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Hydrological Features of the Near Shelf Waters off Fremantle, Western Australia, during 1974

I. Webster, T. J. Golding
and
N. Dyson

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HYDROLOGICAL FEATURES OF THE NEAR SHELF WATERS OFF FREMANTLE, WESTERN AUSTRALIA, DURING 1974

I. Webster, T.J. Golding and N. Dyson

CSIRO Division of Fisheries and Oceanography
P.O. Box 21, Cronulla, NSW 2230

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Abstract

Results are presented for a number of hydrology stations occupied at about 30°S off the Western Australian coast during 1974. Seasonal variations in the surface layer temperature-salinity characteristics are described. The temperature-salinity characteristics of water masses to depths of 1500 m are discussed in detail. The dominant water masses influencing the surface characteristics were the highly saline South Indian Central water mass and a low salinity tropical water mass from northern latitudes. Schematic diagrams are presented for surface circulation patterns during this same period. There was a strongly seasonal pattern of strong southerly flow along the continental slope during May-September and more variable circulation during the rest of the year.

INTRODUCTION

This report presents a summary of some of the data from the first year of operation of the R.V. "Sprightly" oceanography programme off Western Australia. Data from November 1973 to December 1974 are presented.

DATA AND METHODS

Field work on R.V. "Sprightly" consisted of standard hydrology casts Bathythermograph (B/T), casts, surface sampling for salinity and temperature, operation of Geomagnetic Electrokinetograph (G.E.K.) (von Arx 1962) and maintenance of moored current meters. No attempt has been made in this report to deal with the current meter data and only limited use has been made of the B/T data. Many of these data have already been published as data reports (Edwards 1977; Golding *et al.* 1977). The reader is referred to these for the cruise tracks and the raw data discussed in this report.

Table 1 shows details of the work done on the cruises analysed in this report. Chemical analysis was done in accordance with Major *et al.* (1972), although not all the chemical data are presented here.

Standard procedures were used for calculating geopotential anomalies assuming a level of no motion at 1300 m (Hamon 1972). Geopotential anomalies could not be contoured because of inadequate station spacing. Instead, geostrophic velocity vectors were computed where components of the velocity were available at approximate right angles to one another. These currents were computed at depths of 0, 50, 100, 200, 500 and 1000 m.

RESULTS

Temperature-salinity Relationships

Figures 1, 2, 3 and 4 are plots of temperature *vs.* salinity, temperature *vs.* depth, salinity *vs.* depth and density *vs.* depth for a station at about 114°E, 30°S sampled during December 1973, March 1974, June 1974 and September 1974. Although the details on plots for other neighbouring stations differ, these figures exhibit the general features. For convenience, the temperature-salinity relationships of the water column will be discussed separately for the four sections of the Temperature/Salinity (TS) curve shown in Fig. 1.

Section A

Section A was marked by a prominent salinity minimum of 34.4‰. Throughout Section A the temperature decreased with depth. At the salinity minimum the temperature was about 5°C, indicating that this body of water was the northward flowing Antarctic Intermediate described by Rochford (1961). The depth of the salinity minimum ranged from 700 to 1000 m, but usually was found at 900 m during the year. The depth variations of this minimum did not appear to be systematic. Below the salinity minimum the salinity increased with depth while the temperature decreased slowly giving a σ_t gradient of approximately 1.2 per 1000 m. This water mass appeared to be formed from mixtures of the Antarctic Intermediate core layer and the Deep Salinity Maximum South East Indian water mass (Rochford *ibid*). On many of the TS plots a minor salinity maximum occurred below the Antarctic Intermediate water mass. This could represent vestiges of the North West Indian Intermediate water mass (Rochford 1965), which flows southward below the Antarctic Intermediate and can be traced as far as the coast of Western Australia. That these salinity maxima were due to southward flowing water is supported by the fact that they tend to be more pronounced on the northern stations of a given cruise than on the southern stations.

Section B

Section B was characterised by a linear TS plot and had a temperature range of approximately 9.2°C to 14.5°C and salinity range of 34.70‰ to 35.55‰. The linearity of the relationship for this body suggests that it was formed from simple mixtures of the core layers of the cold, low salinity Antarctic Intermediate waters and the warmer high salinity South Indian Central water mass (Rochford 1961) which lies nearer to the surface. The TS characteristics of this water mass 'B' varied very little throughout the year. It would therefore appear that seasonal influences did not extend to the depth of this water mass. On average the water mass was found between approximately 300 m and 500 m. Salinity and temperature gradients in this section were fairly constant during the year. In this water mass there was a relatively low density gradient of approximately 0.5 σ_t change in 1000 m.

Section C

Section C had a pronounced salinity maximum of between 35.7‰ and 35.8‰, temperature between 17.0°C and 19.0°C and σ_t between 25.6 and 26.1. This is the South Indian Central water mass found by Rochford (1967) along 110°E at similar latitudes. He described this water mass as northward spreading with a salinity of 35.8‰ to 35.9‰, a σ_t of 25.9 to 26.0 and a depth ranging between 100 m and 200 m.

The present data gave the depth range of the salinity maximum at 25 m to 325 m, yet it most commonly was found between 100 m and 200 m. Figure 5 shows the seasonal change in the depth of the salinity maximum averaged separately for northern stations (between 29°S and 30°S) and for southern stations (between 31°S and 32°S) occupied during 1974. Although the depths varied considerably from cruise to cruise a systematic seasonal variation was not obvious. The depth of the maximum was more than 50 m greater in the northern area than in the southern area during the months April, May, June and October 1974. In November 1974 the maximum in the southern area was deeper than that in the northern area. For the rest of the year there were insufficient data for a comparison of depths. A fairly consistent meridional variation in the depths of the salinity maximum was evident. Where data existed, the depths of the isohalines were plotted against latitude for two lines running parallel to the W.A. coast approximately 1 degree of longitude apart. For most of the cruises the salinity maxima on the inshore line were significantly deeper than those on the offshore line.

The salinity of Section C reached a maximum value of over 35.80‰ during the early part of 1974 but dropped to 35.70‰ during the Spring months of September and October. In November and December 1973, the salinity of the maximum was 0.1‰ greater than it was during the same months in 1974 (Fig. 6). During winter, greater mixing of the salinity maximum with the lower salinity surface layer would be expected because of the relatively lower stability of the water column and the greater frequency of storms at that time of the year. The temperature at the salinity maximum reached its highest of 19°C during the months of April, May and June. A minimum of around 17°C was recorded during the months August, September and October.

Any seasonal influences which occur deeper than the 14.5°C isotherm (at a depth of around 250 m) were minimal. The large density gradient of the South Indian Central water mass would serve to damp any turbulent downward transfer of properties. The σ_t gradient in this layer varied from 0.5 per 100 m to 1.3 per 100 m. The average value was approximately 0.9 per 100 m.

Section D

The surface layer, as would be expected, was most subject to seasonal variation. At all times of the year, however, it had a negative temperature gradient and a positive salinity gradient down to the depth of the salinity maximum. Rochford (1969) has observed that surface salinities are fairly low during winter and high during summer at least on the continental shelf. He suggested that this is due to the southward spreading of warm, low salinity, tropical water during winter followed by its retreat and replacement by colder saline water during summer.

On some cruises the TS characteristics above the salinity maximum of the various stations were very similar whereas for other cruises there was considerable variety. On Sp3/73 in November 1973, Sp33/74 in October 1974 and Sp37/74 in November 1974 the upper TS characteristics on each cruise displayed linearity which suggests simple mixing between 2 bodies of water — a low salinity, warm water mass and the top layer of the South Indian Central water mass. The upper TS characteristics are plotted in Fig. 7(a) for Sp37/74. On other cruises, however, the TS curves for some stations exhibited bulges and sometimes secondary salinity maxima between the South Indian Central salinity maximum and the surface. Figure 7(b) shows the TS characteristics for cruise Sp9/74 carried out in early April 1974. All the four stations of Sp9/74 were located within a degree square between 29°S and 30°S. The station (55) showing the least evidence of a bulge was the most south easterly of the four stations. There were not enough data to define the geographical extent of the bulge. A time series of TS characteristics for the position 29°30'S and 113°E is plotted in Fig. 8. The bulge here was most prominent during

Sp9/74 where it appeared as a secondary salinity maximum with a salinity of approximately 35.8‰ and a temperature of 21°C. Rochford (1967) described the appearance of the "West Australian Current" which flows north east across 110°E during February to May at similar latitudes above the South Indian Central water mass. This "West Australian Current" with salinity of 35.9‰ and temperature of 20-22°C, is thought likely to be the cause of these salinity maxima.

Sea Surface

Sea surface temperatures obtained along the cruise track provided the information for Fig. 9(a) which shows the latitudes of various isotherms averaged over the width of the survey area during the year. The warmer sea surface temperatures appeared during the period January to May, with temperatures over 24°C north of 30°S during April and May. The coldest surface temperature of 17.7°C occurred at 30°30'S in August. Sea surface salinities plotted in Fig. 9(b) show a slightly altered pattern from surface temperatures. Intrusions of salinity less than 35.3‰ appearing north of 30°S during April to June correspond to the intrusions of relatively high temperature water in the same area. In the following two months northern salinities increased to between 35.4‰ and 35.6‰ before they again decreased to below 35.3‰ in September and October. By contrast, the surface salinities in the area south of 31°S reached their lowest values in June and are less than 35.4‰ from June to mid September. It was not until September that salinities again increased. This is a lag of two months from the time salinities increased 0.3‰ in the north. Salinities of over 35.6‰ were encountered in November 1973 and in occasional isolated intrusions. One was found in May 1974 and another in October 1974. The surface waters during November 1974 were 0.2‰ lower in salinity than during November 1973.

Although the temperature contours and salinity contours reflected similar features, the TS relationship at the surface varied throughout the year. The surface TS signatures for each station on a given cruise had a generally linear relationship. A scheme of these surface TS relationships for the different seasons is shown in Fig. 10. They are superimposed on two-monthly envelopes of the TS characteristics above the salinity maximum. It is evident that these TS characteristics were altered seasonally in the same way as the surface characteristics. Note also that the November-December 1973 envelope is different from that obtained in November-December 1974.

Figure 5 shows that in the area between 29°S to 30°S the appearance of low salinity water at the surface had not increased the vertical salinity gradient but rather the isohalines were vertically displaced. It appears that this depression was virtually undiminished to 300 m and was still fairly significant at 900 m as the depression of the salinity minimum shows in Fig. 11.

Mixed Layer Depths

On most cruises there existed a definite surface mixed layer with temperature gradient less than 0.002°C/m. The depth of the mixed layer was strongly dependent on latitude (see Fig. 11). The depth of this layer was no more than 25 m between latitudes 32°S and 31°S whereas farther to the north between latitudes 30°S and 29°S the depth averaged 40 m but was as deep as 70 m. The vertical extent of the mixed layer was largely correlated with the appearance of low salinity water entering the area from the north.

Shelf Waters

The water lying over the continental shelf (less than 200 m deep) was sampled to 50 m depth only. With one exception it possessed essentially the same TS characteristics as the surface layer found in deeper water. The exception was at station 66 of cruise Sp10/74 located just south of the Pelsart Islands and sampled in mid April 1974, where the top 25 m had a salinity of 35.85‰ and a temperature of 24°C. These values were quite unlike any encountered on the other stations of that cruise or on any other cruise. Although the TS characteristics of the shelf water were similar to those of the deeper water the shelf waters usually had higher or lower temperatures. This suggests that the dominant circulation pattern there was parallel to the coast. However, there are not enough data to substantiate this.

Oxygen

Oxygen depth profiles were generally consistent in shape throughout the year. Above the salinity maximum a succession of minor maxima and minima were evident. Only the deepest of these minima, which was found above the salinity maximum, showed consistently. Figure 11 shows the average depth of this minimum through the year and Fig. 12 shows the value of this minimum compared to surface values. When surface values were at their lowest during the year, April/May, this shallow oxygen minimum also recorded its lowest value and was most pronounced. However, during August when oxygen values were at their maximum this shallow oxygen minimum could just be seen. Its value was only slightly lower than surface values.

Below this shallow minimum the oxygen content increased gradually to a maximum at about 500 m. Values at these peaks were fairly steady throughout the year ranging from 5.66 ml/l in May 1974 to 5.26 ml/l in December 1974. These maxima occurred at a depth where the temperature gradient in the thermocline decreased markedly. Figure 13 shows typical depth profiles of oxygen and temperature.

This depth also marked a significant point of departure of oxygen values from 100% saturation. Figure 14 shows a series of oxygen/ temperature plots taken at 30°00'S, 114°00'E throughout the year with 100% oxygen saturation indicated. An oxygen minimum at about 1200 m which appeared to be associated with the North West Indian Intermediate water mass was encountered frequently during the year.

