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NEW ZEALAND
DEPARTMENT OF SCIENTIFIC AND INDUSTRIAL RESEARCH

BULLETIN 174

WATER MASSES AND FRONTS IN THE SOUTHERN OCEAN SOUTH OF NEW ZEALAND

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Th. J. HOUTMAN

New Zealand Oceanographic Institute
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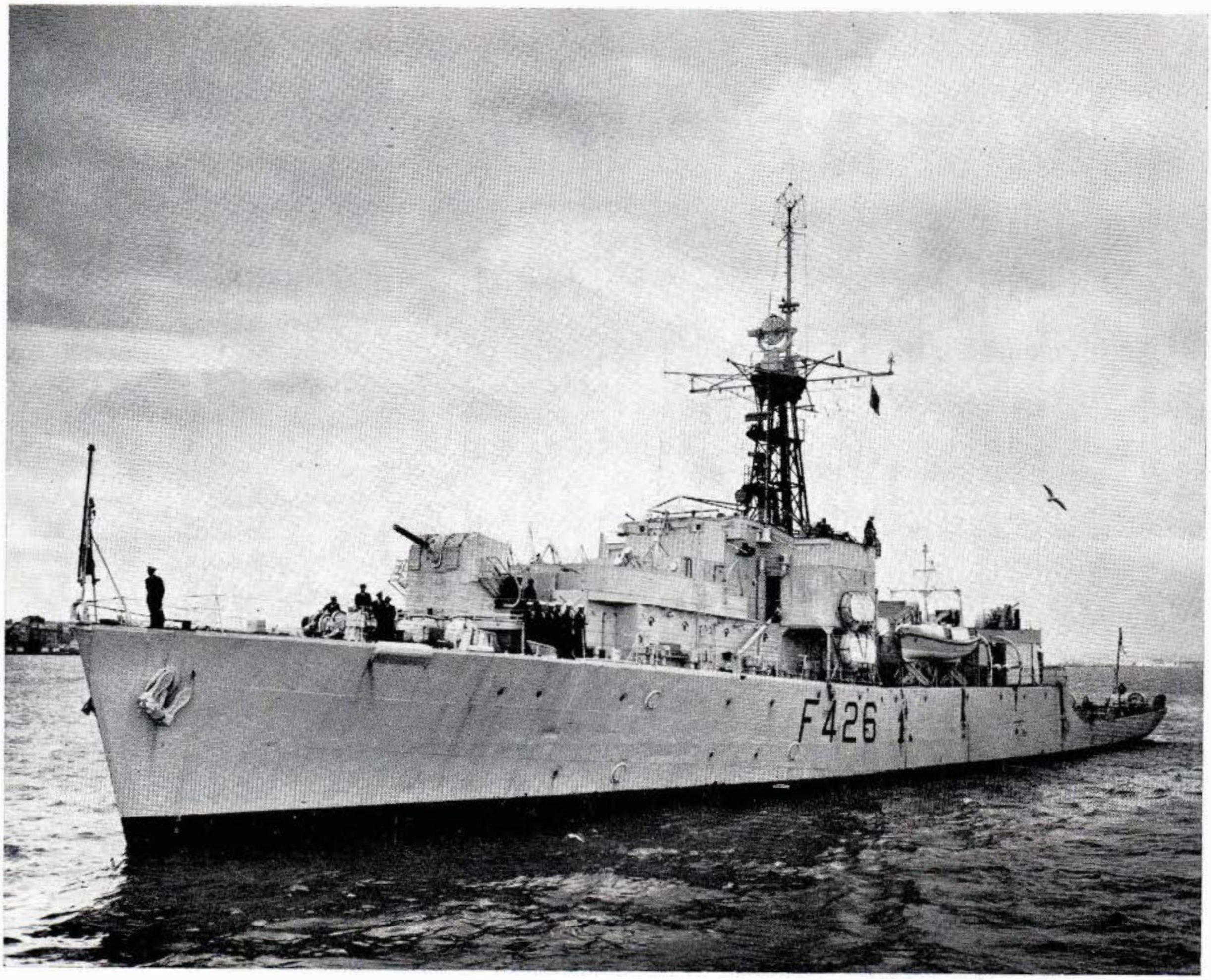

HMNZS *Kaniere* *Photograph by courtesy of the Royal New Zealand Navy.*

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FOREWORD

A considerable stimulus to the study of Antarctic circulation problems originated during the International Geophysical Year and the work then initiated has been continued. In the New Zealand sector of the Southern Ocean, the initial investigations of the structure of the Antarctic Convergence and the behaviour of the associated water masses have already been reported. The present study was planned to increase the available data both in detail of observation and in geographic extent.

Mrs P. M. Cullen has been responsible for the preliminary editing of the manuscript.

J. W. Brodie, Director,
New Zealand Oceanographic Institute.

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WATER MASSES AND FRONTS IN THE SOUTHERN OCEAN SOUTH OF NEW ZEALAND

ABSTRACT

The fine structure of the Antarctic Convergence and its adjoining water masses has been plotted and examined. Westerly winds lie nearly always in a northerly position with respect to the Circumpolar Current axis south of New Zealand. Frontal zones are sharp and can be readily recognised. The cold cores just south of the Antarctic Convergence and a warmer body of water further south, often noticed in vertical sections, can be interpreted as fortuitous in regard to the ship's track with respect to the surface isotherms and meanders in the line of Convergence. These cores require neither upwelling nor vertical "stretching" for their explanation. Between 162° E and 167° E longitudes a meridional confluence of isolines at the surface indicates the narrowing of the Circumpolar Current over and between the Macquarie Rise and the Campbell Plateau. This confluence of isotherms appears to extend the range of the steep temperature gradient of the Antarctic Convergence at its northernmost location in this area. This effect could well cause anomalies in reported Antarctic Convergence temperatures. The "Subantarctic Divergence" as discussed from varying points of view by earlier writers needs investigation by analysis of an appropriate vertical velocity field, for which not enough accurate observations have yet been taken. A well-defined water mass boundary, marked by the $34 \cdot 5 ‰$ isohaline and the 8°c isotherm exists and is more or less continuous in a zonal direction; the name Subantarctic Front is proposed and this front coincides with what has been defined as the Australasian Subantarctic Front which is found south of Australia and New Zealand.

INTRODUCTION

Scope of Survey

During November and December of 1958 a hydrological survey was carried out by the New Zealand Oceanographic Institute from HMNZS *Kaniere* in an area between longitudes 159° E (Macquarie Island) and 172° E, and between latitudes 51° S (Auckland Islands) and 64° S. The aim of this survey was to determine the detailed hydrological circumstances at the Antarctic Convergence, to chart within a short period of time the geographic position of the Convergence* over a range of longitude, and in general to determine the hydrological properties of the water masses in this area. The survey was designed as an extension of the work carried out by the Institute from HMNZS *Pukaki* and *Hawea* (Burling, 1961) and from USS *Brough* (Garner, 1958) as part of the IGY studies of the Southern Ocean circulation.

The Problem

The Antarctic Convergence, which is marked by a permanent steep temperature gradient where mixing occurs between water masses with different hydrological properties, encompasses the Antarctic Continent in the vicinity of latitudes 50–60° S. Although always present, the Convergence has been found to vary in position with longitude, with the prevailing winds and, to a lesser extent, with the time of the year. It is, however, rarely found outside a displacement of 100 miles north and south of its mean position. The probable meridional displacement from the mean position is some 50 miles (Mackintosh, 1946). One of the principal meandering regions lies to the south of New Zealand where an apparent rate of change of some 2·7 miles per day has been recorded (Wexler, 1959). To evaluate a regular pattern of movement, frequent observations would be required over a period of many years and in a large area. Part of the region covered by the present observations at serial temperature and salinity stations had been occupied by RSS *Discovery II* during her circumpolar cruises. In June 1932 two crossings were made of the Antarctic Convergence in longitudes 152° E and 163° E (near 54° S). A closer network of hydrological stations, as taken in this survey, was required to identify the complex structure of the vertical temperature and salinity distribution. It will allow further study of factors contributing to the generation and positioning of the Convergence and the transformation processes of the water masses in this region.

*Where Convergence is written with a capital letter the Antarctic Convergence is meant.

Photograph by R. W. Burling

Plate 1. N.Z.O.I. type B carbon-14 sampler being lowered in open position.

Field Methods and Information Collected

The field work was designed and carried out by R. W. Burling assisted by R. M. Cassie, A. G. York, and N. A. Powell of the New Zealand Oceanographic Institute and the ship's company of HMNZS *Kaniere*. The accompanying chart (in pocket) shows the ship's track and the positions of the 24 stations (B 97 to B 120) where temperature and salinity observations were taken to a maximum depth of 3,200 m. A cast of Knudsen reversing water samplers carrying Negretti and Zambra reversing thermometers of range — 2° C to 30° C was used for this purpose. Salinity samples, stored in 4 oz medicine bottles stoppered with waxed corks, were measured ashore by methods of density (Gilmour, 1958) and conductivity (Houtman, 1961a). The reduced data from these stations is presented in table 2. Between stations a total of 120 temperature-depth profiles to 250 m of depth were obtained by Wallace and Tiernan bathythermograph streamed at approximately two-hour intervals. Six surface carbon-14 samples of 44 gallons each were pumped from the ship's fire main after this had been thoroughly flushed. Five subsurface samples were obtained by means of an N.Z.O.I. type-B sampler (Willis, 1959) and stored in plastic-lined drums for transit.*

Four crossings of the Antarctic Convergence were made at an approximate spacing of 100 nautical miles and over a total period of nine days.

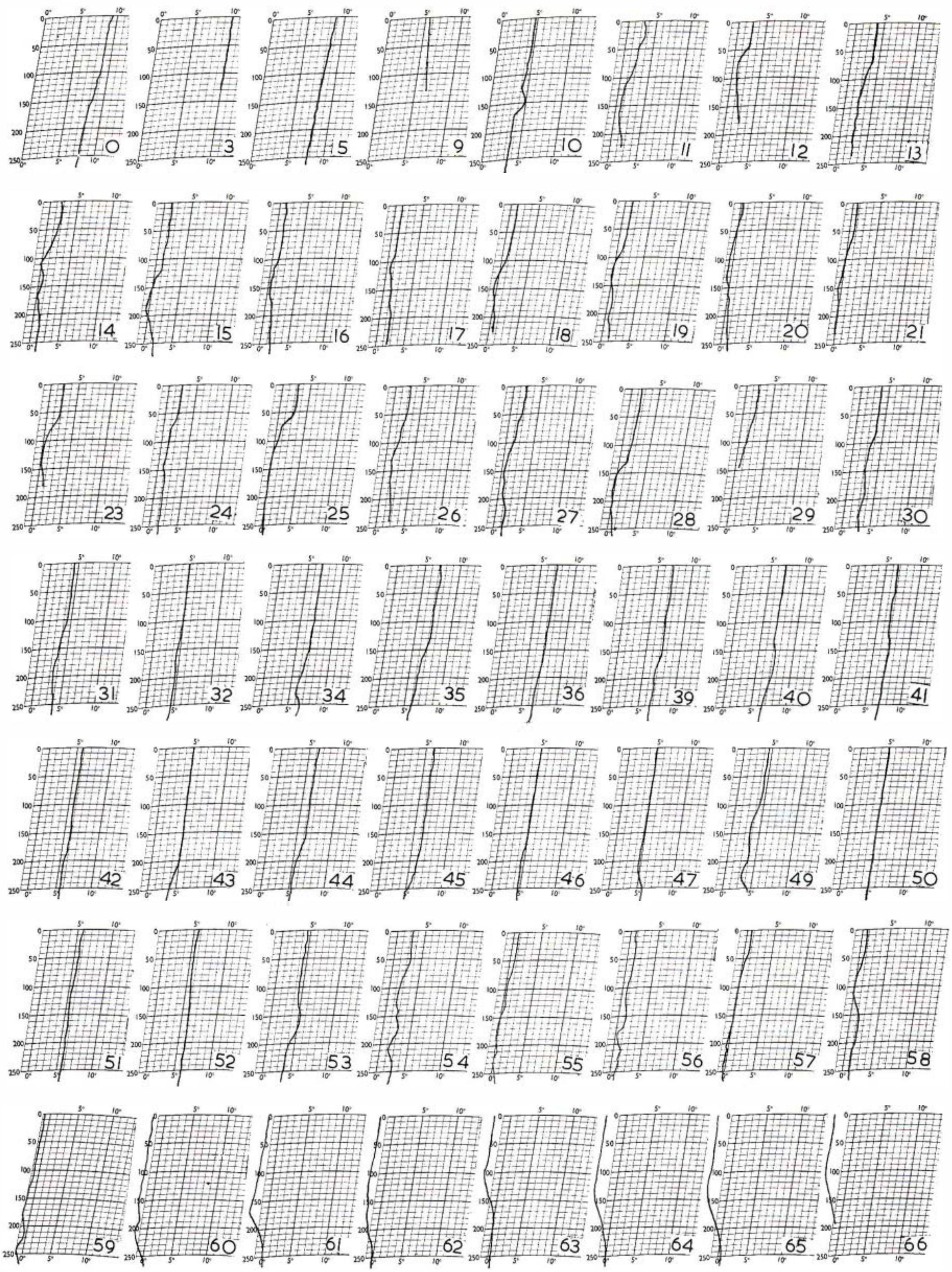
*Amphipods from plankton hauls from stations of this cruise have been described by Kane (1962).

Reduction and Presentation of Data

The thermometer readings were corrected and the depths of reversal computed from these readings by standard oceanographic procedures (La Fond, 1951). An extra correction taking into account readings obtained by the thermometers on a previous occasion at known depths (Houtman, 1961b) was applied and the accepted depths should be within 5 m of the depths of reversal. The bathythermograph slides were projected on to preprinted grids and adjusted for zero depth and temperature errors before tracing the profiles (fig. 1). Temperature adjustments were obtained by reference to the reversing thermometer readings on stations and these were assumed to be constant between stations. This necessitated also the assumption that all slides had been properly pushed home in the bathythermograph. Temperature sections, which were constructed from bathythermograph observations only, show excellent agreement with sections drawn from station data only, and it was found advantageous to combine the observations. In the construction of the vertical sections (figs. 2–5) a logarithmic scale of depth has been employed for depths greater than 100 m. This facilitates the presentation of data and reduces the number of sections that have to be constructed. The effect of the logarithmic scale on the bottom profile is that of accentuating peaks and flattening out troughs. The vertical exaggeration is usually already pronounced and the effect should therefore not prove disturbing. Information for the construction of the bottom profiles was taken from existing charts supported by occasional grenade soundings. These profiles should be regarded as approximate only, but are sufficiently accurate for the purpose intended. When the temperature-salinity diagrams (figs. 6a, b) were drawn some obvious discrepancies were found in the salinity values, probably caused by evaporation during storage of the samples, and it must be assumed that the scatter in measured values is somewhat larger than usual.

