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IN VIVO CHLOROPHYLL *a* FLUORESCENCE IN THE VICINITY OF WARM-CORE EDDIES OFF THE COAST OF NEW SOUTH WALES 3, NOVEMBER 1978

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Abstract

A phytoplankton bloom which developed in the waters of a warm-core eddy (labelled "F") between September and October 1978 was still evident at the surface in November (*in vivo* chlorophyll fluorescence > 400 Turner Units (TU); photosynthetic quantum efficiency > 0.6). The highest fluorescence values (> 600 TU) were found at the centre of the eddy and surface nitrates suggested scope for further growth. Most of the standing crop was in the 0-75 m layer, i.e. above the thermocline which had established since September. Fluorescence values > 200 TU were found east of Newcastle. These were associated with a T_{250} temperature gradient, suggesting the presence of an eddy in that region.

High surface *in vivo* fluorescence (> 800 TU) close to Evans Head was due to the upwelling often found in that locality. North of Evans Head, in the East Australian Current, the standing crop of phytoplankton was often too low to measure, as also was dissolved inorganic nitrate. South of Evans Head, surface fluorescence was higher offshore (> 100 TU) than on the continental shelf (< 50 TU), due possibly to an 8-day interval between the shelf and offshore sections.

Nitrate concentrations south of Sydney were higher than to the north, except in the Evans Head upwelling. The distribution of nitrate in the water column of eddy "F" was much more uniform than in the surrounding sea due, apparently, to the deep winter mixing which characterizes these warm, near-isothermal water bodies.

INTRODUCTION

This report is the third of a series dealing with the dynamics of primary production in eddy "F", a warm-core eddy wandering for most of 1978 through the south-western Tasman Sea between 35° and 38°S and 151° and 154°E. The primary objectives of these cruises were physical and chemical; therefore data have been obtained for our purposes on a "ship of opportunity" basis. Nevertheless, considerable information has been obtained on standing crops and growth rates of phytoplankton, both within eddy "F" and in adjacent seas. In this report, we present data gained from R.V. "Sprightly" Cruise 15 (SP15/78), from 17 to 29 November 1978. This cruise provided an opportunity to sample eddy "F" again. In addition, we examined waters along the probable route of warm-core eddies spawned by the East Australian Current (EAC) (Cresswell and Nilsson, unpublished manuscript).

METHODS AND MATERIALS

The cruise track of SP15/78 is shown in Fig. 1. Eddy "F" and other oceanographic features were located by means of XBT's, GEK, and satellite tracked buoys. Nansen bottle samples were obtained for nutrient profiles, at the stations numbered in Fig. 1. Inorganic nitrate (NO_3) values used in this report were provided by the Oceanographic Services Section of this laboratory from analyses using the strychnidine method (Major *et al.* 1972). Fluorescence is reported in standardized units, herein called "Turner Units" or TU. An index of phytoplankton biomass was obtained by *in vivo* chlorophyll *a* fluorescence of samples treated with DCMU (Diuron) (Slovacek and Hannan 1977). This parameter, called F_M, is an index of the number of photons absorbed by photopigments in the sample and emitted as chlorophyll *a* fluorescence at 685-690 nm wavelength in standardized non-saturating light conditions. The increase in fluorescence (ΔF) above the untreated level (F_A) is an index to the number of electrons used in photosynthesis by the sample under the same standard conditions. This statistic provides an index to primary production (Samuelsson and Öquist 1977). Photochemical quantum efficiency, ϕ_p, ($= \Delta F/F_M$) was standardized relative to midnight on the empirical diel curve shown in Fig. 2. This allowed the corrected values ($\hat{\phi}_p$) to be contoured in the same way as for F_M. Samples were occasionally drawn from the fluorometer waste for chlorophyll *a* extraction, and determination from trichromatic equations. This provided the chl a/F_M relationship shown in Fig. 3. Full details of apparatus and methodology are given in an earlier report (Tranter *et al.* 1979).

RESULTS

Eddy "F"

Isotherms at 250 m (T_{250}) for the section south of 34°S are shown in Fig. 4. These outline the location of eddy "F" and show its relation to the two sections that were made across the eddy (one to the west of an arbitrary centre (+) and the other to the east) and also to the position of three Nansen bottle stations, 269, 270 and 271. Figure 5 shows near-surface isotherms drawn from XBT profiles. The position of the eddy, shown by the 17° T_{250} isotherm (dashed line), is not apparent from these data. Figure 6 shows the surface distribution of F_M superimposed on the T_{250} 17° isotherm. The standing crop of phytoplankton was higher in the eddy (> 400 TU) than in the sea outside (< 200 TU), particularly in the core, near station 271 (> 600 TU). The surface distribution of photosynthetic quantum efficiency, corrected for diel variation ($\hat{\phi}_p$), is shown in Fig. 7; $\hat{\phi}_p$ increased towards the core of the eddy where values up to 0.80 were found. At station 270, on the outer southern margin of the study area, $\hat{\phi}_p$ values up to 0.47 were found, compared with < 0.20 in surrounding waters. Another high value, 0.4, was found near station 272.

Figure 8 shows the vertical temperature distribution across the eddy as a hypothetical north-south section through the arbitrary centre. Each XBT record is aligned along this section according to its radial distance and bearing from the centre. The eddy core is seen as a warm, nearly isothermal body of 17° to 18°C water extending deep into a colder sea. A surface cap of water a few tenths of a degree warmer extended to about 50 m and was continuous with waters to the SE and NW of the eddy (Fig. 5).

Depth profiles of temperature, F_M, ϕ_p and NO_3 from Nansen bottle samples are shown in Fig. 9 for the three "eddy stations", 269, 270 and 271. A thermocline had developed in the core of the eddy (station 271) between 50 and 75 m. Most of the standing crop (F_M) was found in the upper mixed layer. Samples at station 269, on the northwestern edge of the eddy (see Fig. 4), revealed a similar pattern except that the thermocline there was stronger and shallower, and the standing crop was lower. At station 270, to the southwest, beyond the margins of the eddy, there was a different profile: a strong and extensive thermocline (approx. 3°C, between 25 m and 100 m) and a peak in F_M at 50 m. In each case photosynthetic efficiency was highest where biomass was maximal. The major difference was that at eddy stations these maxima were found in the upper mixed layer, while outside the eddy they were within the thermocline. The nitrate profiles suggest that further growth was possible in any of the three locations. What is remarkable, however, is that, compared to the station outside, the eddy stations appear to have lost nitrate from their deeper aphotic waters. Figures 10 and 11 show isopleths of F_M and ϕ_p for the section 269-271-270 across the eddy. Isopleths of NO_3 are shown in Fig. 12. The high nitrate concentration in the euphotic zone (> 1 µg-at N ℓ^{-1}) near the core of the eddy (station 271) suggests that, in respect to NO_3, the large standing crop had further growth potential. This appears to be substantiated by the relatively high ϕ_p values found there (Fig. 7, 11).

30°S to 34°S

Two tracks were followed between 30° and 34° south, the first (November 20-21), proceeding northward, being generally offshore, the second (November 28-29), proceeding southward, being generally inshore. T_{250} isotherms (Fig. 13) suggest the presence of a warm-core eddy off Newcastle (centered near 33.3°S, 153°W), a feature not evident in the surface isotherms (Fig. 14). The core of this second eddy appeared to have a higher surface standing crop than that in the surrounding sea (Fig. 15). An exception was an area of F_M > 200 TU outside but contiguous with the eddy's northwestern boundary.

The surface F_M characteristics along the two tracks were different. Offshore, F_M was usually greater than 100 TU; inshore it was usually less than 50 TU. To treat these data as synoptic may present a misleading picture because of the 8-day time separation. F_M values of 111 TU obtained on the northward track are an order of magnitude larger than the F_M values (14 and 16 TU) obtained on the southward track in the area where the tracks cross (Fig. 15). This would suggest that the phytoplankton had disappeared during the intervening 8 days.

Isopleths of $\hat{\phi}_p$ are plotted in Fig. 16. Those values derived from F_M-F_A < 10 TU, and hence subject to the relatively large error of small numbers, were not used. In general, $\hat{\phi}_p$ was low (< 0.2) along the offshore track and high (> 0.4) along the inshore track, suggesting that on the earlier occasion the phytoplankton population, while relatively dense, was not viable. A week later, at the time of the southward track, the phytoplankton population, although it had declined to a very low standing stock, was vital, and capable of growth. The surface isotherms (Fig. 14) suggest that cold water was upwelling along the coast, particularly off Sugarloaf Pt. (32.4°S) and Crowdy Head (31.8°S), with low F_M.

Two stations were occupied in the area off Smoky Cape (30.9°S), as shown in Fig. 13. Temperature, F_M, ϕ_p and NO_3 profiles are shown in Fig. 17. Both profiles reflected stable water columns; both had shallow (< 25 m) upper mixed layers; both profiles showed low standing crop. Few of the ϕ_p values were usable because of the relatively large errors inherent in calculations using low fluorescence levels. Nitrate was virtually exhausted in the upper 70 m of both water columns although it was plentiful below 100 m.

24°S to 30°S

The cruise track (Fig. 1) passed three times through an interesting area off Evans Head whose physical features are discussed by Godfrey *et al*. (unpublished data). A small portion of this area (29°-29.5°S, 153.5°-154°E) shown in detail in Fig. 18 is of special interest because a sequence of observations was made whilst following a buoy drogued at 20 m (stations 279-282, 24 November 1978). Figure 19 shows the surface isotherms and Fig. 20 the surface standing crop. The temperature/time sequence suggests that cold deep water was upwelling inshore on 22 November but offshore warm surface water remained. Two days later (24 November), the upwelling had apparently ceased, the surface water was warming, and the upwelled water had pushed the warm surface water further offshore. Four days later (28 November) the warm surface water had moved back toward the coast. On the 24th the ship followed a buoy attached to a drogue for seven hours. The vertical sections that were obtained along the way are shown in Fig. 21. Included in these sections are data from inshore station 278. The emergent picture is one of upwelled surface water sinking under subtropical surface water as the colder water mass moved southward. The highest region of F_M was inshore and submerged (Station 278). The nitrate data are anomalous in that NO_3 *increased* at the surface from the next shallowest depth. [This anomaly was found in 15 out of 16 stations where significant reported values (> 0.1 µg-at N ℓ^{-1}) constitute a bias in the data set for the entire cruise.] Aside from this apparent anomaly, the NO_3 data confirm the sinking of previously upwelled water as it is transported south. High ϕ_p values suggest high growth rates in the entire water column in the region of submergence. These observations underline the extremely dynamic nature of the water mass and of primary production in this known upwelling area. Significant changes take place within a few hours and over a few kilometres.

The remaining area north of 30°S was relatively featureless, generally characterized at the surface by warm water (> 24°C) and very low standing crop (F_M < 25 TU). Higher F_M values (50 to 100 TU) were found on the earlier track (22-23 November) eastward and northward of the Evans Head upwelling. These temporal changes may reflect meanderings of the East Australian Current. T_{250} isotherms are shown in Fig. 22. The most striking feature is the rapid increase of temperature at 250 m depth, proceeding off the coast. Vertical profiles (stations 274-276, 283-286) generally showed low NO_3 (< 1 µg-at N ℓ^{-1}) in the euphotic zone (above 100 m) but rapidly increasing concentrations below. F_M was usually low (< 50 TU) at all depths, with the expected maximum at the level compromising light and nutrient limitations.

Vertical profiles for offshore stations are presented in Fig. 23. The selection of stations here was governed by the concept of eddy "F" being shed by the EAC somewhere in the northern sector and floating southward, intact, to its location in November. The isotherms tilt upwards to the south, reflecting the deep penetration of warm water in tropical regions, the northward penetration of cool-temperate water at depth, and the dynamic equilibrium of surface water temperature with that of the overlying air mass. The obvious anomaly in this pattern is caused by the thermal characteristics of eddy "F" at stn. 271, which confirms that the water mass of the eddy must have originated in more northern subtropical waters. The F_M pattern discloses that the autotrophic biomass inside the eddy resembles more that of surrounding waters (Stns 270 and 272) than that of waters where it originated. The ϕ_p pattern suggests a temperature dependency, in that the isopleths also tilt upwards toward the south. Reliable data are sparse in the northern area; the few available suggest ϕ_p values of about 0.5.

Despite surface bias in the nitrate data, the nitrate isopleths show an orderly pattern south of station 288, against which eddy "F" stands in contrast as a marked anomaly. Here the nitrate is distributed much more evenly through the water column.

