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A note on the Labrador and Atlantic Currents to the east of Newfoundland Grand Bank

by

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INTRODUCTION

In recent years there have been two schools of thought concerning the derivation of the North Atlantic Current in the region south-east of Newfoundland Grand Bank. The first is due to Worthington (1962) who argued that the North Atlantic current system was essentially composed of two gyres separated by a trough of low pressure running in a south-easterly direction from the Tail of the Banks, roughly coincident with the South-east Newfoundland Rise. Immediately south of the Rise, and making up the northern part of the southern gyre, he identified the Gulf Stream proper running south-easterly, with the Slope Water Current along its northern edge. The Atlantic Current, regularly reported by the United States Coast Guard's International Ice Patrol to the east of Grand Bank (Soule 1951, Kollmeyer *et al.* 1966, Moynihan and Andersen 1971), he maintained was part of the northern gyre. The two current systems had very similar temperature-salinity curves, but Worthington showed that the oxygen content of the Atlantic Current was significantly higher than that of the Gulf Stream and hence he deduced that there was minimal transport between the two current gyres.

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Mann (1967) considered that the current system was as shown in Figure 1, the Slope Water Current mixing with a branch of the Gulf Stream which separated from the main part of the Gulf Stream in the vicinity of 38°30'N, 44°W and curved back in a north-westerly direction to form the Atlantic Current. Mann explained that the higher oxygen content of the Atlantic Current could have originated from a clockwise gyre to the east of the Atlantic Current, where overturning occurred in winter down to a depth of at least 400 m.

AIM

In April and May 1972, three ships took part in a cooperative physical and chemical oceanographic study of the region in an attempt to resolve this difference of opinion. They were the RV HUDSON from Bedford Institute of Oceanography, RV CHAIN from Woods Hole Oceanographic Institute and RV CIROLANA from MAFF, Fisheries Laboratory, Lowestoft. The intention in this paper is to provide a preliminary and descriptive account of the oceanography of the most northerly part of the survey area, the part allocated to RV CIROLANA. It is hoped that a subsequent joint publication will report the complete three-ship survey in a more comprehensive and analytical manner.

METHOD

The hydrographic sections worked by CIROLANA are also shown in Figure 1. The first crossed the Labrador Current between Flemish Cap and the Grand Bank. Three current meter moorings were laid on this section at positions shown as A, B and D in Figure 6, both to monitor the current velocity and variability and to provide a reference level for geostrophic calculations. The other two sections extended in a south-easterly direction, towards the Azores, and were perpendicular to the expected flow of the Slope Water Current and Atlantic Current; they reached 41°W longitude, and it was hoped that they would penetrate the gyre which Mann maintained was the source of the high oxygen content of the Atlantic Current.

Temperature, salinity, oxygen and silicate were measured down to the bottom, or in the deeper water alternately to 2300 and 4500 m, and XBT probes were launched between series stations to provide more detailed temperature coverage in the surface layer. Salinity samples were analysed using an Auto Lab inductive salinometer; oxygen analysis was carried out by the Carritt and Carpenter (1966) version of the Winkler technique, and silicate by the manual method of Strickland and Parsons (1968).

RESULTS

The temperature, salinity, oxygen and silicate sections for the Flemish Cap-Grand Bank section are shown in Figure 2. The low temperature, low salinity, high oxygen Labrador Current can be clearly seen on the edge of the Grand Bank, flowing in a southerly direction, while the deep water in the Channel is composed of North Atlantic Central water of similar characteristics to that which might be expected at depths greater than 800 m throughout the survey area. The silicate distribution, however, shows an anomalously high level on the edge of Grand Bank at 300-400 m.

Moynihan and Andersen (1971), among others from the US Coast Guard International Ice Patrol Service (USCG), have shown very similar distributions of temperature and salinity for this time of year, although our temperatures appear to be a little colder over the shallow water of Grand Bank by 1 deg. C or so, a reflection perhaps of the unusually bad ice conditions of 1972. USCG have not to our knowledge made oxygen and silicate observations in these waters.

The temperature and salinity distributions for the southern section (Stations 56-76), given in Figure 3, clearly show the Atlantic Current, with associated temperatures rising to 16°C and salinities above 36 ‰. To the west of the Atlantic Current is another north-going stream of slightly lower temperature and salinity (11°C and 35 ‰), which might be thought to be Mann's Slope Water Current. A counter-current flows between these two north-going streams while the Labrador Current can again be seen over the edge of Grand Bank.

On the more northerly section (Stations 78-98, but note the change of direction east of Station 80 to include Station 78), a somewhat similar situation prevails (Figure 4), although the "Slope Water Current" appears almost to have merged with the Atlantic Current, temperatures in the latter rising not much above 14°C. An interesting feature of both the silicate distributions is the very high concentration of silicate at a depth of 4000 m, which on the southern section reached levels of over 25 µg atoms/litre. This is thought to support a belief by Mann (pers. comm.) that Antarctic bottom water can be identified at this latitude, using silicate as the tracer parameter.

A surprisingly high silicate core was also found at 2000 m on the southern section just off the edge of the shelf. This is not thought to be due to sampling errors since high values were found at stations on either side of the main core and at several depths.

In view of the importance attached, by Worthington and Mann, to the oxygen content of the water masses in the area, it is worth noting that in both Figures 3 and 4 the oxygen content of the surface layers decreases steadily proceeding away from the influence of the Labrador Current until the edge of Grand Bank is reached (above a depth of 4000 m). However, whereas from Stations 70 to 76 on the southern section the oxygen content of the surface layer remains reasonably steady, as indicated by the uniform depth at about 300 m of the 5.0 ml/litre contour, on the northern section greater variability occurs, with higher oxygen values being found to twice that depth on Stations 84 and 78. Beneath the surface layers, the oxygen content decreases to a minimum (below 4 ml/litre at 600-700 m at the eastern end of the sections) and then increases with greater depths to a value greater than 6 ml/litre, there being a tendency for higher values to be found near the bottom on the edge of the bank.

Mass transport across the northern and southern sections

One of the main differences between the Mann and Worthington theories concerns the difference of mass transport between the Gulf Stream and the Atlantic Current. [In Figure 1 the volume transports as indicated by Mann (1967) have been converted to units of mass transport for easier comparison, since these units are more commonly used in the computer programs at the Fisheries Laboratory, Lowestoft.] Mann believes that of the total Slope plus Gulf Stream Current of about 67 x 10^6 tonnes/sec which crosses 50°W south of the Grand Bank, 15 x 10^6 tonnes/sec separates as the Slope Water Current and breaks away around the Tail of the Banks following the edge of Grand Bank, while another 21 x 10^6 tonnes/sec separates from the Gulf Stream proper in the vicinity of $38^\circ30'$N, 44°W, eventually joining the Slope Water Current to form a total Atlantic Current transport of 36 x 10^6 tonnes/sec. Worthington (1962) argues that the total transport between his gyres does not exceed 10 x 10^6 tonnes/sec. Although we cannot solve this discrepancy on our data alone, it is interesting to compare Mann's transport for the Atlantic Current with our own.

For this purpose we have used a reference level of 2000 m, so as to compare directly with Mann's data, and the mass transports above this level are given in Table 1 for the two longer sections which cross the Atlantic Current. It is clear that there are both north- and south-flowing streams crossing the sections, but the total mass transport of 27.28 x 10^6 tonnes/

sec across the southern section is remarkably consistent with a flow of 23.87×10^6 tonnes/sec across the northern section after allowing for a flow of 2.69×10^6 tonnes/sec between Stations 76 and 80. The main north-flowing streams across the two sections amount to 34.40×10^6 tonnes/sec (Stations 60-72) and 39.51×10^6 tonnes/sec (Stations 82-88), which compare favourably with the 36×10^6 tonnes/sec quoted by Mann.

However, the separate "Slope Current" appears to have a transport of only 5.84×10^6 tonnes/sec across the southern section, compared with Mann's estimated 15×10^6 tonnes/sec, and seems to have merged with the Atlantic Current on the northern section.

The current velocities

The speed of the Atlantic Current across the two longer sections has been calculated geostrophically, from the data presently available. Velocities over the Bank relative to the 2000 m reference level have been computed by a modification of the method of Helland-Hansen (1934), and appear to have a maximal speed of about 40 cm/sec near the surface between Stations 68 and 70 on the more southerly section and 33 cm/sec between Stations 86 and 88 on the more northerly section. Figure 5(a) shows the geostrophic velocities for the southern section, in which the main north-flowing Atlantic Current is seen as a wide stream with an equally strong but narrower counter-current which may be part of a gyre or meander of the main stream to the east. The maximal velocities in the north-flowing stream to the west of the Atlantic Current, earlier designated "Slope Water Current", are of the order of 13 cm/sec, while the Labrador Current has a maximum velocity of 33 cm/sec. On the northern section, Figure 5(b), a similar situation obtains, but the "Slope Current" and Atlantic Current have merged and a strong and somewhat surprising subsurface counter-current is shown to the west of the Atlantic Current, which may be exaggerated by the arbitrary choice of reference level.

Geostrophic velocities on the Flemish Cap-Grand Bank section, relative to a 600 m reference level, are shown in Figure 6; the velocities above the Grand Bank were computed by a modified version of Helland-Hansen's technique (Ellett and Martin, in press, and Hill 1971). The reference level of 600 m was chosen by fitting the geostrophic velocity profile between Stations 47 and 48 to the residual currents perpendicular to the section recorded at Station B during the 12 h 25 min tidal cycle nearest to the time of occupation of the series stations (i.e. the first). The geostrophic current velocities above Flemish Cap and on Grand Bank at Station 43 were similarly adjusted, using the residual currents recorded at Stations A and D over the nearest 24 h 50 min tidal cycle to eliminate the diurnal periodicity apparent over the banks.

The corrected geostrophic current velocity profile as given in Figure 6 includes the residual current components perpendicular to the Flemish Cap section, as measured at the recording current meter stations. It can be seen that the Labrador Current has a maximal velocity of about 55 cm/sec, extends in depth to at least the adopted reference level and appears to be a shelf edge phenomenon in that it lies against the edge of the Grand Bank itself. The normal clockwise gyre around the Flemish Cap as reported by Kudlo and Burmakin (1972) is seen to be reversed at the time of sampling but it is weak, having a maximum measured mean southerly component velocity of 8.4 cm/sec near the surface. After 21 April, in fact, a relatively steady north-westerly drift of about 3.5 cm/sec, which is more in keeping with Kudlo and Burmakin's report, was calculated from the current meter data recorded at Station A (see Figure 7).

Mass transport of the Labrador Current

We may now calculate the mass transport of the Labrador Current across the three sections and the results are given in Table 2. It is clear from the geostrophic velocity profile at Figure 5(b) that part of the Labrador Current is to the west of Station 98, which accounts for the lower transport value on the northern section, and suggests that the estimates for the Flemish Cap and southern sections are the more realistic.

Our estimates of transport lie within the range of 1-11 x 10^6 tonnes/sec, derived from the 47 estimates over similar sections across the Labrador Current that have been published by a series of authors since 1965 in the USCG Oceanographic Report Series. More often than not the sections that have been sampled are Sections A2 and A3 in USCG nomenclature and most of the estimates lie, in fact, within the range 1-6 x 10^6 tonnes/sec, with an overall mean of 3.6 x 10^6 tonnes/sec. It would appear therefore that the 5.5 x 10^6 tonnes/sec level found in 1972 was rather higher than usual. This accounts for the somewhat lower than normal temperatures previously reported in the current on the Flemish Cap section.

Variability of tidal streams and residual drift on the Flemish Cap section

Wolford (1966) launched a number of parachute drogues in the Labrador Current at a time when he estimated the mass transport to be 5.4 x 10^6 tonnes/sec. The drogue velocities in the core of the Labrador Current over deep water varied from 36 to 81 cm/sec, which agreed reasonably well with the geostrophic velocities calculated from hydrographic sections worked during the same cruise although, as might be expected, the agreement was less good over the shallow banks. Thus our mean near-surface geostrophic velocities of 55, 30 and 33 cm/sec on the Flemish Cap, northern and southern sections respectively seem reasonable, bearing in mind the mass transports which we measured.