The reduced data were adequate to demonstrate the geographic position of the Antarctic Convergence in the area south of New Zealand and in the form of figs. 2–7 were available for detailed examination.

The carbon-14 samples were processed by the Institute of Nuclear Sciences, Department of Scientific and Industrial Research, and the depletions quoted are with respect to the 0·95 N.B.S. Oxalic Acid standard, and corrected for the carbon isotope fractionation. (Rafter, 1960). The results were discussed by Burling and Garner (1959), and Rafter (in press).


0 3 5 9 10 11 12 13
14 15 16 17 18 19 20 21
23 24 25 26 27 28 29 30
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42 43 44 45 46 47 49 50
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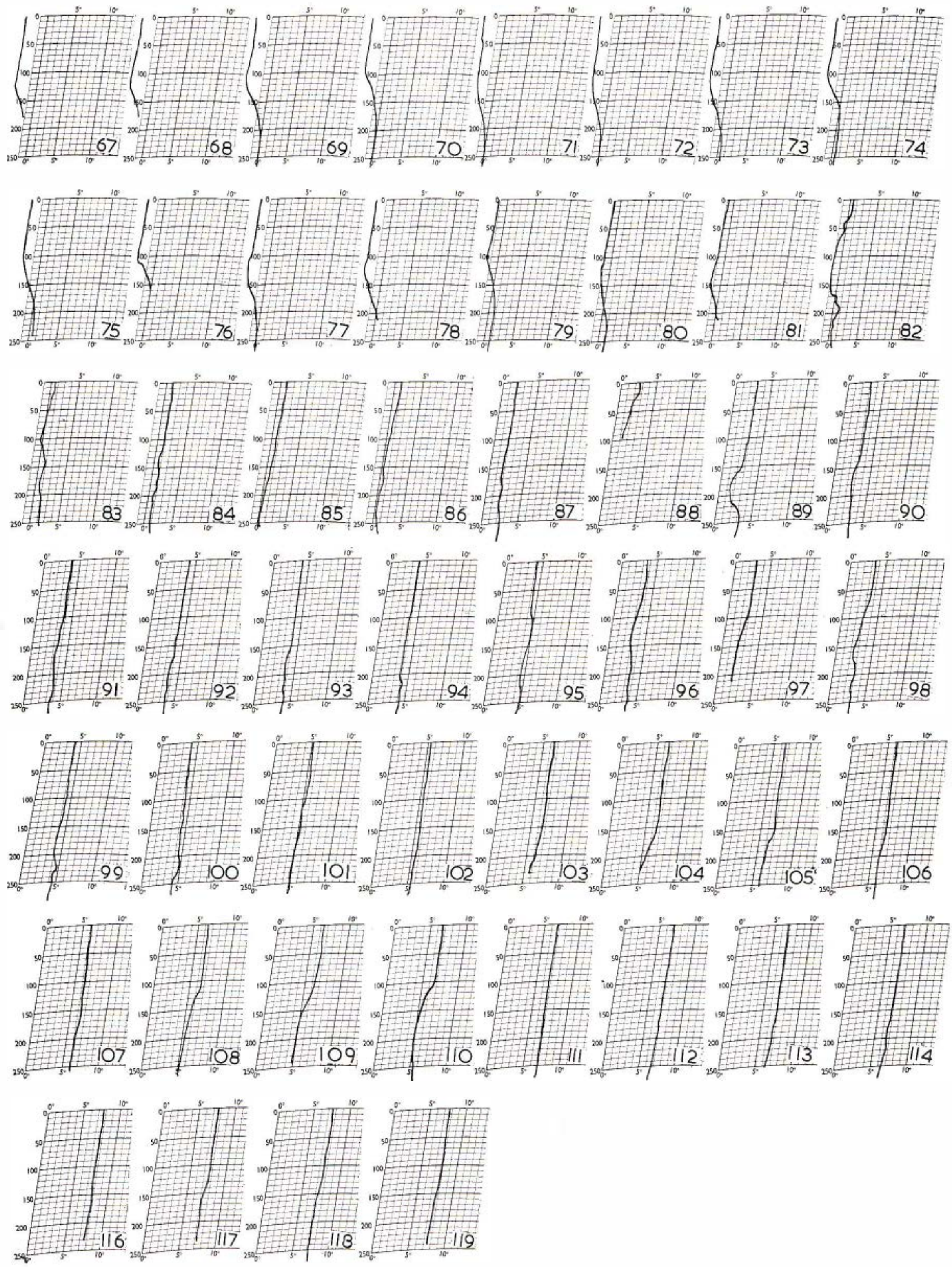

Fig. 1. Bathythermograph traces: the numbers correspond to those in the vertical sections showing temperature (figs. 2a, 3, 4, 5a). Isotherms in °C.

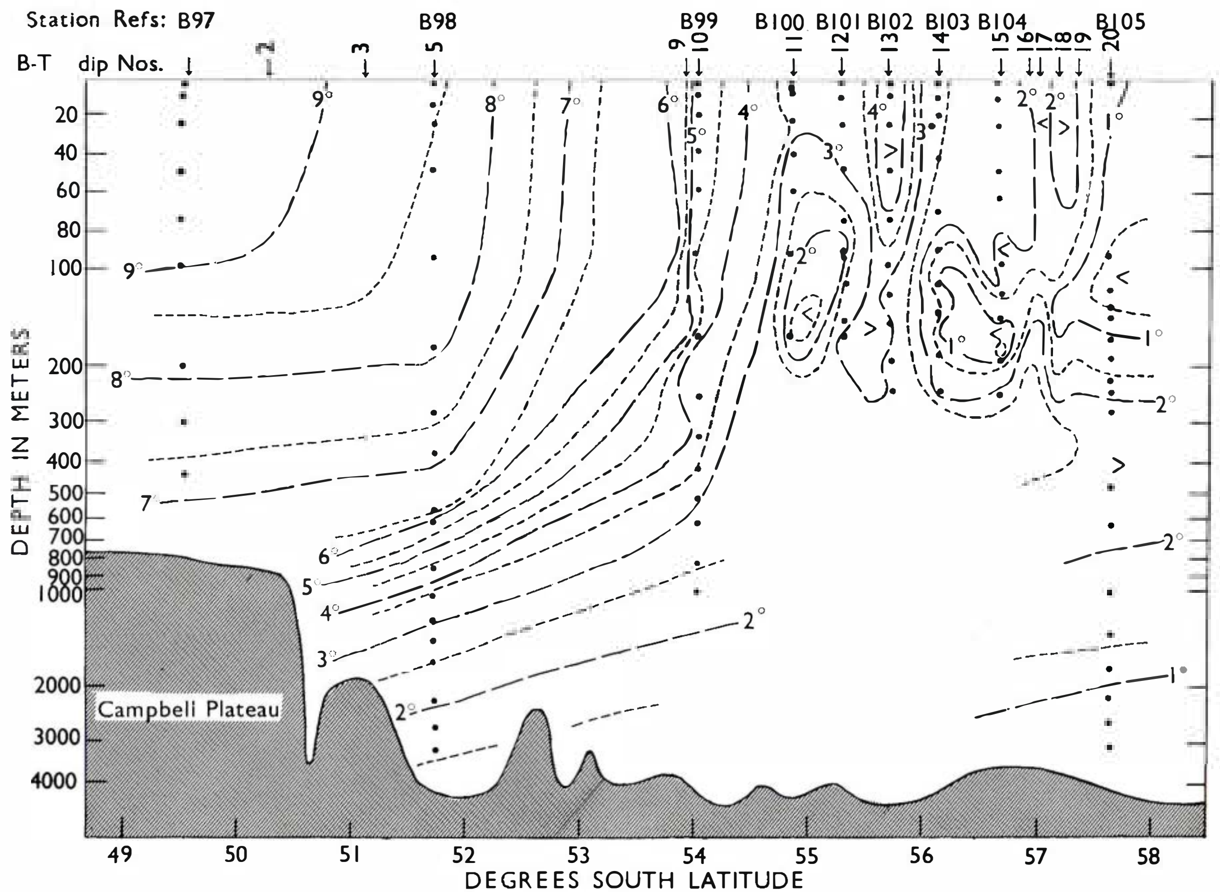

Fig. 2a. Vertical section of temperature distribution between Stations B 97 – B 105 constructed from bathythermograph observations and station data combined. The positions of maxima (>) and minima (<) are shown: dots represent reversing sampler positions. Isotherms in °c.

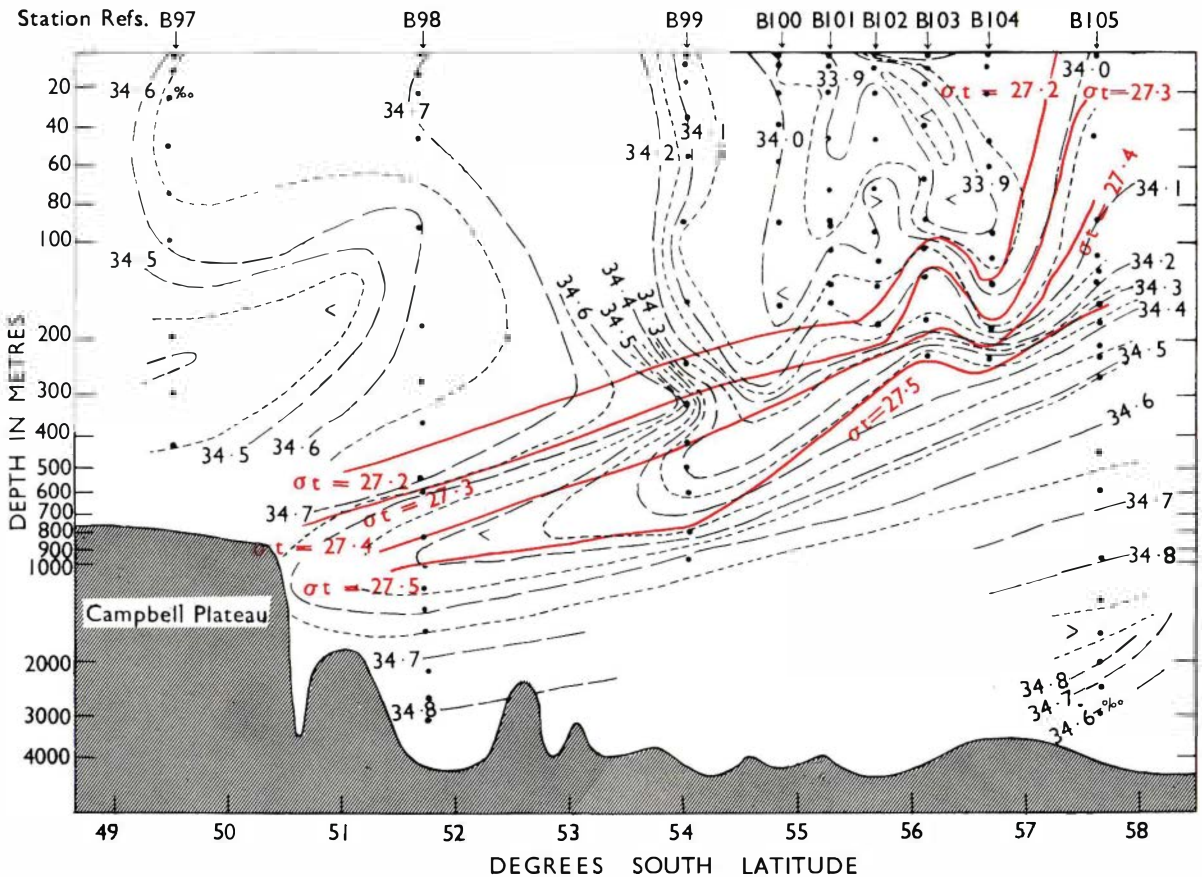

Fig. 2b. Vertical section of salinity distribution between Stations B 97 and B 105. Isopycnals $\sigma_t = 27\cdot2$ mg/l to $27\cdot5$ mg/l are given. Positions of maxima (>) and minima (<) are shown.

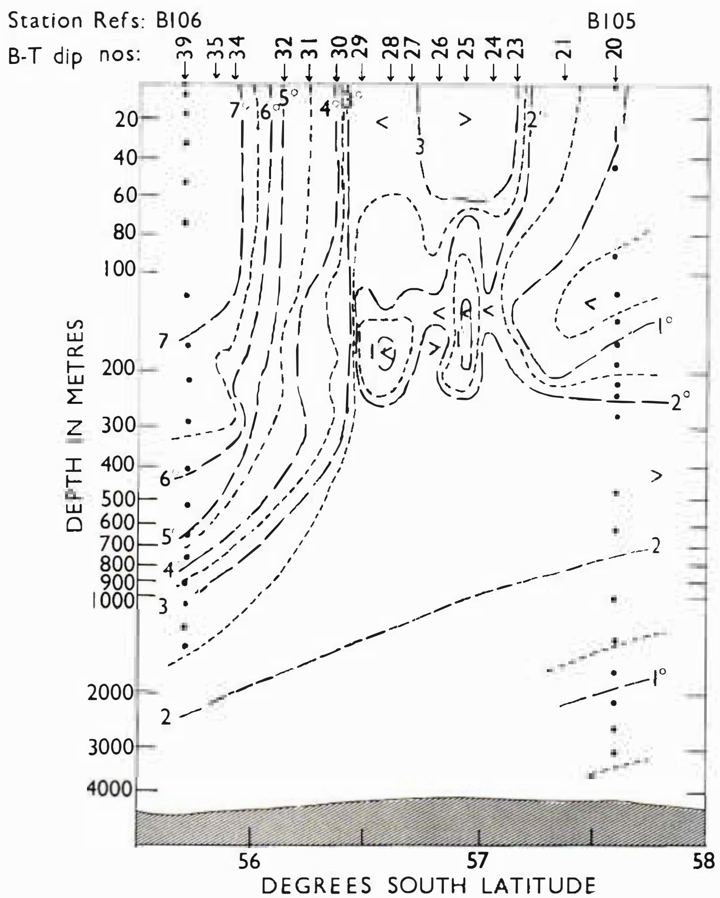

Fig. 3. Section of temperature distribution between Stations B 105 and B 106 constructed from bathythermograph observations and station data combined (note extended vertical scale): positions of maxima (>) and minima (<) are shown: dots represent reversing sampler positions. Isotherms in °c.