In summary, Fig. 23 demonstrates that the warm-core eddy contains a sufficient store of nitrate for significant phytoplankton production, and that this store was not exhausted by November when the cruise took place.

DISCUSSION

Our working hypothesis at the start of this study (Tranter *et al.* 1979) was as follows: The nutrients available within the eddy during its lifetime originate with the original tongue of water isolated from the East Australian Current, and these constantly diminish because of detrital fallout. The only other exchanges take place through faunal migration across the boundaries. In time, the water within the eddy becomes impoverished, while the surrounding water is renewed seasonally. The food chain loses its primary production base and species composition changes. Eventually the whole biotic system runs down, until the eddy becomes a biological desert.

This hypothesis was based on the knowledge that a large component of the water which feeds the EAC is West Central South Pacific water (Godfrey 1973), characteristically poor in nutrients (Rochford 1959) and primary production (Jitts 1965). The low *in vivo* chlorophyll *a* fluorescence and nitrogen reserves stored as nitrate observed along the offshore track between 26^{o} and 28^{o}S on this cruise are consistent with that view. The fact that nitrate was found in the euphotic zone of the eddy and that a phytoplankton bloom was in progress seems, at first, a contradiction of our working hypothesis. Evidently NO_3 was brought into the surface waters after the eddy had been established and moved south of its original position. This suggests either deep mixing or intrusions of NO_3-rich water from outside the eddy. The isopleths in Figs 9 and 23 indicate that deep convective mixing as reported for similar warm-core eddies by Cheney (1977) was the likely mechanism for a nutrient source. However, while nitrogen was brought into the euphotic zone and a phytoplankton bloom followed, the nitrogen stores of the eddy as a whole were less than those originally present. These problems are the subject of further research in this continuing study.

ACKNOWLEDGMENTS

We are indebted particularly to Dr G.R. Cresswell, the Cruise Leader, for the opportunity to participate in SP15/78. This manuscript was discussed with Dr Cresswell and with Dr J.S. Godfrey who made a special study of water movements in the area near Evans Head.

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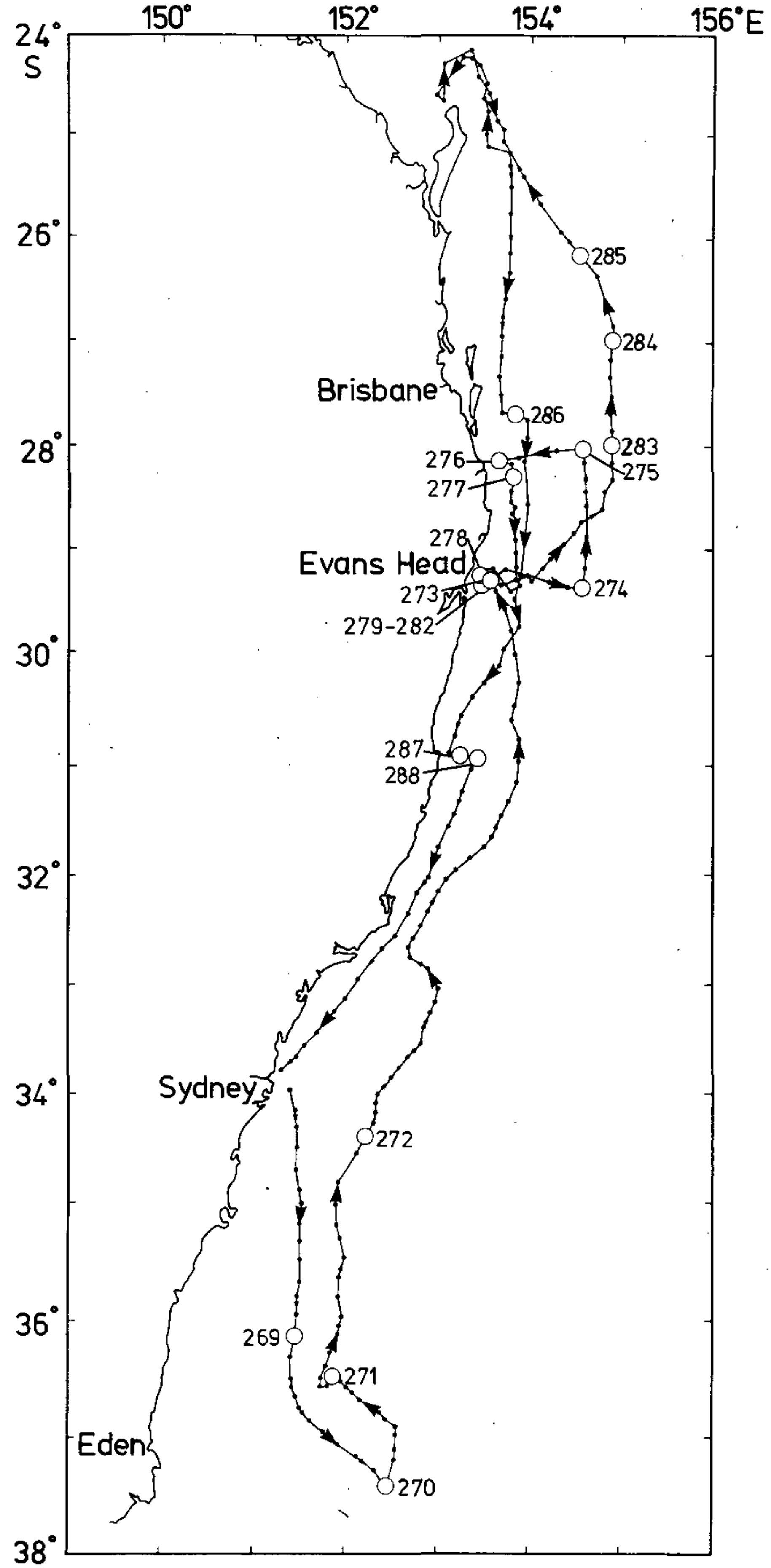

Fig. 1. Cruise track of "Sprightly" 17-29 November 1978 (SP15/78). Dots indicate XBT locations, circles locate stations held for water sample profiles. Arrows indicate direction of ship's track.

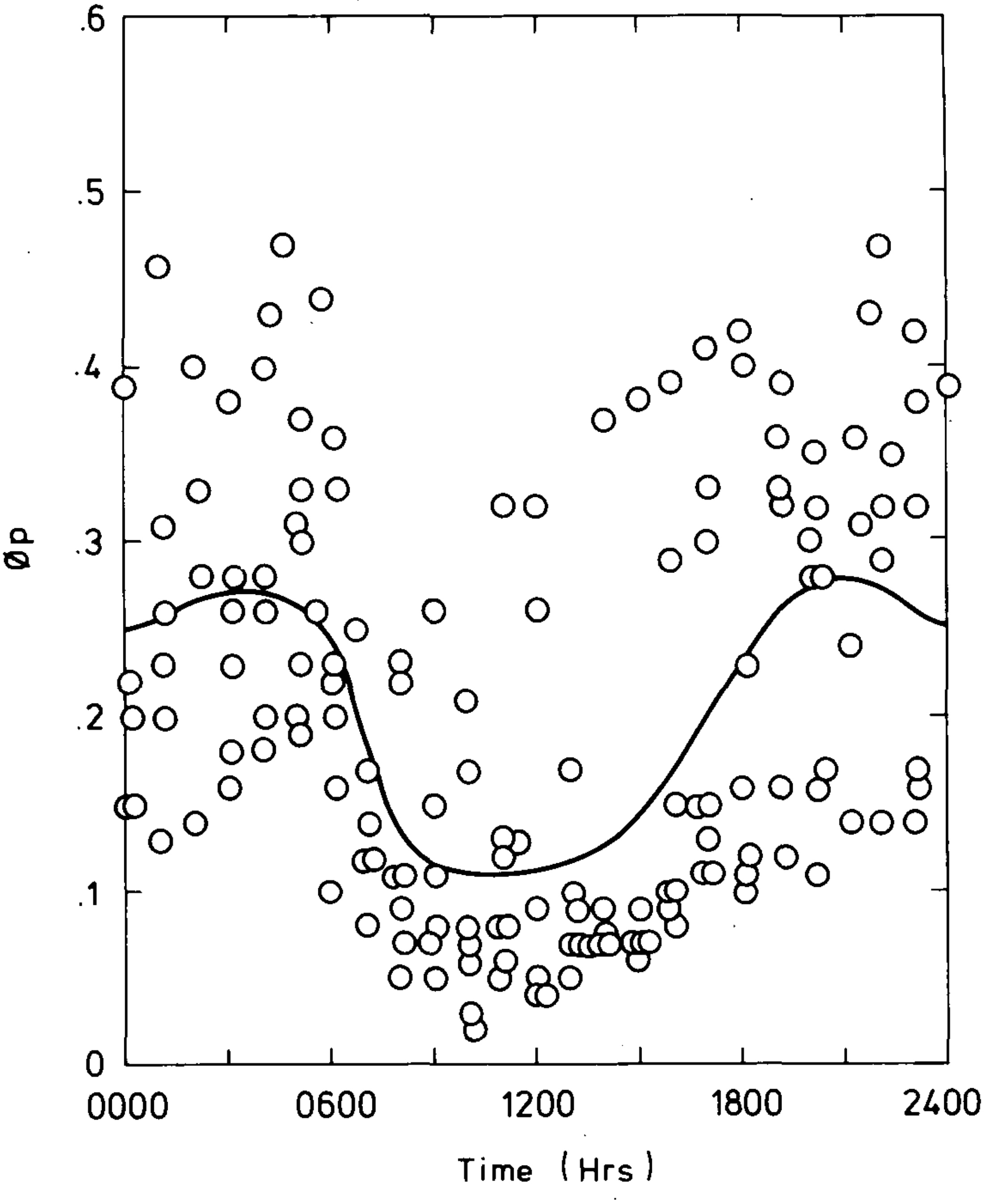

Fig. 2. The diel effect on ϕ_p calculated from surface on-stream data, SP15/78. Data were averaged within 3-hour time periods and a faired line drawn to connect average ϕ_p, T values. This curve was used to standardize individual data to a midnight value, to yield $\hat{\phi}_p$.

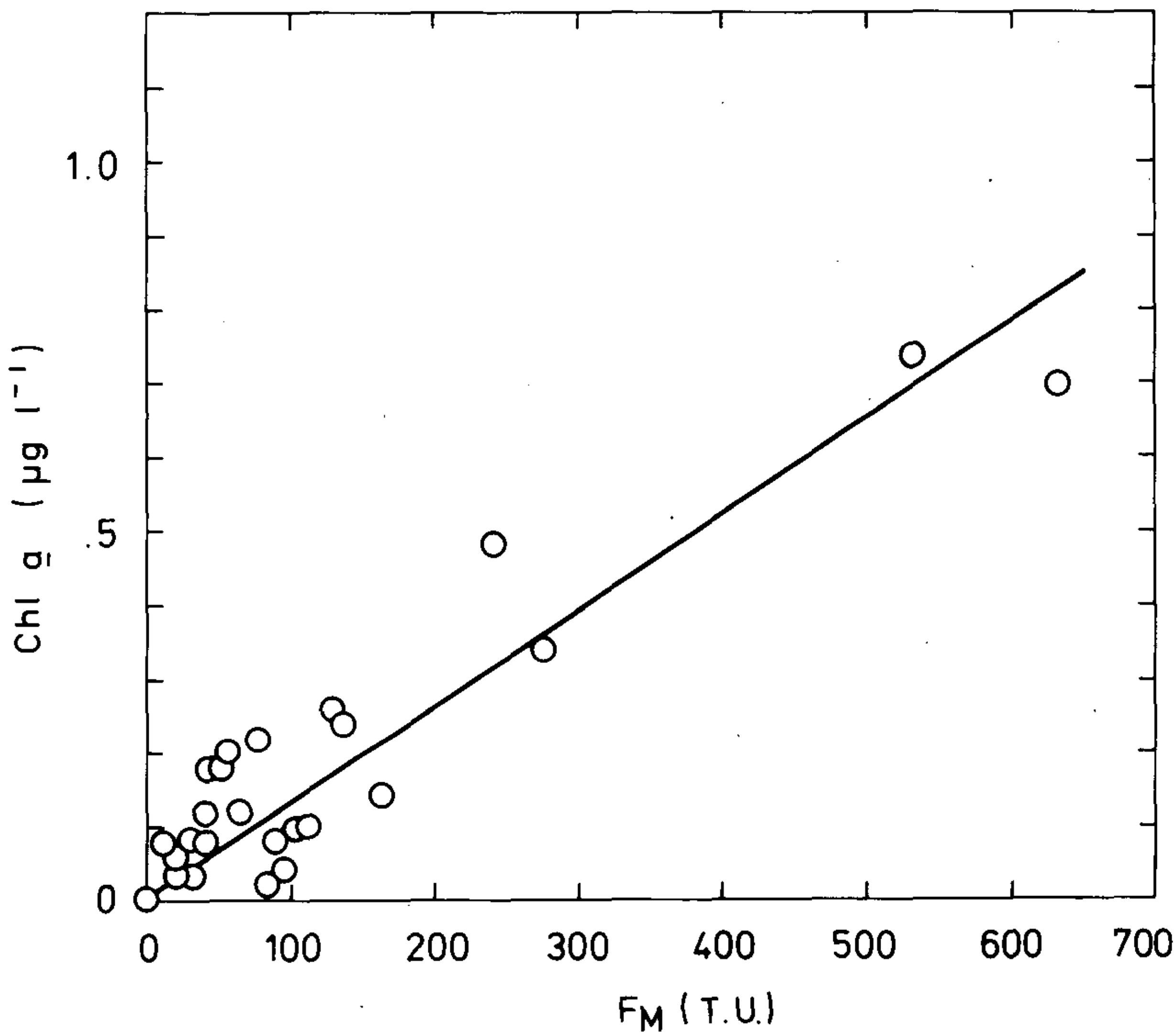

Fig. 3. The relationship between chlorophyll *a* and F_M for underway samples on SP15/78. The equation through 0,0 is $\hat{Chl}$ *a* = 1.30×10^{-3} F_M, $R_l^2 = 0.71$, n = 25.

