DETAIL OF THE THERMAL STRUCTURE OF OCEANIC FRONTS IN THE SOUTHERN OCEAN SOUTH OF AFRICA

By

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A THESIS SUBMITTED IN FULFILLMENT OF THE REQUIREMENTS OF THE MASTER OF SCIENCE DEGREE, OCEANOGRAPHY DEPARTMENT, UNIVERSITY OF CAPE TOWN

1997

ABSTRACT

This investigation addresses the thermal characteristics of the major oceanic frontal systems in the Southern Ocean south of Africa based on data collected to a depth of 500 m on forty-three cruises during a fifteen year period.

The width of the Agulhas Front has been shown to vary considerably in both its sea surface and sub-surface thermal manifestation as a result of mesoscale turbulence. Its mean sea surface width of 84 km has a standard deviation of 53 km, and the mean sub-surface width of 37 km has a standard deviation of 33 km. The Agulhas Front has been found to be a separate front north of the Subtropical Convergence in 56% of the cruises investigated. It has only been observed from 18,2° E to 24,7° E, with a mean sea and sub-surface temperature gradient across the Agulhas Front of 0,05 °C/km and 0,13 °C/km respectively. It has a mean sea surface middle temperature of 17,8° C and a mean sub-surface middle temperature of 12,6° C. The mean sea and sub-surface geographic positions of the thermal expression of the Agulhas Front are 39,3° S; 22,7° E and 39,1° S; 22,7° E.

The Subtropical Convergence at surface has been found to be a single, broad frontal zone across the Central/South East Atlantic Ocean, that does not bifurcate. It has a mean sea surface middle temperature of 14,3° C and a mean sub-surface middle temperature of 8,4° C. The mean sea and sub-surface temperature gradients across the Subtropical Convergence are 0,03 °C/km and 0,05 °C/km respectively. The mean sea and sub-surface geographic positions of the thermal expression of the Subtropical Convergence are 41,8° S; 21,9° E and 41,7° S; 22,0° E. The Subtropical Convergence has a mean sea surface width of 146 km and a mean sub-surface width of 79 km.

The Sub-antarctic Front is pressed northward from 45° S to 43° S by the Mid-Ocean Ridge in the South West Indian Ocean sector, after which it converges with the Subtropical Convergence at approximately 60° E to form a united STC/SAF at sub-surface. This united STC/SAF does not however form a "Crozet Front" by joining the Agulhas Front between 52° E and 65° E. It has a mean sea surface middle temperature of 4,4° C and a mean sub-surface middle temperature of 4,0° C. The mean sea and sub-surface temperature gradients across the Sub-antarctic Front are 0,02 °C/km. The mean sea and sub-surface geographic positions of the thermal expression of the Sub-antarctic Front are 48,7° S; 18,9° E and 46,8° S; 19,9° E. The Sub-antarctic Front has a mean sea surface width of 73 km and a mean sub-surface width of 77 km.

In 30% of the sections investigated the Antarctic Polar Front consisted of a primary and secondary front. The Antarctic Polar Front does not join the Sub-antarctic Front east of 40° E at sub-surface and subsequently no quadruple front is formed. It has a mean sea surface middle temperature of 2,1° C and a mean sub-surface middle temperature of 2,3° C. The mean sea and sub-surface temperature gradients across the Antarctic Polar Front are 0,01 °C/km and 0,02 °C/km respectively. The mean sea and sub-surface geographic position of the thermal expression of the Antarctic Polar Front are 52,7° S; 14,9° E and 49,2° S; 20,8° E. The Antarctic Polar Front has a mean sea surface width of 66 km and a mean sub-surface width of 74 km.

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ACKNOWLEDGEMENTS

I am grateful to God, my heavenly Father, for His grace and for being the motivation to do this M.Sc. I thank my father P.I. Matthysen for all his support and love and dedicate this thesis to his memory. I acknowledge Dr Marten Gründlingh at the South African Data Centre for Oceanography (SADCO), for his time and effort in helping me with the dataset. I would also like to thank my supervisor Professor Johann Lutjeharms for advice, suggestions and guidance during this research and the writing of this thesis.

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CHAPTER 1

INTRODUCTION

This thesis deals with the detail of the thermal structure of the main oceanic frontal systems in the African sector of the Southern Ocean, that is between Cape Town and Antarctica and between South Georgia Island in the west and Kerguelen Island in the east.

In general these frontal zones have a favourable effect on biological productivity (Boden et al., 1988; Bidigare et al., 1986 and Lutjeharms and Walters, 1985). They also play a prominent role in the weather of southern Africa and in the control of global climate (Jury, 1993).

Apart from the intrinsic value of a greater knowledge about these fronts, a better understanding of the structure of frontal regions in the Southern Ocean may be of benefit also to the fishing industry and, because of their influence on weather and on climate, to the agriculture of the summer-rainfall regions of Southern Africa.

The major oceanic frontal systems in the Southern Ocean have been described during the first half of this century by Deacon (1937) and Mackintosh (1946). Since 1956 the knowledge of fronts in the Southern Ocean between Africa and Antarctica has increased through regular hydrographic surveys conducted by research expeditions (e.g. Jacobs and Georgi, 1977) and by supply and research vessels steaming to Antarctic bases from South Africa (e.g. Lutjeharms and Valentine, 1984). Quality sea surface data sets obtained from these many surveys have presented the opportunity of establishing the sea surface thermal characteristics of the major ocean fronts in the Southern Ocean south of Africa with a spatial and temporal resolution not possible before (Lutjeharms and Valentine, 1984). These data as a rule do not give any information on the sub-surface expression of fronts.

Although numerous descriptions of the sub-surface thermal structure of fronts in the Southern Ocean have been published (Gordon, 1967; Emery, 1977) it is only from 1978 that the detail of this aspect of the oceanic frontal systems in the Southern Ocean between Cape Town, Antarctica and the sub-antarctic islands south of Africa has been substantially addressed (Lutjeharms, 1985a). The set of sub-surface data that has been accumulated over the past two decades allows one now also to investigate these Southern Ocean fronts in the upper layer of the water column with a spatial and temporal resolution comparable to that of continuous underway measurements at the sea surface.

Over the last fifteen years a number of cruises dedicated specifically to hydrographic observations by expendable bathythermograph (XBT) in this region of the world's oceans have been conducted. All the sub-surface temperature data collected on these cruises have been assembled and collated for this investigation. The data obtained during only forty three of these cruises consist of sufficiently closely spaced stations and adequate, quality data to add new information to the detail of the Southern Ocean thermal fronts. An analysis of these thermal data may more closely quantify the biological and physical relationships that have been observed at the following frontal systems in the ocean south of Africa.

Well-established frontal systems and widely accepted names (see figure 1.1) for them are:

Cape Upwelling Front: This frontal regime exists in the vicinity of Cape Town, between the cold water of the wind-driven, coastal upwelling cells and the warmer, offshore, oceanic water of the South East Atlantic and South East Indian Oceans. Warm, intense Agulhas Current filaments that frequently advect along this upwelling front and complicate the physical environment off Cape Town may facilitate the formation of good anchovy year-classes (Shannon et al., 1992).

Agulhas Front: This front lies between the southern edge of the Agulhas Return Current and the Subtropical Convergence. According to Belkin and Gordon (1996) the Agulhas Front changes its temperature/salinity (t/s)-characteristics substantially downstream because of the northward leakage of the warm, salty water out of the Agulhas Return Current (also Ansorge, 1996). Analysis of hydrographic data shows an intermittent confluence between the Agulhas Front and the Subtropical Convergence (Lutjeharms and Emery, 1983).

Subtropical Convergence: The Subtropical Convergence in the African sector of the Southern Ocean has the strongest horizontal thermal and saline gradients of all the major fronts in the Southern Ocean (Lutjeharms, 1985a). This front is formed to the south of the Agulhas Return Current, where the denser Sub-antarctic Surface Water subducts northwards beneath the Subtropical Surface Water to form South Atlantic and South Indian Ocean Central Water (Gordon, 1967). The occasional confluence between the Agulhas Front and Subtropical Convergence results in a single and enhanced Subtropical Convergence (Lutjeharms, 1985a) at which time no Agulhas Front is present. The Subtropical Convergence also stands out as a zone with considerable horizontal oxygen and nutrient gradients (Khimitsa, 1987).

Sub-antarctic Front: According to Clifford (1983) the Sub-antarctic Front occurs at the position of the maximum westerlies. An eastward current is generally associated with the Sub-antarctic Front (Belkin and Romanov, 1990). Allanson et al. (1981) have shown that the Sub-antarctic Front is associated with a sea surface chlorophyll maximum.

Antarctic Polar Front: It is defined as the northernmost limit of the 2° C isotherm that is part of the sub-surface temperature minimum (Lutjeharms, 1985a; Joyce and Patterson, 1978). According to Clifford (1983) the Antarctic Polar Front is related to the ice-cover. Sea surface chlorophyll readings here sometimes exhibit peaks at the surface expression of the Antarctic Polar Front which are ten times that of the surrounding waters (Lutjeharms et al., 1986). The Antarctic Polar Front reveals a primary and secondary polar frontal zone in the South Pacific (Gordon, 1971).

Weddell-Scotia Confluence: The Scotia Front and the Weddell Front, form the northern and southern limits of the Weddell-Scotia Confluence (Gordon, 1967). The Weddell-Scotia Confluence is the boundary between the cold Weddell Sea Water and the warmer Scotia Sea Water (Deacon, 1982). Its northern limit is the Scotia Front and its southern limit the Weddell Front. This front trends east and north from the tip of the Antarctic Peninsula before reaching the South Sandwich Island Arc, where it tends to lie northwards along this island group (Clifford, 1983). According to Clifford (1983) this front is not visible downstream of the South Sandwich Island group.

Antarctic Divergence: This is a hypothesized front which is thought to result from a juxtaposition of the prevailing westerly and easterly wind regimes, north and south of the front respectively. These winds cause the surface layer in the proximity of the Antarctic Divergence to diverge due to Ekman transport. This surface divergence of cold surface water is then thought to be compensated by an upwelling of warmer deep water. It remains uncertain whether such a front would be formed between the cold surface waters of the Antarctic and the warmer deep upwelled water (Lutjeharms, 1985a), or by recirculating Weddell Sea Water (Gordon et al., 1982).

Continental Water Boundary: This term refers exclusively to a frontal feature in the Antarctic Circumpolar Current (Sievers and Emery, 1978). According to Ostapoff (1962), the easterly wind regime near the Antarctic coast drives the cold diverging surface water of the Antarctic Divergence towards the Antarctic coast. After cooling further and mixing with the more saline sub-surface water this water sinks (Ostapoff, 1962). Where this sinking water reaches water colder than 1° C the Continental Water Boundary is formed (Nowlin and Clifford, 1982).

Antarctic Slope Front: Less is known about this front than about aforementioned ones since for most of the time it is to be found beneath the pack-ice. There are few research ships that are able to study the front beneath the ice-cover and as a result our knowledge of this front is inadequate, particularly in the region south of Africa (Jacobs, 1991). Ainley and Jacobs (1981) have however been able to define the Antarctic Slope Front as that region where there is an increase in the horizontal gradients of water temperature, salinity, density, chemistry, colour and transparency, in the vicinity of the shelf break of the Antarctic continent.

Although the abovementioned fronts have these distinctly different characteristics, they have in common that they are all identifiable in temperature distributions. The thermal detail of the frontal morphology and structure in each case is clearly apparent in high-quality XBT sections taken in the region. It is therefore important to establish what is already known about the thermal expressions of these main oceanic fronts in the Southern Ocean south of Africa in order to establish what further information on the thermal structure may be required.

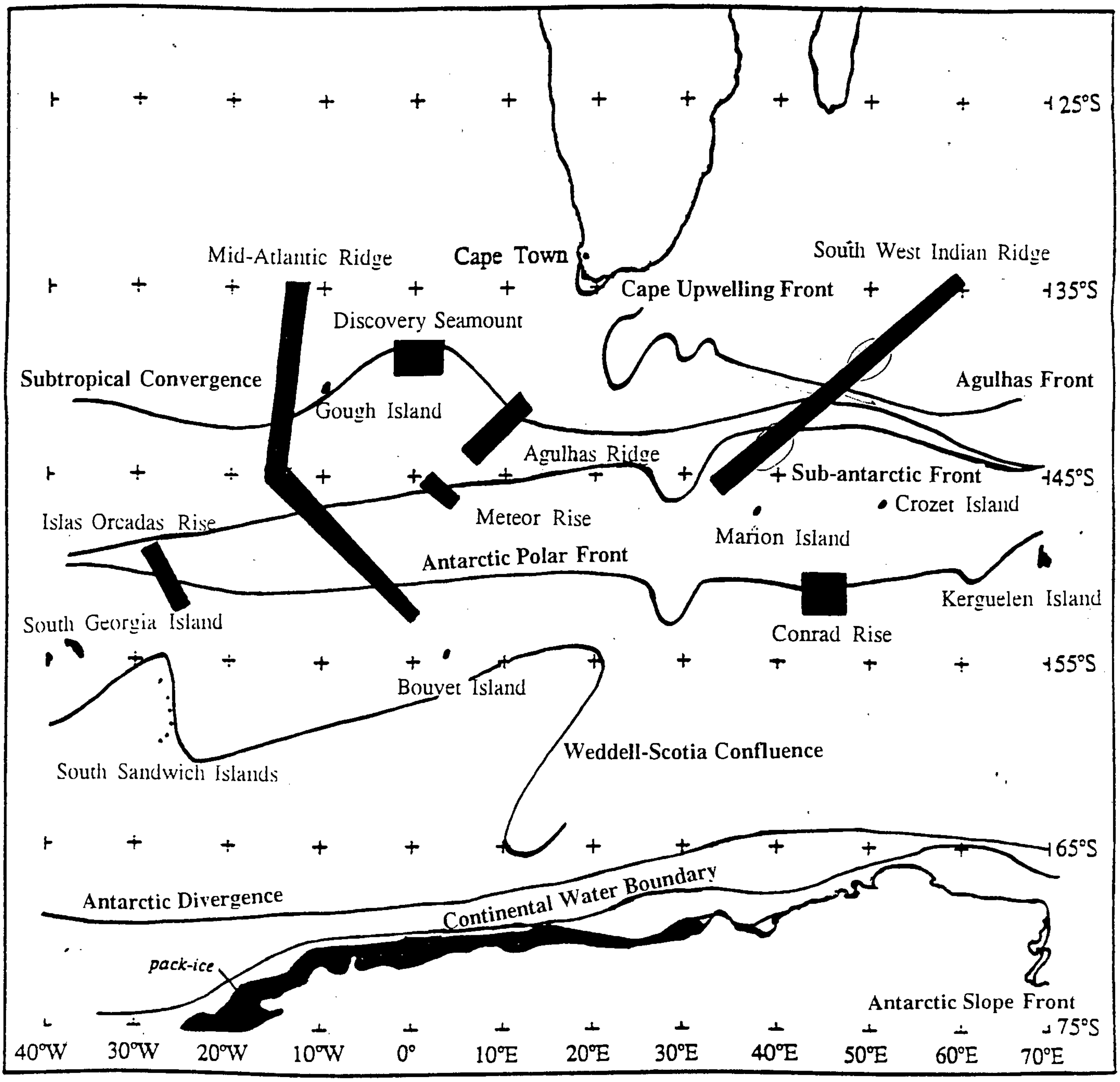

Figure 1.1 The geographic locations of the main oceanic frontal systems in the Southern Ocean south of Africa. These geographic locations of the thermal signatures of these various fronts have been determined by various authors and are discussed in chapter 2 (Belkin, 1993 and Belkin and Gordon, 1996). The locations of the principle bathymetric features are indicated in a stylised way.