No obvious seasonal variation was apparent in the oxygen profiles. However, the decrease in oxygen values at the surface in early May 1974 was at the time when the TS curve was distorted above the salinity maximum. At this time the high salinity, high temperature waters of the "West Australian Current" were observed in the study area at about 50-100 m depth.

G.E.K. Currents

Although the G.E.K. data and surface temperature data are not so comprehensive in early 1974 as for later cruises it would appear that there was not a simple circulation pattern. One could characterise the circulation during early 1974 as a series of zonal jets. These jets had a width of approximately 50 nautical miles and alternated between an easterly and a westerly flow. A possible circulation pattern for Sp9/74 is shown in Fig. 15(a). On Sp8/74 held two weeks earlier the currents were 180° out of phase with those on Sp9/74. Unfortunately no surface temperature data exist for that cruise so it is impossible to determine whether the circulation pattern had shifted north or south.

A strong G.E.K. current pattern prevailed on eight of nine cruises in the period May to September 1974. This pattern is schematised in Fig. 15(b). Currents entered the study area between 28°S to 30°S in a south easterly direction, after crossing 30°S, tended to shift towards the south without altering their magnitudes.

These currents generally had a strength of about a knot but ranged up to 2 knots. It seemed to be primarily warm, low salinity tropical water which comprised this current. South of 30°S the current extended to about a degree west of the 200 m line but, unfortunately, no data are available on its extent in water shallower than 200 m. In the south west of the study area cooler, more saline surface water was evident. Sometimes this body of water was separated from the warmer, less saline water by quite pronounced surface fronts in salinity and temperature.

Cruise Sp37/74 held at the beginning of November marked a change in the May-September circulation pattern and for three other cruises up to the end of 1974 the circulation pattern was again altered. As in the period prior to April 1974 no stationary circulation system existed. On cruise Sp37/74 a dynamically stable anticyclonic eddy of warm, low salinity water appeared in the middle of the study area (see Fig. 15(c)). By Sp41/74 four weeks later, this eddy had disappeared from the study area and was replaced by what seemed to be a meandering northward flowing stream of moderately saline water (see Fig. 15(d)). The surface temperature structure of Sp3/73 in November 1973 was to some degree similar to that on Sp41/74. Cruise Sp43/74 exhibited yet a different circulation pattern altogether (see Fig. 15(e)). It appeared that warm, low salinity water flowed in from the north then westward before it reached 30°30'S. South of this latitude moderately saline water flowed in from the west only to flow westwards out of the study area further south. The pattern of G.E.K. currents suggests that the moderately saline water could be part of an unstable cyclonic eddy. Although there was only a single cruise track for Sp9/74 the pattern of G.E.K. currents and temperature distribution was quite similar to Sp43/74.

Geostrophic Currents

The strength of the geostrophic current almost always decreased monotonically with depth. Its magnitude at the surface ranged between near zero to almost 1.5 knots averaging about 0.5 knot. Current magnitudes were largest during the period May to September, and agreed well with the G.E.K. currents during that time. For cruises before April 1974 the geostrophic surface currents were less than 0.5 knot. The direction of the geostrophic current mostly tended to be towards the east in the north of the study area and more towards the south in the southern half. For the two cruises Sp8/74 and Sp9/74 on which G.E.K. results and geostrophic results existed for the same section of cruise track, the two current types did not agree. The eddy-like structure evident on Sp37/74 was evident in the geostrophic currents to a depth of 200 m.

The geostrophic currents at 50 m and 100 m had similar magnitudes to those at the surface. At 200 m the current magnitude was of the order of half that at the surface and further decreased with depth. Also, the direction of the current had a tendency to swing to the north at 200 m and deeper. When the surface geostrophic currents were relatively weak, as they were prior to April 1974, the currents at 200 m and deeper were northward flowing. However, the dynamical condition which gave rise to the stronger geostrophic currents in the middle of the year seemed to dominate current directions all the way to 1000 m and so sometimes reversed the currents at 200 m and deeper. As the South Indian Central water mass found at approximately 200 m is expected to be basically northward flowing the observation of a northward tendency in the geostrophic current at this depth is not surprising.

SUMMARY AND CONCLUSIONS

The major water masses encountered in the study area have largely confirmed the work of Rochford (1961, 1965, 1967).

The Northward flowing Antarctic Intermediate water mass manifested itself as a pronounced salinity minimum of 35.40‰ at an average depth of 900 m.

At depths to 1500 m, below the salinity minimum, the Antarctic Intermediate water mixed with the cooler, more saline water of the Deep Salinity Maximum. The frequent intermittent appearance of North West Indian Intermediate waters at depths of 1200 m resulted in a local salinity maximum.

Above the salinity minimum the Antarctic Intermediate water mixed with the South Indian Central water mass which also is a basically northward spreading body of water. The core of the South Indian Central, appearing as a salinity maximum of approximately 35.8‰ and temperature 17.0 to 19.0°C, occured at an average depth of 200 m.

Possibly because it has a high density gradient the South Indian Central salinity maximum is a fairly stabilising feature which effectively isolates the deeper waters from surface influences.

An oxygen maximum was located in the thermocline and an oxygen minimum was evident just above the salinity maximum for much of the year. This was most pronounced during the appearance of the "West Australian Current".

The surface layer was characterised by decreasing temperature and increasing salinity to the depth of the salinity maximum. Over most of the year the surface layer was formed from a mixture of a low salinity, high temperature tropical water and the cooler, higher salinity South Indian Central water mass. The tropical water which originated in the north spread south over the South Indian Central while at the same time became more saline as it mixed with the latter water mass. The temperature and salinity of the surface layer were determined by several factors which included seasonal variation in solar heating, evaporation-precipitation effects, dynamical uplifting of the South Indian Central water, the supply of tropical water and the rate at which it is mixed with the South Indian Central water beneath it. During March and April the "West Australian Current" appeared to inject warm, high salinity water into the layers above the South Indian Central water to cause a secondary salinity maximum below the surface.

The surface circulation pattern in the study area showed considerable seasonal variation during 1974. From late April to early November the dominant pattern was that of warm, low salinity water flowing in from the north-west to then flow out in a southerly direction along the coast. During November 1973 to mid-April 1974, November 1974 and December 1974 the circulation pattern appeared extremely variable. The movement of eddies of some 50 nautical miles radius made it difficult to determine any general circulation pattern.

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Table 1. Details of data collected on cruises SP3/73 to SP41/74

						Nansen Stations						
Cruise	Date	G.E.K.	Hourly surface temperature (°C)	Hourly surface salinity (‰)	B/T	Nº	Temperature (°C)	Salinity (‰)	NO_3N	Inorganic PO_4	SIL.	Oxygen
3/73	15.11.73 -20.11.73	√	√	-	-	10	10	10	10	8	10	10
6/73	13.12.73 -17.12.73	√	√	-	-	8	8	8	8	8	8	8
8/74	27. 3.74 -30. 3.74	√	-	-	-	7	7	7	2	1	2	2
9/74	6. 4.74 -10. 4.74	√	√	-	-	8	8	8	8	8	8	8
10/74	17. 4.74 -21. 4.74	-	√	-	-	12	12	12	1	-	1	-
12/74	29. 4.74 - 4. 5.74	√	√	-	-	7	7	7	7	7	7	7
16/74	13. 5.74 -17. 5.74	√	√	-	-	10	10	10	1	-	1	1
17/74	29. 5.74 -30. 5.74	√	√	-	-	4	4	4	4	4	4	4
20/74	10. 6.74 -14. 6.74	√	√	-	-	6	6	6	2	-	2	2
21/74	24. 6.74 -28. 6.74	√	√	-	-	3	3	3	1	-	1	1
24/74	9. 8.74 -15. 8.74	√	√	√	√	2	2	2	2	2	2	2
29/74	7. 9.74 -12. 9.74	√	√	√	√	12	12	12	12	12	12	12
33/74	5.10.74 - 7.10.74	-	√	√	-	7	7	7	6	5	6	6
34/74	9.10.74 -12.10.74	√	√	√	-	19	19	19	5	4	4	4
37/74	2.11.74 - 8.11.74	√	√	√	√	12	12	12	10	9	10	10
41/74	30.11.74 - 5.12.74	√	√	√	√	9	9	9	8	8	8	8

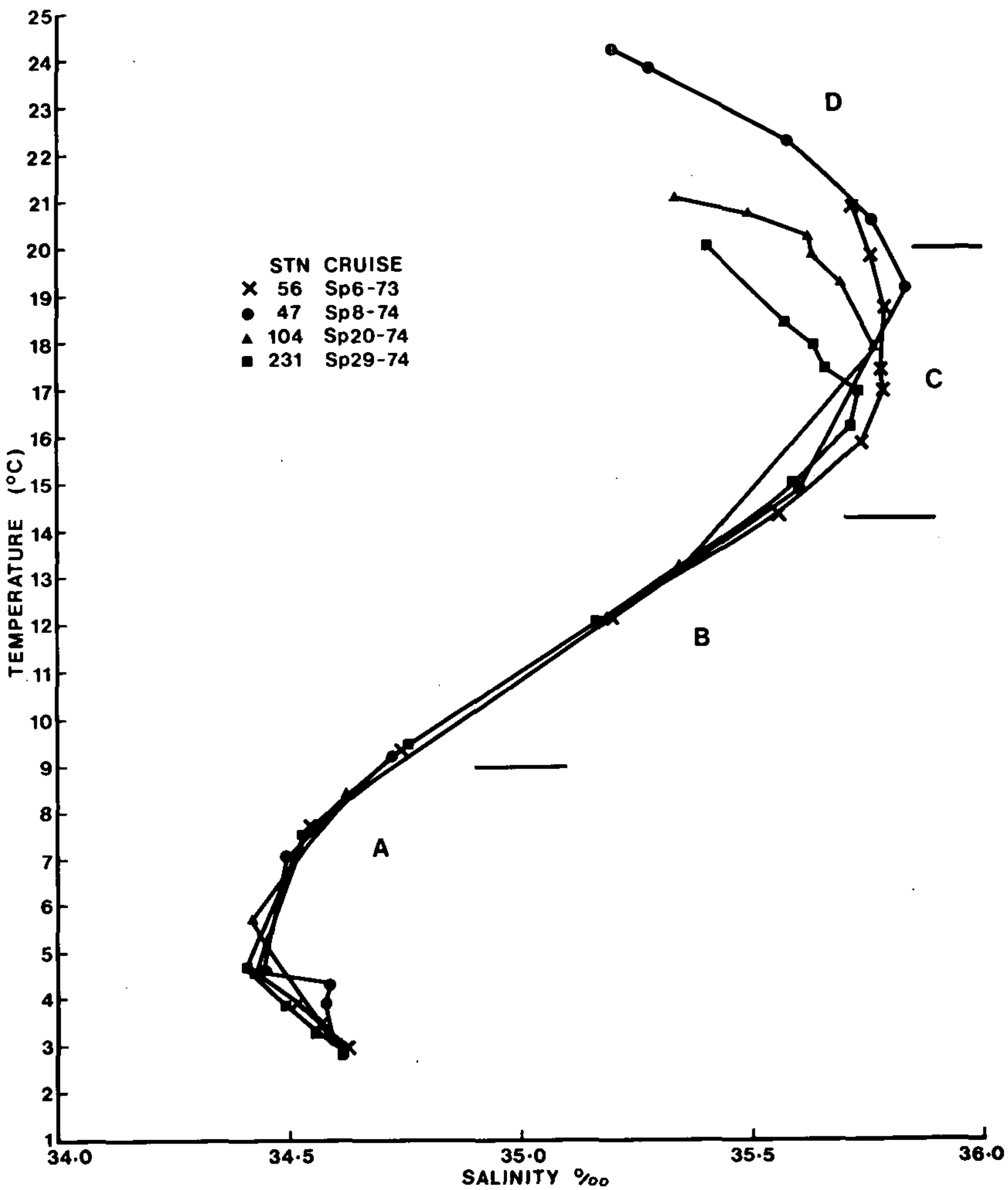

Fig. 1. Temperature-salinity curves for station at 30°00'S, 114°00'E occupied during cruises Sp6/73 (December), Sp8/74 (March), Sp20/74 (June) Sp29/74 (September). See text for description of sections A-D.