However, it is clear from Figure 7, which shows the 24 h 50 min residuals at each of the current meter positions (see Figure 6), that there is a considerable variability in both velocity and direction about the mean flow at each of the three points on the Flemish Cap section at which observations were made, with very great and abrupt changes of regime occurring on the Grand Bank itself. At Station D, for example, which lies to the west of the core of the Labrador Current, an essentially south-going regime of 18 cm/sec/day at all sampling depths comes to an end suddenly on 24 April and is replaced by north-easterly advective drift of the order of 6 cm/sec/day. This change in overall character is paralleled by a change in tidal stream character. In the period 21-23 April, the direction of drift remains fairly steady at about 200°, but a diurnal periodicity can be seen in the velocity record. Maximum velocities recorded fall in 10 cm/sec stages from 40 cm/sec on 21 April to 20 cm/sec on 23 April. After 23 April directions rotate round the compass in 24 hour periods, with stream velocity maxima occurring at 20 cm/sec. Then on 28 April steady drift in the 0-100° direction zone with a diurnal velocity regime becomes established. Such transient tidal stream characters are presumably the result of changes in residual drift patterns being imposed on a weak diurnal tidal regime. However, no such radical changes are found in the temperatures recorded in the middle and near the bottom of the water column at this station. In both cases the water temperatures lie between -0.6 and -1.6°C throughout the period. This suggests that the gross variability found in the residual drift regime was the result either of large-scale changes in the advective drift of the waters to the west of the core of the Labrador Current, or of a change in the position of the core itself.

Some evidence in favour of the idea that the position of the core of the Labrador Current actually changed in position is provided by the temperature record of the top current meter (286 m) at Station B; here, temperatures of 4°C occurred until early on 26 April, when they fell in 30 min to 1.75°C and for the next two days varied in the range 1.75-3°C before returning to the 3-4°C level on 28 April, where they remained until the meter was recovered on 1 May. Reference to Figure 2(a) shows that these changes would be made possible by an easterly translation, of some 40 km, of the core of the Labrador Current, followed by a return to the position at which we had observed it on 17-18 April. Although the rapid temperature change occurred two days later than the direction change at Station D, it seems that the two processes may be related.

There is in fact no drastic change in the residual drift regime at Station B, at any time, similar to that found at Station D on 24 April. The record at 286 m depth shows that after three days of small and variable residual drift a steady 5 cm/sec south-easterly drift develops on 23 April and continues for the rest of the time the station was maintained. At 688 m depth a south-westerly trend begins on 22 April and lasts until 26 April, when a south-easterly regime becomes established. Residual velocities at this depth lie in the range 2-7 cm/sec/day. Tidal streams at both levels are very poorly developed. At 286 m depth there is diurnal periodicity throughout the velocity record and also in the first half of the direction record. After 0600 h on 26 April, however, all recorded directions lie in the zone 150° ± 50°, with very little discernible periodicity. At 688 m depth the recorded velocities suggest the presence of a semi-diurnal tidal regime (maxima 9 cm/sec) for the period 21-23 April, but after this a diurnal pattern is more pronounced. The recorded directions show little periodicity, but do change in general character at times. In the period 21-23 April, for example, directions lie between 250° and 050°, but during

23-26 April steady drift at 200° ± 50° is found and is replaced for the last five days of the record by drift in the zone 150° ± 50°.

Finally, the temperature and current meter data recorded at Station A suggest that a third distinct residual drift regime occurs at the eastern end of the Flemish Cap section. It has already been noted that previous workers in the region have suggested that normally there is a clockwise gyre round the Flemish Cap itself, and the essentially north-west-going drift (mean daily velocity 3.5 cm/sec) found in both records at this station on and after 21 April provides support for this view. Further corroboration is supplied by the fact that the temperatures recorded at the near-bed instrument lie in the range 3.9-4.3°C and this is quite different from those found at either of the other two anchored stations in this section. The atypical south-going component of drift found in both records on 20 April is presumably a consequence of the north-westerly gale that blew for most of the day and reached 40 knots at times in the vicinity of Station A.

Throughout the data collected at this station there is a clear diurnal periodicity, the tidal streams rotating through 360° in 24 hours for most of the time, and the velocities, especially at the near-bottom meter, forming distinct sinusoidal waves. Peak velocities are attained at both levels during the period 19-23 April, with absolute maxima being 46 cm/sec at the near-bottom meter and 34 cm/sec in the near-surface layer. After 23 April peak levels do not exceed 30 and 20 cm/sec in the near-bed and near-surface levels respectively.

The temperature-salinity curve of the Slope Water Current

It has been stated earlier that the north-going stream found to the west of the main Atlantic Current, and centred on Station 62 on the southern section, might be thought to be Mann's "Slope Water Current" although, as we have shown, it is deficient in mass flow. However, an examination of the temperature-salinity curves, a selection of which are given in Figure 8, shows that this is not completely so. The temperature-salinity curve representing Stations 70 and 72 follows closely the expected curve for Atlantic Current water (and indeed Gulf Stream water) as given by previous workers, e.g. the 20-year mean produced by Morgan (1969). Station 57 is representative of Labrador Current water and the remaining stations are clearly mixtures of these two water masses, with a steadily increasing percentage of Atlantic Current water as the stations proceed to the east, i.e. Stations 58, 62 and 68. Thus at Station 62, we have a well-mixed layer down to 150 m, with a mixture of Labrador Current and Atlantic Current water beneath this depth which is almost the same percentage mixture as that at Station 68. Both of these may properly be called Slope Current water, since the Slope Current originates further south as a mixture of these two currents, and clearly the stream centred on Station 62 is not of itself Mann's "Slope Current", since this extends into, and indeed is part of, the main northerly transport of water between Stations 68 and 70. In fact it is suggested that the mixing process has already begun south of this section and that we are examining part of this mixing process. This would account for the low transport of the "Slope Current" centred on Station 62, and we should properly take the region between Stations 62 and 68, including the southerly stream, as Slope Current. It would seem reasonable in fact to think of advective movements in this area as forming part of an eddy produced by the velocity shear between the 40 and 13 cm/sec streams indicated on Figure 5.

O_2- σ_t curves from April-May 1972

It is of interest to consider the oxygen/sigma-t curves as first used by Worthington (1962) to distinguish the highly-oxygenated water of the

Atlantic Current. Worthington showed that the O_2-σ_t relationship for waters in his southern gyre conformed very closely to the curve established by Richards and Redfield (1955) for the Sargasso Sea, whereas all the O_2-σ_t curves drawn for stations in the area of his northern gyre (Atlantic Current) lay above the Richards and Redfield curve in a similar fashion to Stations 68 and 70 on Figure 9, which includes the O_2-σ_t curves for selected stations on the southern section.

The O_2-σ_t curves for Stations 59 and 62 are also shown and when compared with Stations 68 and 70 on Figure 9 it will be noticed that the oxygen content at a given density surface decreases consistently eastwards, particularly in the surface layers at densities less than σ_t = 27.2. When the remaining stations are plotted this trend is still apparent, though the decrease is not as regular as indicated by the selected stations. This is to be expected, bearing in mind the temperature-salinity relationship, since we are getting a smaller percentage of the more highly-oxygenated Labrador Current water. If this were the only source of highly-oxygenated water we would expect this decreasing trend towards the east to continue, but Station 78 shows a reversal of the trend in that the oxygen content increases again at depths less than 600 m (σ_t = 27.16) and in fact the oxygen values are greater than 4.94 ml/l down to this depth. A similar unexpected high oxygen content to a depth of 500 m occurs on the northern section at Station 84, but the decreasing trend easterly is less marked than on the southern section.

It is therefore possible that at the easterly end of our survey we have entered the gyre which Mann believes is the source of the high oxygen values in the Atlantic Current.

ACKNOWLEDGEMENTS

The authors wish to acknowledge the assistance given during the cruise and in subsequent data processing by other members of the staff of the Fisheries Laboratory, Lowestoft and Mr D. I. Gaunt of the National Institute of Oceanography.

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Table 1 Mass transport between pairs of stations, in 10^6 tonnes/sec

Stations	92–90	90–88	88–86	86–84	84–82	82–80	Total
Transport	–0.31	–10.24	26.52	10.18	2.81	–5.09	23.87

Stations	76–80	78–80	Total
Transport	0.65	2.04	2.69

Stations	58–60	60–62 *	62–64 *	64–66	66–68	68–70	70–72	72–74	74–76	Total
Transport	–0.13	2.88	2.96	–3.06	6.70	23.46	1.46	–14.35	7.36	27.28

Positive flow is north-east-going (for Stations 76–80, east-going).
* Reference level at maximum observed depth of 1800 m.

Table 2 Mass transport of the Labrador Current, in 10^6 tonnes/sec

Section	Mass transport
Flemish Cap	5.32
Northern	2.92
Southern	5.60

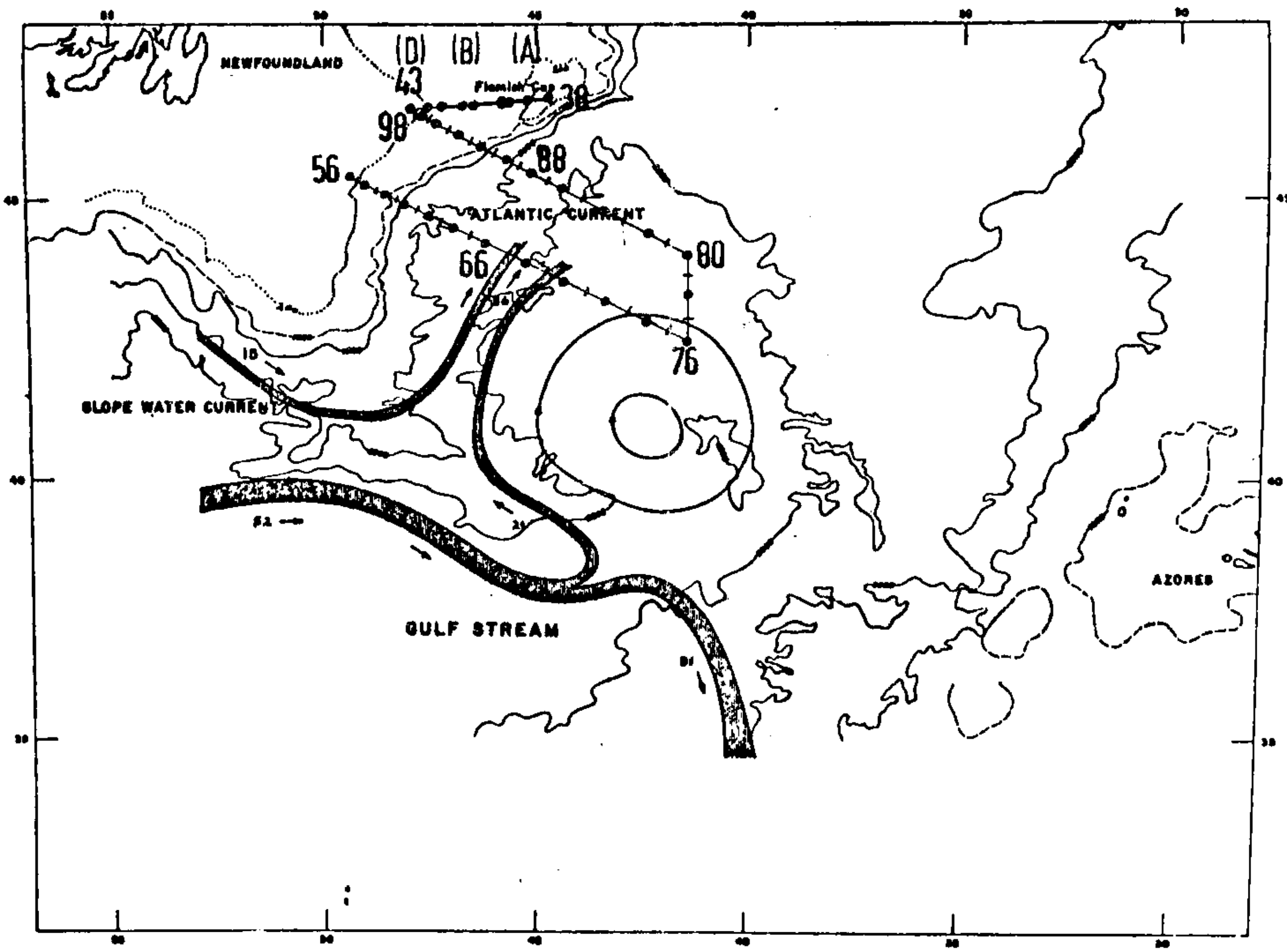

Fig. 1. The current system south-east of the Grand Bank. Nominal transport in million tones per second (based on Mann, 1967) with CIROLANA stations superimposed.