CHAPTER 2

OCEANIC FRONTAL SYSTEMS IN THE AFRICAN SECTOR OF THE SOUTHERN OCEAN

The presently known characteristics of the main oceanic fronts in the Southern Ocean region between South Africa and Antarctica, briefly mentioned in chapter 1, are here discussed in detail. This review of the published literature will allow us to identify the shortcomings in current understanding of these oceanic fronts and enable us to determine what the remaining and unresolved problems are concerning them.

Cape Upwelling Front

The Cape Upwelling Front is part of the Benguela Upwelling System (Shannon, 1985). Lutjeharms and Emery (1983) have even noted the Cape Upwelling Front at the discontinuity between the warm, surface water of the Agulhas Current and the colder, upwelled water of the Cape Upwelling Cell. The Cape Upwelling Front is morphologically complex and is occasionally intensified by this influx of warm water from the Agulhas Current (Bang and Andrews, 1974). The geographic position of the Cape Upwelling Front is from 18° E to 14° E, with a strong, horizontal, thermal gradient of more than 6° C across the front (Lutjeharms, 1981b).

The influx of warm water from Agulhas rings (Lutjeharms and Valentine, 1988a) and Agulhas Current filaments has been thought to facilitate the formation of good anchovy year-classes (Shannon et al., 1992). This movement of warm water may carry ichthyoplankton and small fish from spawning to nursery grounds and reduce the advective loss of these organisms offshore (Shannon et al., 1992).

According to Shannon (1985) the northward shift of the atmospheric pressure systems in winter causes the frequency of the non-upwelling favourable winds to increase, limiting the appearance of the Cape Upwelling Front to the summer period September to March.

Agulhas Front

Lutjeharms and Valentine (1984) have identified the Agulhas Front only from 13,5° E to 25° E as part of a statistical analysis of the Agulhas Front's sea surface, thermal characteristics in the African sector of the Southern Ocean. Holliday and Read (1996) have traced the Agulhas Front as far east as 56° E from surface observations south and east of South Africa in the austral summers from 1993 to 1995. Belkin and Gordon (1996) on the other hand believe that the Agulhas Front extends even further east, through the Kerguelen-Amsterdam Passage and into the South East Indian Ocean as the South Subtropical Front in the Australian sector of the Southern Ocean (SSTF-Aus). They have identified the Agulhas Front by summarising the criteria used by a range of authors to define all the fronts in the region since the Agulhas Front changes its temperature/salinity (t/s)-parameters so substantially downstream that it prevents the use of any fixed t/s-isoline. These criteria have then been imposed on the available meridional oceanographic sections between 0° E and 150° E, and between 30° S and 60° S, a detailed, copious analysis of data that unfortunately consists of a mixture of high quality conductivity, temperature and depth (CTD)-sections, a few XBT-sections and substantial sets of bottle data. Ansorge (1996) has stated that the Agulhas Front terminates between 66° E and 70° E since the Sub-antarctic Surface Water "caps" the surface water of the Agulhas Return Current here, weakening the Agulhas Front beyond recognition at 70° E. Clearly the different criteria and the quality of the non-uniform data sets used by different investigators has led to varying geographic locations of the thermal expression of the AF. The longitudinal geographic range of the sea surface and sub-surface thermal expression of the Agulhas Front therefore needs to be thoroughly examined.

As the Agulhas Front is traced eastward (Belkin and Gordon, 1996) there is a substantial decrease in the temperatures and salinities along the north side of the Agulhas Front/SSTF-Aus even though the front's latitude remains nearly constant at 40° S. This evolution is partially due to the winter processes in this area which modify the north side of the Agulhas Front/SSTF-Aus making it colder and fresher than usual (Belkin and Gordon, 1996). The northward leakage of the warm, salty water out of the Agulhas Return Current may also cause the Agulhas Front to diminish in strength downstream (Ansorge, 1996). It has been proposed that the major component of this northward branching of Agulhas water occurs east of the Amsterdam Plateau and closes the large-scale, anticyclonic circulation of the South Indian Ocean (Belkin and Gordon, 1996). Ansorge (1996) believes that this northward branching of the AF occurs no further east than 70° E.

Eddies and rings are characteristic, mesoscale features of the terminal region of the Agulhas Current (Lutjeharms and Valentine, 1988a,b; Lutjeharms and van Ballegooyen, 1988). With the aid of radiometry measurements Lutjeharms (1981a) discovered that this melange of mesoscale features contributes significantly to the variable morphology of the Agulhas Front (see figure 2.1). This instability causes a strong interaction between the Agulhas Front and the Subtropical Convergence that causes the Agulhas Front to press the Subtropical Convergence further south (Belkin and Gordon, 1996). This enhances the meridional gradient of the Subtropical Convergence south of Africa (Lutjeharms and Emery, 1983). This AF/STC confluence however remains unquantified.

Therefore, the longitudinal geographic range of the sea surface and the sub-surface thermal expression of the Agulhas Front remains uncertain and needs to be studied in detail. The Agulhas Front undergoes a substantial decrease in both temperature and salinity across the Indian Ocean both as a result of the winter processes in this area as well as the northward leakage of warm, salty water from the Agulhas Return Current. With suitable data this eastward weakening could be more closely described. The mesoscale activity at the terminal region of the Agulhas Current causes a strong AF/STC interaction. This AF/STC confluence, however needs to be better quantified.

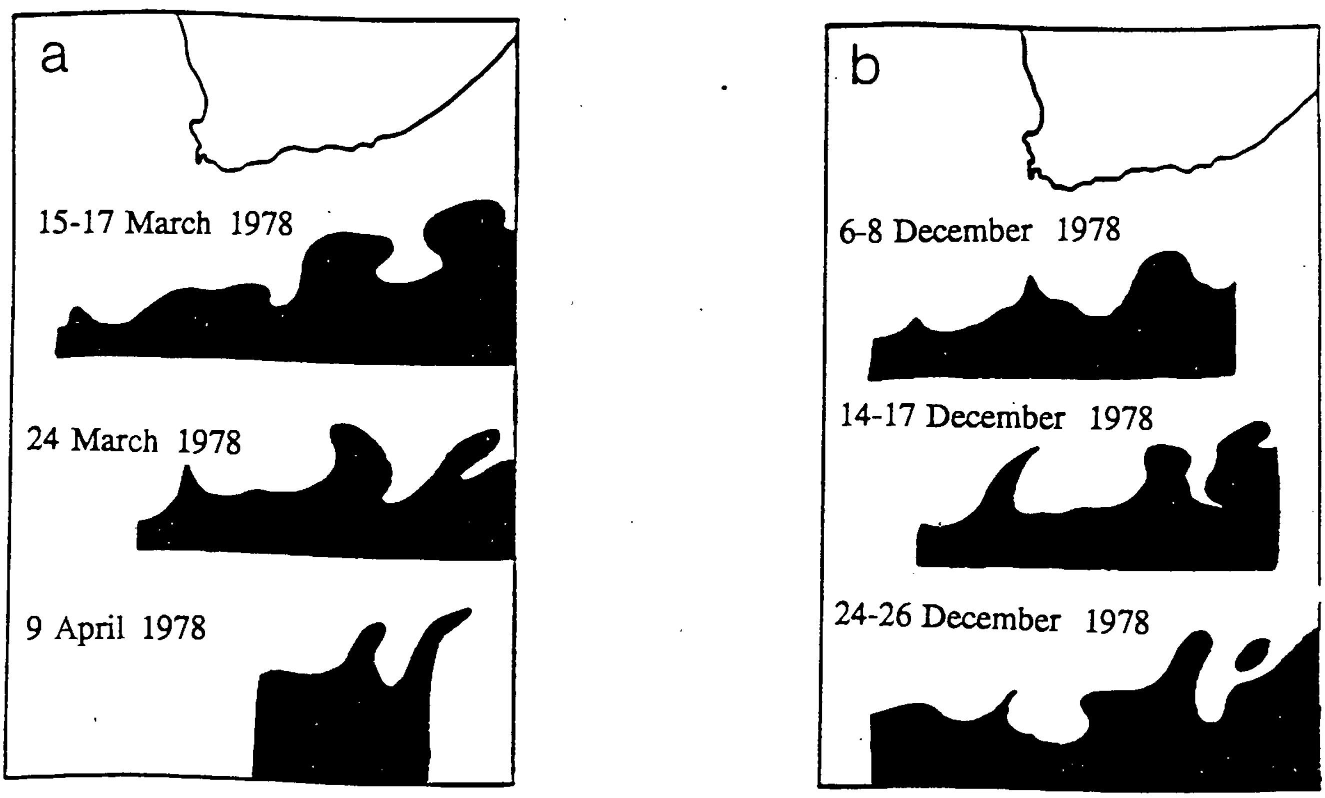

Figure 2.1 (a) An interpretive time series of images of the Subtropical Convergence south of South Africa. The data were derived from thermal infrared images from the Meteosat satellite. The manner in which the shape and dimensions of lateral features on this front change in time, may be observed. (b) A series of composite Meteosat satellite images in the thermal infrared. The behaviour of the Subtropical Convergence south of Africa is shown over a period of about three weeks. During this period the formation of what is assumed to be a cold water eddy occurred (Lutjeharms, 1981a).

Subtropical Convergence

Gordon (1967) has associated the discontinuity of the Subtropical Convergence with the region where the denser Sub-antarctic Surface Water subducts northwards beneath the Subtropical Surface Water to form the South Atlantic and the South Indian Ocean Central Water. Clifford (1983) has identified the Subtropical Convergence as the region where the 10° C to 12° C isotherms surface. Belkin (1992) has in turn identified the Subtropical Convergence in the Atlantic Ocean in a study of CTD and XBT sections and some underway continuous sea surface measurements in the Southern Ocean. According to Lutjeharms (1985a) the Subtropical Convergence exhibits the strongest horizontal thermal and saline gradients both at the surface and at depth of the major fronts in the African sector of the Southern Ocean. Table 2.1 shows the typical sea surface temperature ranges from north to south across the Subtropical Convergence. From this table the mean sea surface middle temperature of the Subtropical Convergence is $15,5^{\circ}$ C, with a standard deviation of $1,1^{\circ}$ C and the mean sea surface temperature range across the Subtropical Convergence is $8,8^{\circ}$ C, with a standard deviation of $3,9^{\circ}$ C. According to Orsi et al. (1995) the circumpolarity of the Subtropical Convergence is broken only by the South American continent at 56° S in the South East Pacific Ocean.

Source	Sea surface temperature range(°C)	Sea surface middle temperature (°C)
Lutjeharms(1985a)	17.9-10.6	14.3
Lutjeharms and Emery(1983)	22-10	16.8
Lutjeharms and Foldvik(1986)	22-10	16.0
Belkin and Romanov(1990)	17-13	15.0

Table 2.1 Typical sea surface temperature ranges and middle temperatures form north to south across the Subtropical Convergence in the African sector of the Southern Ocean.

According to Belkin (1992) the Subtropical Convergence is evident in the South West Atlantic Ocean as the Brazil Current Front (BCF). Belkin (1992) has traced the Subtropical Convergence across the Atlantic Ocean as the BCF, becoming the North Subtropical Front (NSTF) in the Central South Atlantic Ocean. In the Central South Atlantic Ocean the Subtropical Convergence zone reveals a deep and strong double frontal structure, being bordered to the north by the NSTF and to the south by the SSTF. The NSTF is traced across the South Indian Ocean as a shallower and weaker front than the South Atlantic NSTF due to cross-frontal mixing and strong air-sea interaction in the

Crozet-Kerguelen region (Belkin and Gordon, 1996). According to them the weakening of the NSTF in the South Indian Ocean region is due to the Subtropical Convergence zone being squeezed between the Agulhas Front and Sub-antarctic Front. This squeezing of the Subtropical Convergence probably occurs east of South Africa and west of 60°E, explaining the observation of a single Subtropical Convergence in this region (Belkin, 1989a). Belkin and Gordon (1996) have stated that this single Subtropical Convergence may also exist because the NSTF probably turns due north, joining the Benguela Current, while the SSTF slips south of the Agulhas Current Retroflection. Belkin (1989a) has used mainly quasi-synoptic hydrological data with a mesoscale resolution, and conducted a comparative study with published material to analyse the Subtropical Convergence. The double frontal structure of the Subtropical Convergence in the Central South Atlantic/South Indian Ocean has not been confirmed in later investigations. The dramatic changes in the morphology of the Subtropical Convergence in the region from the South East Atlantic to the South West Indian Ocean are also probably due to the influence of mesoscale features, in particular Agulhas eddies.

Lutjeharms and Valentine (1988b) have defined four distinct and nonoverlapping geographical groupings of eddies at the Subtropical Convergence south of Africa, namely: Agulhas Current Retroflection eddies that are warm and roughly 220 km in diameter, Agulhas Plateau eddies, some of which are large and warm, the others also small and cold, and Transkei Basin eddies that are cold. According to Lutjeharms and Valentine (1988b) the formation of these eddies may be related to the underlying bottom topography. Since none of these eddies have been found east of 21° E it has been assumed by Lutjeharms and Valentine (1988b) that the eddies move slowly but lose their distinctive surface characterstics rapidly and are reabsorbed by the Subtropical Convergence, complicating the Subtropical Convergence morphology south of Africa. According to Lutjeharms and van Ballegooyen (1988) these eddies may also "scavenge" warm surface water from the Agulhas Return Current without being reabsorbed across the Subtropical Convergence.

Lutjeharms and Walters (1985) have inferred that the mixing of the warm, Subtropical Surface Water southwards across the Sub-antarctic Surface Water may have a stabilizing effect on the water column. The transport of Sub-antarctic Surface Water northwards across the Subtropical Surface Water at the Subtropical Convergence may in turn have biologically enhancing effects since it transports nutrients from the well- mixed side of the frontal boundary, to the stratified subtropical zone. According to Khimitsa (1987) this hydrochemical and dynamic structure of the Subtropical Convergence has a considerable effect on the increased biological productivity at the Subtropical Convergence (Weeks and Shillington, 1996). According to Lutjeharms and Walters (1985) there is a general increase in the chlorophyll concentration from north to south across the Subtropical Convergence, coinciding with a chlorophyll peak. These increases in the surface chlorophyll concentrations correlate well with the increases in the surface potential primary production at the Subtropical Convergence (Allanson and Parker, 1983). This peak in surface chlorophyll values however, occurs between 40° S and 42° S whereas the Subtropical Convergence is located at 40° S according to the sea surface temperatures (Boden et al., 1988) (see figure 2.2). The chlorophyll peak therefore does not necessarily coincide exactly with the thermal front but does coincide with the surface salinity front.