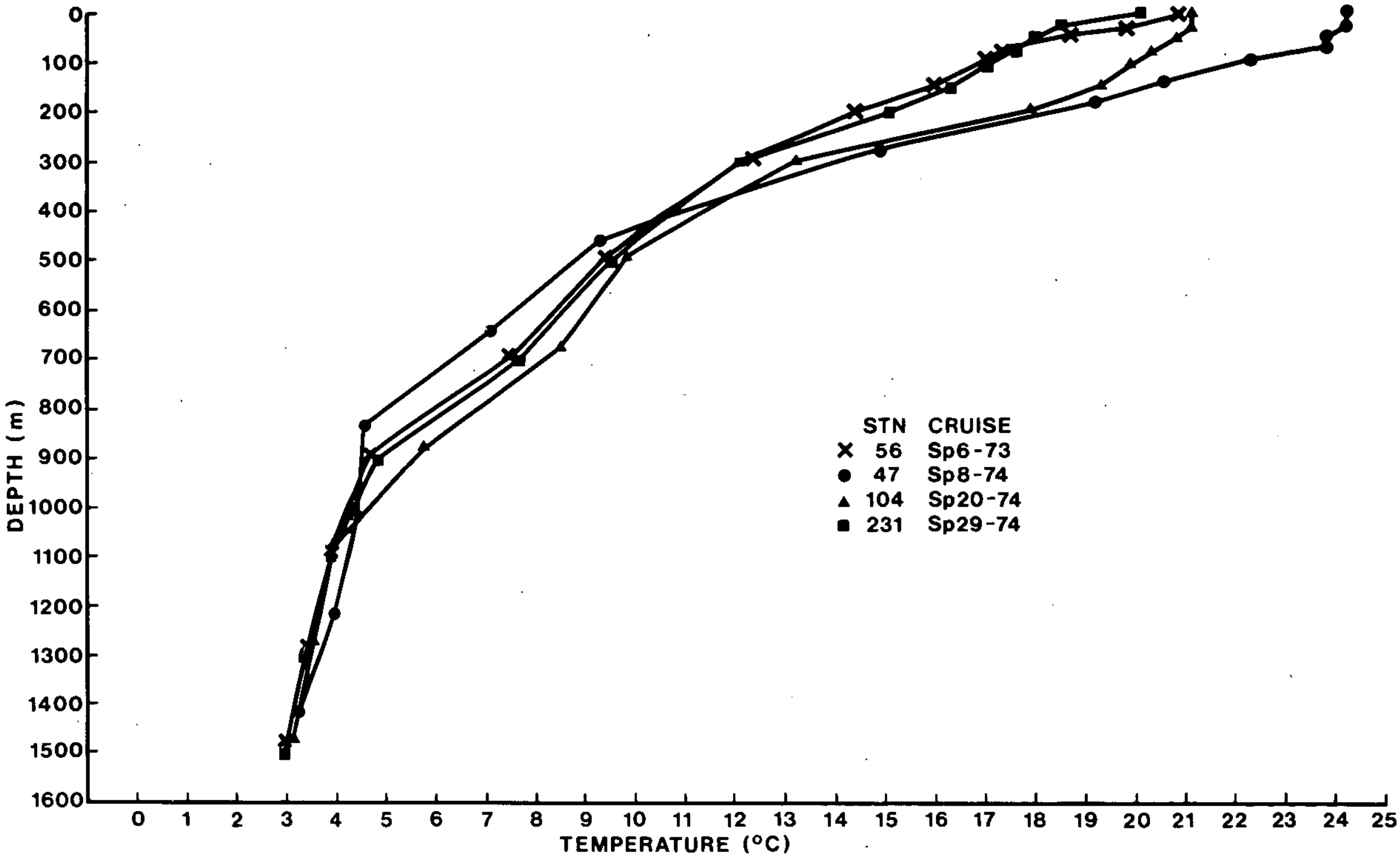

Fig. 2. Temperature profiles for station and cruises as in Fig. 1.

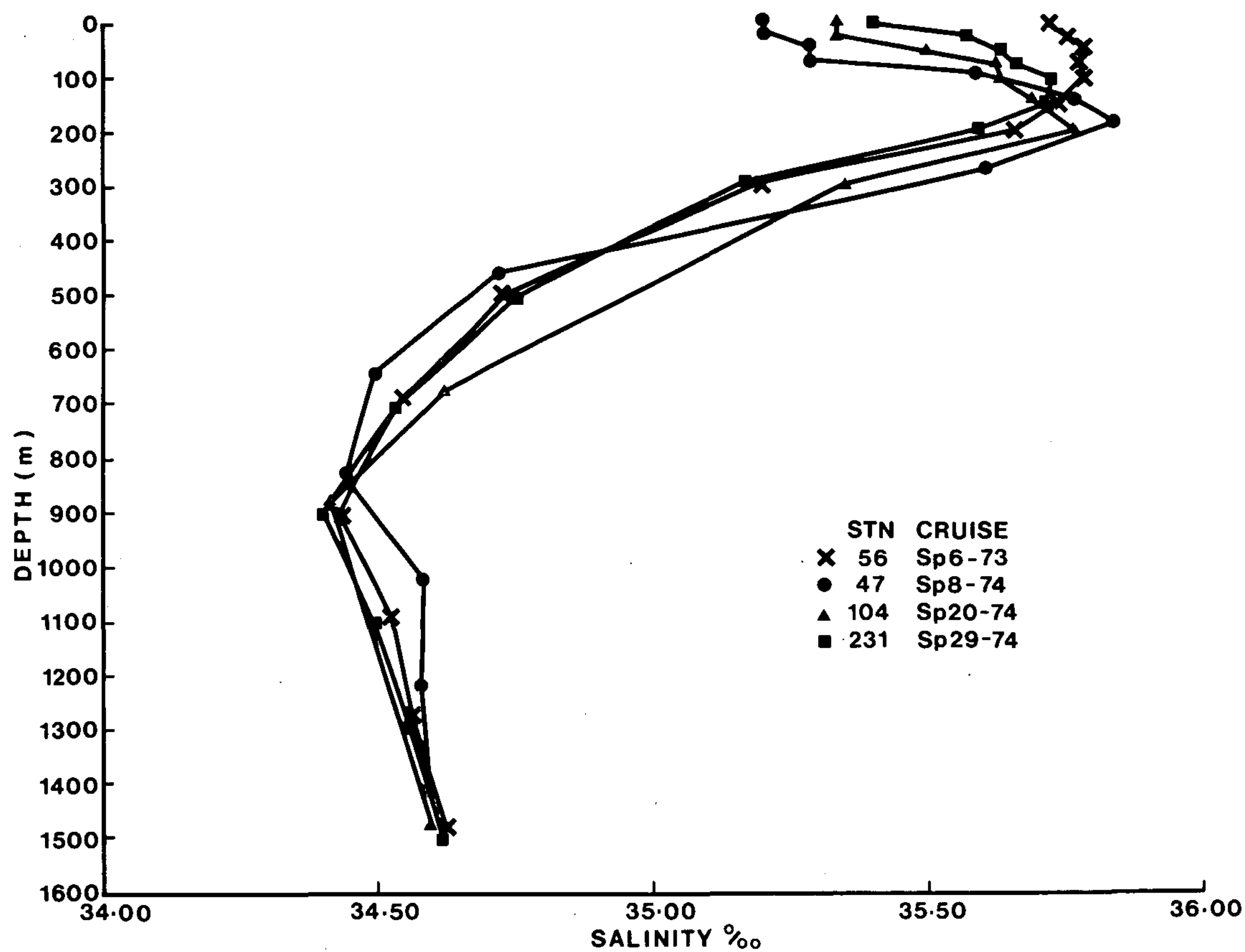

Fig. 3. Salinity profiles for station and cruises as in Fig. 1.

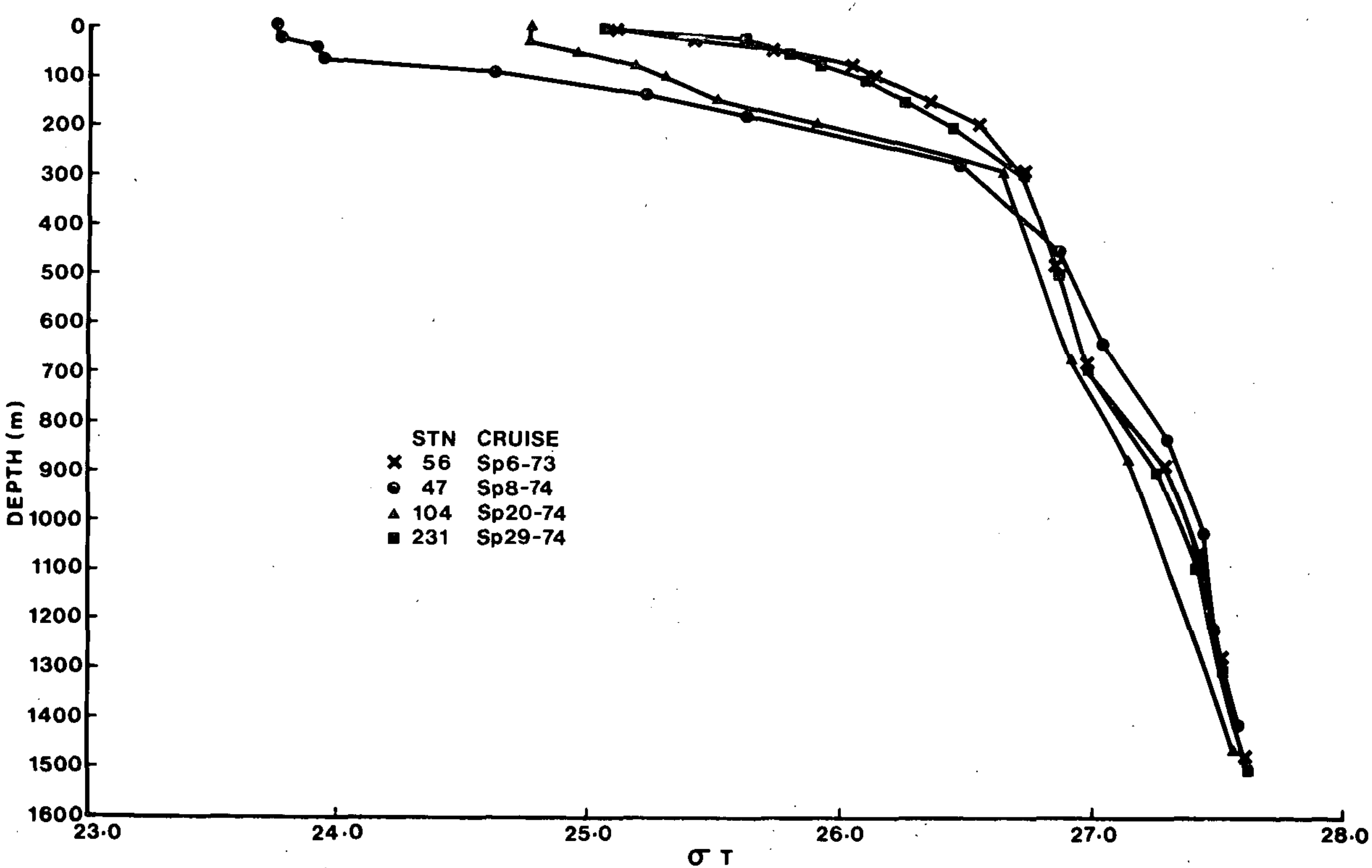

Fig. 4. Density profiles for station and cruises as in Fig. 1.