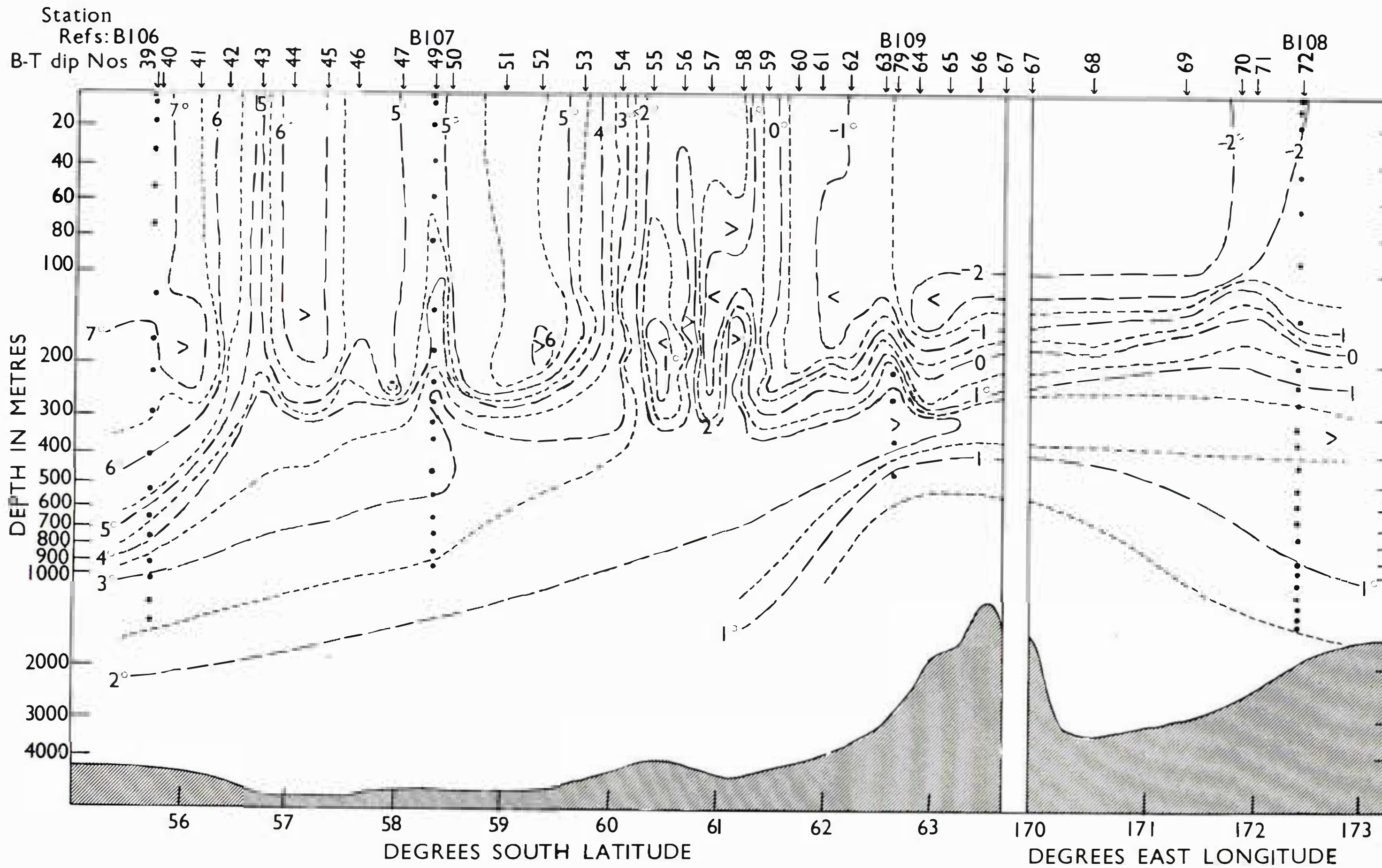

Fig. 4. Vertical section of temperature distribution between Stations B 106 and B 108 constructed from bathythermograph observations and station data combined (from Station B 109 only values below 200 m have been taken into account): positions of maxima (>) and minima (<) are shown: dots represent reversing sampler positions. Isotherms in °C.

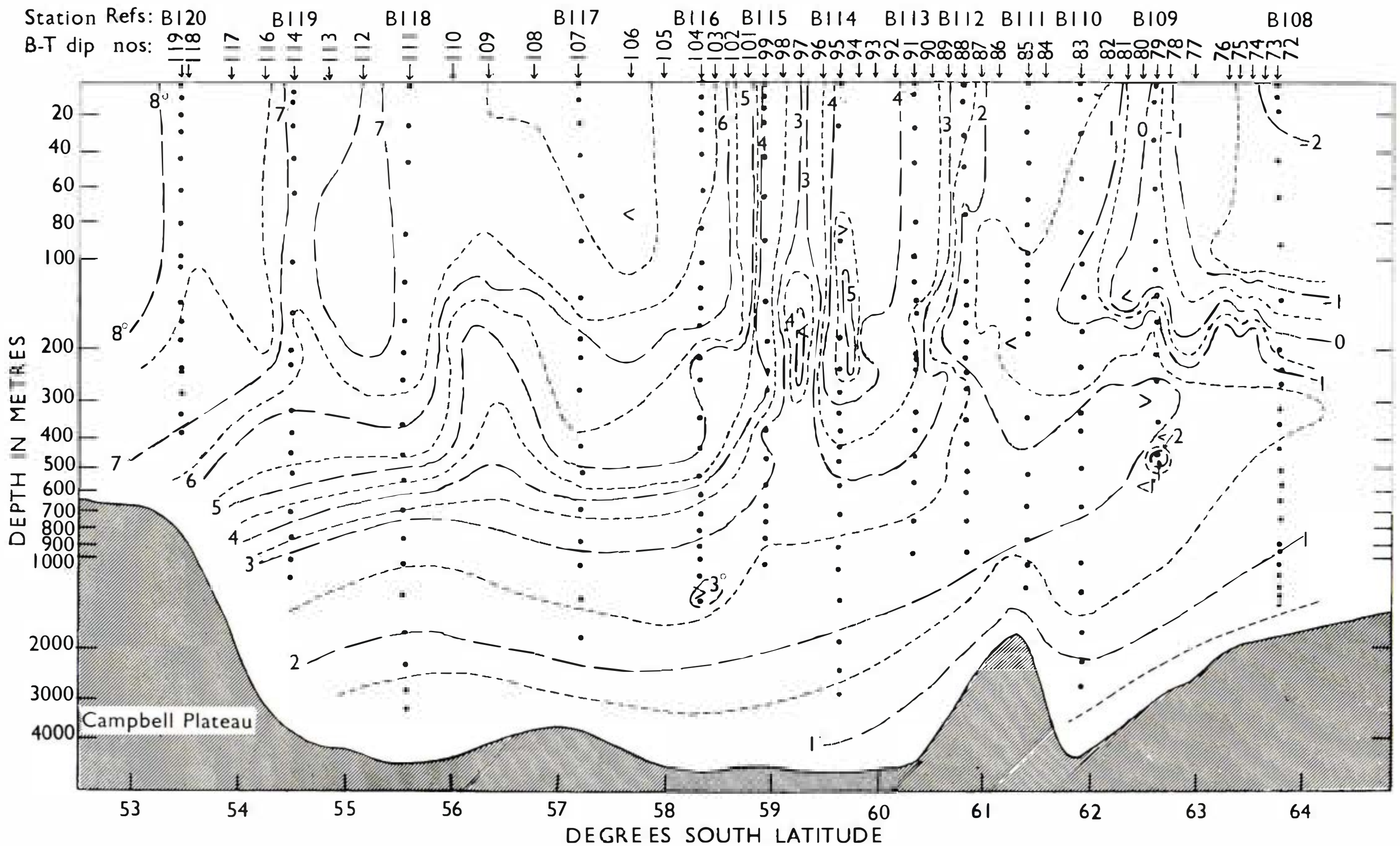

Fig. 5a. Vertical section of temperature distribution between Stations B 120 and B 108 constructed from bathythermograph observations and station data combined: positions of maxima (>) and minima (<) are shown: dots represent reversing sampler positions. Isotherms in °c.

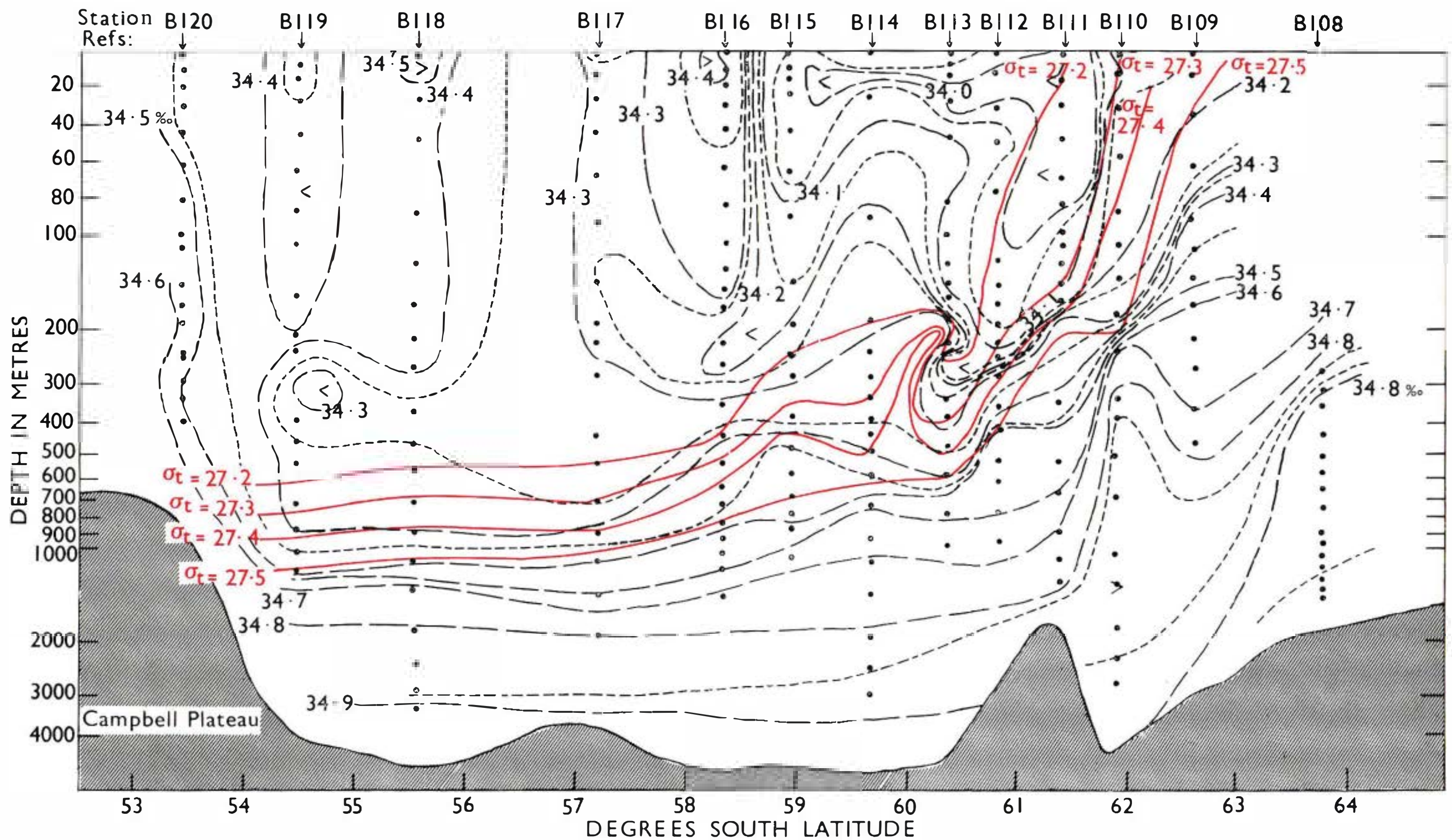

Fig. 5b. Vertical section of salinity distribution in $^{0}/_{00}$ between Stations B 120 and B 108: positions of maxima (>) and minima (<) are shown: dots represent reversing sampler positions. The isopycnals $\sigma_t = 27\cdot2$ mg/l to $27\cdot5$ mg/l are given.

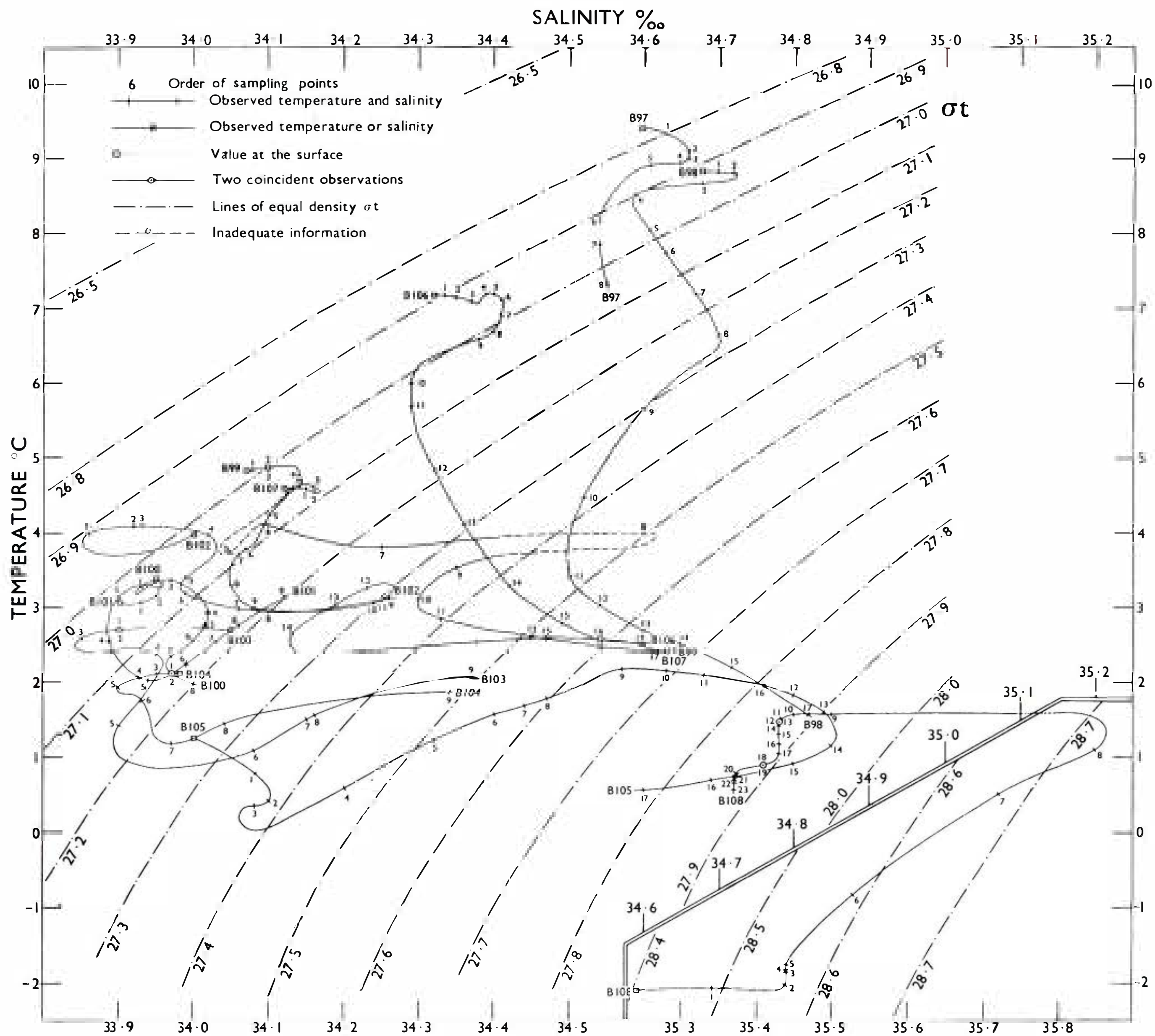

Fig. 6a. Temperature-salinity characteristics for Stations B 97 to B 108. (Note: Bottles of first cast at B 108 were probably frozen.)