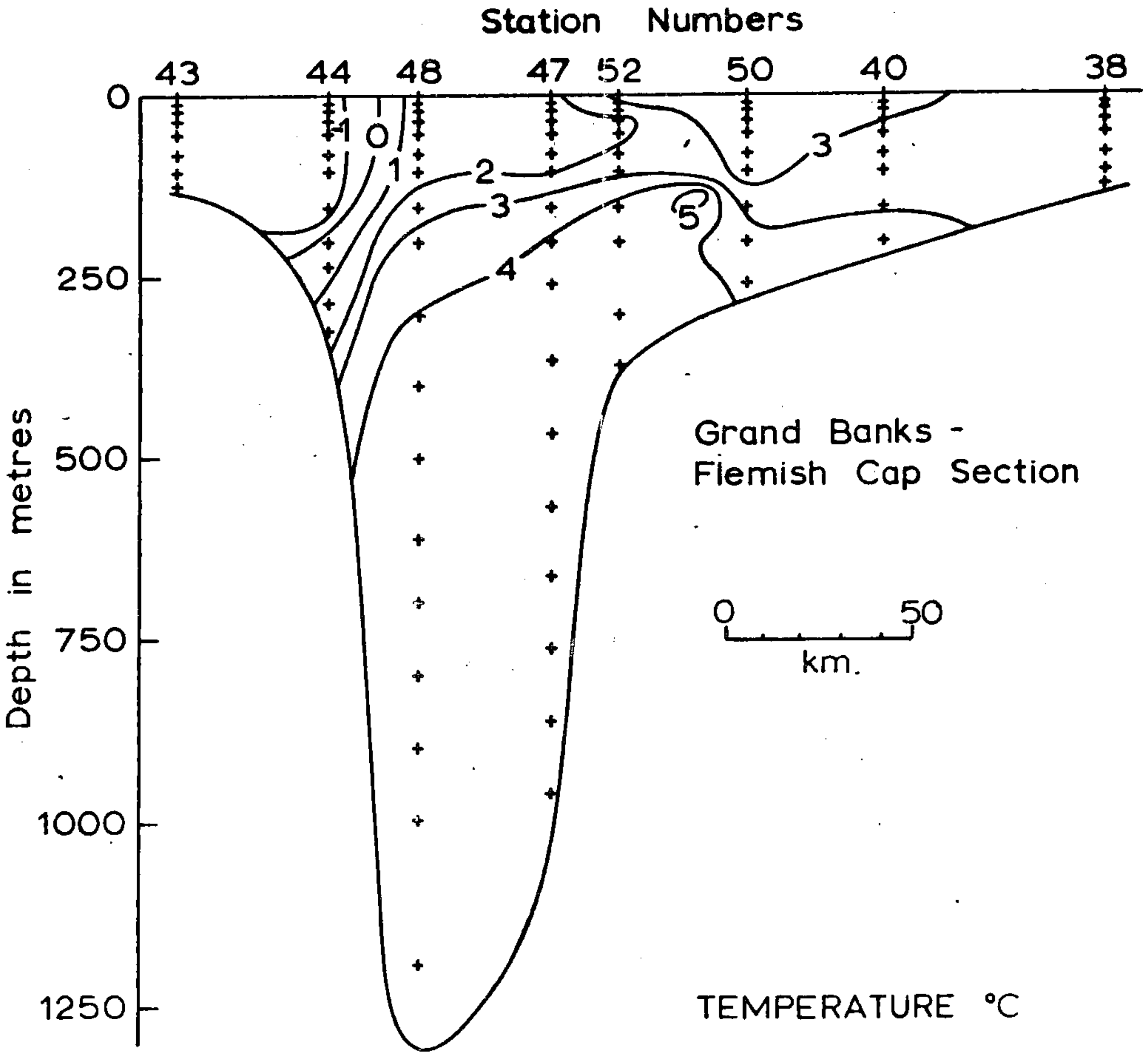

Fig. 2(a) Grand Bank - Flemish Cap section - temperature, °C.

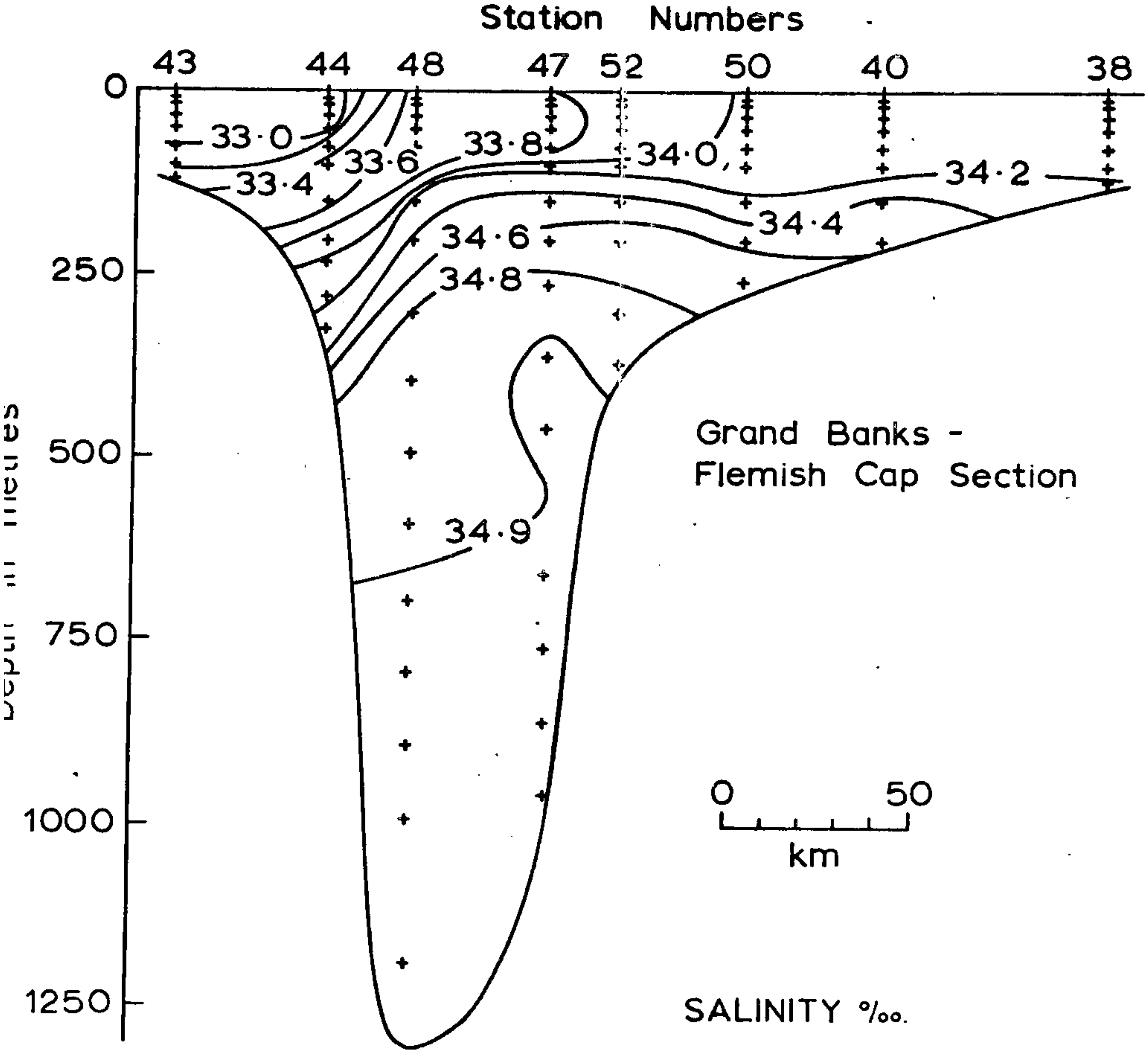

Fig. 2(b) Grand Bank - Flemish Cap section - salinity, °/oo.

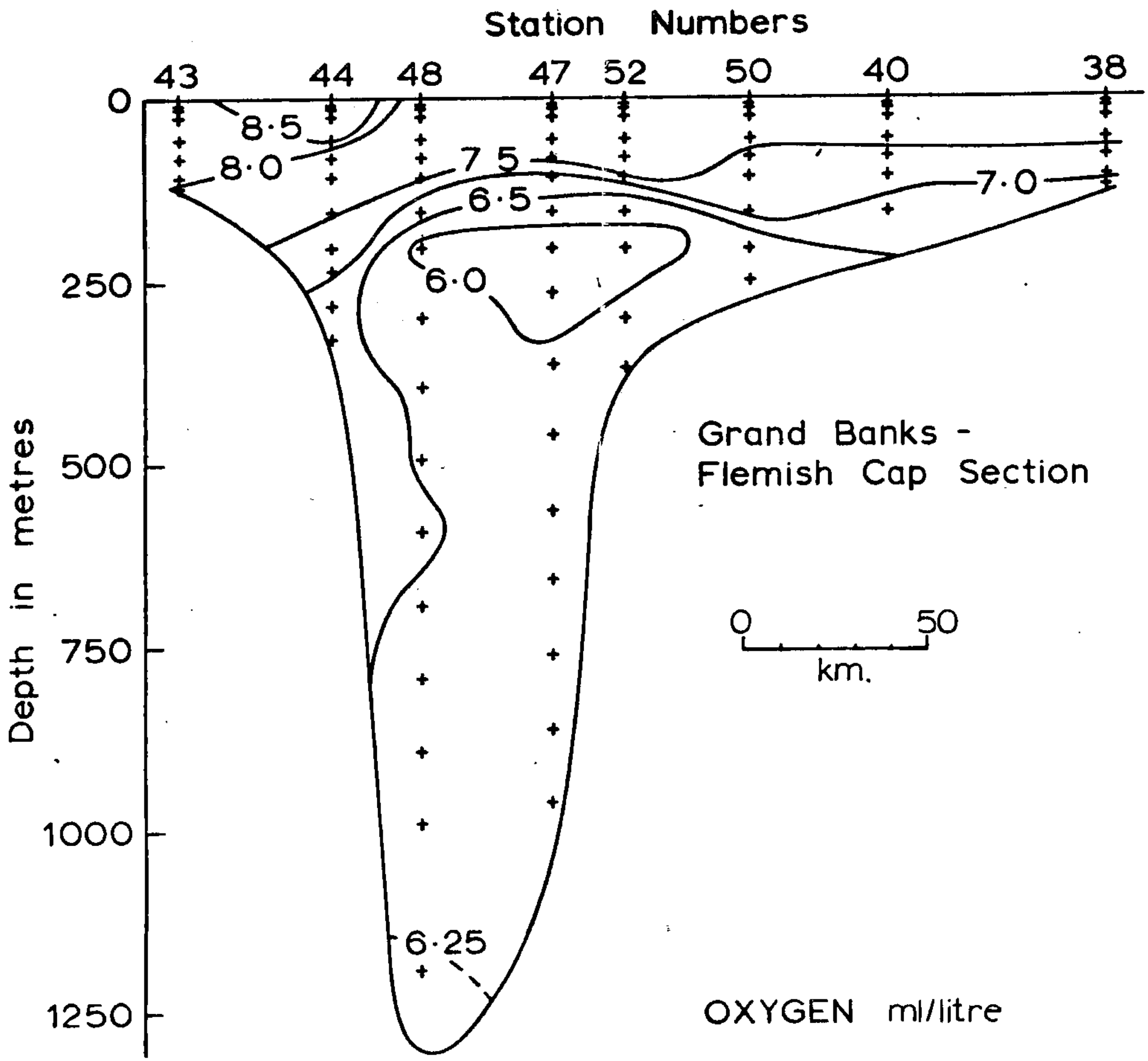

Fig. 2(c) Grand Bank - Flemish Cap section - oxygen, ml/litre.

