°08·0'
5075	24°07·0'	66°10·0'
5076	22°00·0'	63°26·9'
5077	19°06·3'	57°49·9'
5078	18°01·1'	56°33·0'
5079	17°37·5'	55°24·2'
5080	17°34·0'	55°25.2'
5081	17°32·8'	55°23·5'
5082	17°24·9'	55°24·1'
5083	17°19·2'	55°47·2'
5084	17°25·5'	55°49.7'
5085	17°23·2'	55°54·6'
5086	17°20·3'	55°49·6'
5087	17°13.6'	55°54·0'
5088	17°25·7'	55°42·8'
5089	13°14·0'	50°14·4'
5090	15°19·3'	53°02·9'
5091	15°33·3'	52°37·3'
5092	15°35·5'	52°34·7'
5093	15°43·0'	52°58·8'

Table II. Station Positions (Continued)

Station	Latitude North	Longitude East
5094	15°45·0'	53°11·8'
5095	15°43·5'	53°09·3'
5096	15°44·3'	53°04·9'
5097	15°47·1'	52°24·8'
5098	15°01·0'	51°52·4'
5099	14°04·2'	51°04·2'
5100	13°59·0'	50°58·5'
5101	13°10·4'	47°38·0'

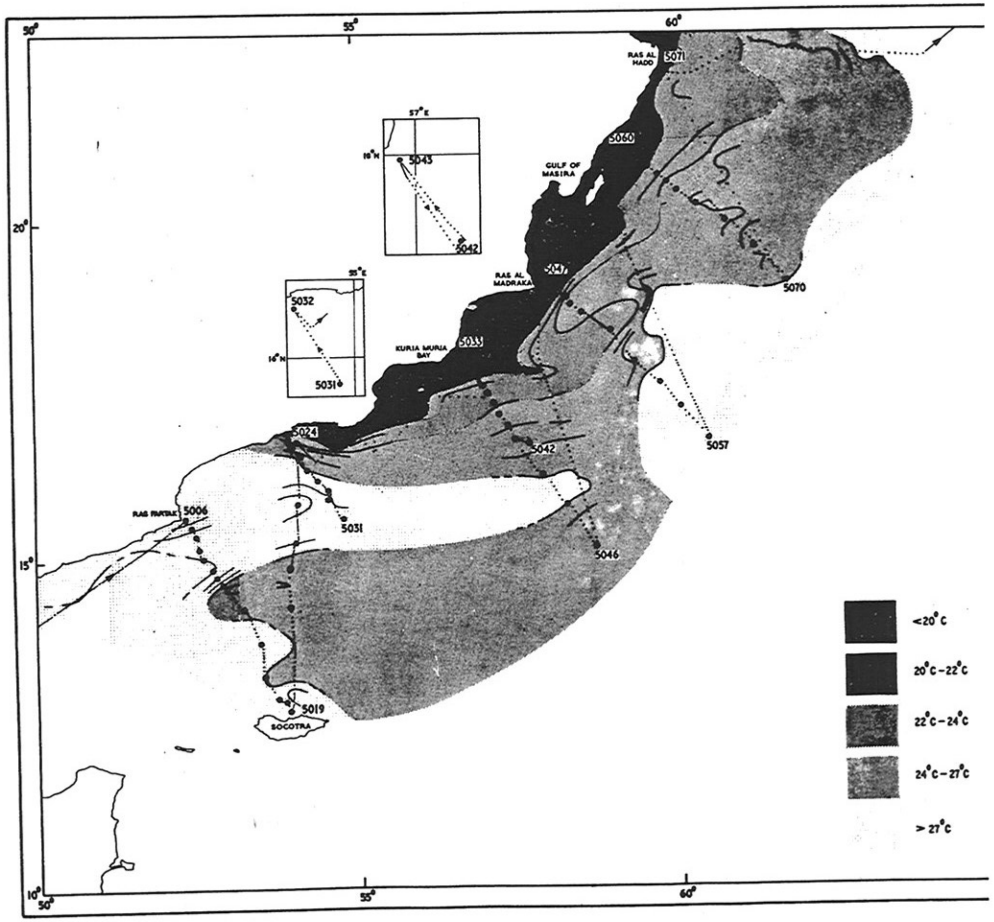

Figure 1. Track chart showing station positions (solid circles), bathythermograph observations (dots) and sea surface temperature, 25 June to 22 July 1963.

igure 2. Track chart showing station positions (open circles), bathythermograph observations (dots) and sea surface temperature from Ras as Madraka to the Kuria Muria Islands, 30 July to 7 August 1963.