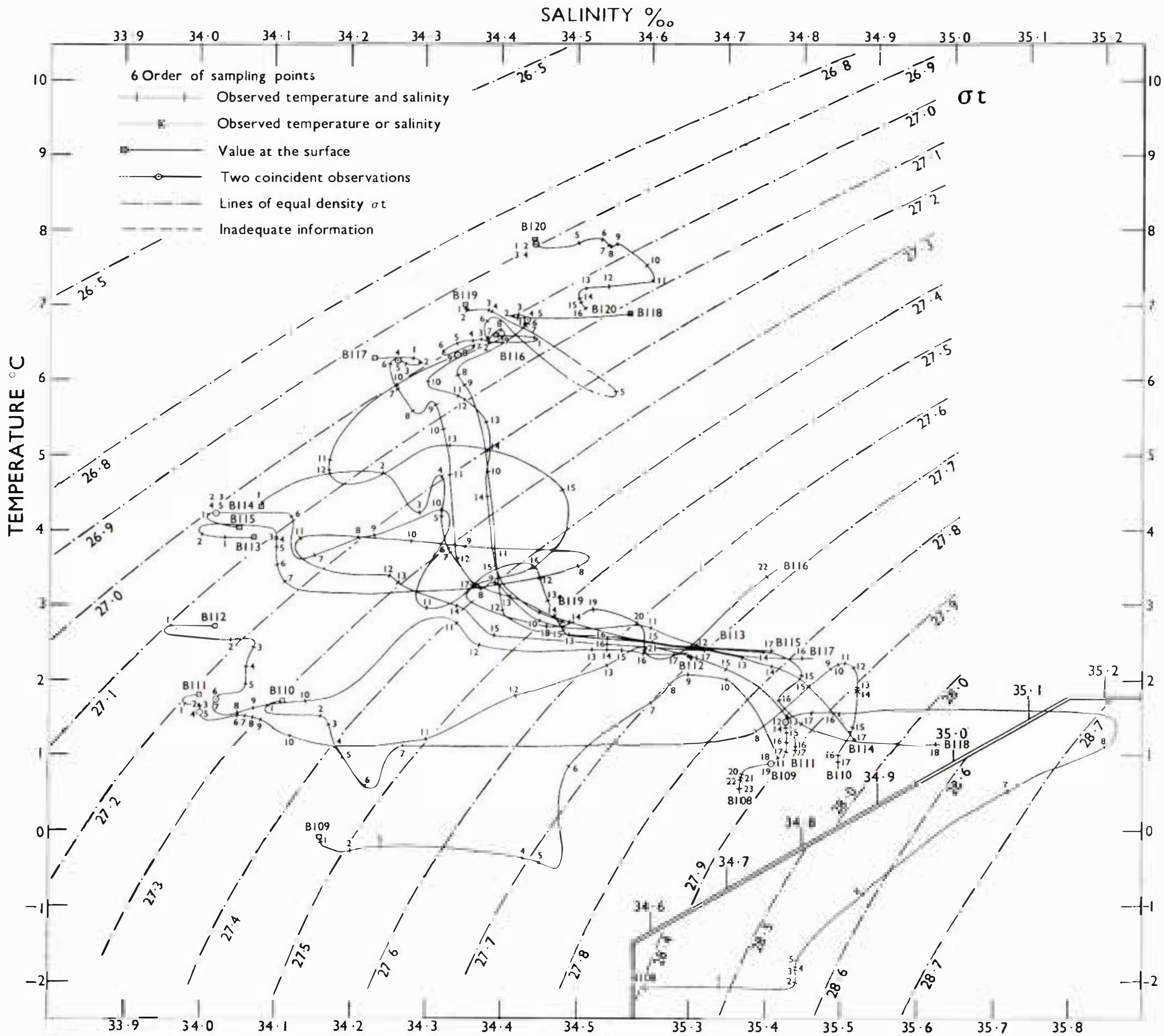

Fig. 6b. Temperature-salinity characteristics for Stations B 120 to B 108.

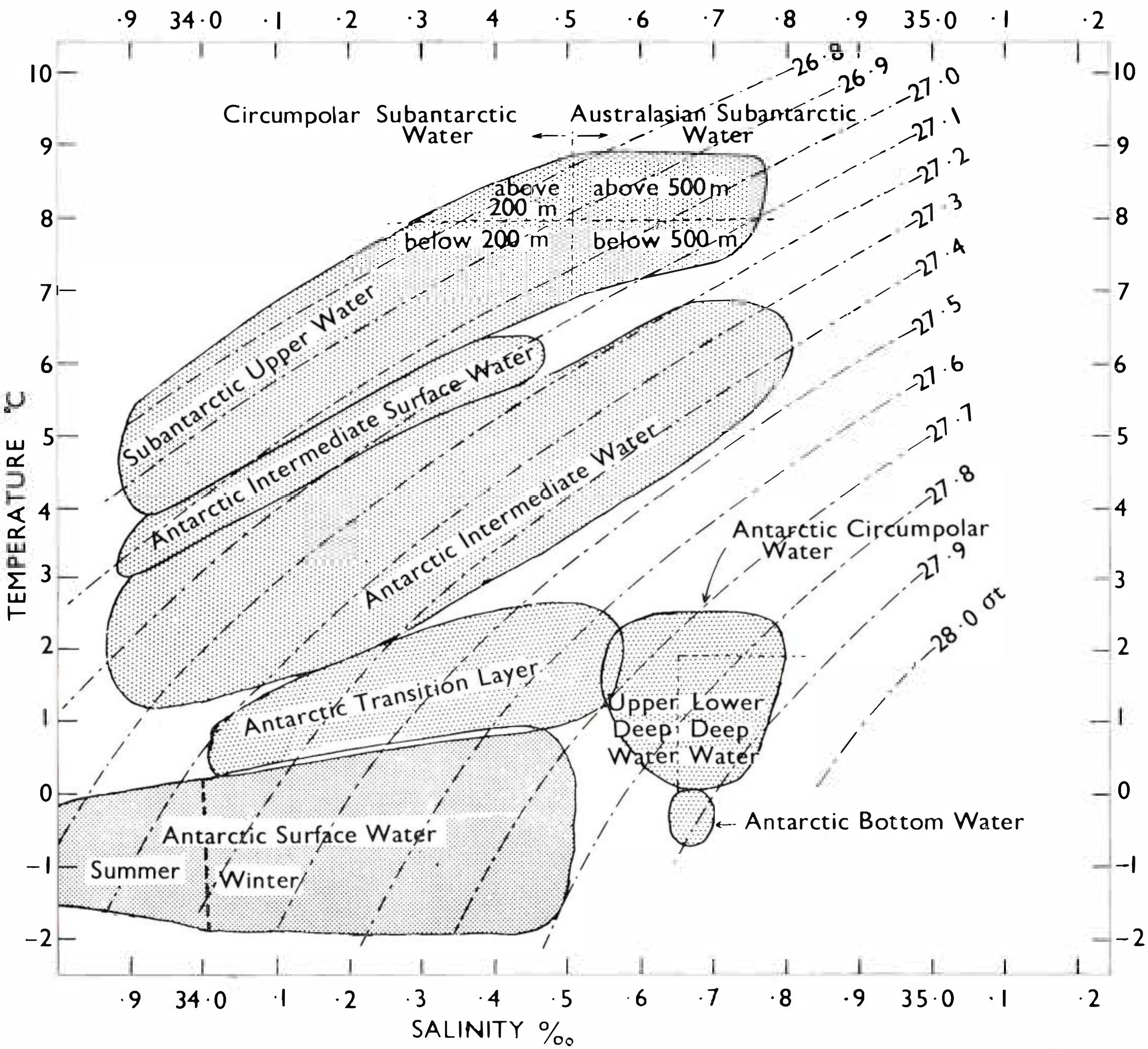

Fig. 6c. Temperature-salinity characteristics for regional water masses.

RESULTS

Ranges of Values

Temperatures at the surface (Chart 1) range from 8° C to 1° C between 53° S and 62·5° S respectively at longitude 171° E and between 52° S and 57·5° S at longitude 161° E. The isotherms thus lie generally closer together in the western portion of the area examined. Corresponding temperatures also lie further north at 161° E longitude than at 171° E. Here, near 61° S, temperatures rise steeply towards the north over a range of about 2° C. This rapid temperature increase – the Antarctic Convergence – is horizontally and vertically continuous (Mackintosh 1946, Ostapoff 1962b). Near stations B 105 and B 107 the temperature range across the Convergence has increased to some 2·5° C. The overall surface temperature values are in good agreement with the mean circumpolar values shown on the chart constructed by Mackintosh (1946) for November, although his values were based on very limited data. The middle temperatures of the steep gradients do not show such good agreement with Mackintosh's curves as interpolated for 30 November. At 60° S, where for November 2·6° C is given, fig. 7 shows 3·3° C and at 56° S, where 3·0° C is expected, fig. 7 shows 3·4° C. The estimates* (3·31° C and 3·35° C respectively) given by Houtman (1964), which take into account corrections for the day of observation, are, however, practically coincident with the recorded data. The ranges at the corresponding longitudes are somewhat shorter than Mackintosh's estimates. At the other two crossings of the Convergence the temperature ranges seem abnormally great, as fig. 7 shows. This may, however, result from the confluence of surface isolines in the "constricted current" area (Burling, 1961), where the Circumpolar Current is narrowed on account of its passage over and between the Macquarie Ridge and the Campbell Plateau. This confluence of isolines would cause an extension of the steep gradient at the high temperature side which is

*These estimates were independent of the present values.

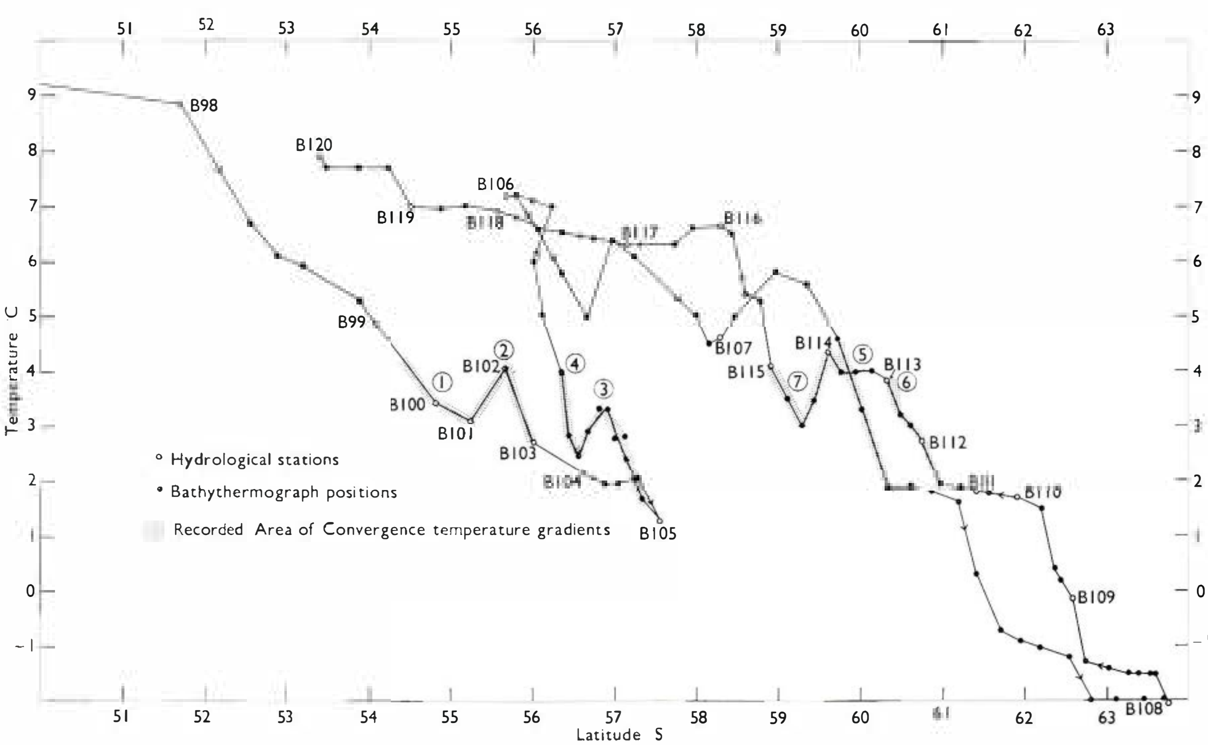

Fig. 7. Surface temperature plotted against latitude along ship's tracks. Complete crossings of the Convergence numbered 2, 4, 5, 6; partial crossings numbered 1, 3, 7.

not directly related to the Antarctic Convergence. Here, a probable temperature range can only be found by reference to the predicted middle temperatures. Several Convergence tongues which lead to partial crossings can also be seen in the temperature-latitude plot. The fanning out of the isolines towards the east could be caused by the "free stream current" (Burling, 1961), generated by the stream as it expands again past the Campbell Plateau.

Surface salinity values (Chart 1) vary between 33·9‰ and 34·7‰ and also show a pronounced change of position to the south-east. The 34·0‰ salinity minimum is situated approximately at the Convergence and a steep salinity gradient coincides with the temperature gradient just north of this minimum. Unfortunately the scarcity of surface salinity data allows only a very generalised presentation of the isohalines on Chart 1.