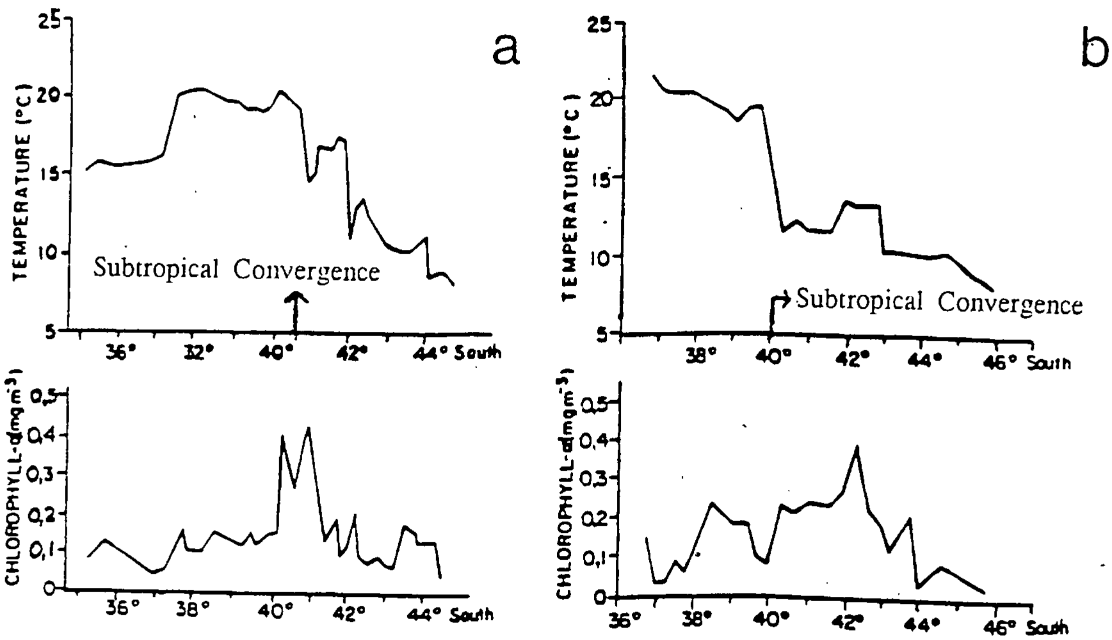

Figure 2.2 The relationship between the sea surface chlorophyll and the sea surface temperature from north to south across the Subtropical Convergence, on two separate occasions, namely a: 8 to 12 November 1983, and b: 18 to 21 November 1983 (after Boden et al., 1988).

Lutjeharms and Valentine (1984) have discovered that the sub-surface expression of the Subtropical Convergence lay 1° latitude north of the surface expression in 66 % of the cases they studied. Since the surface and sub-surface expressions of the Subtropical Convergence hardly ever coincide, the degree of thermal stability required to retain phytoplankton in the euphotic zone comes about, and this causes maxima in the surface distribution of chlorophyll at the Subtropical Convergence (Lutjeharms and Walters, 1985; Allanson et al., 1981).

In conclusion therefore, the Subtropical Convergence exhibits the strongest horizontal thermal gradients both at the surface and at the sub-surface of all the fronts in the African sector of the Southern Ocean., It has been proposed that the Subtropical Convergence reveals a deep and strong double frontal structure in the Central South Atlantic Ocean. This idea needs to be confirmed. Agulhas eddies complicate the morphology of the Subtropical Convergence in the region south of Africa. There is an increase in the chlorophyll concentration as one moves from north to south across the front, coinciding with a chlorophyll peak.

Sub-antarctic Front

Sievers and Emery (1978) have defined the Sub-antarctic Front as that front found at the most vertically orientated isotherm within the sub-surface temperature gradient between the 3° C and 5° C isotherms in the Southern Ocean. According to Lutjeharms and Foldvik (1986) the Sub-antarctic Front cannot be identified by the definition of Sievers and Emery (1978) below 500 m depth because the horizontal thermal contrast of the Sub-antarctic Front becomes eroded. Isotherms do, however, continue with increased vertical alignment from 7° C at 150 m to 2,5° C at 1000 m suggesting this front is present throughout the upper 1000 m of the water column (Lutjeharms and Foldvik, 1986). Table 2.2 shows the typical sea surface and sub-surface temperature ranges from north to south across the Sub-antarctic Front. Its mean sea surface middle temperature is 8,0° C with a standard deviation of 1,6° C, and its sub-surface middle temperature is 5° C.

Source	Sea surface temperature range(°C)	Sub-surface temperature range(°C)	Sea surface middle temperature (°C)	Sub-surface middle temperature (°C)
Lutjeharms and Emery(1983)	8-4	-	6	-
Lutjeharms and Foldvik(1986)	-	7-3	-	5
Lutjeharms and Valentine(1984)	11-3,5	-	7,3	-
Belkin and Romanov(1990)	13-6	-	9,5	-
Belkin(1989a)	12-6	-	9	-

Table 2.2 Typical sea surface and sub-surface temperature ranges and middle temperatures from north to south across the Sub-antarctic Front in the African sector of the Southern Ocean.

According to Lutjeharms and Foldvik (1986) the surface expression of the Sub-antarctic Front lies in general 220 km south of the sub-surface expression. In 50 % of the then available 89 crossings in the South East Atlantic and the South West Indian Oceans, statistically analysed by Lutjeharms and Valentine (1984), the surface expression of the Sub-antarctic Front however lay to the north of the sub-surface expression. Lutjeharms and Emery (1983) have also found that the surface expression of the Sub-antarctic Front lay to the north of the sub-surface expression.

The Sub-antarctic Front reveals a characteristic step-like structure north and south of the front proper (Lutjeharms and Valentine, 1984; Belkin and Romanov, 1990; Lutjeharms and Foldvik, 1986 and Belkin, 1989a) in the sea surface temperature gradient structure. This step structure in the sea surface temperature gradient structure indicates a slight temperature increase both north and south of the front and has been viewed by Allanson et al. (1981) and Belkin and Romanov (1990) as the effects of poleward eddy shedding. According to Lutjeharms and Emery (1983) the Sub-antarctic Front is further noticeable in the sub-surface temperature gradient structure across the Sub-antarctic Front by the inverted L-shape isotherm structure within the sub-surface temperature gradient between 3° C and 5° C.

Belkin and Romanov (1990) and Hofmann (1985) have found a good agreement between the sea surface temperature gradients across the Sub-antarctic Front and the currents at the Sub-antarctic Front. Wherever the sea surface temperature gradient increases towards the south, the current is directed southwestward.

Allanson et al. (1981) have shown that the Sub-antarctic Front can be associated with a sea surface chlorophyll maximum. Boden et al. (1988) have also observed a chlorophyll peak at the Sub-antarctic Front that coincided with the sea surface saline expression of the Sub-antarctic Front. Lutjeharms et al. (1986) have even observed increases in the biological activity at the Sub-antarctic Front.

Based upon Geosat altimetry data Gille (1994) has observed the Sub-antarctic Front gradually to narrow at the Drake Passage before moving northward through the Scotia Ridge and along the northern edge of the Ewing Bank and Falkland Ridge. Along the Falkland Ridge to about 30° W the Sub-antarctic Front appears to be closely controlled by bathymetry, but further east, past the Islas Orcadas Rise, its path becomes less well defined and substantial meandering occurs (Gille, 1994). According to Belkin (1992) the Sub-antarctic Front combines with the eastern branch of the Falkland (Malvinas) Current in the South Western Atlantic Ocean, bends around the Falkland Islands and forms a vast northward-elongated loop in the western Argentine Basin after which it continues zonally at 48° S along the Falkland Escarpment and Ridge. Belkin (1992) has inferred that near the Ewing Bank and Falkland Ridge the Sub-antarctic Front is not only strongly controlled by bottom topography but also flows closely parallel to the Antarctic Polar Front and occasionally merges with it.

In the Central and Eastern South Atlantic Ocean the Sub-antarctic Front lies to the south of Gough Island and then continues between the Discovery and Meteor banks (Belkin, 1992). In the South East Atlantic/South West Indian Ocean the Sub-antarctic Front is identified as a single separate front well south of the Agulhas Current Retroflection. In the South Indian Ocean between 40° E and 50° E the Sub-antarctic Front shifts abruptly northward (Gille, 1994). According to her a deep passage in the Crozet Plateau steers the Sub-antarctic Front from its southern position at 40° E to the north side of the Crozet Plateau. According to Belkin (1989a) the deviation of the Sub-antarctic Front between 40° E and 50° E occurs at the northern extremity of the high, steep African-Antarctic Ridge that runs from southwest to northeast, forcing the front northwards. Between 53° E and 55° E, the broad, shallow Crozet Plateau then steers the Sub-antarctic Front further northward. According to Belkin (1989b) the cause of the Sub-antarctic Front deviating to the north is the high, steep Atlantic-Indian Ridge that runs from southwest to northeast from 53° S to 55° S, followed by the shallow, broad Crozet Plateau. According to Belkin and Gordon (1996) the Sub-antarctic Front is pressed northward to 43° S from 45° S by the South West Indian Ocean Ridge, after which it converges with the Subtropical Convergence and forms the united STC/SAF north of the Crozet Plateau. This united STC/SAF has yet to be confirmed by later investigations.

The broadening of the temperature range of the Subtropical Convergence which occurs during this STC/SAF merger is less extensive than the broadening of the salinity range. This occurs because as the Sub-antarctic Front moves northward by roughly 4° latitude between 40° E to 50° E, the temperature of the Sub-antarctic Front automatically rises from (5° C - 9° C) to (9° C to 13° C), because of the average meridional temperature change of about 1° C/° latitude (Belkin, 1989a,b). Belkin (1989b) has done a systematic analysis of all the available regular hydrographic data from the Japanese Antarctic Research Expeditions from Mauritius and Australia to Antarctica. This data includes discrete temperature and salinity measurements in the upper ocean and CTD data to a depth of 2000 m.

According to Belkin and Gordon (1996) this united STC/SAF proceeds eastward and becomes a triple united front by confluencing with the Agulhas Front between 52° E and 65° E. This represents the AF/STF/SAF or "Crozet Front" (Belkin and Gordon, 1996). According to Holliday and Read (1996) this so-called "Crozet Front" where several fronts apparently merge is as a result of widely spaced sampling, and this feature can be resolved into individual fronts with continuous surface sampling. This conclusion of Holliday and Read (1996) is based upon a study of the surface locations of fronts in the Southern Ocean south and east of South Africa during the austral summers from 1993 to 1995. It is therefore uncertain whether there indeed exists a "Crozet Front" or not. A detailed study in this region of the Southern Ocean that simultaneously analysis both the surface and sub-surface thermal structure is therefore needed to resolve the nature of these fronts in this region.

In summary, the Sub-antarctic Front is generally defined as that front found at the most vertically orientated isotherm within the sub-surface temperature gradient between the 3° C and 5° C isotherms in the Southern Ocean. The surface and sub-surface thermal geographic position of this Sub-antarctic Front are inconsistent in that they lie north and south of each other. The Sub-antarctic Front morphology is affected by poleward eddy shedding from the Agulhas Current Retroflection south of Africa. A good agreement exists between the sea surface temperature gradients across the Sub-antarctic Front and the currents of the SAF. The Sub-antarctic Front is associated with a sea surface chlorophyll maximum. It has been suggested that the Sub-antarctic Front converges with the Subtropical Convergence north of the Crozet Plateau. The existence of this united STC/SAF needs to be confirmed. Uncertainty also exists about whether there is a

"Crozet Front" or not. This frontal morphology at 60° E needs to be researched.

Antarctic Polar Front

According to Botnikov (1963), and Rama Raju and Somayajulu (1983) the Antarctic Polar Front can be regarded as a convergent or divergent feature at the sea surface depending on the wind conditions. According to Clifford (1983) however the Antarctic Polar Front is coincident with the northern edge of the austral winter ice pack and seems to be related to the ice cover and not to a feature in the wind field. Gordon et al. (1982) have stated that the 0° isotherm is a reliable indicator of the location of the Antarctic Polar Front. Gordon (1967) has described the Antarctic Polar Front as that discontinuity which changes at about 50° S its sea surface temperature by more than 2° C in one half of a degree latitude. Gordon (1971) has been careful in using this drop in sea surface temperature as a definition, because in summer the surface water is warmed and the gradient is as a result destroyed. This temperature gradient is also eroded whenever a thin layer of Sub-antarctic Surface Water overrides the Antarctic Surface Water (Gordon, 1971). Table 2.3 shows the typical sea surface temperature ranges and sea surface middle temperatures from north to south across the Antarctic Polar Front south of Africa. The mean sea surface middle temperature of the Antarctic Polar Front is 4,0° C with a standard deviation of 0,8° C, and its mean sea surface temperature range is 2,9° C with a standard deviation of 1,7° C.

Source	Sea surface temperature range(°C)	Sea surface middle temperature (°C)
Lutjeharms and Emery(1983)	4,5-3	3,3
Lutjeharms(1985b)	6,8-3,3	5,1
Allanson et al.(1981)	5,0-3.4	4.2
Deacon(1945)	6-1	3,5

Table 2.3 Typical sea surface temperature ranges and middle temperatures from north to south across the Antarctic Polar Front.

According to Joyce and Patterson (1978) and Lutjeharms (1985a) the Antarctic Polar Front can be defined in the sub-surface as the northernmost limit of the 2° C isotherm which is part of the sub-surface temperature minimum. Clifford (1983) has subsequently defined the Antarctic Polar Front as the maximum gradient between the northern extent of the 2° C isotherm in the 200 m to 300 m depth layer and the northern limit of the temperature minimum layer. Deacon (1983) has shown that in a region like Kerguelen Island, with shallow soundings, currents and complex bottom topography, there is a variable transition between the Sub-antarctic and Antarctic Surface Water, disallowing the use of the conventional definition of the Antarctic Polar Front as the place where the 2° C temperature minimum intersects the 200 m isobath.

According to Belkin and Gordon (1996) the PF latitude is about 50° S or more everywhere in the Southern Ocean except near Kerguelen where the PF is deflected to the north by the Kerguelen Plateau, reaching north of Kerguelen. This sub-surface temperature minimum may however be broken up by water colder than 2° C (Lutjeharms and Emery, 1983). Joyce and Patterson (1978) have also noted this erosion of the minimum and its splitting up into multiple extrema of interleaving antarctic and sub-antarctic waters (figure 2.3). Gordon (1971) has observed this phenomenon in the South Pacific and defined the northernmost extent of the temperature minimum as the primary polar frontal zone (57°30'S to 58° S), and the southern extent of the temperature minimum as the secondary polar frontal zone (59°30'S to 63° S). This breaking up of the Antarctic Polar Front into a primary and secondary polar front however remains unquantified. This double frontal structure may be caused by an isolated storm system that passes and interupts the mean wind field (Gordon, 1971). This may cause a zone of warmer water to result from the ensuing upwelling and thus generate two polar frontal zones (Gordon, 1967, 1971). The temperature minimum that occurs at sub-surface is believed by Clifford (1983) to be a remnant of the winter water related to the austral winter ice pack. The causal mechanism of the breaking up of the Antarctic Polar Front into a primary and secondary Antarctic Polar Front is therefore unclear.

