WSRL-TM-7/89

AR-005-869

DEEP STRUCTURE OF THE EAST AUSTRALIAN CURRENT AND TASMAN FRONT

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MARITIME SYSTEMS DIVISION
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Approved for Public Release.

APRIL 1989

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TECHNICAL MEMORANDUM
WSRL-TM-7/89

DEEP STRUCTURE OF THE EAST AUSTRALIAN CURRENT AND TASMAN FRONT

P.J. Mulhearn, L.J. Hamilton and B.D. Scott

SUMMARY (U)

In order to investigate the deep structure of the East Australian Current and the Tasman Front, surface to bottom Conductivity-Temperature-Depth (CTD) casts were obtained along various sections through them on eight different research cruises between October 1985 and December 1987. From this data set it was found that the depth to which these major oceanographic features extended was highly variable, lying between 2500 m and 4500 m. It was found that any flow below 1500 m in the Tasman Front was blocked from flowing eastward firstly by the Dampier Ridge and then by the Lord Howe Rise, and so flowed either north or south, depending on the orientation of the near-surface flow. On many sections, at abyssal depths, near-bottom bodies of water were found with temperatures approximately 0.05°C lower than their surroundings and with widths and depths of order 50 km and 600 m respectively. Their mode of generation is unknown.

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1. INTRODUCTION

The East Australian Current (EAC) and its warm-core eddies have been the subject of investigation for many years. These features are of some importance for antisubmarine warfare, because they cause major changes in sound-speed profiles (and hence in acoustic propagation) in the major focal area seaward of Newcastle, Sydney and Wollongong. These changes have proven to be difficult to forecast, but in recent years it has become possible to follow, in real-time, the major ocean-fronts and warm-core eddies which govern the sound-speed variations.

It was anticipated that, by discovering how deep the East Australian Current system penetrates and by investigating its interaction with major bathymetric features, it would be possible to develop simple rules for the motions of warm-core eddies, the East Australian Current and the Tasman Front, which is the EAC's eastward extension across the Tasman Sea.

Typically the (warm) EAC flows southward along the east Australian coast to approximately 31°S to 32°S, where it leaves the coast and sweeps around eastwards and then northwards to form a large warm-core meander. The current then continues to meander eastward as the Tasman Front. (See Mulhearn, 1987.) The large meanders, especially the one nearest to the coast, pinch off episodically to form warm-core eddies with a diameter of approximately 200 km.

The depth of the EAC has been examined statistically in Mulhearn (1983 and 1988) using archived hydrological data. It was found that, on average, the EAC system penetrates to at least 4000 m. Mulhearn et al (1986), in an investigation with seafloor moorings from December 1983 to April 1984, found that near-bottom currents could respond strongly to the passage of a warm-core eddy. Lilley et al (1986) and Mulhearn et al (1988) have shown that the depth structure of this same eddy was relatively simple, with time variations in the near-surface, barotropic (ie depth-averaged) and near-bottom currents being highly correlated and flowing in the same direction.

To gain a better understanding of the deep structure of the East Australian Current and Tasman Front System and its interaction with bathymetry, it was decided to carry out a number of cruises on which temperature and salinity sections would be obtained over the full ocean depth using CTD (Conductivity-Temperature-Depth) casts. This report presents the results of that measurement program.

In Section 2 details on the relevant instrumentation are presented, and in Section 3 results from the eight oceanographic cruises are discussed. This is followed by a short discussion of results from earlier cruises using Nansen casts, and in Section 5 general conclusions are drawn.

2. INSTRUMENTATION AND DATA PROCESSING

2.1 The CTD and salinity estimates

The data were obtained with a Plessey model 9041 CTD, with data rate 1.66 Hz, conductivity and temperature resolutions of 0.005 mmho/cm and 0.005°C, and depth (pressure) resolution of 2.4 dbar (1 dbar ≅ 1 m depth of water). Conductivity and temperature were recorded to 0.01 units, and depth to 1 m. Lowering rate below 300 m was 50 m/min (equivalent to samples being spaced at 0.5 m intervals). Lowering rate above 300 m was usually 30 m/min. Calibrations were determined by comparison with samples taken by Niskin bottles mounted in a rosette sampler. This was not available for all cruises. Depth accuracy is 6 dbar, temperature accuracy is 0.015°C, and conductivity accuracy is 0.02 mmho/cm or better at intermediate depths, worsening towards the surface to = ± 0.03 mmho/cm or higher (Hamilton, 1986). The temperature sensor is a platinum wound resistor with highly linear output; the conductivity sensor an inductive type; and the pressure sensor a strain gauge. Data for downcasts were pre-smoothed using a two point centred running average, recursively filtered to match temperature and conductivity time constants (eg Millard, 1982) (though this had little effect on salinity calculations because of the low data rate), and then averaged over 10 m intervals for calculation of derived parameters. As a CTD wire is paid out from a heaving ship the CTD's depth sometimes decreases and does not always continuously increase. In our analysis only monotonically increasing pressure values were used. The calibrations for the temperature, and for the inductive conductivity sensor, are simple linear equations, nominally with fixed slopes and intercepts. However the conductivity sensor was often subject to shifts in the intercept term of the linear calibration from one station to the next on some cruises, so that precise absolute salinity calibrations could not always be obtained. Even on cruises with the same conductivity calibration for all stations, the recorded resolutions of 0.01 units for conductivity and temperature do not allow salinity to be calculated with the degree of accuracy necessary to resolve the small salinity differences encountered at abyssal depths. However salinity data, which were useful for the purposes of this report, were obtained over much of the water column.

On two cruises when a rosette sampler was not available with the CTD (cruises RANRL 1/87 and MSD 2/87), Nansen bottles were strung on the CTD wire to obtain an indirect salinity calibration. The regression relations between temperature and salinity (T-S curves) showed that the T-S curves were tight (ie highly correlated) for temperatures of 2.5 to 19.5°C, so that good CTD conductivity calibration equations were obtained. The standard errors of estimate for salinity calculated from the regression equations were 0.02 psu (practical salinity unit) for both cruises. (1 psu is very nearly one part per thousand (see eg Lewis (1980).)

2.2 Sigma-t

Sigma-t, σ_t, is the density of the water, ρ, minus 1000 kg m^{-3} calculated from the measured temperature and salinity, as if the water were at atmospheric pressure ie

$$\sigma_t = (\rho\ (S,T,\ Patm) - 1000)\ \text{kg m}^{-3}. \tag{1}$$

σ_t contours are only presented for one cruise, 12/84, in figure 4. From these it can be seen that in the Tasman Sea σ_t contours do not provide any additional information to that provided by temperature and salinity contours, at least for the purposes of this report. Given the previously discussed accuracies in temperature and salinity, σ_t accuracy varied from ± 0.005 kg m^{-3} at 25°C to ± 0.002 kg m^{-3} at 2°C.

2.3 Geostrophic currents

As shown in standard oceanographic texts (eg Pond and Pickard, 1983), from the geostrophic balance and the hydrostatic equation it is possible to show that the difference in geostrophic current between two pressure levels P_1 and P_2 is given by

$$V_1 - V_2 = \left[\int_{P_2}^{P_1} \delta_B \, dp - \int_{P_2}^{P_1} \delta_A \, dp \right] / (2L\,\Omega \sin \phi) \qquad (2)$$

where δ_B and δ_A are the specific volume anomalies at stations B and A respectively, which are a distance L apart. $(V_1 - V_2)$ is perpendicular to the line joining A and B,

Ω = angular speed of rotation of the earth about its axis,
$\varnothing$ = latitude,
δ_B = $1/\rho\,(S,T,p)_B - 1/\rho\,(35, 0, p)$, and
δ_A = $1/\rho\,(S,T,p)_A - 1/\rho\,(35, 0, p)$.

δ's rather than ρ's are used in oceanographic calculations for the sake of convenience.

In this report P_1 is usually chosen as 2000 dbar, simply because it is a commonly used value. It appears to have no physical significance. Due to the averaging nature of the $(V_1 - V_2)$ calculations both the salinity and temperature accuracies are adequate to obtain velocity estimates from the sea-surface down to abyssal depths. The accuracy of such calculations is hard to estimate. No geostrophic currents were calculated when salinities were not obtained.

3. RESULTS FROM INDIVIDUAL CRUISES

The eight research cruises to be considered are listed in Table 1. Five of these obtained measurements for the deep structure over the Lord Howe Rise and/or the Dampier Ridge. The cruises are discussed below in turn, in terms of the structures observed over the whole ocean depth and those found at abyssal depths.

3.1 RANRL Cruise 23/85 (8 to 18 October 1985)

This cruise followed a zig-zag track back and forth across the East Australian Current between Jervis Bay and Brisbane (figure 1). Only temperature sections are shown, because the conductivity sensor on the VCTOD was poorly calibrated. The sloping isotherms in figures 2(a), (b) and (c) show the effects of the EAC penetrating to approximately 4000 m. Figures 2(a) and (b) show a near bottom cold feature at stations 12 and 8 on the western edge of the Tasman Sea, but this feature is not so apparent at station 4. The north-south section in figure 2(d) shows a deep warm-core feature, at station 9, penetrating to 4500 m, and a relatively cold patch at station 15, east of Brisbane, centred at 3750 m.

3.2 RANRL Cruise 12/84 (4 to 14 November 1985)

This cruise, with its closer station spacings was designed to investigate the deep structure of the EAC over the Tasman Abyssal Plain from 34°S to 38°S. The track chart is shown in figure 3. Temperature, salinity and σ_t are shown for four sections in figures 4(a) to (l).

TABLE 1. LIST OF CRUISES

Cruise No.	Dates	Region covered
RANRL 23/85	8 to 18 October 1985	Tasman Sea, west of 156°E; Brisbane to Jervis Bay (SURVEY).
RANRL 12/84	4 to 14 November 1985	Tasman Sea, west of 154°30' E; Sydney to Cape Howe (SURVEY).
*RANRL 1/86	28 January to 6 February 1986 18 to 25 March 1986	East-northeast from Sydney to 165°E; north-east of Sydney from 161°E; ie both out to Lord Howe Rise (SECTIONS).
RANRL 17/86	18 August to 10 September 1986	South-east from Sydney to 158°E (SECTIONS).
*RANRL 6/86	14 to 20 September 1986	Off NSW to 153°50' E along 30°43' S, and along 28°04' S, west of 160°E (SECTIONS).
*RANRL 1/87	25 May to 5 June 1987	Over Lord Howe Rise 30° to 35°S, 154° to 166°E (SURVEY).
*RANRL 12/87	29 July to 2 August 1987 16 to 21 September 1987	East-northeast from Sydney to 164°21'E; North-east of Sydney from 166°33'E (SECTIONS).
*MSD 2/87	9 November to 3 December 1987	Over Lord Howe Rise 28°30' to 32°S, 155° to 161°E (SURVEYS).

* These cruises included coverage of the Lord Howe Rise/Dampier Ridge.

On the outward leg from Sydney to station 7, at the centre of a meander of the EAC, the salinity and σ_t contours in figures 4(b) and (c) show this structure persists to approximately 2000 m, while the temperature contours in figure 4 (a) suggest it reaches to approximately 3000 m . On the shorter section from stations 21 to 25 (figures 4(j) to (l)) on the return leg back into Sydney, the contours show the meander reaching down to only approximately 2000 m. The small, relatively cold bottom water body at 153°E on the outward leg had shifted slightly by the time of the return leg and bottom temperatures were less cold.

The transect off Jervis Bay was through a cold feature and then out to the edge of the EAC meander. Temperature, salinity and σ_t sections are shown in figures 4(d) to (f) respectively. EAC structure can be seen to persist to 2000 m in figures 4(e) and (f) and to 3000 m in figure 4(d). A relatively cold patch of bottom water can be seen, on figure 4(d), near the foot of the continental slope.

The most southern transect, off Cape Howe, crossed a small warm feature near the coast and entered a cold feature further east. Salinity and σ_t sections (figures 4(h) and (i) respectively) show the near surface features persisting only to approximately 1500 m while the temperature section (figure 4(g)) suggests a depth of 2000 m. Cold, near-bottom patches are found near the foot of the continental slope and over the abyssal plain near 152°E.

Geostrophic current profiles are shown between several pairs of stations in figures 5(a) to (c). Appreciable current shear below 2000 m, can only be seen between stations 1 and 2, which span the EAC off Sydney. This suggests the current extends to a deeper level than 2000 m between these stations. Elsewhere 2000 m may be a satisfactory level of no motion for the time of this oceanographic survey, if one assumes that zero shear implies zero velocity.

3.3 RANRL Cruise 1/86 (outward leg: 28 January to 6 February 1986; inward leg: 18 to 25 March 1986)

Deep CTD sections were taken between Sydney and the eastern flank of the Lord Howe Rise on this cruise which was the third of the SEAMAP series (Hamilton and Boyle, 1989a). The cruise tracks and station positions are shown on figure 6. The XBT section eastward from Sydney on the outgoing leg is shown in figure 7(a) and that for the incoming leg, from the north-east is in figure 7(b). The edge of the EAC is encountered between CTD stations 3 and 4 on the outgoing leg, and CTD station 35 is in the centre of a meander or eddy on the incoming leg. The CTD temperature and salinity contours for the outgoing leg on figures 8(a) and (b) suggest the EAC persists to 2500 to 3000 m. On the incoming leg (figures 9(a) and (b)) the cold feature near 156°E can be observed from the surface to nearly 4000 m. On this cruise the conductivity sensor was not calibrated with sufficient accuracy to distinguish the fine salinity variations present below 2500 m.

Geostrophic velocity profiles across the EAC, on the return leg, showed significant shear down to 4600 m between stations 32 and 33 and to approximately 3200 m between stations 34 and 35. (See figure 10.) (However salinity is poorly calibrated for these stations and the velocity profiles should be viewed with caution.)

3.4 RANRL Cruise 17/86 (18 August to 10 September 1986)

This was SEAMAP Cruise No 4 (See Hamilton and Boyle, 1989b). The ship's track is shown on figure 6 and the temperature section from the CTD shown in figure 11. Infra-red satellite imagery (not presented here) showed that the EAC was present off Sydney. It can be seen in figure 11 west of 155°E and the EAC's structure persists to at least 2000 m. The westward dipping isotherms between 2000 m and 4000 m may also be associated with the EAC. Relatively cold patches of bottom water can be seen near 156°E and 158°E. (The conductivity sensor was inoperative on this cruise).

3.5 RANRL Cruise 6/86 (14 to 20 September 1986)

On this cruise one short deep section was taken off the northern NSW coast at 30°45' S, and a long, deep section taken along 28°S, which retraced part of the route of USNS Eltanin Cruise 29 of 1967 (Warren 1973), (see figure 6). The shorter section (figure 12(a)) showed no clear deep structure and is included here only for completeness. The EAC was not crossed.

On the longer section (see the deep-XBT section on figure 12(b)) the mesoscale feature near 155°15' E, persisted to only 1000 m, but near 157°E the eastward dipping isotherms can be observed down to almost 3000 m (See figure 12(c)). The conductivity sensor only behaved satisfactorily between 156° and 160°E on the longer leg, and its calibration was insufficiently precise to detect the small variations in salinity below 2500 m, but eastward dipping isohalines are observed down to approximately 2500 m near 157°E in figure 12(d).

3.6 RANRL Cruise 1/87 (25 May to 5 June 1987)

This cruise, together with a pair of surveys with airborne expendable bathythermographs (AXBT's), investigated the Tasman Front as it crossed over the Lord Howe Rise. The ship's track and station positions are shown in figure 13.

The configuration of the Tasman Front is shown on figure 14 by contours of T250 (the temperature at 250 m depth) obtained from an AXBT survey two weeks before the cruise. The sea-surface temperature and T250 contours during the cruise are shown in figures 15 and 16. These were obtained from a combination of AXBT, ship and infra-red satellite data. A warm core ring was lying south-west of the study area with its centre near 34°30' S, 153°30' E and its north-eastern edge can be seen in the lower left-hand corner of these figures. The Tasman Front had an elongated meander with its axis running approximately from 32°S, 155°E to 34°S, 157°E. The front then looped northward over the Dampier Ridge to approximately 31°10' S, 157°40' E, then southeastward, and beyond 159°E headed approximately eastward over the Lord Howe Rise, becoming more diffuse.

The XBT section along the ship's track ,shown in figure 17, shows the warm meander from 156° to 157°30' E, the cold region over the Dampier Rise from 157°30' to 159°E and some less pronounced structures further east. The deep CTD temperature and salinity sections are shown in figures 18(a) and (b). The varying slopes of the isotherms west of 159°E show the features of the Tasman Front persisting almost to the sea floor, with a cold region over the Dampier Ridge and warmer features further west. Near-bottom waters in the Lord Howe Basin, between the Dampier Ridge and Lord Howe Rise, are unusually cold on the flank of the Lord Howe Rise. This phenomenon will be the subject of a short, separate paper. The salinity contours of figure 18(b) do not show much structure or correlation between near-surface and deeper levels, except for the general dipping of contours from east to west between 158°30' and 155°E, which can also be seen for temperatures in figure 18(a). Geostrophic velocity profiles between pairs of stations spanning the edges of the cold feature centred near 32°S, 152°30' E show significant current shear down to depths of 3000 m or more - figures 19(a) and (b).

From the bathymetry shown in figure 18(a) and the orientation of the Lord Howe Rise it is obvious that the flow at depths below approximately 1500 m cannot pass over the Rise and must turn either north or south. In this case the flow west of the Dampier Ridge, below 3000 m, most likely flows northwards, in the same direction as the surface flow, because there is no change in the direction of the isotherms' slope or in the sign of the geostrophic velocity gradient (figure 19(a)). Between the Dampier Ridge and the Lord Howe Rise the same holds true above 2000 m. Below that depth the velocity gradient changes sign and this may be associated with a topographically trapped flow within the Lord Howe Basin, which, as was said above, will be discussed in a separate publication.

Previous sections across the Lord Howe Rise were taken on cruises 1/86 and 6/86 (discussed earlier) but insufficient ancilliary data were obtained to infer the configuration of the Tasman Front on those occasions.

3.7 RANRL Cruise 12/87 (outward leg: 29 July to 2 August 1987; inward leg: 16 to 21 September 1987)

This was the sixth in the SEAMAP Series of cruises (See Hamilton and Boyle, 1989b) and covered a similar route to that of the summer cruise 1/86. Its track and station positions are shown in figure 20.

The XBT sections for the outward and inward legs from and to Sydney are shown in figures 21(a) and (b) respectively. On the outgoing leg a meander of the EAC is crossed near 155°E and a meander of the Tasman Front, or another eddy, crossed near 159°E. On the incoming leg the meanders or eddies are centred near 154° and 157°E.

Only CTD temperature sections to 2000 m depth were obtained on this cruise (figures 22(a) and (b)) and they show the EAC/Tasman Front structure persisting to at least that depth.

3.8 MSD Cruise 2/87 (leg 1: 9 to 19 November 1987; leg 2: 24 November to 3 December 1987)

This cruise, like 1/87, investigated the Tasman Front near the Dampier Ridge and Lord Howe Rise. The cruise track for leg 1 with station positions, is shown on figure 23, and the sea-surface temperature and T_{250} contours are shown on figures 24 and 25. As can be seen, the cruise investigated a northward loop of the Tasman Front whose centre line was approximately along 157°30' E, once again near the longitude of the Dampier Ridge. The XBT sections show this cool feature centred near station 3 (figure 26(a)) and between waypoints G and H (figure 26(b)). The CTD temperature section (figure 27(a)) shows the influence of the meander reaching to the sea-floor. The salinity values were insufficiently accurate to be contoured below 2500 m, but figure 27(b) shows that the meander influenced salinities to at least that level.

A cross-section, from leg 1, of geostrophic current, relative to 1000 dbar, is presented in figure 28. The measurements at stations 1 to 7 were obtained over a two day period. The reference level chosen is quite arbitrary. The point of interest is the significant current shears, down to approximately 3000 dbar for the average profiles between station pairs 2 and 3, and 3 and 4, ie across the edges of the northward loop in the Tasman Front. There is also significant shear to approximately 1600 m between stations 6 and 7, which span the edge of the Tasman Front as it loops northward again.

On leg 2 the meander was in a similar position. Cruise track, sea-surface temperature and T250 charts are presented in figures 29 to 31 and XBT sections in figures 32(a) and (b). The deep temperature and salinity sections on figure 33 use CTD data from leg 1 (stations 8 to 10) and Nansen cast data from leg 2 (stations 11 to 15). (The CTD system was faulty during leg 2 so Nansen bottles were used instead). Figure 32 shows the cold section between station 12 and 13 due to the northward loop in the Tasman Front. This colder section was slightly to the west of the Dampier Ridge on this leg. The effect of the meander can be seen to a depth of approximately 3000 m, and it may have gone deeper.

4. RESULTS FROM EARLIER CRUISES

Deep hydrology sections across the Pacific were obtained with Nansen casts on the Scorpio Expedition by USNS Eltanin along 28°S and 43°S (Warren, 1973). In the Tasman Sea at 43°S the influence of a near-surface perturbation persisted to approximately 2500 m, while at 28°S the influence of the East Australian Current could be seen close to the coast down to approximately 3000 m.

In 1981, staff of the CSIRO Division of Fisheries and Oceanography executed a deep hydrology section, with Niskin bottles, along 33°45' S, across an eddy or meander of the East Australian Current (Thompson, 1981). The temperature and salinity sections presented here in figures 34(a) and (b) were drawn using data from the CSIRO data bank. Salinity values were very difficult to contour below 3000 m, but the temperature contours show the EAC's influence extending down to 3500 to 4000 m. There is also a cool, low salinity patch near 4000 m, adjacent to the continental slope. (Near 155°E some anomalously high near-bottom salinity values were obtained, but it is not known if this is a real effect or a pair of measurement errors).

A deep hydrology section obtained in December 1983, is reported in Mulhearn (1985). This trans-Tasman section did not cross the East Australian Current, or one of its eddies, but did find patches of relatively cool near-bottom water at the foot of the NSW continental slope near 36°S and further east near 37°S, 155°E.

5. DISCUSSION AND CONCLUSIONS

5.1 The depth of the East Australian Current and its Eddies

This collection of CTD sections shows that the depth of the East Australian Current is, like everything else about it, highly variable, ranging between 2500 m and 4500 m. The earlier statistical results of Mulhearn (1988) showed high correlations between deep and near-surface perturbations. These two findings together suggest that, while the EAC may not always penetrate very far below 2500 m, when it does so it is a strong influence. This is supported by the near-bottom current measurements of Mulhearn et al (1986) which showed that on one side of an eddy, as it passed, the bottom currents remained weak and unaffected, while on the other side the near-bottom currents were significantly affected by the eddy.

5.2 The influence of the Dampier Ridge and Lord Howe Rise

The positions of these important bathymetric features are shown in figure 6. Mulhearn (1987) showed on the basis of satellite infra-red imagery that, on average, the Tasman Front looped northward near 158°E (the longitude of the Dampier Ridge), back southward near 159°30' E and then tended north-eastward over the Lord Howe Rise. Out of the four cruises which crossed the Lord Howe Rise (1/86, 1/87, 12/87, 2/87), two encountered this "typical" condition ie 1/87 and 2/87. The relevant temperature sections are on figures 8(a), 9(a), 18(a), 22(a) and (b), 27(a) and 33(a).

On the western flank of the Dampier Ridge the isotherm slope did not change sign with depth between the surface and approximately 4000 m in all cases, except for leg 1 of Cruise 1/86 where the isotherm slope changed slope between 2000 and 4000 m. (Compare figures 8(a) and 9(a)). As previous work has shown that the flow in an EAC eddy is in the same direction throughout the water column (Mulhearn et al (1986), Mulhearn et al (1988)), ie a level of no motion does not occur within the water column, this suggests that in all cases,the flow adjacent to the west flank of the Dampier Ridge is in the same direction as the near-surface flow. In the case of leg 1 of Cruise 1/86 the Tasman Front may only be approximately 2000 m deep with the deeper flow being independent of it.

On the western flank of the Lord Howe Rise (near 159°E) the isotherm slope has the same sign between the surface and 2000 m to 3000 m, eg isotherms slope upwards to the east in figures 8(a), 9(a), 22(a) and 33(a), but downwards in figures 18(a), and 27(a). Below these levels the isotherm slope often changes sign. (See figures 8(a), 9(a), 18(a) and 27(a).)

The thermal-wind equation (See eg Pond and Pickard, 1983) may be expressed as:

$$\rho_o f \, \partial V/\partial z = -g \, \partial \rho/\partial x,$$

where ρ_o is an average density,

- f is the Coriolis parameter,
- V is the horizontal geostrophic velocity component perpendicular to the x-direction,
- g is acceleration due to gravity,
- z is the vertical direction, and
- x is a horizontal direction (taken herein to be parallel to a CTD section).

In the Tasman Sea temperature, T, and density, ρ, are highly correlated, so that when $\partial T/\partial x$ changes sign with depth so in general does $\partial \rho/\partial x$ and hence so does $\partial V/\partial z$. From the sea-surface V and $\partial V/\partial z$ decrease with depth (see for example figure 19(a)) but if $\partial V/\partial z$ goes through zero and changes sign, then V must start to increase with depth, as for example in the velocity profile of figure 19(b), which was calculated from the data displayed in figures 18(a) and (b). It seems that west of the Dampier

Ridge, V and $\partial V/\partial z$ generally decrease monotonically with depth (figures 5, 10, 19(a)) but on the western flank of the Lord Howe Rise V and $\partial V/\partial z$ increase with depth below 2000 to 3000 m. The Lord Howe Basin forms a practically enclosed basin between the Dampier Ridge and the Lord Howe Rise (see figure 6) and the Ridge crest is at 3000 m to 2500 m depth. Hence this effect of bottom intensified flow is a phenomenon occuring within and above the Lord Howe Basin.

Only the flow shallower than 2500 m to 3000 m can pass over the Dampier Ridge and only flow shallower than 1500 m can pass over the Lord Howe Rise. The deeper flows associated with the East Australian Current and Tasman Front must be deflected north or south by the ridges. The observed weakening of the Tasman Front, over the Lord Howe Rise (see figure 16 herein, and Mulhearn, 1987) is doubtless a result of this blocking of the flow.

5.3 The relatively cold near-bottom water bodies

On many of the cruises small bodies of water were found near the sea-floor with temperatures lower than their surroundings. On average, the approximate height and width of these water bodies were 600 m and 50 km respectively, and their minimum temperature was, on average, approximately 0.05^{o}C less than their surroundings. Over their 600 m height the geostrophic velocity difference was of order 2 or 3 cm s^{-1}. There was no measurable salinity difference between the water bodies and their surroundings, ie any difference was less than 0.02 psu. The positions of the cool water bodies and their minimum temperatures are shown on figure 35. They were often (9 out of 15 times) encountered near the foot of the NSW continental slope, but were not always present there. This suggests that there is an intermittent cold bottom current flowing there, as surmised in Mulhearn et al (1985). The isolated cold water bodies found elsewhere may have been advected eastward from the foot of the slope by East Australian Current eddies or may have migrated northwards as isolated lenses from Antarctic waters. A north-westward bottom current was inferred by Jenkins (1984) to flow across the southern Tasman on the basis of seismic stratigraphic data. This is indicated on figure 35, but the distribution of the cold bodies of water does not support its existence at the present day. It may however be present as an intermittent feature.

5.4 Sea mounts

Influences attributable to the seamounts in the Tasman Sea were not discernible in this data set. No doubt there are effects occuring on length scales similar to the diameters of the seamounts but these would not be detectable with the station spacing used in this investigation.

6. ACKNOWLEDGEMENTS

This work was facilitated by the efforts of the officers and men of HMAS Cook and the sea-going personnel of the Maritime Systems Division and the then RAN Research Laboratory. The bulk of the programs used for processing the CTD data were provided by Dr Neil White of CSIRO Marine Laboratories, Hobart. The data presented in figure 34 were obtained from the CSIRO Division of Oceanography's data bank. They were obtained on a cruise led by Dr R.O.R.Y. Thompson.