Carbon-14 depletions at the surface range from −170‰ to −124‰ between 62° S and 47° 50′ S respectively, showing the great difference in age and/or the comparatively slow horizontal interchange between Antarctic and Subantarctic Waters.

Below the surface the temperature varies within the same range as at the surface. The steep gradient persists to a depth of some 1,000 m but conditions in the upper 150 m are otherwise practically isothermal (figs. 2–5). South of the steep gradient there is a temperature maximum at about 500 m and a minimum near 100 m, but to the north of the gradient the temperature sections show a much more regular decrease of temperature towards the bottom. Subsurface salinity values are slightly greater in range than at the surface and vary between 33·9‰ and 34·9‰.

Identification of Water Masses

The presence and extent of water masses is best discussed with the aid of a temperature-salinity (T-S) diagram (fig. 6a, b). Any point on a T-S curve represents a water type; only where a water type is consistent over a range of depth can a water mass be distinguished.

However, such water masses mix continuously at their boundaries. Some distance away from the source even the properties at the core of a water mass may be modified, although the core can still be traced by extreme values (Wüst, 1935). The immediate surface layer is not useful in the present considerations because of seasonal variations and other external influences.

Station B 97 is in Australasian Subantarctic Water as defined by Burling (1961). Salinities are above 34·5‰ and temperatures between 500 and 200 m above 8° C. Station B 98 is typical of the conditions prevailing in this area; the surface layers show great stability of stratification between sampling depths 4 and 8 (80 m and 500 m) where the T-S curve is perpendicular to the isopycnal curves (fig. 6a). Between sampling depths 8 and 11 (500 m and 700 m), the Antarctic Intermediate Water flows along constant σ_t surfaces, in this case about 27·3 mg/l at a depth of 800 m. The salinities seem high between 250 m and 600 m although the temperatures are not anomalous. Station B 97 is close to Circumpolar Subantarctic Water, but the boundary between this and Australasian Subantarctic Water should lie between B 97 and B 98, at 51° S, where the 34·5‰ isohaline cuts the 8° isotherm between 500 m and 200 m of depth. At the surface this corresponds to a position between stations B 98 and B 99 where the 34·5‰ isohaline cuts the ship's track. Some Australasian Subantarctic Water may reach near Station B 120 below 60 m. A small tongue of 34·5‰ salinity water is present at the surface at Station B 118, it can be seen though that the Australasian Water is destroyed by mixing in or just near this area. Station B 106 is similar to B 120 in that temperatures are above 7° C at depths less than 150 m, but salinities are less than 34·5‰. Either this station (B 106) lies just south of an extension of Australasian Subantarctic Water or there has been some lateral mixing across the boundary rather than a pure parallel (NW–SE) flow. This possibility was suggested by Burling (1961) and is also reinforced by the presence of warmer water south of Station B 119. Stations B 99, B 107, and B 113 to B 117 are in Circumpolar Subantarctic Water but Station B 100 is on the boundary of the newly formed Antarctic Intermediate Water as are B 113, B 114, and B 115. Both Stations B 99 and B 119 have a high salinity at 300 m and 100 m of depth respectively. At Station B 119 this might be construed as a faulty value but at B 99 there are two other observations supporting the existence of high salinities here, as also at B 113 (200 m). This perhaps indicates upwelling of traces of Deep Water near the Antarctic Convergence. In the case of B 113, situated between two Convergence loops, it may well be an unstable remnant of the cold core just south of the Antarctic Convergence. B 101 and B 102 with B 112 are in Antarctic Intermediate Water, but south of these stations at B 104, B 105, and B 111 to B 109 the rather fast transition of surface density to the higher values associated with Antarctic Circumpolar Water is evident. Between Stations B 109 and B 108 there is a very sudden salinity increase which can only be ascribed to freezing of the sample bottles of the first cast (marked * in table 2) at Station

B 108 which was completed 4 miles south-east of the remainder of the Station. Although the shape of the T-S curve is not much affected, its salinity values up to sampling depth 8 must be discarded. Thus the curve should have been positioned below and to the right of the curve for B 109. The Antarctic Bottom Water is very near the lowest sampling depth as the shift to the left at 1,200 m in the T-S curve indicates. The Lower Deep Water is already present at the 275 m level showing that the Antarctic Divergence can not be far away. Heavy pack ice prevented the extension further south of the observations, however.

Australasian Subantarctic Water, on this occasion, occurred at the surface north of 162·5° E 52·5° S, and remnants, partly destroyed by mixing, occurred near 170° E 53·5° S, and 170° E 55·5° S. Salinities of this water were in excess of 34·5‰ and temperatures were above 8° C. Below the surface (at 300 m) one southernmost position was 165° E 51° S. South of the zone of Australasian Subantarctic Water the Circumpolar Subantarctic Surface Water, with salinities between 34·0‰ and 34·5‰ and with temperatures between 5° C and 8° C, extended to a southern boundary crossed at 160·5° E 54·5° S, 164° E 56° S, 167·5° E 58·5° S, and 171° E 58·5° S. The southernmost boundary of this water followed approximately the northernmost 34·0‰ isohaline at the surface, though a tongue of Circumpolar Subantarctic Water was also present at 170° E between 59·5° S and 60·5° S. At a depth of 300 m the southern boundary was observed at 160·5° E 54·5° S, 164° E 56° S, 168° E 60° S, and 170·5° E 61° S.

The Antarctic Intermediate Water (formed by mixing of Circumpolar Subantarctic Water and Antarctic Surface Water) was indicated at the surface and at depth by the salinity minimum zone where salinities lay between 33·9‰ and 34·0‰ and temperatures were between 1°C and 5°C. Its surface boundaries were the 34·0‰ isohalines both to the north and south. At a depth of 300 m the southern boundary extended through 161° E 57° S, 162° E 57° S, 169° E 61° S, and 170·5° E 61·5° S, close to the surface boundary position.

The Antarctic Surface Water with salinities in excess of 34·0‰ and with temperatures below 1° C extended southwards from the above positions.

Frontal Zones

South of New Zealand the Circumpolar Current is deflected rather abruptly to the south as a result of the bottom topography. This southward shift (some 10° of latitude in 10° of longitude) is much larger than the southward trend of the wind belt itself. Therefore east of Macquarie Island and probably to 160° W longitude the winds will often be in an extreme northerly position with respect to the Circumpolar Current as compared with other areas. The sharp salinity minimum, noted by Ostapoff (1962b) south of New Zealand, which is also visible in the present sections, is consistent with conditions of downward motion just north and upward motion just south of the Antarctic Convergence and is probably a function of this peculiar wind distribution. Westerlies are predominantly strong and therefore an intensive Antarctic Convergence must be expected where chiefly Antarctic Surface Waters sink. A well developed divergence would lie just to the south of it and would tend to recirculate some Intermediate Waters. A Subantarctic Divergence may also be present but must of necessity be weak since divergence tends to destroy frontal zones whilst convergence intensifies frontogenesis.

Identification of Frontal Zones

When vertical sections are interpreted it is often difficult to assess the relationship of the lines drawn to the actual conditions. These are often more complex than represented; the placing of isolines by linear or attempted proportional interpolation is only an approximation at the most. Preconceived ideas, overfamiliarity and oversimplification, can sometimes mask the existence of real phenomena, and interpretation of vertical sections is therefore open to subjective errors.

The section between Stations B 106 and B 108 (fig. 4) does not display any Convergence loops at the surface and the bathythermograph and station data have been combined. Near BT dips 43 and 49 (B 107) rising isotherms indicate the presence of upwelling cold water which could be associated with a Subantarctic Divergence. Since the surface isotherms are very curved near this position it is not surprising that the upwelling is present over a wide area, and possibly loops in the Subantarctic Front are present here. Further south, at BT dips 53–55 the steep temperature gradient of the Antarctic Convergence is present and extends to 1,000 m of depth. A narrow upwelling with a core of 1° C can be seen just south of this Front, and another tongue of 2° C indicates a warmer body of water to the south. These cores are discussed separately below.

Section B 105 – B 106 (fig. 3) is very similar in structure and another cold tongue is present which could well be an extension in a zonal direction of the temperature minimum between 90 m and 250 m at BT dip 57 in the previous section.

A Subantarctic Divergence cannot here be recognised and the Antarctic Convergence occurs near BT dip 29.

The section B 97 – B 105 (figs. 2a, b) shows the Antarctic Convergence near Station B 99 where both isotherms and isohalines steepen markedly. Lack of temperature evidence between B 98 and B 99 does not permit the isotherms to be drawn differently but the salinity section suggests that they may well be more complex. The flow of Intermediate Water shows up well in the salinity section and the 27·4 mg/l isopycnal lies in its axis. At B 105 the salinity maximum lies at 1,500 whilst a temperature maximum lies near 400 m, indicating the colder but less saline nature of the Deep Water towards the bottom. Between B 100 and B 101 and also between B 103 and B 104 cold cores exist in the temperature section, both reinforced by slight upward bending of the isohalines. Such a pattern would be expected to show in an area of divergence. It has been assumed that these pockets of colder water are remnants of the cold water further south.

The northernmost core coincides with a salinity minimum, the other with a higher salinity value. It can be directly established that the southernmost core is a continuation of the temperature minimum near 100 m at Station B 105, where the salinity values are equal; the northernmost core has been assumed to be a remnant of this cold water also. Close scrutiny of the temperature values at B 103 and B 104 does not allow the connection to be drawn in, however. The sections B 120 – B 108 are very similar also. The Convergence was crossed between B 112 and B 113, and there was also a partial loop at BT dip 97. This loop appears to have been rather well developed and caused spreading of the Intermediate flow over a large area. A temperature maximum, with salinity minimum, can be seen at BT dip 113 between B 119 and B 118 and a similar body of water lies near B 117 where it is slightly cooled. These pockets are separated by regions of lower temperature, which at the 200 m level also show a reduction in temperature in a southward direction. These are probably continuous with each other in a horizontal plane. The bathythermograph section adds considerable detail in the upper layers and shows a cold core at BT dip 97 which is separated from identical water further south at BT dip 87 by a warmer body of water extending down to at least 250 m of depth. The salinity section shows shallow pockets of high salinity at B 118 and B 116, also indicative of horizontal connections. Salinities are, however, otherwise fairly uniform in this region and isopleths of constant density would be shaped like the isotherms. The water above 200 m at B 119 cannot be the same as that at B 98 where the salinities are much higher. The decrease may be caused by mixing with water from the south although it would be expected that mixing with water from the north would offset this. The Antarctic Convergence, as defined by Mackintosh (1946), was found in the position given in table 1 and it coincides approximately with the salinity minimum of 33·9‰ to 34·0‰ (Chart 1); whilst the middle temperatures, depending on the latitude and day of observation, were all near 3° C. A divergent front indicated by rising isotherms in the Subantarctic Region was clearly recognised at 165° E 51° S and 170° E 53·5° S, and at the first of these positions it was analogous to the Australasian Subantarctic Front as defined by Burling (1961).

TABLE 1. Position, Middle Temperatures and Ranges in °C of the Steep Temperature Gradient at the Surface at the Antarctic Convergence

Date 1958	Latitude S		Longitude E		Temperature °C				
					As Predicted by Mackintosh (1946)		As Predicted Houtman (1964)	As Recorded in the Present Survey	
					Middle Temperature	Range	Middle Temperature	Middle Temperature	Range
	°	′	°	′					
14/11	55	50	160	59	3·0	*(2·8)*	3·4	3·4	*(1·3)*
26/11	56	56	162	15	2·9	*(2·6)*	3·4	3·3	*(2·4)*
28/11	60	04	168	22	2·6	*(2·4)*	3·3	3·3	*(2·7)*
2/12	60	39	170	46	2·5	*(2·3)*	2·7	2·9	*(1·9)*

PREVIOUS WORK

The Antarctic Convergence

The Antarctic Convergence and the water masses of the Southern Ocean have been studied as circumpolar phenomena by many authors, amongst them Deacon (1933, 1937), Mackintosh (1946), Wexler (1959), Wyrtki (1960), and Ostapoff (1962a, b).

At present there is no comprehensive agreement on the causes of many of the hydrological features observed in this area. Many authors have attempted explanations from analyses of individual aspects such as the thermohaline circulation, the wind-pressure field, bottom topography, etc., but no analysis has so far taken into account the relative significance of these aspects of the total circulation. Aspects of some of the more significant phenomena are now summarised.

At a position near 64° S a circumpolar boundary exists between water masses with opposite directions of flow. North of the boundary, the surface layers of the Antarctic Circumpolar Waters* are driven eastward by westerly winds, south of it Antarctic Circumpolar Coastal Waters (a subdivision introduced here) are driven westward by easterly winds. Due to the Coriolis force these waters are deflected to the left of the zonal direction of motion and a divergence is created (the Antarctic Divergence). The north-east flowing component of surface water meets warmer, less dense, Subantarctic Water at about 60° S at the Antarctic Convergence. Mixing produces water of higher density than either of these; under the name of Antarctic Intermediate Water it sinks and flows further northwards along appropriate density surfaces, in places as far as the Equator.

Definitions of the Antarctic Convergence

There are several definitions of the Convergence, in fact the very name of "convergence" has recently been doubted (Wexler, 1959). Mackintosh defines it as "the line at the surface along which the Antarctic Surface Water sinks below the less dense Subantarctic Water and it is distinguished by a more or less sharp change of temperature at the surface." Deacon speaks of "the latitude reached by Antarctic Bottom Water". Wexler proposed the use of a "narrow subsurface minimum temperature zone south of the strong temperature gradient". Mackintosh's definition is convenient, it requires only the use of a temperature recorder at the surface to establish the position. Wexler's definition requires the use of a bathythermograph at close intervals and Deacon's a close network of deep hydrological stations. The position of the Convergence can vary greatly according to these different definitions.

According to Wyrtki (1960) Deacon's model applies only to a condition of strong westerly winds. All the features defined may be simultaneously recognisable, but the narrow minimum temperature zone may easily be missed and, as is later shown, bears no direct relation to the phenomenon of convergence. The concept utilised in Mackintosh's definition is also more suited to obtaining continuous observations.