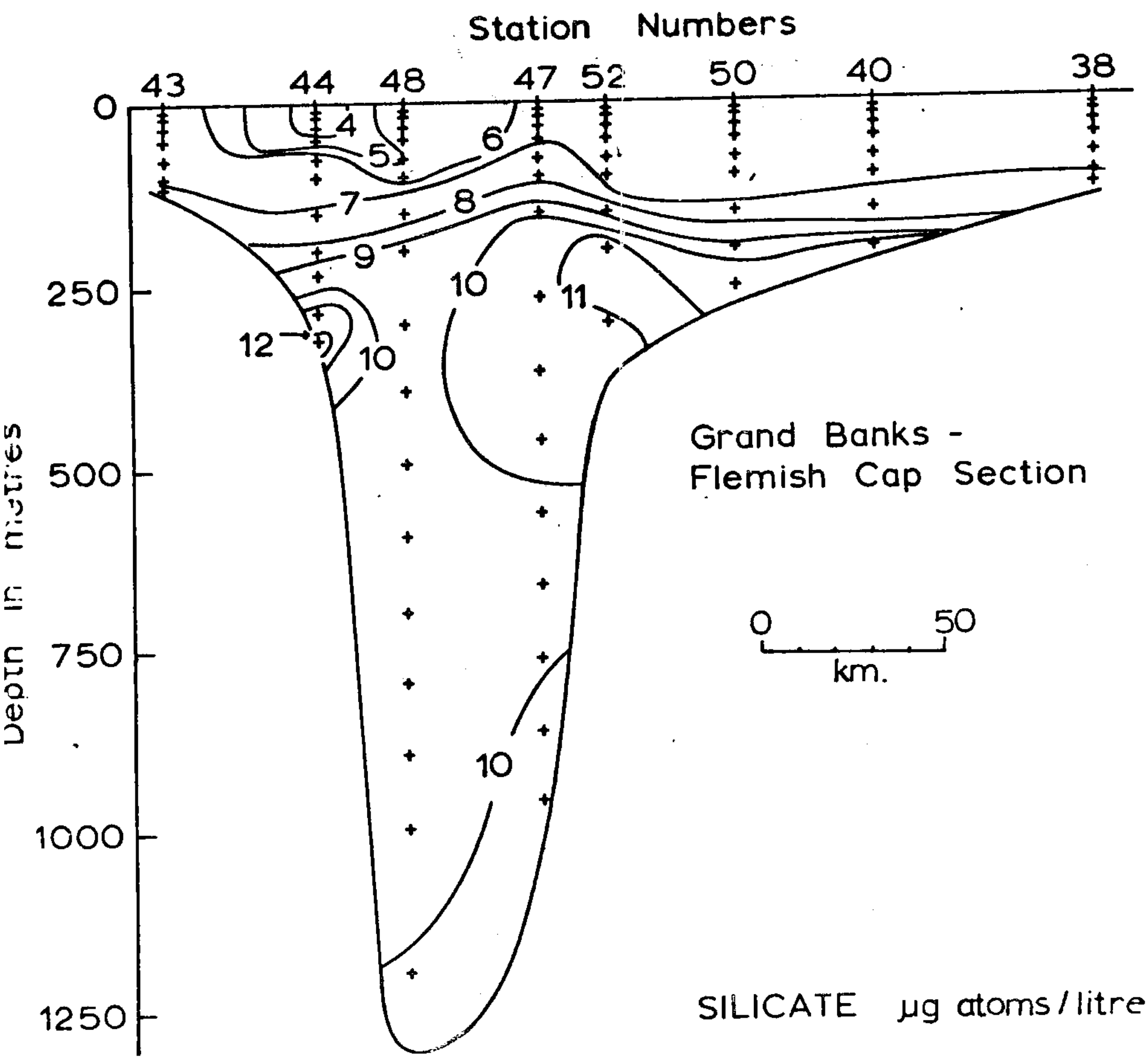

Fig. 2(d) Grand Bank - Flemish Cap section - silicate, μg atoms/litre.

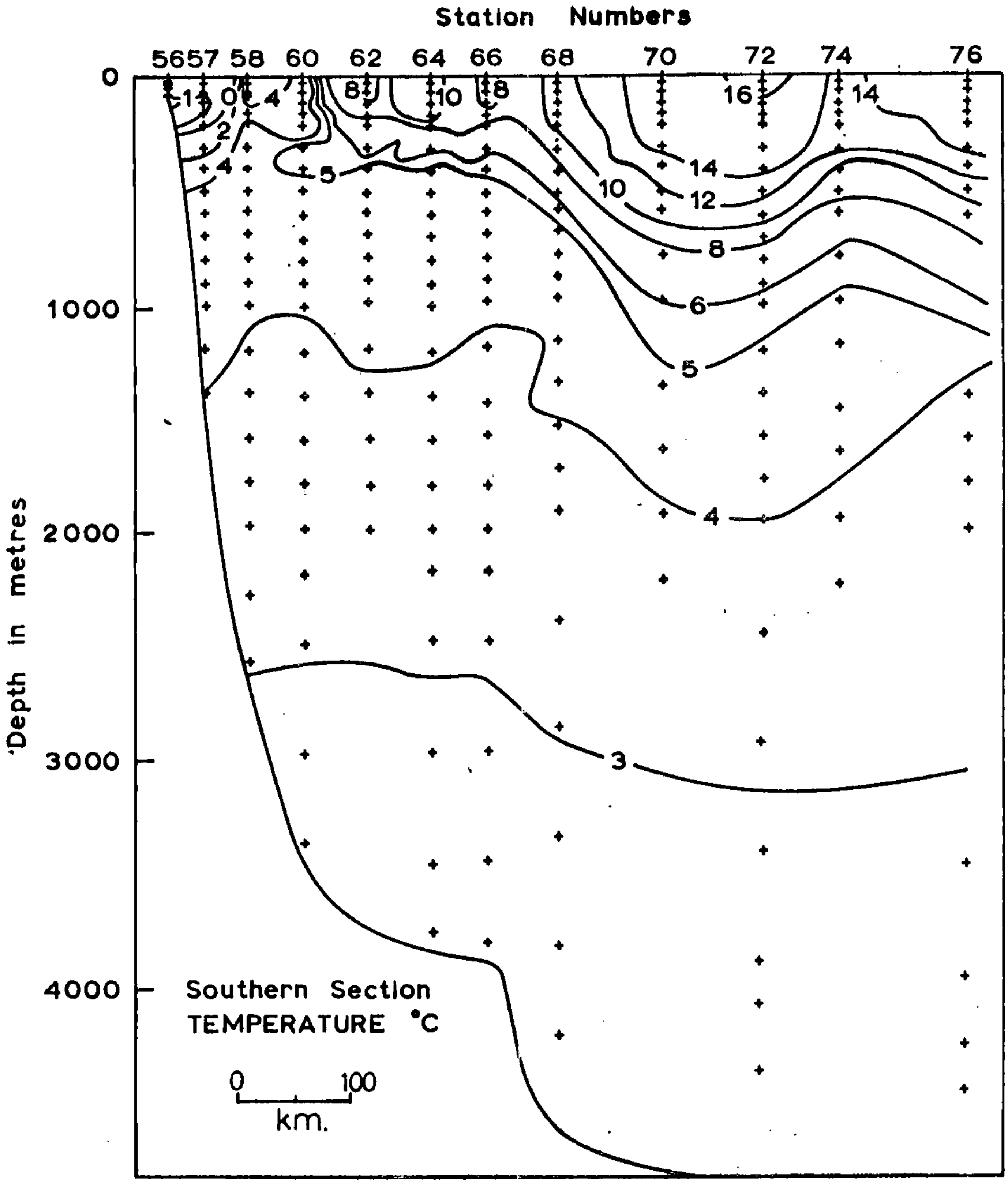

Fig. 3(a) Southern section - temperature, °C.

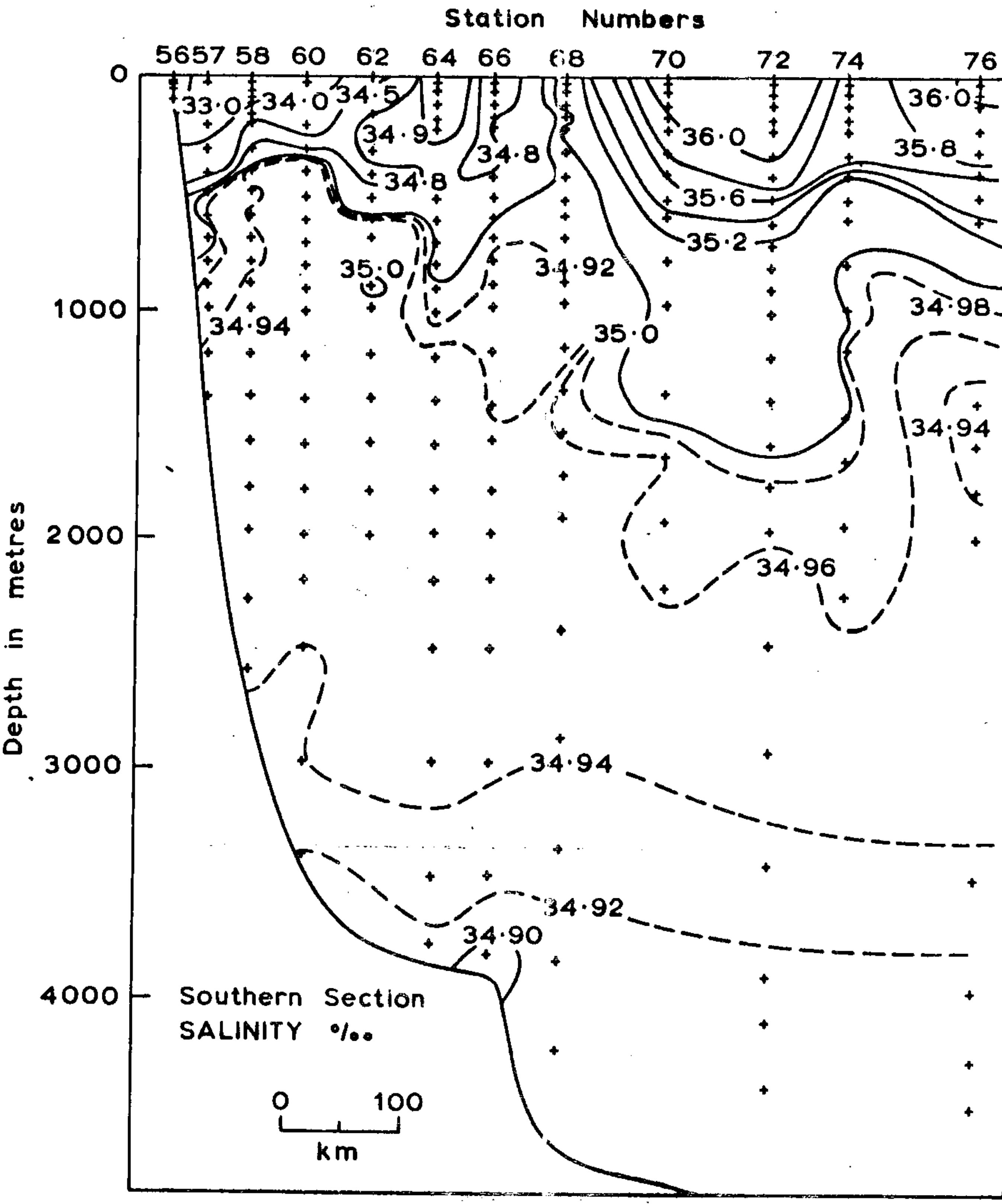

Fig. 3(b) Southern section - salinity, ‰.