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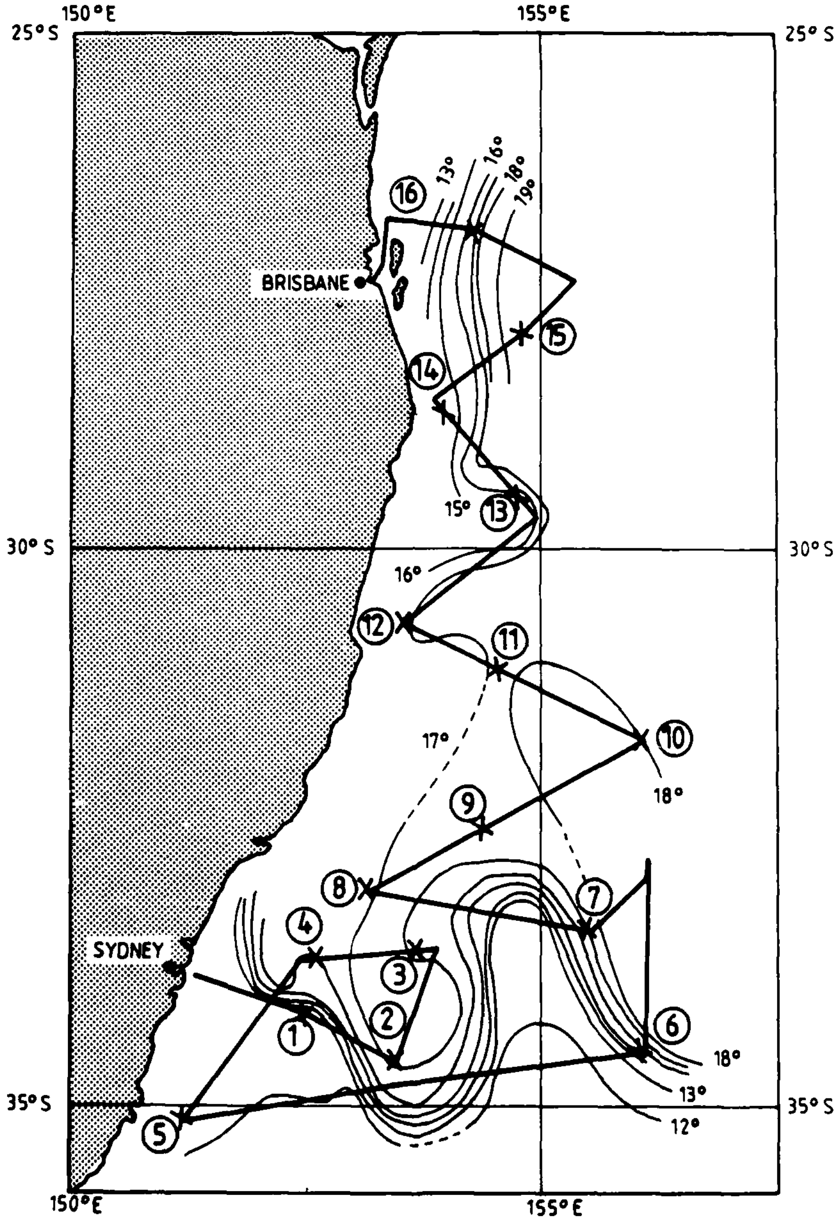

Figure 1. Cruise track and T_{250} contours for RANRL Cruise 23/85, 8 to 18 October 1985. (Station numbers are circled). (T_{250} = temperature at a depth of 250 m)

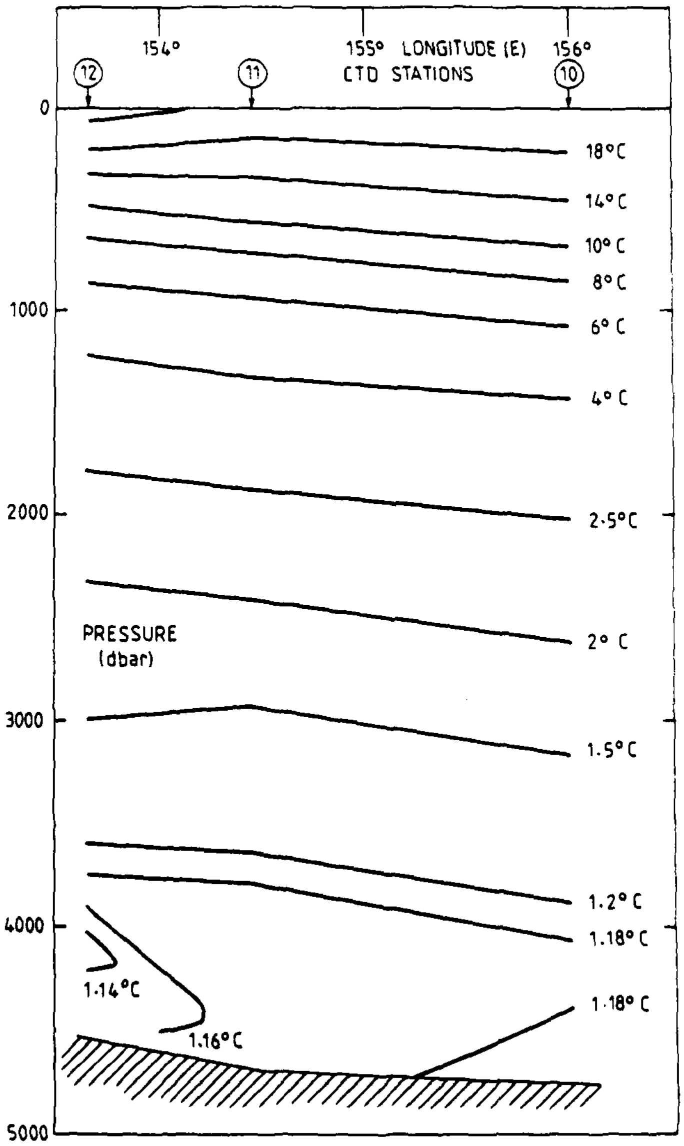

Figure 2(a). Temperature section off northern NSW, RANRL Cruise 23/85

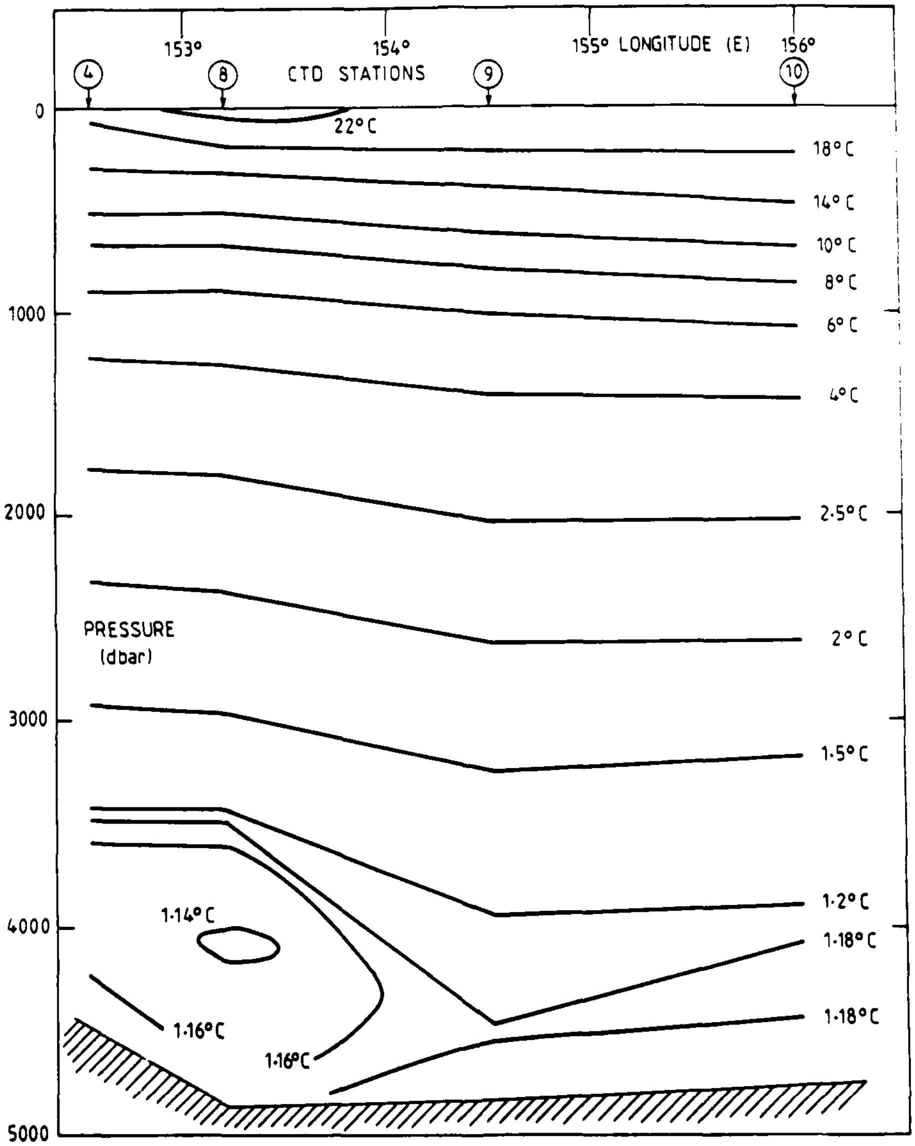

Figure 2(b). Temperature section, north-east from Sydney, RANRL Cruise 23/85

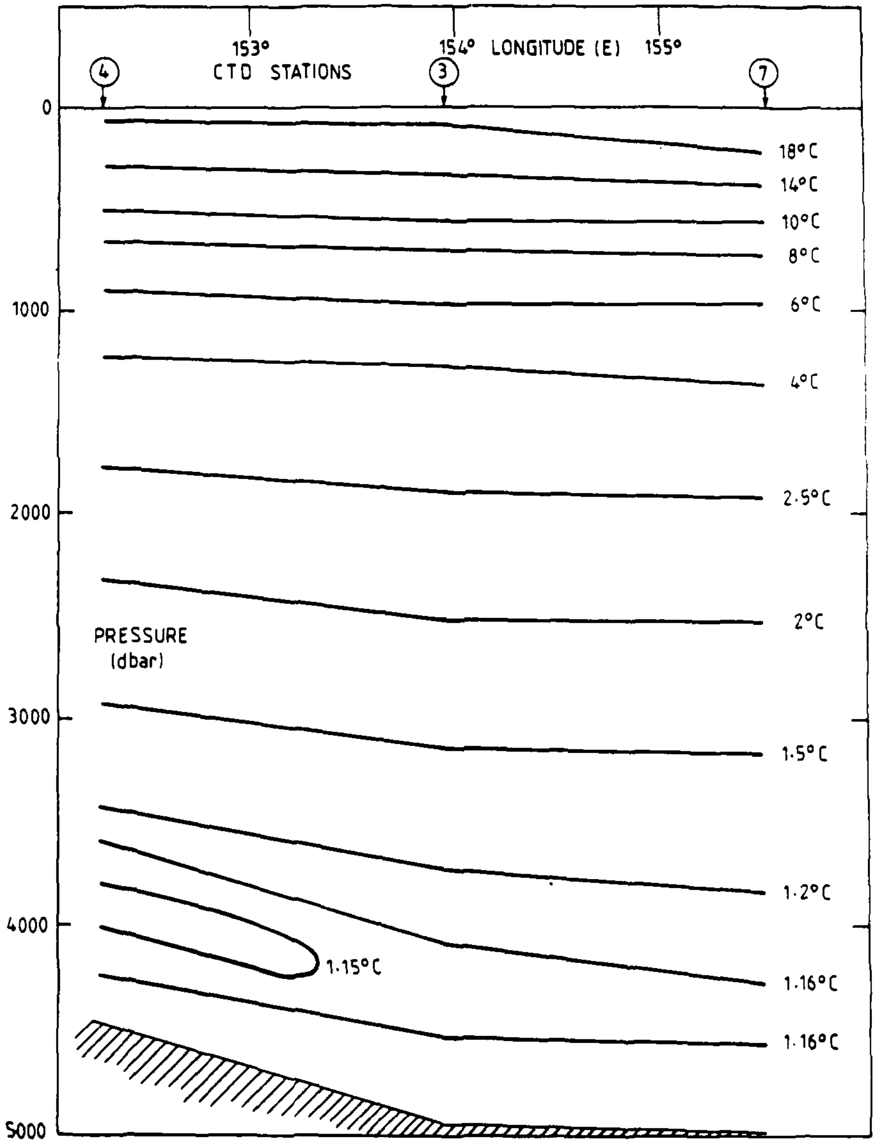

Figure 2(c). Temperature section, east from Sydney, RANRL Cruise 23/85

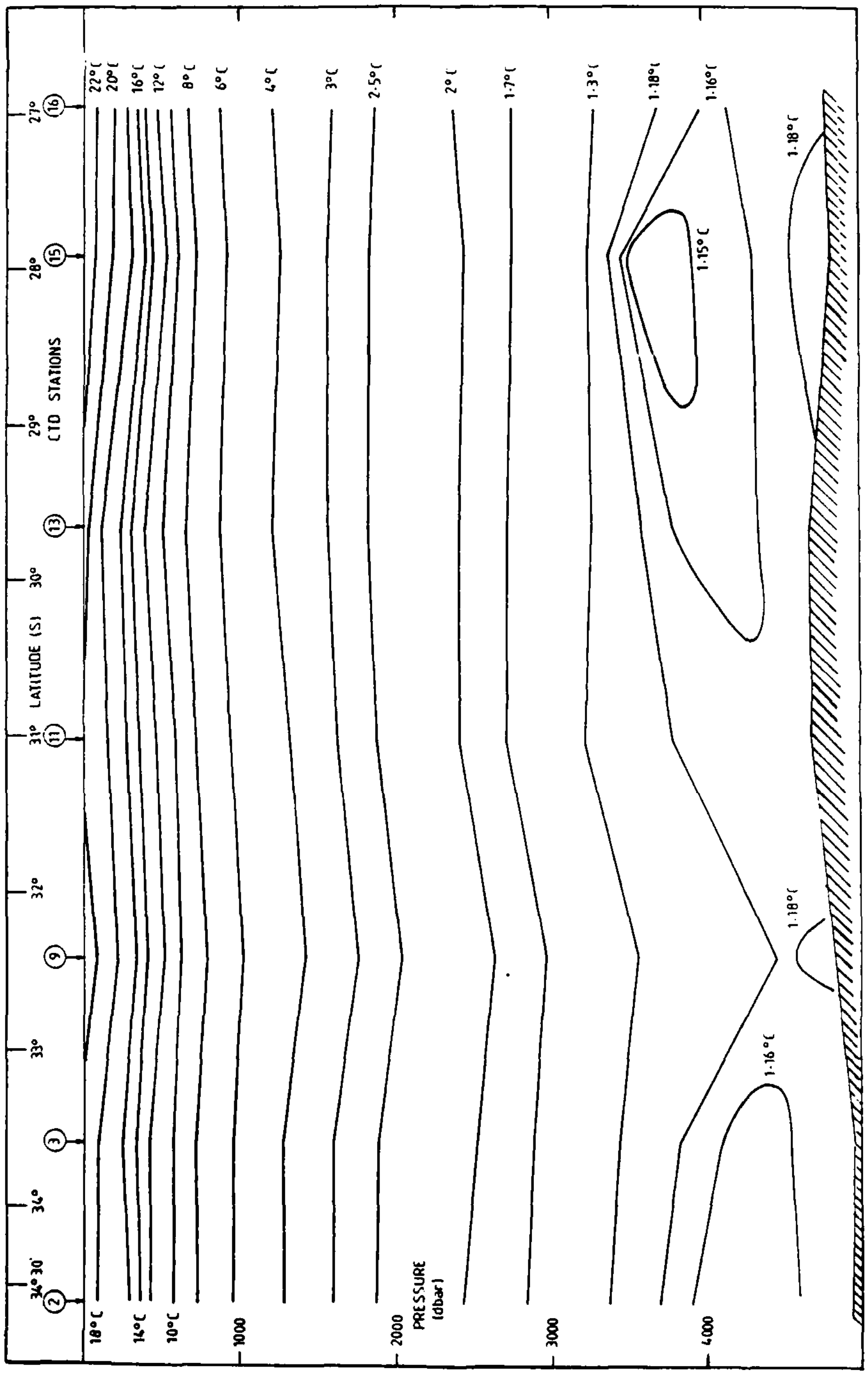

Figure 2(d). North-south temperature section, RANRL Cruise 23/85

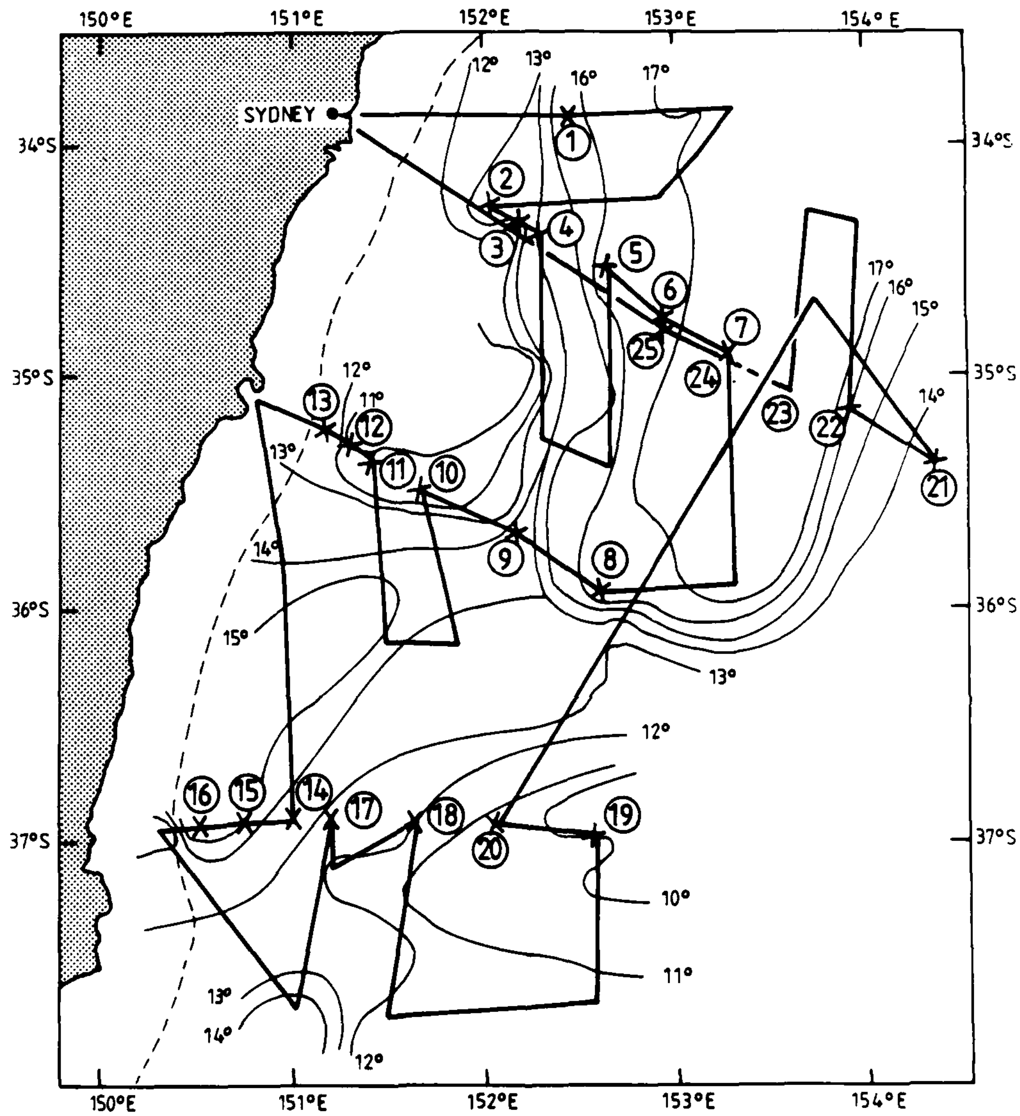

Figure 3. Cruise track and T_{250} contours for RANRL Cruise 12/84, 4 to 14 October 1985. (Station numbers are circled). (T_{250} = temperature at a depth of 250 m)

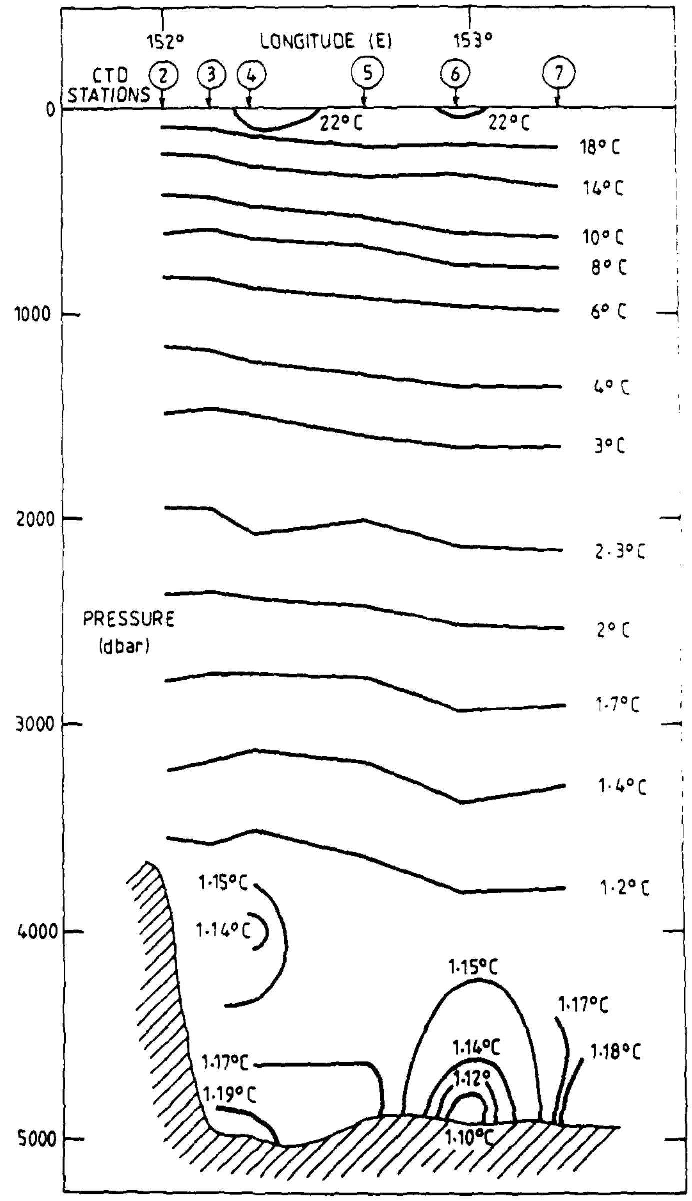

Figure 4(a). Temperature section, south-east from Sydney, outward leg, RANRL Cruise 12/84

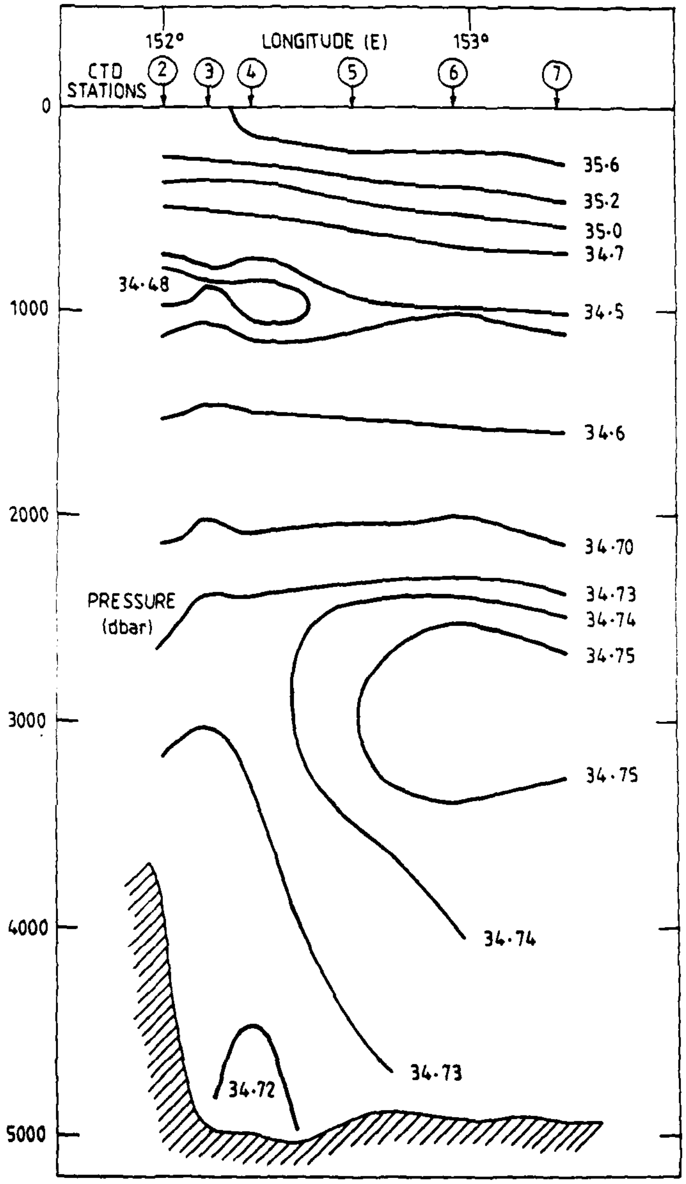

Figure 4(b). Salinity section (psu), south-east from Sydney (outward leg), RANRL Cruise 12/84

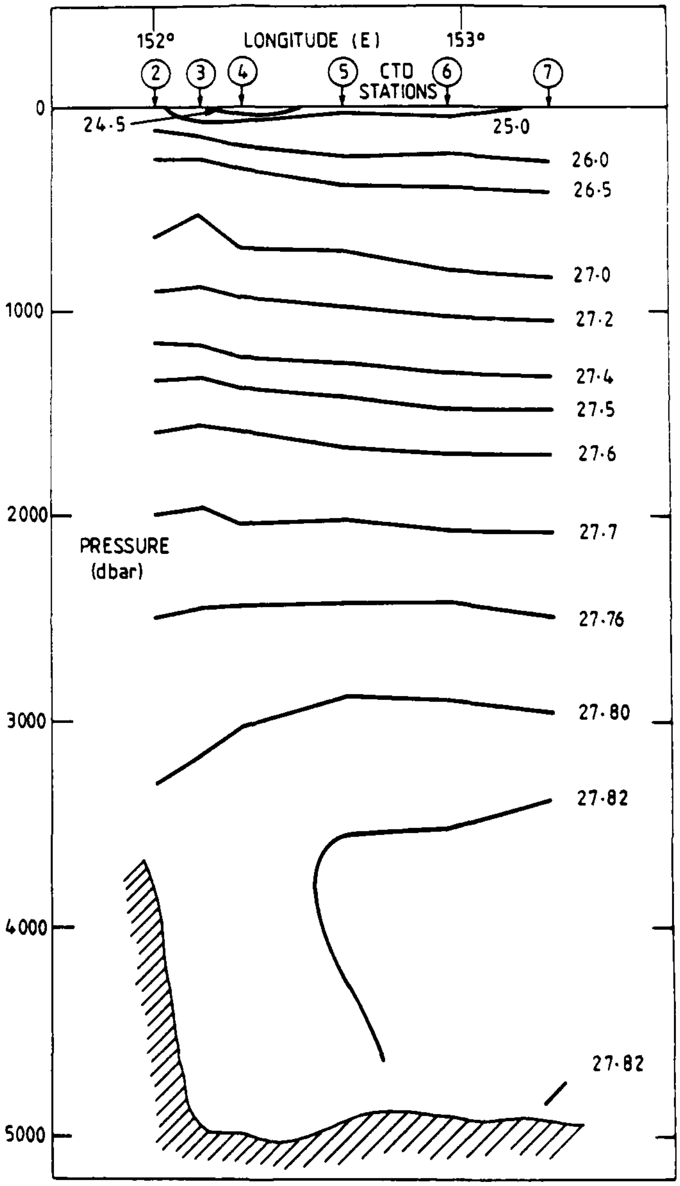

Figure 4(c). σ_t section, south-east from Sydney (outward leg), RANRL Cruise 12/84