General Water Circulation

The Antarctic Ocean is divided by the Antarctic Convergence into two regions: the Antarctic Region to the south and the Subantarctic Region to the north. Within these regions water masses can be classified according to their temperature-salinity characteristics (fig. 6c). In the Antarctic Region a cold near-freezing layer of high salinity surface water is present. According to its salinity it is often classified as Antarctic Summer- or Antarctic Winter-Water (Garner, 1958). Beneath this is a transition layer with temperatures above 2° C and salinities above 34·5‰. Below this again there is the Antarctic Circumpolar Water (temperature: 0–2° C, salinity: > 34·7‰). This water can also be found north of the Antarctic Convergence at a depth of some 2,000 m. Close to the Antarctic Continent is Antarctic Bottom Water with temperatures below 0° C, and salinities below 34·7‰. As previously mentioned the wind shear at the Antarctic Divergence causes a flow of surface water to the north-east and south-west. An upwelling of Antarctic Circumpolar Water replenishes the divergence. The south-west component meets the Antarctic Continent and becoming denser through loss of water by freezing, sinks and forms Bottom Water. The amount that sinks is small and much of it could mix again with the

*Antarctic Circumpolar Water is a useful term that includes Summer and Winter Water, Upper and Lower Deep Water and Bottom Water. (See fig. 8.)

ascending Circumpolar Water a little further north (Brennecke 1921, Mosby 1934). The main source of Bottom Water appears to be in the Weddell Sea. The north-east flowing component, sometimes called Antarctic Circumpolar Surface Water, meets warmer, less dense Upper Deep Water which, flowing south, is forced to rise when it meets the Antarctic Circumpolar Water Mass. Near the surface the Antarctic Surface Water "flows over the steep ascent of the warm Deep Water like a stream over a waterfall" as Deacon puts it. The Deep Water climbs from some 2,500 m to within 200 m of the surface and by its high salinity preserves the salinity level of the Antarctic Ocean, which otherwise would be lowered by excess precipitation and melting of glacier ice. The southward flow of Deep Water also balances the transport of surface water to the north-east. Antarctic Surface Water, sinking at the Antarctic Convergence, forms the core of the Intermediate Water which by its salinity minimum can be traced at great distances from the Antarctic Region. Fig. 8 shows the distribution of the water masses in cross section.

A system of convergences and divergences formed under the influence of the prevailing westerly winds is superimposed on this thermohaline circulation.

Wind-induced Circulation

Hidaka (1958) has computed average wind stresses over the oceans and showed that the maximal stress occurs between 45° S and 50° S, reaching values above 1 dyne/cm.^{2} Westerly winds predominate between 30° S and 60° S, whilst easterly winds prevail north and south of these positions. The maximum westerly wind belt shows a shift from 40° S to 45° S in the central Atlantic to between 55° S and 60° S in the eastern South Pacific. (Wexler, 1959). The Circumpolar Current shows a similar general trend and the influence of the westerly winds must therefore be considerable. Although the structure of the west wind zone remains virtually unchanged during the year a meridional displacement of some 4° of latitude from spring to autumn was predicted by Ivanov (1961) on the basis of an analysis of the field of tangential wind stress.

When two adjoining wind streams have different velocities a wind shear develops at the boundary. In the Southern Hemisphere the relative velocity of the northernmost stream is in an eastward direction with respect to the other stream, then the wind-driven waters will be deflected by the Coriolis force in a horizontal direction away from the boundary and a divergence develops. Similarly, if the relative velocity of the northernmost stream is westward a convergence results. Transport of water in a vertical direction must then also take place. Frontal zones in the ocean may be defined as areas of maximum velocities towards (divergence) or away from (convergence) the sea surface.

Wyrtki (1960) discussed the approximate positions of such frontal zones that might be developed in the Southern Ocean (fig. 9). The westerly winds

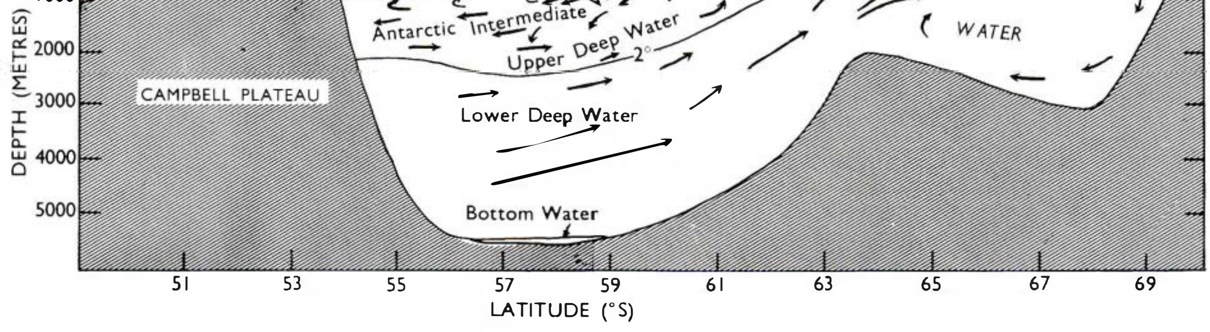

Fig. 8. Vertical geographic distribution of regional water masses and fronts at longitude 170° E. [Note: The term Subantarctic Front is here synonymous with Subantarctic Divergence.]

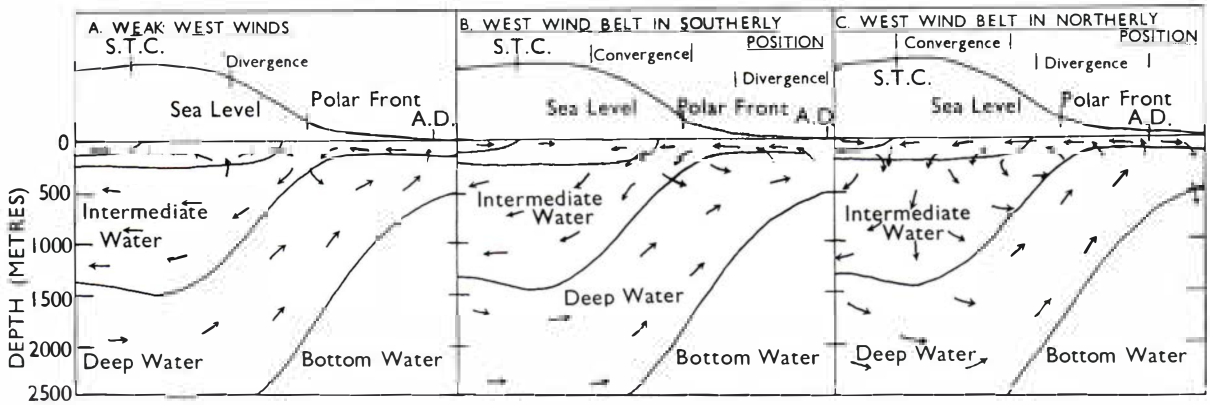

Fig. 9. Location of divergences and convergences induced by the westerly wind system according to Wyrtki (1960).
(S.T.C. = Subtropical Convergence.)
(A.D. = Antarctic Divergence.)

are relatively permanent during the year and one or other of the effects described by him should be visible in short-term observations. Generalised data, however, will not necessarily show any effects in simple form. According to Wyrtki, when westerlies are weak a convergence will be formed to the south of the main zonal current, which intensifies the Antarctic Convergence and a divergence is formed to the north. When strongly developed westerly winds lie in a southward position with respect to the axis of the Circumpolar Current a convergence develops north of the wind-belt and chiefly Antarctic Surface Water will sink at the Antarctic Convergence. This and the accentuation of divergence at the Antarctic Divergence accelerate the upwelling of Deep Water. Intermediate Water must also flow strongly to maintain the pressure balance of the Southern Ocean. Deacon (1937) used this model for his discussion. When westerly winds lie in a northerly position, with respect to the axis of the Circumpolar Current, however, the divergence and convergence are created much further north. The easterly wind belt at the Antarctic Continent widens and under these conditions a weak convergence will develop at the ice edge as discussed by Koopmann (1953). The divergence now lies just south of the Antarctic Convergence. The upwelling that occurs under these wind conditions (westerly winds in a northerly position with respect to the Circumpolar Current axis) has been suggested by Wyrtki as fitting the temperature distribution in the vicinity of the Antarctic Convergence as discussed by Wexler (1959). In view of the common occurrence in the New Zealand sector of temperature distributions of this kind a close examination has been made of the present material in the light of this suggested correlation.

DISCUSSION

The Cold Cores South of the Antarctic Convergence

Wexler (1959) commented on the narrow minimum temperature zones which can often be found just south of the Antarctic Convergence. These are usually no more than 50 miles in width and are placed within some 100 miles of the Convergence. The cores extend to at least the 250 m level and have centres with temperatures below 2·2° C. A warmer body of water with temperatures over 3° C may separate the cores from the cold water further south. In the section observed from HMNZS *Pukaki* (Burling, 1961) the cold core had a temperature of −1° C at 200 m, where it was thus much colder than the water further south at the same level whilst the only other similar temperatures were found by Deacon (1933) below 3,000 m in the Bottom Water. Wexler says that it is inconceivable that upwelling from 3,000 m could have occurred in the 12 days that separated this observation from a *Glacier* section to 180 m of depth, but he neglects the fact that the observations were taken at 177° E and 175° E respectively and that such a core may well have been present below 180 m. He takes the mechanism of formation to be "horizontal motion northwards from the cold subsurface Antarctic Water, breaking off of this water from its source region and strong vertical stretching to produce cooling both at the surface and to below 200 m". Wyrtki (1960) comments that "there can be no doubt about the fact that with strong westerly winds the drift current within the Ekman layer is divergent to the south of the maximal westerlies thus causing upwelling . . . on the bottom of the Ekman layer near 100 m a well developed temperature minimum exists . . . patches of this water can rise to the surface or at least near to it producing the temperature pattern observed by Wexler." Burling (1958) noted that the cold tongues could (if steady state conditions were obtained) be associated with vigorous horizontal (cyclonic) eddies and ascribes their presence to large fluctuations in mean flow in a horizontal direction.

If the water in the core had its source at some 2,500 m of depth near the Upper Deep Water then the adiabatic expansion on its way upwards would produce cooling. However, the average temperature coefficient given by Hesselberg and Sverdrup (1914–15) is only $50\cdot10^{-6}$° C/m of ascent so that, when the 50 m depth level was reached, a reduction of only 0·13° C would have occurred and this source must therefore be ruled out.

The replenishing connection may also be situated further east or west where the warmer body of water south of the core may be absent. The section B 106 – B 105 (fig. 3) suggests a definite association with the temperature minimum further south. Here parcels of water with temperatures of 1° C or less are separated off in a northwards direction. In the adjoining section B 97 – B 105 (fig. 2a) the body of warmer water has a core of over 4° C and lies much deeper down (to 250 m). In the eastwards section B 106 – B 108 (fig. 4) the northernmost "bulge" of the lower 2° C isotherm (also present in the other sections) has risen from 150 m to 30 m increasing the local temperature by approximately 0·3° C. The warmer body of water is not present here. Further eastwards again (B 120 – B 108, figs. 5b, c) the northernmost "bulge" of the lower 2° C isotherm has broken surface and a pocket of 2° C and colder water now lies to the north. If the surface isotherms of 2, 3, 4, and 5° C are sketched from this information, fig. 10 results. Slight extension by the broken lines in this figure yields a configuration roughly equal to the isotherms in Chart 1. Thus a mechanism of supply of cold water by horizontal motion northwards in gaps or embayments in the curved isotherms near the Antarctic Convergence is clearly a feasible explanation for the formation of cold cores. These curved isotherms, meanders and loops or embayments would be a function of large horizontal cyclonic eddies which cause zonal intrusions of the warm water in vertical transverse sections. The presence or absence and the extent of cold and warm cores in vertical

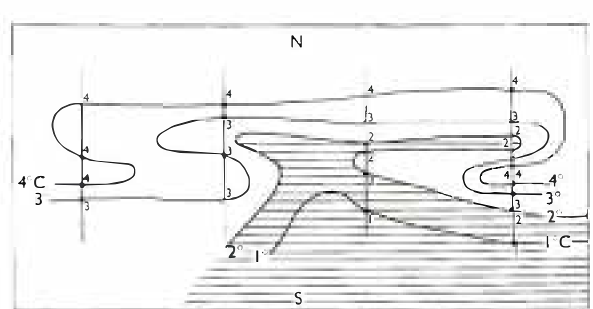

Fig. 10. Schematic plan sketch of surface isotherms south of the Antarctic Convergence as deduced from the subsurface cold and warm cores in the vertical temperature sections.

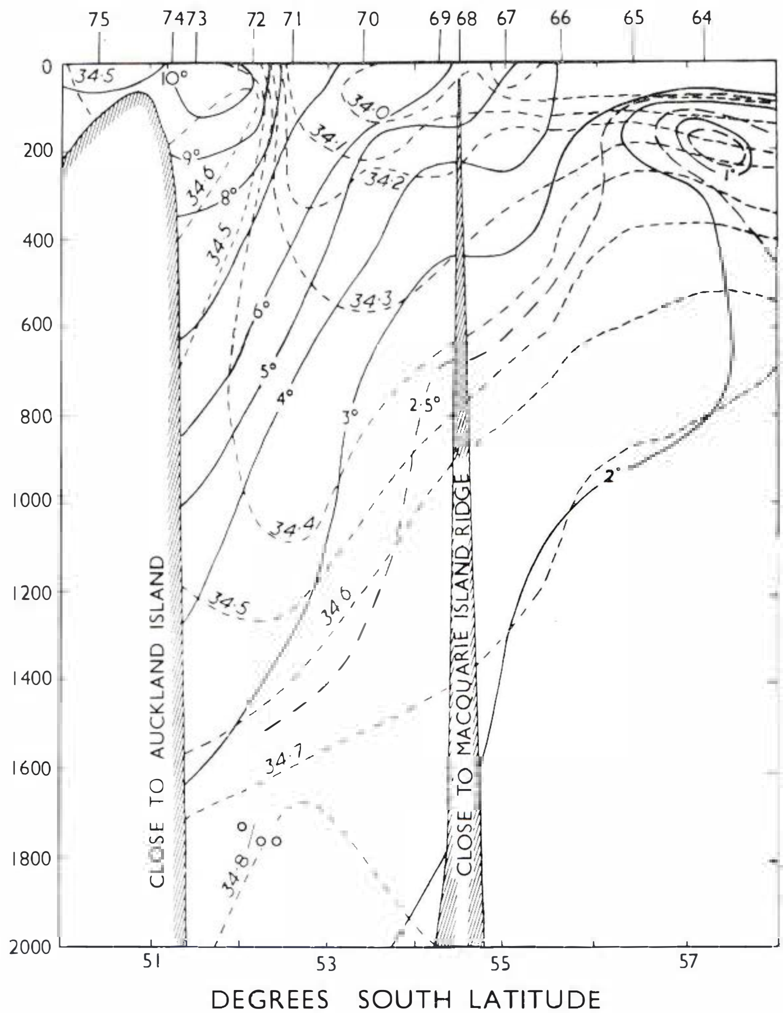

Fig. 11. Vertical section of temperature distribution re-plotted from data obtained the by Russian R.V. *Ob* between Auckland Islands and Macquarie Island in 1956. Isotherms in °c.

sections are then fortuitous in regard to the position of the ship's track in relation to the surface configuration of the Convergence and its parallel isotherms. Cold cores can thus not be used as a criterion for the recognition of the Antarctic Convergence as proposed by Wexler (1959). An increase in depth of the cores in a northerly direction is consistent with the down-slope of isopycnals in the salinity sections (figs. 2b and 5b) and explains why the water is colder in the core than the water further south at the same level, and cooling produced by "vertical stretching" is not required. Although the cold cores need thus not be caused by upwelling, or be directly wind-induced, the vertically stretched shape of the temperature minimum agrees with the condition of westerly winds in a northerly position with respect to the Circumpolar Current axis, which calls for divergent motion just south of the Antarctic Convergence (Wyrtki, 1960).