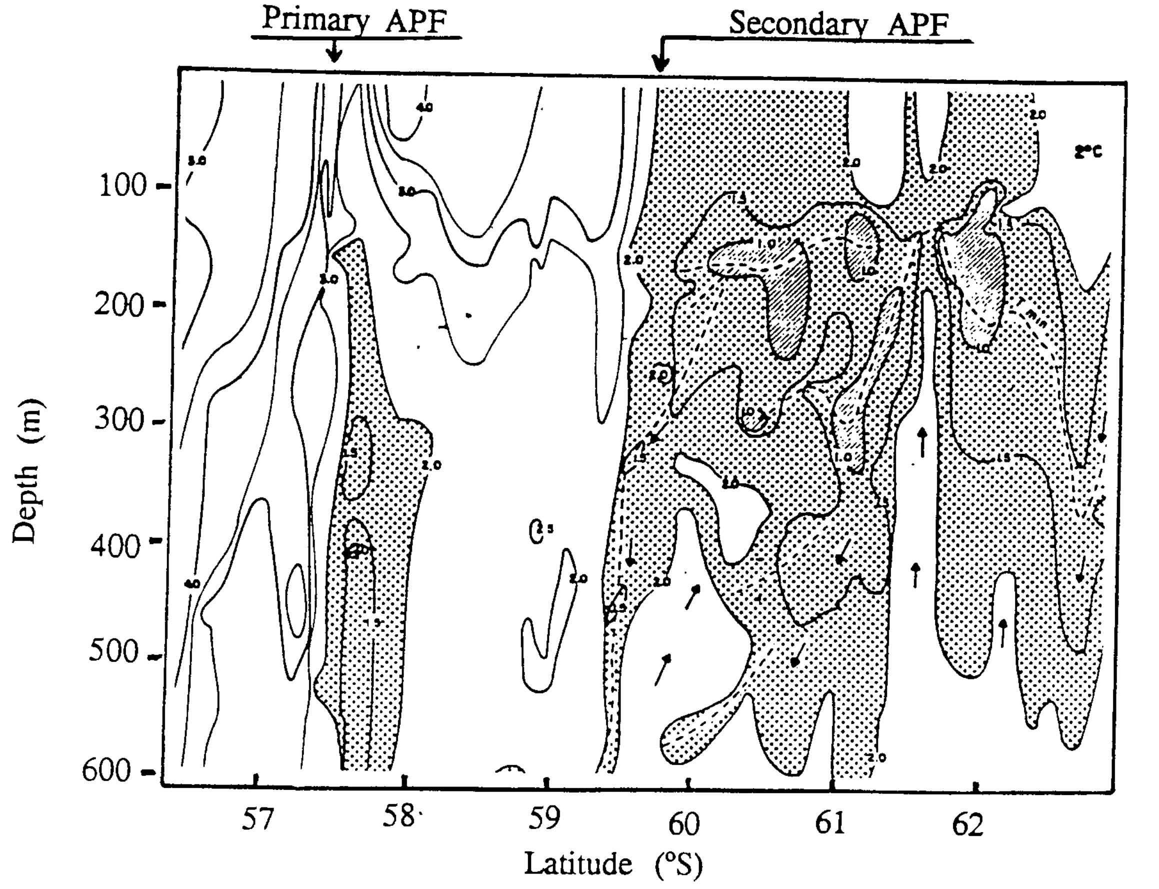

Figure 2.3 A meridional temperature section across the Antarctic Polar Front showing the primary and secondary Antarctic Polar Front (after Gordon, 1971).

According to Deacon (1982) the sub-surface expression of the Antarctic Polar Front is more stable than the surface discontinuity. According to Lutjeharms and Valentine (1984) the surface expression of the Antarctic Polar Front may also be less distinct than the sub-surface expression. The Antarctic Polar Front has even been noticed with its sub-surface expression 380 km north of the surface expression (Lutjeharms and Foldvik, 1986). The latitudinal locations of the surface and sub-surface expressions of the Antarctic Polar Front are therefore inconsistent, with the surface expression sometimes lying to the north and sometimes to the south of the sub-surface expression (Lutjeharms, 1985a; Lutjeharms and Emery, 1983). Lutjeharms and Valentine (1984) have seen this phenomenon in about 75 % of their case studies. The southward shift in the geographic position of the sea surface thermal expression of the Antarctic Polar Front during summer explains why the surface expression of the front has been observed more to the south than to the north of the sub-surface expression by Lutjeharms and McQuaid (1986), since their studies have been conducted mainly in summer.

According to Deacon (1945) an examination of the *Discovery* collections have revealed that the Antarctic Polar Front is a biological boundary separating plant and animal species that are typical of either the antarctic or sub-antarctic zone. Sea surface chlorophyll readings also exhibit peaks at the surface expression of the Antarctic Polar Front which are occasionally ten times that of the surrounding Antarctic Surface Water (Lutjeharms et al., 1986). Where the Antarctic Surface Water sinks below the Sub-antarctic Surface Water at the Antarctic Polar Front, the iodate concentrations which are high to the south of 56° S are low to the north (Chapman, 1983).

Gouretski and Danilov (1994) have discovered that warm rings at the Antarctic Polar Front are shed from the meandering Antarctic Circumpolar Front in the African sector and develop over the deep abyssal plain immediately behind the Mid-Ocean Ridge. This result of Gouretski and Danilov (1994) has been founded upon a good agreement between their modelled Antarctic Circumpolar Front which exhibited pronounced meanders over the abyssal plain and drifting buoy data. They believe that such rings are responsible for the net southward heat and salt transport and the high variability extending from a maximum at the Antarctic Polar Front southward to 65° S.

The Antarctic Polar Front has a zonal orientation in the west (Belkin, 1992). At 30° W in the vicinity of the Ewing Bank and the Falkland Ridge, the Antarctic Polar Front virtually merges with the Sub-antarctic Front to form a united front (Belkin, 1992). In the Indian Ocean the Antarctic Polar Front bends southward along 30° E due to the influence of the South West Indian Ocean Ridge (Belkin and Gordon, 1996). East of 40° E the temperature characteristics of the Antarctic Polar Front gradually increases not withstanding its constant latitude (Belkin, 1988). This warming is due to the "protection" of the Antarctic Polar Front by the Ob-Lena Rise which prevents the northward penetration of the cold antarctic waters (Belkin, 1988). The temperature of the Antarctic Polar Front increases from (2,5° C - 4,3° C) to (4,1° C to 5,7° C) (Belkin, 1989a,b). Belkin (1988) has used data for a systematic study of the fronts of the Antarctic Circumpolar Front southeast of Africa and southwest of Australia. These data consist of the JARE (Japanese Antarctic Research Expedition) observations accumulated from 1965. The JARE data consists of CTD data to 2000 m, XBT data from 250 m to 1750 m depth, and continuous and periodic measurements of temperature in the upper 8 m.

The Antarctic Polar Front continues between the Crozet Plateau and the Ob-Lena (Conrad) Rise, 49° S to 50° S, passes north of Kerguelen and nearly joins the "Crozet Front", according to Belkin and Gordon (1996). Belkin and Gordon (1996) have in fact observed that this Antarctic Polar Front proceeds so close to the triple front that it forms a quadruple front with the Agulhas Front, Subtropical Convergence and Sub-antarctic Front. This quadruple front notion in the vicinity of the Kerguelen Plateau remains to be confirmed by other investigations.

The Antarctic Polar Front then deflects northward of the Kerguelen Plateau (Belkin and Gordon, 1996). This northward deflection may be as a result of the conservation of potential vorticity that causes an equatorward deviation to the flow over shallowing depths (Belkin and Gordon, 1996). According to Belkin (1989a) the most probable Antarctic Polar Front position is immediately south of the island at 50° S to 52° S. Belkin (1989a) has therefore hypothesised that this occasional northern position of the Antarctic Polar Front is the result of an oceanic anticyclone which forces antarctic water to round Kerguelen from the east and to penetrate northward up to 46° S to 48° S. According to Belkin (1989a) this occasional northerly position of the Antarctic Polar Front can also be as a result of a seasonal shift, i.e. shifts north in winter and south in summer. Belkin (1989a) has discounted any notion of the Antarctic Polar Front bifurcating into northern and southern branches around Kerguelen.

According to Sparrow et al. (1996) the Antarctic Polar Front does indeed bifurcate in the region of the Ob-Lena Rise, during which time the geographic positions of the surface and sub-surface thermal expressions of the Antarctic Polar Front become separated by as much as 8° latitude immediately west of the Kerguelen Plateau. The "APF (sub-surface)" passes north of Kerguelen Island and is identified by Sparrow et al. (1996) as being the northern limit of the 2° C isotherm below 200 m. The "APF (surface)" swings to the south, passing through the Kerguelen Plateau. These results of Sparrow et al. (1996) are based on results from the Fine Resolution Antarctic Model (FRAM). The surface and sub-surface thermal expression of the Antarctic Polar Front merge east of Kerguelen Island according to this model (Sparrow et al., 1996). There is clearly therefore a need to determine the nature of the Antarctic Polar Front in the vicinity of Kerguelen ie. does the Antarctic Polar Front bifurcate into a northern and southern branch around Kerguelen?

To summarise what is known at present: the Antarctic Polar Front is best defined in the sub-surface as the northernmost limit of the 2° C isotherm which is part of the sub-surface temperature minimum. This temperature minimum layer is warmer in the Kerguelen-Amsterdam region because it warms up from 2° C to 2,5° C since its northernmost latitude changes from 47° S to 46° S. This sub-surface temperature minimum can be broken up by water colder than 2° C, subsequently forming a primary and secondary Antarctic Polar Front. The breaking up of the Antarctic Polar Front into a primary and secondary Antarctic Polar Front needs to be quantified. The latitudinal locations of the surface and sub-surface expressions of the Antarctic Polar Front are inconsistent, with the surface expression sometimes to the north and sometimes to the south of the sub-surface expression. Sea surface chlorophyll readings exhibit peaks at the surface expression of the Antarctic Polar Front occasionally ten times that of surrounding Antarctic Surface Water. Eddies shed from the Antarctic Circumpolar Current contribute to the high variability at the Antarctic Polar Front. The idea that the APF joins the "Crozet Front" in the vicinity of the Kerguelen Plateau remains unconfirmed. The nature of the Antarctic Polar Front at Kerguelen, especially its bifurcation into a northern and southern branch around Kerguelen is unconfirmed.

Weddell-Scotia Confluence

The Scotia Front (Scotia Sea Divergence) and the Weddell Front (Weddell Sea Divergence) form the northern and southern limits of the Weddell-Scotia Confluence (Gordon, 1967 and Belkin, 1993). The Weddell-Scotia Front is therefore the boundary region between cold water flowing from the Weddell Sea and the warmer water reaching the Scotia Sea through the Drake Passage (Deacon, 1982). The Scotia Front is identified as the southern border of the Weddell-Scotia Confluence, which is identified as a maximum thermal gradient between the 2° and 6° isotherms in the deep temperature maximum core layer of the Circumpolar Deep Water (CDW) between 200 m to 700 m (Belkin, 1996). According to Belkin (1996) the 1° isotherm in the 300 m to 500 m layer is a good indicator of the location of the Scotia Front.

The Scotia Front lies north of the South Shetland Islands in the west (Belkin, 1994). It then flows along the Scotia Arc and then east of the South Orkney Islands (Belkin, 1996). According to Deacon (1982) and Clifford (1983) the Weddell-Scotia Confluence loops to the northwest off the northeast coast of South Georgia before continuing eastward across the Atlantic Ocean. The Scotia Front is then deflected northward and after bending around the South Sandwich Islands it travels east-north-east along the South West Indian Ocean Ridge up to 15° E to 20° E. Where the ridge turns northward the Scotia Front turns southward and south of Bouvet Island (Belkin, 1996). The Weddell-Scotia Confluence is not observed downstream of the South Sandwich Island Arc (Clifford, 1983).

The nature, structure and characteristics of the Weddell-Scotia Confluence in this region of the Southern Ocean needs to be studied so as to compare it to these earlier investigations.

Antarctic Divergence

Ostapoff (1962) has simply defined the Antarctic Divergence as a region of broad upwelling. Grigor'ev and Kornilov (1974) have defined the Antarctic Divergence as that zone between 66° S to 67° S in which there is a maximum rise of warm deep waters that break the layer of water colder than -1° C. Grigor'ev and Kornilov (1974) have used data collected on board four cruises between Africa and Antarctica during the summer seasons of 1968 and 1969 to derive this result. The data consisted of surface measurements and two deep-sea observations at a section along 20° E. According to Deacon (1983) and Lutjeharms and Foldvik (1986) the region where the cold surface waters with temperatures of less than -1° C are broken by warmer waters occurs at 65° S. Lutjeharms (1985a) and Lutjeharms and McQuaid (1986) have considered this weakening of the sub-surface temperature minimum at about 65° S to be a result of the upwelling of warmer, deeper water.

Lutjeharms (1985a) has used XBT data in the African sector of the Southern Ocean gathered between 1978 and 1981 to obtain this definition. This data set consists of twenty four sections with a station spacing of less than 50 km. Lutjeharms and Foldvik (1986) have pinpointed the Antarctic Divergence to within 50 km of 65° S. Deacon (1982) has located the Antarctic Divergence at 68° S to 69° S in the Weddell Sea, 62° S to 63° S where the Antarctic continent extends far north in the Indian Ocean and at 70° S to 71° S north of the Ross Sea. These locations coincide not only with the average boundary between the westerly and easterly winds, but also with the upwelling of warmer deeper water (Deacon, 1982). According to Gordon et al. (1982) however, this is not the Antarctic Divergence but rather the edge of the recirculating Weddell Sea Water. It therefore still remains uncertain whether this region separating the warmer deeper water from the colder surrounding waters is the Antarctic Divergence or the edge of the recirculating Weddell Gyre.

Allanson et al. (1981) have shown that this front coincides with an area of silicate values higher than the surrounding waters. Since deep water has a higher silicate content than surface water, the higher than usual silicate values at the sea surface at the Antarctic Divergence therefore indicates the advection of silicate to the surface by strong upwelling (Ostapoff, 1962).

It therefore still needs to be unambiguously determined if there is an Antarctic Divergence or not.

Continental Water Boundary

The term Continental Water Boundary was first used to delineate the northern boundary of waters found at the southern extent of the Antarctic Circumpolar Current and not as a name for a deep-reaching frontal feature to the north of this boundary (Orsi et al., 1995). It is now accepted that the term Continental Water Boundary refers exclusively to a frontal feature in the Antarctic Circumpolar Current (Sievers and Emery, 1978). Although this southernmost of Antarctic Circumpolar Current fronts and the poleward edge of Upper Circumpolar Deep Water (UCDW) are therefore often located adjacent to one another in the Drake Passage, they are distinct features since the one is a deep-reaching current core and the other is a water mass boundary (Orsi, 1995). Nowlin and Clifford (1982) have associated this front with the base of the continental rise. Coarse sampling has prevented any previous delineation of these features and influenced the assignment of the name Continental Water Boundary to both the current core and the water mass boundary (Orsi et al., 1995). According to Clifford (1983) the Continental Water Boundary has not been observed in the austral winter season and so if it exists it is covered by the winter ice pack (Clifford, 1983).