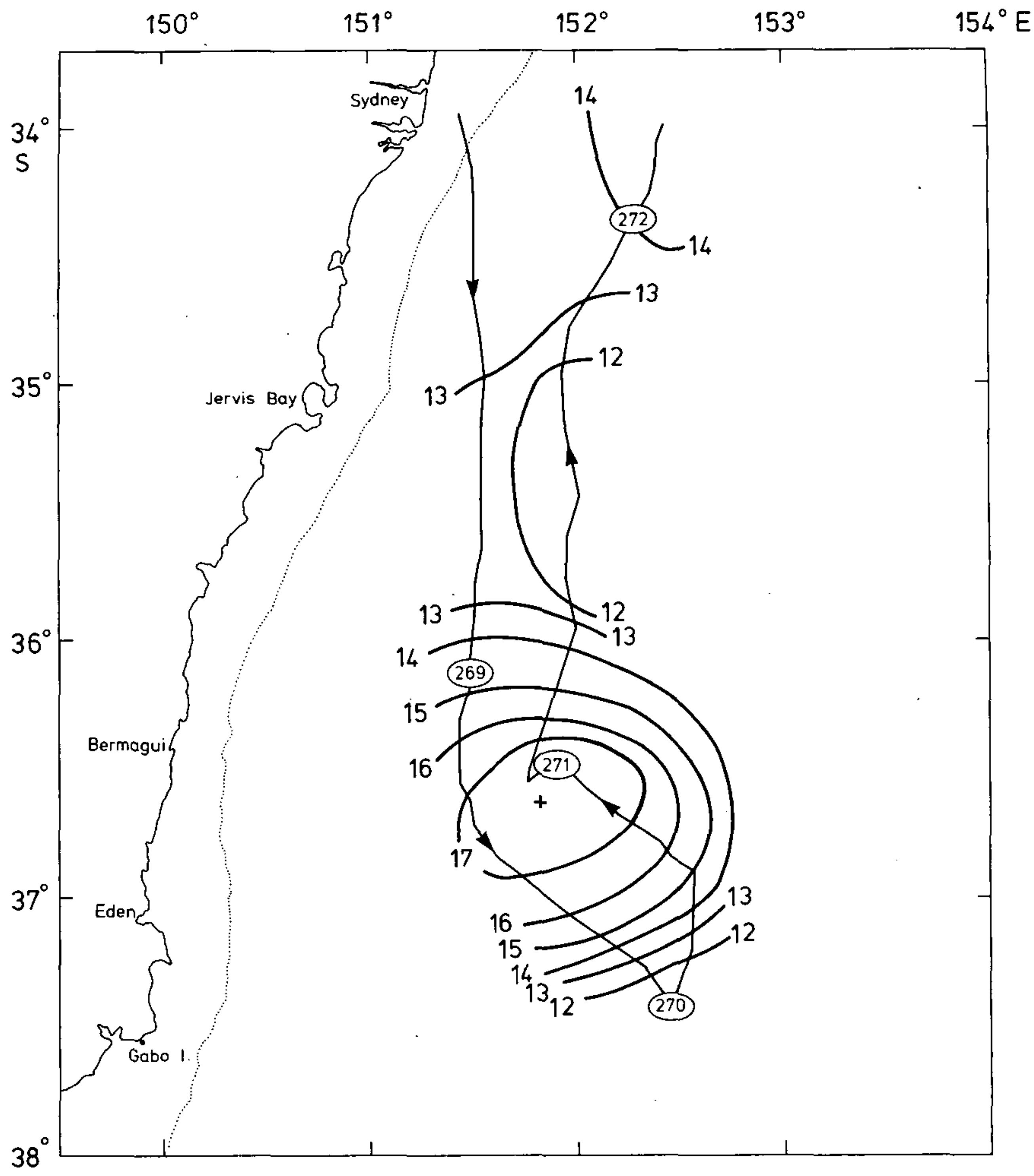

Fig. 4. Isotherms at 250 m for the section south of 34°S, drawn from XBT data. The + designates an arbitrarily chosen centre for the eddy (after Cresswell 1978).

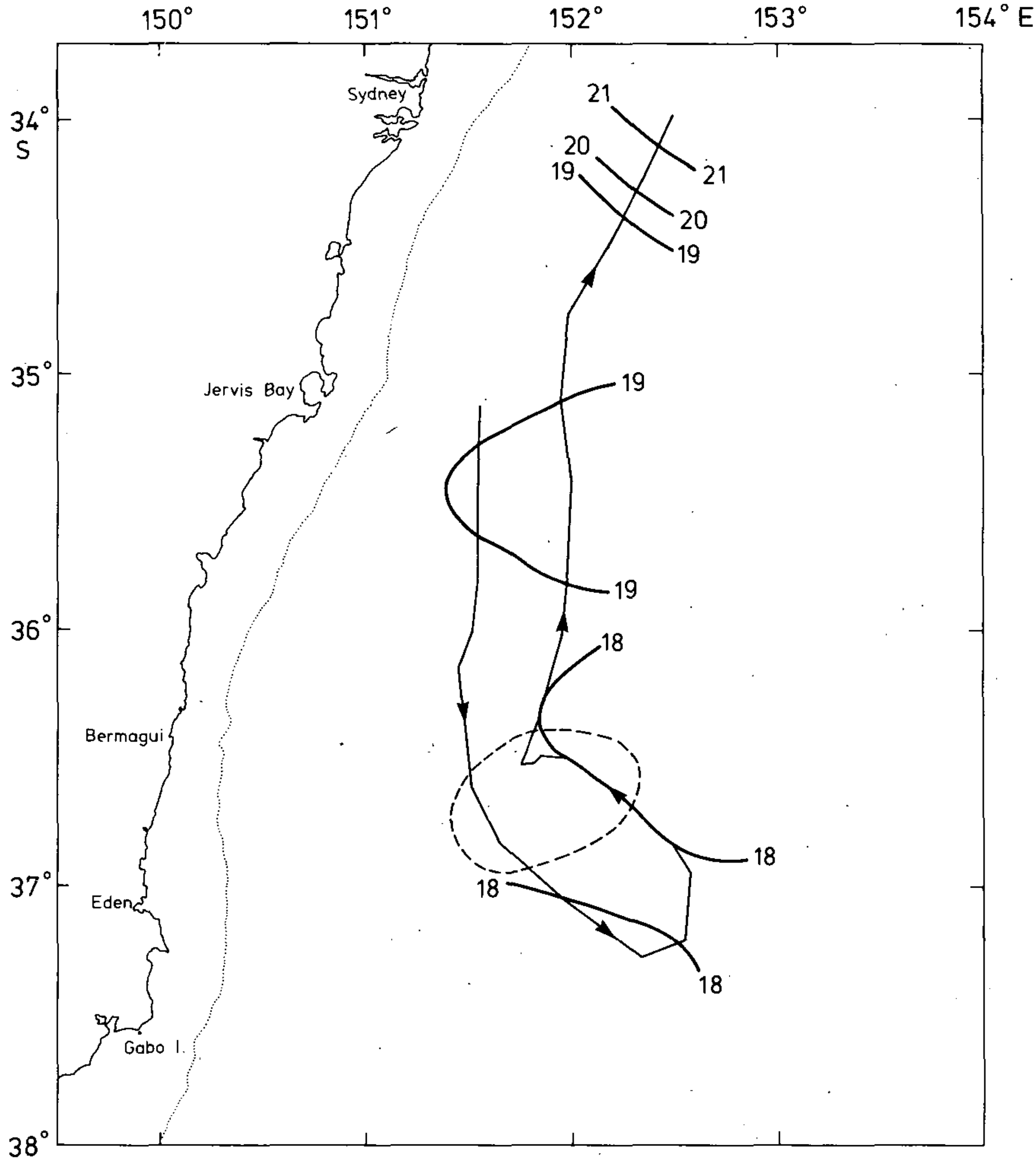

Fig. 5. Near surface isotherms for the section south of 34°S, drawn from XBT data, and superimposed on the 17° T_{250} isotherm (----).

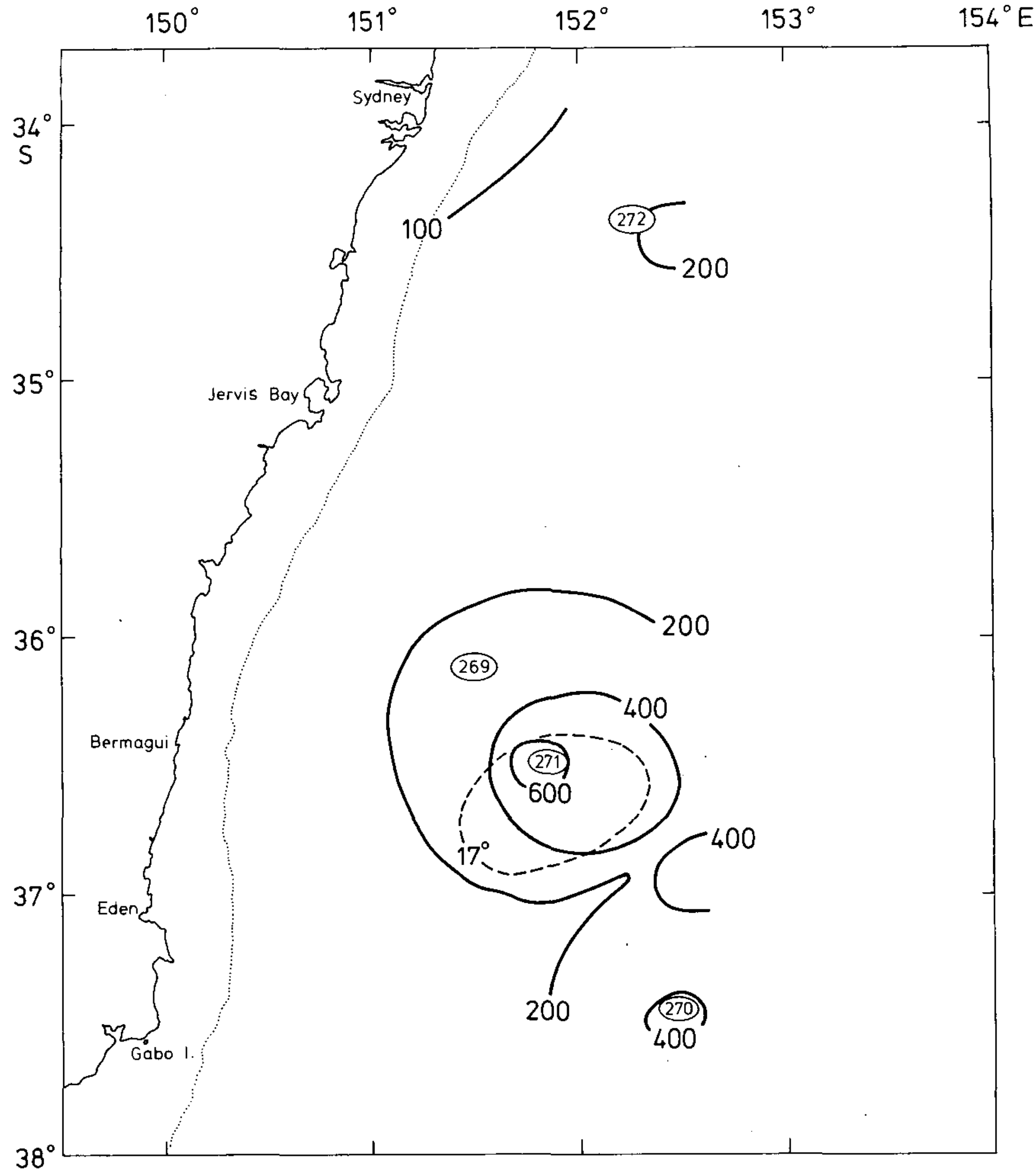

Fig. 6. Isopleths of surface F_M (TU) from on-stream data, superimposed on the T_{250} 17° isotherm (----). The eddy has a high standing crop of phytoplankton.