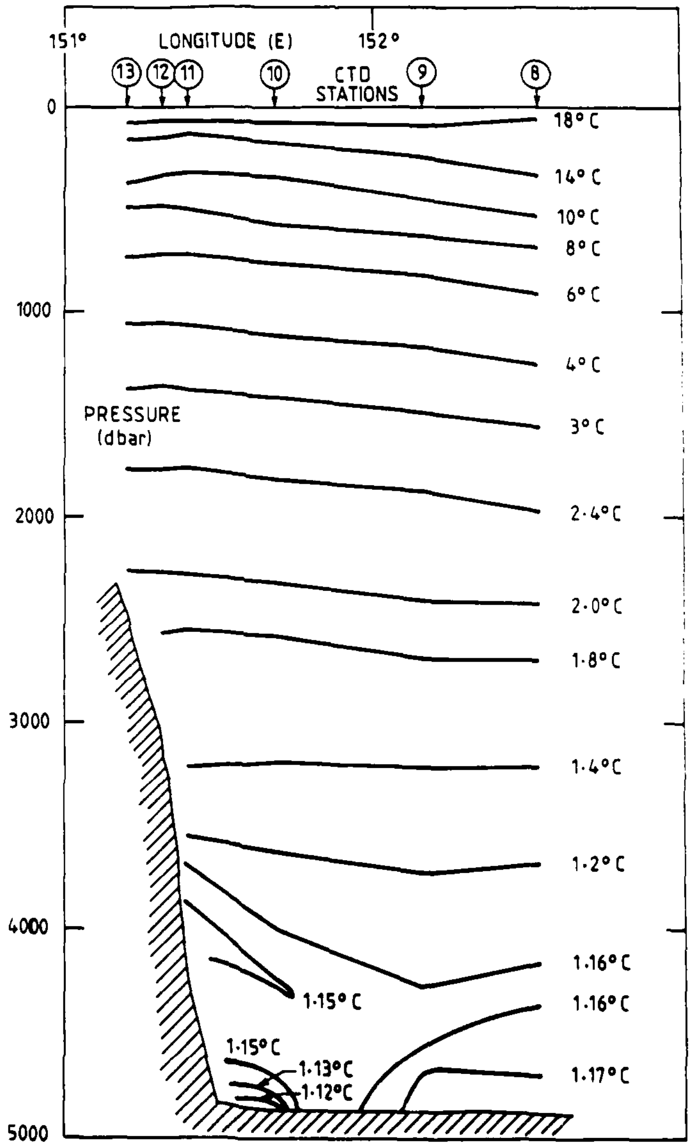

Figure 4(d). Temperature section, south-east from Jervis Bay, RANRL Cruise 12/84

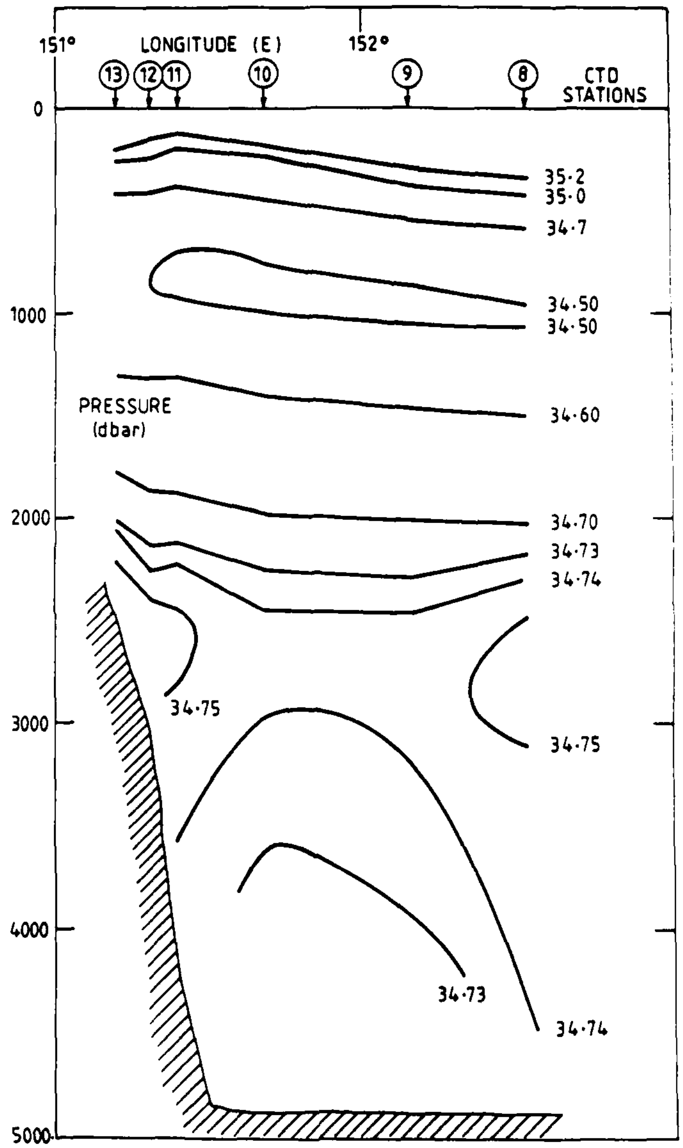

Figure 4(e). Salinity section, south-east from Jervis Bay, RANRL Cruise 12/84

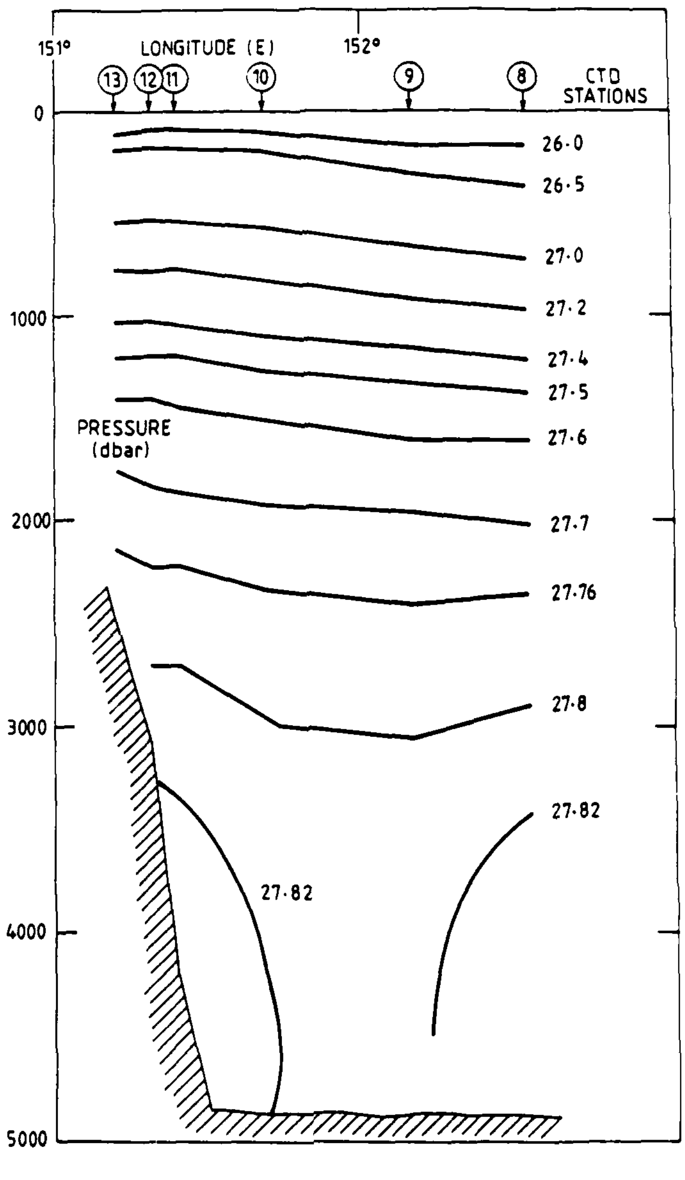

Figure 4(f). σ_t section, south-east from Jervis Bay, RANRL Cruise 12/84

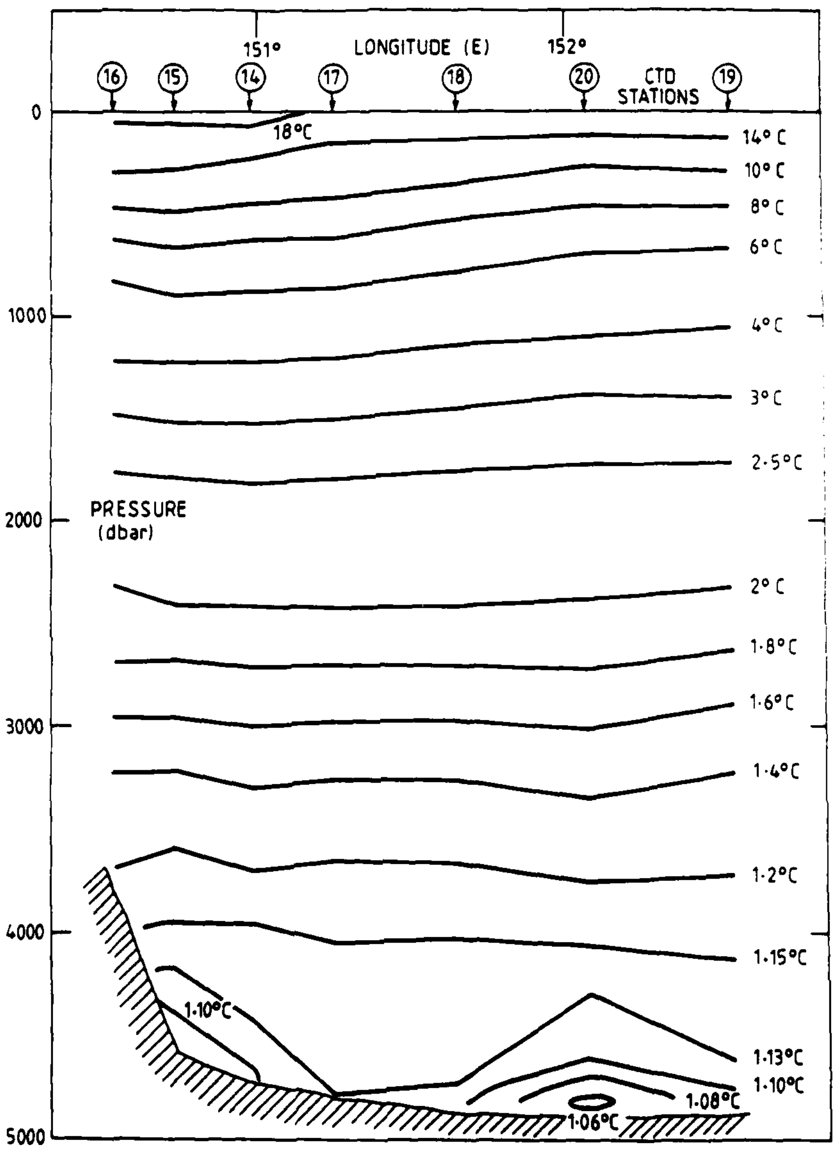

Figure 4(g). Temperature section, eastward from Cape Howe, RANRL Cruise 12/84

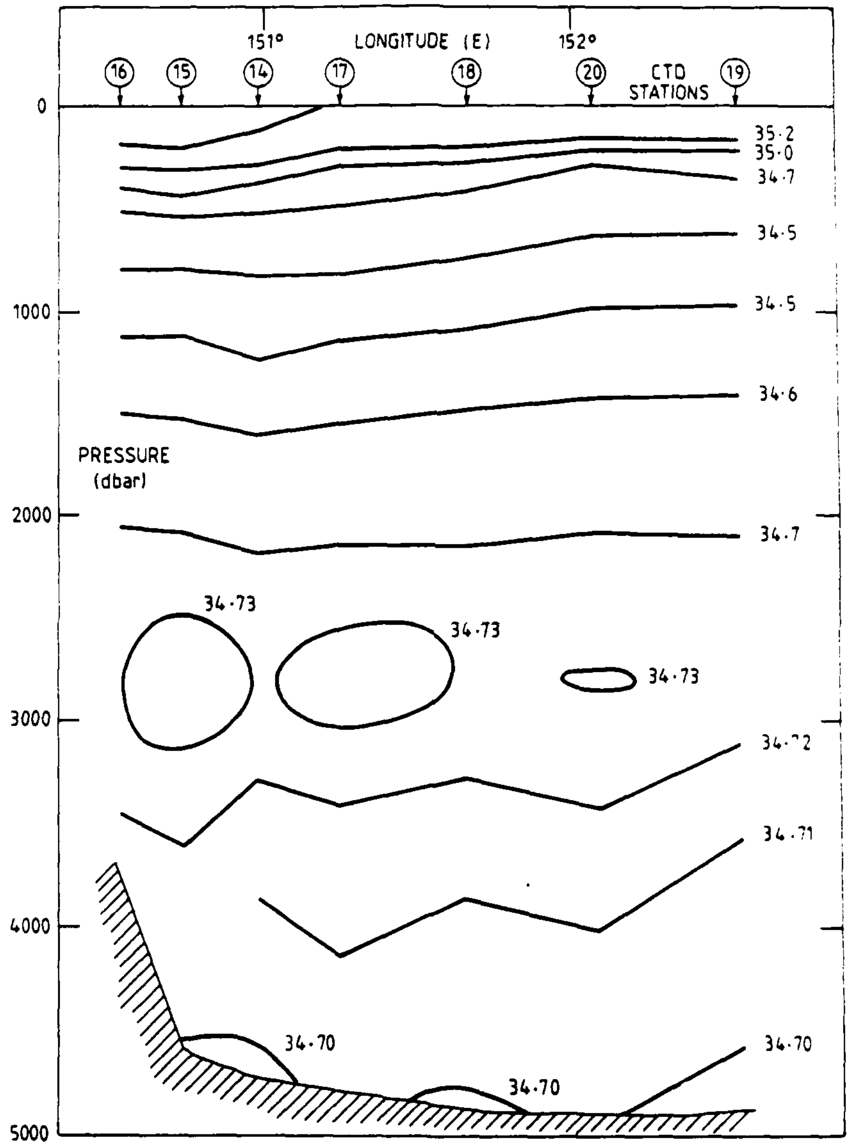

Figure 4(h). Salinity section, eastward from Cape Howe, RANRL Cruise 12/84

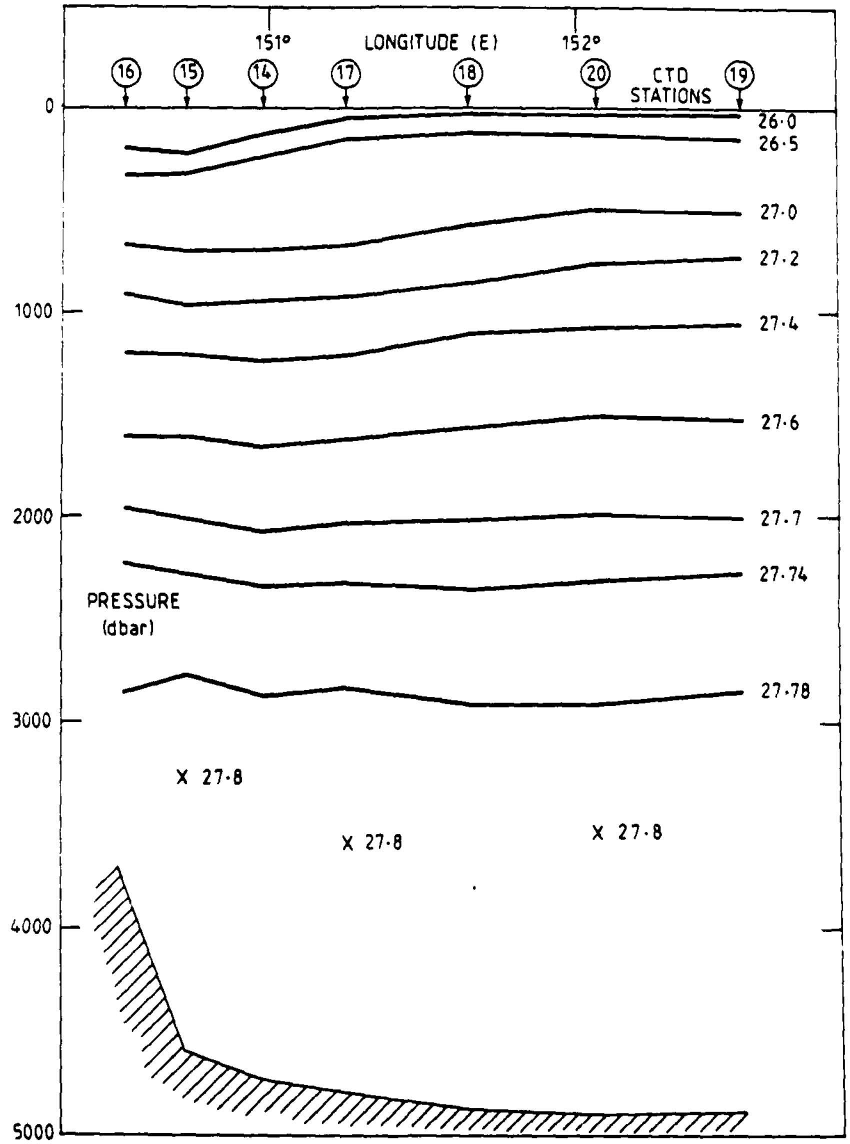

Figure 4(i). σ_t section, eastward from Cape Howe, RANRL Cruise 12/84

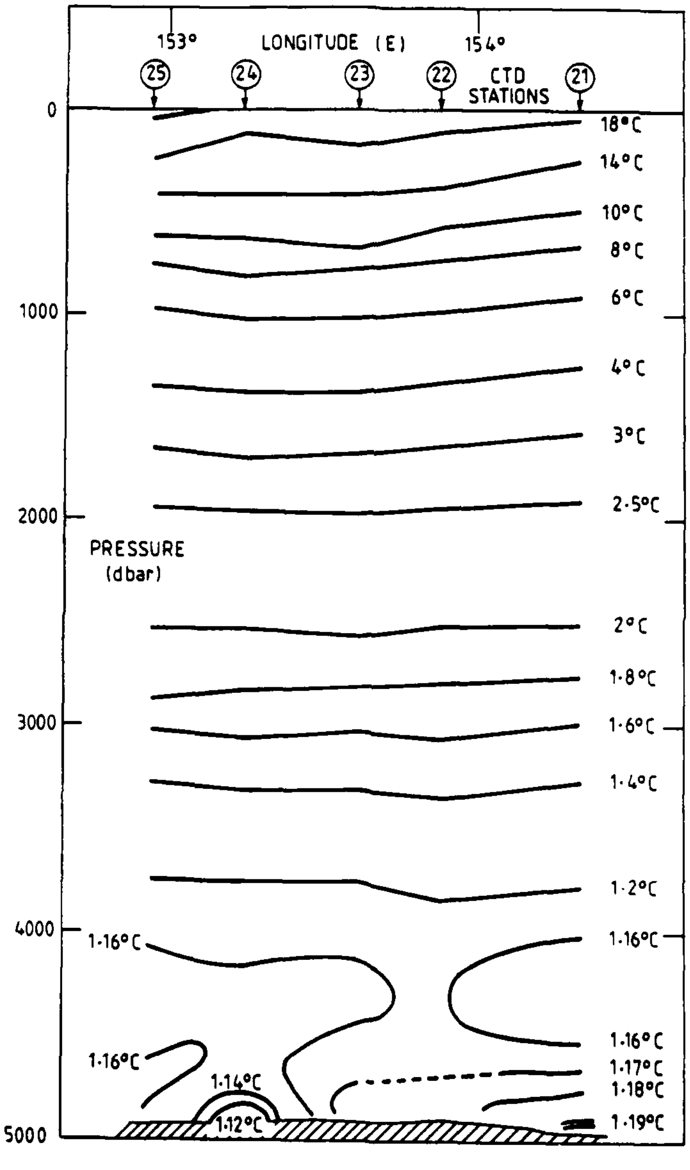

Figure 4(j). Temperature section, south-east from Sydney (inward leg), RANRL Cruise 12/84

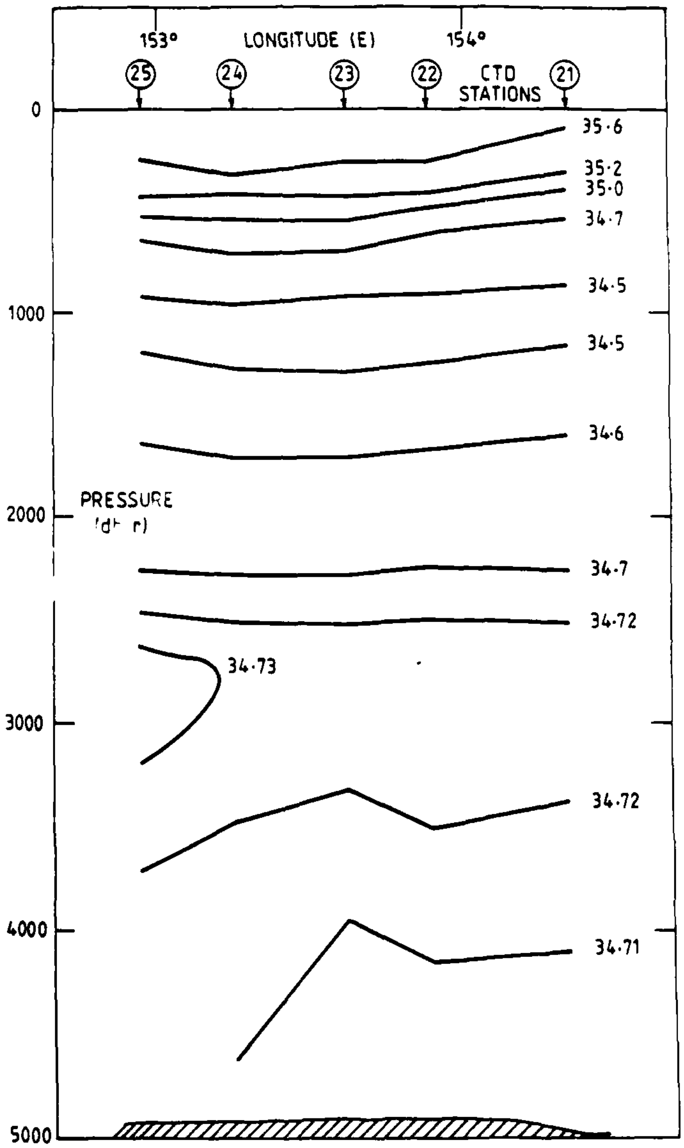

Figure 4(k). Salinity section, south-east from Sydney (inward leg), RANRL Cruise 12/84

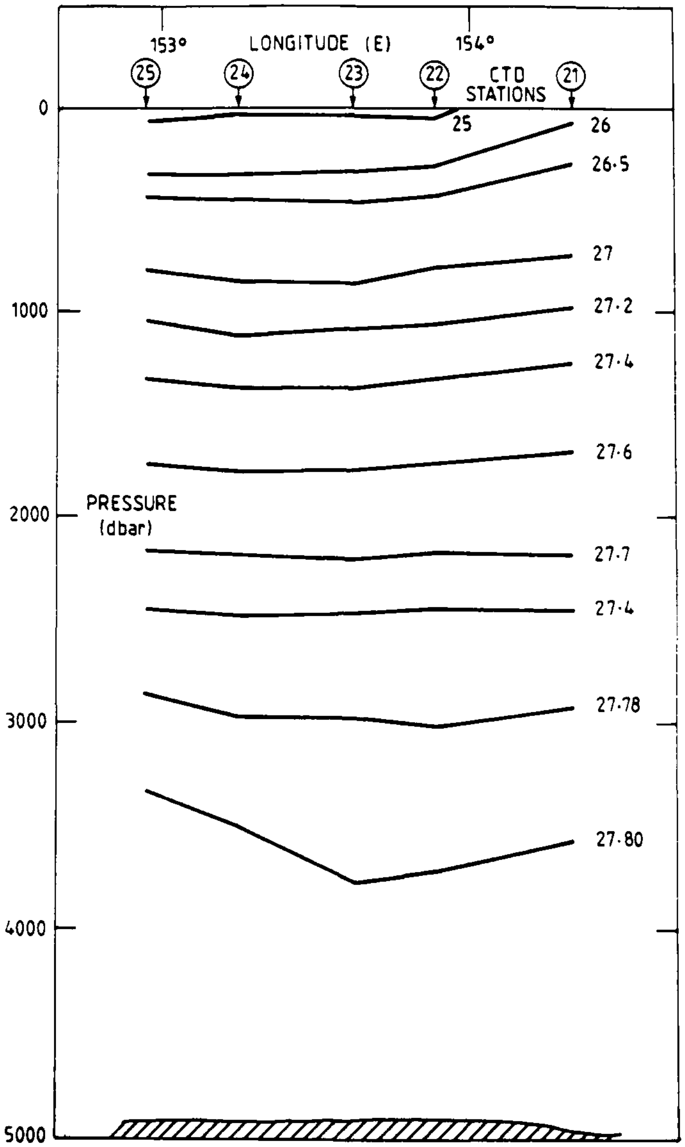

Figure 4(l). σ_t section, south-east from Sydney (inward leg), RANRL Cruise 12/84

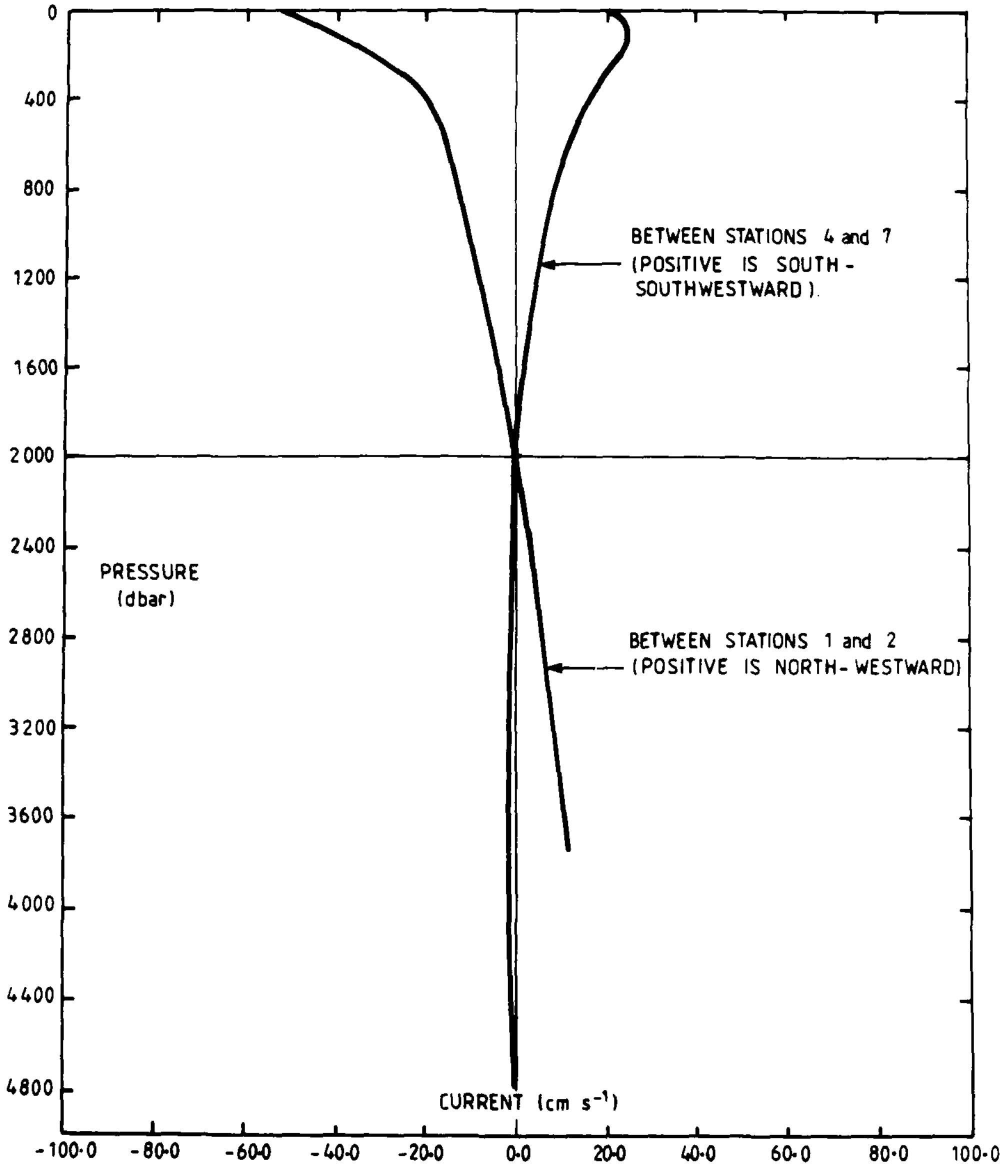

Figure 5(a). Geostrophic current relative to 2000 dbar between station pairs 1,2 and 4,7. RANRL Cruise 12/84

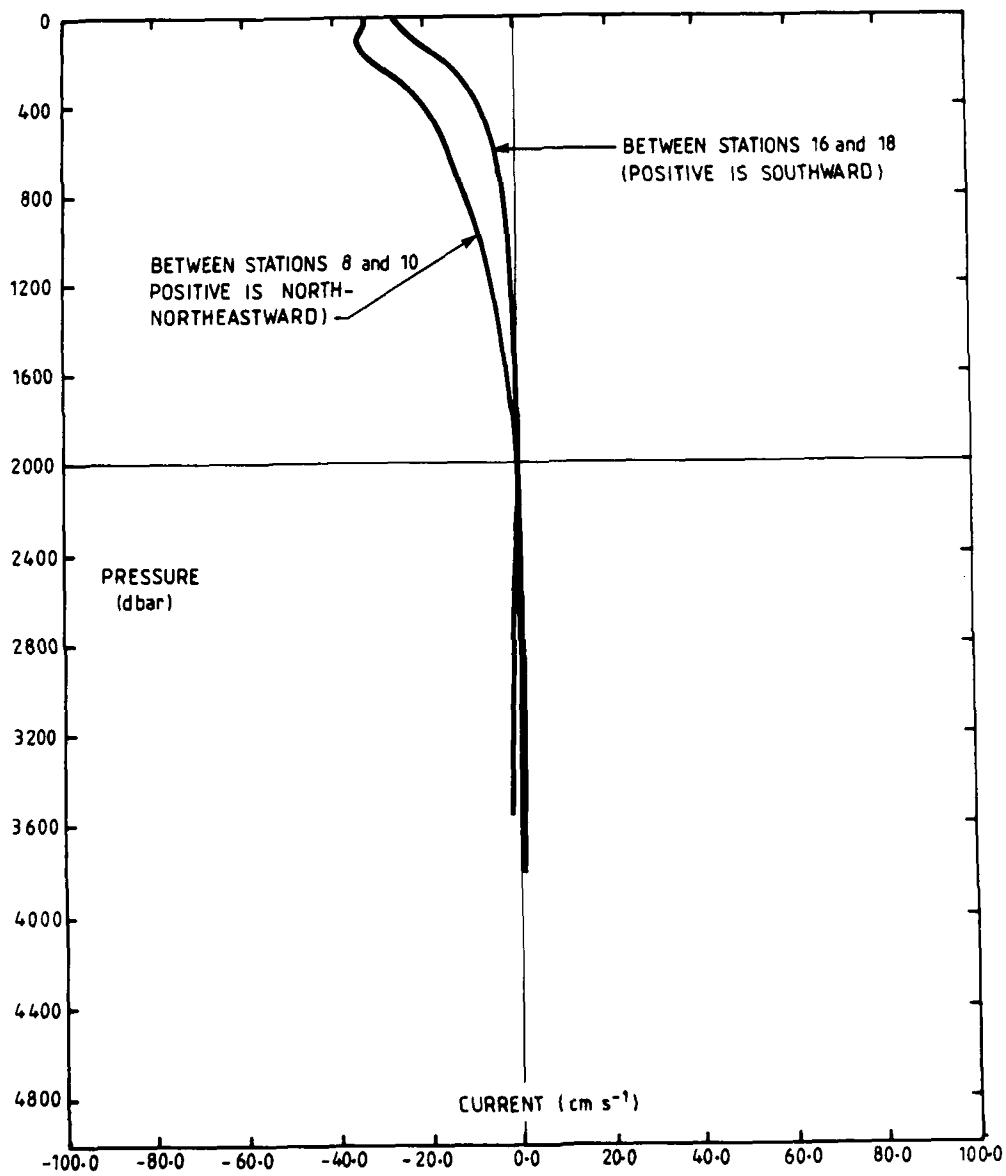

Figure 5(b). Geostrophic current relative to 2000 dbar between station pairs 8,10 and 16,18.
RANRL Cruise 12/84

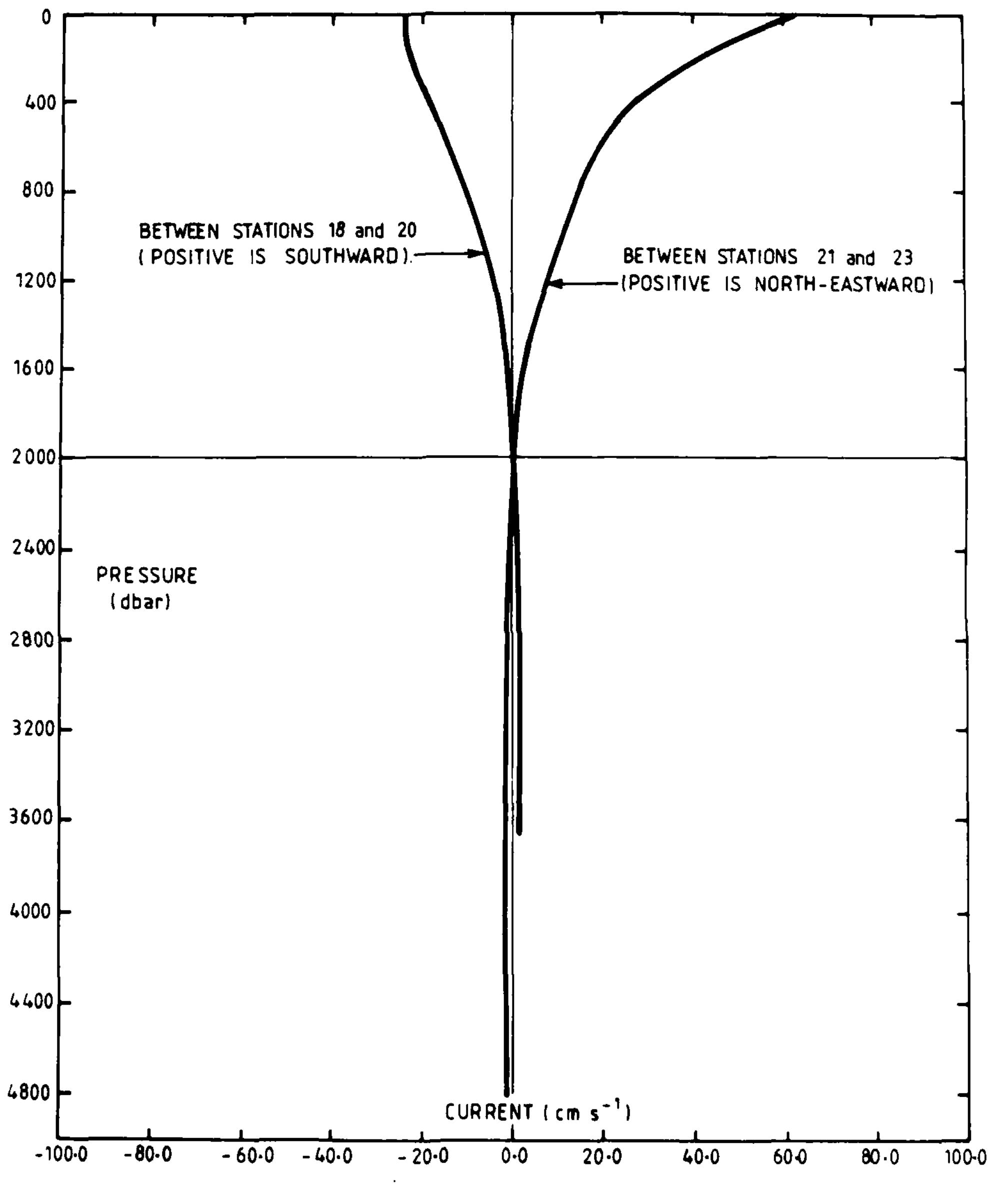

Figure 5(c). Geostrophic current relative to 2000 dbar between station pairs 18,20 and 21,23. RANRL Cruise 12/84