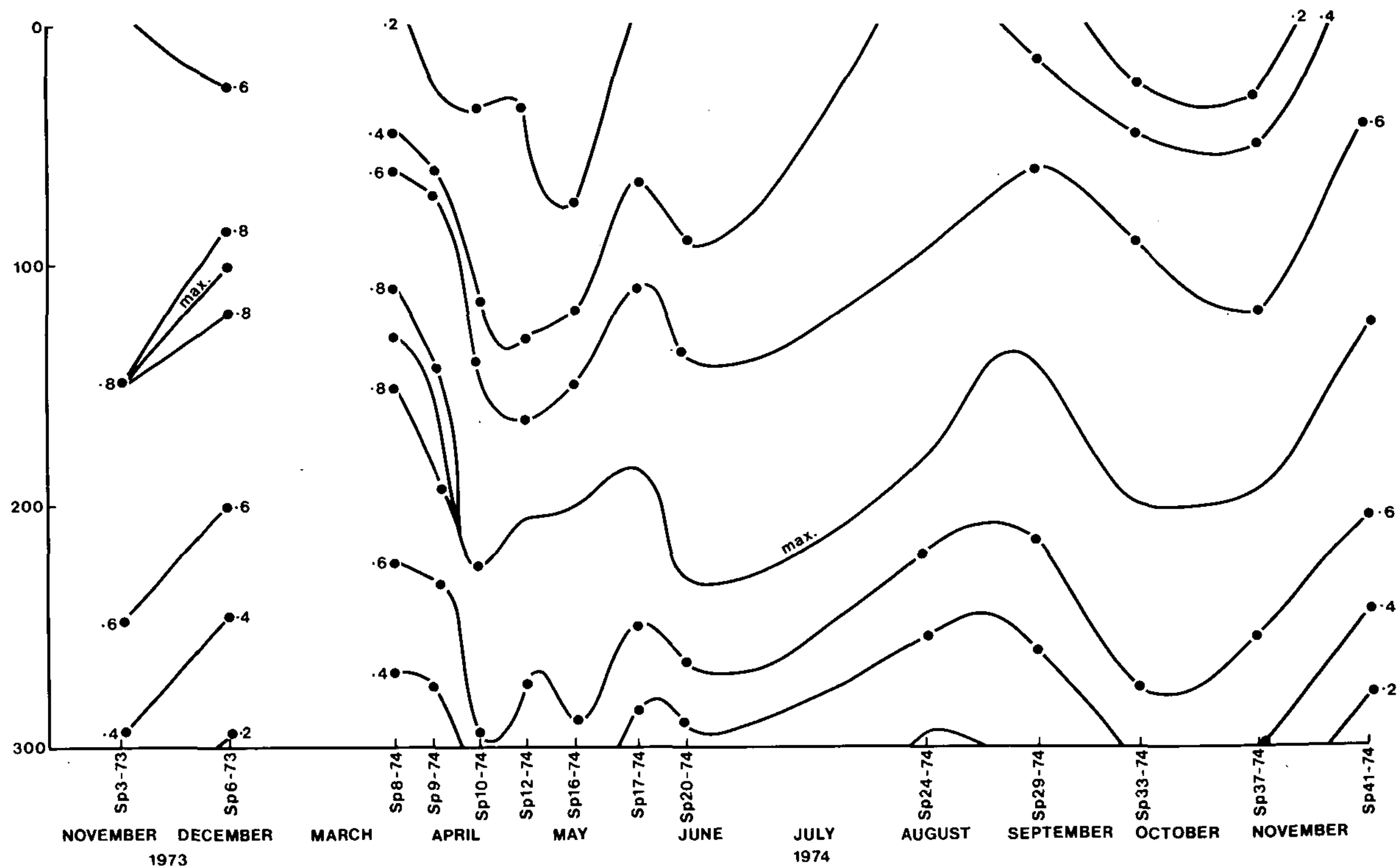

Fig. 5(a). Salinity distribution from surface to 300 m during 1974.
Average between 29° and 30°S.

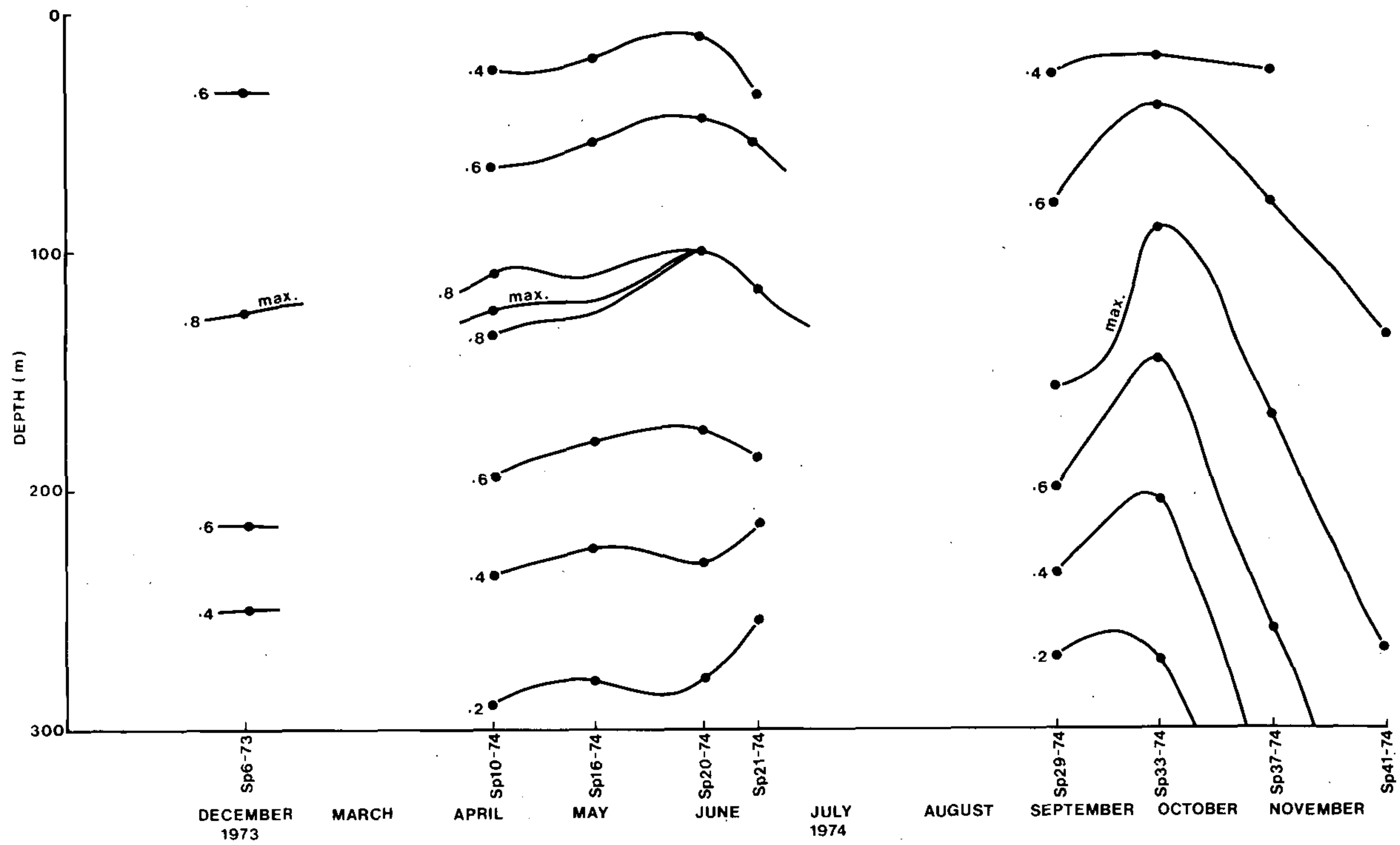

Fig. 5(b). Salinity distribution from surface to 300 m during 1974.
Average between 31° and 32°S.

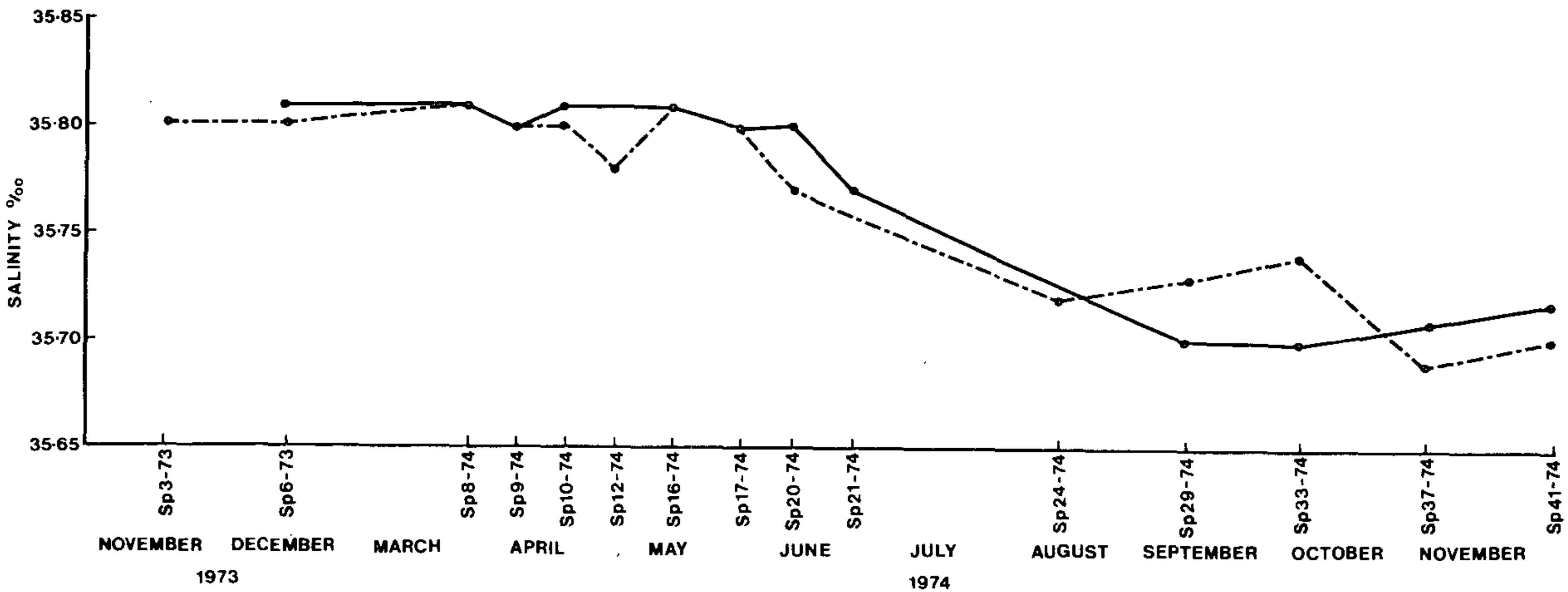

Fig. 6. Variation in salinity maximum during 1974.
Full line : average between 29° and 30°S.
Dashed line : average between 31° and 32°S.

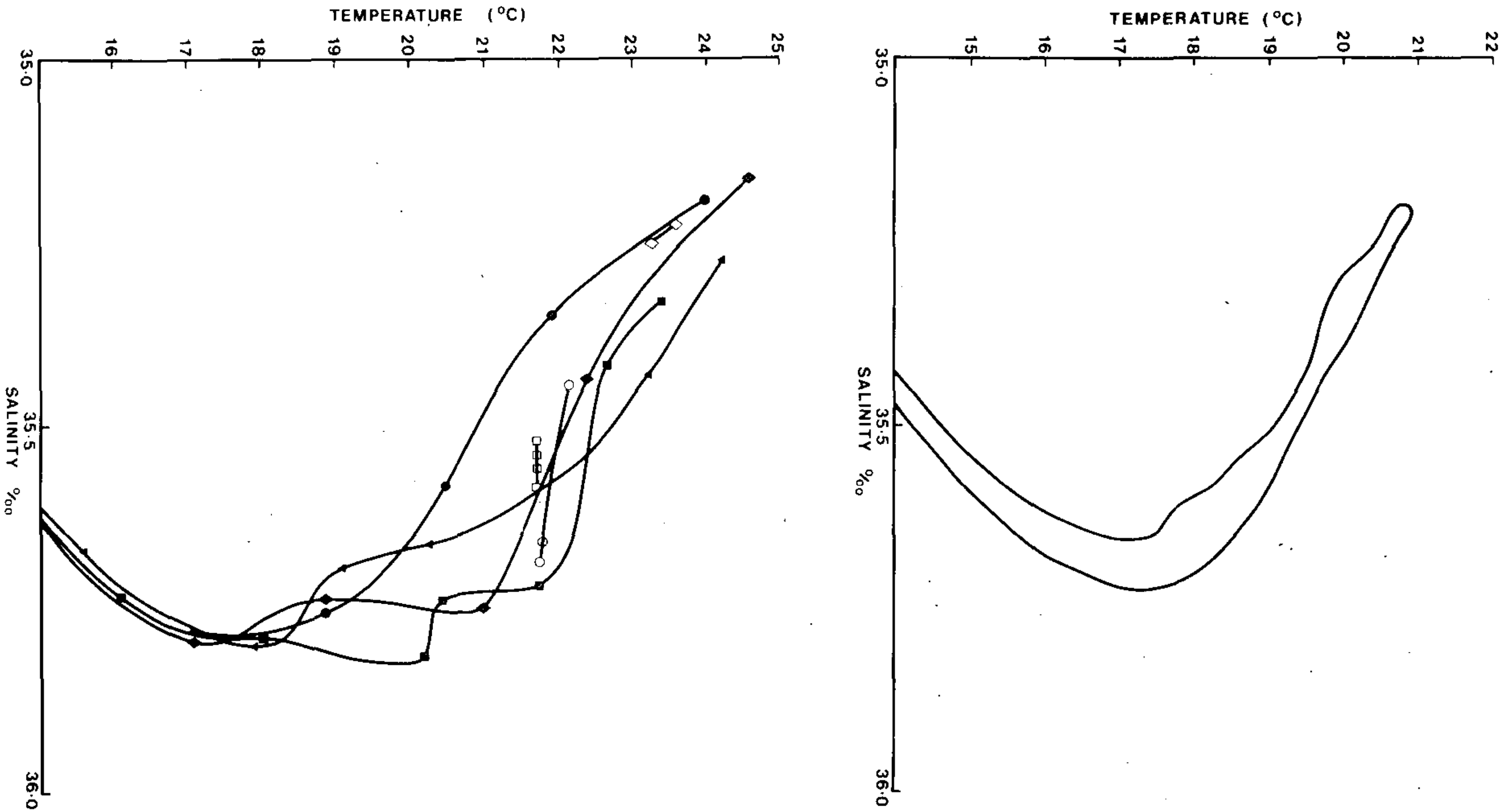

Fig. 7. (a) Section D (November) Temperature-salinity envelope for cruise Sp37/74.
(b) Section D (April) Temperature-salinity curves for cruise Sp9/74.