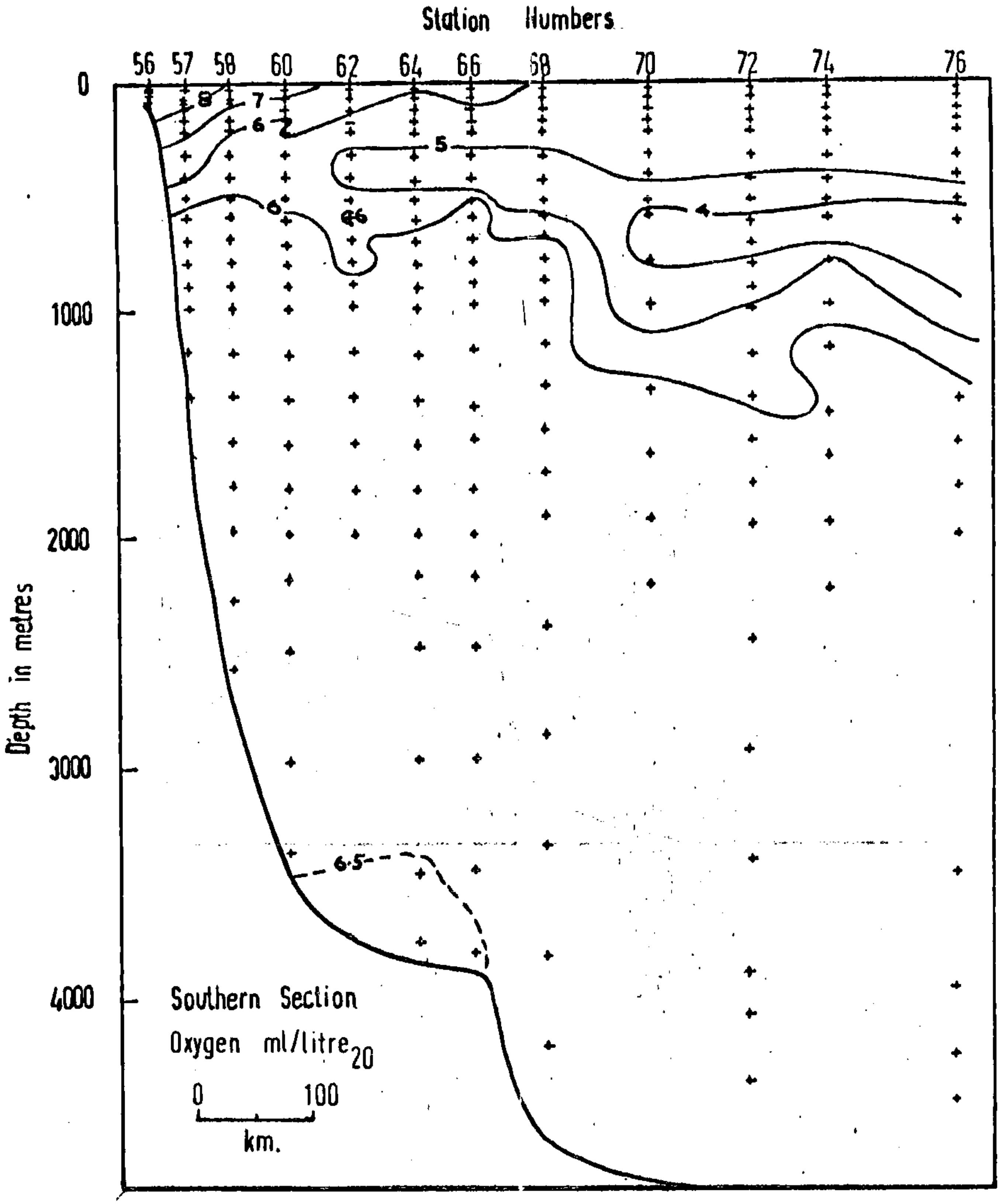

Fig. 3(c) Southern section - oxygen, ml/litre.

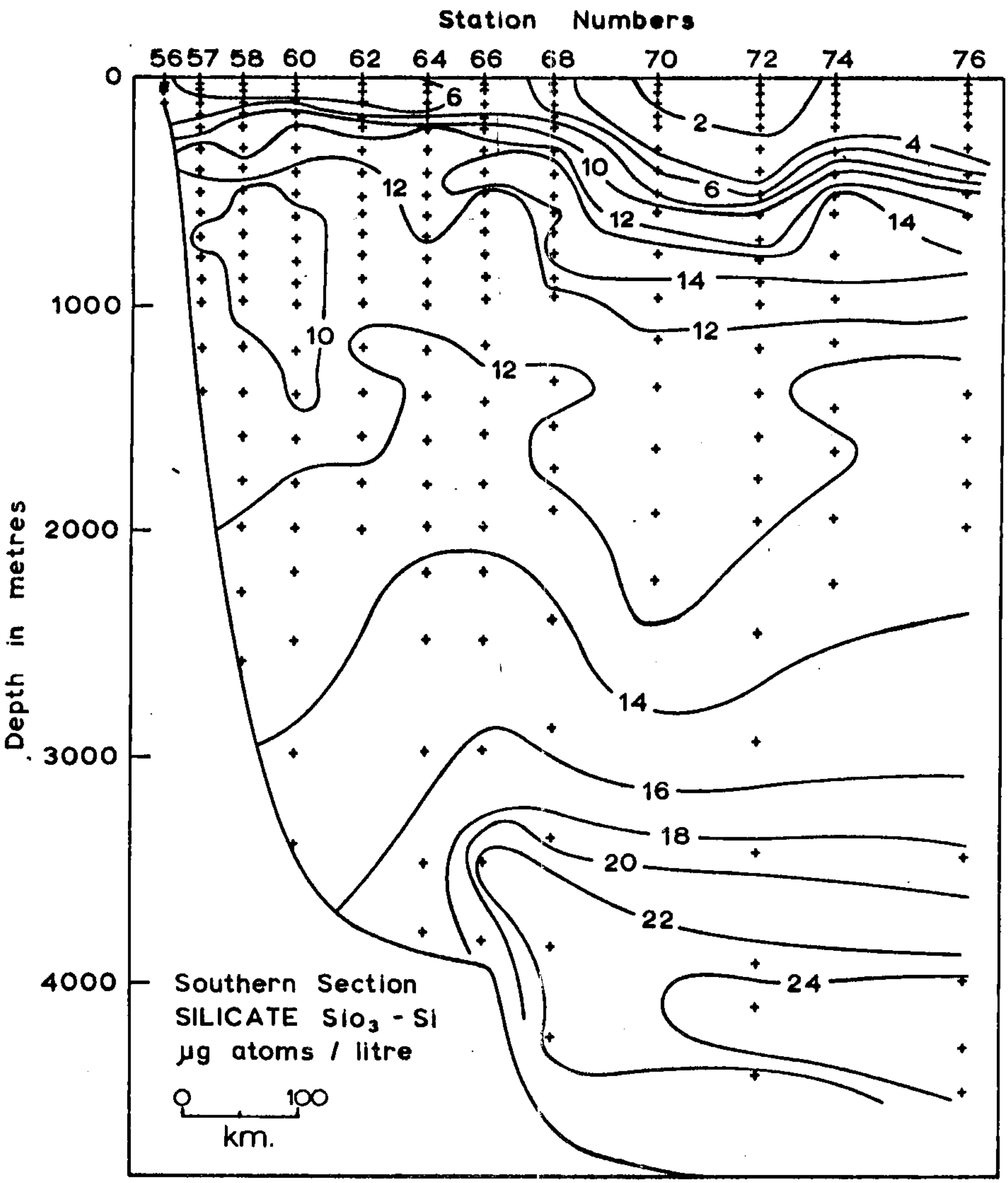

Fig. 3(d) Southern section - silicate, µg atoms/litre.

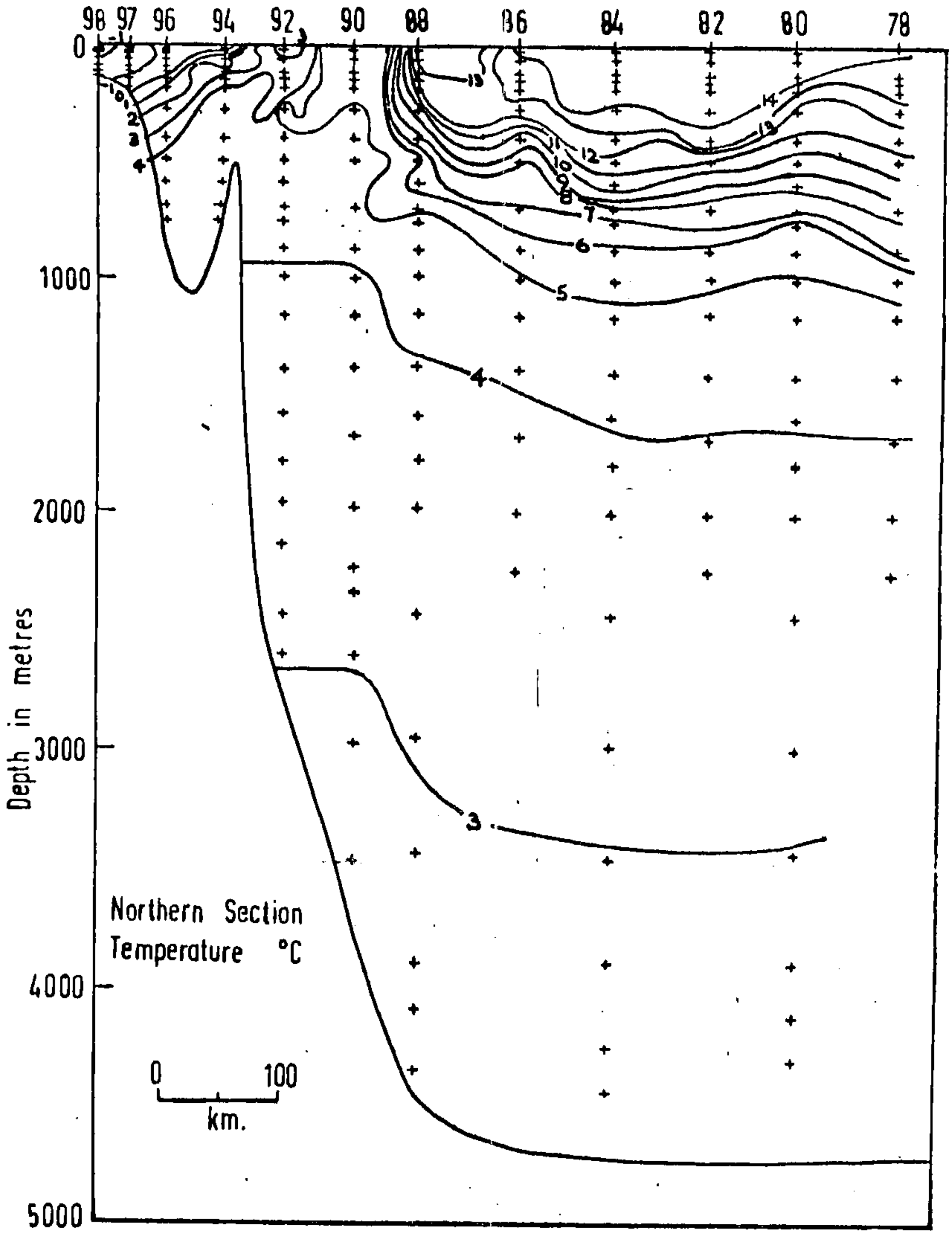

Fig. 4(a) Northern section - temperature, °C.