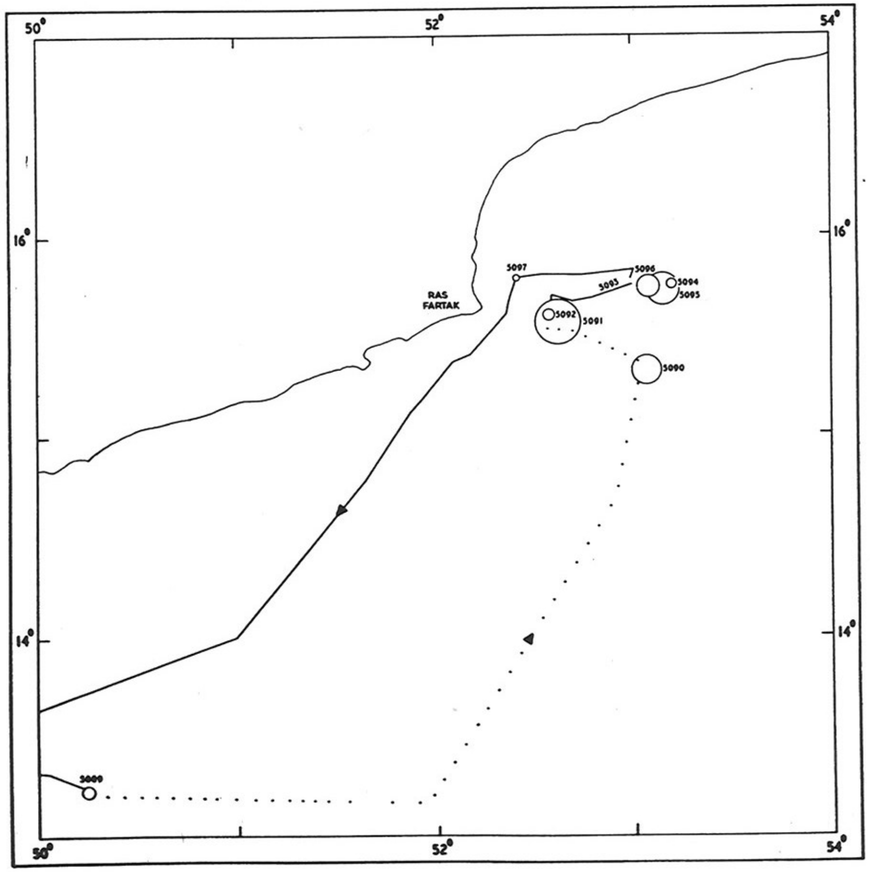

Figure 3. Track chart showing station positions (open circles) and bathythermograph observations (dots) near Ras Fartak, 11 to 18 August 1963.