At 30° W the South Scotia Arc deflects this front to the northwest (Orsi, 1995). The Kerguelen Plateau between 70° E to 80° E forces this front farther south (Orsi, 1995). The data used by Orsi (1995) consisted of all the available, historical and hydrographic data collected up to 1990 in the Southern Ocean.

The nature, structure and characteristics of the Continental Water Boundary in this region of the Southern Ocean therefore needs to be examined so as to compare it to these earlier investigations.

Antarctic Slope Front

Ainley and Jacobs (1981) have defined the Antarctic Slope Front as that region where there is an increase in the horizontal gradients of water temperature, salinity, density, chemistry, colour and transparency, in the vicinity of the shelf break of the Antarctic continent. The position of this front is further marked in the hydrochemical transects by the dipping down of these isolines through the water column toward the coast (Phillips, 1994). This front also shoals and flattens towards the north beneath the thick and deep temperature minimum layer (Jacobs, 1991). The Antarctic Slope Front has sometimes been defined by the 0^{o} C isotherm which lies 10 km to 55 km seaward of the continental shelf break (Ainley and Jacobs, 1981). The position of the Antarctic Slope Front coincides with the sharp dipping of this 0^{o} C isotherm (Phillips, 1994).

According to Phillips (1994) the near-surface layers at the Antarctic Slope Front are derived from the warmer, Deep Water which has upwelled. The reduced ice concentrations found at the Antarctic Slope Front indicate the upwelling of this warm, Deep Water. Interleaving observed at locations along this front show that diffusion and salt-fingering enhance the mixing across the Antarctic Slope Front (Foster and Carmack, 1976). Comparing the definition of the Continental Water Boundary and the Antarctic Slope Front makes it evident that it is uncertain whether these are two separate fronts or the same front, since they both have their surface layer derived from warmer, Deep Water that has upwelled and both occur roughly at the continental rise.

There is growing evidence that the Antarctic Slope Front coincides with a region of higher primary production (Ainley and Jacobs, 1981; Allanson et al., 1981 and Phillips, 1994). It remains unclear to what extent the physical dynamics of the Antarctic Slope Front contribute to the biological production here and what part the marginal ice edge zone has been responsible for the observed peaks in production at the Antarctic Slope Front (Phillips, 1994).

Where the continental shelf is wide there is a split in the Antarctic Coastal Current, the current component of the Antarctic Slope Front, and the Antarctic Slope Front appears as a V-shaped double front which branches along the shelf break and the coastline (Jacobs, 1991 and Foster and Carmack, 1976). Where the continental shelf is narrow only the northern part of this V-shaped structure is visible (Jacobs, 1991).

It is therefore necessary to determine whether the Continental Water Boundary is a separate and independent front from the Antarctic Slope Front or if the Continental Water Boundary and Antarctic Slope Front are one and the same front.

Knowledge of the individual fronts vary considerably. This is largely dependent on data distribution, and the quality of the data. A number of key gaps in our knowledge can be identified; gaps that may suggest appropriate research objectives for this study.

CHAPTER 3

RESEARCH OBJECTIVES

From the review of Southern Ocean fronts in chapter 2 it is evident that the Southern Ocean south of Africa ("African sector of the Southern Ocean") includes complicated frontal systems. The fronts metamorphosise strongly between the Atlantic Ocean sector and Indian Ocean sector under the strong influence of the sub-antarctic islands, bottom topographic features, oceanic currents, water mass circulations, mesoscale phenomenon, winds and even rainfall.

A large variety of dedicated investigations have been conducted in order better to understand the hydrography of these fronts and their affects on climate. From the results of these investigations and in particular the dedicated work done by Belkin (1988, 1989 a, b, 1992), Belkin and Romanov (1990), Belkin and Gordon (1996), Holliday and Read (1996), Gille (1994) and Clifford (1983) it is clear that a number of gaps in our knowledge still persist.

The quality data used by earlier investigators although high, contains mainly surface data. Where good quality sub-surface data were available they were sparse and often unable to resolve the thermal frontal morphology. Where detailed, quality, sub-surface data were available, containing closely spaced stations, the data were seldom in the African sector of the Southern Ocean. Where these types of quality data were available, they have not been compared with other similar data in the vicinity in order to examine any spatial and temporal variations in the nature of these Southern Ocean fronts.

The present study therefore consisted of the assembly and collation of all the available, quality, closely-spaced, sub-surface temperature data into a homogenous dataset, extending over fifteen years. The majority of the cruises used were South African, from South Africa to and from Antarctica. The rest of the forty-three cruises used here are American, German, British and Japanese. "R" has been used in this study to denote the return legs of cruises. Some of these data were obtained from the SADCO (South African Data Center for Oceanography). This dataset extends across the entire African sector of the Southern Ocean, from 40° W to 70° E and from Africa to Antarctica, covering an area of $3,65 \times 10^7$ km^2 (see figure 3.1).

In chapter 4 the data used in this investigation and the research methodologies employed to address the objectives of this study are discussed in detail. The research objectives of this study are the following:

The exact longitudinal geographic range of the sea surface and sub-surface thermal expression of the Agulhas Front is uncertain. The Agulhas Front therefore needs to be studied in detail in order to **determine the exact longitudinal geographic extent of the sea surface and sub-surface thermal expression of the Agulhas Front.**

Eddies and rings spawned at the terminal region of the Agulhas Current (Lutjeharms and Valentine, 1988a) contribute to the variable frontal zone morphology of the Agulhas Front (Lutjeharms, 1981a). This instability causes a strong interaction between the AF and STC. **How often the AF and the STC come together needs to be established.**

According to Belkin (1993) the Subtropical Convergence reveals a deep and strong double frontal structure, being bordered to the north by the NSTF and to the south by the SSTF. **This double frontal structure of the Subtropical Convergence in the Central South Atlantic Ocean needs to be investigated with greater thermal precision.**

Belkin and Gordon (1996) have stated that the South West Indian Ocean Ridge presses the Sub-antarctic Front northward from 45° S to 43° S, causing it to converge with the Subtropical Convergence and to form the United STC/SAF north of the Crozet Plateau. **This proposed convergence between the Subtropical Convergence and Sub-antarctic Front to form the united STC/SAF has to be examined with appropriate data.**

According to Belkin (1989b) this united STC/SAF proceeds eastward and becomes a triple united front or ("Crozet Front") (Belkin and Gordon, 1996), by confluencing with the Agulhas Front. Holliday and Read (1996), however, have considered that this idea of a "Crozet Front" is the result of widely spaced sampling. **It therefore needs to be determined whether there exists a "Crozet Front" at about 65° E, or not.**

According to Lutjeharms and Emery (1983) the northernmost limit of the 2° C isotherm which is part of the sub-surface temperature minimum and defines the Antarctic Polar Front at sub-surface (Joyce and Patterson, 1978), may occasionally be broken up by water colder than 2° C. This results in the Antarctic Polar Front splitting up into a primary and secondary polar front (Gordon, 1971). **This splitting up of the Antarctic Polar Front needs to be quantified.**

The Antarctic Polar Front nearly joins the "Crozet Front" north of Kerguelen (Belkin and Gordon, 1996). The Antarctic Polar Front in fact proceeds so close to the triple front that it forms a quadruple front with the Agulhas Front, Subtropical Convergence and Sub-antarctic Front. **The idea that the Antarctic Polar Front joins the "Crozet Front" north of Kerguelen to form a quadruple front therefore needs to be studied.**

The thermal nature, structure and characteristics of all the main fronts in this region of the Southern Ocean also need to be described in greater detail and the results compared to earlier investigations.

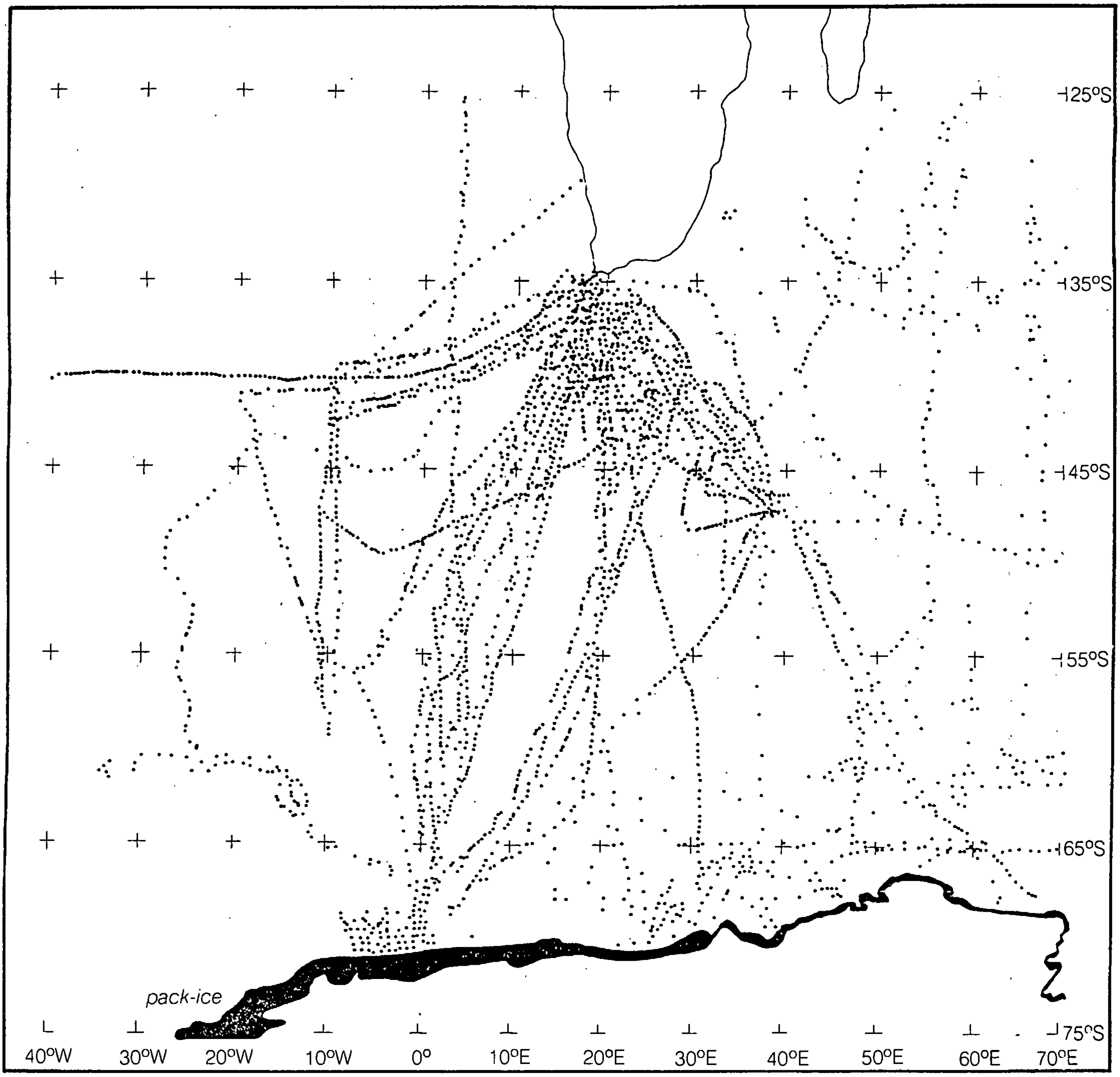

Figure 3.1 Cruise tracks of all forty-three cruises used during this investigation.

CHAPTER 4

DATA AND METHODS

If the clearest description of thermal nature of the oceanic fronts in the African sector of the Southern Ocean is to be presented and if the identified gaps in current knowledge are to be addressed appropriately, the data and methodology are important.

Data and Instrumentation

All the available published and unpublished high-quality, vertically continuous, sub-surface temperature data taken at closely spaced, logged stations during cruises in the Southern Ocean between Africa and Antarctica and between 40° W and 70° E have been assembled and collated to form a single homogenous data set.

Sub-surface data refers to measurements taken between 150 m and 500 m depth and not at any specific depth. The depths also vary depending on the criteria used to define a specific front eg. The most vertically orientated isotherm between the 3° C and 5° C isotherms within a horizontal sub-surface temperature gradient, denotes the Sub-antarctic Front, and clearly this point's depth can and does vary. Furthermore, before the assembly and collation of the data into a single homogenous data set, the data sometimes extended to 1000 m depth, it was then clear that the upper 500 m of the water column was representative of what was happening lower down the water column. Since most of the data went to 500 m depth, this was chosen as the reference level. The sub-surface front therefore represents the geostrophic transport, and the surface front is just this front's displacement along the mixed layer.

These sub-surface thermal data are recorded as a separate temperature profile per station. Much thermal detail of each temperature profile is lost when portraying the temperature traces as temperature sections, but it nonetheless affords one the opportunity of studying the thermal structure of the upper oceanic layers in the Southern Ocean south of Africa with detail and precision not possible before. These temperature sections have been plotted from north to south for continuity, labelled with important station numbers, latitudes and longitudes, and the identified oceanic fronts. Additional measurements of continuous sea surface temperature and continuous sea surface salinity, and bottom topography are included with the respective cruise temperature sections where available and presented in the Addendum.

Temperature data

A variety of instruments were employed to measure the sea surface temperatures and temperatures of the water column, inter alia: canvas bucket, thermograph, Crawford bucket (Crawford, 1972), surface bottle samples, a variety of bathythermographs and CTD probes.

Ideally the devices had to be released less than forty-five kilometres apart, especially at the fronts, in order to resolve spatially its thermal structure. Since one is in many cases now unable to establish the accuracy with which these measurements were made and in some cases even the instruments used to carry out these measurements, one has to make realistic assumptions. For most observational projects run from South Africa the sea surface temperature readings were also taken using a Crawford Bucket (Crawford, 1972) and the bathythermograph trace adjusted if its surface reading differed by more than 0,5° C from the average of two Crawford readings, to ensure precision. The trace was also adjusted for depth where required and individual XBT traces checked according to the criteria set out by Kroner and Blumenthal (1977) and those that showed spikes or radio interference ignored. I assume that similar quality controls were also carried out for the other data sets used.

Mesoscale features complicate the structure of surface waters, especially in the vicinity of the Subtropical Convergence and therefore make the identification of fronts almost impossible. One therefore needs to analyse sub-surface data to get a clear picture of what is going on. Experience has however shown that the surface and sub-surface thernal signatures of fronts correspond closely to one another.

Salinity data

The temperature manifestation of the Subtropical Convergence is often smeared and indistinct whereas its cross-frontal salinity gradient is substantial, making it pronounced in the salinity field. Salinity is therefore a good indicator of the Subtropical Convergence and other regions where the temperature signature is eroded. Unfortunately, detailed salinity data comparable to the temperature data used in this study was unavailable and temperature therefore remains the main data of this study.

Research methodology

The correct identification of the Southern Ocean frontal systems from the temperature sections is crucial. First one needs to define an oceanic front in general. An oceanic climatic front is large-scale, quasi-stationary, relatively narrow zone of enhanced horizontal gradients of ocean properties that separates broader zones of different thermohaline stratification (Belkin and Gordon, 1996).