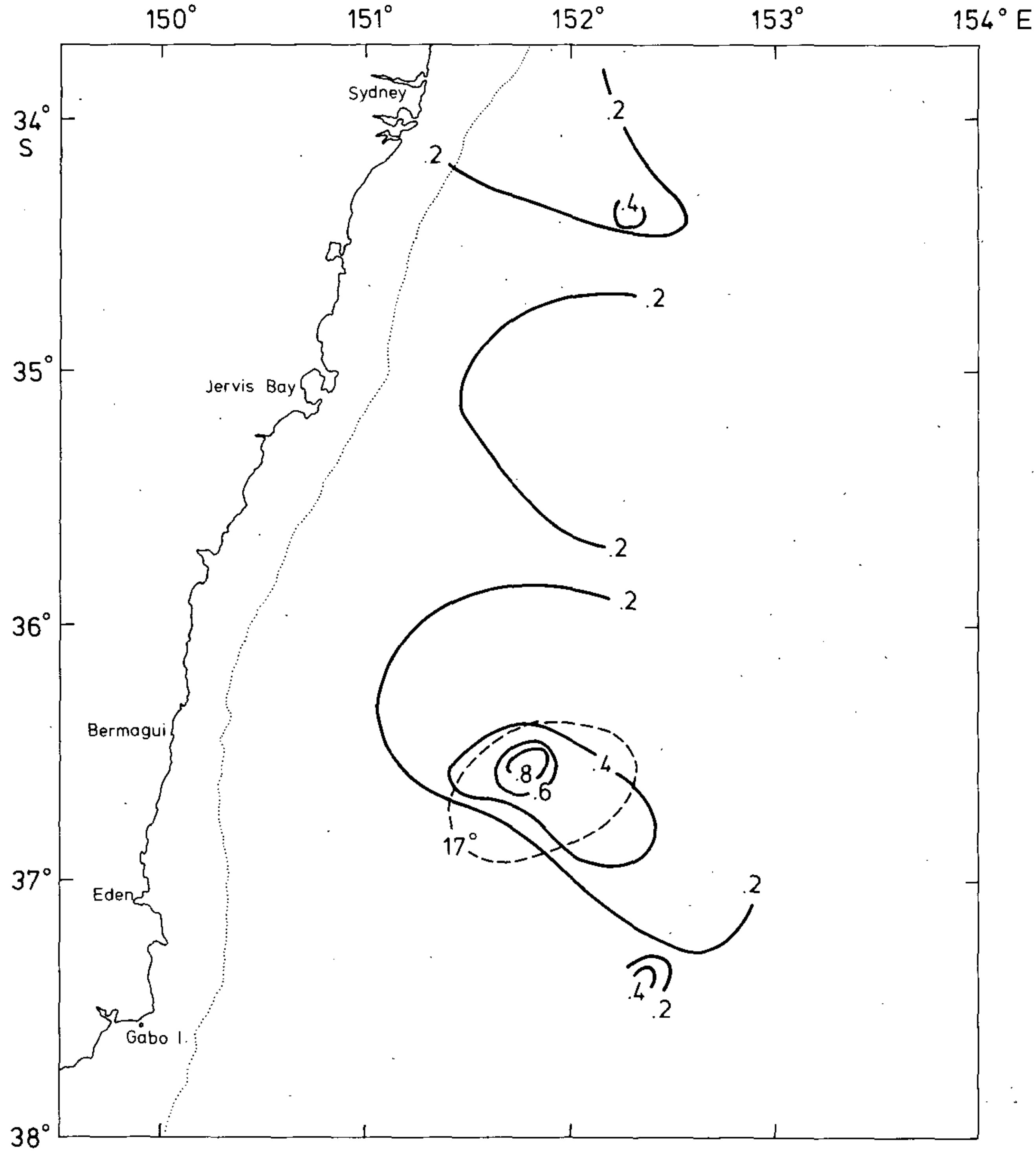

Fig. 7. Isopleths of surface $\hat{\phi}_p$ from on-stream data, superimposed on T_{250} 17° isotherm (----). *Photosynthetic efficiency is high at the eddy centre.*

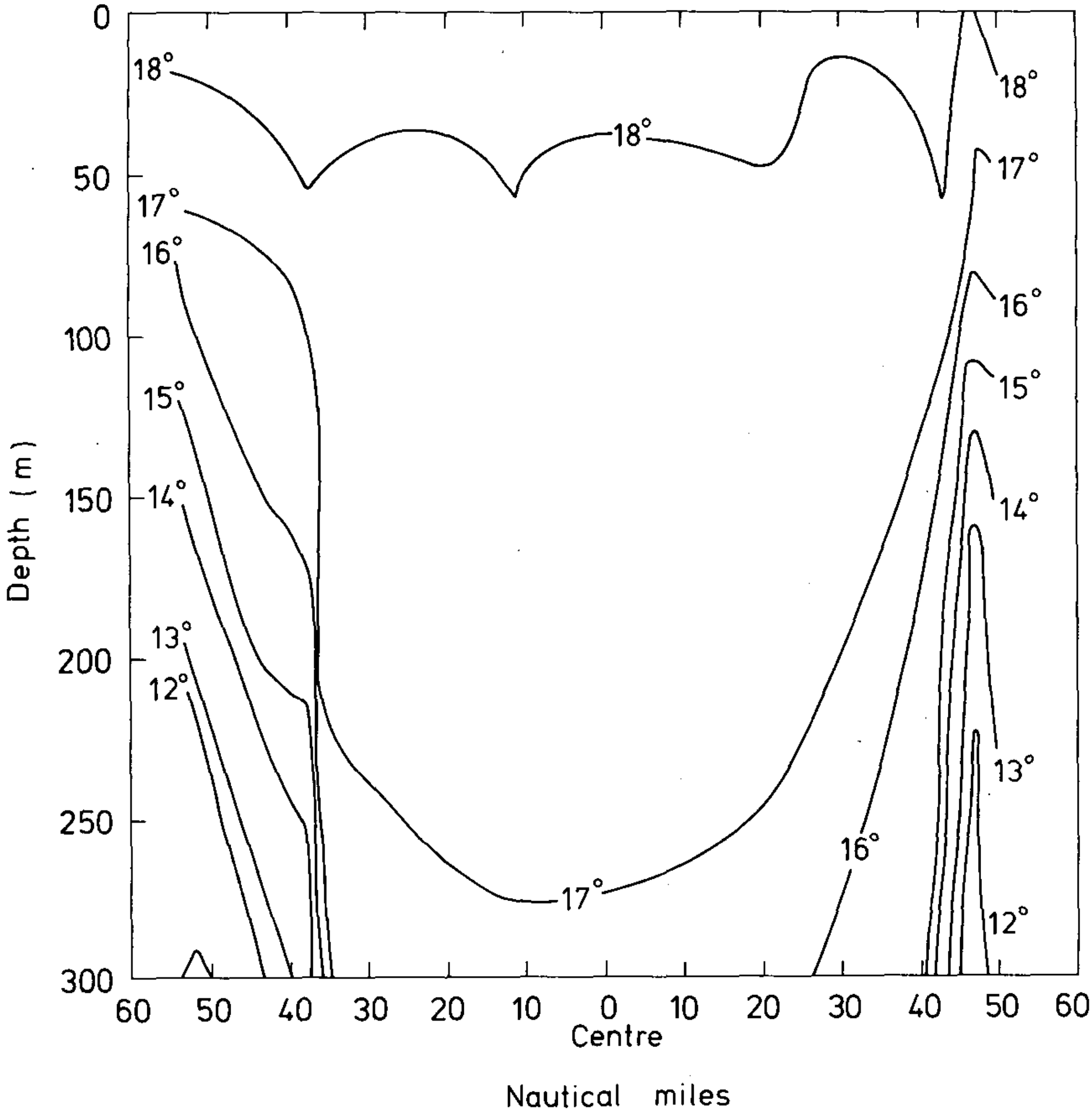

Fig. 8. Conceptual construction of a vertical section through the eddy centre based on vectors to XBT positions rotated to a common N-S transect. The eddy is a warm near-isothermal body of water with a shallow cap.

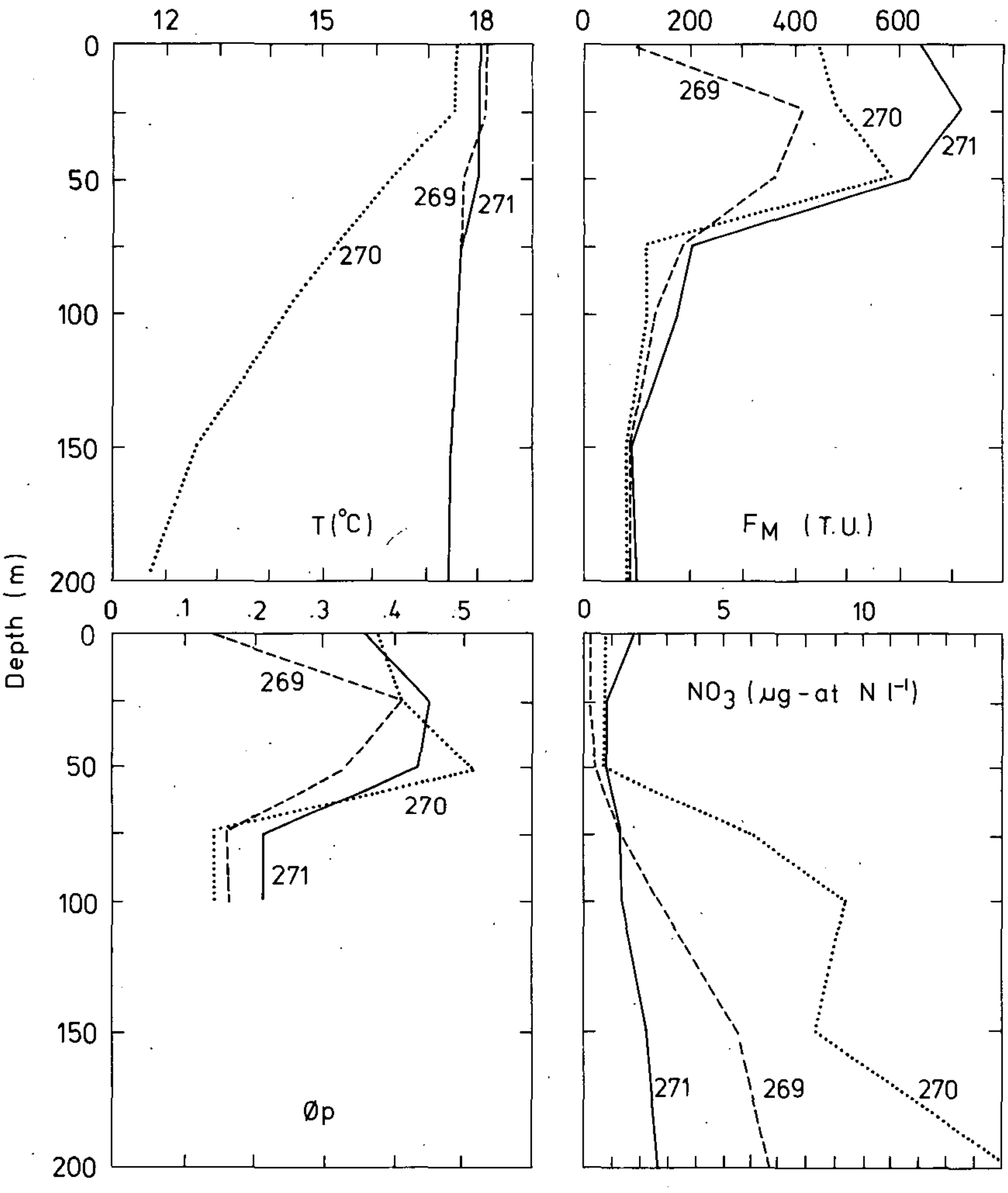

Fig. 9. Profiles of T, F_M, ϕ_p and NO_3 for stations 269-270 and 271.