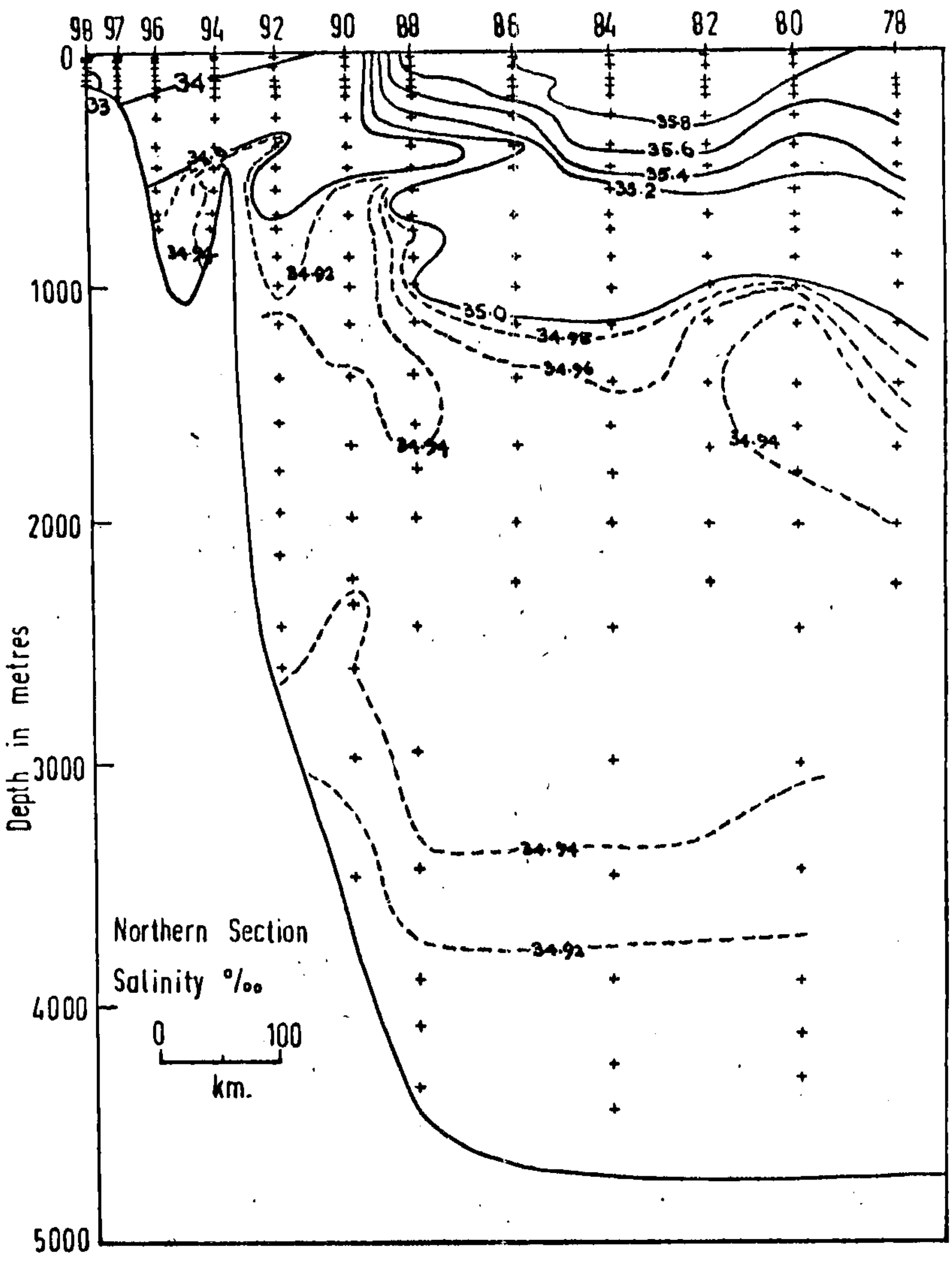

Fig. 4(b) Northern section - salinity, °/oo.

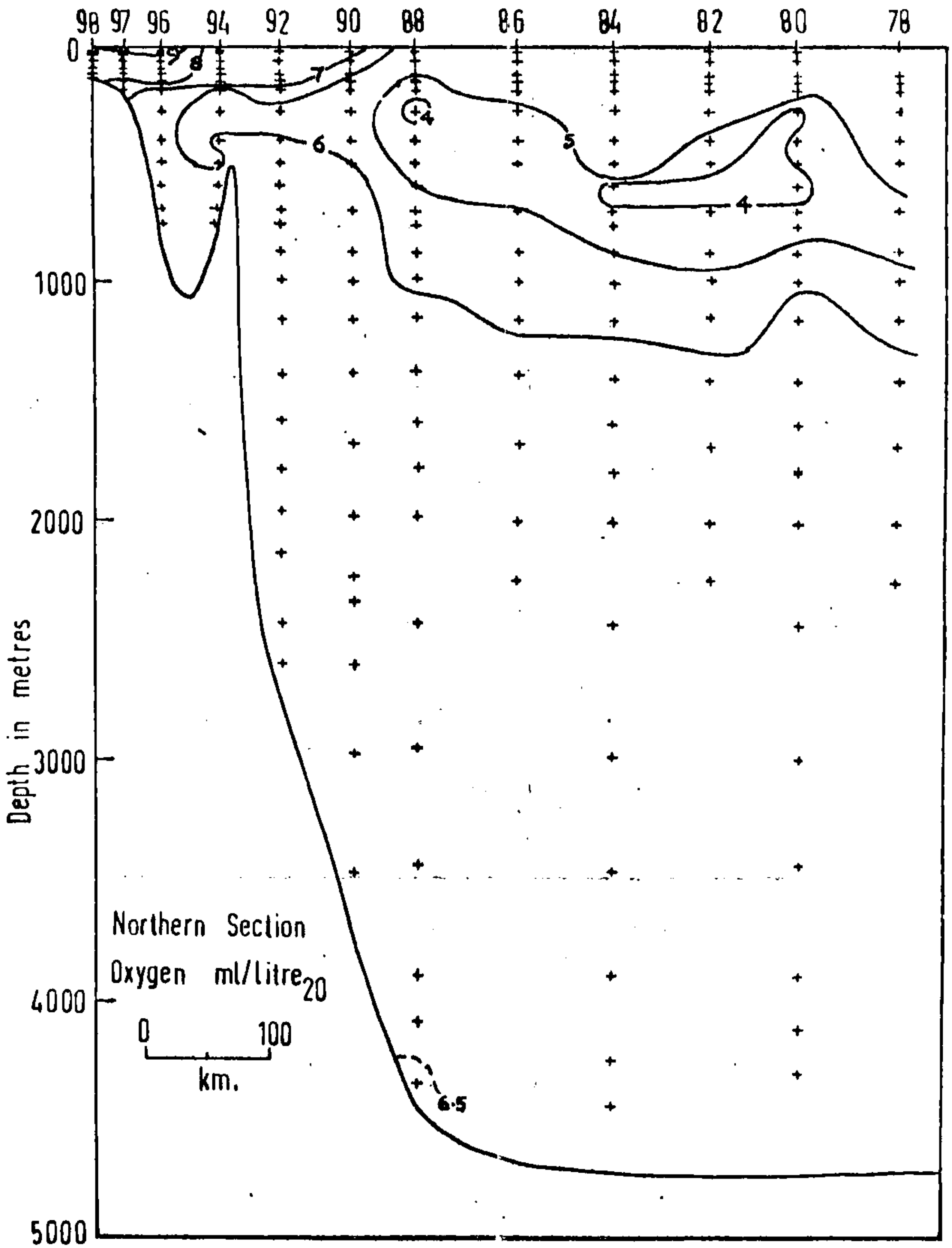

Fig. 4(c) Northern section oxygen, ml/litre.

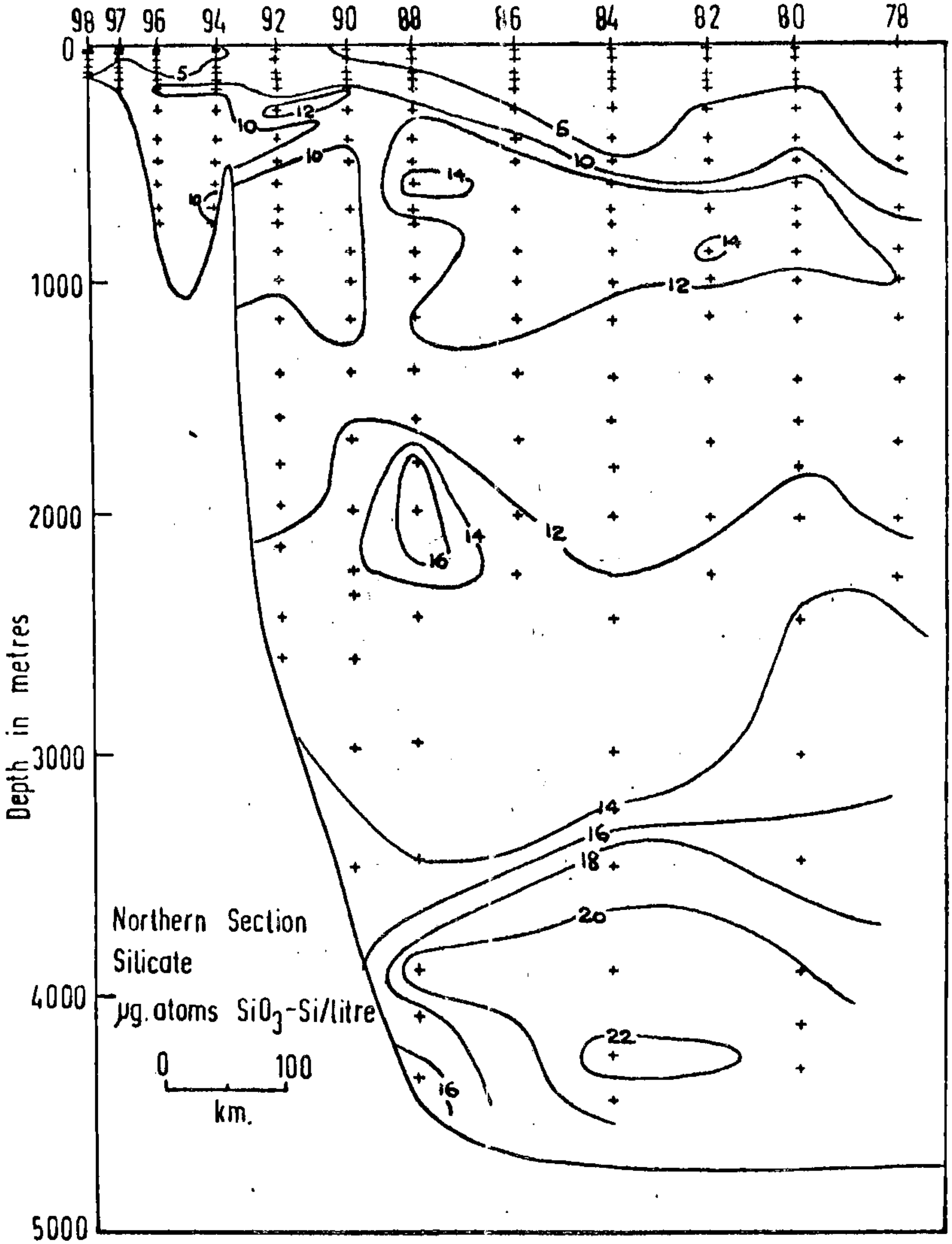

Fig. 4(d) Northern section - silicate, µ g atoms/litre.