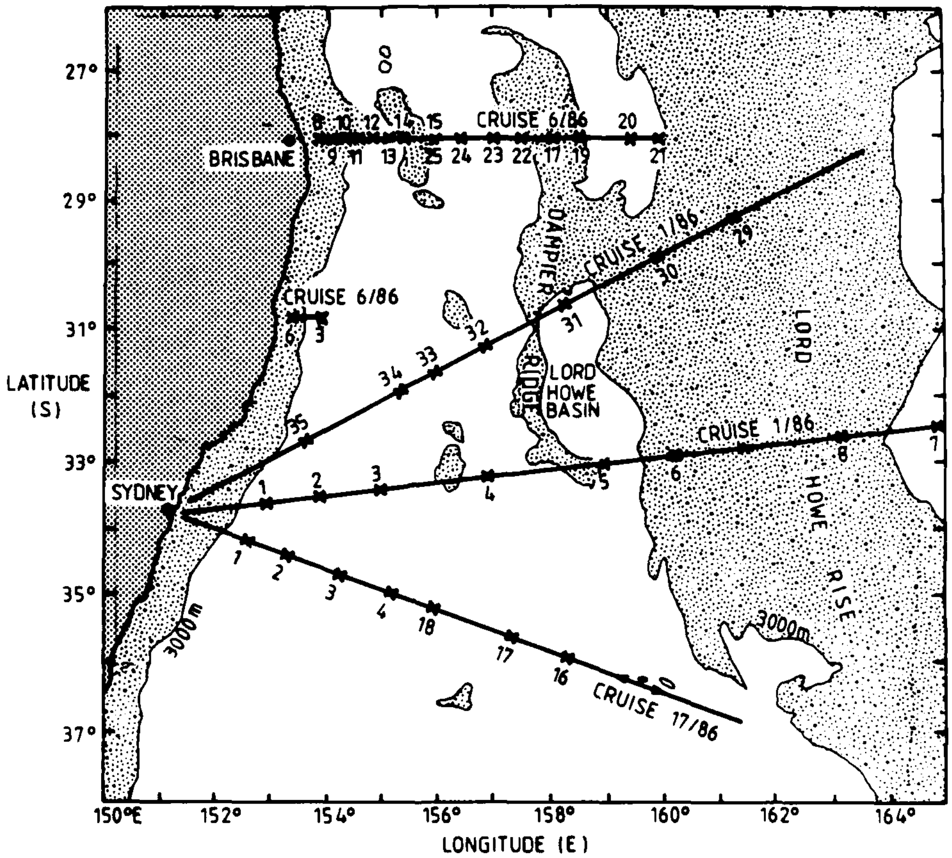

Figure 6. Tracks and stations for RANRL Cruises 1/86, 6/86, 17/86. (Depths below 3000 m are indicated by shading)

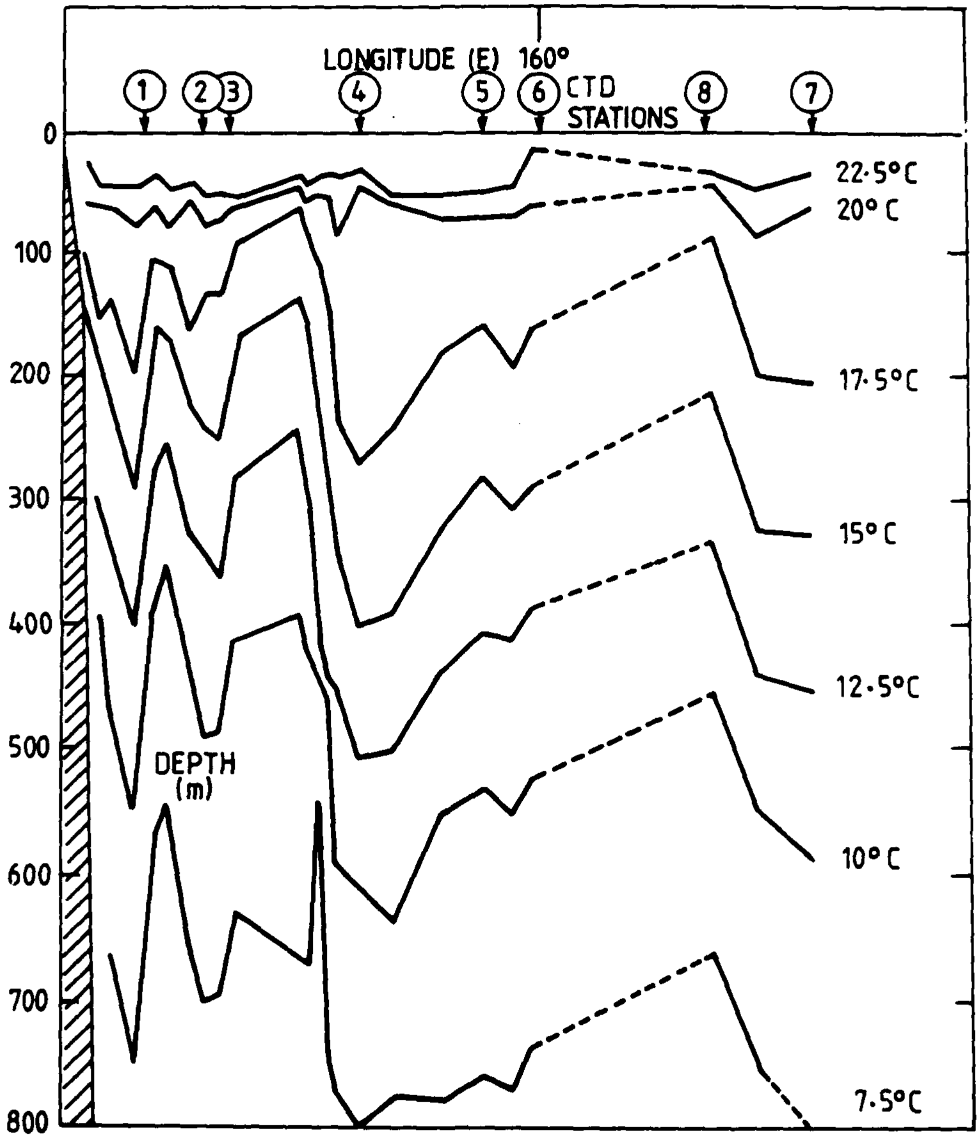

Figure 7(a). XBT section, east from Sydney, RANRL Cruise 1/86

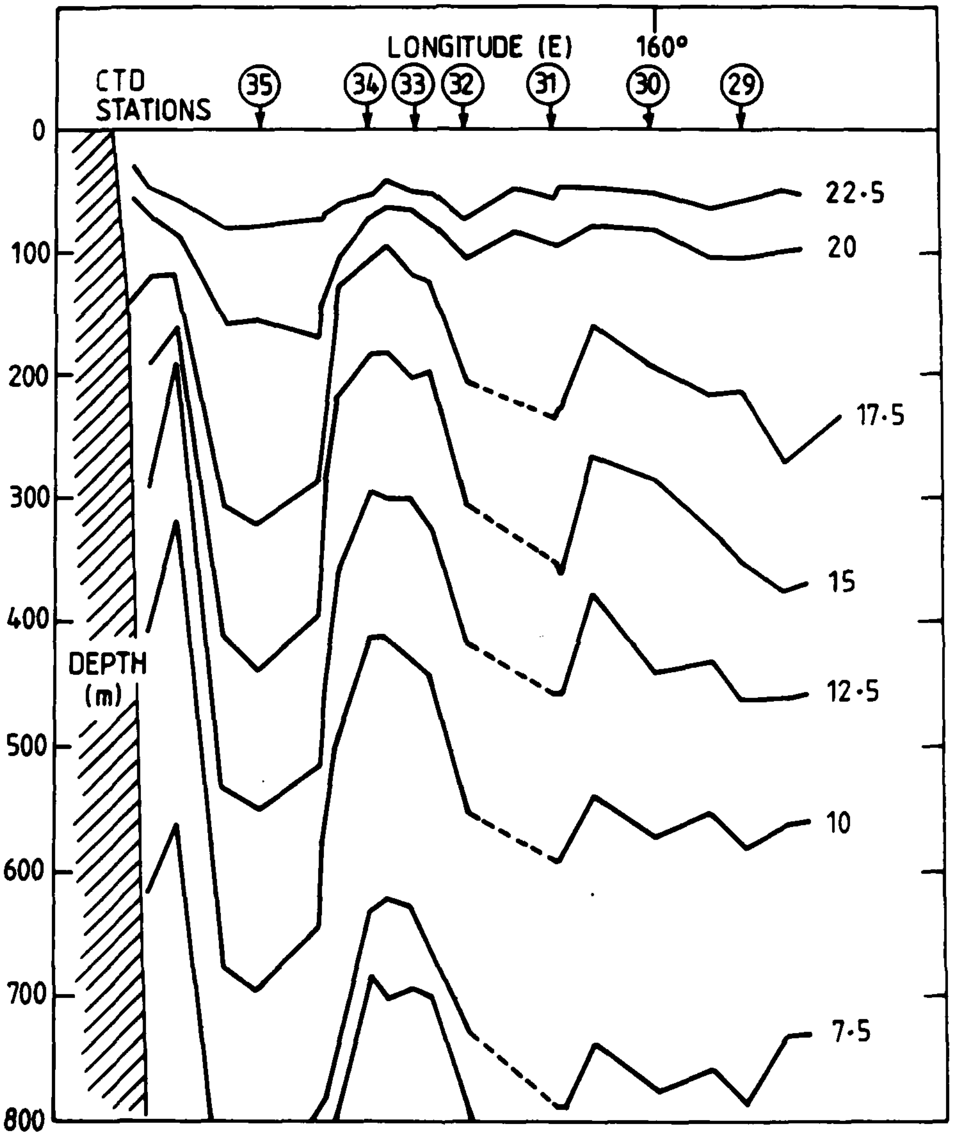

Figure 7(b). XBT section, north-east from Sydney, RANRL Cruise 1/86

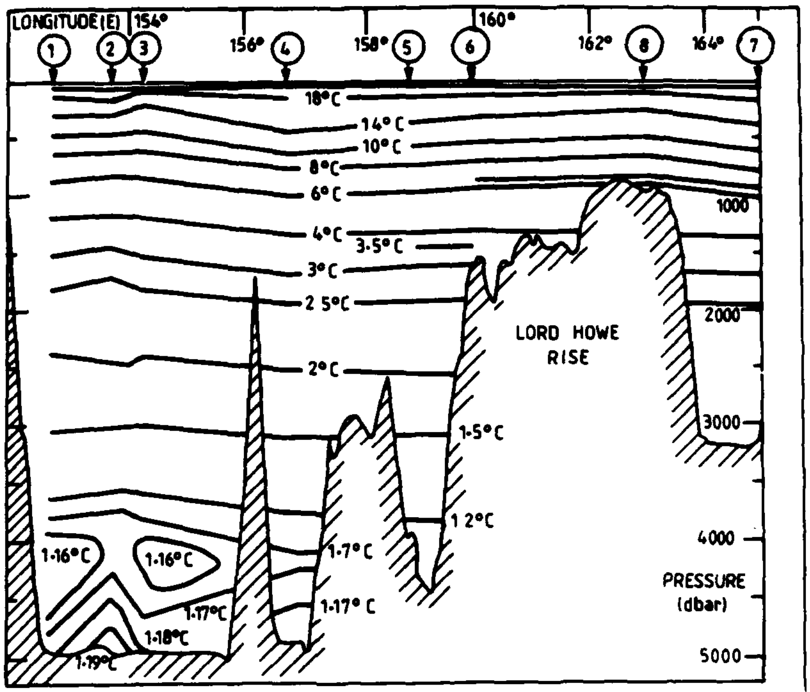

Figure 8(a). Temperature section, east from Sydney, RANRL Cruise 1/86

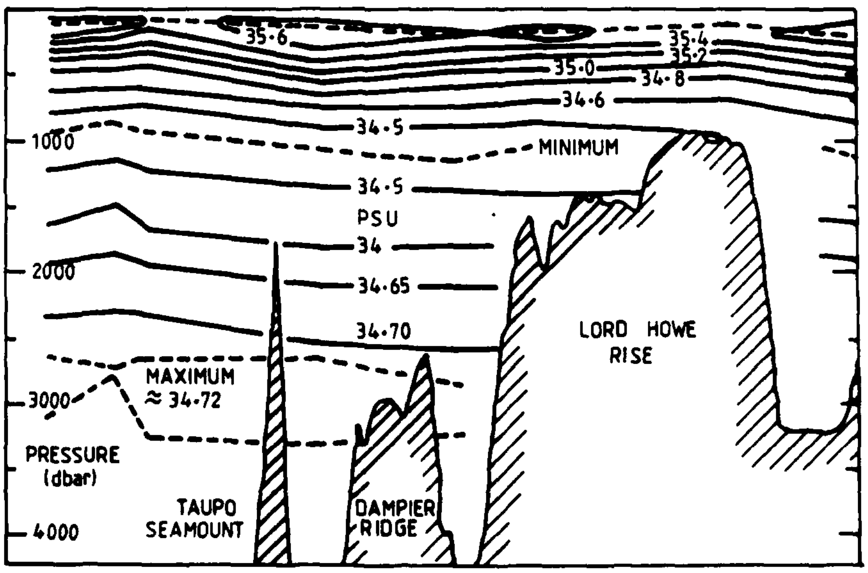

Figure 8(b). Salinity section, east from Sydney, RANRL Cruise 1/86

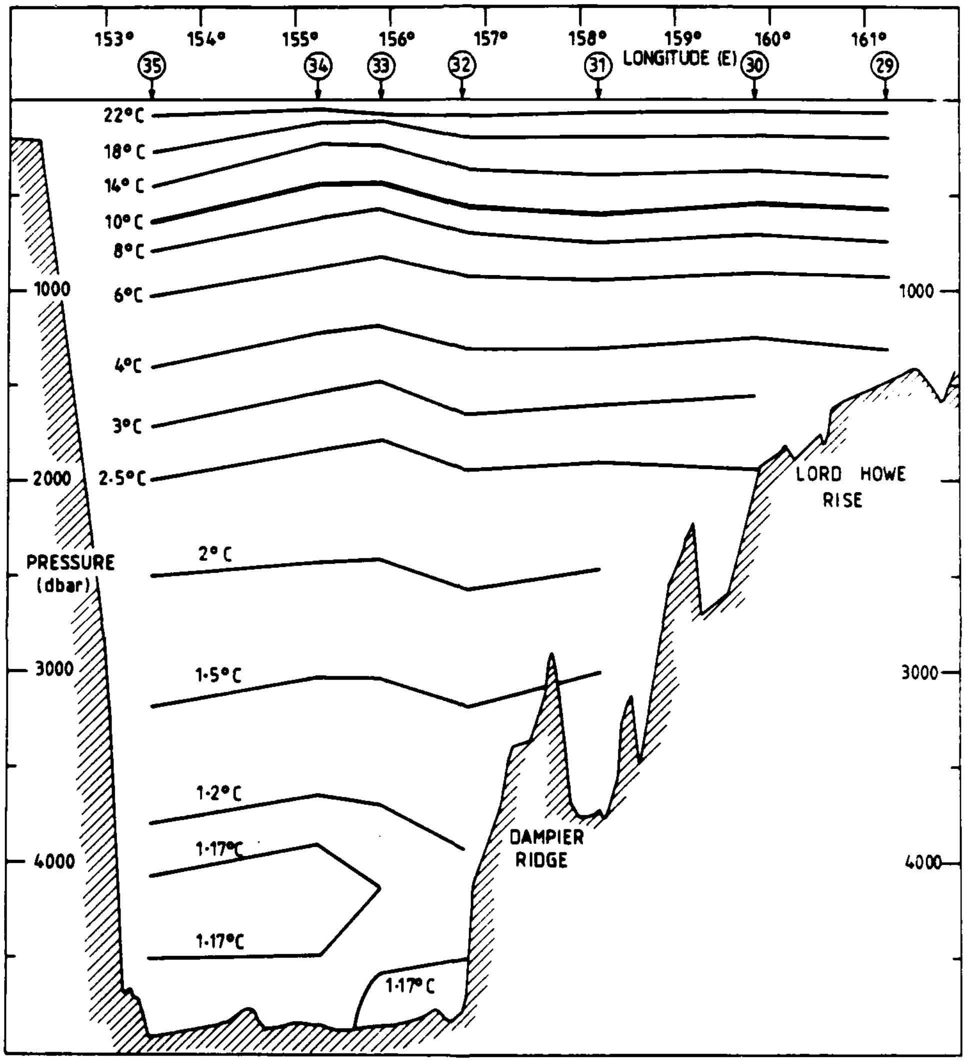

Figure 9(a). Temperature section, north-east from Sydney, RANRL Cruise 1/86, incoming leg

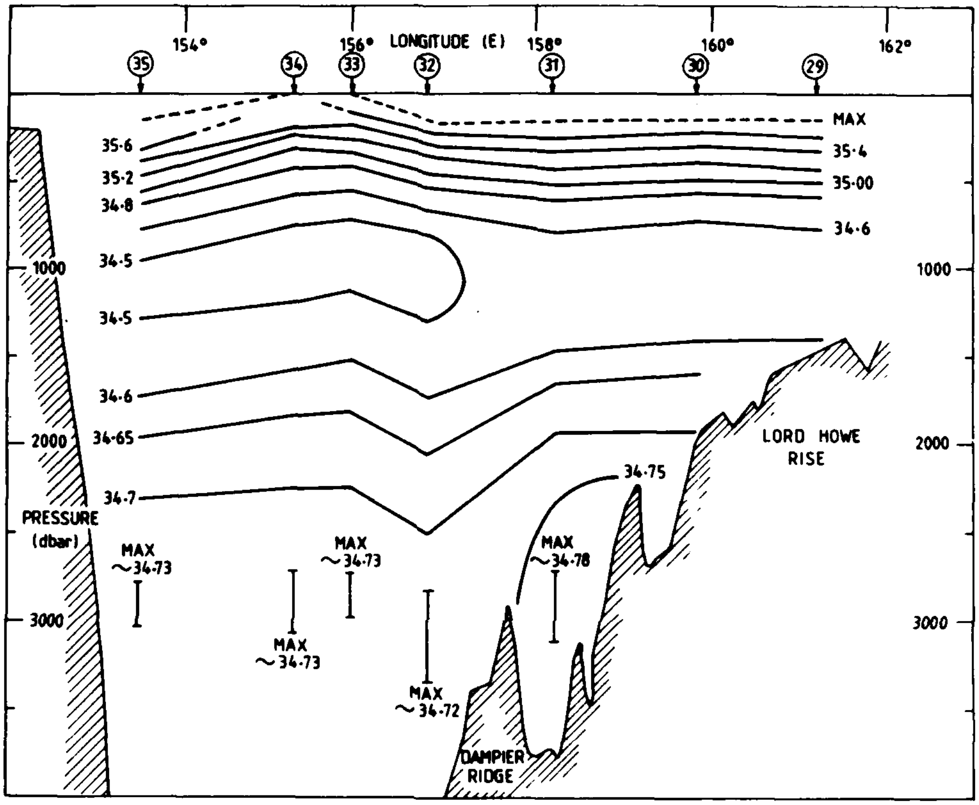

Figure 9(b). Salinity section, north-east from Sydney, RANRL Cruise 1/86

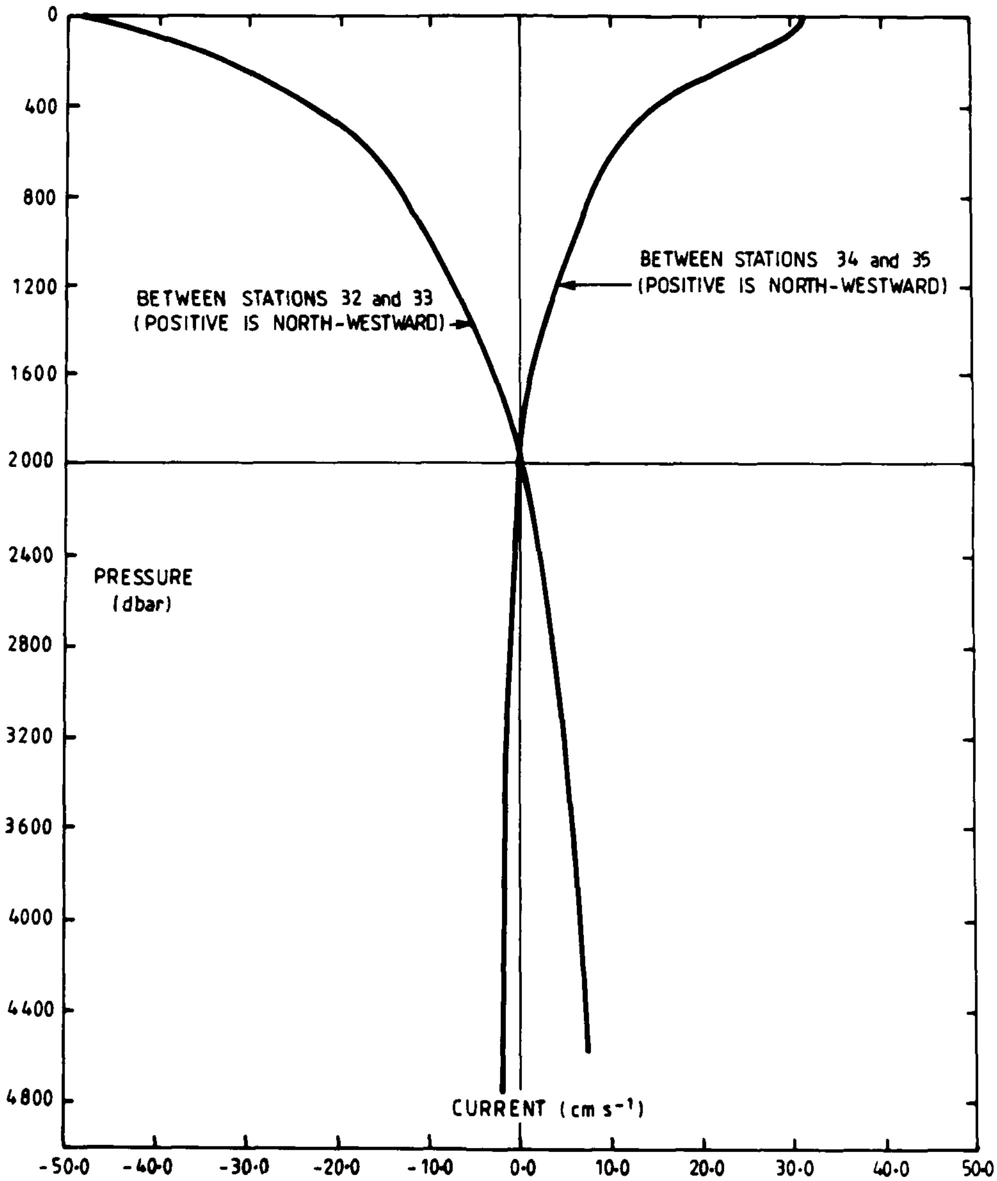

Figure 10. Geostrophic current relative to 2000 dbar between stations, RANRL Cruise 1/86

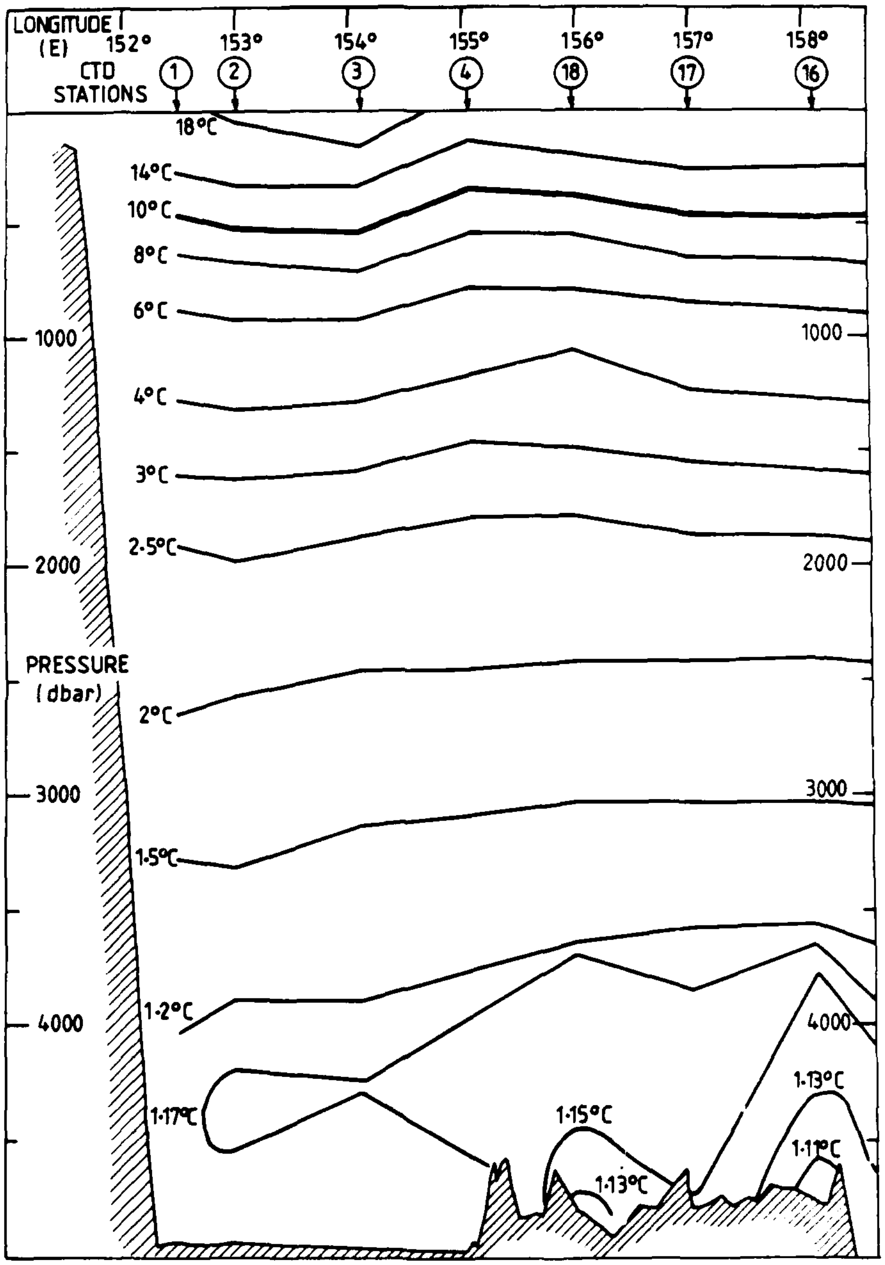

Figure 11. Temperature section, south-east from Sydney, RANRL Cruise 17/86

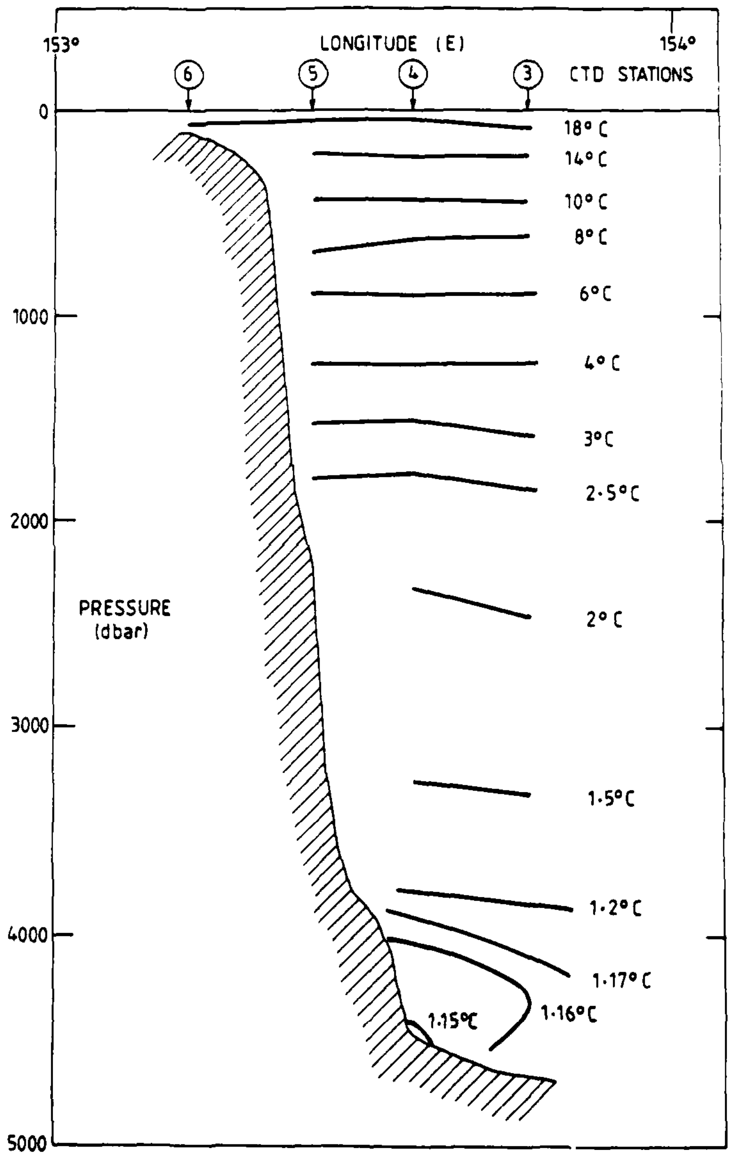

Figure 12(a). Temperature section, along latitude 30°43' S, RANRL Cruise 6/86, 14 to 15 September 1986