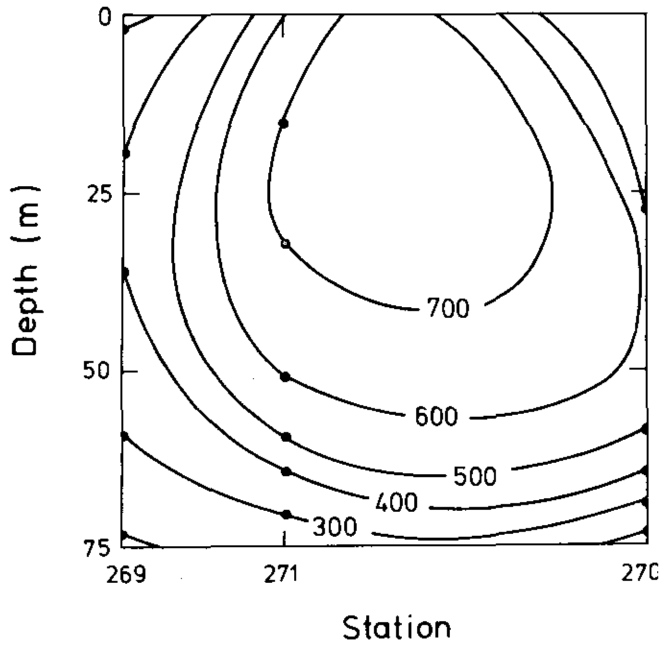

Fig. 10. Vertical isopleths of F_M (TU) for the section 269-271-270 across eddy "F". There is a large standing crop in the middle of the eddy throughout the upper 50 m.

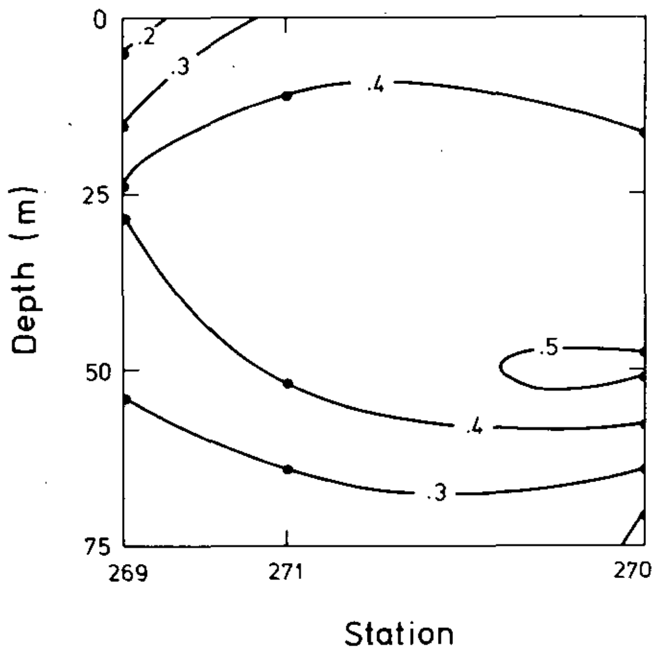

Fig. 11. Vertical isopleths of ϕ_p for the section 269-271-270 across eddy "F". Note that surface values are uncorrected for diel variation and much higher values would pertain at stn 269, commenced at 0916 hrs, and at stn 271, commenced at 1427. Surface values at stn 270, commenced at 1747, would be less affected. The subsurface ϕ_p suggest that the standing stock was capable of higher production in the eddy than in contiguous waters to the NW, but that the highest potential observed was to the south, at the top of the thermocline.

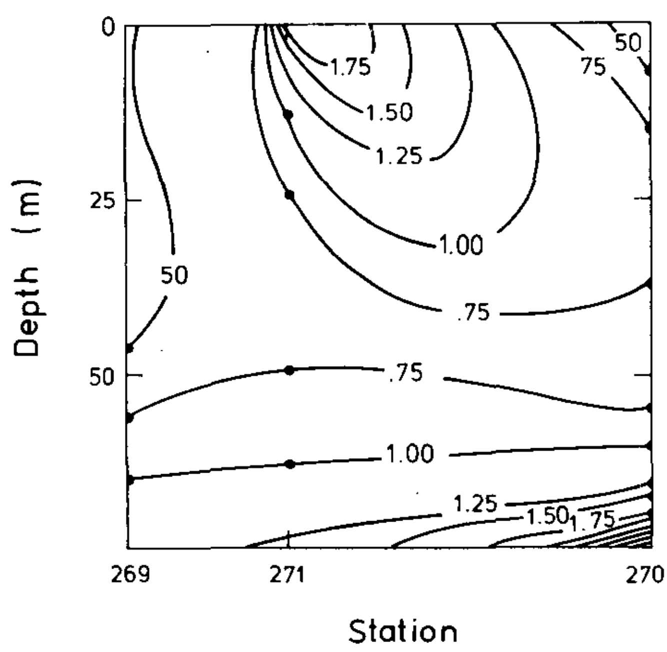

Fig. 12. Vertical isopleths of NO_3 (μg-at N ℓ^{-1}) for the section 269-271-270 across eddy "F". There was still sufficient nitrate near the middle of the eddy for further growth.

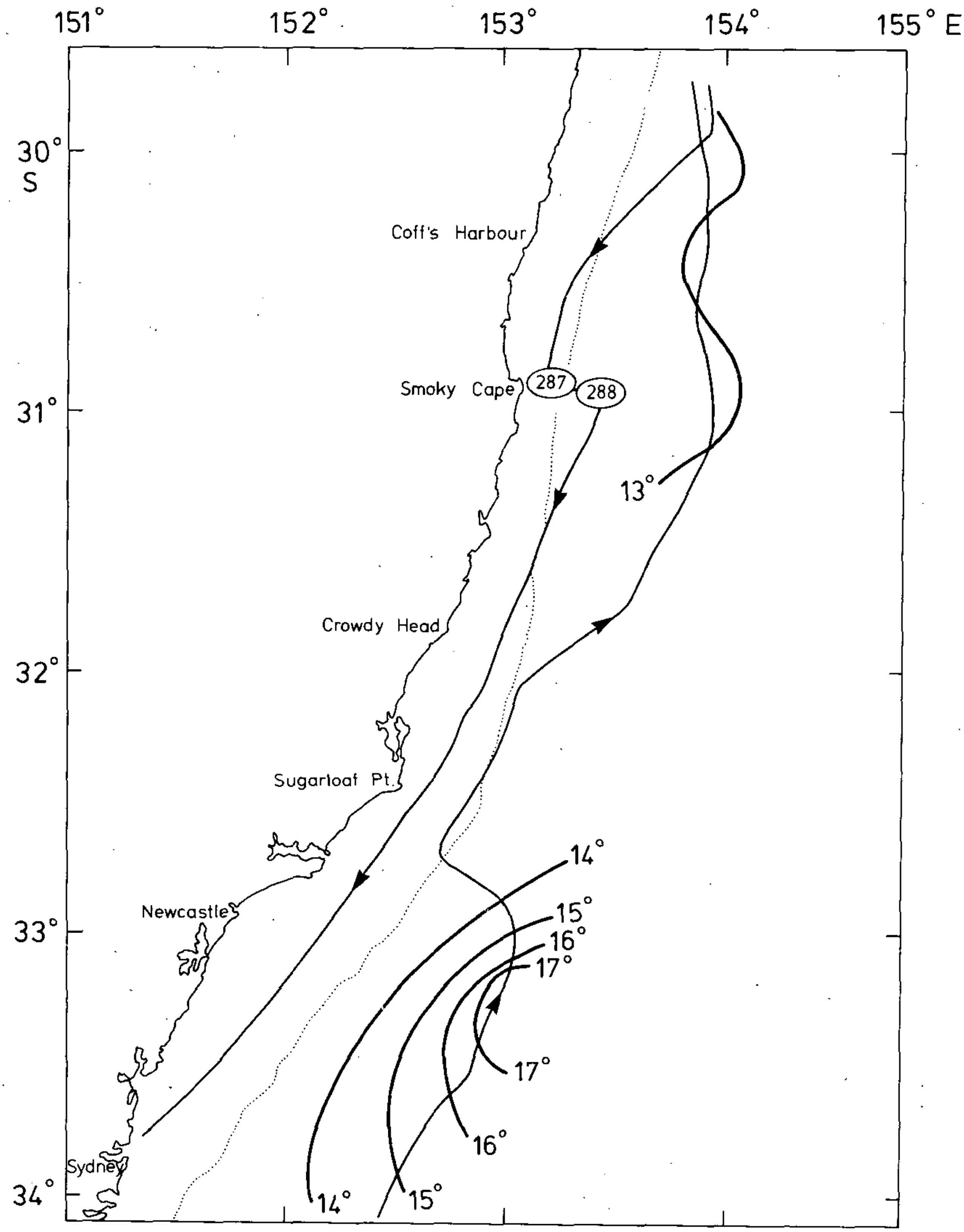

Fig. 13. Isotherms at 250 m for the section 30°S to 34°S drawn from XBT data. There are indications of a second warm-core eddy off Newcastle.

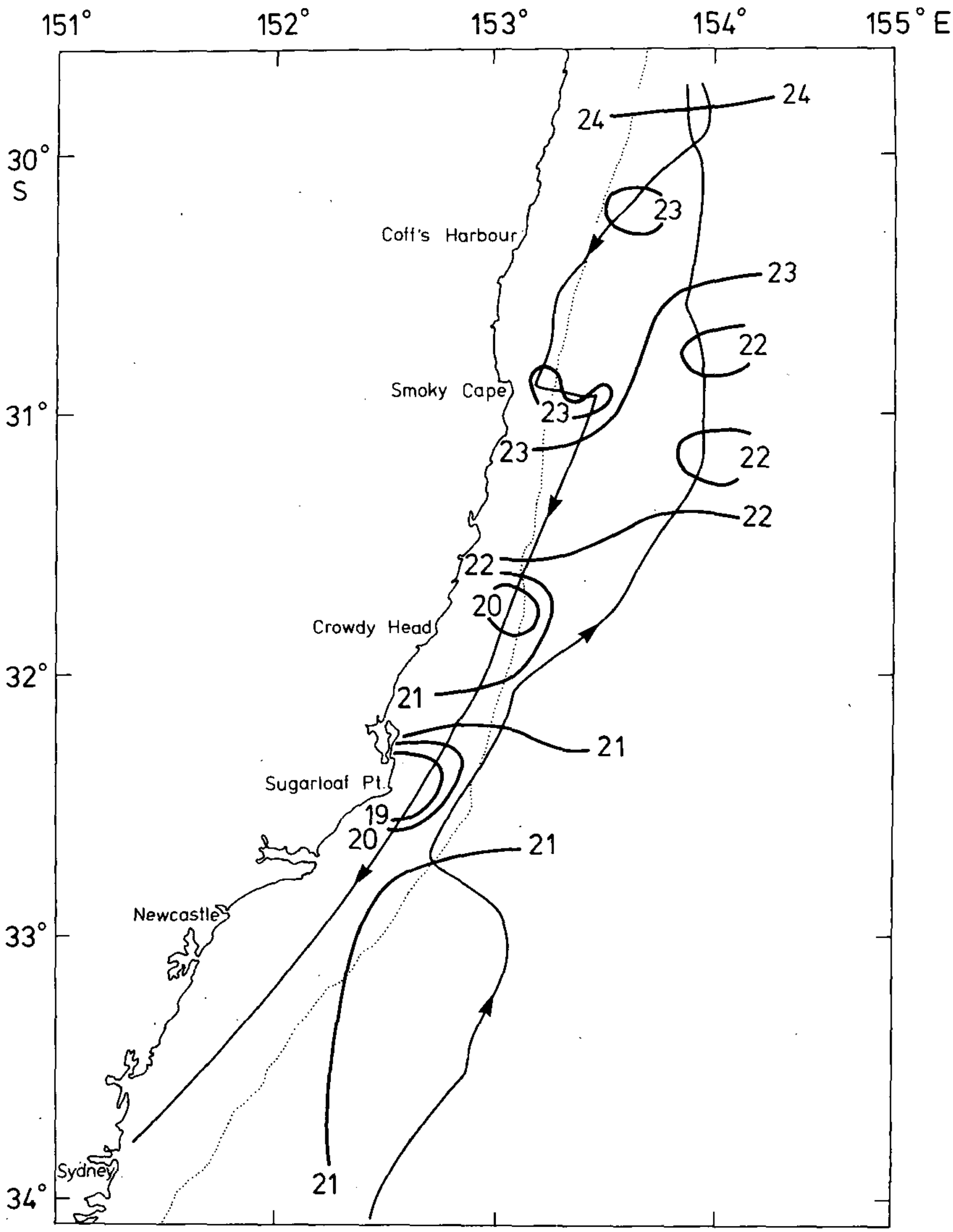

Fig. 14. Near surface isotherms for the section 30°S to 34°S drawn from XBT data. Patches of cool water are found near the coast.