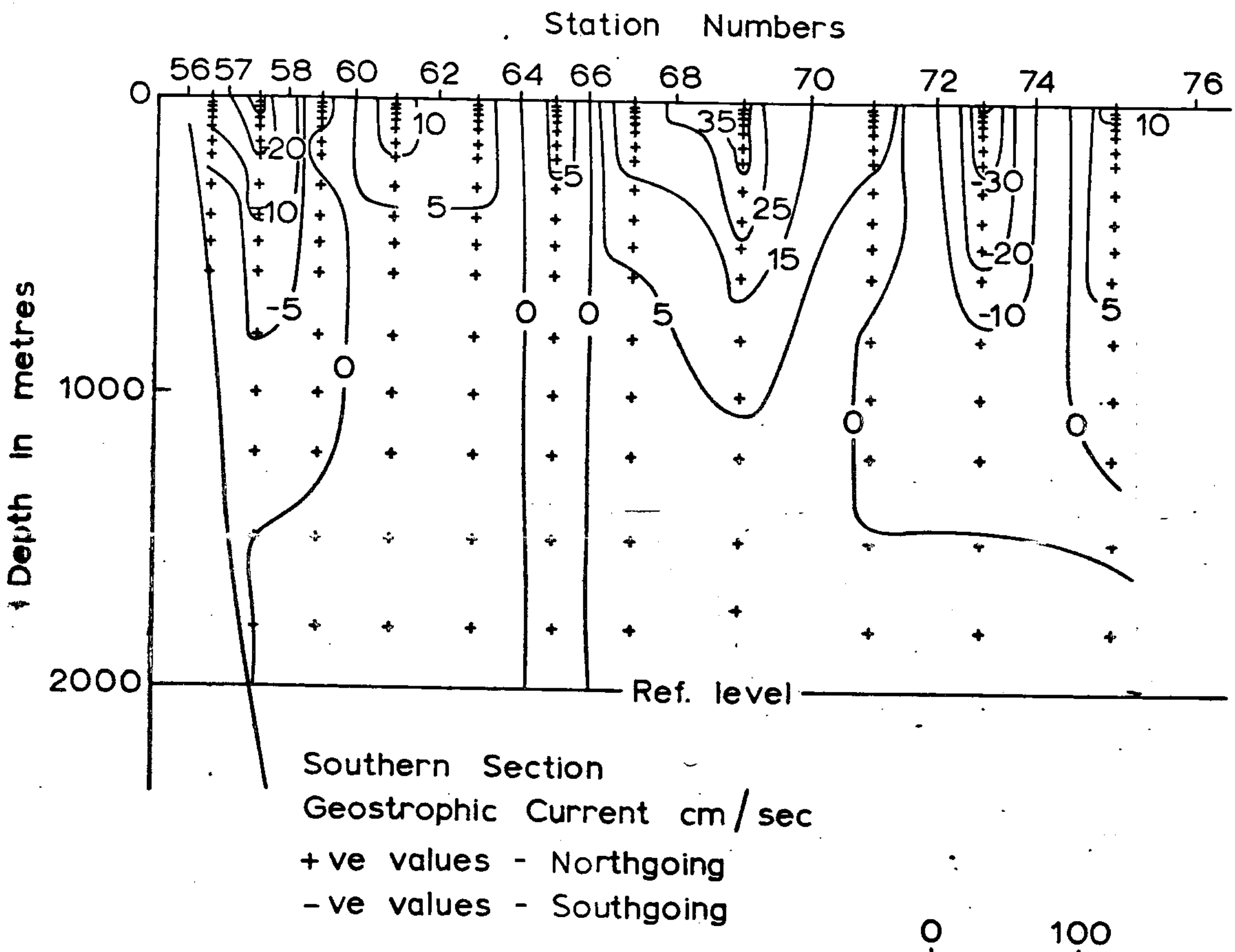

Fig. 5(a) Geostrophic currents - southern section.

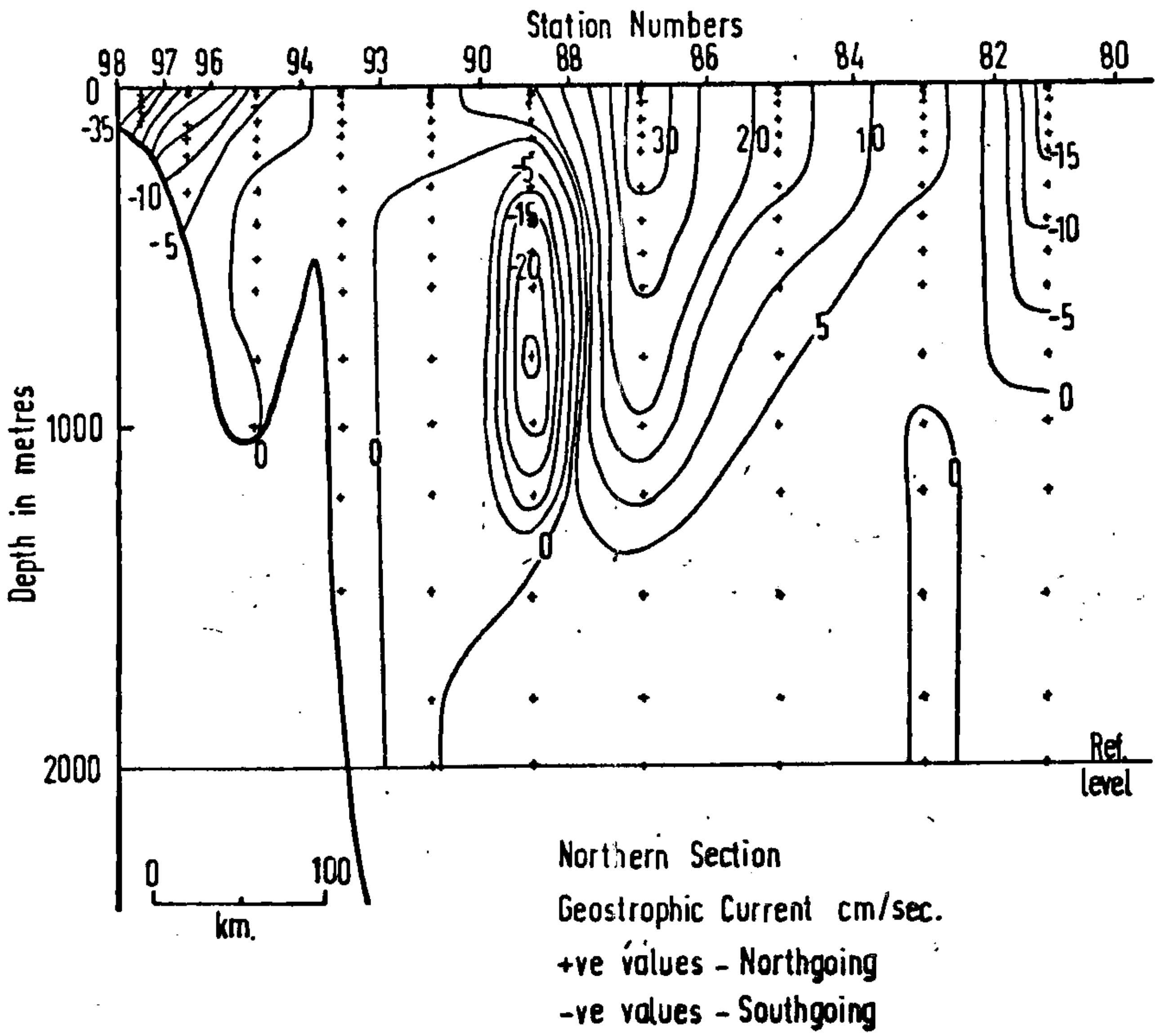

Fig. 5(b) Geostrophic currents - northern section.

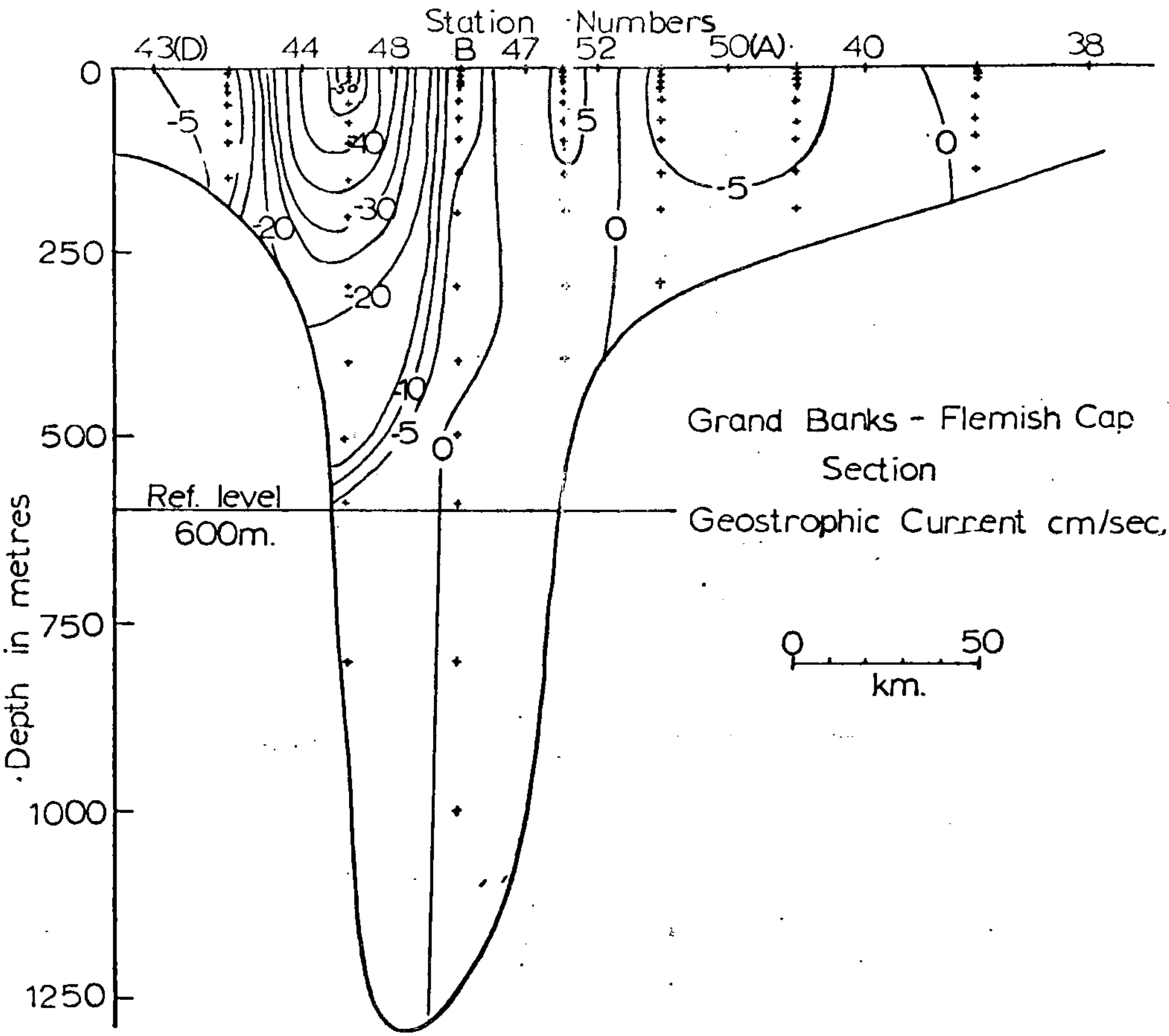

Fig. 6. Geostrophic currents, Grand Bank - Flemish Cap section.