The "Subantarctic Divergence" and Australasian Subantarctic Front

In his description of frontal zones in Antarctic waters Ivanov (1961) discusses a "Subantarctic Divergence", as derived from tangential wind stress calculations, and states the necessity for a divergence separating the Antarctic Convergence and the Subtropical Convergence to satisfy conditions of continuity. He places his Divergence south of New Zealand at a calculated 53° S (according to his table 1) but finds it at 56° S in the section completed by *Ob* in April 1956 (fig. 11).

He has selected the 34·1–34·6‰ isohalines "bulging" towards the surface together with the 3° C, 2° C, and 1·5° C isotherms as its markers. It is hard to see, however, how near-surface temperatures below 4° C can possibly be associated with a subantarctic feature in this month, but at 53° S there is a pronounced front displayed by both isotherms and isohalines.

Burling (1961) uses the same section from *Ob* with one from *Pukaki* (January 1957) to define the Australasian Subantarctic Front. He associates with it the 34·5‰ isohaline, and the 8° C isotherm between 500 and 200 m of depth. This front separates the Subantarctic Waters above 600 m into Subantarctic Circumpolar Water to the south and Australasian Subantarctic Water to the north and extends furthest south in late summer and autumn. In the section from *Ob* along 20° E longitude Ivanov associates his "Subantarctic Divergence" with a structure similar to Burling's feature at 40–42° S; here figures and text do not agree, but it appears to be either where the 34·5‰ isohaline cuts the 8° C isotherm at 200 m or at 40° S where the 1·5° C – 3·0° C isotherms show a pronounced upward "bulge" down to 1,000 m of depth. Also in the section from *Ob* between the Shackleton ice shelf and Indian Ocean (April 1957) he places his "Subantarctic Divergence" in 45° S: exactly where the 8° C isotherm intersects the 34·5‰ isohaline, although here he stresses the significance of the adjacent upward "bulge" of the 3, 4, 5, and 6° C isotherms and the 34·3‰ – 34·8‰ isohalines.

Wyrtki (1960) indicated a divergence placed between Subtropical Convergence and Antarctic Convergence, which was especially pronounced at times of weak westerly winds, a condition not often met with south of New Zealand.

Ostapoff (1962a) calculated vertical velocity components resulting from eddy viscosity, neglecting the direct effects of the wind distribution; he also finds upward motion in this area.

In the section B 97 – B 105 the 34·5‰, 8° C intercept is readily visible at 51° S (at 200 m in figs. 2a, 2b), but in the B 120 – B 108 section it is partially masked by a possible loop in the front. The 8° C isotherm rises to the surface at B 120 and B 119 and so does the 34·5‰ isohaline. The position here is not well defined but appears to lie at 53·5° S. Is the steep front of isohalines and isotherms lying between the two Convergences a Subantarctic Divergence? It is not the "Subantarctic Divergence" according to Ivanov on the basis of the *Ob* section south of New Zealand, but it possibly could be on the basis of the other two *Ob* sections: On the other hand Ivanov requires there to be upward "bulges" in isolines, generally lying just to the south or north of the given positions. It is possibly not the divergence according to Wyrtki (1960), for weak westerlies were notably absent. Moreover, both these writers obtained the divergence from theoretical premises that do not take into account the peculiar conditions that exist in the New Zealand area and which were outlined before. Nevertheless a front seems to exist, more or less continuous in a zonal direction, and clearly recognisable as a major feature. It lies always in the Subantarctic Region between the two Convergences. Furthermore, it is the only major feature in this area that can be unambiguously recognised in observational data and therefore it should deserve the name of *Subantarctic Front*. On the basis of this analysis the Australasian Subantarctic Front is only that part of the Front which lies south of Australasia. Waters with temperatures over 8° C and salinities over 34·5‰, derived from mixing of Circumpolar and Subtropical Waters, should be most prevalent to the east of continents and there the Subantarctic Front should be sharp and displaced southwards. From the present observations the early summer position of the Subantarctic Front lies somewhat north of the Australasian Subantarctic Front figured by Burling (1961): however, the difference is small and the Front could be expected to lie further south in late summer and autumn (Ivanov, 1961).

Ivanov (1961) places divergent motion to the north of the Front in the 20° E section from *Ob* and to the south of the Front in the Shackleton Ice Shelf - Indian Ocean section. The Front thus lies within a region of divergent motion and the divergent motion itself would tend to destroy its sharp boundary. Many upward "bulges" in isolines lie in this area and some may be caused by the action of the Coriolis force. An analysis of a vertical velocity field, for which the numbers obtained in this survey are not accurate or numerous enough, would be necessary to provide conclusive evidence of divergent motion. It could well be that the Subantarctic Front here defined and the "Subantarctic Divergence" discussed by Ivanov are related phenomena but, since his Divergence is visualised as a wind-induced phenomenon and the Front is a boundary between two water masses defined by thermohaline properties, they need not be wholly identical.

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TABLE 2. Station Circumstances, Temperatures, Salinities, Densities and ^{14}C Depletions

NZOI Station No.	Date	Time	Latitude (°S)	Longitude (°E)	Sonic Depth (m)	Depth (m)	Temp. (°C)	Salinity (‰)	σ_t (g/ml)	Δ^{14}/C (‰) ± 5
	Nov 1958									
B 97	23	1541–1710	49 32·0	167 22·5	805	0	9·40	34·60	26·74	
						10	9·35	34·63	26·80	
						25	9·11	34·66	26·86	
						50	9·01	34·66	26·87	
						75	8·97	34·65	26·88	
						100	8·93	34·61	26·84	
						200	8·18	34·54	26·91	
						300	7·87	34·54	26·98	
						440	7·34	34·55	27·04	
B 98	24	1050–1455	51 41·5	163 49·0	4,140	0	8·85	34·68	26·91	
						14	8·83	34·70	26·93	
						23	8·81	34·72	26·95	
						47	8·69	34·68	26·94	
						94	8·54	34·59	26·90	
						188	8·06	34·61	26·97	
						281	7·75	34·63	27·04	
						376	7·20	34·67	27·16	
						564	6·66	34·70	27·28	
						cast 2				
						608	5·67	34·60	27·31	
						860	4·48	34·52	27·38	
						1,047	3·40	34·50	27·47	
						1,240	3·02	34·54	27·54	
						1,435	2·69	34·60	27·62	
						1,699	2·50	34·65	27·67	
						2,185	2·19	34·72	27·76	
						2,681	1·93	34·76	27·82	
						3,180	1·56	34·82	27·89	
B 99	25	0905–1110	54 05·5	160 26·0	4,411	0	4·84	34·07	26·98	
						8	4·86	34·08	26·98	
						18	4·88	34·10	27·01	
						37	4·88	34·10	27·01	
						57	4·77	34·14	27·05	
						101	3·75	34·05	27·08	
						162	4·11	34·10	27·08	
						250	3·81	34·25	27·23	
						333	4·00	34·60	27·49	
						423	3·54	34·35	27·42	
						518	3·12	34·30	27·51	
						618	2·87	34·33	27·39	
						828	2·63	34·45	27·50	
						1,012	2·44	34·63	27·66	
B 100	25	1540–1621	54 49·5	160 48·0	..	0	3·39	33·95	27·03	
						3	3·29	33·93	27·02	
						6	3·36	33·95	27·03	
						8	3·38	33·97	27·05	
						22	..	34·02	..	
						39	2·85	..	..	
						59	2·56	34·00	27·15	
						102	2·35	33·97	27·14	
						189	1·99	34·00	27·20	
B 101	25	1910–1950	55 15·8	160 59·0	..	0	3·08	33·90	27·02	
						9	3·09	33·93	27·04	
						23	3·17	33·95	27·05	
						48	3·15	33·90	27·01	
						73	2·57	..	..	
						93	2·06	33·94	27·14	
						99	2·26	..	..	
						111	2·56	34·03	27·17	
						144	2·78	34·06	27·17	
						188	3·15	34·12	27·19	

TABLE 2. Station Circumstances, Temperatures, Salinities, Densities and ^{14}C Depletions—*continued*

NZOI Station No.	Date	Time	Latitude (°S)	Longitude (°E)	Sonic Depth (m)	Depth (m)	Temp. (°C)	Salinity (‰)	σ_t (g/ml)	$\Delta^{14}C$ (‰) ± 5
	Nov 1958									
B 102	25	2241–2317	55 41·0	160 59·0	—	0	4·00	34·00	27·01	
						9	4·01	33·86	26·90	
						24	4·11	33·92	26·94	
						48	4·11	33·93	26·95	
						73	3·99	34·02	27·03	
						97	3·42	33·99	27·06	
						122	3·21	33·99	27·08	
						146	3·00	34·06	27·16	
						193	2·95	34·10	27·19	
						241	3·14	34·26	27·30	
B 103	26	0205–0310	56 06·5	160 59·0	4,221	0	2·71	34·05	27·18	
						7	2·72	33·90	27·05	
						19	2·72	33·90	27·05	
						41	2·61	33·85	27·02	
						65	2·39	33·95	27·12	
						89	1·43	33·90	27·15	
						113	1·10	34·08	27·32	
						136	1·51	34·15	27·35	
						186	1·57	34·16	27·35	
						236	2·07	34·37	27·49	
B 104	26	0600–0650	56 38·0	160 59·0	3,590	0	2·14	33·98	27·17	
						9	2·14	33·97	27·16	
						23	2·14	33·97	27·16	
						48	2·14	33·95	27·14	
						72	2·07	33·93	27·13	
						97	1·95	33·90	27·12	
						121	1·78	33·93	27·15	
						146	1·22	33·97	27·22	
						196	1·47	34·04	27·26	
						246	1·88	34·34	27·48	
B 105	26	1335–1720	57 36·0	161 02·0	—	0	1·27	34·00	27·24	
						45	0·80	34·08	27·34	
						92	0·43	34·10	27·38	
						116	0·36	34·08	27·37	
						140	0·61	34·20	27·45	
						165	1·25	34·32	27·50	
						190	1·59	34·40	27·55	
						cast 2				
						220	1·70	34·44	27·57	
						240	1·80	34·47	27·59	
						279	2·20	34·57	27·64	
						484	2·17	34·62	27·68	
						620	2·12	34·68	27·73	
						1,015	1·84	34·80	27·85	
						1,383	1·62	34·84	27·90	
						1,740	1·16	34·85	27·93	
						2,102	0·92	34·80	27·83	
						2,560	0·72	34·69	27·83	
						3,050	0·57	34·60	27·77	
B 106	27	1246–1500	55 42·5	165 23·0	—	0	7·19	34·32	26·88	
						7	7·18	34·34	26·90	
						17	7·16	34·35	26·91	
						33	7·10	34·37	26·94	
						54	7·21	34·39	26·94	
						75	7·20	34·40	26·94	
						121	7·12	34·41	26·94	
						170	6·92	34·41	26·99	
						219	6·70	34·40	27·01	
						cast 2				
						294	6·59	34·38	27·01	
						413	6·02	34·29	27·01	
						533	5·71	34·29	27·05	
						653	4·85	34·32	27·17	

TABLE 2. Station Circumstances, Temperatures, Salinities, Densities and ^{14}C Depletions—*continued*

NZOI Station No.	Date	Time	Latitude (°S)	Longitude (°E)	Sonic Depth (m)	Depth (m)	Temp. (°C)	Salinity (‰)	σ_t (g/ml)	$\Delta^{14}C$ (‰) ± 5
	Nov 1958									
B 106	*(continued)*					766	4·13	34·36	27·28	
						923	3·29	34·42	27·42	
						1,086	2·80	34·49	27·52	
						1,274	2·56	34·55	27·59	
						1,459	2·52	34·60	27·63	
B 107	28	0840–1040	58 19·0	167 18·0	..	0	4·60	34·12	27·05	
						7	4·59	34·15	27·07	
						19	4·55	34·16	27·08	
						40	4·62	34·16	27·07	
						62	4·61	34·14	27·06	
						85	4·25	34·10	27·07	
						135	3·78	34·07	27·09	
						185	3·74	34·06	27·09	
						235	3·31	34·05	27·12	
						275	3·00	34·08	27·17	
						cast 2				
						319	3·08	34·24	27·29	
						366	3·11	34·25	27·30	
						461	3·28	34·23	27·26	
						557	3·05	34·19	27·25	
						655	2·66	34·13	27·26	
						754	2·62	34·47	27·52	
						853	2·59	34·54	27·58	
						953	2·45	34·62	27·65	
B 108	29	0709–2345	63 44·3	172 26·7	1,865	0	−2·11	35·24*	28·41*	−170
						9	−2·07	35·34*	28·47*	
						18	−2·05	35·45*	28·57*	
						46	−1·86	35·44*	28·55*	
						65	−1·79	35·44*	28·55*	
						94	−1·77	35·44*	28·55*	−156
						142	−0·85	35·53*	28·58*	
						203	0·51	35·72*	28·66*	−183
						240	1·09	35·85*	28·72*	
						cast 2				
						274	1·59	34·85	27·91	
						320	1·57	34·80	27·87	
						367	1·51	34·79	27·86	−178
						438	1·48	34·78	27·86	
						510	1·48	34·78	27·86	
						582	1·44	34·78	27·86	
						655	1·32	34·78	27·87	
						754	1·18	34·78	27·88	
						904	1·05	34·78	27·88	
						cast 3				
						979	0·92	34·76	27·88	
						1,078	0·90	34·76	27·88	
						1,176	0·75	..	..	
						1,275	0·71	..	..	
						1,375	0·68	34·72	27·86	
						1,459	0·56	34·72	27·87	−197
	Dec 1958									
B 109	1	1327–1450	62 37–0	170 51–0	2,886	0	−0·13	34·16	27·46	
						13	−0·19	34·16	27·47	
						34	−0·29	34·20	27·50	
						62	−0·25	34·24	27·54	
						92	−0·38	34·43	27·69	
						111	−0·46	34·45	27·76	
						135	0·85	34·49	27·67	
						168	1·70	34·60	27·70	
						211	1·96	34·63	27·70	
						263	2·08	34·65	27·71	
						362	2·01	34·70	27·76	
						462	0·96	34·77	27·88	

*Suspect due to freezing.