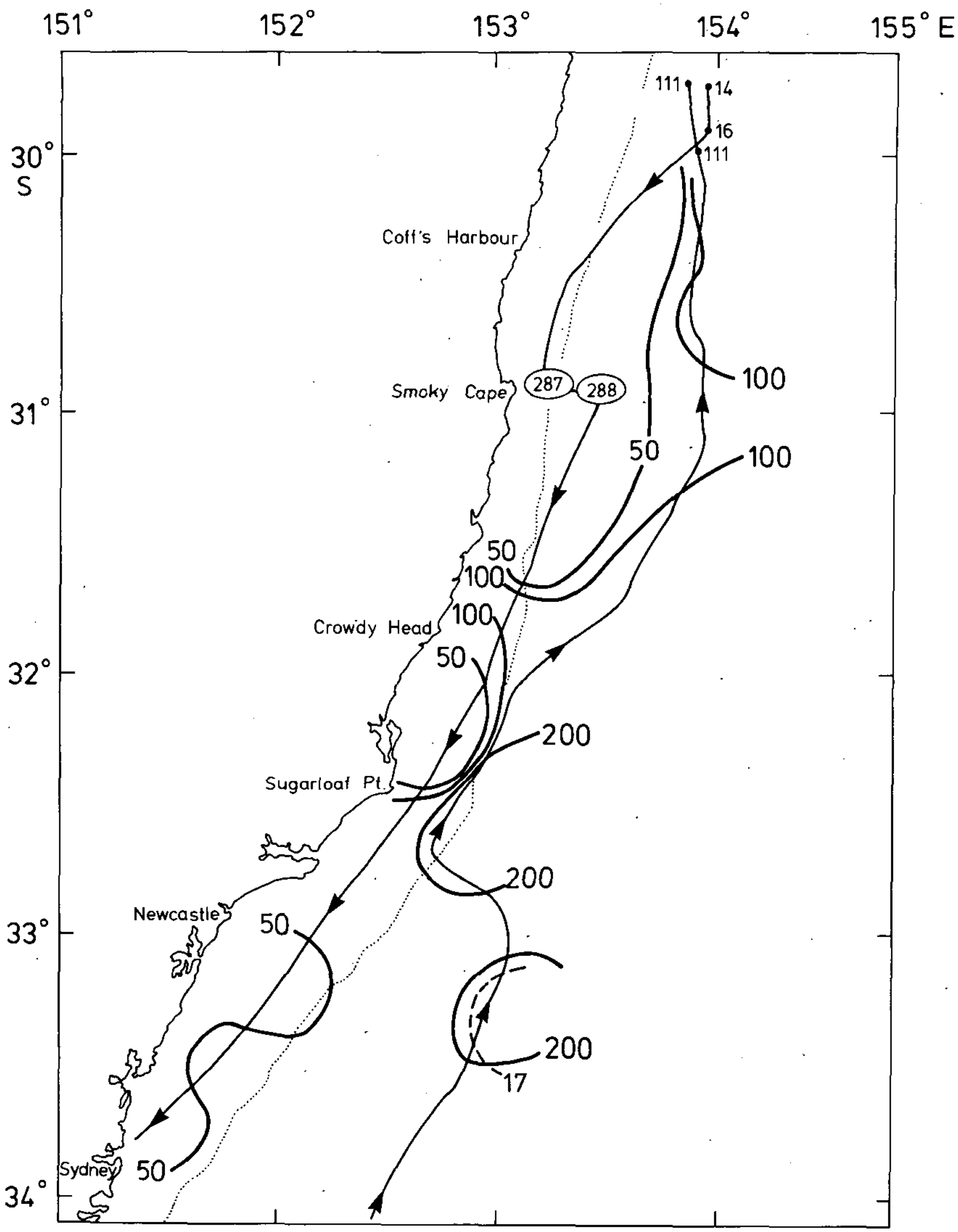

Fig. 15. Isopleths of surface F_M (TU) from on-stream data, superimposed on the T_{250} 17° isotherm. Where there appeared to be an eddy (----) the standing crop of phytoplankton was relatively high.

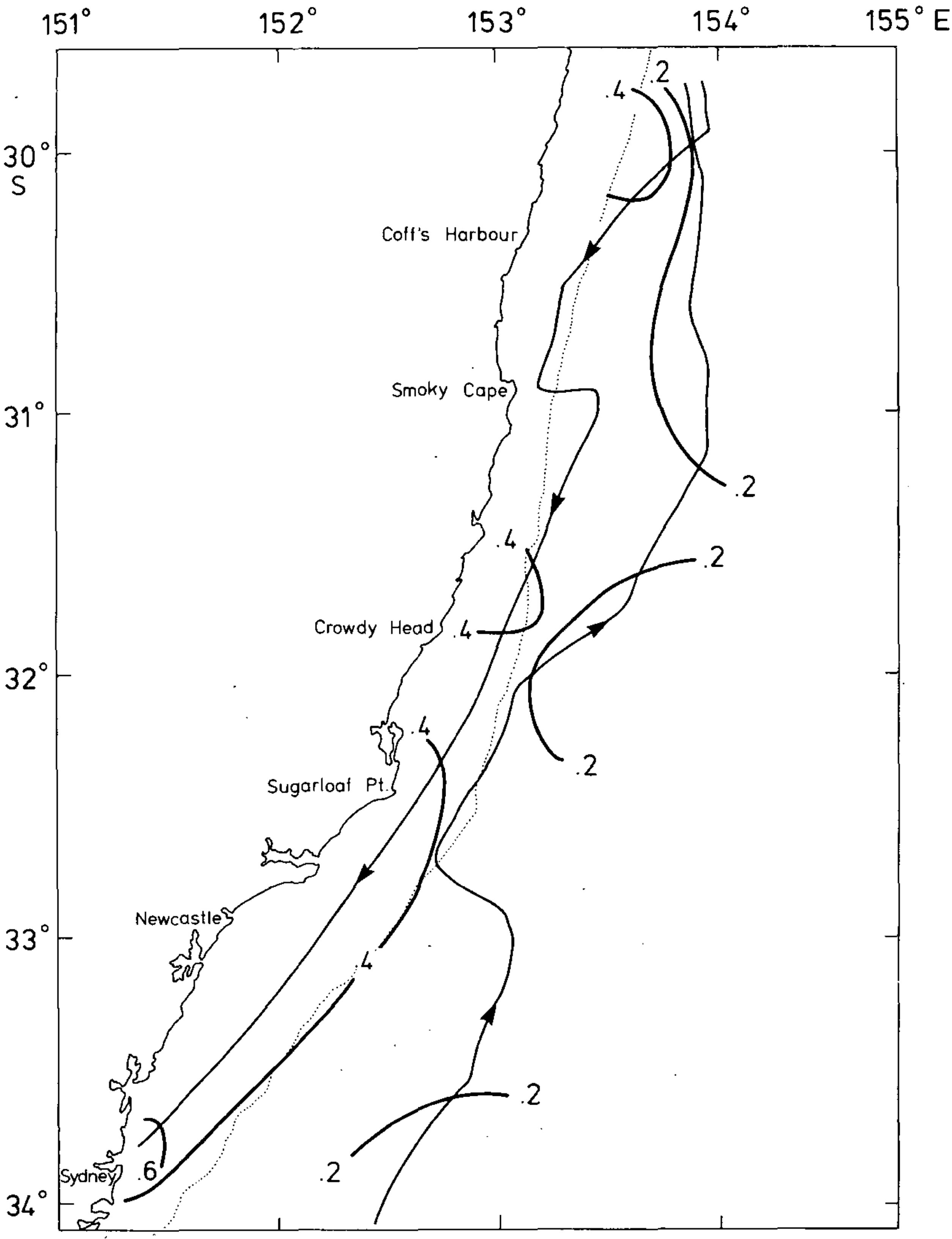

Fig. 16. Isopleths of surface $\hat{\phi}_p$ from on-stream data. Photosynthetic efficiency appeared to be higher inshore than offshore despite the low standing crop (see Fig. 15).

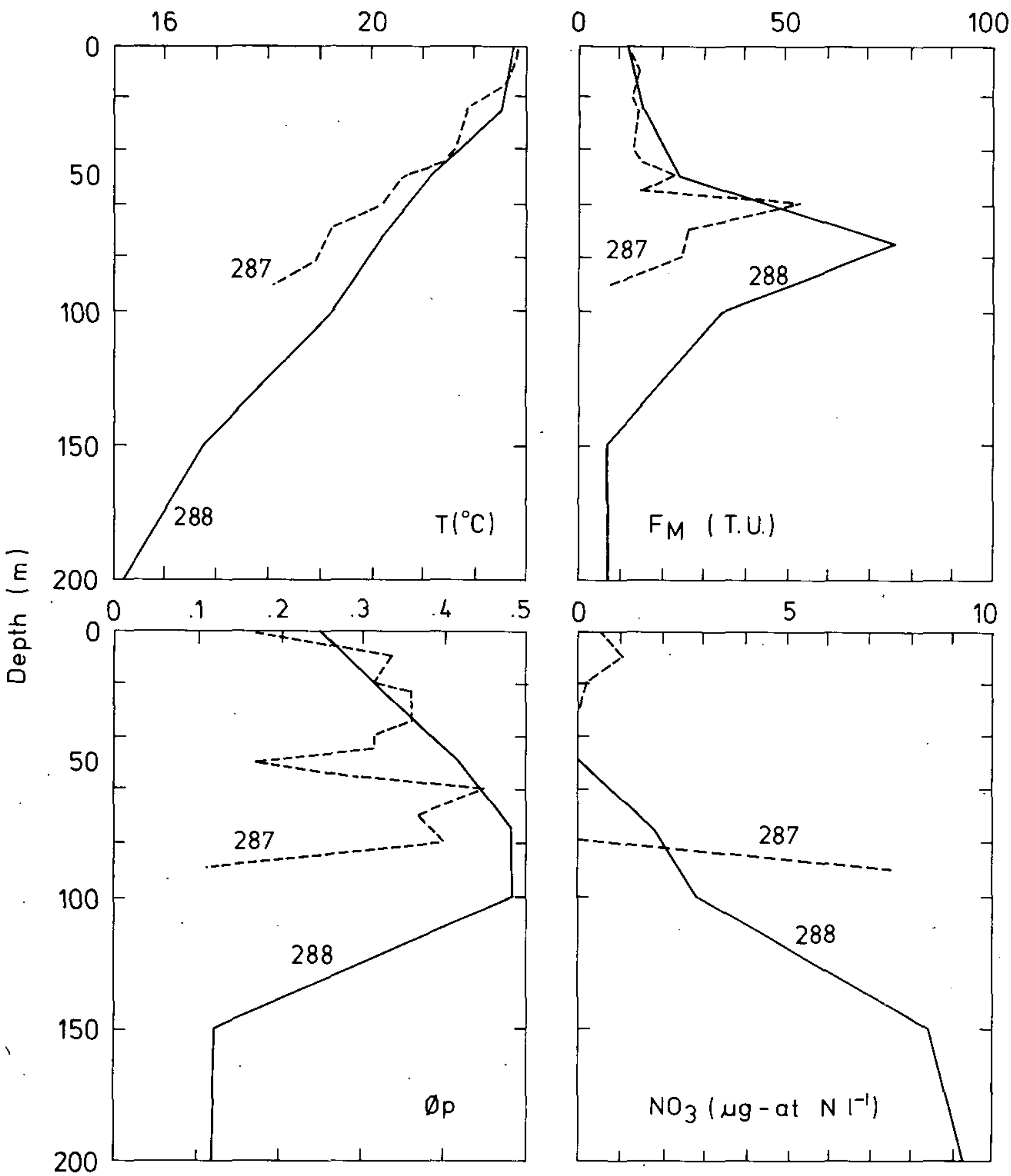

Fig. 17. Profiles of T, F_M, ϕ_p and NO_3 for stations 287 and 288.