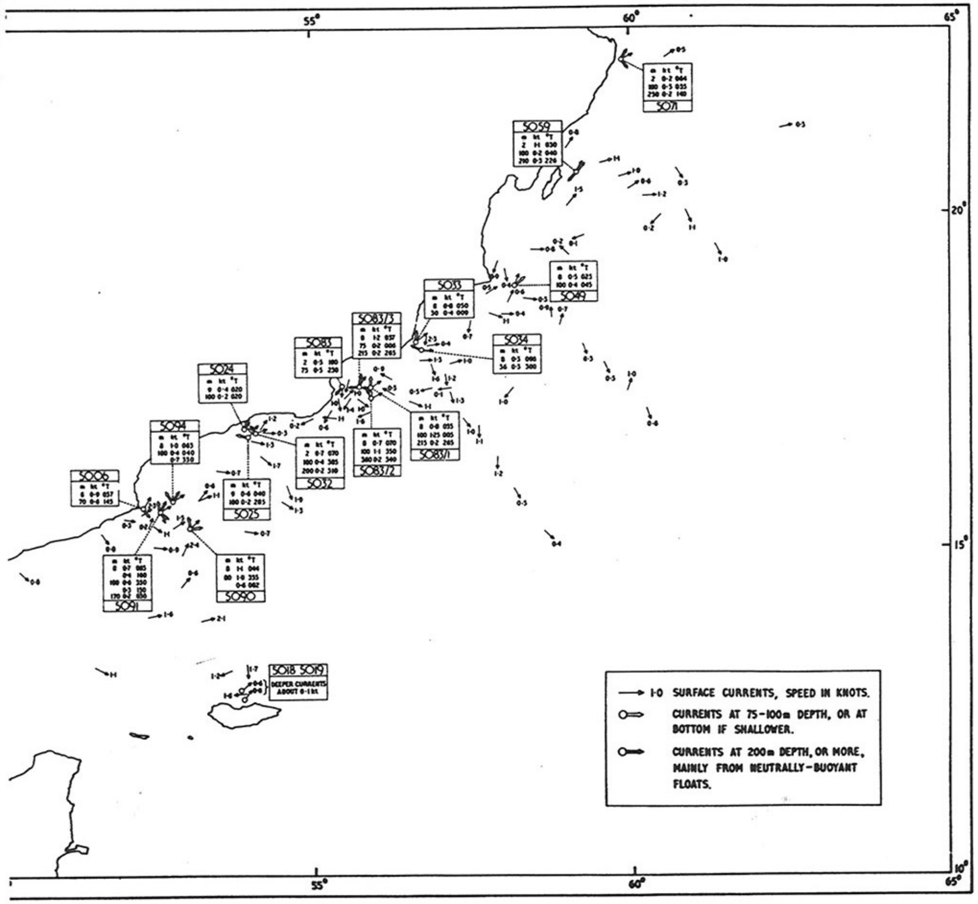

Figure 4. Observed currents. For explanation see text.

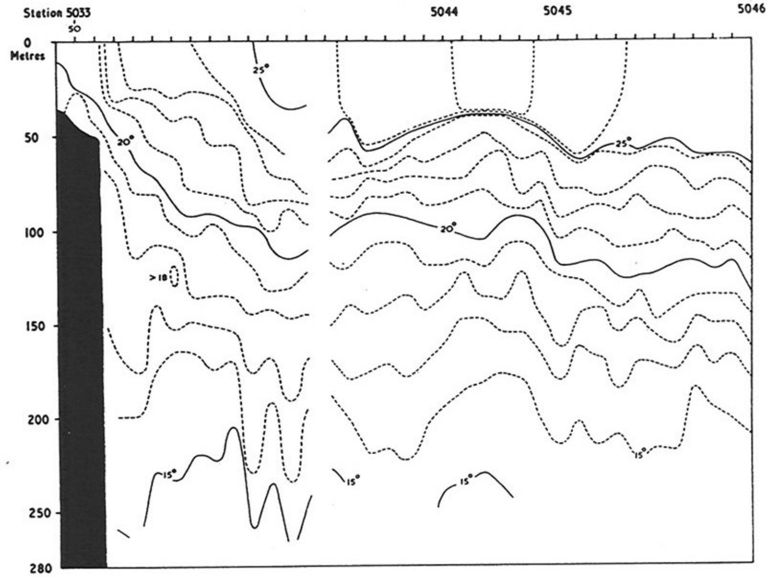

Figure 5. Vertical section showing distribution of temperature from bathythermograph observations on section 3.

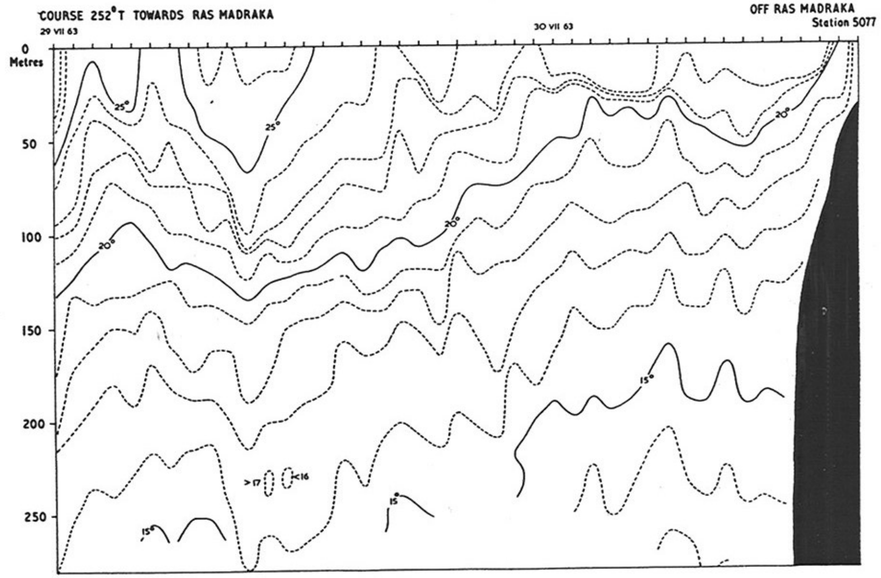

Figure 6. Vertical section showing distribution of temperature from bathythermograph observations on passage to Ras al Madraka, 29 July 1963.