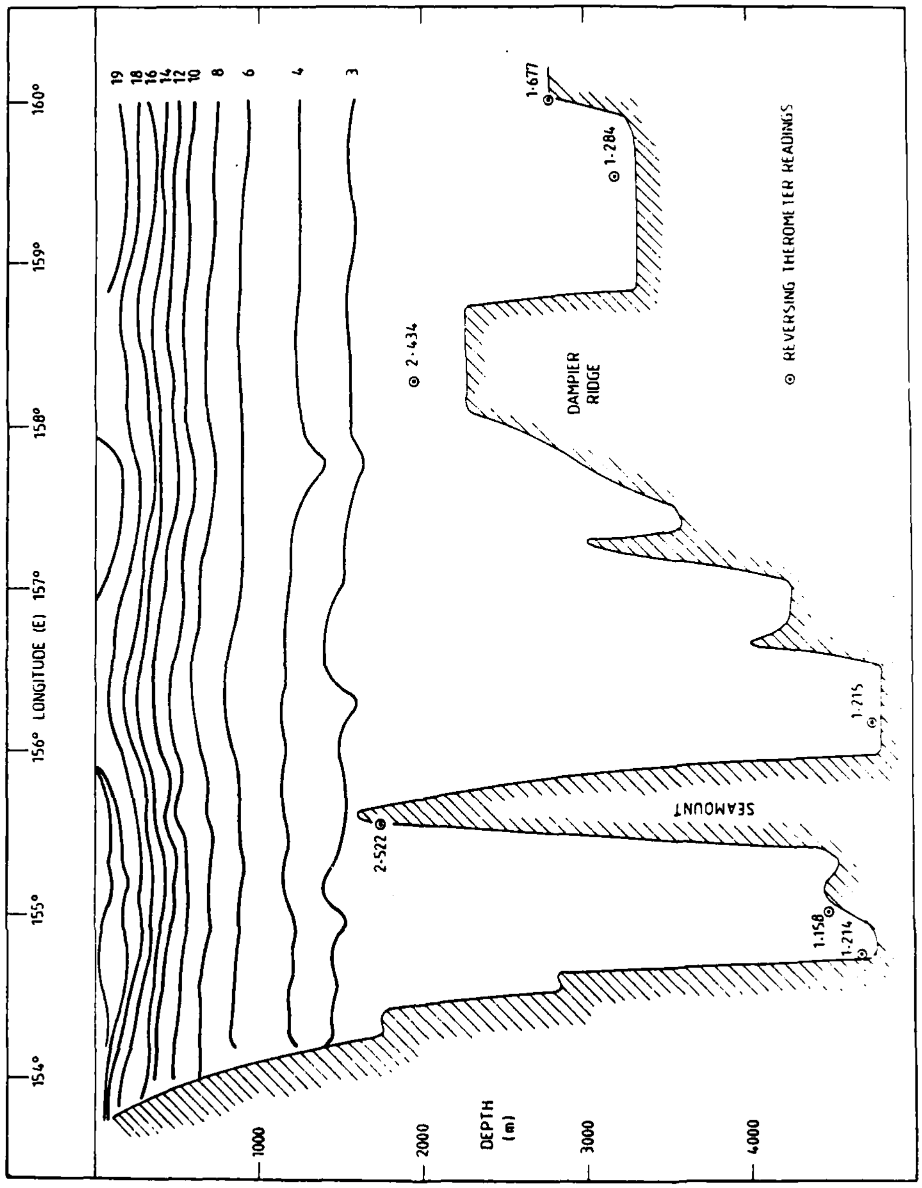

Figure 12(b). XBT section, along latitude 28°04' S, RANRL Cruise 6/86, 16 to 20 September 1986

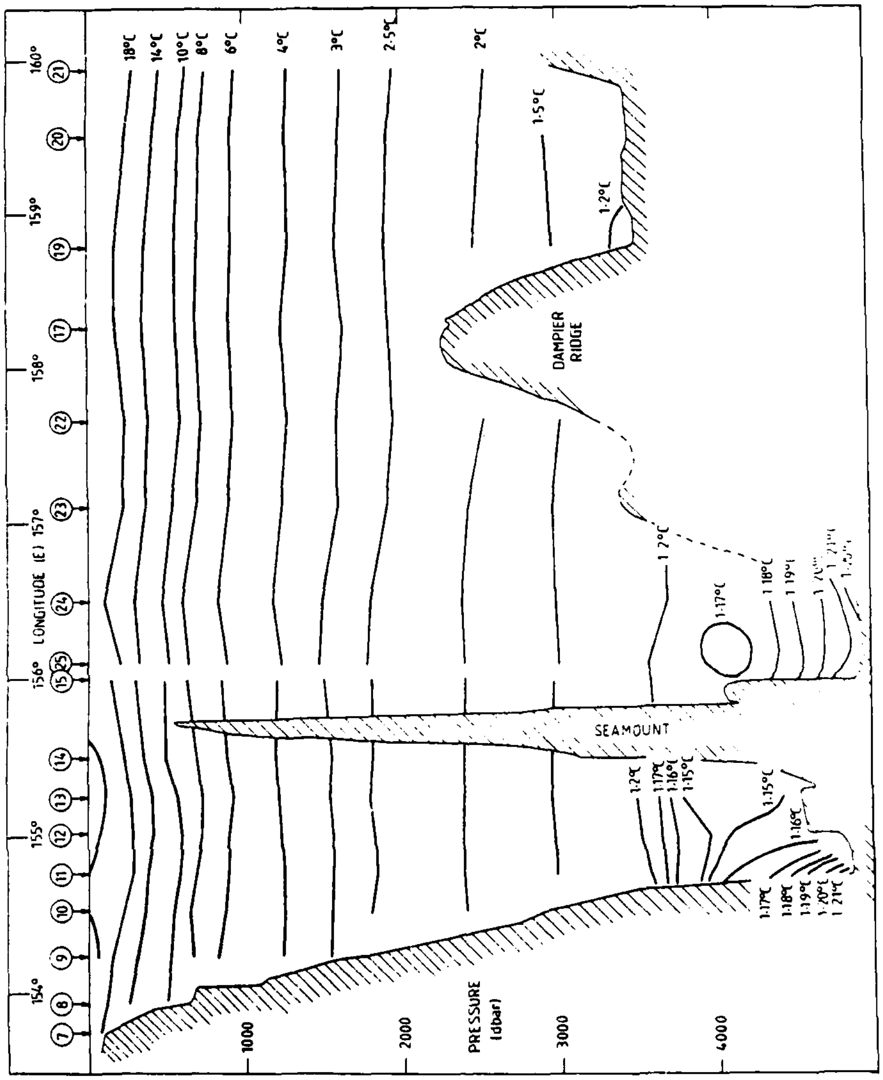

Figure 12(c). Temperature section, along latitude 28°04' S, RANRL Cruise 6/86, 16 to 20 September 1986

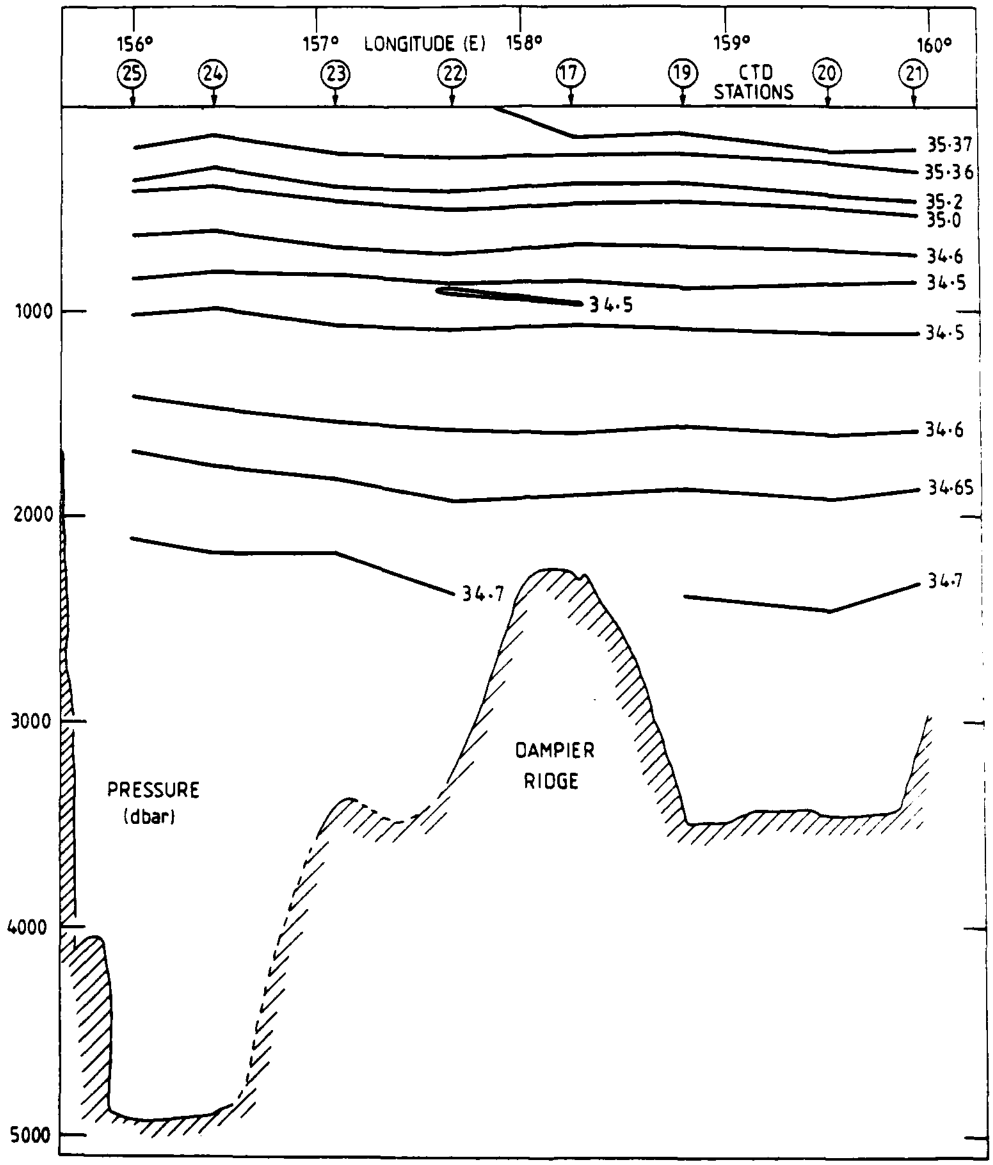

Figure 12(d). Salinity section, along latitude 28° S, RANRL Cruise 6/86, 16 to 20 September 1986

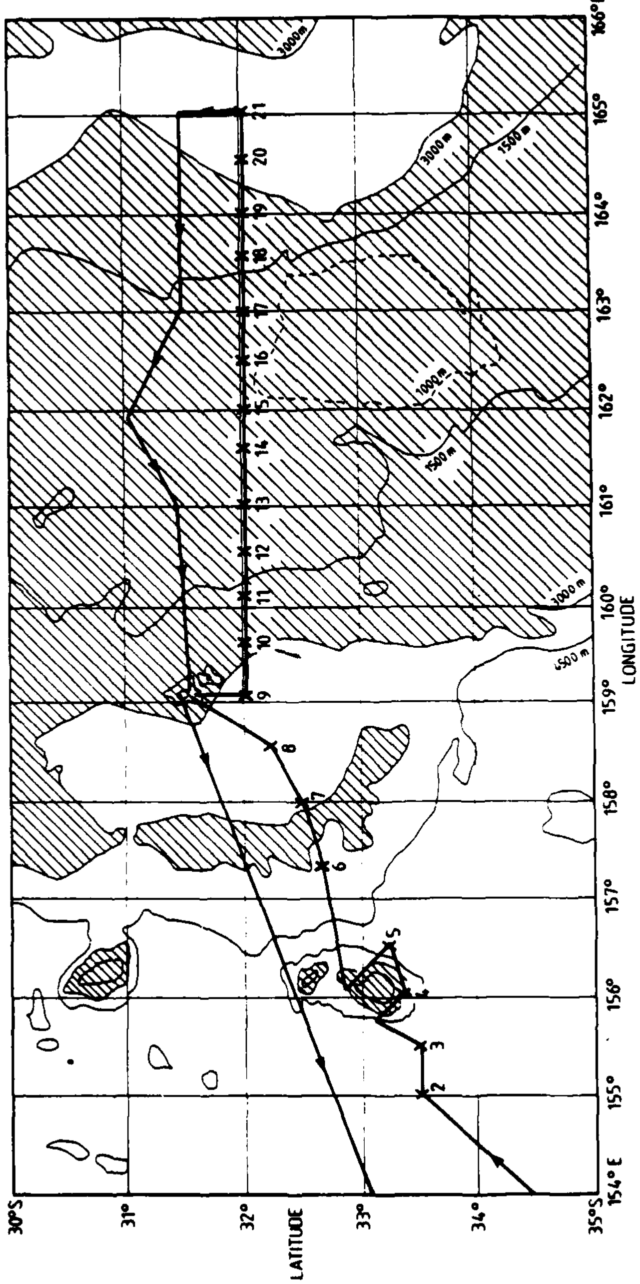

Figure 13. Ship's track and station positions, RANRL Cruise 1/87. (Depths less than 3000 m are shown by hatching)

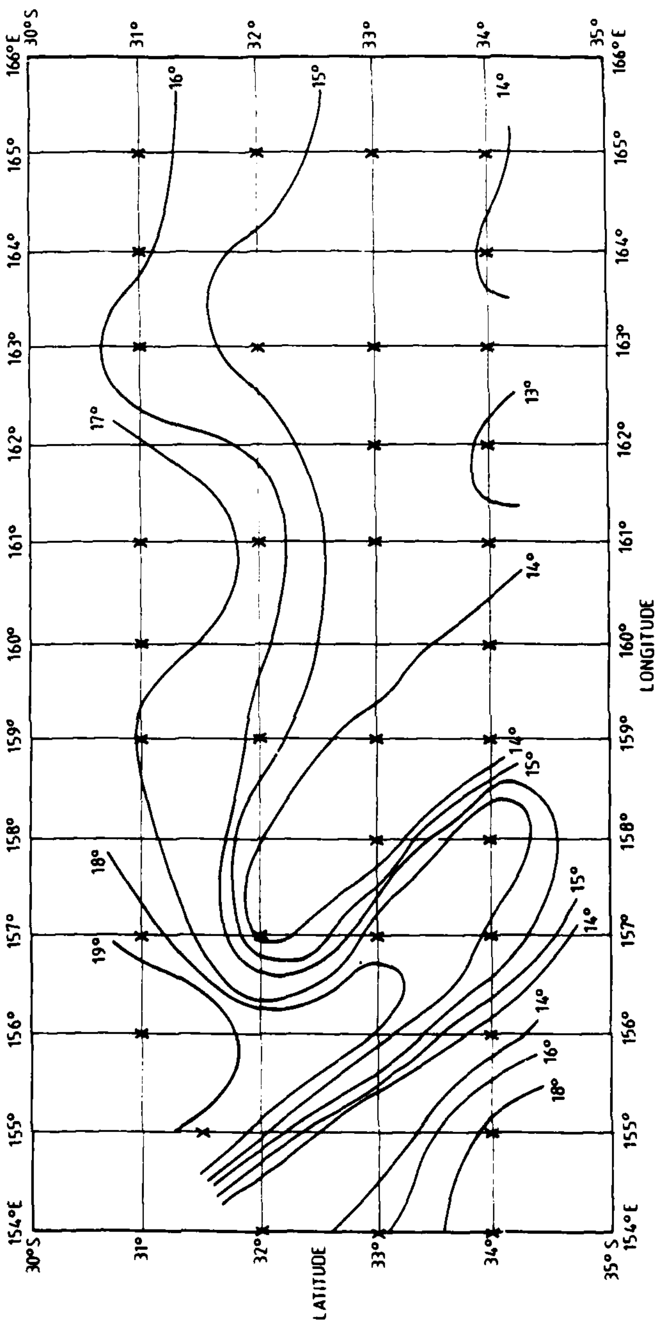

Figure 14. T_{250} (^{o}C) contours from AXBT survey of 13 May 1987. (x AXBT positions)

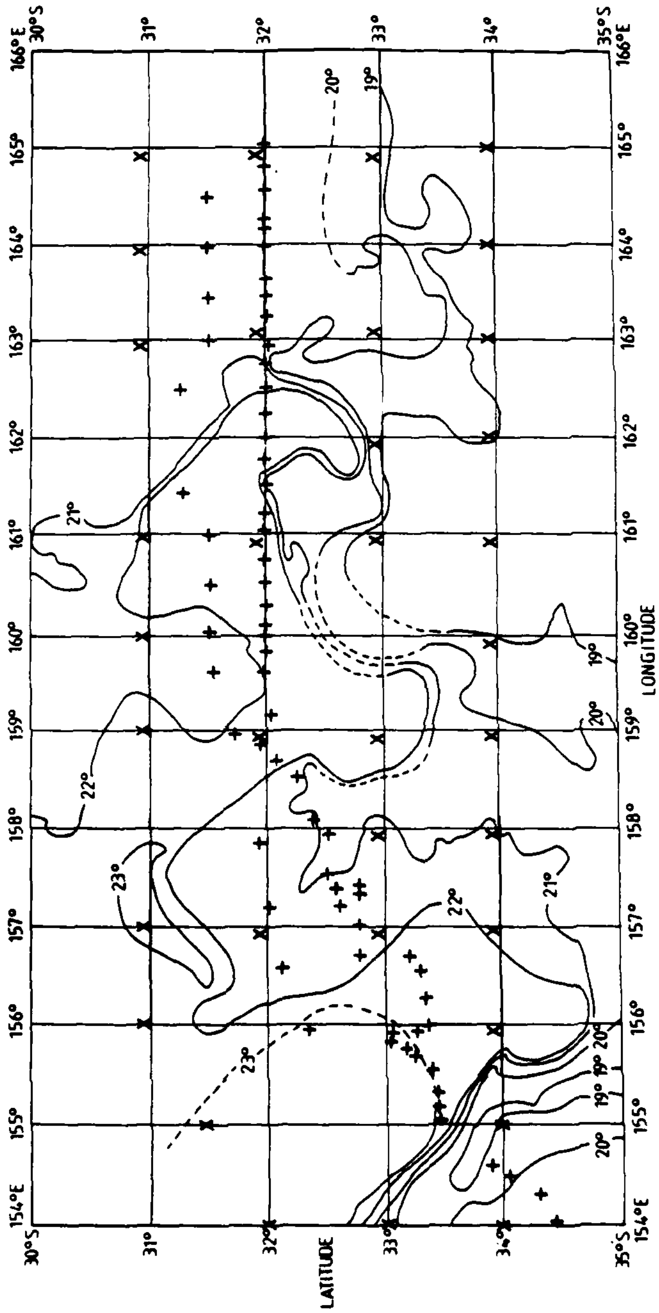

Figure 15. Sea surface temperature (°C) contours, RANRL Curise 1/87, (based on AXBT survey of June 1987, Cook's XBT's and ir image on 2 June 1987). x AXBT positions, + XBT positions

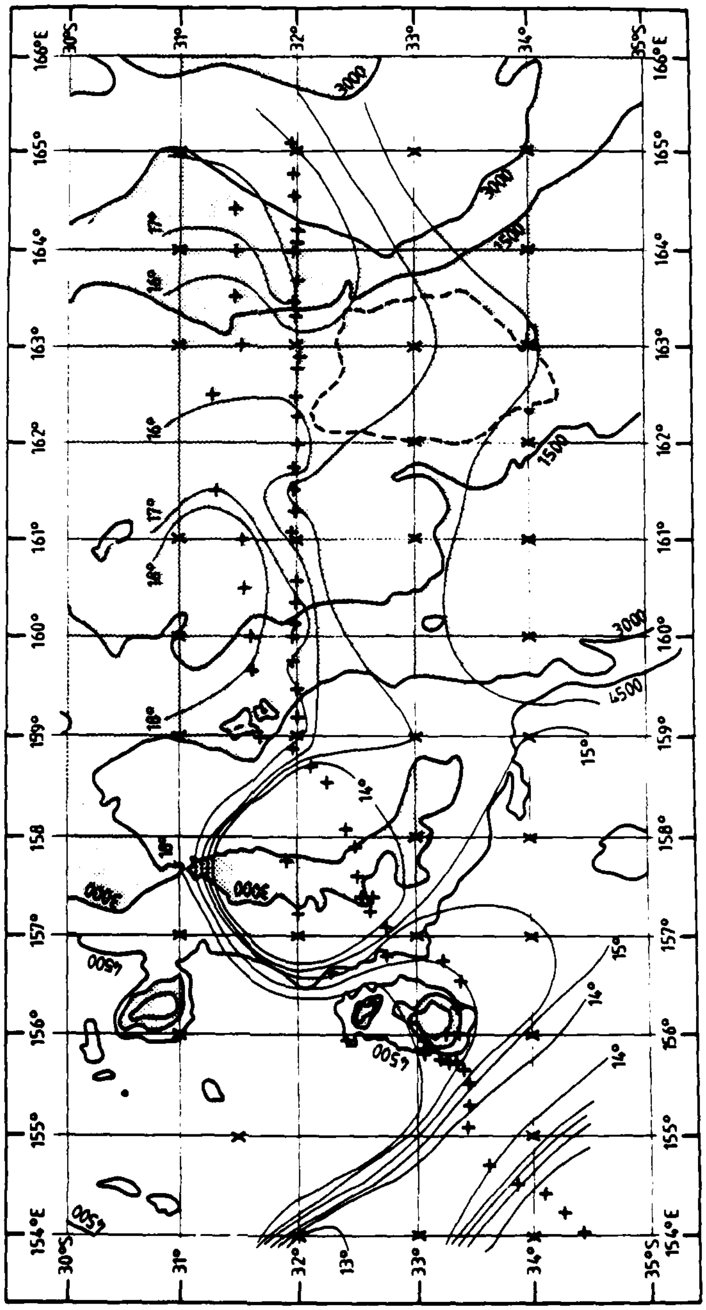

Figure 16. T_{250} (°C) contours - Cruise 1/87, (x AXBT positions, + XBT positions). (Depths less than 3000 m are shown by shading)

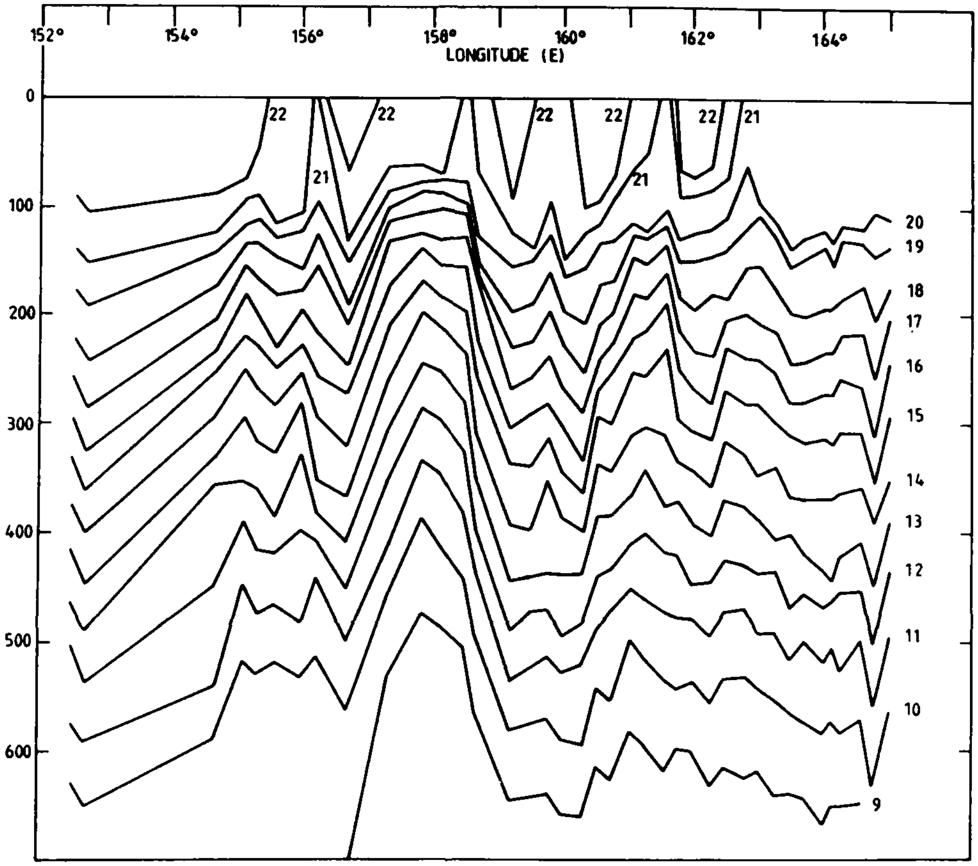

Figure 17. XBT section, RANRL Cruise 1/87, outward leg

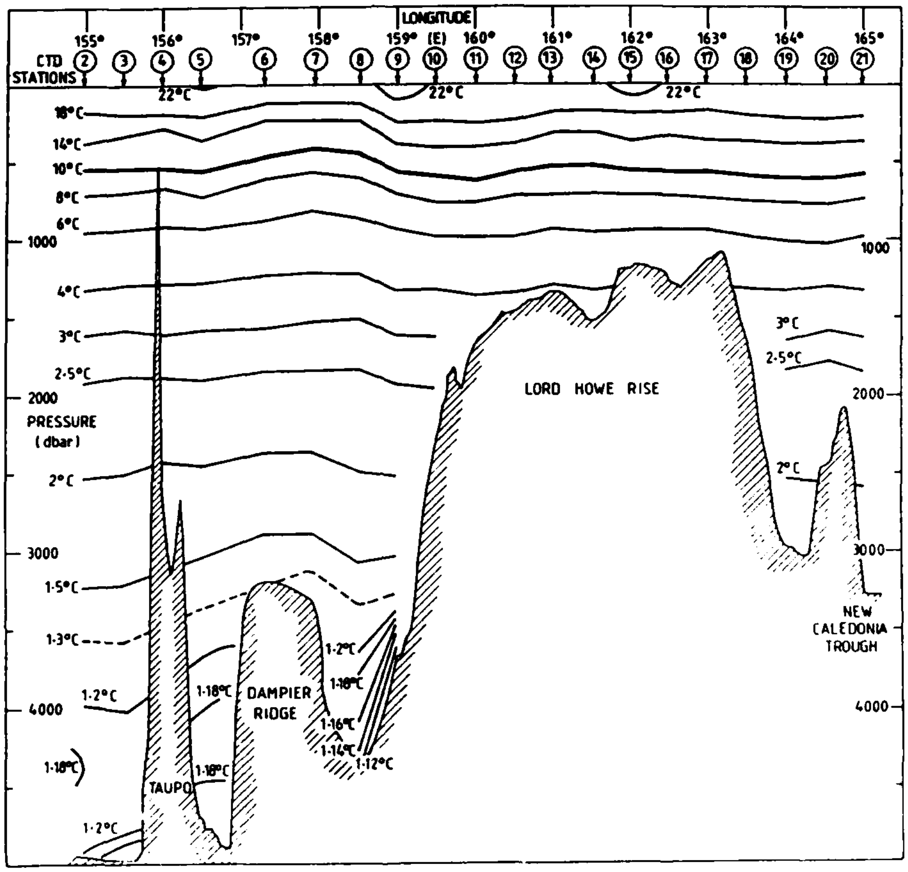

Figure 18(a). Temperature section, north-east from Sydney, RANRL Cruise 1/87

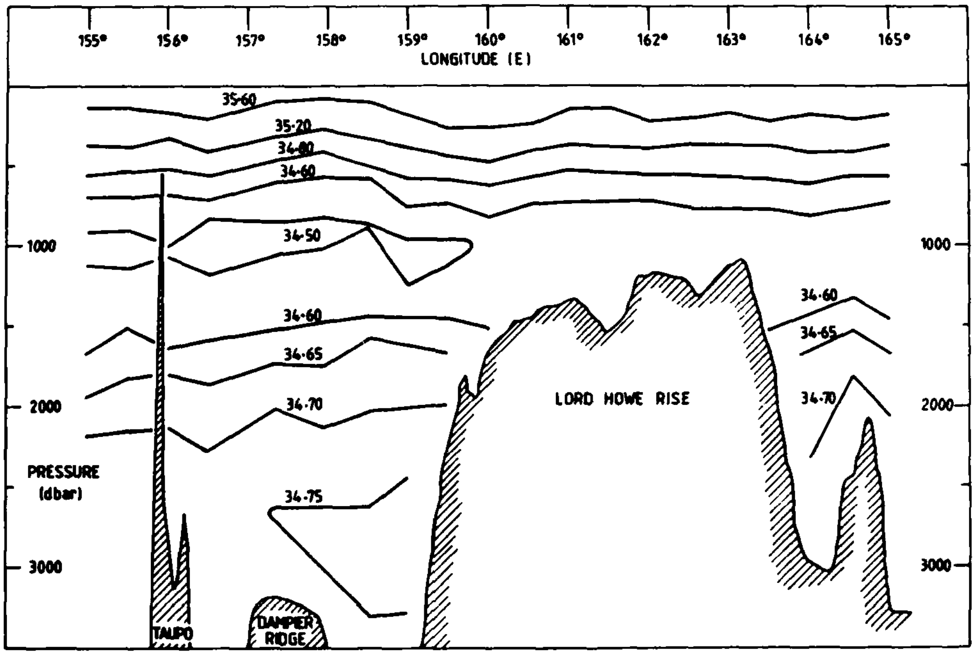

Figure 18(b). Salinity section, RANRL Cruise 1/87

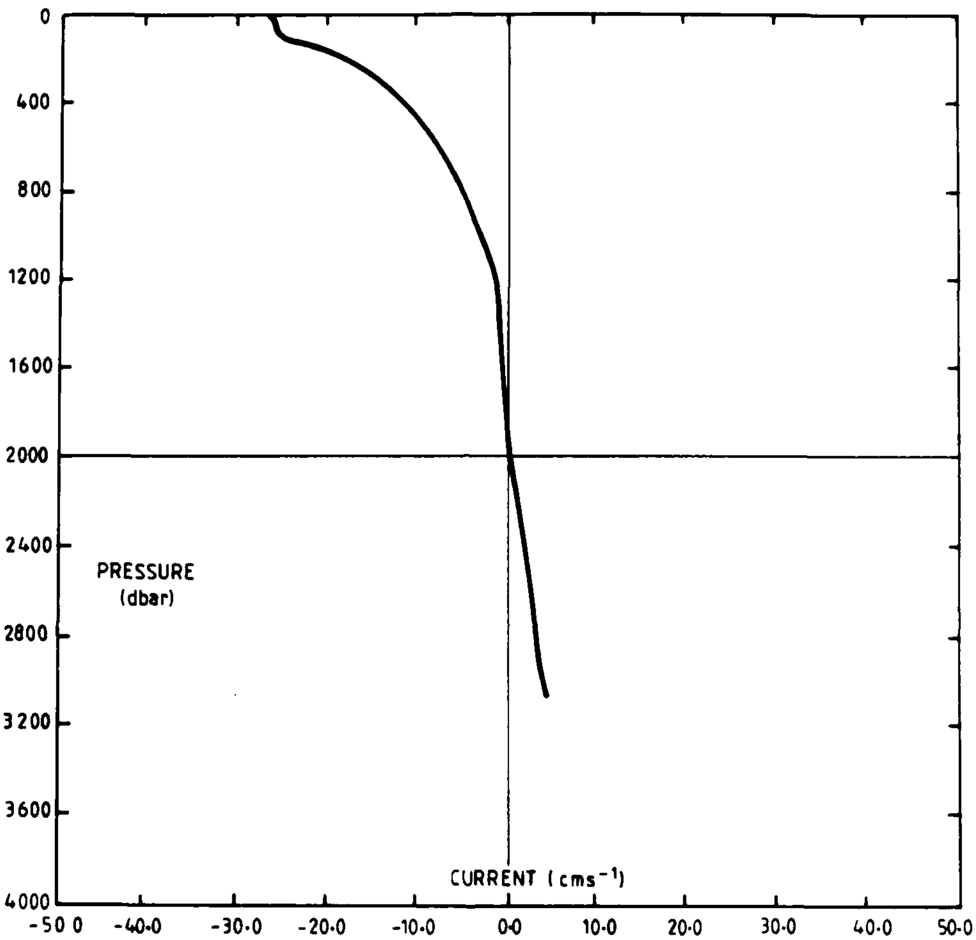

Figure 19(a). Geostrophic current relative to 2000 dbar between station pairs 5 and 6, RANRL Cruise 1/87 (positive is south-south eastward)