In order therefore to locate these Southern Ocean fronts in temperature sections one has to identify the maximum thermohaline stratification change along cross-frontal sections by determining the zones of enhanced horizontal thermal gradients. To do this the following oceanographic research technique (Thermohaline stratification technique), adapted from Belkin and Gordon (1996) has been used, ie. The data from hydrographic stations that are as close to the northern and southern boundaries of the fronts are chosen so that the data is as representative of the front as possible, and not of the surrounding water to the north and south of the front. The use of this technique when studying fronts allows for very accurate information on these zones which separate different thermohaline stratified zones. In order to calculate the ts-gradients and widths of the fronts the distances between the boundary stations need to be calculated. The distances have been determined by calculating the great circle distances (gcd) between the hydrographic stations.

The great circle distances (gcd) between the hydrographic stations was calculated according to the formula:

$$\boxed{gcd = R.\arctan\sqrt{\left(\frac{1}{\alpha^2}\right) - 1}}$$

where α = cos(lat1).cos(lat2).cos(lon1-lon2) + sin(lat1).sin(lat2) and R is the radius of the earth and the latitudes and longitudes are given in radians.

Although the width of the front will vary depending on the angle the section crosses the front, the widths are very meaningful since the widths are relative to the positions of the boundary stations used to calculate the distances. The widths are therefore a function of the latitudes and longitudes of the respective boundary stations. This should be remembered when interpreting the widths.

The following criteria have been used in conjunction with the thermohaline stratification technique. These definitions are best suited for when analysing temperature data, other defintions may well be better when analysing salinity data.

The Cape Upwelling Front is defined as the front that exists between 14° E and 20° E, 15° S and 35° S, and exhibits a radical seaward sea surface temperature increase.

The Agulhas Front is defined as that front that lies at the southern edge of the Agulhas Return Current when it is not contiguous with the Subtropical Convergence.

The Subtropical Convergence is defined as the region where the enhanced horizontal sea surface temperature gradient has a middle temperature of about 15,5° C at approximately 40° S latitude, accompanied by these sea surface isotherms dipping northward.

The Sub-antarctic Front is defined as the front that is situated at the most vertically orientated isotherm within a sub-surface temperature gradient between the 3° C and 5° C isotherms.

The Antarctic Polar Front is defined as the front that is located at the northernmost limit of the 2° C isotherm which is part of the sub-surface temperature minimum. At the northern flank of the Kerguelen Plateau the Antarctic Polar Front is defined as the front that is located at the northernmost of the 2,5° C isotherm which is part of the sub-surface temperature minimum. Where an isolated cold water cell of 2° C water is found north of the northernmost limit of the unbroken plume of 2° C isotherm water that is part of the sub-surface temperature minimum, the cold water cell is regarded as the primary

Antarctic Polar Front, and the northernmost limit of the 2° C isotherm water that is part of the sub-surface temperature minimum is regarded as the secondary Antarctic Polar Front.

The Weddell-Scotia Confluence is defined as the front that occurs at the position of the 0° C isotherm in the 300 m to 500 m depth layer. Since the Scotia Front forms the northern boundary of the Weddell-Scotia Confluence, identification of the Scotia Front indicates the northern extreme of the Weddell-Scotia Front.

The Antarctic Divergence is defined as the front that occurs at the maximum rise of warm deep waters which breaks the cold water sub-surface layer (-1 ° C) at approximately 65° S.

The Continental Water Boundary is located at the southern boundary of the warm deep water, revealing a distinct temperature gradient as it shoals towards 500 m depth near the Antarctic continent.

The Antarctic Slope Front is identified by the shoaling and flattening of the isotherms north of the shelf break below the thick and deep temperature minimum. Where the 0° C isotherm is present it is used to identify the position of the Antarctic Slope Front. The sharp dipping of this 0° C isotherm southwards coincides with the position of the Antarctic Slope Front.

CHAPTER 5

RESULTS AND DISCUSSION

Agulhas Front

The Agulhas Front has been defined as the front that lies at the southern edge of the Agulhas Return Current when it is not contiguous with the Subtropical Convergence (see figure 5.1). According to Ansorge (1996) the Agulhas Front can only exist between the Agulhas Current Retroflection and 70° E since the Sub-antarctic Surface Water "caps" the surface water of the Agulhas Return Current from 66° E to 70° E, making the identification of the Agulhas Front east of 70° E impossible. Also, the northward leakage and branching of warm, salty water out of the Agulhas Return Current causes the Agulhas Return Current to diminish to such an extent that the Agulhas Front identification is impossible beyond 70° E (Ansorge, 1996). The geographic location of the thermal expression of the Agulhas Front determined by Ansorge(1996) should therefore relate to the results of this study, since in both cases the Agulhas Return Current determines the geographic longitudinal range of the Agulhas Front.

The Agulhas Front is traced from 18,2° E to 24,7° E in its sea surface temperature profile and from 18,2° E to 24,7° E in its sub-surface temperature profile (see table 5.1). These results compare well with the longitudinal range of the Agulhas Front determined by Lutjeharms and Valentine (1984) except for their most westward observation of the Agulhas Front. Their 13,5° E longitude is an extreme westward observation of the Agulhas Front, typical westward longitudes are in the vicinity of 18° E, agreeing with the results of this study. This anomalous situation could possibly have resulted due to the occlusion of an Agulhas Ring at the Agulhas Current Retroflection and its subsequent westward migration into the South Atlantic Ocean. This westward moving Agulhas Ring could therefore have been misinterpreted as the Agulhas Current Retroflection, and therefore the most westward longitude of the Agulhas Front. The eastward geographic position of the thermal expression of the Agulhas Front determined by Holliday and Read (1996), namely 56° E, Belkin and Gordon (1996), namely the Australian sector of the Southern Ocean, and Ansorge (1996), namely 66° E and 70° E do not however compare well with these results. In the case of Holliday and Read (1996) and Belkin and Gordon (1996) these different results can be attributed to the different criteria used to identify the Agulhas Front. In the case of Ansorge (1996) however sparse data in the Central South Indian Ocean in this study is probably the reason for the Agulhas Front not being observed at 60° E to 70° E.

Although Belkin and Gordon (1996) have noticed a strong interaction between the Agulhas Front and Subtropical Convergence, in 56% of the sections investigated during this study the Agulhas Front was found to be an independent and separate front north of the Subtropical Convergence. The Agulhas Front and Subtropical Convergence show an overlap at 16° E and 23° E. The average width of the Agulhas Front at the sea surface is 84 km, but the width varies considerably, with a standard deviation of 53 km (see table 5.1). Its average sub-surface width is 37 km, but the width varies considerably, with a standard deviation of 33 km (see table 5.1). This high variability in the width of the Agulhas Front both at surface and sub-surface indicates the severe instability experienced by frontal zones in this region of the Southern Ocean as a result of mesoscale turbulence (Lutjeharms, 1981a).

The detailed geographic locations, widths, middle temperatures, thermal gradients, thermal ranges, and their standard deviations and means, have been determined for the thermal surface and sub-surface expression of the Agulhas Front and have been presented in table 5.1 and 5.2.

The fact that many of the sections analysed in this study were not exactly perpendicular to the Agulhas Front has resulted in the calculated widths of this study being greater than previous studies. All sub-surface measurements in this study have not been taken at any specified reference depth as in other studies, but rather between 150 m and 500 m depth. This has resulted in characteristics (gradients, widths, ranges, positions) being obtained at sub-surface during this study, for the Agulhas Front, being different from other studies. Only two cruises, namely the Ajax Cruise along 1° E latitude and another SADCO Cruise, have been studied in the South Atlantic/Indian Ocean. This lack of data has not allowed for the determination of the Agulhas Front where it has been found by others, namely : Holliday and Read (1996), namely 56° E, Belkin and Gordon (1996), namely the Australian sector of the Southern Ocean, and Ansorge (1996), namely 66° E and 70° E. These results also are only based on thermal data, whereas other studies have used salinity also. Salinity is a more accurate indicator of the Agulhas Front because it is very pronounced, whereas the temperature manifestation is smeared and less distinct. Furthermore, this study has averaged the statistics of the Agulhas Front over the entire Southern Ocean south of Africa, and have therefore taken into account the times when the Agulhas Front meanders far southward, dropping in temperature. Lower mean temperatures have therefore been obtained during this study, compared to earlier investigations.

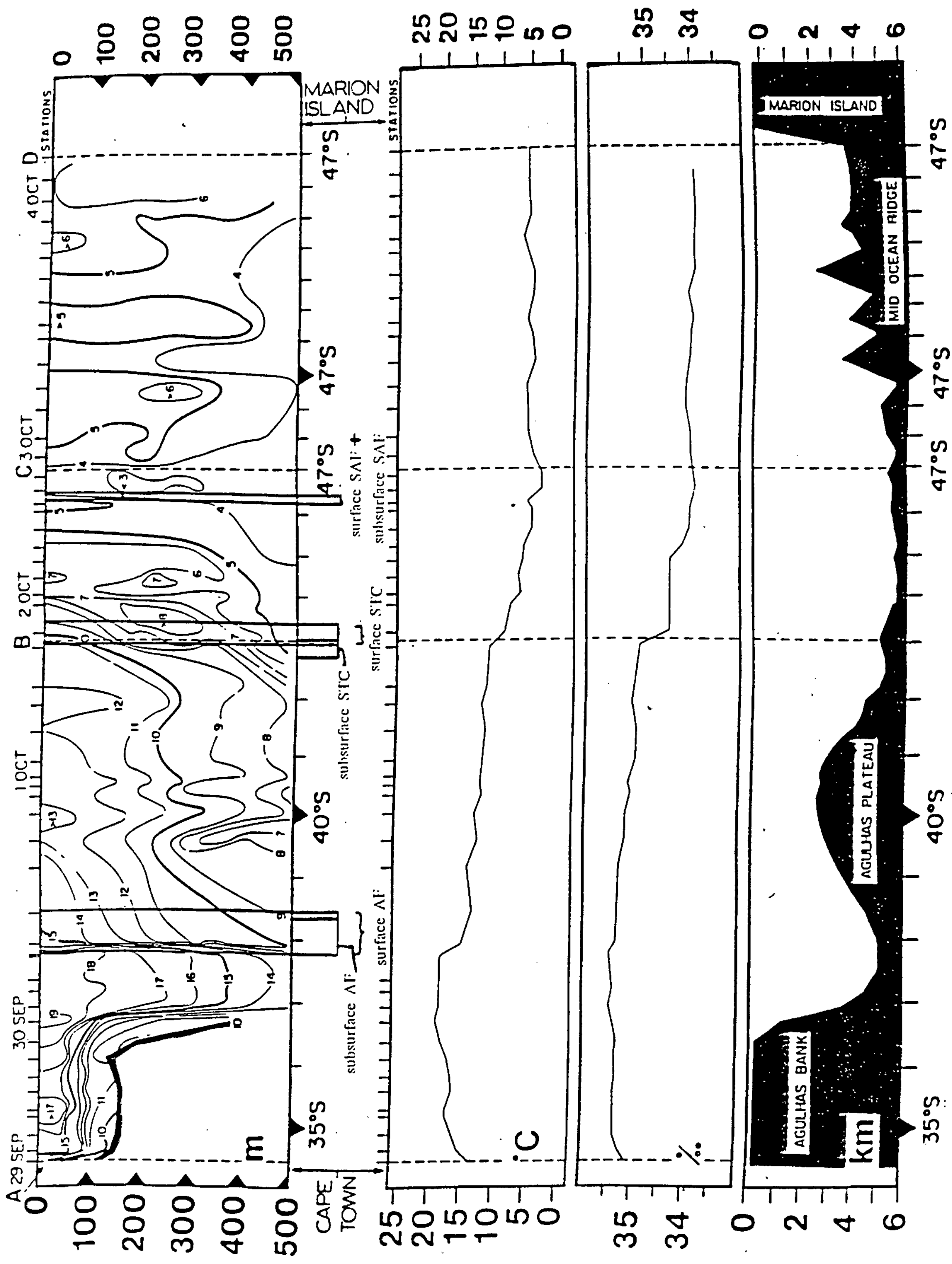

Figure 5.1 A meridional temperature section from the Marion78 Cruise showing the Agulhas Front and other main Southern Ocean frontal systems.

Table 5.1 The locations and widths of the Agulhas Front.

Cruise	Sea surface latitudinal range(°S)	Sea surface longitudinal range(°E unless otherwise stated)	Sub-surface latitudinal range(°S)	Sub-surface longitudinal range(°E unless otherwise stated)	Sea surface mean position (°S;°E unless otherwise stated)	Sub-surface mean position (°S;°E unless otherwise stated)	Sea surface width (km)	Sub-surface width (km)
SANAE 20	40,6-41,0	18,2-18,2	40,2-40,4	18,1-18,2	40,8; 18,2	40,3;18,2	63,1	22,6
SANAE 21	40,0-40,2	18,9-18,9	39,7-40,2	18,9-18,9	40,1;18,9	40,0; 18,9	39,6	11,7
SANAE 22^{R}	39,7-40,1	24,1-24,2	39,3-39,5	23,8-24,0	39,9;24,1	39,4;23,9	44,7	17,2
SANAE 22	39,1-39,9	23,7-24,2	39,2-39,3	23,8-23,9	39,5; 24,0	39,2;23,8	91,2	28,1
SANAE 19^{R}	39,0-39,9	24,3-24,1	39,0-39,2	24,3-24,2	39,3; 24,1	39,1; 24,2	102,6	19,0
MAR78	37,7-38,5	22,5-23,5	37,7-38,2	22,7-23,6	38,1;23,0	38,0; 23,2	134,6	92,2
MAR78^{R}	38,2-39,5	23,3-24,9	38,3-38,9	23,3-24,0	38,8;23,0	38,6;23,7	196,6	98,1
MAR83^{R}	37,2-37,8	22,6-23,5	37,4-37,7	22,9-23,3	37,5; 23,0	37,5; 23,1	100,5	51,9
MAR85.1	38,8-39,1	24,5-24,8	38,8-38,9	24,5-24,7	38,9; 24,7	38,8; 24,6	41,8	16,0
SIBEX 126	40,4-40,5	23,4-23,7	40,4-40,5	23,4-23,6	40,5; 23,6	40,4; 23,5	26,9	14,6
Mean	0,6	0,5	0,3	0,3	39,3; 22,7	39,1; 22,7	84,1	37,1
Standard deviation	0,4	0,5	0,2	0,3	1,0;2,2	1,0;2,3	52,6	32,6

Table 5.2 The thermal characteristics of the Agulhas Front.