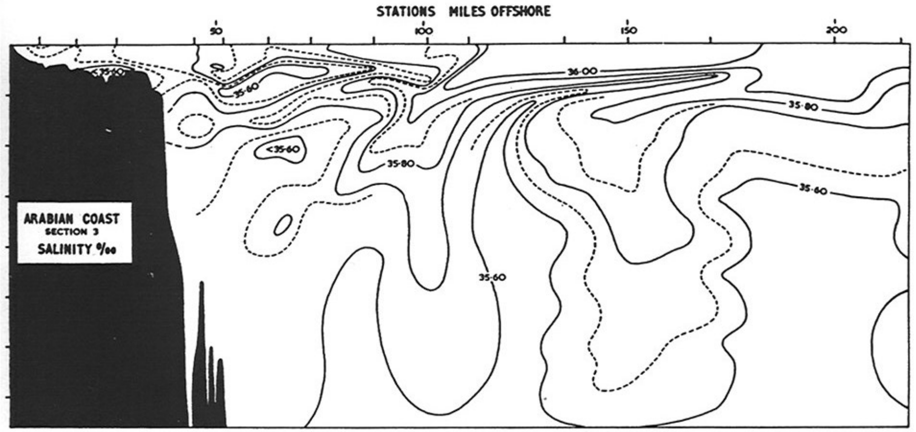

Figure 7. Vertical section showing the distribution of salinity (‰) on section 3.

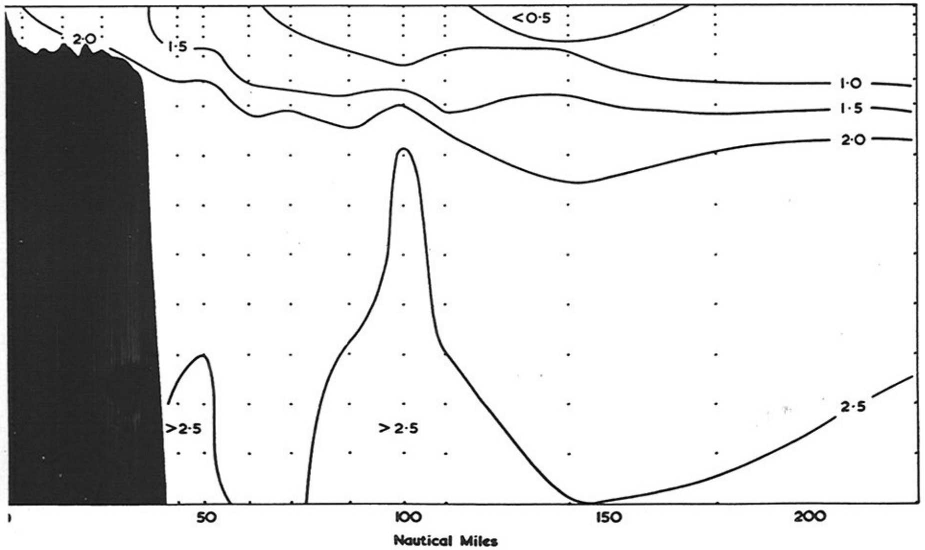

Figure 8. Vertical section showing the distribution of inorganic phosphate (μg ats P/1) on section 3.

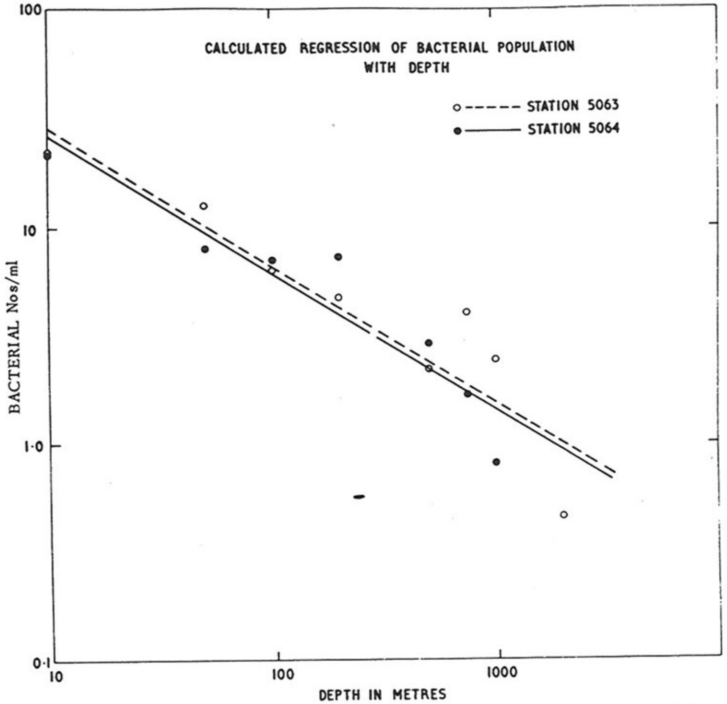

Figure 9. Decrease in number of heterotrophic bacteria with depth.