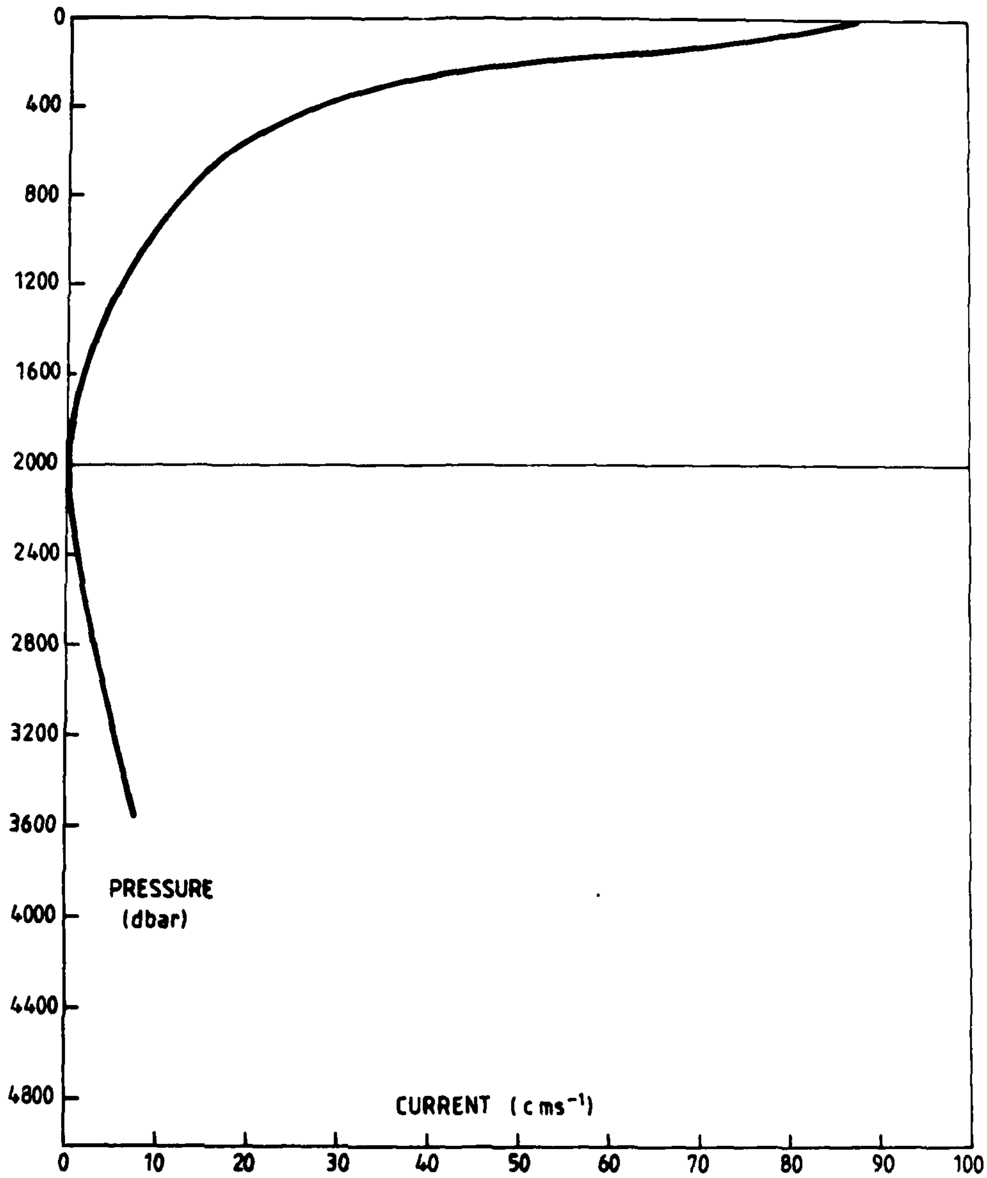

Figure 19(b). Geostrophic current relative to 2000 dbar between station pairs 8 and 9, RANRL Cruise 1/87 (positive is south-eastward)

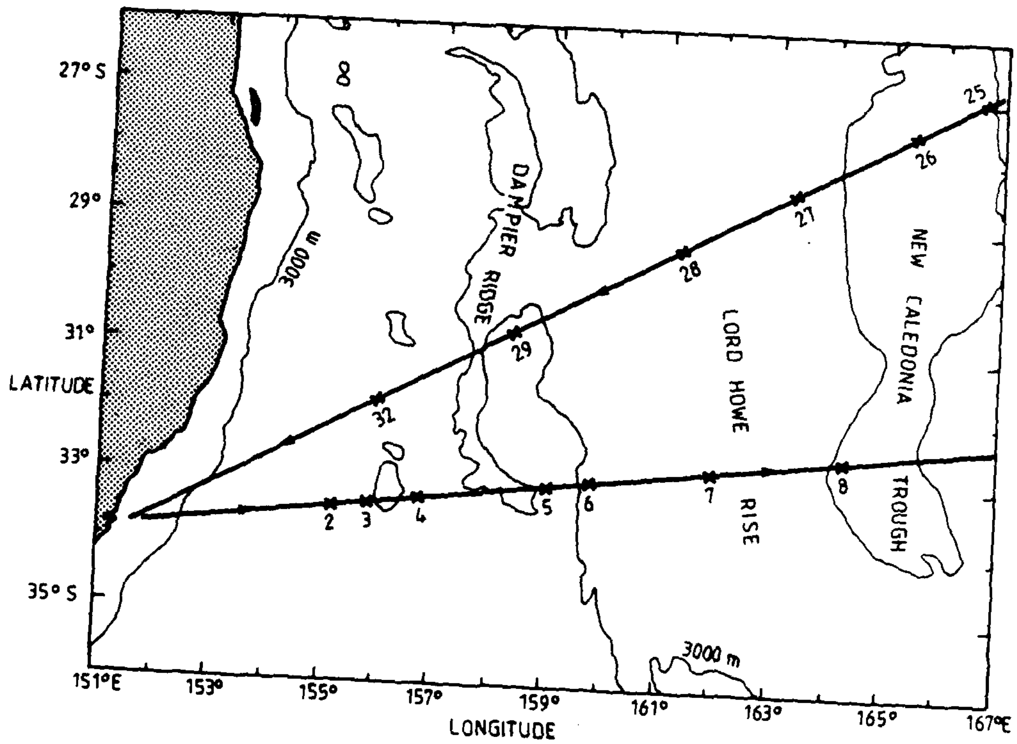

Figure 20. Track and stations for RANRL Cruise 12/87

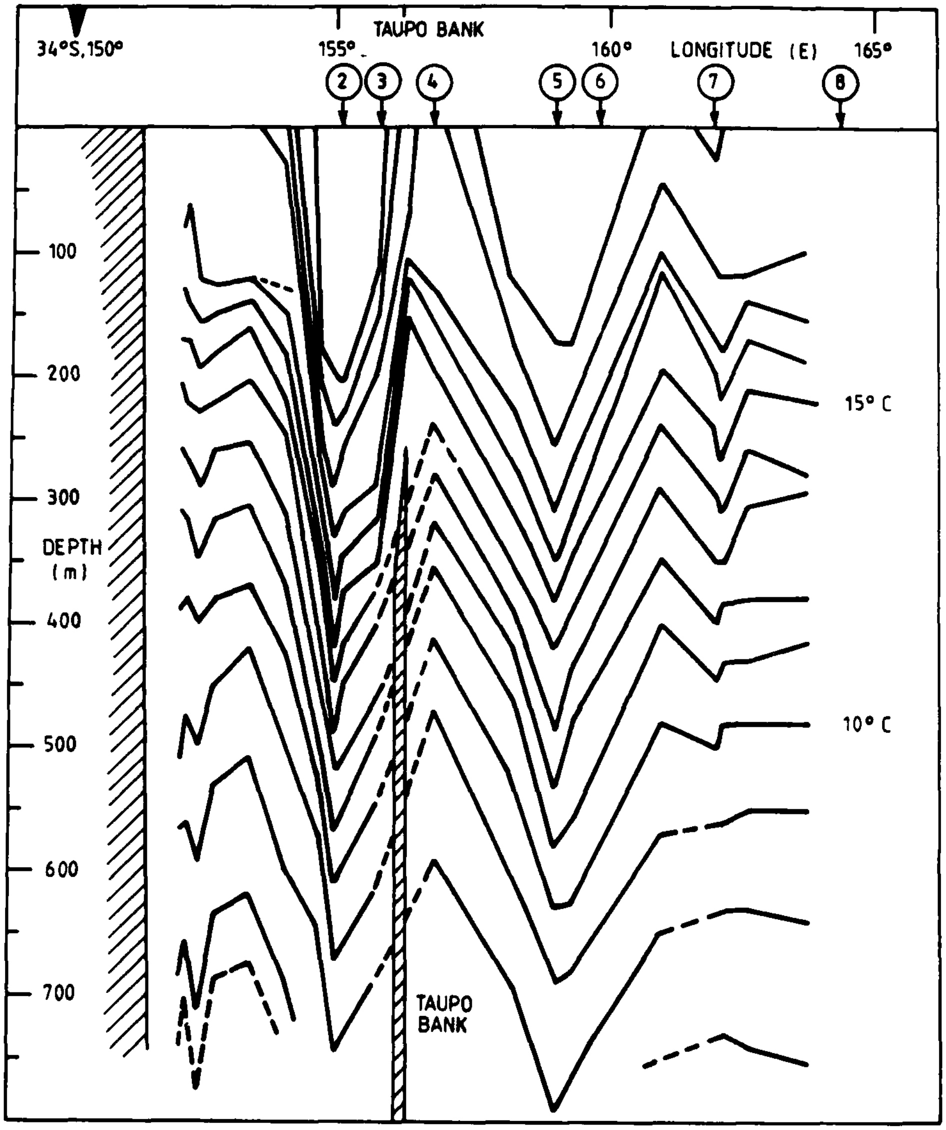

Figure 21(a). XBT section, north-east from Sydney, RANRL Cruise 12/87, 28 July 1987 to 05 August 1987, (GMT)

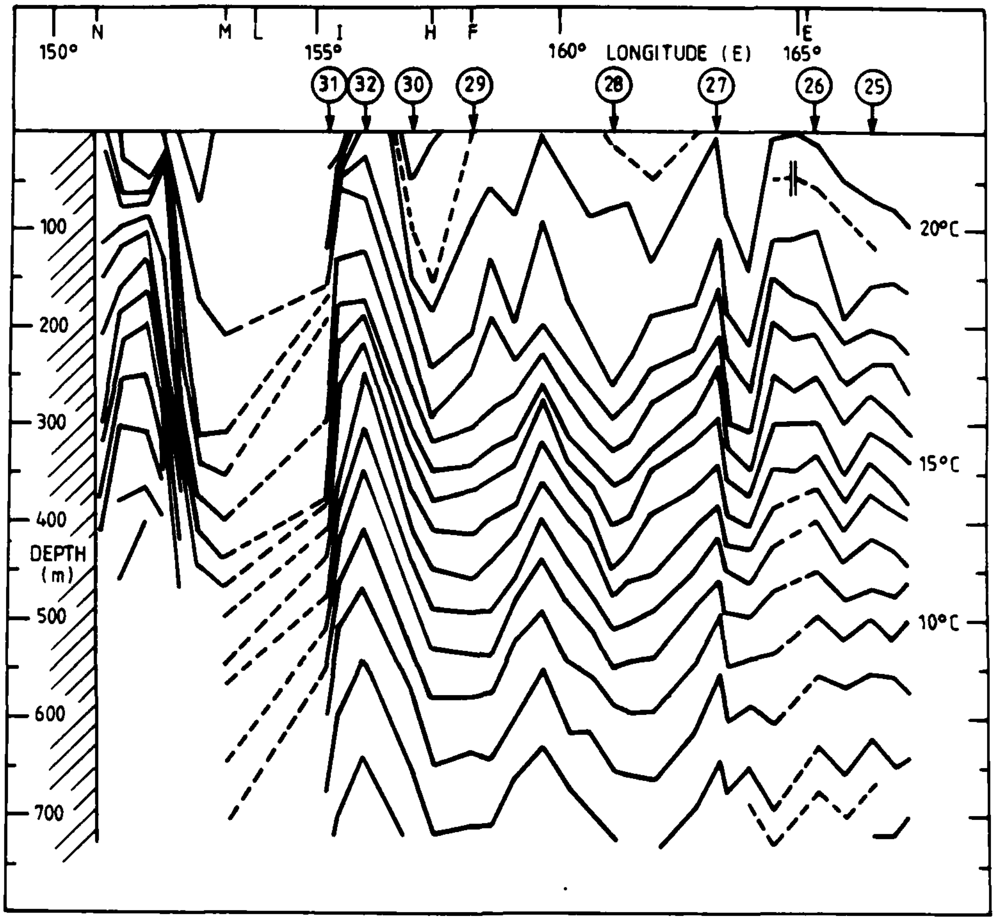

Figure 21(b). XBT section, north-east from Sydney, RANRL Cruise 12/87

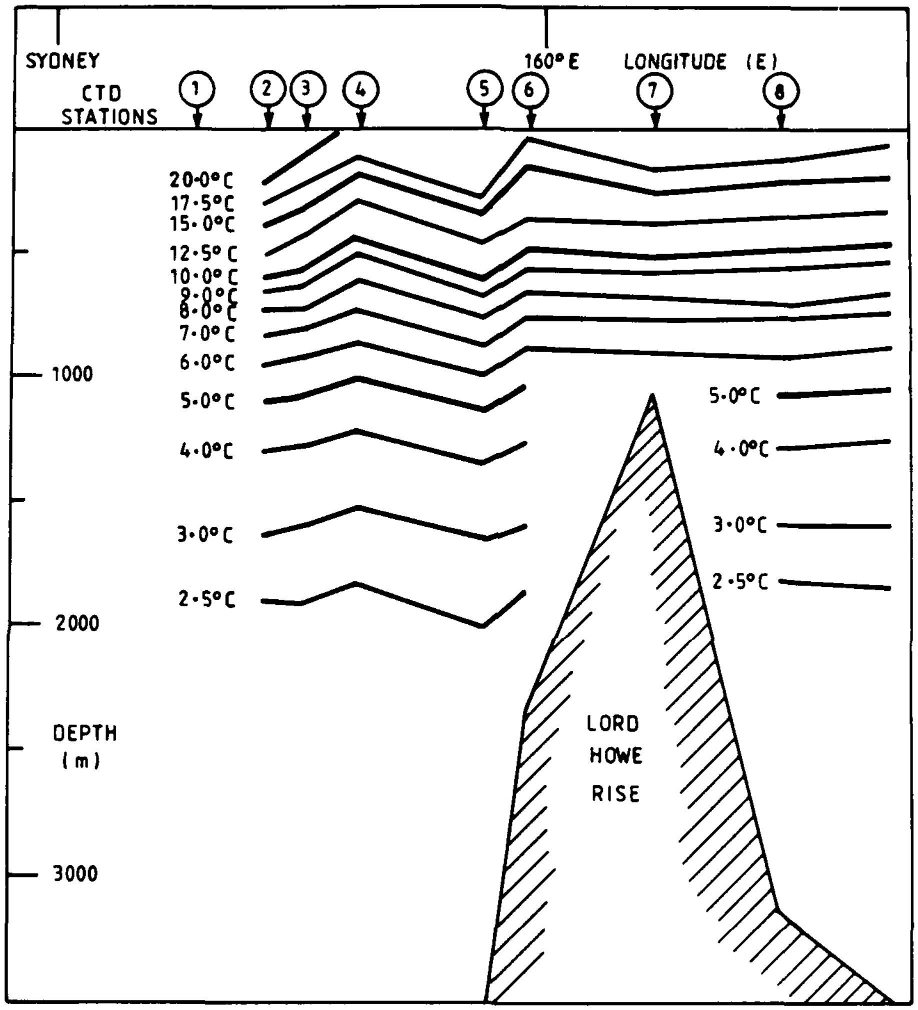

Figure 22(a). Temperature section, east-northeast from Sydney, RANRL Cruise 12/87