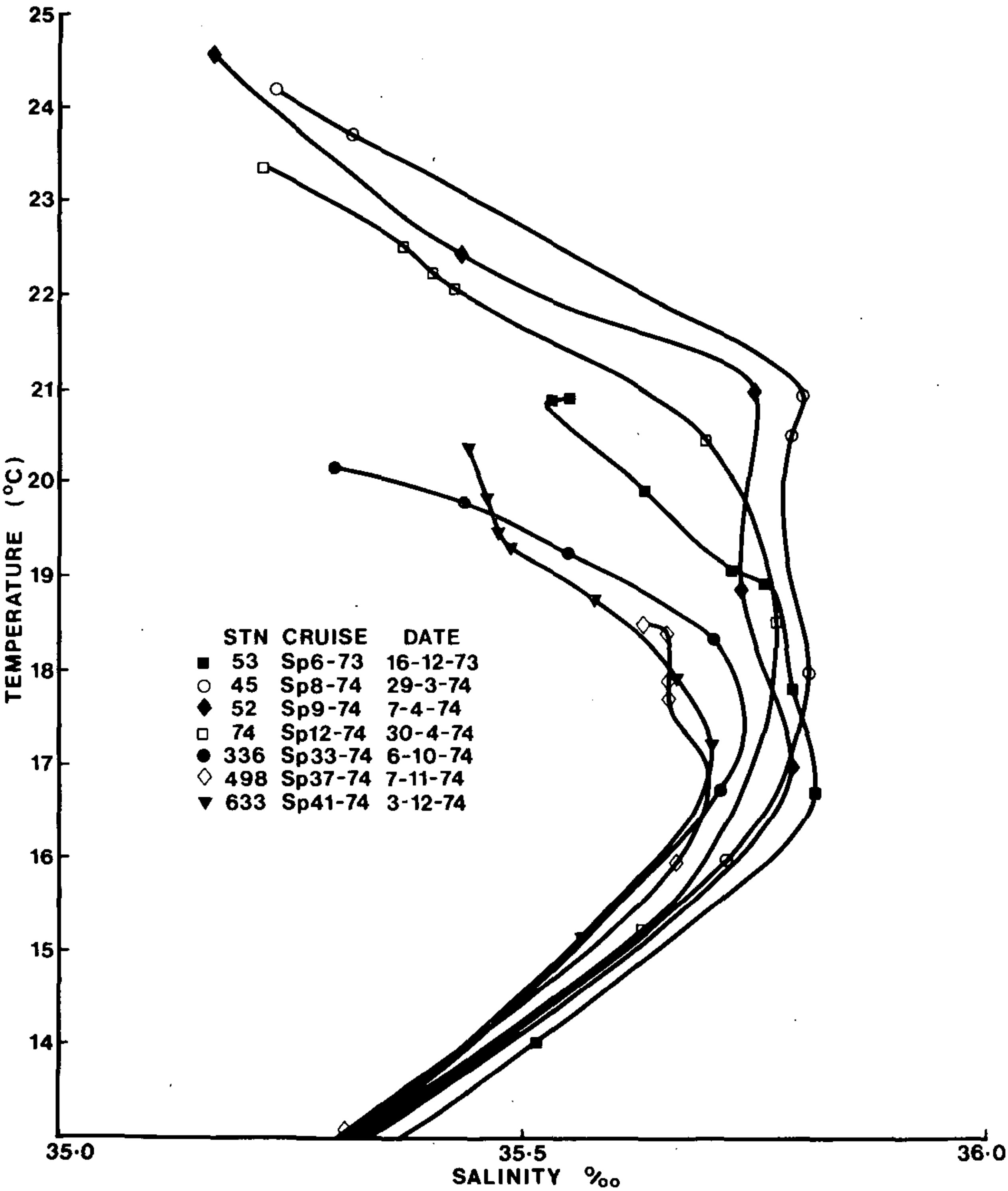

Fig. 8. Section D: Temperature-salinity curves for station at 29°30'S, 113°30'E occupied during 1974.

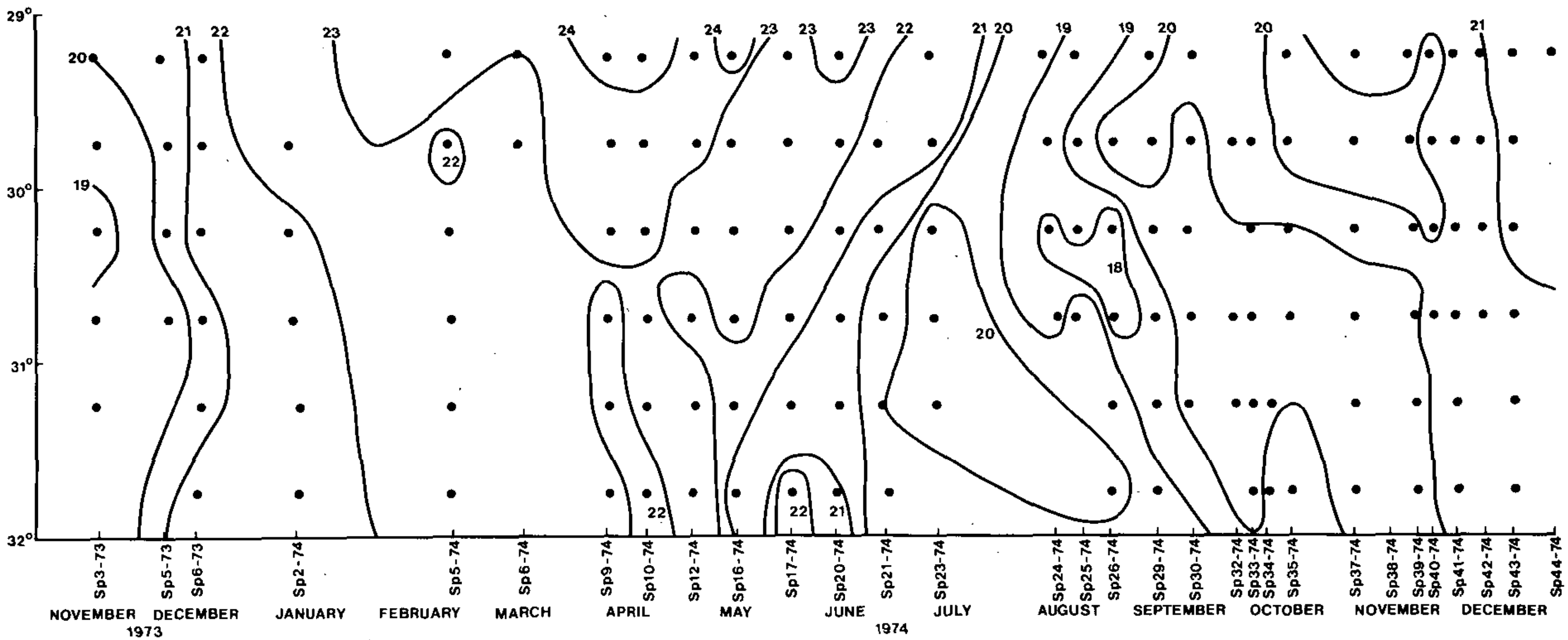

Fig. 9(a). Distribution with latitude of surface temperature (from towed thermograph) during 1974.

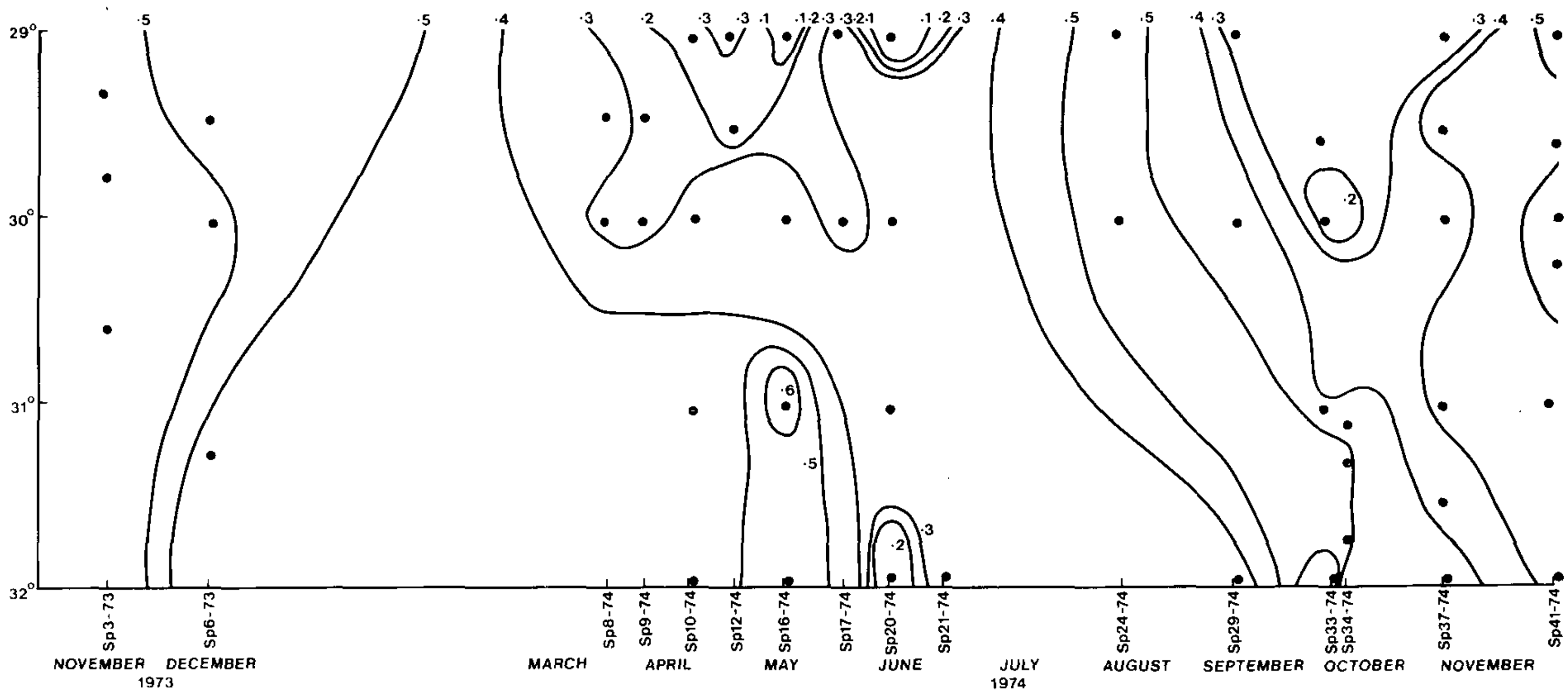

Fig. 9(b). Distribution with latitude of surface salinity (from Nansen stations) during 1974.