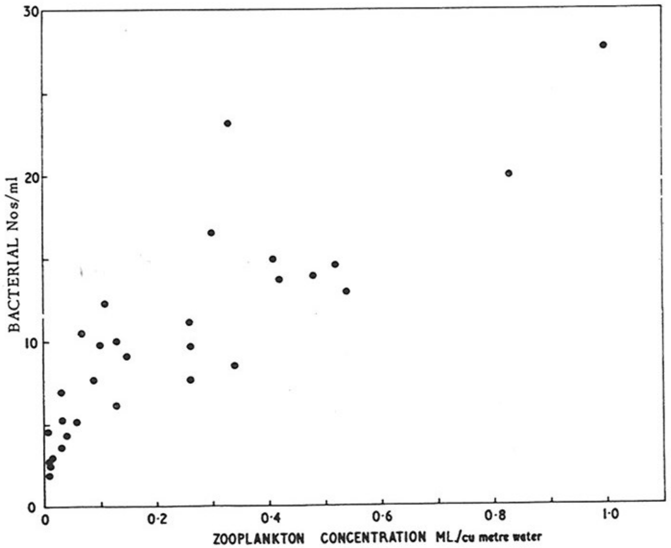

Figure 10. Relationship between number of heterotrophic bacteria and zooplankton volume.

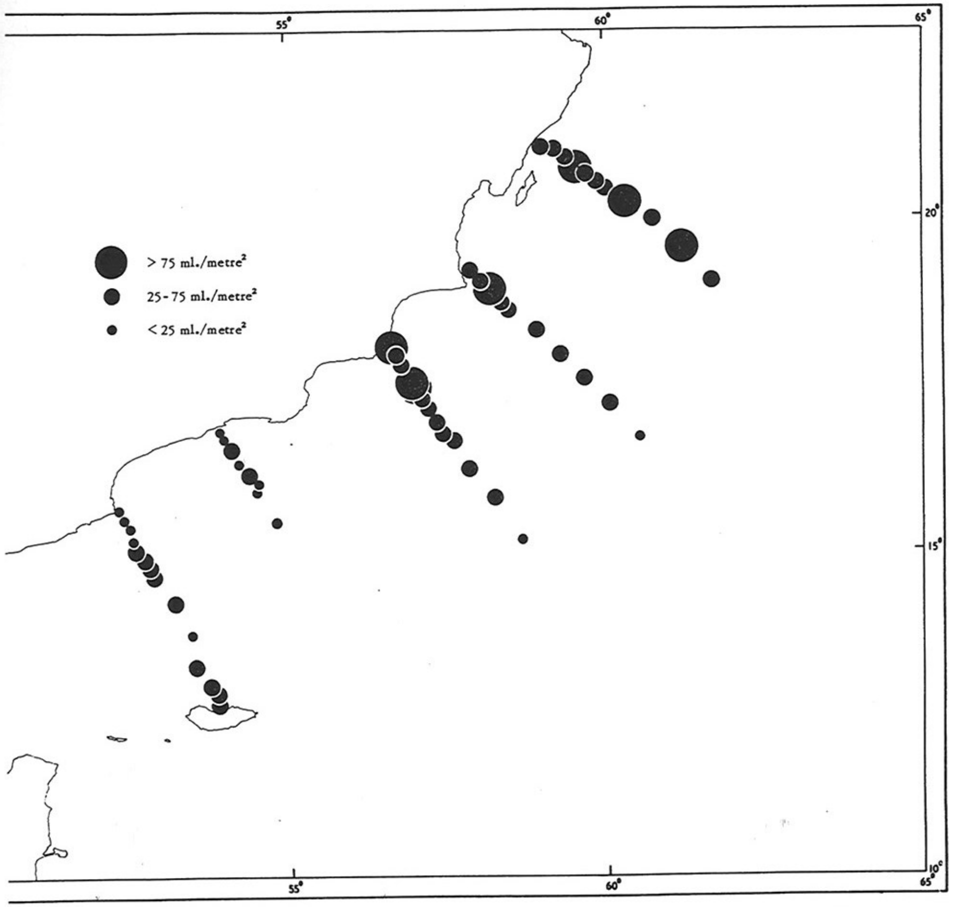

Figure 11. Quantitative distribution of zooplankton in the upper 1000 metres of water, or to the sea bed in shallower water, expressed as ml displacement volume per m^2.