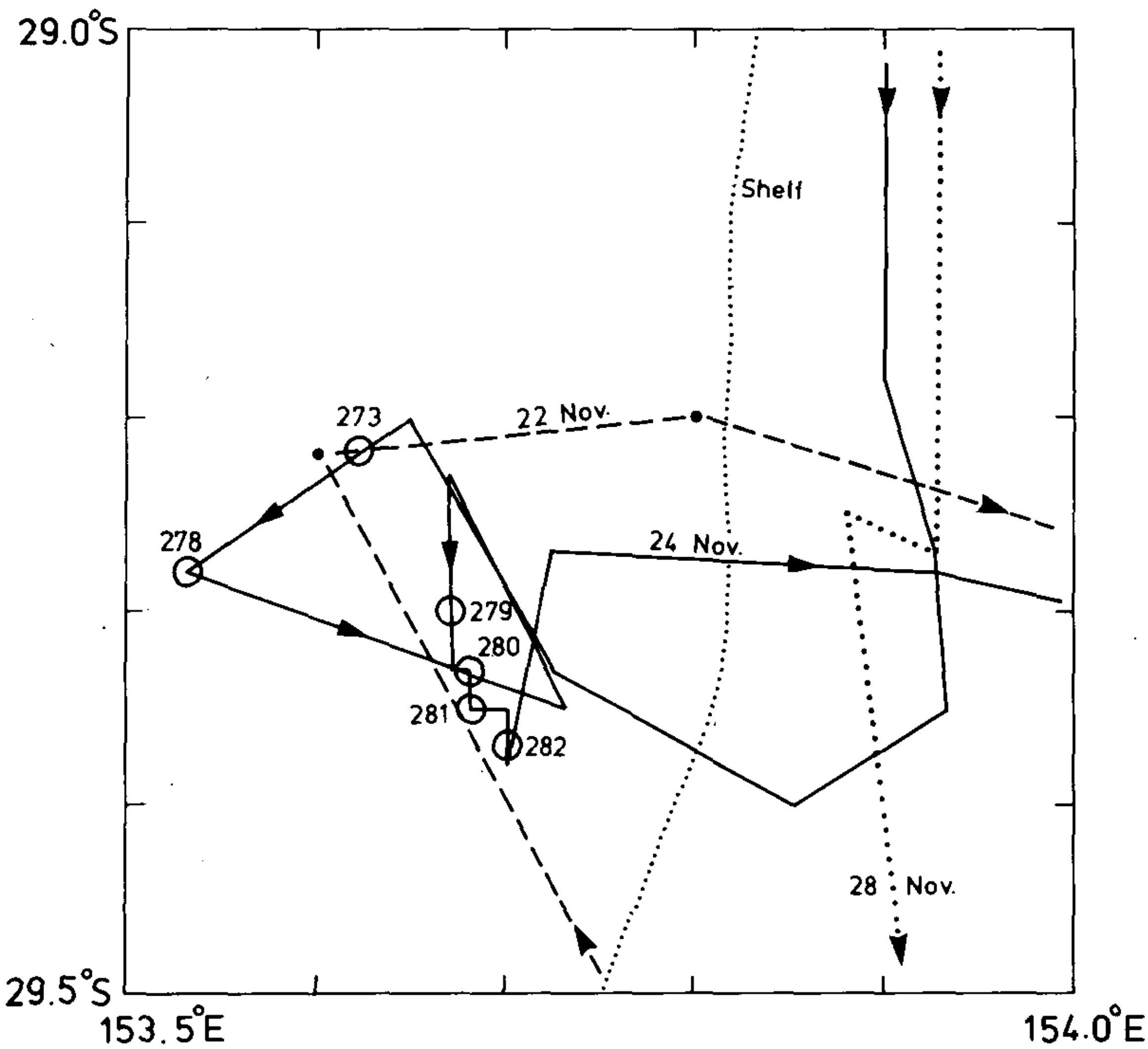

Fig. 18. Enlarged plot of "Sprightly" track off Evans Head in the area bounded by 29.0-29.5S and 153.5-154.0E. The first track on 22 November, which included profiling station 273, is shown as a dashed line. The second track, which included stations 278, 279, 280, 281 and 282, on 24 November is shown as a solid line. The third track on 28 November is shown as a dotted line.

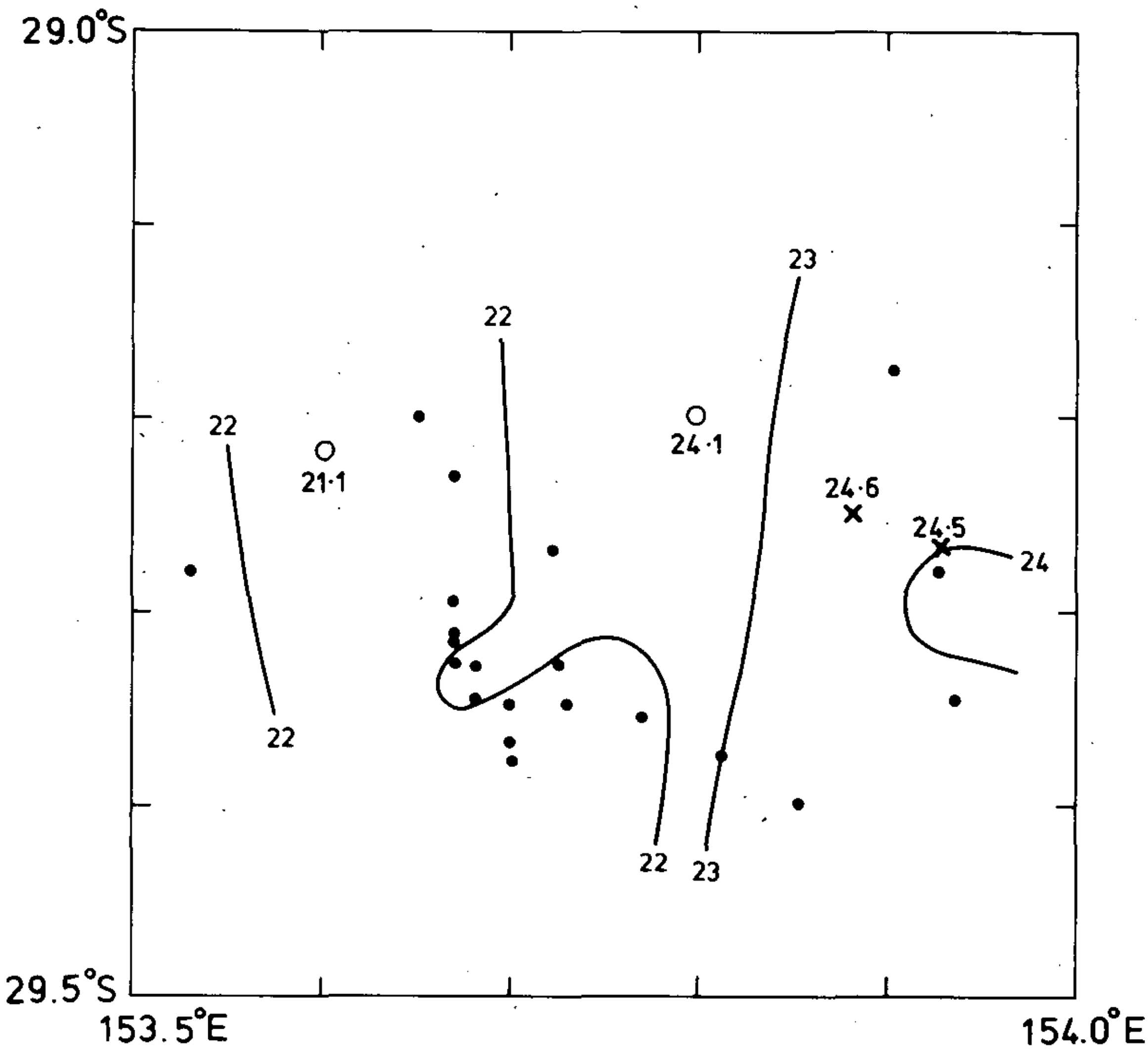

Fig. 19. Near surface isotherms for the Evans Head area based on XBT data. The circles (2) indicate 22 November observations, the crosses (2) indicate 28 November observations. The rest of the data points, indicated by dots, were obtained on 24 November. The cold water which was evident inshore on November 22 suggests upwelling.

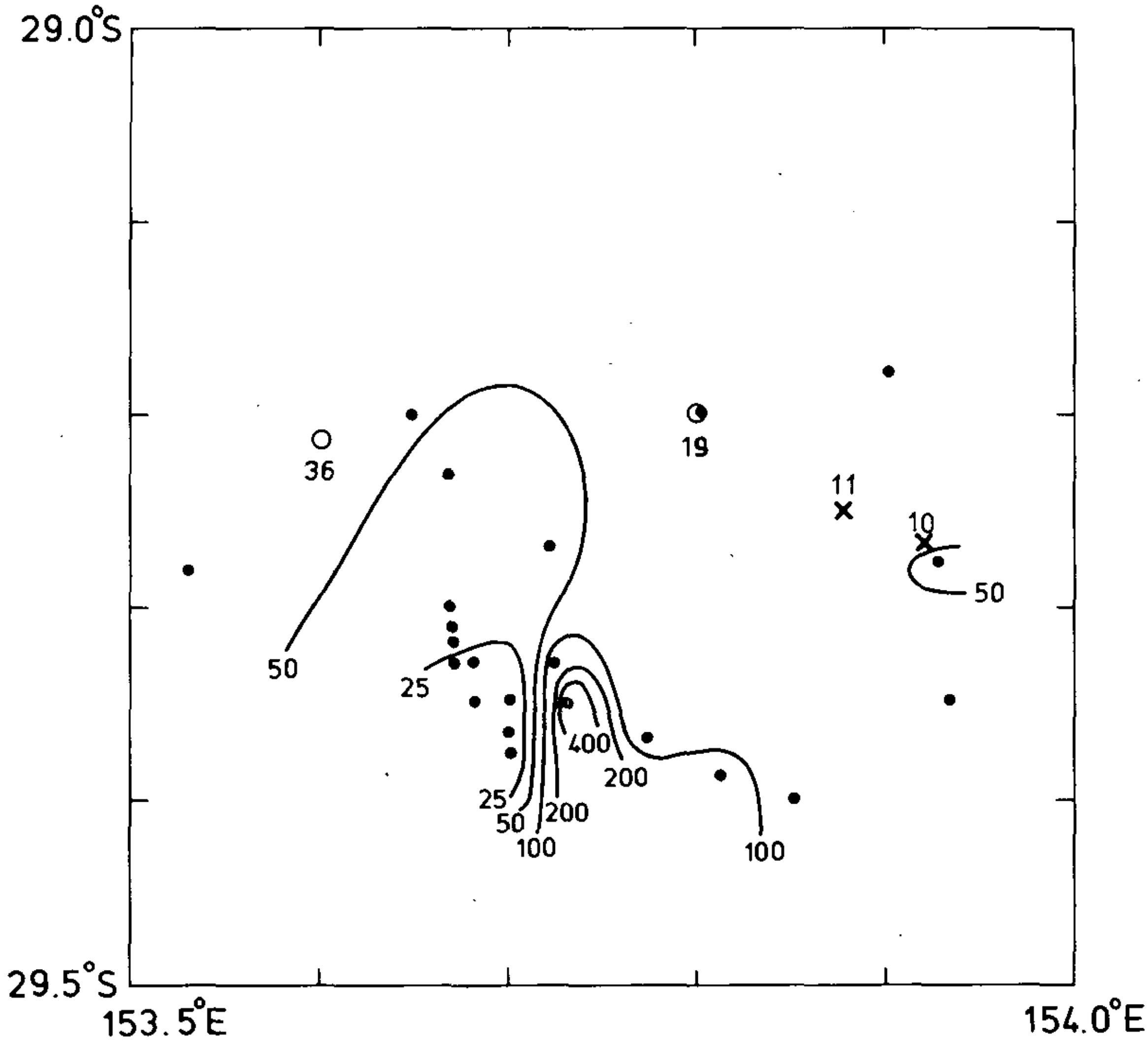

Fig. 20. Near surface F_M isopleths for the Evans Head upwelling area. The circles (2) indicate 22 November observations, the crosses (2) indicate 28 November observations. The rest of the data points, indicated by dots, were obtained on 24 November. Some very dense concentrations of phytoplankton occur within the area of apparently upwelled water.