Cruise	Sea surface temperature range(°C)	Sea surface temperature gradient (°C/km)	Sub-surface temperature range(°C)	Sub-surface temperature gradient (°C/km)	Sea surface middle temperature (°C)	Sub-surface middle temperature (°C)
SANAE20	20,0-17,5	2,5/63,1	20,0-18,0	2/22,6	19,0	19,5
SANAE21	18,0-16,0	2/39,6	12,0-8,5	3,5/11,7	17,0	10,0
SANAE22^R	20,0-16,0	4/44,7	20,0-16,0	4/17,2	18,0	18,0
SANAE22	22,0-16,0	6/91,2	18,0-16,0	2/28,1	19,0	17,0
SANAE19^R	22,0-16,0	6/102,6	12,0-10,0	2/19,0	19,0	11,0
MAR78	18,0-14,5	3,5/134,6	13,0-9,0	4/92,2	16,0	11,0
MAR78^R	17,5-13,0	4,5/196,6	13,0-8,0	5/98,1	16,0	9,5
MAR83^R	21,0-18,0	3/100,5	14,0-10,0	4/51,9	19,0	12,0
MAR85.1	19,0-14,0	5/41,8	9,0-7,0	2/16,0	17,0	8,0
SIBEX126	21,0-20,0	1/27,0	11,0-8,0	3/14,6	20,0	9,5
Mean	3,8	0,05	3,2	0,13	17,8	12,6
Standard deviation	1,7	0,03	1,1	0,08	1,2	4,1

Subtropical Convergence

The Subtropical Convergence has been defined as the region where the enhanced horizontal sea surface temperature gradient has a middle temperature of 15,5° C at approximately 40° S latitude. The isotherms in the 15° C vicinity dip down strongly northward. In general it has stronger horizontal thermal gradients than the Agulhas Front (see STC in figure 5.2 compared to AF in 5.1). The 15,5° C sea surface middle temperature of the Subtropical Convergence, and the 40° S latitude, is based upon the findings of previous studies.

The Subtropical Convergence has been traced in this data set from about 13° W to 65° E in the sea surface and sub-surface temperature profile. In the South East Atlantic Ocean between 13° W and O° W, the Subtropical Convergence is present in the sea surface temperature profile as a particularly broad frontal zone, 185 km to 204 km wide (see table 5.3). As the geographic position of the thermal surface expression of the Subtropical Convergence is traced in the South East Atlantic Ocean it lies as a broad frontal zone to the north and south of Gough Island. In the South East Atlantic Ocean the Subtropical Convergence is present in the sub-surface temperature profile as a narrow frontal zone however , 43 km to 52 km wide. As the Subtropical Convergence is traced in the sub-surface temperature profile across the South East Atlantic Ocean the Subtropical Convergence is traced both north and south of Gough Island as a single, narrow frontal zone. Although the Subtropical Convergence in its sea surface thermal geographic position presents itself as a broad frontal zone passing north and south of Gough Island, the north and south positions are due to temporal differences in the data north and south of Gough Island. East of Gough Island the Subtropical Convergence remains a single frontal zone (see figure 6.1). No NSTF nor SSTF as proposed by Belkin (1993) is evident in the South East Atlantic/South Indian Ocean. The Subtropical Convergence therefore does not exhibit a double frontal structure here. The observation of a double structure in this region by Belkin (1992) is probably due to his criteria used to identify the front.

As the STC is traced eastwards across the South East Atlantic/South West Indian Oceans, the STC reveals substantial meandering. This meandering is clearly evident in both the surface and sub-surface temperature profiles (figures 6.1 and 6.2). This is probably the result of a lack of topographic steering and the fact that this is the region where the most instability occurs due to mesoscale features spawned at the Agulhas Current Retroflection and Agulhas Return Current. The detailed geographic locations, widths, middle temperatures, thermal gradients, thermal ranges, and their standard deviations and means, have been determined for the thermal surface and sub-surface expression of the Subtropical Convergence (see tables 5.3 and 5.4). The average sea surface width is 146 km, but the width varies considerably, with a standard deviation of 57 km. The average sub-surface width is 79 km, but here the width also varies considerably, with a standard deviation of 45 km. This extremely high variability in the width of the Subtropical Convergence and its highly convoluted structure between 10° E and 35° E is probably as a result of the severe instability experienced by frontal zones in this region of the Southern Ocean and is seen in this analysis more clearly because of the large number of ship crossings in this particular region. The mean sea surface middle temperature of the Subtropical Convergence in this study is 14,3° C compared to the 15,5° C of earlier studies. The mean sea surface temperature gradient across the Subtropical Convergence is 4,2° C compared to the 8,8° C of earlier studies.

The fact that many of the sections analysed in this study were not exactly perpendicular to the Subtropical Convergence has resulted in the calculated widths of this study being greater than previous studies. All sub-surface measurements in this study have not been taken at any specified reference depth as in other studies, but rather between 150 m and 500 m depth. This has resulted in characteristics (gradients, widths, ranges, positions) being obtained at sub-surface during this study, for the Agulhas Front, being different from other studies. These results also are only based on thermal data, whereas other studies have used salinity also. Salinity is a more accurate indicator of the Subtropical Convergence because it is very pronounced, whereas the temperature manifestation is smeared and less distinct. This could be a major reason for this studies inability to distinguish the NSTF from the SSTF. Belkin and Gordon (1996) have used salinity data extensively. Furthermore, this study has averaged the statistics of the Subtropical Convergence over the entire Southern Ocean south of Africa, and have therefore taken into account the times when the Subtropical Convergence meanders far southward, dropping in temperature. Lower mean middle temperatures (14,3° C) have therefore been obtained during this study, compared to earlier investigations (15,5° C).

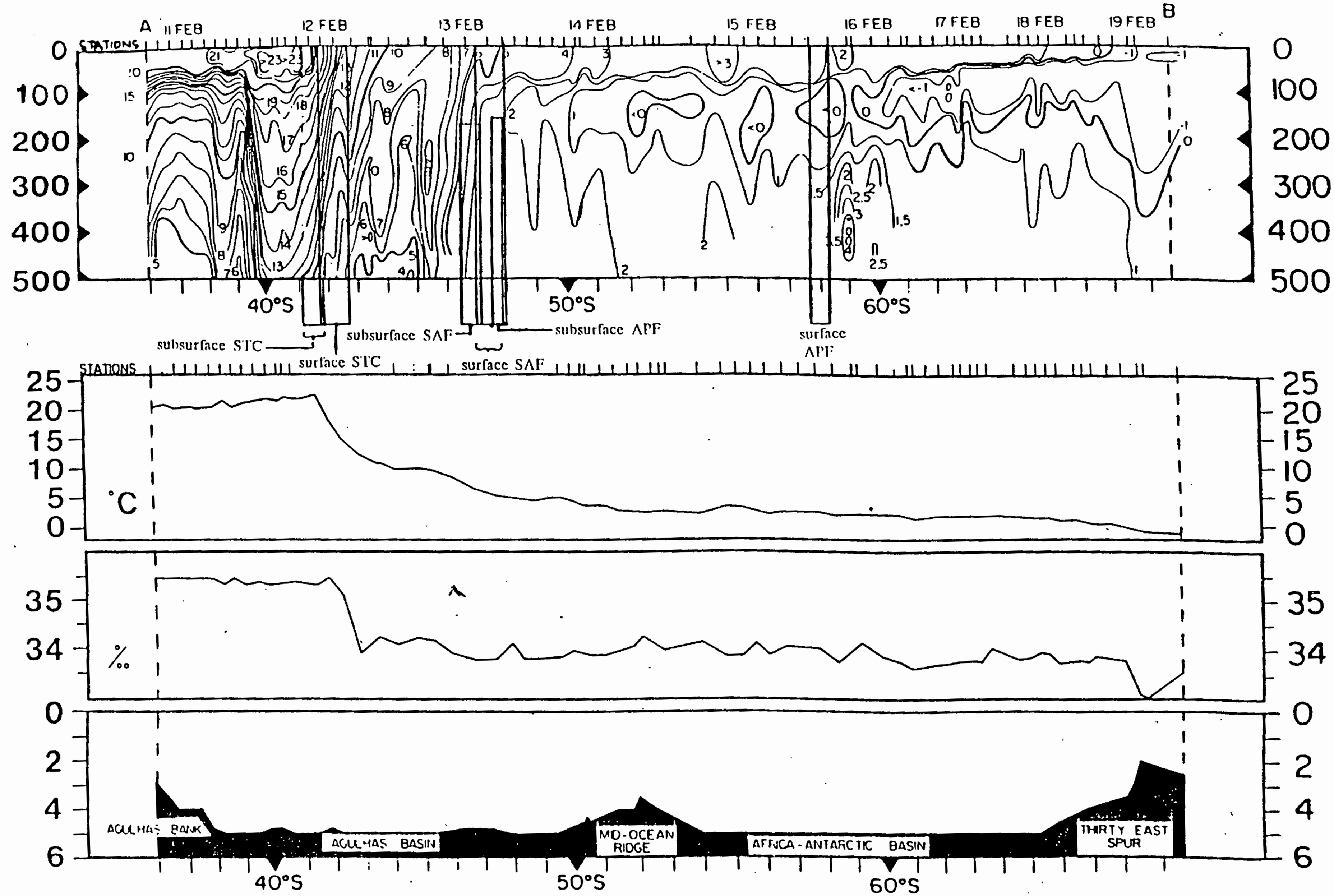

Figure 5.2 A meridional temperature section from the Fibex Cruise showing the Subtropical Convergence and other main Southern Ocean frontal systems.

Table 5.3 The locations and widths of the Subtropical Convergence.

Cruise	Sea surface latitudinal range(°S)	Sea surface longitudinal range(°E unless otherwise stated)	Sub-surface latitudinal range(°S)	Sub-surface longitudinal range(°E unless otherwise stated)	Sea surface mean position (°S;°E unless otherwise stated)	Sub-surface mean position (°S;°E unless otherwise stated)	Sea surface width (km)	Sub-surface width (km)
SANAE 22	42,2-43,7	23,3-22,9	42,4-42,6	23,3-23,3	42,9; 23,1	42,5; 23,3	169,0	24,1
SANAE 22^R	41,9-43,4	13,0-11,7°W	41,9-42,3	13,0-12,7°W	42,7; 12,3°W	42,1; 12,8°W	204,0	52,3
SANAE 21	43,4-44,7	18,9-18,9	43,7-43,8	18,9-18,9	44,1; 18,9	43,8; 18,9	150,1	9,4
SANAE 21^R	41,6-43,0	12,8-11,7	42,0-42,4	12,4-12,1	42,3; 12,2	42,2; 12,2	169,5	54,0
SANAE 20	41,3-42,8	18,3-18,4	42,4-42,8	18,5-18,4	42,1; 18,4	42,6; 18,4	161,3	46,8
SANAE 20^R	40,3-41,9	9,7-10,5°W	41,5-41,9	10,3-10,5°W	41,1; 10,1°W	41,7; 10,4°W	185,4	42,6
SH1970	44,3-46,0	65,0-65,0	44,3-44,7	65,0-65,0	45,1;65,0	44,5;65,0	194,6	50,0
SANAE 25	38,4-39,9	15,2-14,6	38,7-39,9	15,0-14,6	39,1; 14,9	39,3; 14,8	176,4	131,4
SANAE 24	40,0-40,7	2,1-1,2	40,0-40,7	2,1-1,2	40,0;1,6	40,4;1,6	106,6	106,6
RRS164	40,5-41,4	40,0-38,7	39,7-39,8	40,9-40,7	40,9; 39,3	39,7; 40,8	149,6	26,0
SANAE 86	39,5-40,0	15,9-16,2	39,5-40,0	15,9-16,2	39,8; 16,0	39,8; 16,0	66,9	66,9
SANAE 26	40,2-41,3	14,7-14,3	40.6-41,3	14,4-14,3	40,7; 14,5	41,0; 14,3	134,0	78,3
SANAE 19	40,6-41,1	11,6-11,3	40.1-41,1	12,1-11.3	40,8; 11,5	40.6; 11,7	86,0	126,2
SANAE 19^R	41,6-42.5	23,4-22.4	41.9-43,5	23.4-23.2	42,0:23,0	42,7;23,3	228,2	113,1
SIBEX 126	41,5-41,8	25,8-26.3	41.4-41,5	25.1-25.8	41.7: 26,0	41,5; 25,5	48,8	56,7
SIBEX 126^R	42,4-43.0	34,7-35,6	42,7-43,4	35,1-35.9	42,7: 35,2	43,0: 35,5	100,6	107,0
MAR78	42,9-43,4	29,3-29,0	42,3-43,2	28.8-29.3	43,2; 29,2	42,7; 29,1	130,2	103,0
MAR78^R	43,4-44,0	30,1-29,7	43.4-44,2	30.1-30.0	43,7: 29,9	43,8; 30,0	105,1	23,7
MAR83	40,5-40,8	22,5-23,0	39.7-40.4	20.5-22,2	40.6; 22,7	40.1; 21,3	48.2	159,2

Table 5.3 The locations and widths of the Subtropical Convergence (Cont.).

Cruise	Sea surface latitudinal range(°S)	Sea surface longitudinal range(°E unless otherwise stated)	Sub-surface latitudinal range(°S)	Sub-surface longitudinal range(°E unless otherwise stated)	Sea surface mean position (°S;°E unless otherwise stated)	Sub-surface mean position (°S;°E unless otherwise stated)	Sea surface width (km)	Sub-surface width (km)
BOU-CT	38,7-40,8	12,0-10,5	38,5-38,8	11,5-12,5	39,8; 11,3	38,7;12,0	271,3	93,0
FIBEX	41,8-42,9	21,2-21,6	41,0-41,9	20,9-21,6	42,3; 21,4	41,5; 21,3	122,5	147,3
FIBEX^R	42,2-43,8	31,5-33,5	42,2-43,3	31,5-33,0	43,0; 33,0	42,7; 32,3	203,0	151,3
KRILL	40,8-42,0	15,8-15,2	41,2-41,7	15,6-15,4	41,4;15,5	41,5; 15,5	144,6	52,7
Mean	1,1	0,7	0,6	0,6	41,8;21,9	41,7;22,0	145,9	79,2
Standard deviation	0,6	0,5	0,4	0,6	1,5;13,1	1,5;13,1	56,5	44,9

43,78 46°
43

Table 5.4 The thermal characteristics of the Subtropical Convergence

Cruise	Sea surface temperature range(°C)	Sea surface temperature gradient (°C/km)	Sub-surface temperature range(°C)	Sub-surface temperature gradient (°C/km)	Sea surface middle temperature (°C)	Sub-surface middle temperature (°C)
SANAE22	17,0-12,0	5/169,0	11,0-7,5	3,5/24,1	15,0	9,5
SANAE22^R	17,0-12,0	5/204,0	14,0-10,0	4/52,3	15,0	12,0
SANAE21	14,0-9,0	5/150,1	7,0-5,0	2/9,4	12,0	6,0
SANAE21^R	15,0-11,5	3,5/169,5	14,0-13,0	1/54,0	13,0	13,5
SANAE20	15,5-9,5	6/161,3	6,5-5,5	1/46,8	13,0	6,0
SANAE20^R	17,5-11,0	6,5/185,4	10,0-5,5	4,5/42,6	15,0	8,0
SH1970	11,0-6,0	5/194,6	7,0-3,5	3,5/50,0	9,0	5,0
SANAE25	18,0-14,0	4/176,4	11,0-6,0	5/131,4	16,0	8,0
SANAE24	13,0-12,0	1/106,6	13,0-12,0	1/106,6	12,0	12,5
RRS164	18,0-15,0	3/149,6	16,0-14,0	2/26,0	16,0	15,0
SANAE86	22,0-20,0	2/66,9	13,0-8,0	5/66,9	21,0	11,0
SANAE26	19,0-14,0	5/134,0	8,0-7,0	1/78,3	17,0	7,5
SANAE19	19,0-13,0	6/86,0	10,0-5,0	5/126,2	16,0	8,0
SANAE19^R	16,0-9,5	6,5/228,2	11,0-6,0	5/113,1	13,0	9,0
SIBEX126^R	13,0-8,0	5/100,6	6,0-4,0	2/106,9	11,0	5,0
MAR78	11,0-9,0	2/130,2	5,0-4,5	0,5/103,0	10,0	5,0
MAR78^R	9,0-7,0	2/105,1	8,0-6,0	2/23,7	8,0	7,0
MAR83	18,0-16,5	1,5/48,2	13,0-5,0	8/159,2	17,0	9,0
SIBEX126	20,0-17,0	3/48,8	10,0-8,5	1,5/56,7	19,0	9,0
BOUV-CT	18,0-13,0	5/271,3	10,0-7,0	3/93,0	16,0	8,5
FIBEX	20,0-13,0	7/122,5	11,5-8,5	3/147,3	17,0	10,0
FIBEX^R	14,0-11,0	3/203,0	7,0-5,0	2/151,3	12,0	6,0
KRILL	17,0-12,0	5/144,6	7,0-6.0	1/52,7	15,0	6,5
Mean	4,2	0,03	2,9	0,05	14,3	8,4
Standard deviation	1,7	0.01	1,9	0.04	3,2	3,0

Sub-antarctic Front

The Sub-antarctic Front has been defined as the front that occurs at the most vertically orientated isotherm within the sub-surface temperature gradient between the 3° C and 5° C isotherms in the Southern Ocean (Sievers and Emery, 1978) (see figure 5.3).