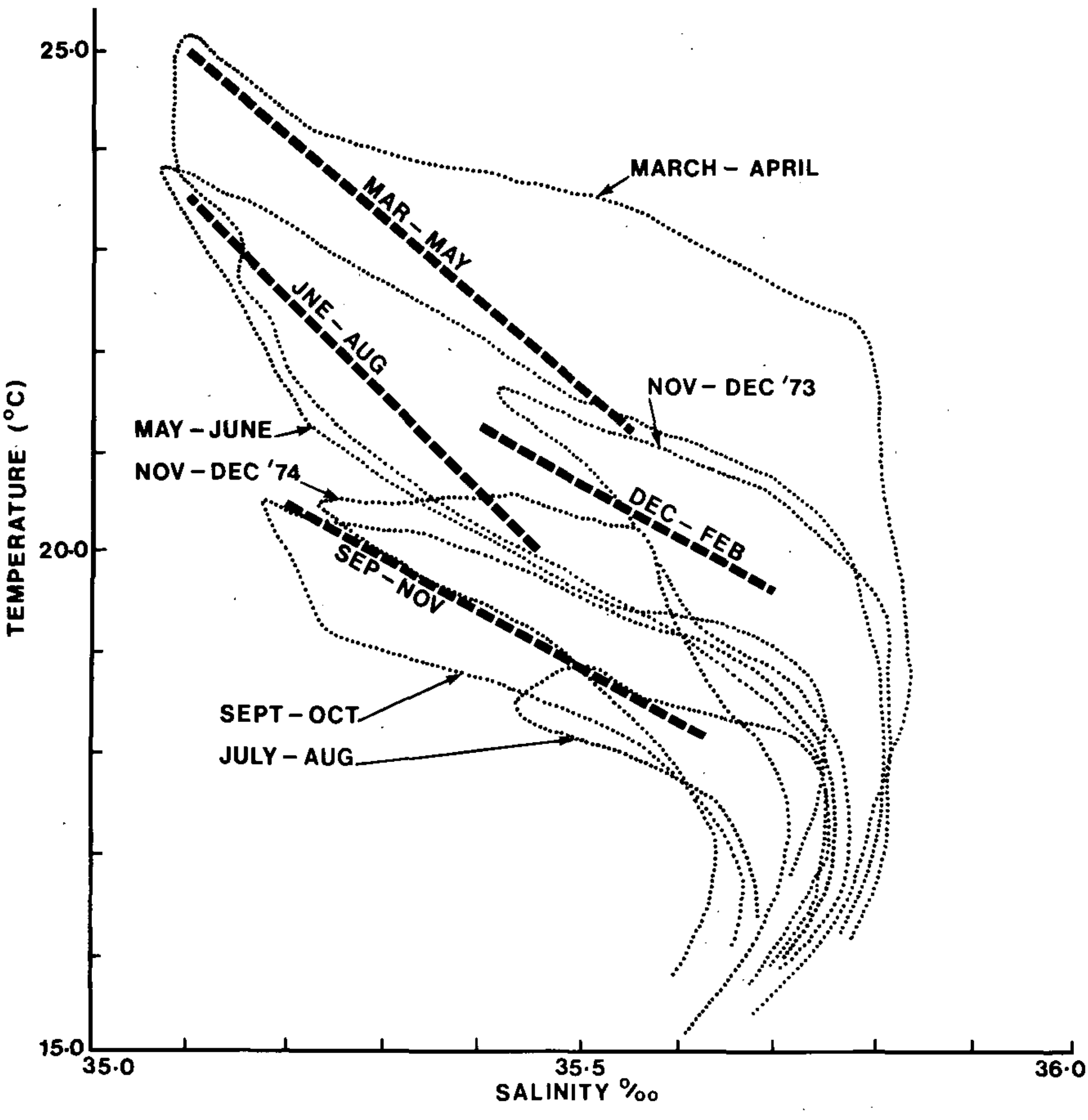

Fig. 10. Envelopes of temperature-salinity curves above the salinity maximum for indicated bimonthly periods during 1974. A schema of surface temperature-salinity characteristics obtained during the 1974 seasons (dashed lines is superimposed.

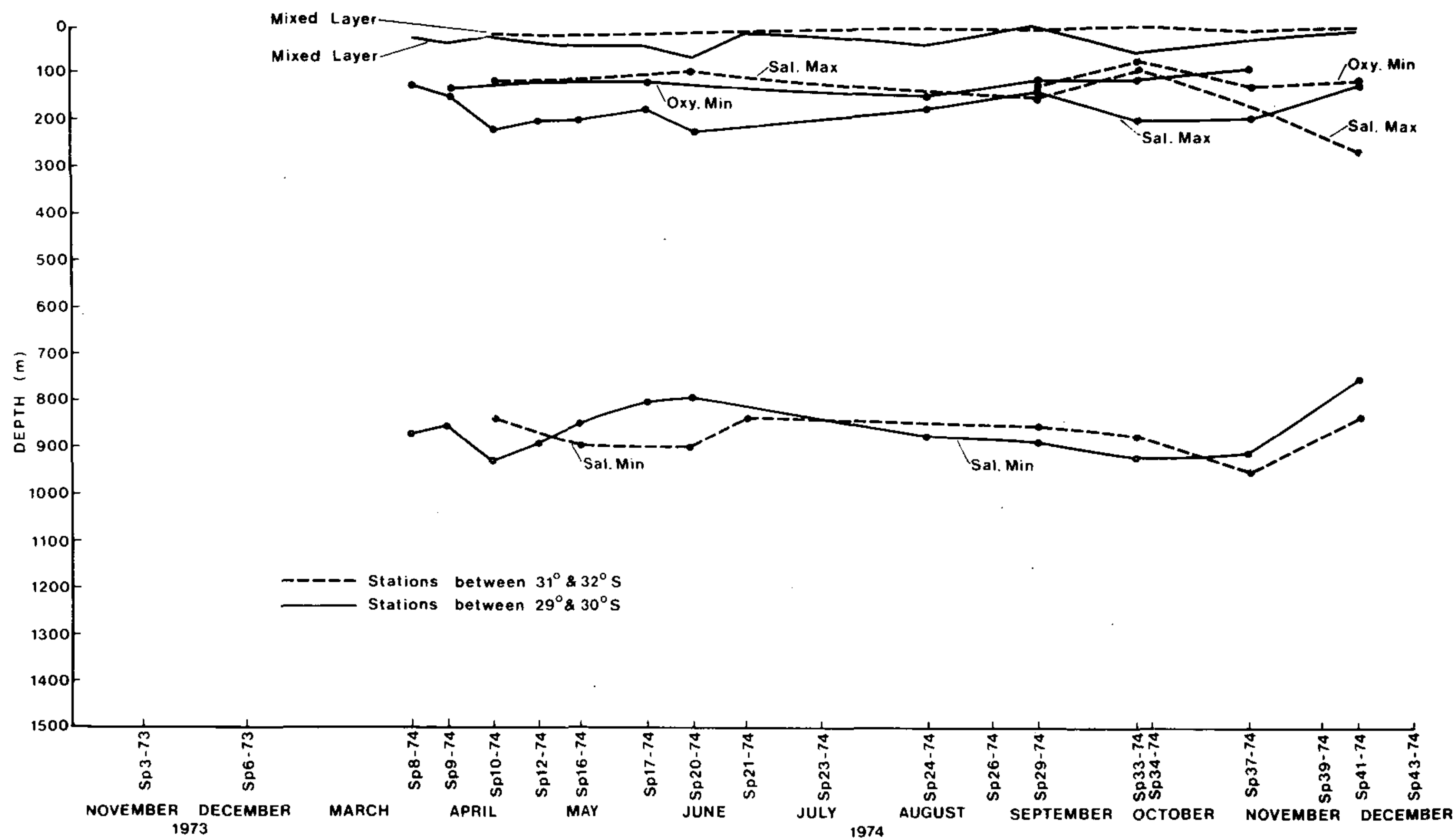

Fig. 11. Variations in depth of salinity maximum and minimum mixed layer and the shallow oxygen minimum during 1974.
Full line : average between 31o and 32oS.
Dashed line : average between 29o and 30oS.

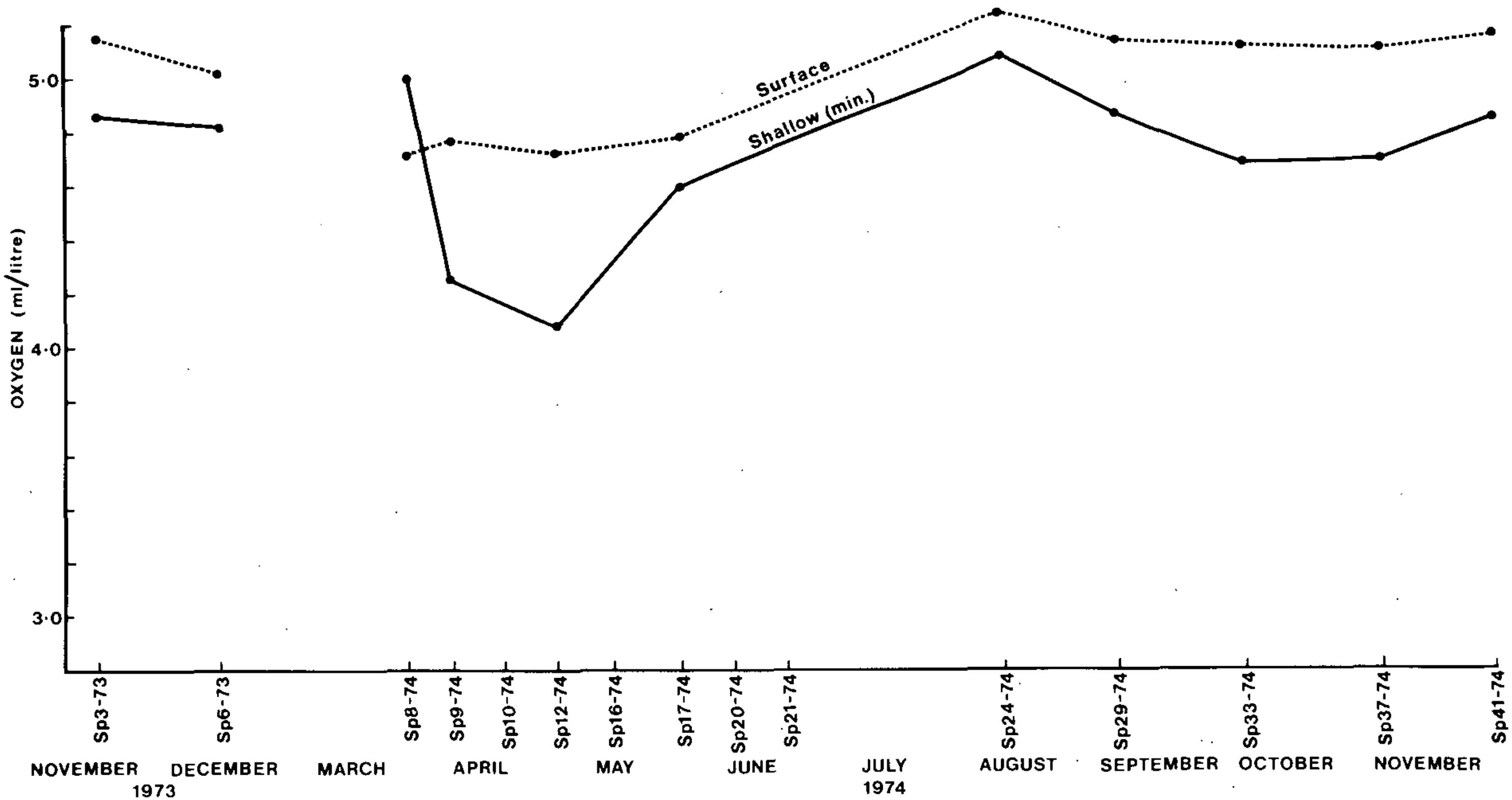

Fig. 12. Variation in average oxygen content at the surface (dashed line) and the shallow oxygen minimum (full line).

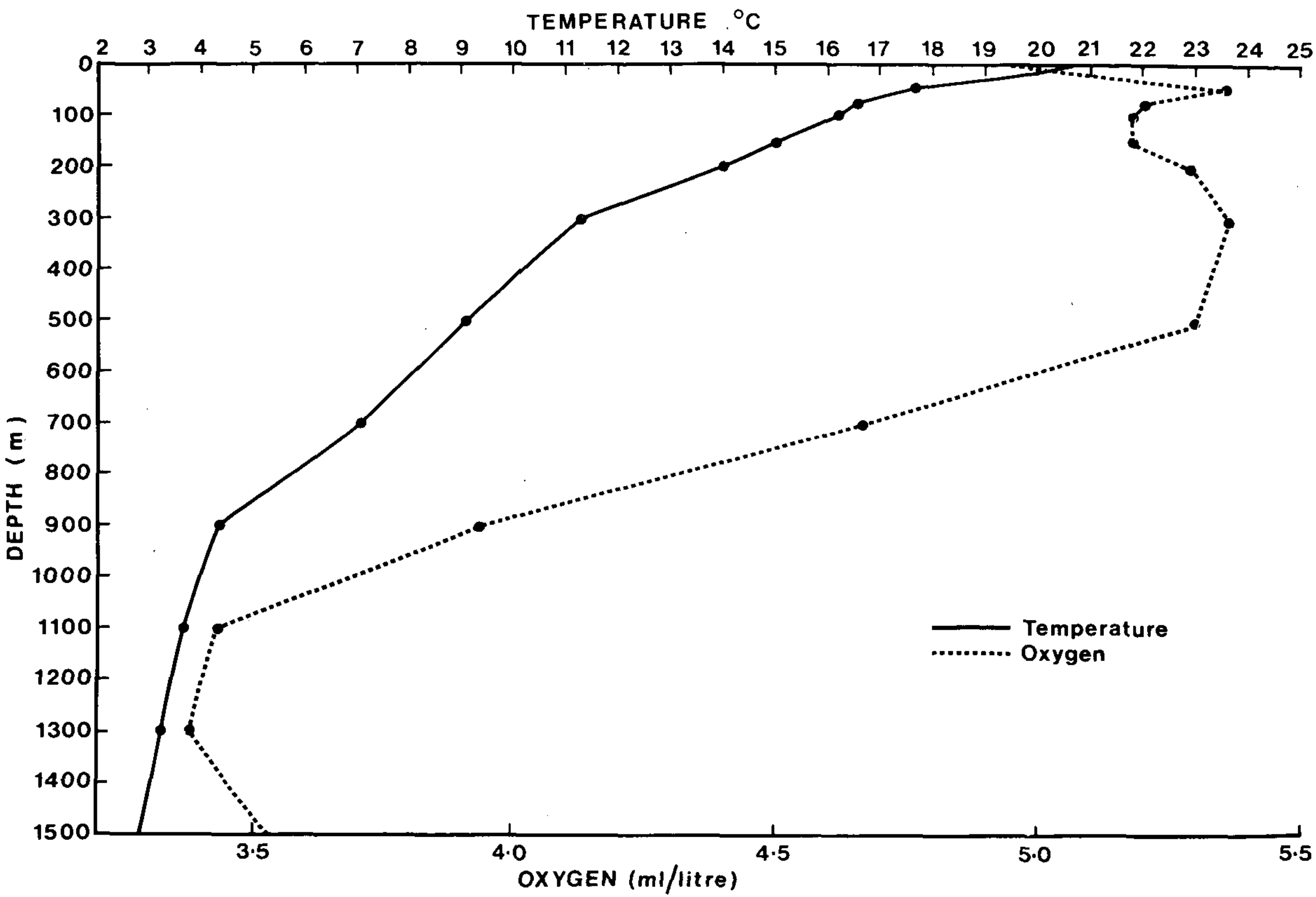

Fig. 13. Typical oxygen and temperature depth profiles (station 55, cruise Sp7/73).
Full line : temperature; dashed line : oxygen.