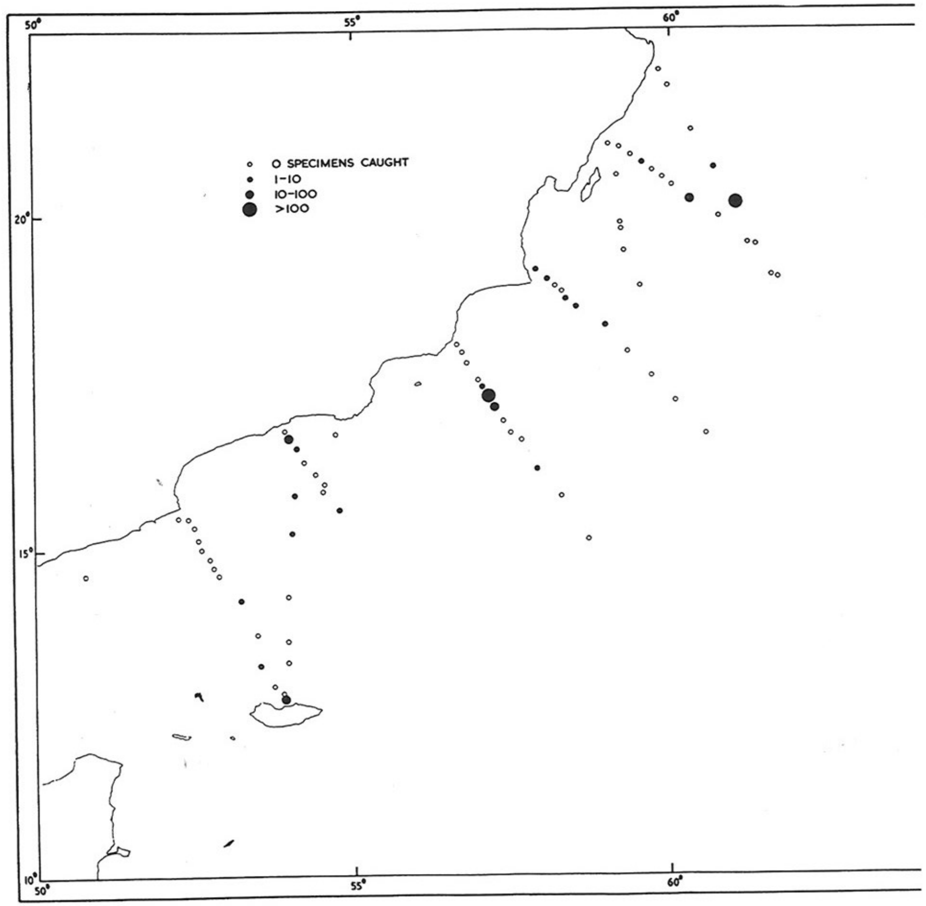

Figure 12. Distribution of tuna-like larvae in neuston net hauls.