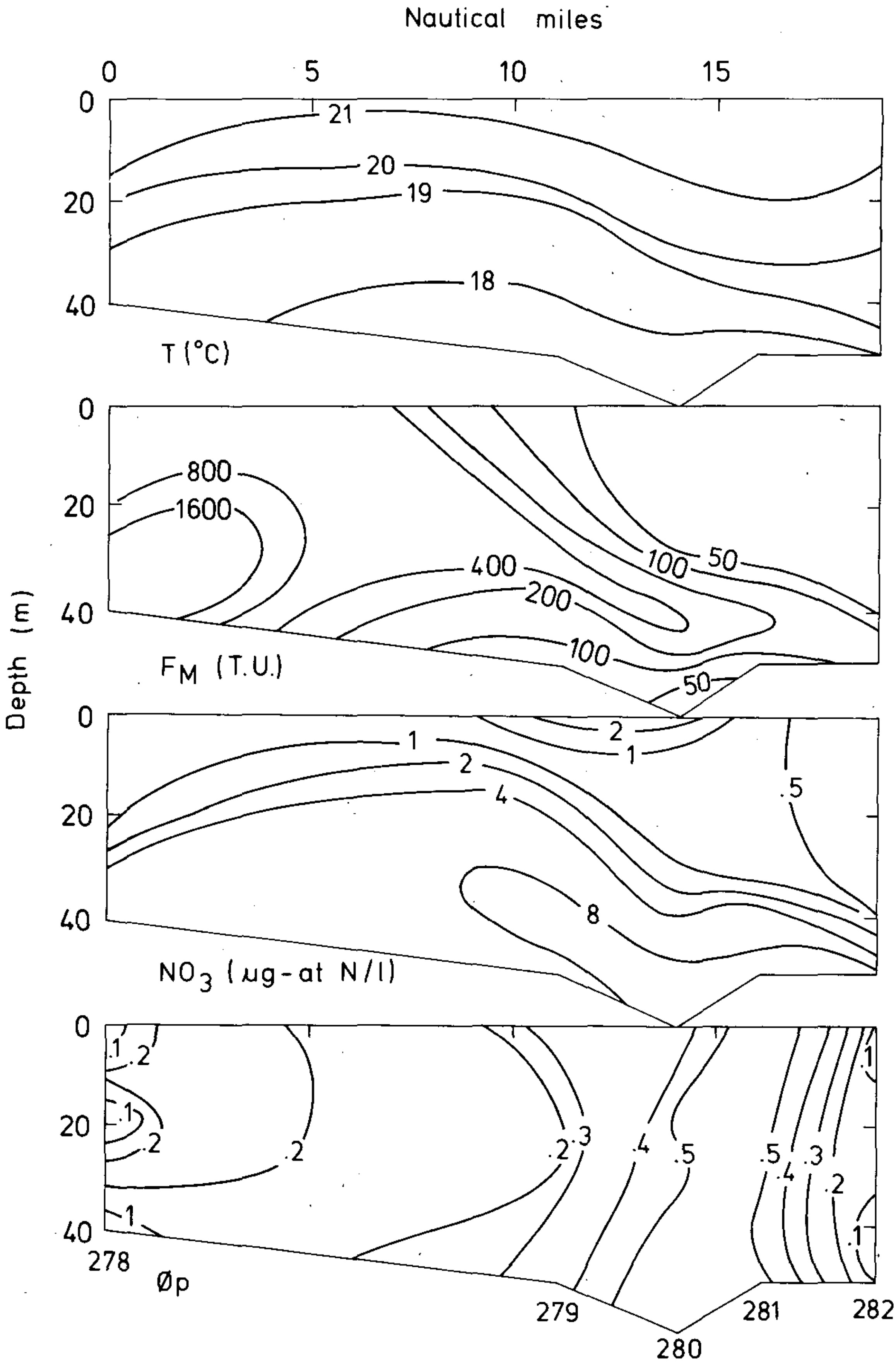

Fig. 21. Vertical sections of T, F_M, ϕ_p and NO_3, connecting stations 278, 279, 280, 281 and 282. Between stations 279 and 282 the ship was following a buoy drogued at 20 m depth, drifting southwards; 278 was close inshore (see Fig. 18). The doming of temperature and nitrate contours between 278 and 279 suggests upwelling as also does the high subsurface maximum in F_M.

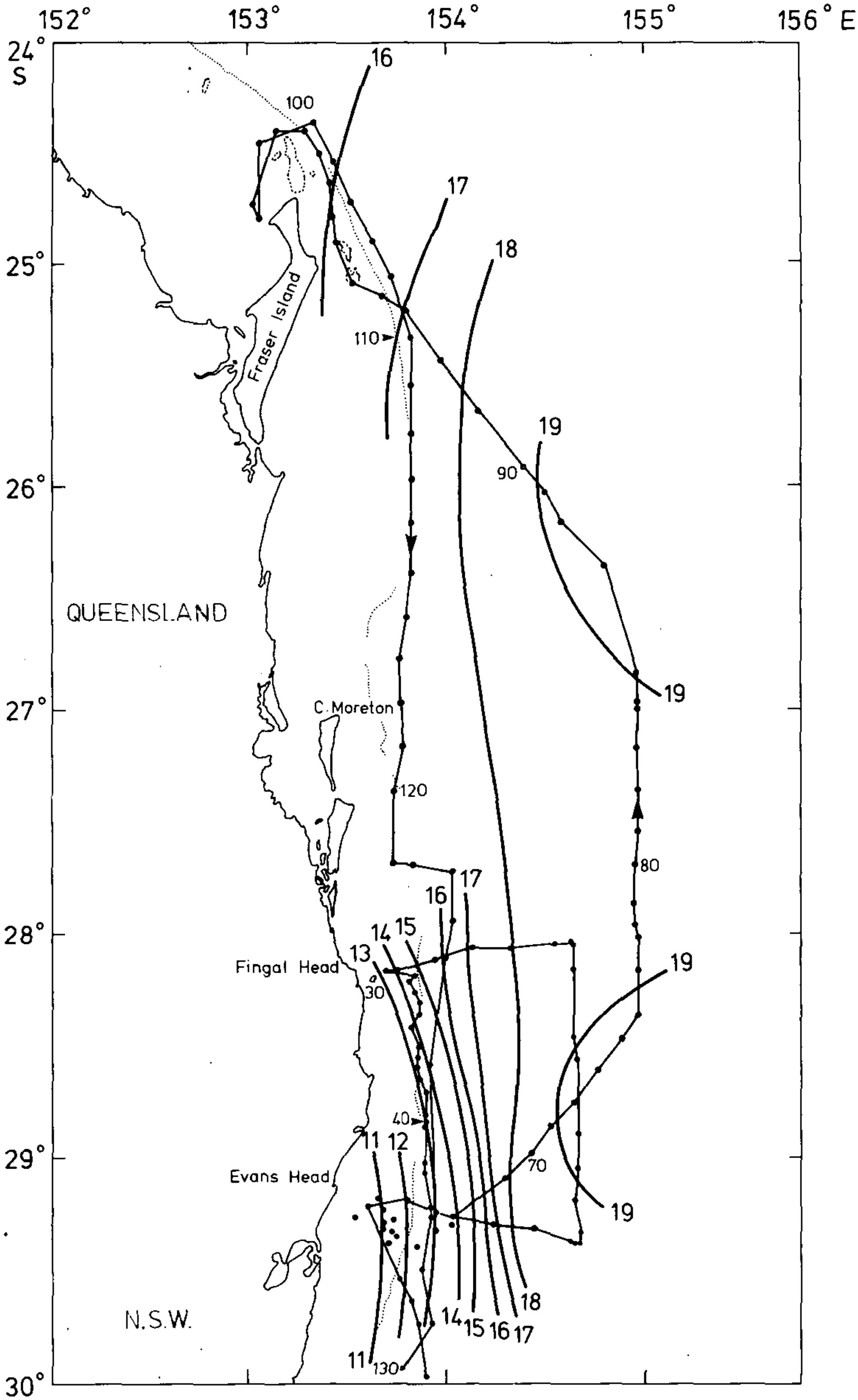

Fig. 22. T_{250} isotherms from XBT data for the area between 24° and 30°S (after Cresswell 1978). The outstanding feature is the deep penetration of warm water to depth off the shelf.

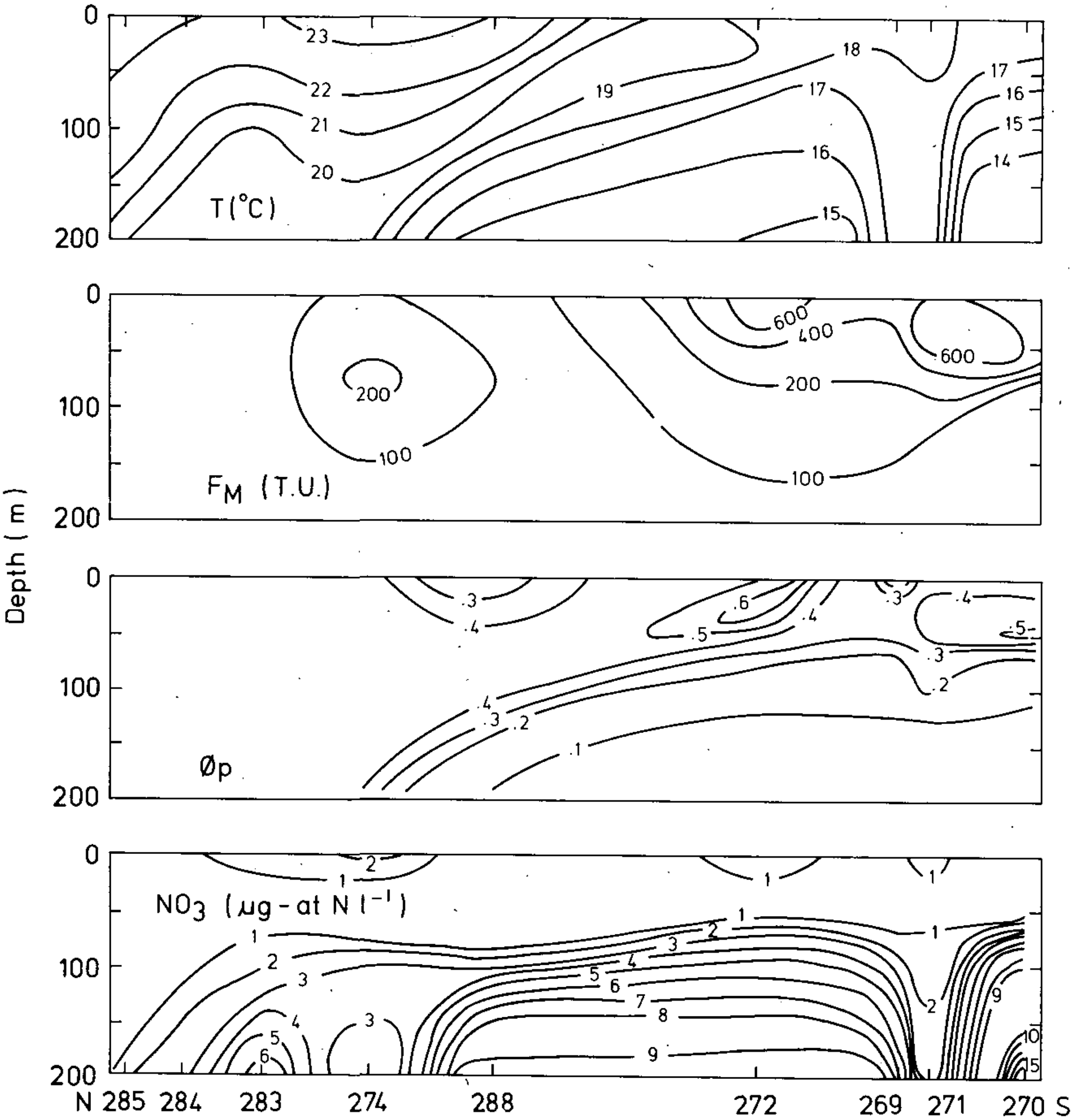

Fig. 23. N-S section through offshore stations from 26.0° to 37.5°S. This section shows eddy "F" as an anomaly in the otherwise orderly ascension of isotherms from deep in the north to shallow in the south, verifying the hypothesis that an eddy is a unit of subtropical water maintaining its integrity as it moves south. The F_M isopleths suggest that this body of water becomes productive in its southern location but would not have done if it had remained in the region of its genesis. The NO_3 isopleths suggest this production was possible through deep mixing in the southern location.

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