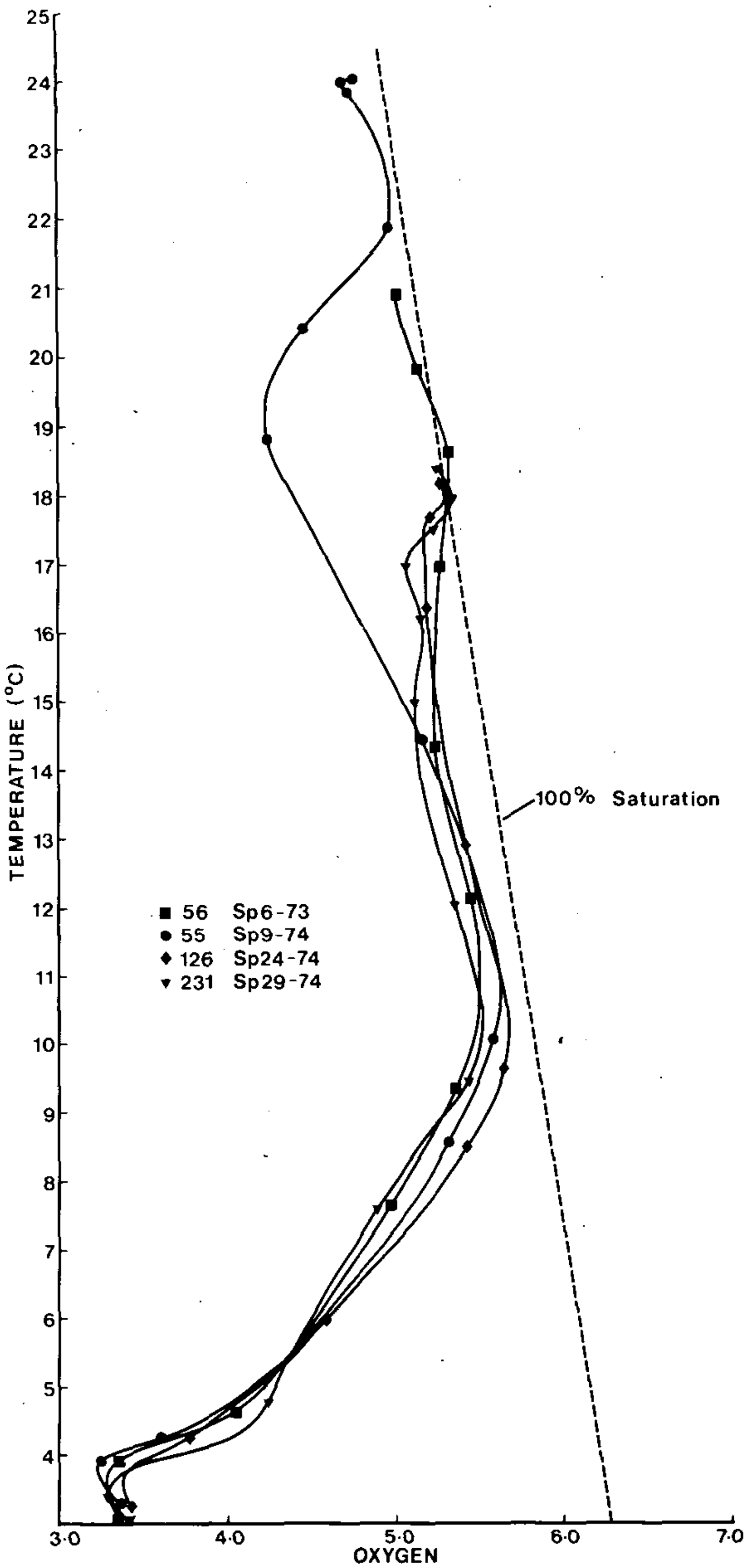

Fig. 14. Temperature-oxygen curves for station at 30°00'S, 114°00'E occupied during Sp6/73 (December), Sp9/74 (April), Sp24/74 (August), Sp29/74 (September). 100% saturation is also indicated.

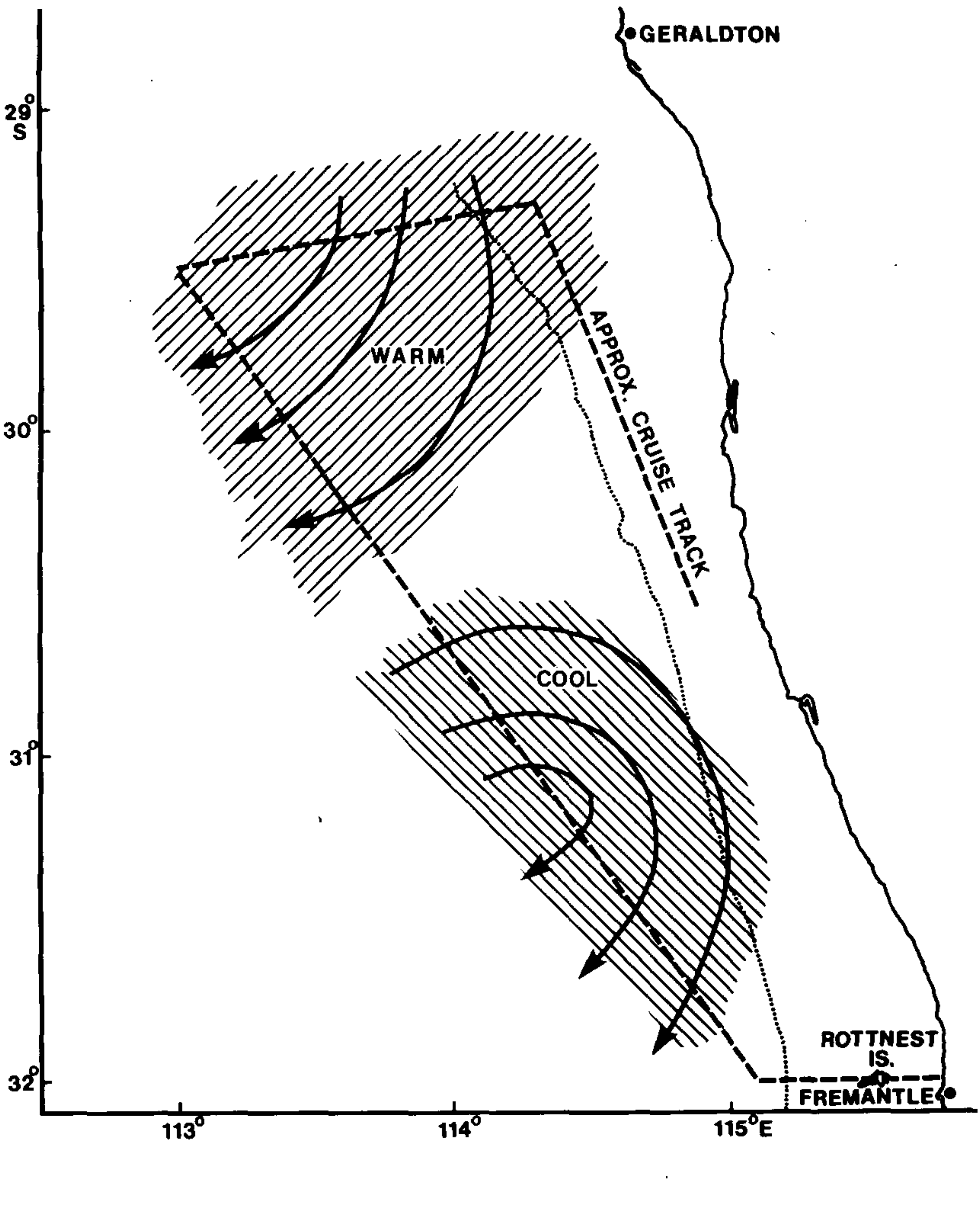

Fig. 15(a). Schematic surface circulation during cruise Sp9/74, 6-10 April 1974.

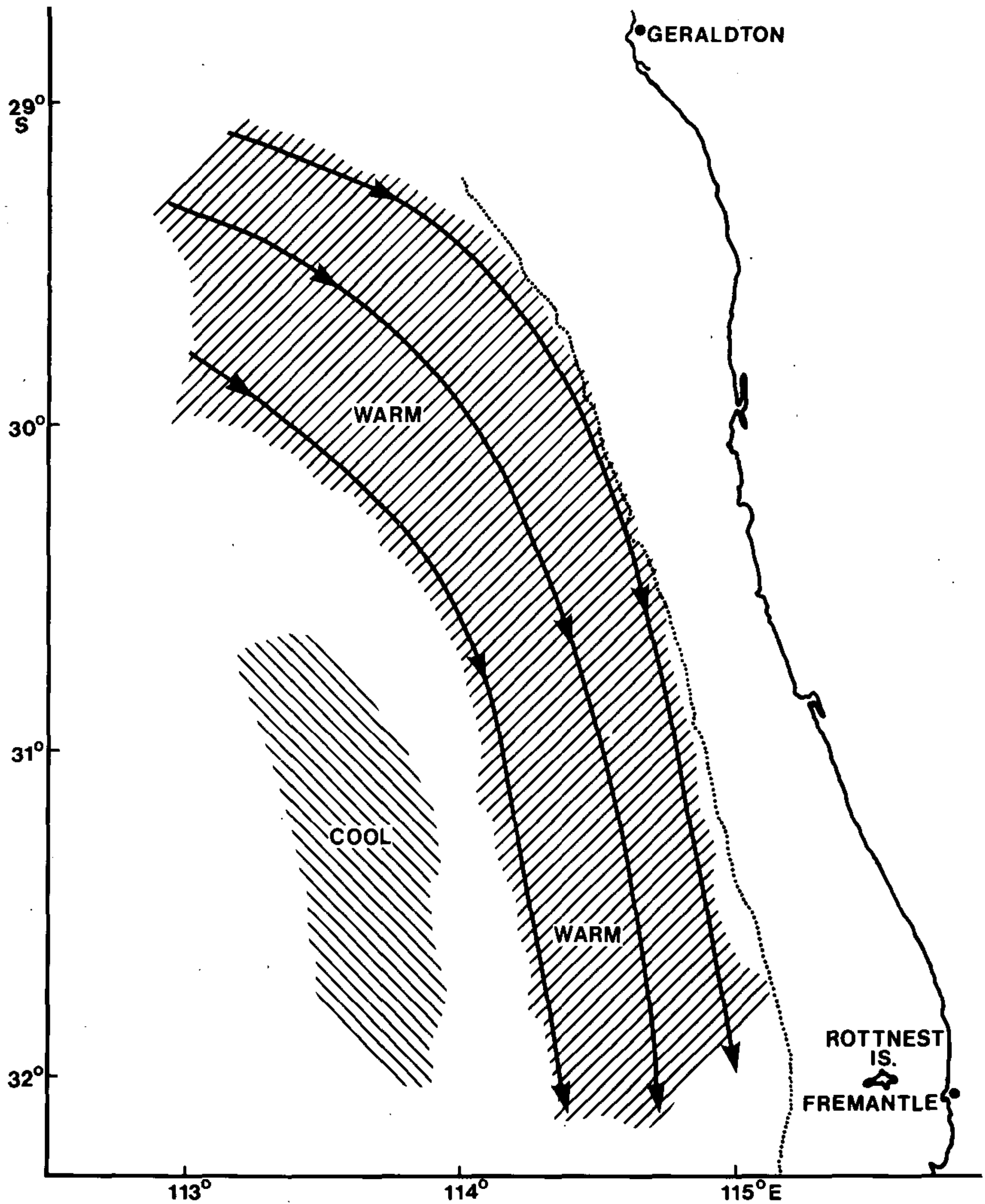

Fig. 15(b). Schematic surface circulation during May-September 1974.