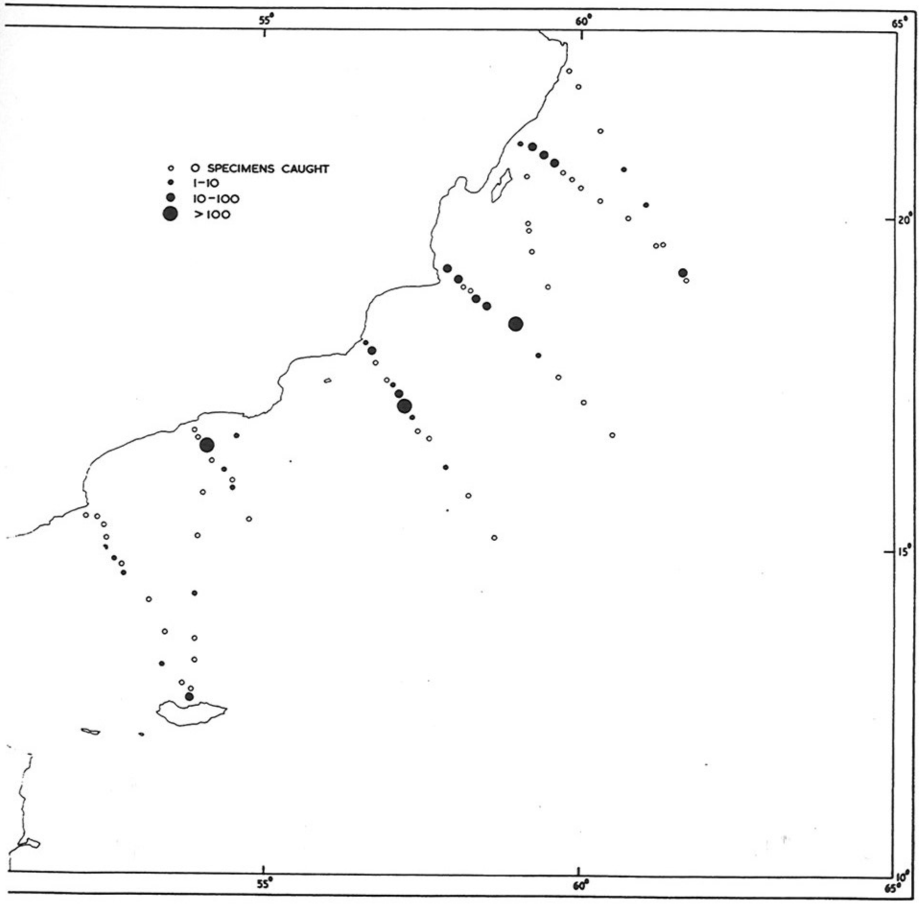

Figure 13. Distribution of Clupeoid larvae in neuston net hauls.

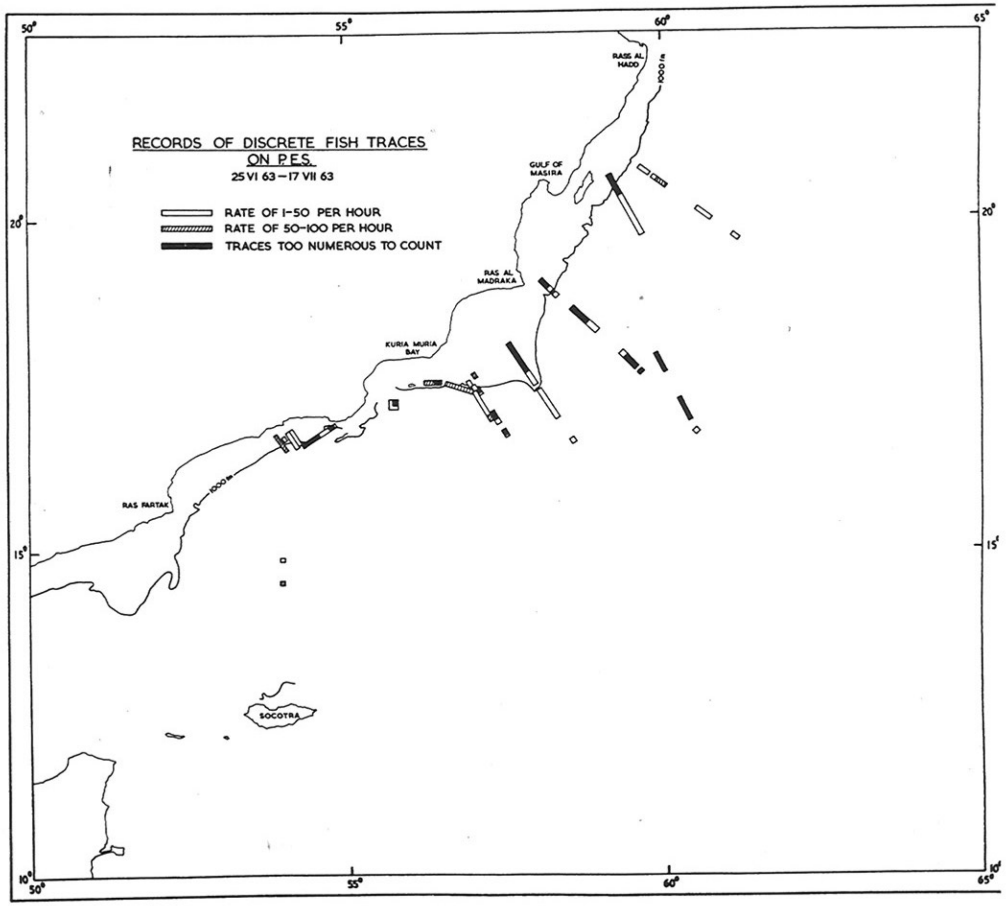

Figure 14. Occurrence of fish traces on echo-sounder records.