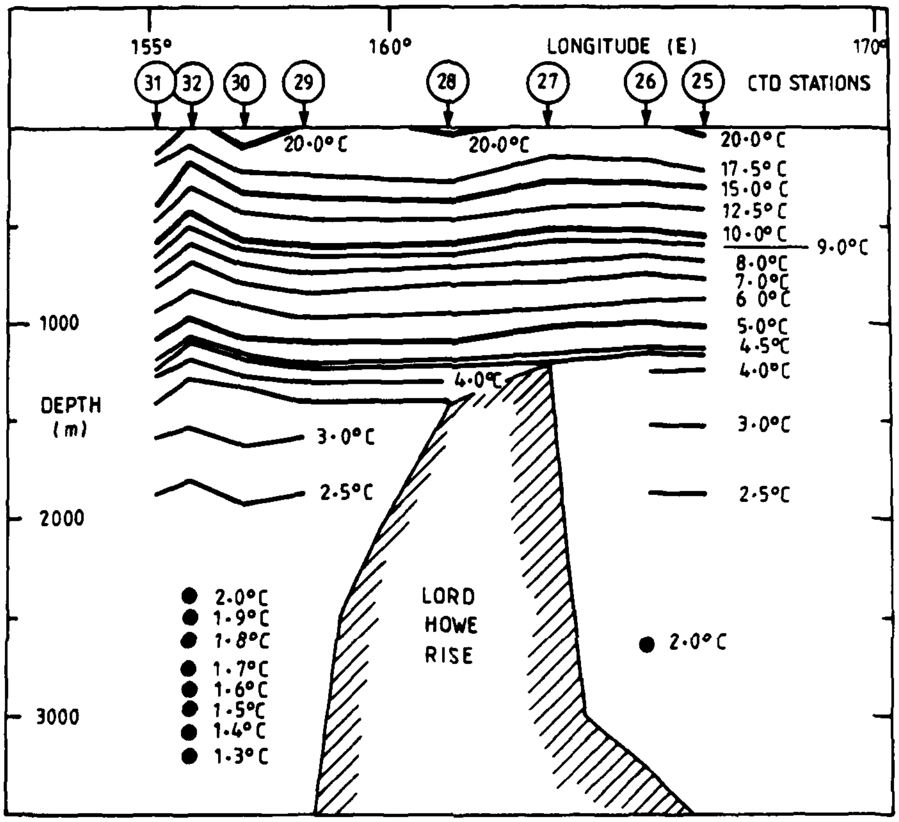

Figure 22(b). Temperature section, north-east from Sydney, RANRL Cruise 12/87

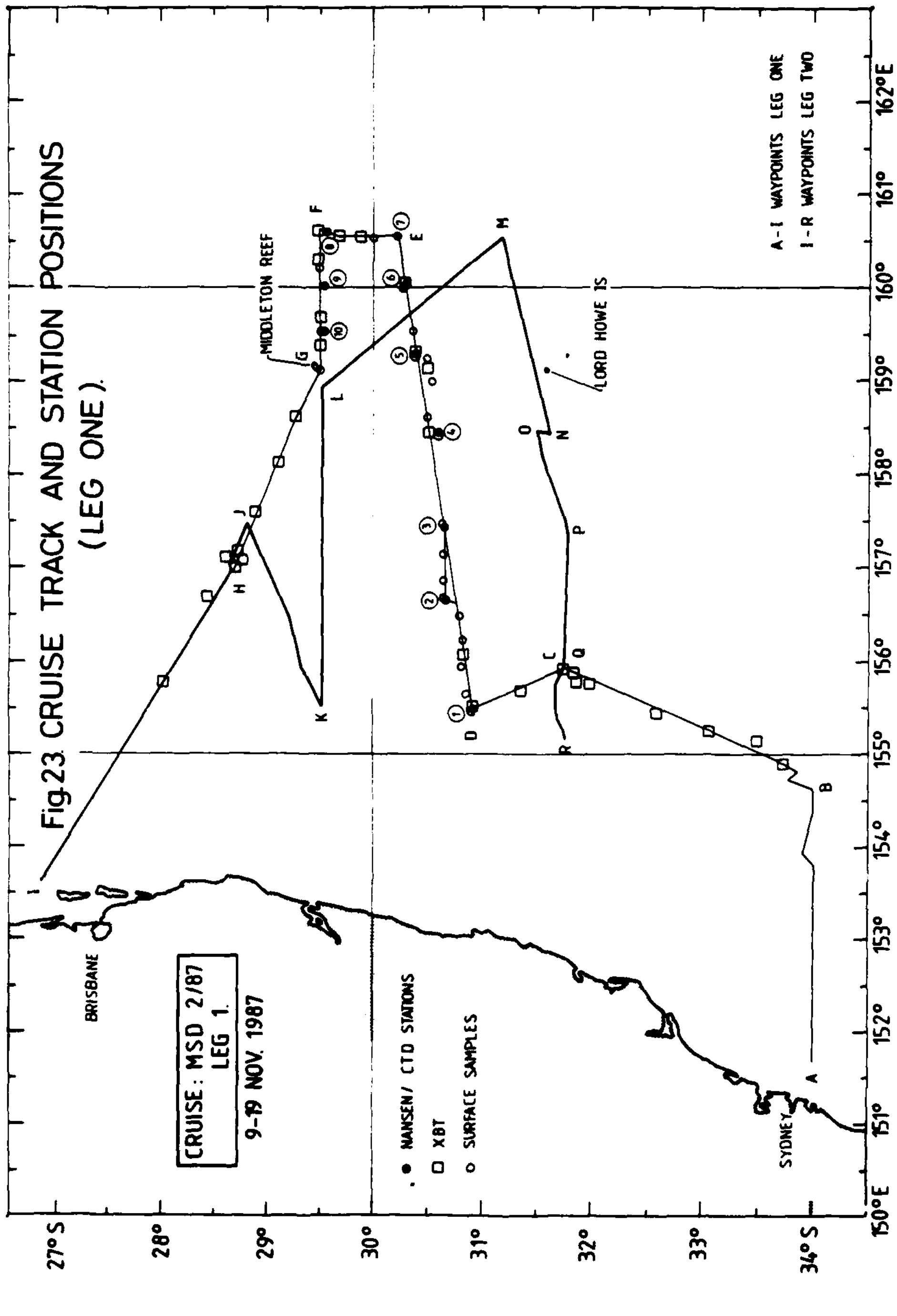

Figure 23. Cruise track and station positions, leg one, MSD Cruise 2/87

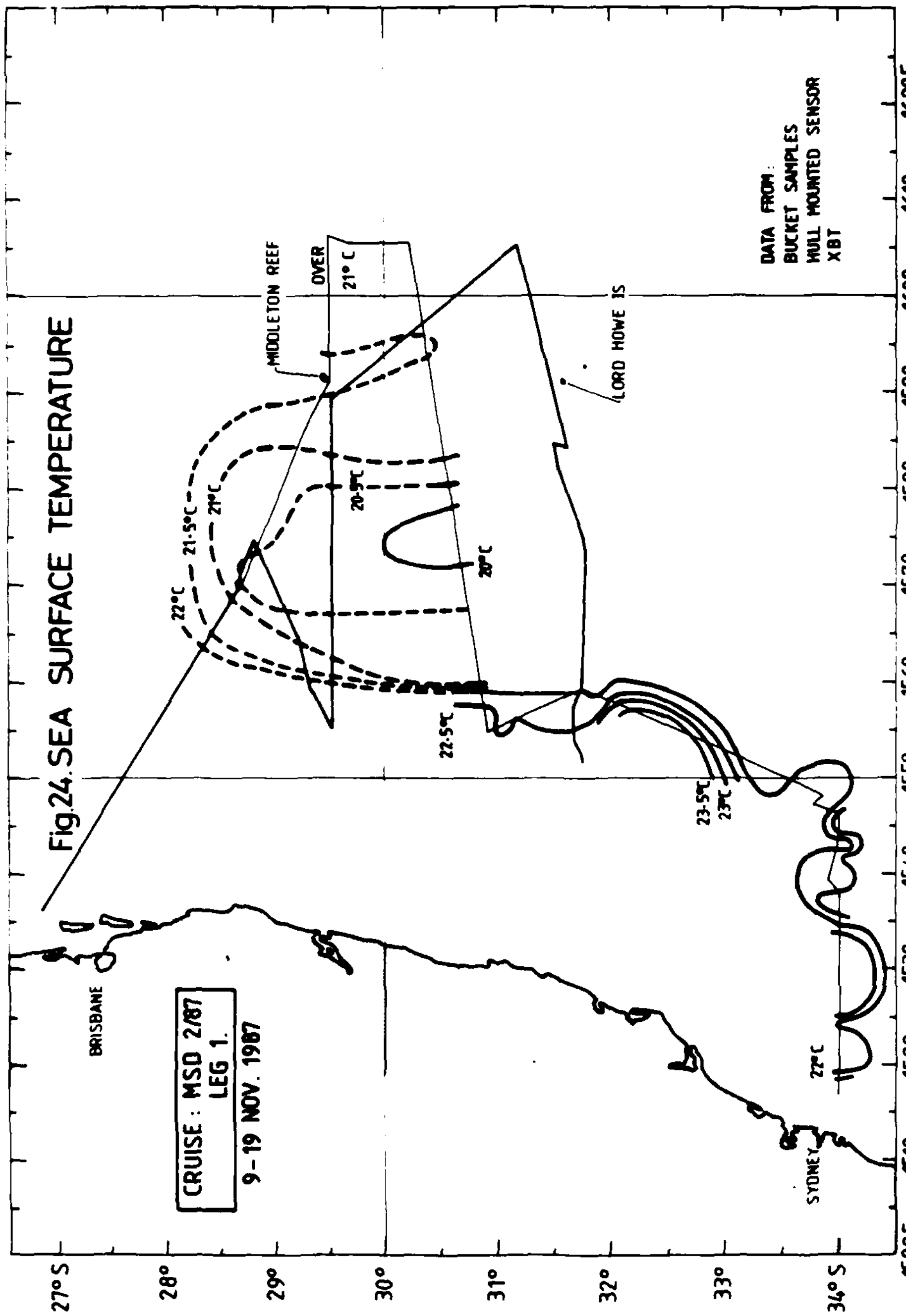

Figure 24. Sea surface temperature, leg one, MSD Cruise 2/87

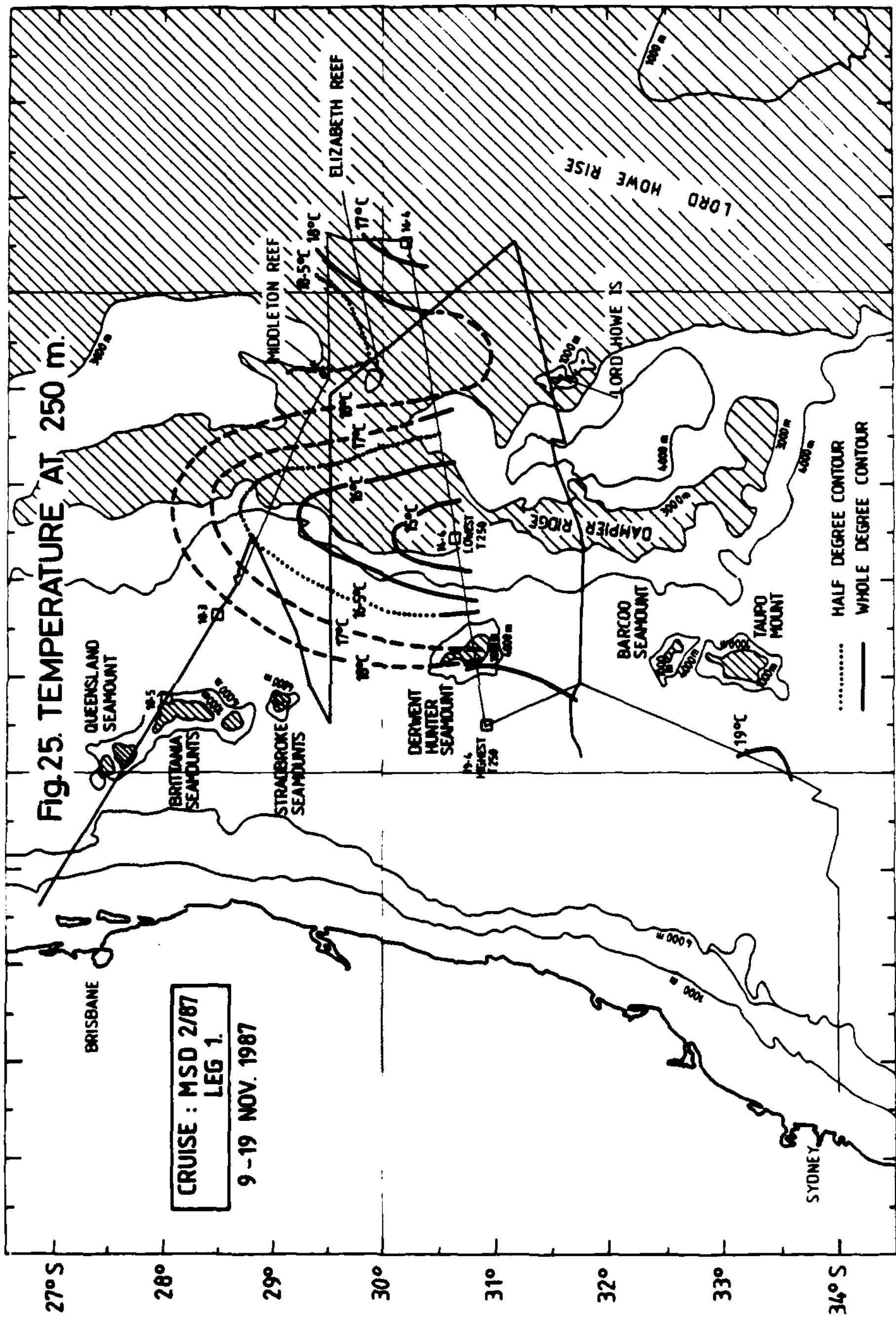

Figure 25. Temperature at 250 m, leg one, Cruise 2/87

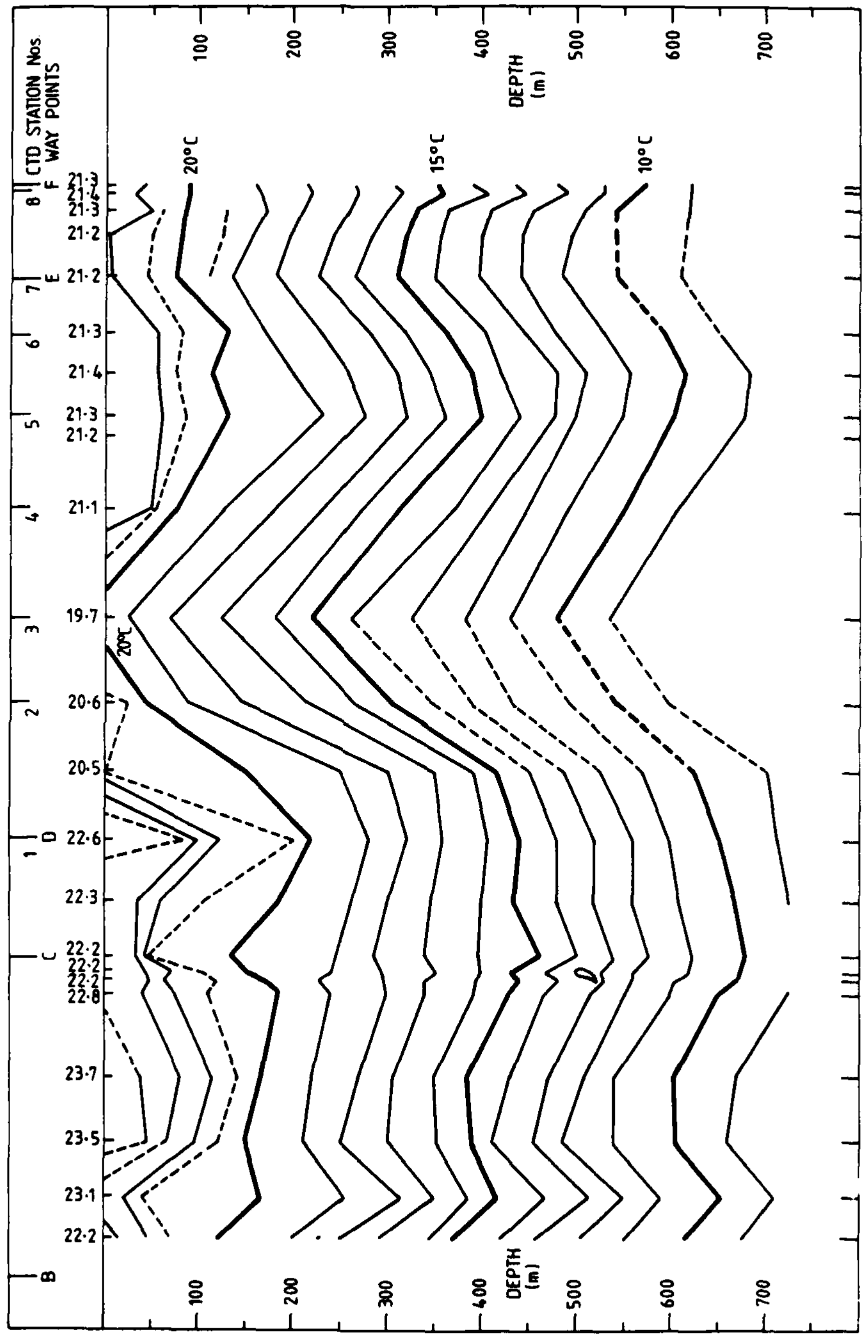

Figure 26(a). XBT section, leg 1, MSD Cruise 2/87, B to F

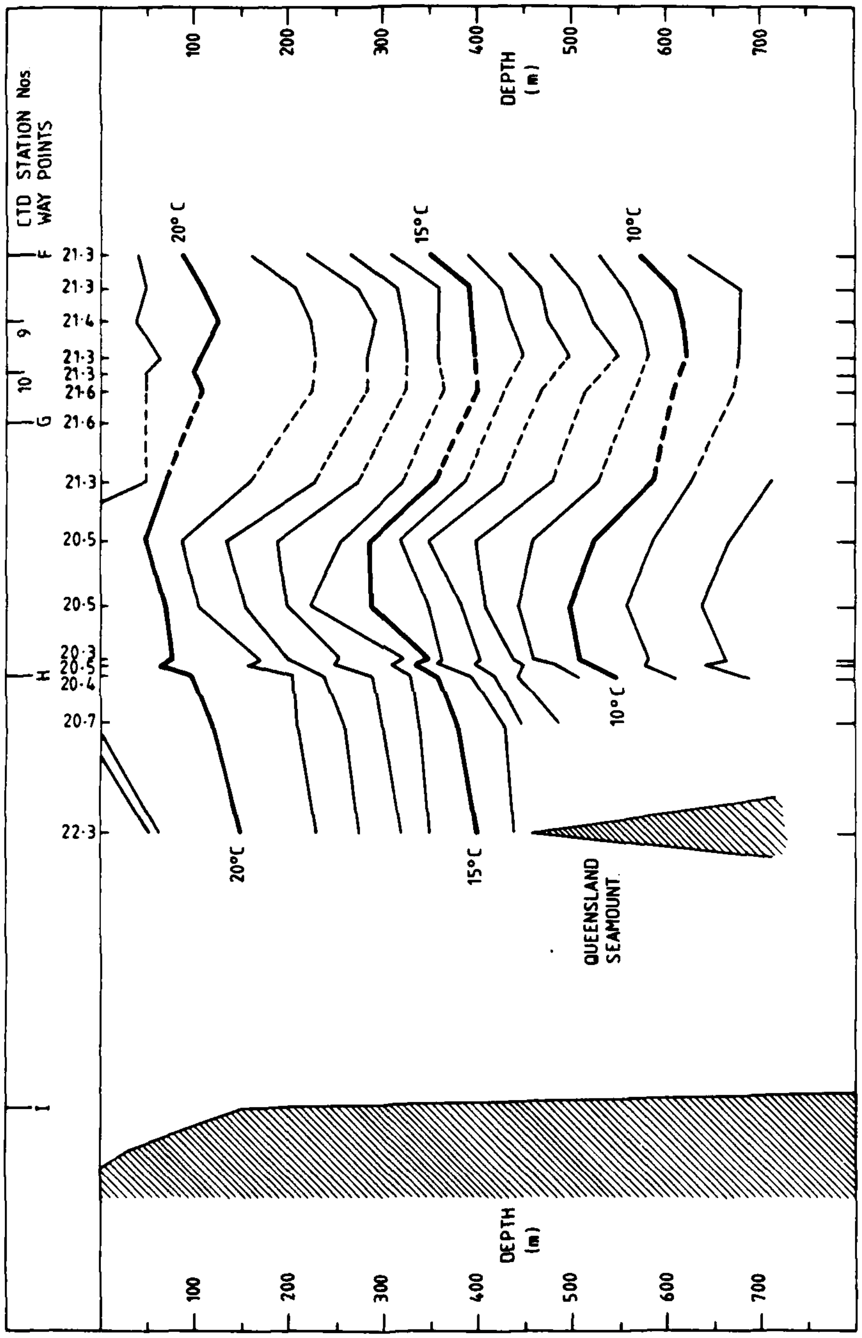

Figure 26(b). XBT section, leg 1, MSD Cruise 2/87, F to I

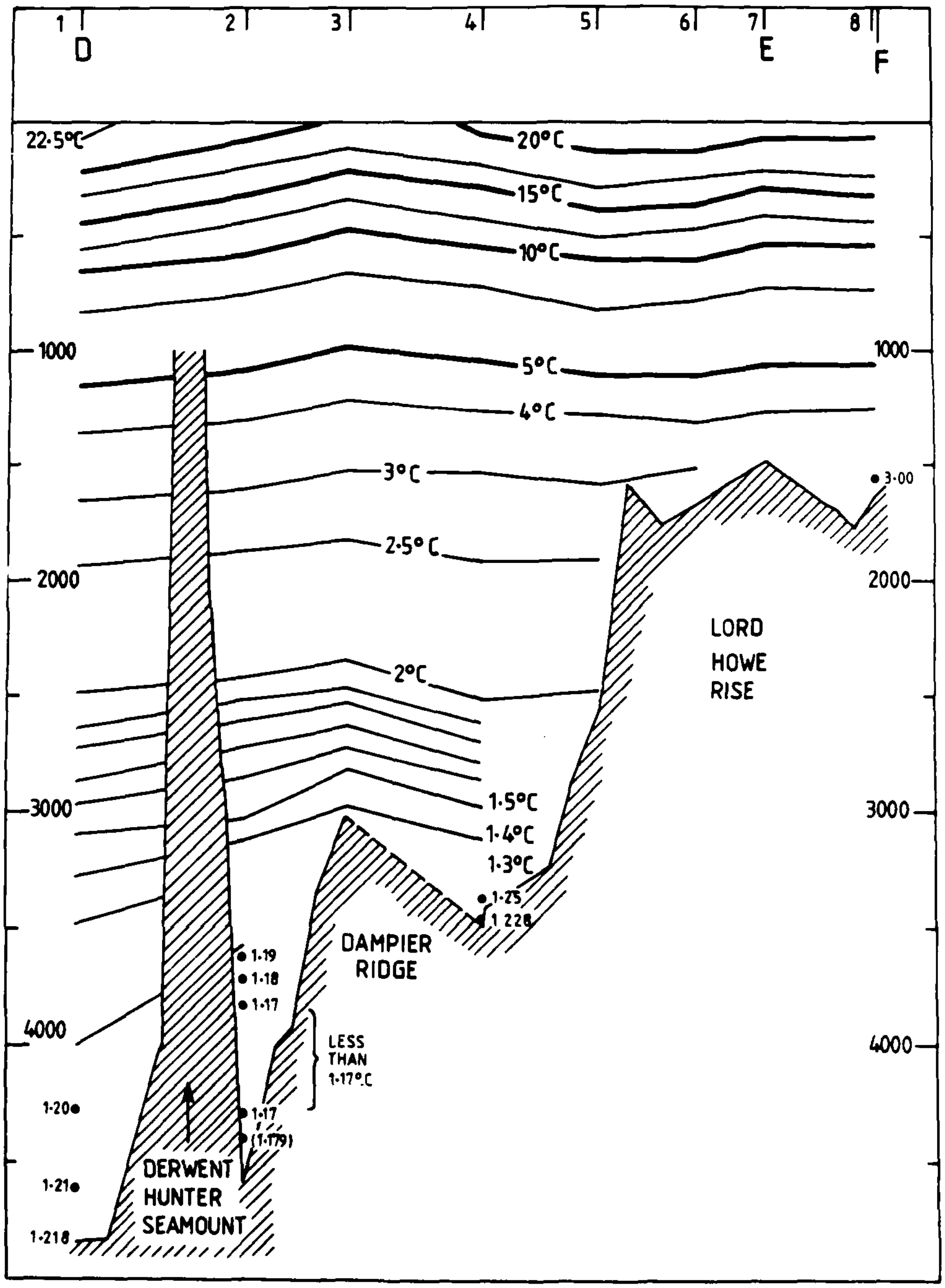

Figure 27(a). CTD temperature section, leg 1, MSD Cruise 2/87

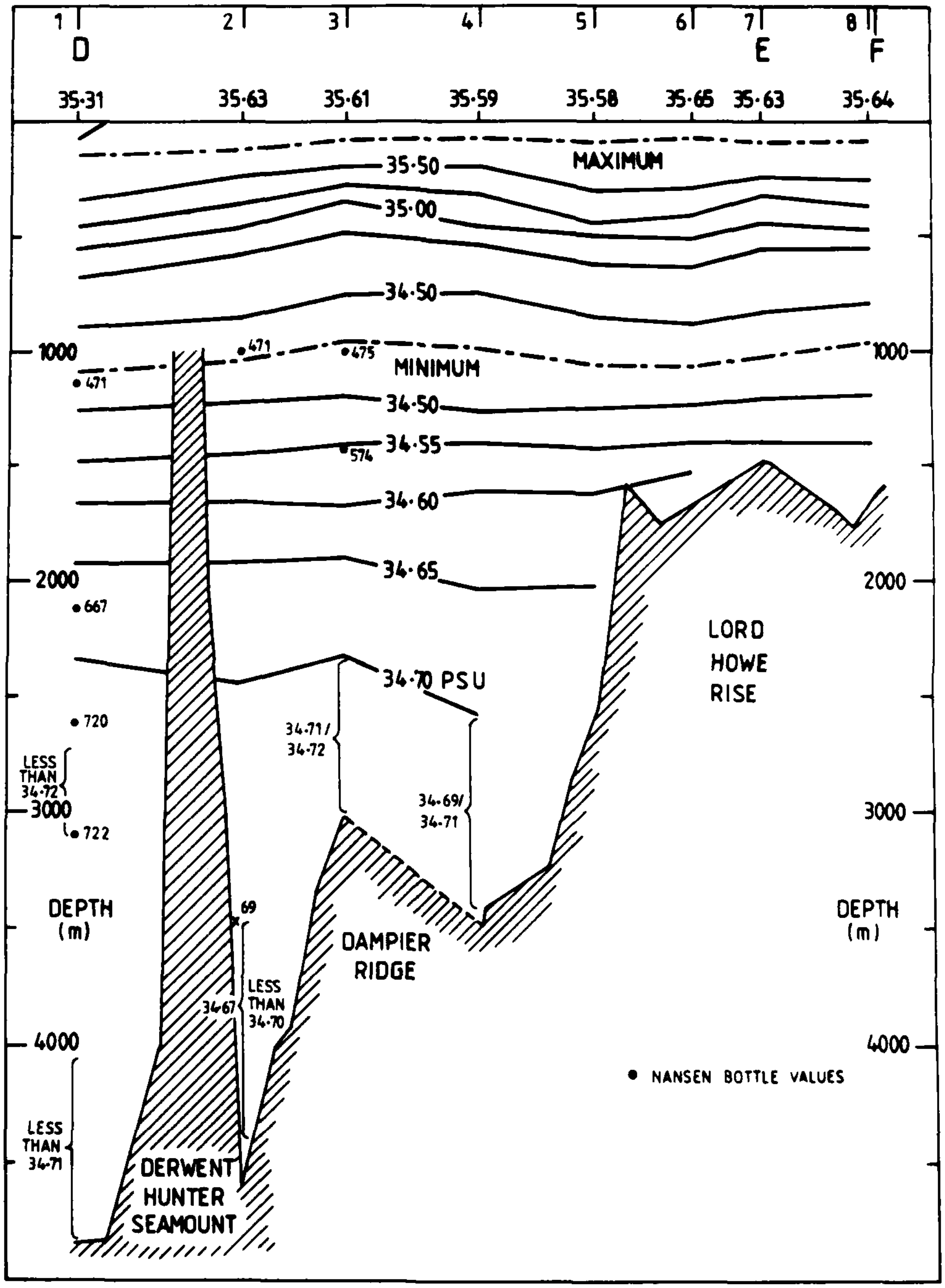

Figure 27(b). CTD salinity section, leg 1, MSD Cruise 2/87

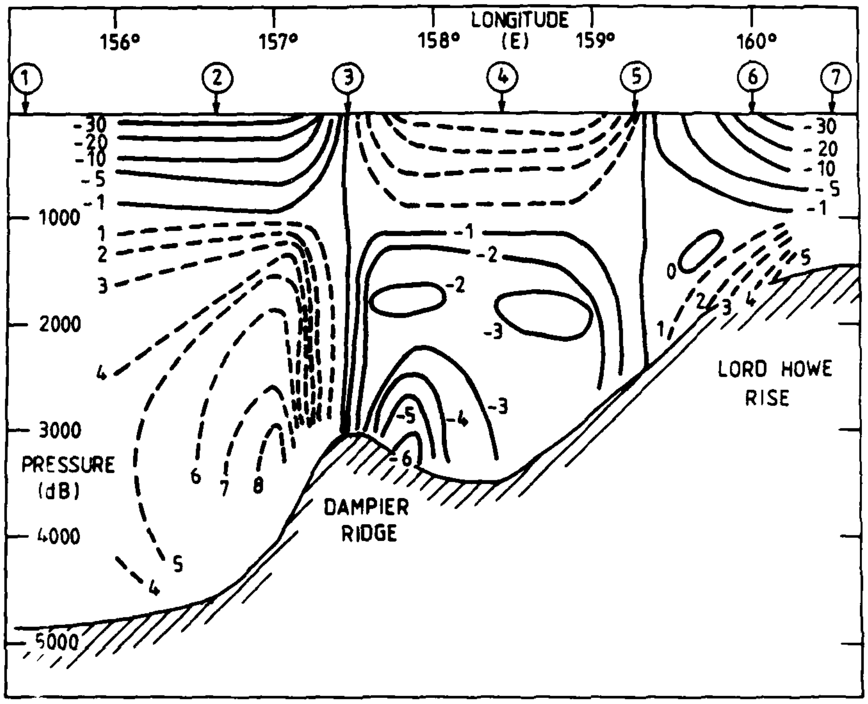

Figure 28. Cross-section of geostrophic currents relative to 1000 dbar from stations 1 to 7 of MSD Cruise 2/87. (Contours are labelled in centimetres^{-1}, contours of northward velocities are full lines and southward velocities are dashed lines)