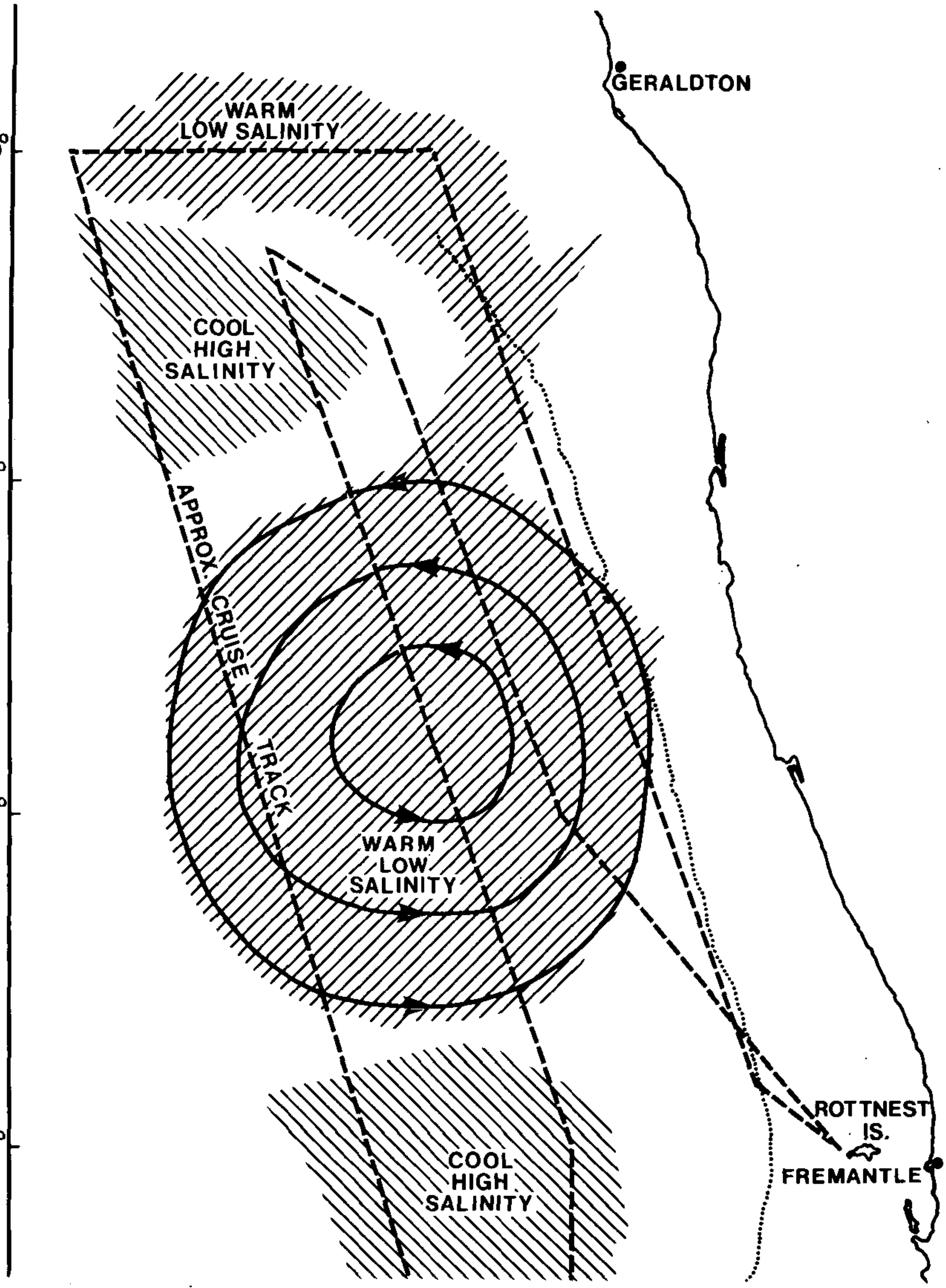

Fig. 15(c). Schematic surface circulation during cruise Sp37/74, 2-8 November 1974.

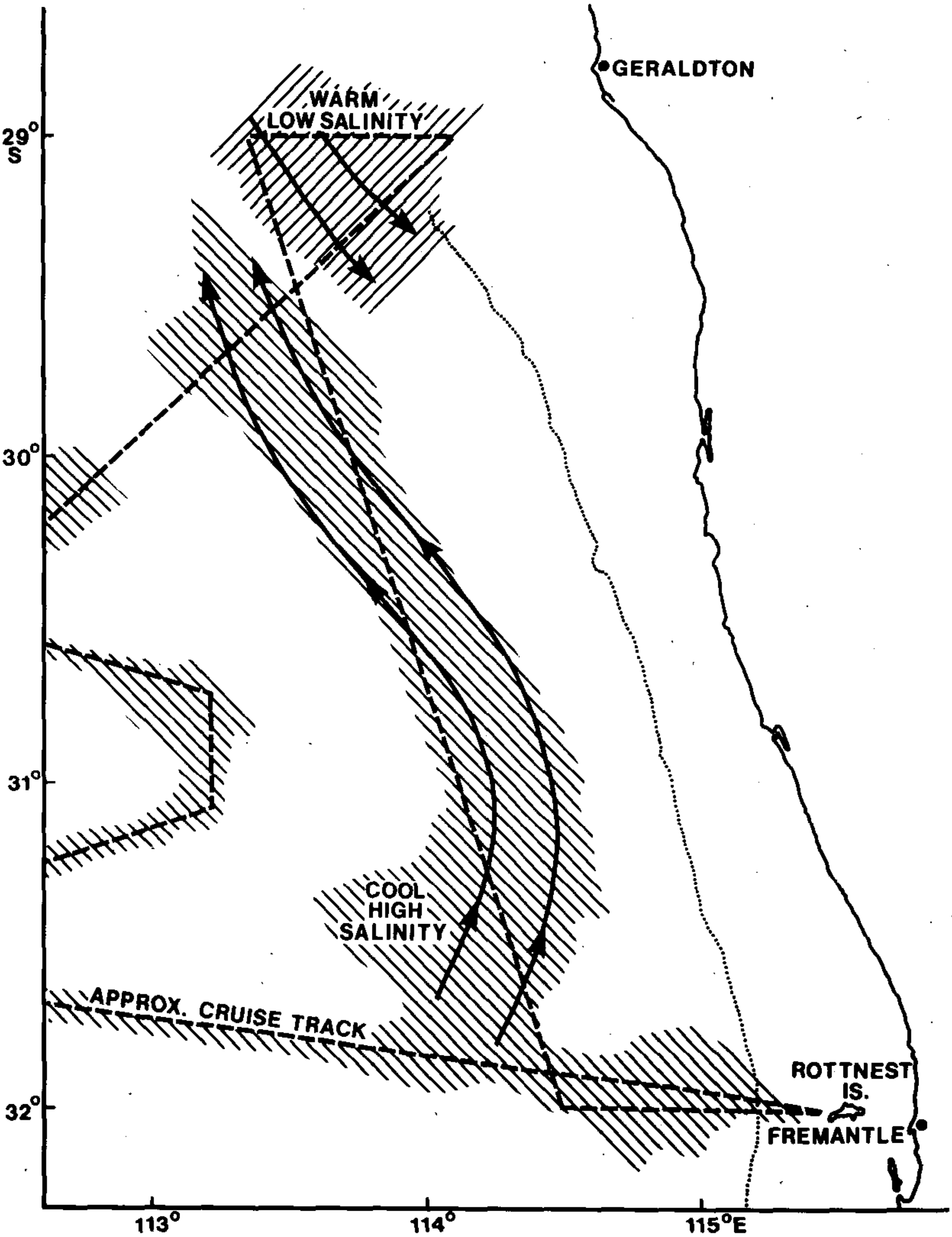

Fig. 15(d). Schematic surface circulation during cruise Sp41/74, 30 November-5 December 1974.

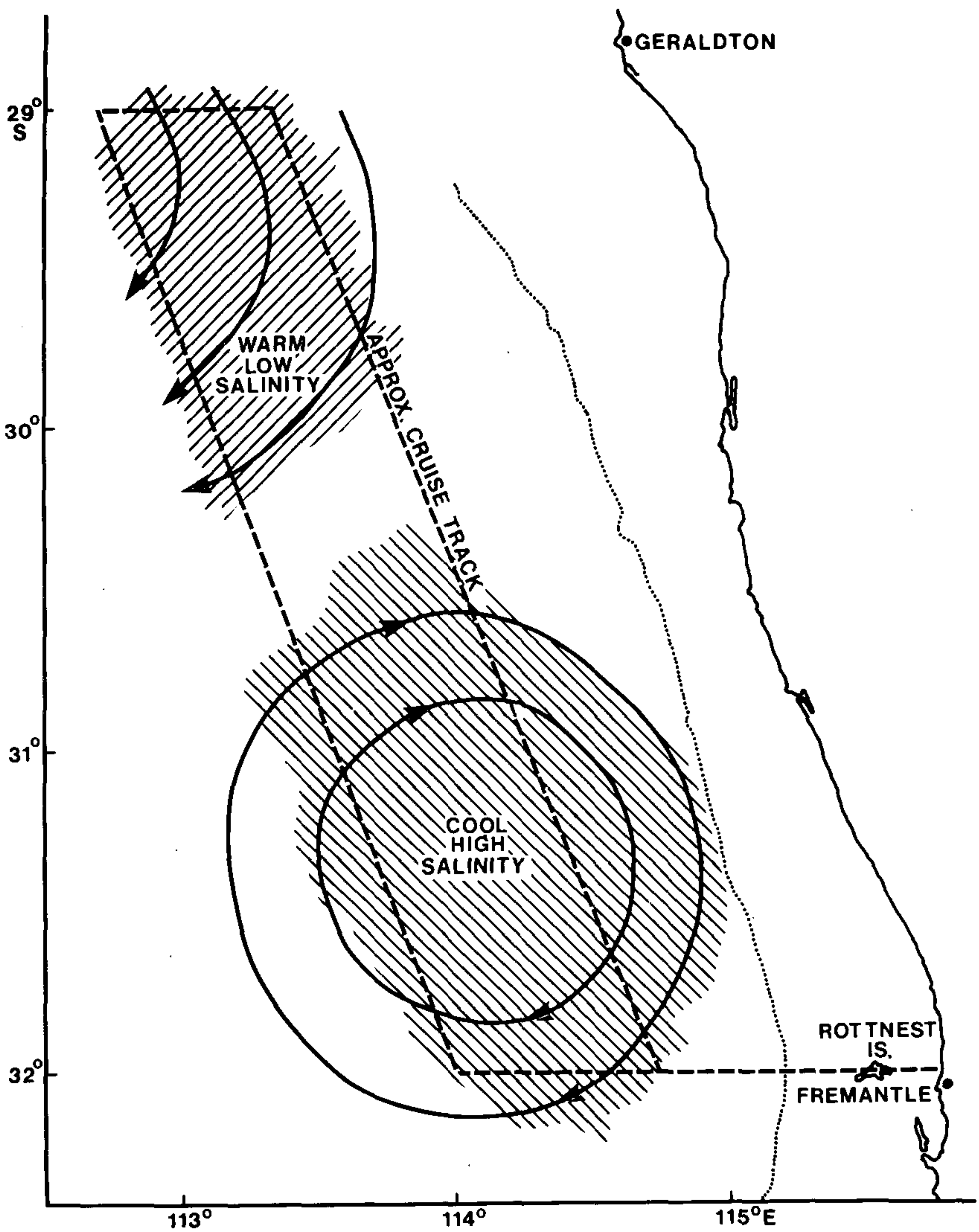

Fig. 15(e). Schematic surface circulation during cruise Sp43/74, 17-20 December 1974.

CSIRO
Division of Fisheries and Oceanography

HEADQUARTERS

202 Nicholson Parade, Cronulla, NSW

P.O. Box 21, Cronulla, NSW 2230

NORTHEASTERN REGIONAL LABORATORY

233 Middle Street, Cleveland, Qld

P.O. Box 120, Cleveland, Qld 4163

WESTERN REGIONAL LABORATORY

Leach Street, Marmion, WA 6020

P.O. Box 20, North Beach, WA 6020