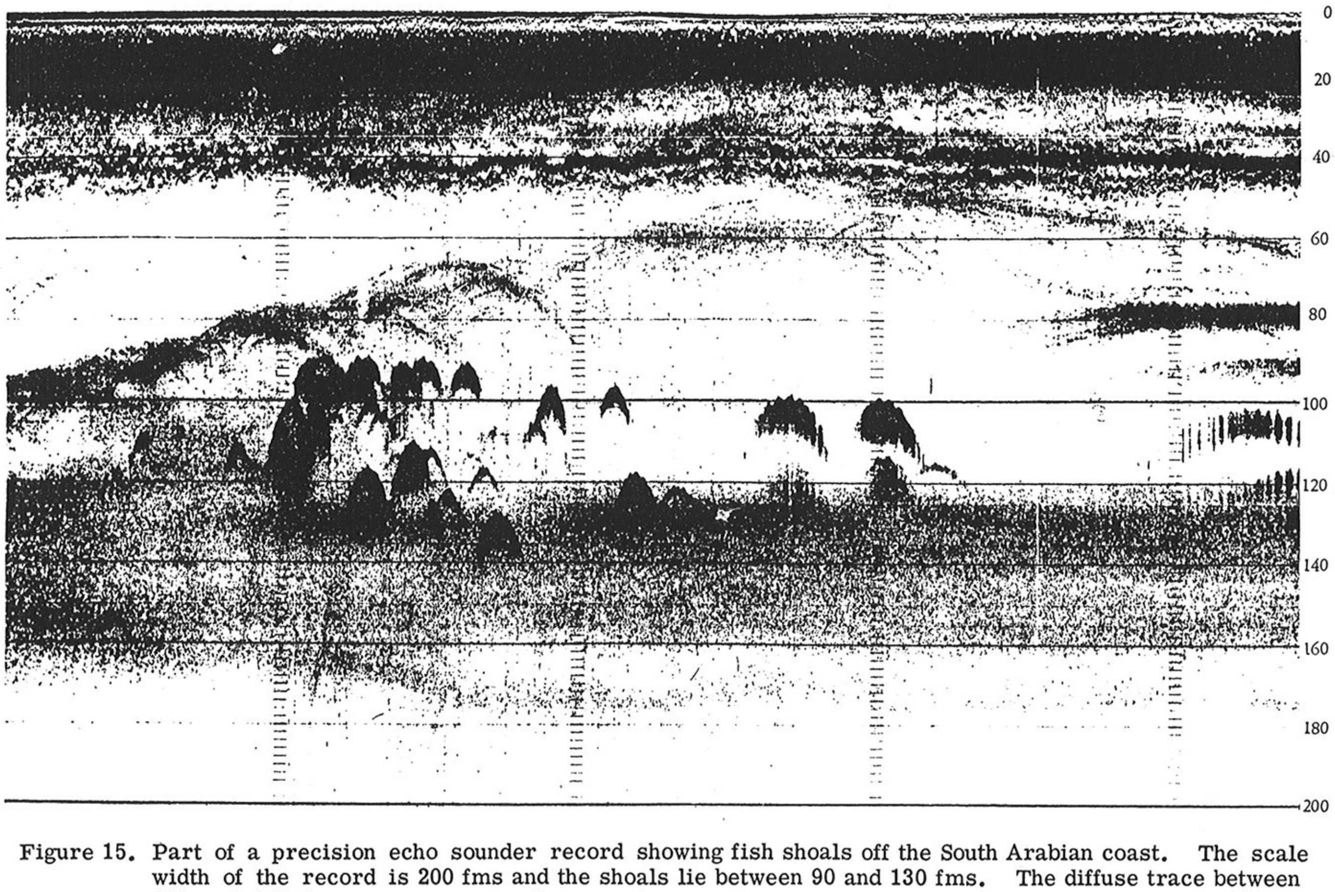

Figure 15. Part of a precision echo sounder record showing fish shoals off the South Arabian coast. The scale width of the record is 200 fms and the shoals lie between 90 and 130 fms. The diffuse trace between 120 and 160 fms is a scattering layer and many discrete echoes from organisms can also be seen between the surface and 50 fms. Since the record shows repeated phases of 200 fms the sea bed also appears (the larger crescent shaped marks above the fish traces) although lying at a much greater depth. The broken vertical lines are time marks at five minute intervals.

INTERNATIONAL INDIAN OCEAN EXPEDITION

R.R.S. 'DISCOVERY'

Cruise 1 Report Corrigendum

Page 20 - References

For 'Rozanor' read Rozanov'

Page 21 - Table I

Add:	P. Herring	Zooplankton	University of Cambridge
	M.V. Angel	Zooplankton	University of Bristol
	T. Vertue	General Assistant	National Institute of Oceanography

Page 22 - Table II

Twenty-third station: for 5038 read 5028

Page 23 - Table II

Longitude of station 5035 to read 56°50.5'

Latitude of station 5063 to read 20°45.7'