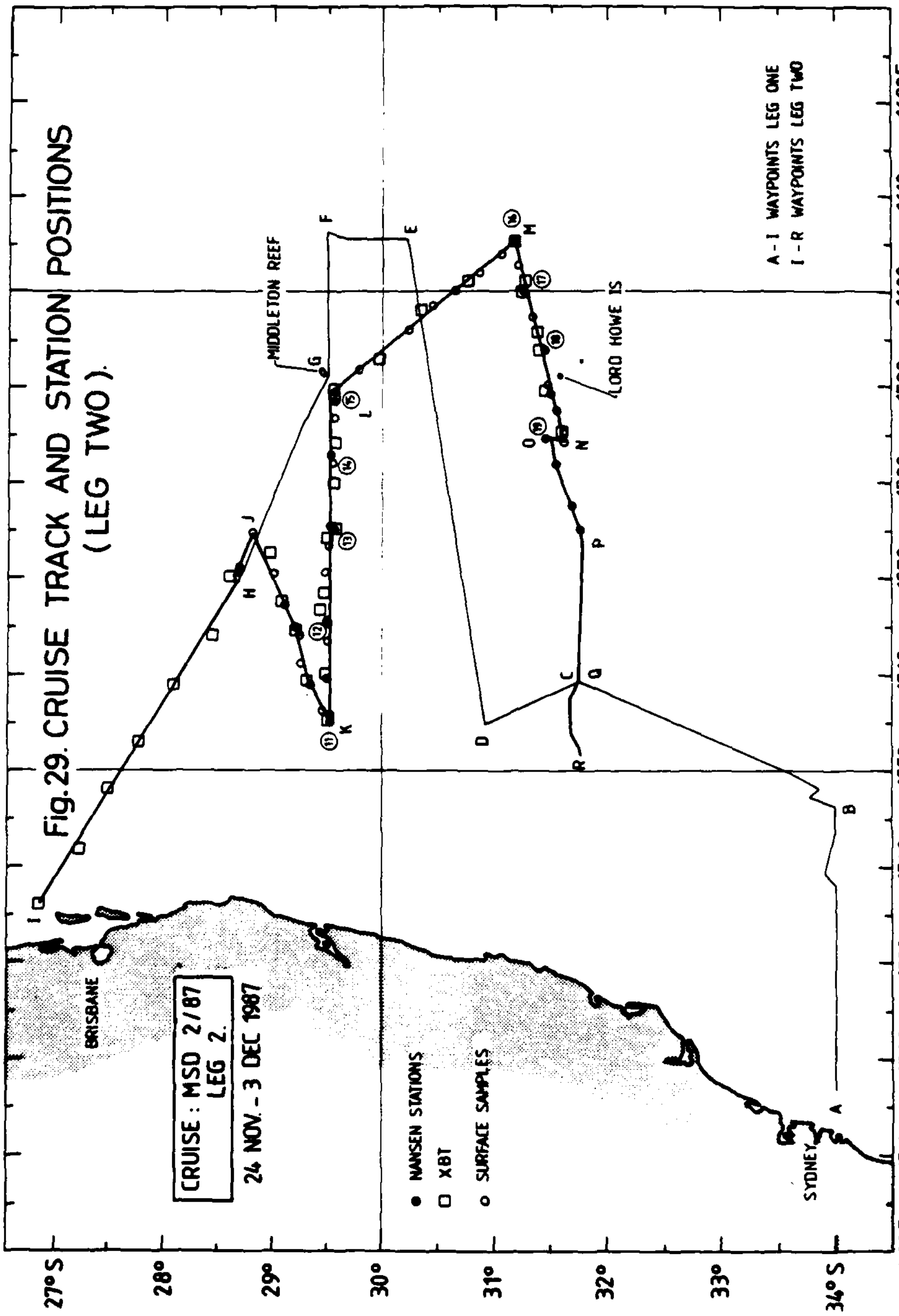

Figure 29. Cruise track and station positions, leg two, MSD Cruise 2/87

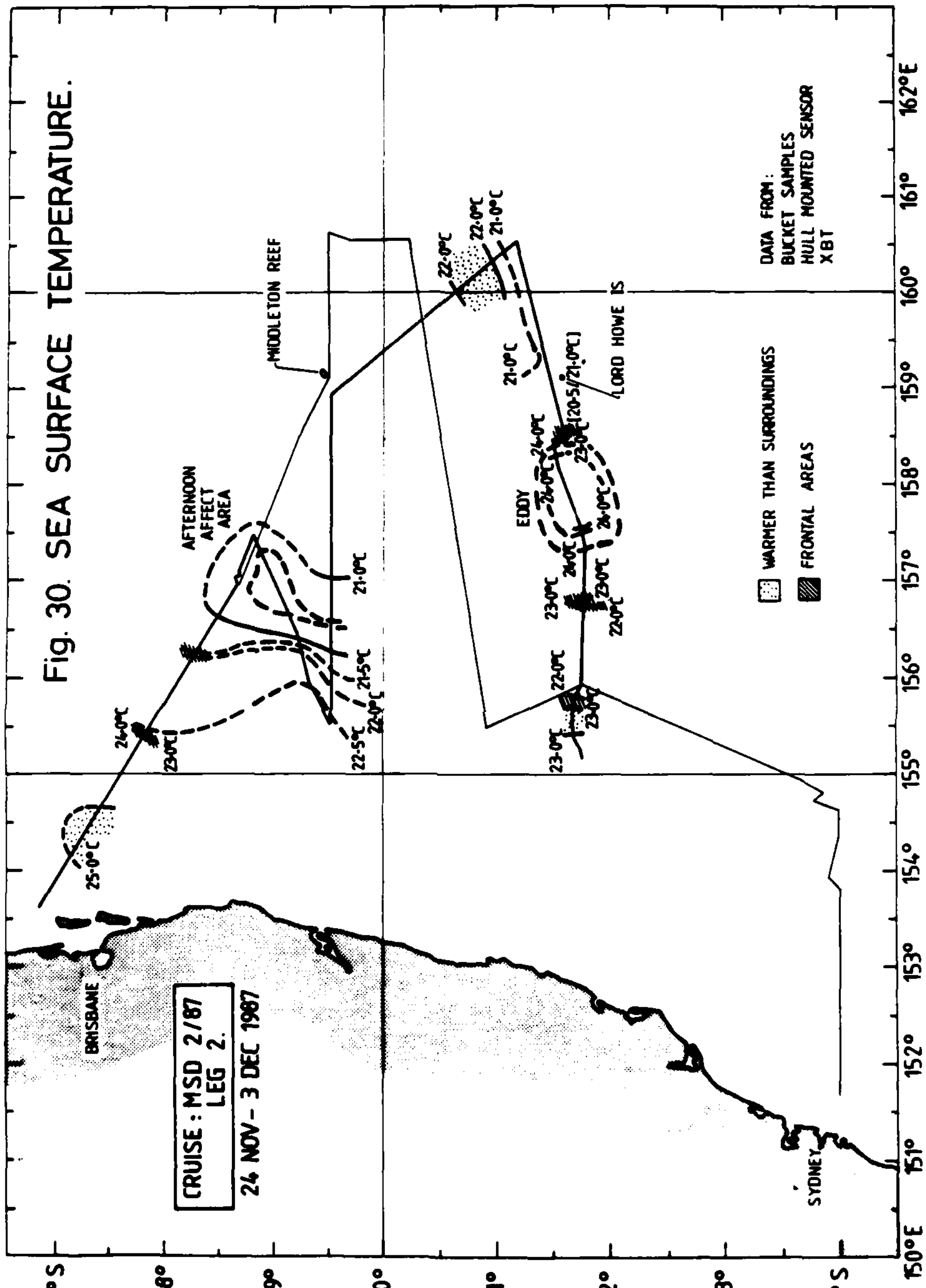

Figure 30. Sea surface temperature, leg two, MSD Cruise 2/87

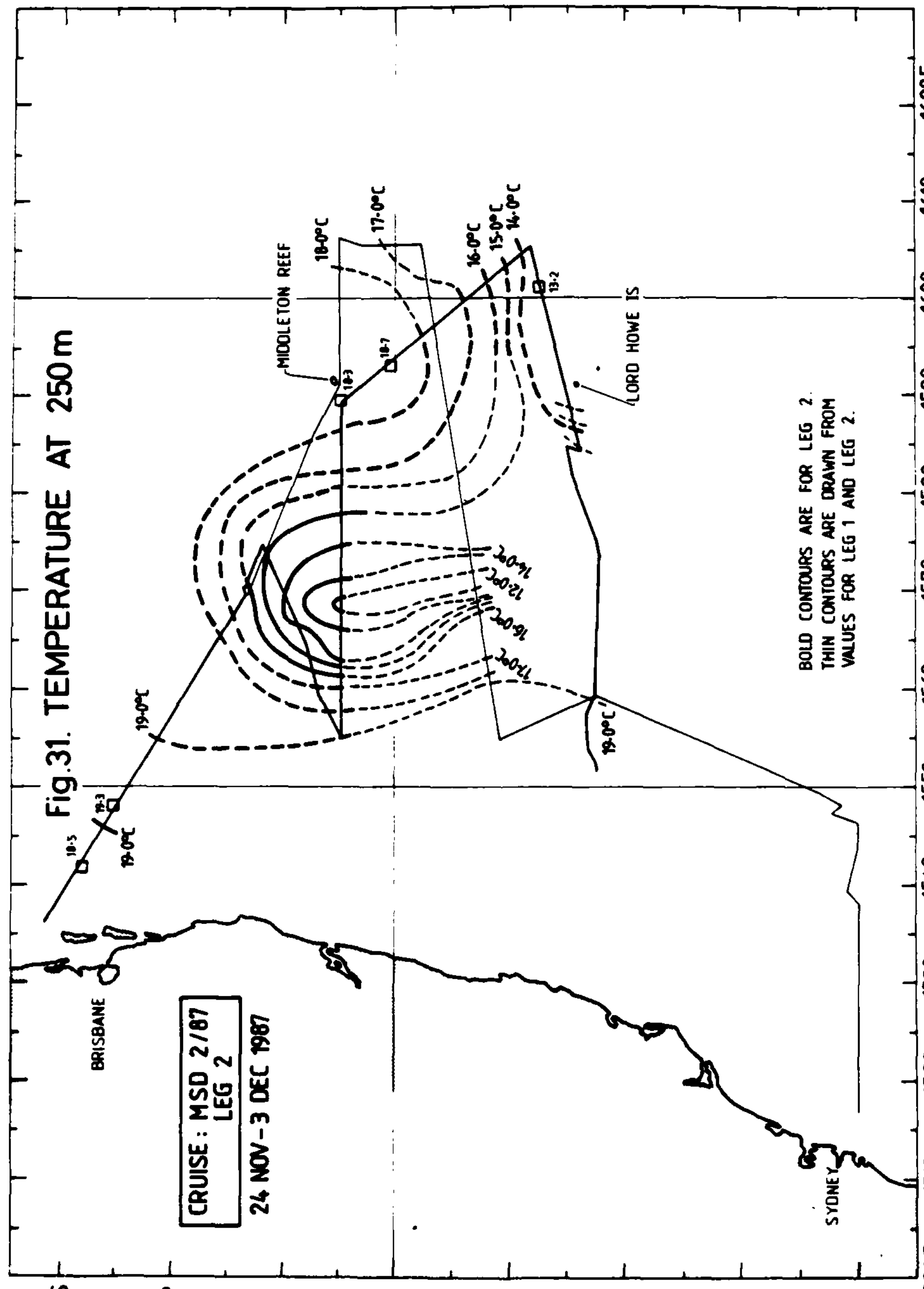

Figure 31. Temperature at 250 m, leg two, MSD Cruise 2/87

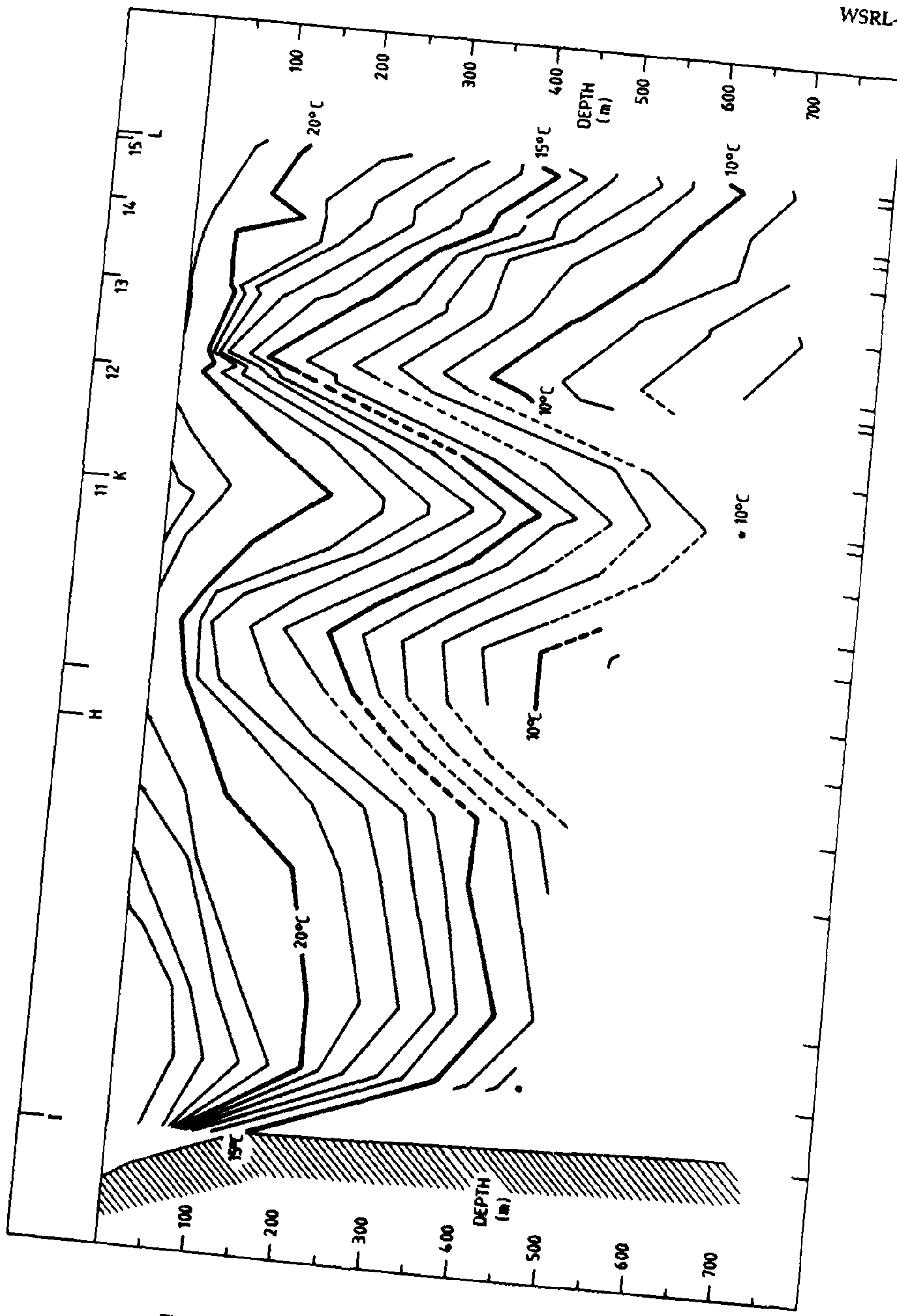

Figure 32(a). XBT section, leg 2, MSD Cruise 2/87, I to L

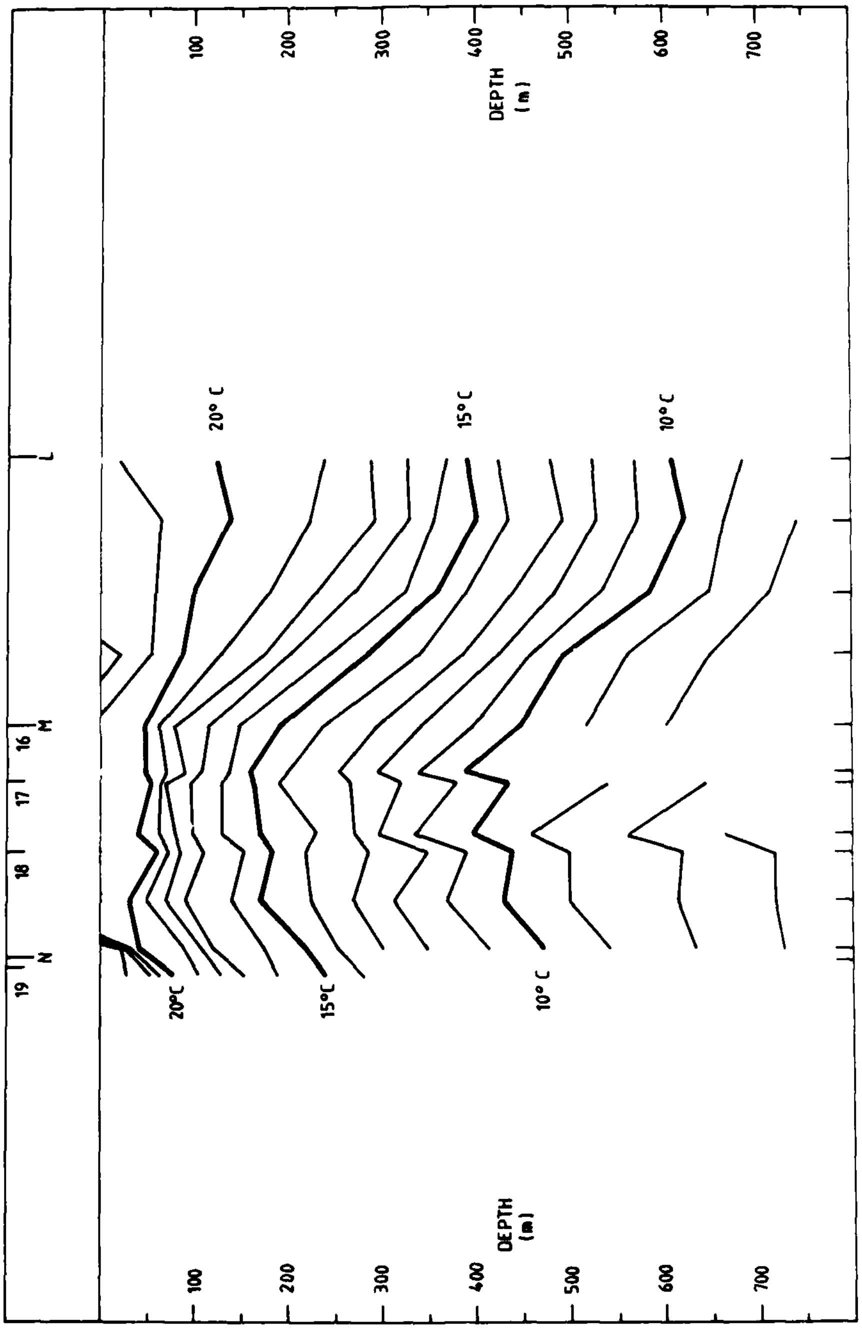

Figure 32(b). XBT section, leg 2, MSD Cruise 2/87, L to N

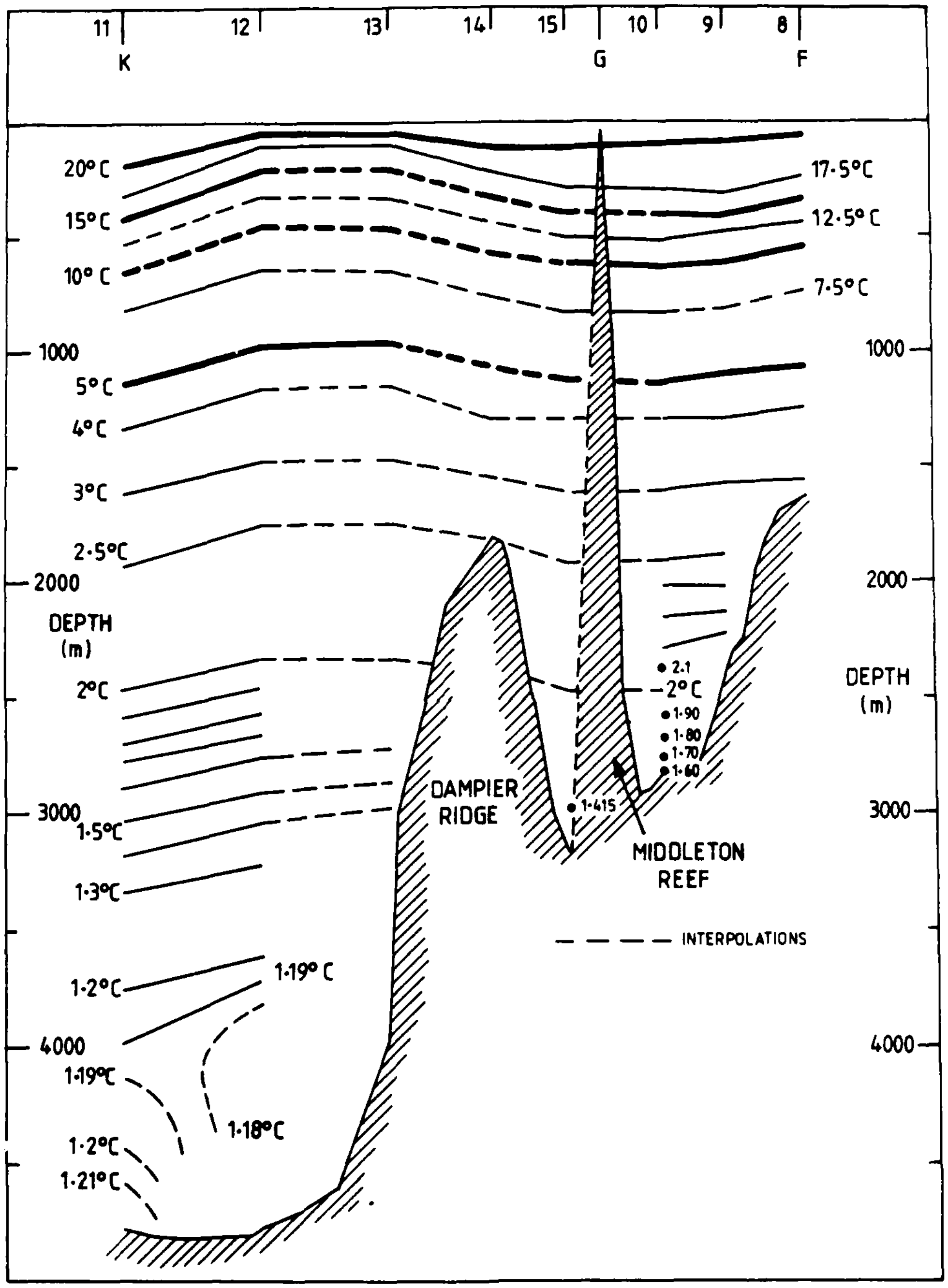

Figure 33(a). CTD/Nansen temperature section, MSD Cruise 2/87, leg 2

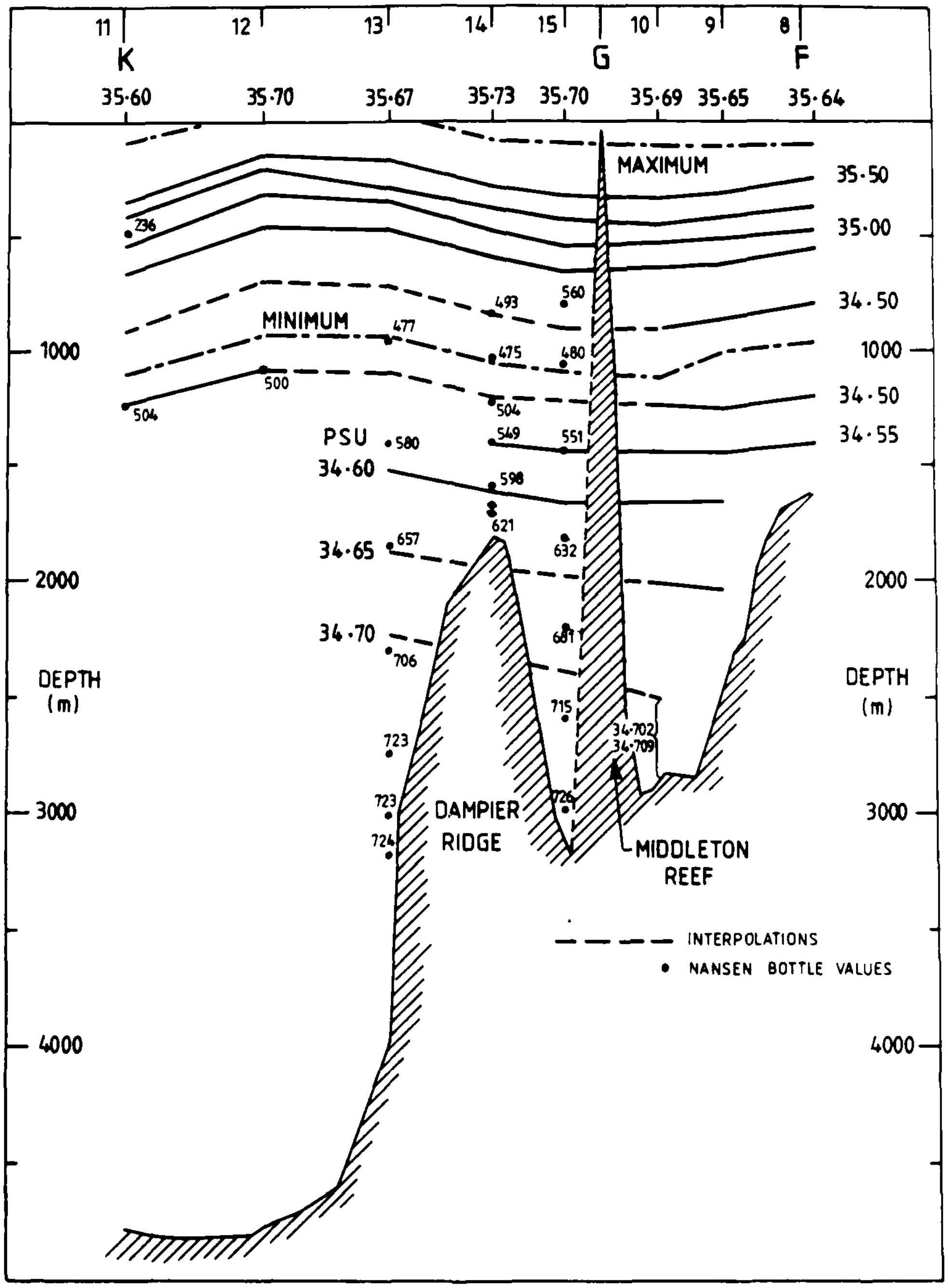

Figure 33(b). CTD/Nansen salinity section, MSD Cruise 2/87, leg 2

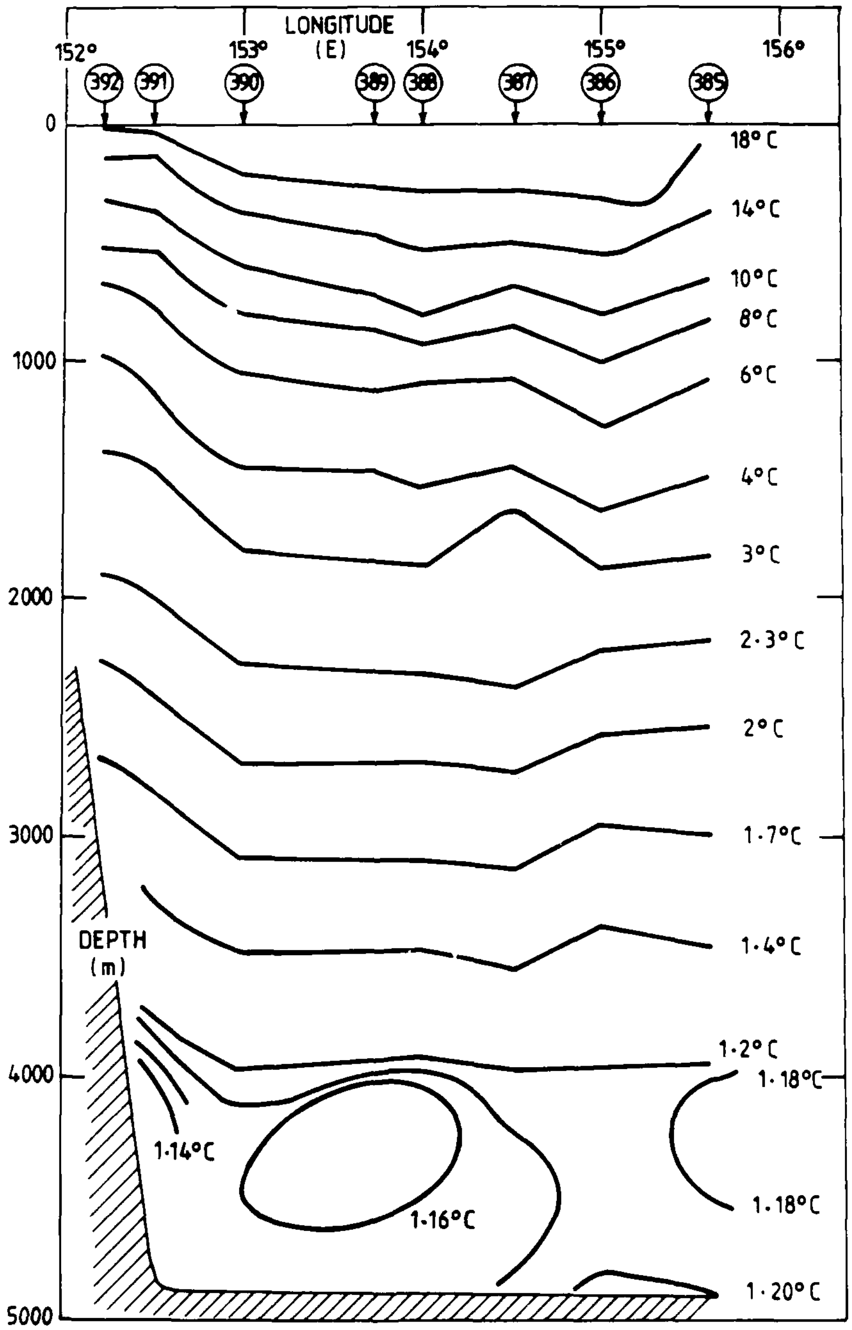

Figure 34(a). Temperature section, along latitude 33°45' S, CSIRO's Sprightly Cruise SP 10/81

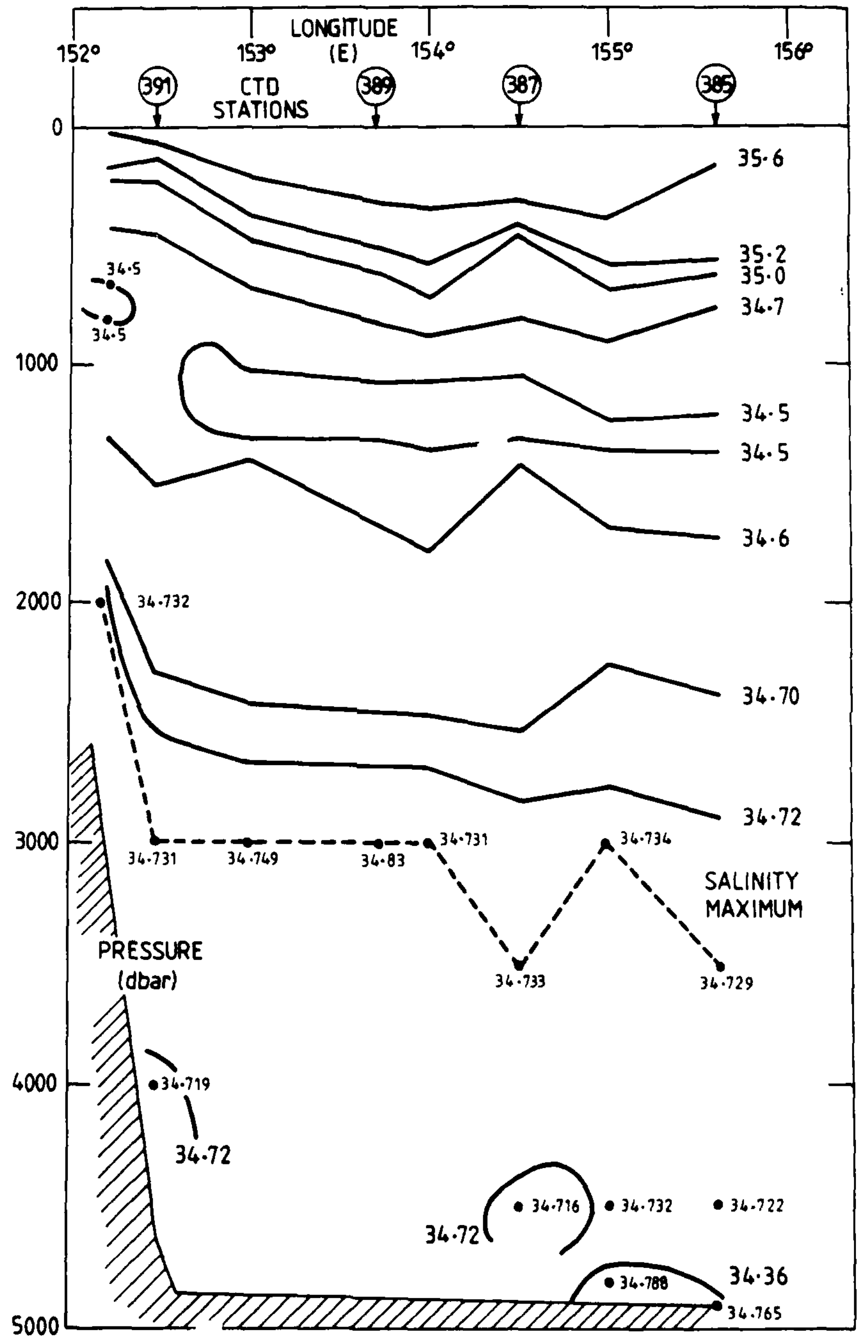

Figure 34(b). Salinity (psu) section along latitude 33°45' S. CSIRO's Sprightly Cruise SP 10/81

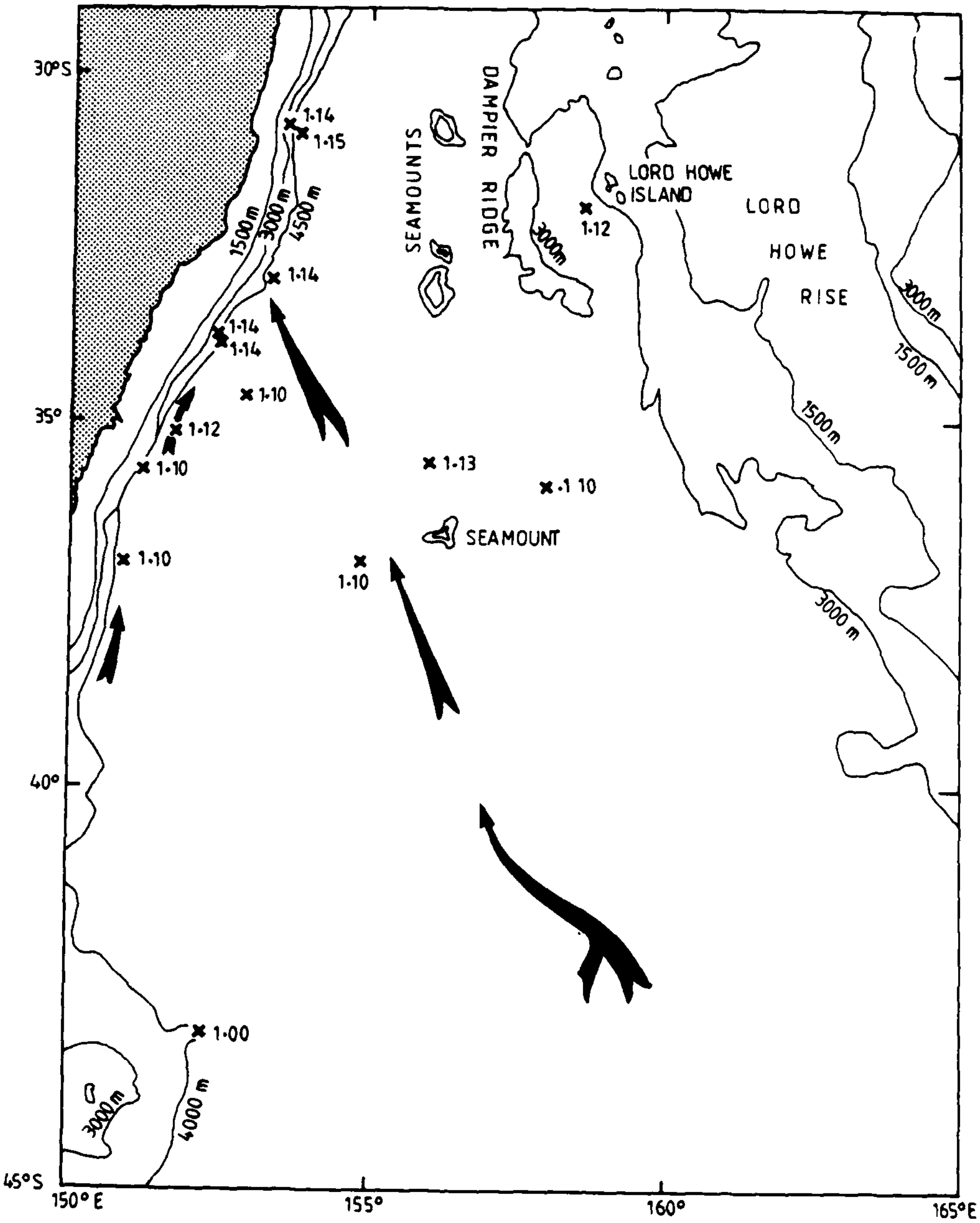

Figure 35. Positions of near-bottom, cold water bodies, and their minimum temperatures. (Broad arrows show bottom current directions inferred by Jenkins (1984))

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DOCUMENT CONTROL DATA SHEET

Security classification of this page : UNCLASSIFIED

1 DOCUMENT NUMBERS

AR Number : AR-005-869

Series Number : WSRL-TM-7/89

Other Numbers :

2 SECURITY CLASSIFICATION

a. Complete Document : Unclassified

b. Title in Isolation : Unclassified

c. Summary in Isolation : Unclassified

3 DOWNGRADING / DELIMITING INSTRUCTIONS

4 TITLE

DEEP STRUCTURE OF THE EAST AUSTRALIAN CURRENT AND TASMAN FRONT

5 PERSONAL AUTHOR (S)

P.J. Mulhearn,
L.J. Hamilton and
B.D. Scott

6 DOCUMENT DATE

April 1989

7 7.1 TOTAL NUMBER OF PAGES 77

7.2 NUMBER OF REFERENCES 15

8 8.1 CORPORATE AUTHOR (S)

Weapons Systems Research Laboratory

8.2 DOCUMENT SERIES and NUMBER
Technical Memorandum
7/89

9 REFERENCE NUMBERS

a. Task : DST 86/145

b. Sponsoring Agency : DSTO

10 COST CODE

11 IMPRINT (Publishing organisation)

Defence Science and Technology Organisation

12 COMPUTER PROGRAM (S) (Title (s) and language (s))

13 RELEASE LIMITATIONS (of the document)

Approved for Public Release

Security classification of this page : UNCLASSIFIED

Security classification of this page : UNCLASSIFIED

14 ANNOUNCEMENT LIMITATIONS (of the information on these pages)

No limitation

15 DESCRIPTORS

a. EJC Thesaurus Terms

Dynamic oceanography
Physical oceanography

b. Non - Thesaurus Terms

16 COSATI CODES

0803
0810

17 SUMMARY OR ABSTRACT
(if this is security classified, the announcement of this report will be similarly classified)

In order to investigate the deep structure of the East Australian Current and the Tasman Front, surface to bottom Conductivity-Temperature-Depth (CTD) casts were obtained along various sections through them on eight different research cruises between October 1985 and December 1987. From this data set it was found that the depth to which these major oceanographic features extended was highly variable, lying between 2500 m and 4500 m. It was found that any flow below 1500 m in the Tasman Front was block from flowing eastward firstly by the Dampier Ridge and then by the Lord Howe Rise, and so flowed either north or south, depending on the orientation of the near-surface flow. On many sections, at abyssal depths, near-bottom bodies of water were found with temperatures approximately 0.05°C lower than their surroundings and with widths and depths of order 50 km and 600 m respectively. Their mode of generation is unknown.

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