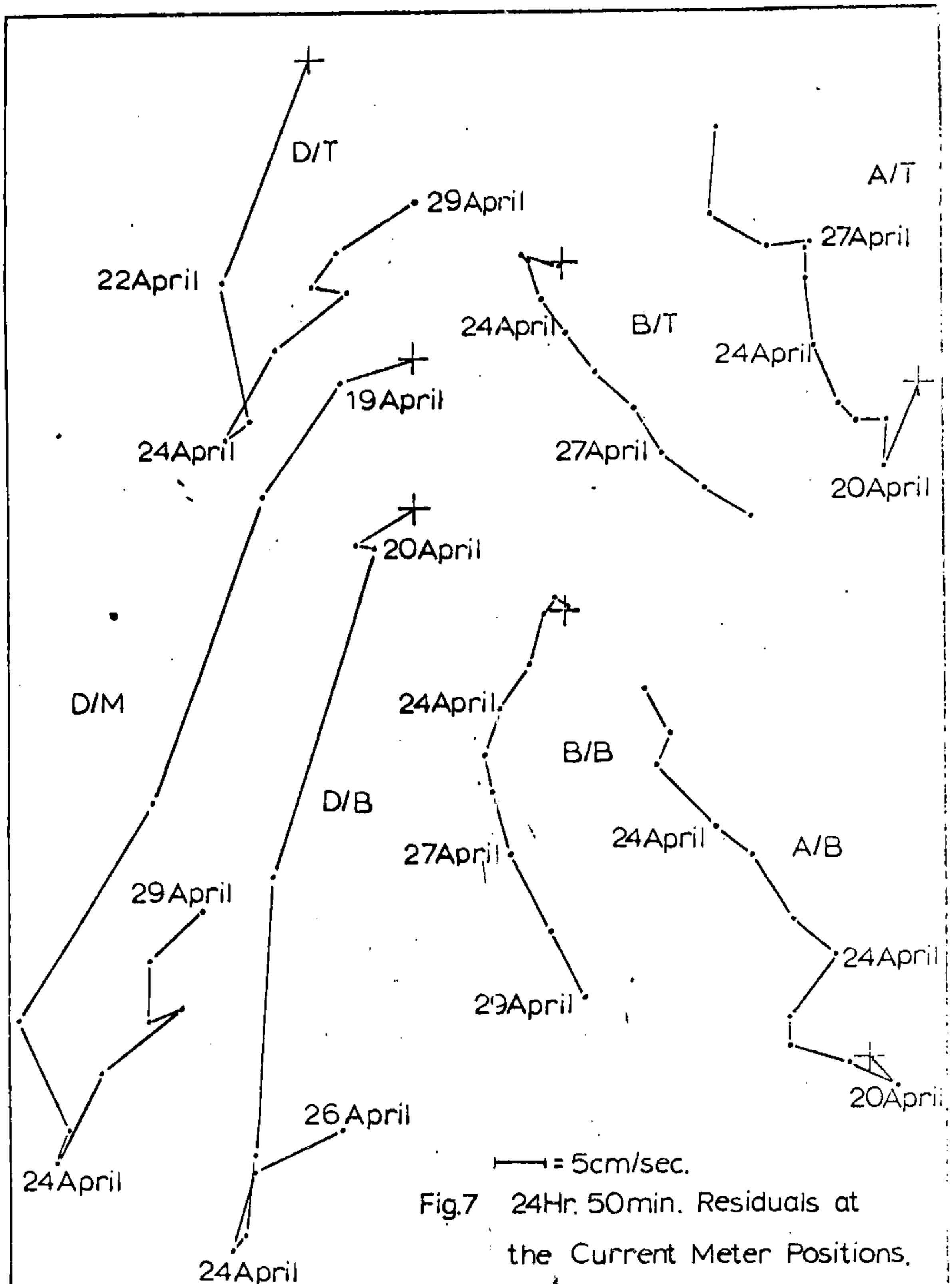

Fig. 7. 24 hour 50 min current meter residuals.

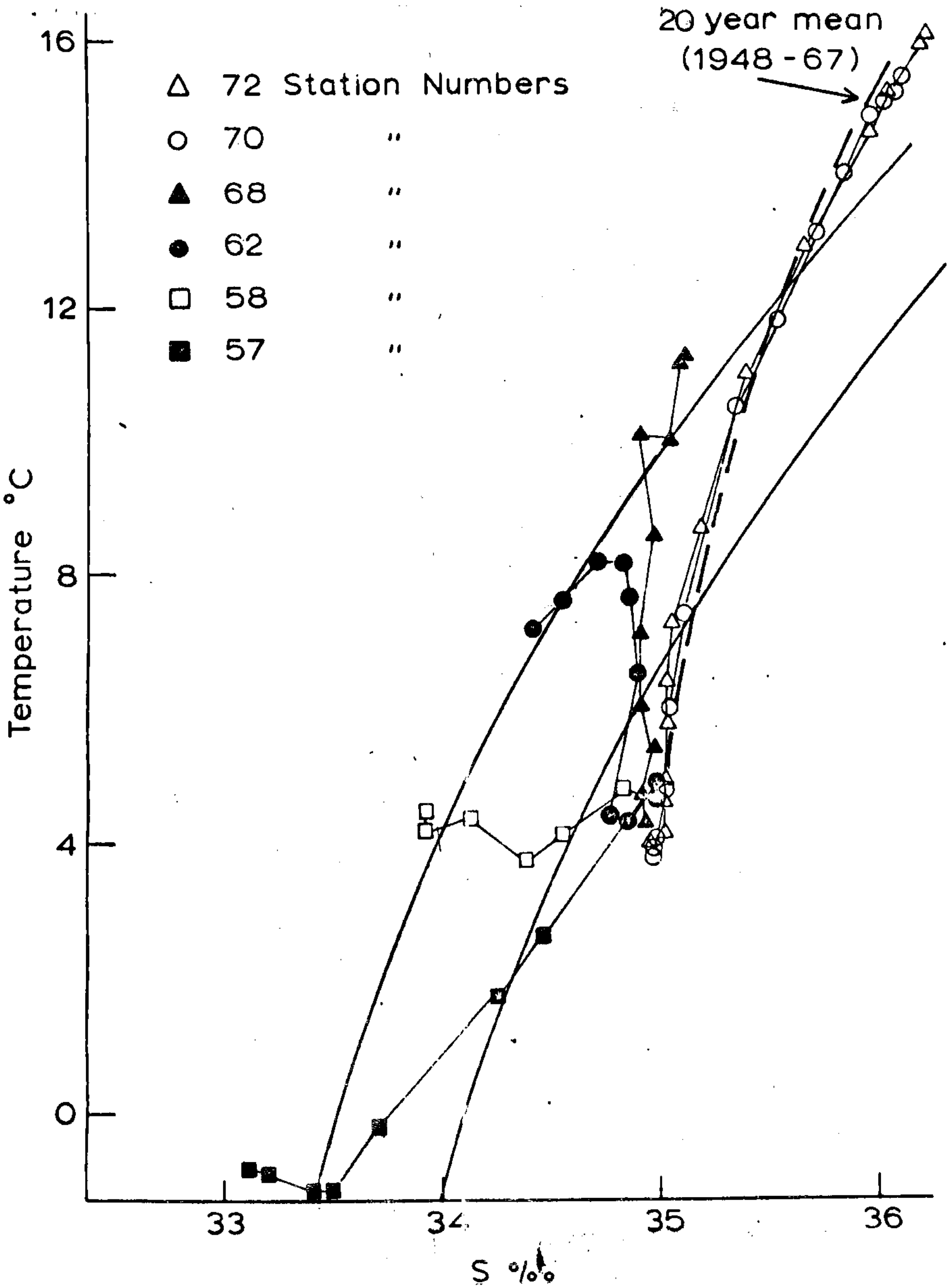

Fig. 8. Temperature-salinity diagram, southern section.

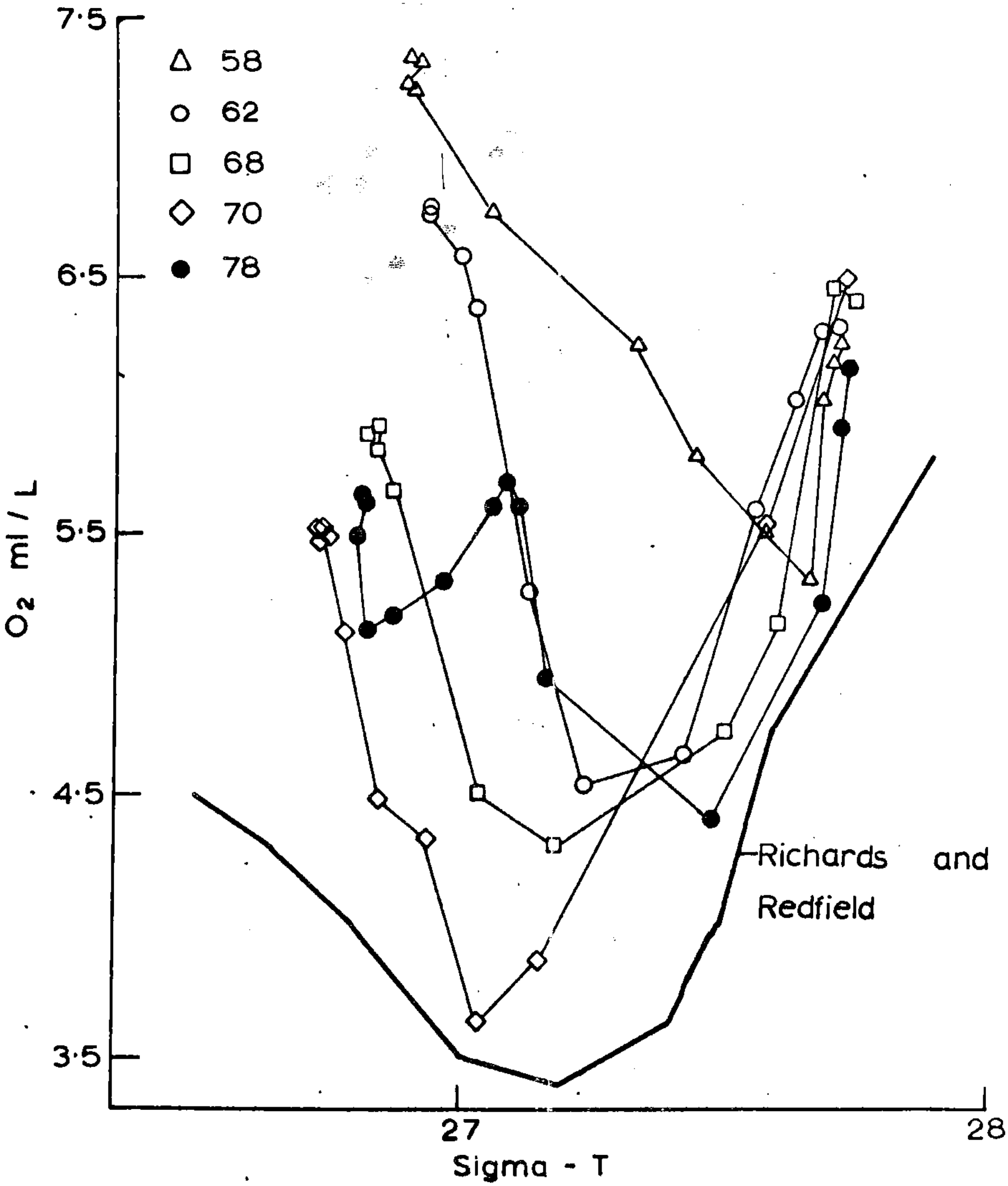

Fig. 9. Oxygen/sigma-t diagram.