TABLE 2. Station Circumstances, Temperatures, Salinities, Densities and ^{14}C Depletions—*continued*

NZOI Station No.	Date	Time	Latitude (°S)	Longitude (°E)	Sonic Depth (m)	Depth (m)	Temp. (°c)	Salinity (°/₀₀)	σ_t (g/ml)	Δ^{14}/C (°/₀₀) ± 5
	Dec 1958									
B 110	1	1925–0225	61 55·9	170 34·0	4,528	0	1·69	34·11	27·31	−142
						12	1·65	34·09	27·29	
						30	1·52	34·16	27·36	
						57	1·39	34·17	27·37	
						86	1·09	34·18	27·40	
						107	0·91	34·19	27·42	
						138	0·58	34·22	27·47	−198
						179	1·11	34·27	27·47	
						234	1·33	34·74	27·83	
						332	2·16	34·84	27·85	
						cast 2				
						381	2·22	34·85	27·86	
						509	2·22	34·86	27·86	−164
						685	2·17	34·87	27·88	
						1,055	1·91	34·88	27·90	
						1,335	1·78	..	..	
						1,810	1·37	34·87	27·94	
						2,258	1·00	34·85	27·94	
						2,712	0·91	34·85	27·95	
B 111	2	0540–0837	61 25·5	170 41·0	..	0	1·79	34·00	27·21	
						15	1·67	33·98	27·20	
						29	1·66	34·00	27·21	
						47	1·65	34·00	27·22	
						68	1·55	34·00	27·22	
						82	1·55	34·00	27·22	
						97	1·50	34·05	27·27	
						107	1·50	34·06	27·28	
						122	1·49	34·07	27·28	
						141	1·46	34·08	27·30	
						162	1·24	34·12	27·35	
						184	1·20	34·30	27·49	
						cast 2				
						392	1·82	34·42	27·53	
						536	2·18	34·54	27·62	
						679	2·46	34·60	27·64	
						870	2·17	34·70	27·34	
						1,065	1·11	34·79	27·89	
						1,264	1·07	34·79	27·89	
B 112	2	1255–1435	60 7·0	170 44·0	..	0	2·72	34·02	27·15	
						12	2·71	33·96	27·10	
						31	2·52	34·04	27·18	
						49	2·43	34·07	27·21	
						77	2·18	34·01	27·19	
						120	1·94	34·01	27·21	
						144	1·75	34·02	27·23	
						168	1·76	34·02	27·23	
						191	1·55	34·05	27·25	
						217	1·62	34·07	27·28	
						242	1·70	34·14	27·33	
						cast 2				
						279	2·76	34·34	27·49	
						350	2·47	34·36	27·44	
						422	2·40	34·52	27·58	
						518	2·41	34·54	27·60	
						615	2·39	34·56	27·61	
						762	2·35	34·59	27·64	
						961	2·36	34·63	27·67	
B 113	2	1738–1924	60 22·0	170 54·0	4,810	0	3·82	34·07	27·09	−134
						13	3·83	34·03	27·06	
						27	3·85	34·00	27·03	
						47	3·91	34·10	27·10	
						81	3·89	34·10	27·10	
						121	3·78	34·10	27·12	
						141	3·54	34·10	27·14	
						156	3·30	34·11	27·17	

TABLE 2. Station Circumstances, Temperatures, Salinities, Densities and ^{14}C Depletions—*continued*

NZOI Station No.	Date	Time	Latitude (°S)	Longitude (°E)	Sonic Depth (m)	Depth (m)	Temp. (°C)	Salinity (‰)	σ_t (g/ml)	$\Delta\, ^{14}C/C$ (‰) ± 5
	Dec 1958									
B 113	*(continued)*					195	3·52	34·50	27·46	
						212	3·72	34·55	27·32	
						220	3·86	34·28	27·25	
						245	3·90	34·14	27·13	
						cast 2				
						331	3·39	34·25	27·27	
						800	3·28	34·26	27·29	
						477	2·99	34·34	27·38	
						575	2·59	34·39	27·46	
						773	2·49	34·54	27·58	
						973	2·41	34·67	27·70	
B 114	2	2318–0225	59 39·0	171 02·0	5,391	0	4·33	34·08	28·04	
						45	4·38	34·08	27·04	
						92	4·78	34·24	27·12	
						188	4·24	34·29	27·22	
						237	4·74	34·32	27·19	
						286	4·20	34·32	27·25	
						336	3·76	34·33	27·30	
						386	3·73	34·33	27·30	
						435	3·22	34·37	27·38	
						485	3·22	34·40	27·40	
						585	2·82	34·45	27·48	
						733	2·72	34·60	27·61	
						925	2·48	34·66	27·68	
						1,117	2·30	34·72	27·74	
						1,410	2·21	34·76	27·78	
						1,905	1·92	34·81	27·84	
						2,400	1·55	34·84	27·90	
						2,900	1·24	34·87	27·94	
B 115	3	0635–0838	58 56·0	171 08·0	5,079	1	4·10	34·05	27·00	
						8	4·22	34·01	27·00	
						15	4·21	34·02	27·00	
						24	4·21	34·02	27·00	
						43	4·21	34·02	27·00	
						66	4·25	34·02	27·00	
						90	4·18	34·12	27·09	
						140	3·66	34·15	27·17	
						190	3·89	34·21	27·19	
						240	3·93	34·23	27·20	
						cast 2				
						280	4·27	34·32	27·24	
						377	2·97	34·30	27·35	
						473	3·38	34·45	27·43	
						571	3·05	34·46	27·47	
						670	2·85	34·47	27·50	
						770	2·66	34·48	27·52	
						870	2·56	34·54	27·58	
						1,070	2·41	34·76	27·77	
B 116	3	1228–1755	58 20·0	171 14·0	5,282	0	6·63	34·39	27·01	
						9	6·59	34·44	27·06	
						18	6·54	34·38	27·02	
						28	6·57	34·37	27·00	
						42	6·54	34·36	27·00	
						62	6·51	34·34	26·99	
						84	6·43	34·32	26·98	
						106	6·48	34·36	27·00	
						127	6·36	34·34	27·00	
						148	6·36	34·34	27·00	
						170	5·97	34·26	26·99	
						214	4·94	34·17	27·04	
						258	4·81	34·17	27·06	
						345	5·15	34·33	27·15	
						434	5·07	34·38	27·20	
						526	4·55	34·48	27·34	

TABLE 2. Station Circumstances, Temperatures, Salinities, Densities and ^{14}C Depletions—*continued*

NZOI Station No.	Date	Time	Latitude (°S)	Longitude (°E)	Sonic Depth (m)	Depth (m)	Temp. (°C)	Salinity (°/₀₀)	σ_t (g/ml)	$\Delta^{14}C$ (°/₀₀) ± 5
	Dec 1958									
B 116 *(continued)*						619	3·55	34·44	27·41	
						716	3·26	34·36	27·37	
						814	2·74	34·46	27·50	
						913	2·96	34·52	27·53	
						1,012	2·76	34·58	27·60	
						1,161	2·44	34·59	27·63	
						1,411	3·46	34·76	27·67	
B 117	4	0010–0320	57 11·0	171 05·0	3,780	0	6·32	34·23	26·93	
						11	6·32	34·28	26·97	
						24	6·26	34·29	26·97	
						42	6·24	34·27	26·97	
						66	6·31	34·26	26·95	
						89	6·29	34·26	26·98	
						137	6·24	34·25	26·95	
						187	5·90	34·26	27·00	
						214	5·61	34·28	27·05	
						277	5·68	34·31	27·07	
						426	5·36	34·32	27·12	
						512	4·75	34·33	27·20	
						694	3·64	34·34	27·32	
						884	3·13	34·41	27·42	
						1,075	2·78	34·49	27·52	
						1,370	2·54	34·60	27·63	
						1,870	2·31	34·80	27·81	
B 118	4	1130–1440	55 34·5	170 27·0	4,921	0	6·91	34·57	27·11	−136
						25	6·86	34·42	27·03	
						46	6·88	34·41	26·99	
						86	6·87	34·42	27·02	
						120	6·80	34·43	27·02	
						161	6·82	34·43	27·00	
						207	6·80	34·43	27·02	
						256	6·76	34·43	27·08	
						355	6·06	34·34	27·05	
						455	5·95	34·35	27·07	
						555	4·78	34·38	27·23	
						690	3·70	34·39	27·35	
						866	2·93	34·40	27·43	
						1,046	2·60	34·49	27·54	
						1,318	2·39	34·75	27·76	
						1,776	2·07	34·80	27·83	
						2,246	1·76	34·77	27·83	
						2,742	1·44	34·80	27·88	
						3,240	1·17	34·98	28·04	
B 119	4	2035–2340	54 31·0	170 20·0	4,181	6	6·99	34·35	26·94	
						12	7·02	34·35	26·94	
						25	6·97	34·35	26·94	
						44	6·95	34·38	26·95	
						64	6·93	34·38	26·95	
						84	5·87	34·55	27·24	
						104	6·82	34·38	26·98	
						150	6·55	34·38	27·02	
						200	6·71	34·40	27·01	
						225	6·61	34·40	27·02	
						cast 2				
						320	6·00	34·30	27·02	
						380	5·79	34·34	27·08	
						448	5·75	34·35	27·09	
						520	5·40	34·38	27·16	
						700	4·47	34·38	27·26	
						850	3·52	34·39	27·37	
						1,010	2·92	34·45	27·47	
						1,150	2·78	34·48	27·51	

TABLE 2. Station Circumstances, Temperatures, Salinities, Densities and ^{14}C Depletions—*continued*

NZOI Station No.	Date	Time	Latitude (°S)	Longitude (°E)	Sonic Depth (m)	Depth (m)	Temp. (°c)	Salinity (‰)	σ_t (g/ml)	$\Delta^{14}C$ (‰) ± 5
	Dec 1958									
B 120	5	0610–0811	53 26·3	170 15·0	..	0	7·90	34·44	26·87	−124
						9	7·89	34·44	26·87	
						18	7·87	34·44	26·87	
						27	7·90	34·44	26·87	
						44	7·85	34·44	26·88	
						62	7·85	34·50	26·92	
						80	7·90	34·53	26·94	
						99	7·83	34·54	26·98	
						107	7·83	34·54	26·98	
						140	7·85	34·55	26·97	
						cast 2				
						163	7·56	34·58	27·03	
						186	7·36	34·60	27·07	
						233	7·28	34·54	27·04	
						236	7·21	34·51	27·03	
						282	7·14	34·50	27·03	
						331	7·07	34·50	27·04	
						381	6·99	34·51	27·06	
B 121	5	2145–2200	47 50·0	171 22·5	..	0	..	..	..	−124

INDEX

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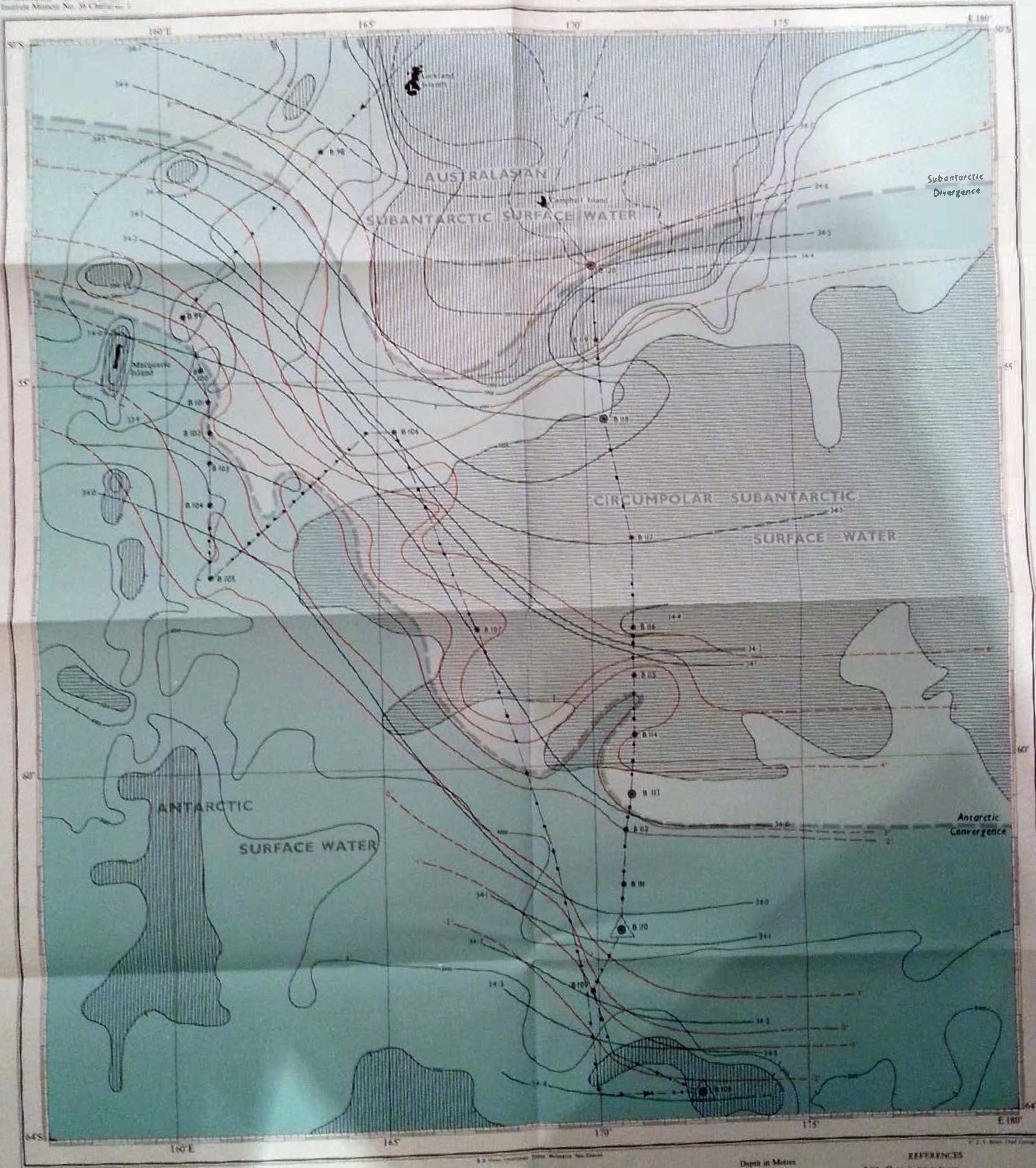

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