The Sub-antarctic Front has been traced from 27,3° W to 65,1° E in the sea surface temperature profile and from 27,4° W to 65,1° E in the sub-surface temperature profile. In the South East Atlantic Ocean the Sub-antarctic Front moves northeastward from 27° W, 54° S to about 10° W, 47° S through a col in the Mid-Atlantic Ridge (see table 5.5). Then in the sub-surface temperature profile the Sub-antarctic Front moves slightly south and through the rift in the Meteor Rise. In the sub-surface temperature profile the Sub-antarctic Front then drastically dips southward as it encounters the large, broad Meteor Rise, before moving northwards. In the South East Atlantic/South West Indian Ocean the Sub-antarctic Front shows extensive meandering. In the sub-surface temperature profile between 30° E to 40° E the Sub-antarctic Front extends far northwards (44° S, 35° E). In the sea surface temperature profile the Sub-antarctic Front moves from 50° S to 46° S almost reaching the Subtropical Convergence near the South West Indian Ocean Ridge. This northward movement is caused by the South West Indian Ocean Ridge that steers the Sub-antartic Front northeast. A plateau in the South West Indian Ocean Ridge then allows for the bending of the Sub-antarctic Front southwards.

In the sea surface and sub-surface temperature profile between 40° E and 50° E the Sub-antarctic Front lies south of the Prince Edward Islands. In the sub-surface temperature profile a deep passage in the Crozet Plateau steers the Sub-antarctic Front abruptly northward of the Crozet Plateau (see figure 6.2). This agrees with the findings of Gille (1994) that a deep passage in the Crozet Plateau steers the Sub-antarctic Front to the north side of the Crozet Plateau. Between 53° E to 55° E the broad, high Crozet Plateau also steers the Sub-antarctic Front further northward, from 45° S to 43° S, after which it converges with the Subtropical Convergence at approximately 60° E to form a united STC/SAF. This is particularly strong in the sub-surface temperature profile (see figure 6.2). This result agrees well with Belkin and Gordon (1996) who note the northward movement of the Sub-antarctic Front in this region of the South West Indian Ocean. Also, this result confirms the idea of Belkin and Gordon (1996), that the Sub-antarctic Front moves northeastward and combines with the Subtropical Convergence upstream of the Crozet Plateau, to form the united STC/SAF at 45° S. The Sub-antarctic Front diverges southward farther east and separates from the Subtropical Convergence at approximately 63° E resulting in a separate and single Sub-antarctic Front at 65° S in the sub-surface temperature profile (see figure 6.2).

The detailed geographic locations, widths, middle temperatures, thermal gradients, thermal ranges, and their standard deviations and means, have been determined for the thermal surface and sub-surface expression of the Sub-antarctic Front and presented in tables 5.5 and 5.6. The mean sea surface middle temperature of the Sub-antarctic Front in this study is 4,4° C compared to the 8° C of earlier studies. The mean sub-surface middle temperature of the Sub-antarctic Front in this study is 4° C compared to the 6,1° C of earlier studies.

The fact that many of the sections analysed in this study were not exactly perpendicular to the Sub-antarctic Front has resulted in the calculated widths of this study being greater than previous studies. All sub-surface measurements in this study have not been taken at any specified reference depth as in other studies, but rather between 150 m and 500 m depth. This has resulted in characteristics (gradients, widths, ranges, positions) being obtained at sub-surface during this study, for the Sub-antarctic Front, being different from other studies. Furthermore, this study has averaged the statistics of the Sub-antarctic Front over the entire Southern Ocean south of Africa, and have therefore taken into account the times when the Sub-antarctic Front meanders far southward, dropping in temperature. Lower mean middle temperatures (4,4° C at the surface) have therefore been obtained during this study, compared to earlier investigations (8° C at the surface).

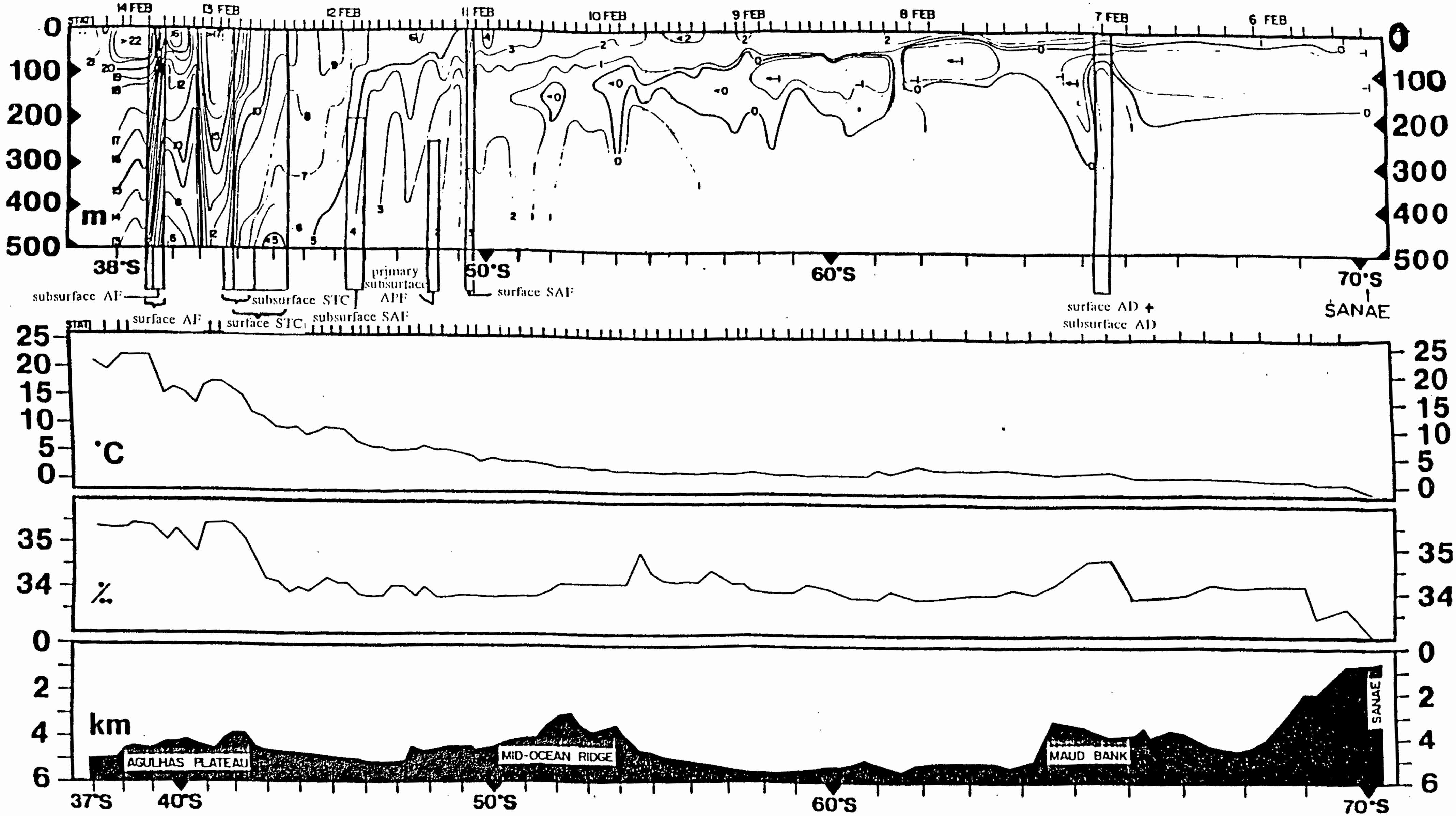

Figure 5.3 A meridional temperature section from the Sanae19 Cruise (return leg) showing the Sub-antarctic Front and other main Southern Ocean frontal systems.

Table 5.5 The locations and widths of the Sub-antarctic Front.

Cruise	Sea surface latitudinal range(°S)	Sea surface longitudinal range(°E unless otherwise stated)	Sub-surface latitudinal range(°S)	Sub-surface longitudinal range(°E unless otherwise stated)	Sea surface mean position (°S;°E unless otherwise stated)	Sub-surface mean position (°S;°E unless otherwise stated)	Sea surface width (km)	Sub-surface width (km)
SANAE 22	48,4-48,8	20,6-20,4	47,6-47,9	21,0-20,8	48,6; 20,5	47,7; 20,9	52,9	35,6
SANAE 22R	48,8-49,0	7,1-6,7°W	46,1-46,5	9,4-9,1°W	48,9; 6,9°W	46,3; 9,2°W	52,5	45,2
SANAE 21	46,8-47,8	18,9-18,9	47,1-47,4	18,9-19,0	47,3; 18,9	47,3; 18,9	146,4	96,4
SANAE 21R	48,1-48,6	7,2-6,8	45,9-46,1	9,3-9,0	48,3; 7,0	46,0; 9,1	61,4	43,1
SANAE 20	47,0-47,5	18,6-18,7	47,0-47,5	18,6-18,5	47,2; 18,6	47,2; 18,5	48,6	48,6
SANAE 20R	48,8-49,0	10,6-11,0°W	46,2-46,4	11,0-11,0°W	48,9; 10,8°W	46,3; 11,0°W	39,8	27,8
UK1969	48,5-49,2	65,2-65,1	45,4-46,4	65,0-65,2	48,9; 65,1	45,9; 65,1	85,3	110,1
RRS164	48,1-48,1	32,8-32,8	47,9-48,2	32,7-32,8	48,1; 32,8	48,0; 32,7	7,4	39,0
SANAE 26	48,6-49,5	10,0-9,3	46,6-47,0	11,3-10,9	49,1; 9,6	46,8; 11,1	113,4	56,7
SANAE 25	48,4-49,0	8,7-8,2	46,5-47,8	10,4-9,2	48,7;8,5	47,2;9,8	76,1	164,0
SANAE 24	53,8-54,4	27,2-27,4° W	49,8-50.5	28,3-28,4°W	54,1; 27,3° W	50,1; 28,4° W	101,0	39,6
SANAE 19	48,6-49,5	3,3-3,3	44,9-45,6	7,6-6,4	49,3; 3,3	45,2;7,0	70,4	155,3
SANAE 19R	48,6-49,5	19,6-19,3	45,4-46,0	21,5-21,3	49,3; 19,4	45,7; 21,4	102,2	71,4
SH1970	46,5-47,9	65,0-65,0	46.5-47.9	65,0-65,0	47,2;65,0	47,2;65,0	166,8	166,8
MAR78	46,3-46,4	29.3-29.3	46,3-46.4	29,3-29,3	46,3; 29,3	46,4; 29,3	53,7	53,7
SIBEX 126	49.4-49.7	41.8-42,2	44,1-44,5	36,3-36.5	49.5;42,0	44,3; 36,4	45,5	45,1
BOUV-CT	48.3-49.2	7.0-7,0	45,0-46,0	10,0-10,0	48,7;7,0	45,5;10,0	96,4	111,2

Table 5.5 The locations and widths of the Sub-antarctic Front (Cont.).

Cruise	Sea surface latitudinal range(°S)	Sea surface longitudinal range(°E unless otherwise stated)	Sub-surface latitudinal range(°S)	Sub-surface longitudinal range(°E unless otherwise stated)	Sea surface mean position (°S;°E unless otherwise stated)	Sub-surface mean position (°S;°E unless otherwise stated)	Sea surface width (km)	Sub-surface width (km)
PACK-ICE	46,8-47,2	11,0-11,0°W	46,8-47,2	11,0-11,0°W	47,0; 11,0°W	46,9; 11,0°W	46,3	46,3
MAR-GOU	47,4-47,6	2,6-1,9	49,0-48,7	4,6-5,8	47,5;2,2	48,9;5,2	57,6	91,0
MAR-GOU	47,8-48,0	8,5-9,0	46,1-46,6	9,9-10,0	47,9;8,8	46,4; 9,9	45,0	53,8
KRILL	50,0-50,6	11,8-11,6	46,0-46,6	13,6-13,4	50,2; 11,7	46,3; 13,5	64,6	68,5
FIBEX	47,4-48,0	23,3-23,7	46,7-47,5	23,2-23,5	47,7;23,5	47,1; 23,4	64,8	82,9
FIBEX	51,9-52,7	31,5-31,4	47,7-48,2	37,5-36,2	52,3; 31,4	47,9; 36,8	89,3	107,6
Mean	0,6	1,0	0,6	0,3	48,7; 18,9	46,8; 19,9	73,4	76,5
Standard deviation	0,4	3,4	0,3	0,4	1,7;15,1	1,2;14,0	35,9	42,1

Table 5.6 The thermal characteristics of the Sub-antarctic Front.

Cruise	Sea surface temperature range(°C)	Sea surface temperature gradient (°C/km)	Sub-surface temperature range(°C)	Sub-surface temperature gradient (°C/km)	Sea surface middle temperature (°C)	Sub-surface middle temperature (°C)
SANAE22	5,0-4,0	1/52,9	5,0-4,0	1/35,6	4,5	4,5
SANAE22^R	5,0-6,0	-1/52,5	5,0-4,0	1/45,2	5,5	4,5
SANAE21	7,0-6,0	1/146,4	6,0-5,0	1/96,4	6,5	5,5
SANAE21^R	7,0-6,0	1/61,4	6,0-5,0	1/43,1	6,5	5,5
SANAE20	4,0-3,0	1/48,6	4,0-3,0	1/48,6	3,5	3,5
SANAE20^R	4,0-3,0	1/39,8	4,0-3,0	1/27,8	3,5	3,5
UK1969	6,0-5,0	1/85,3	5,0-4,0	1/110,1	5,5	4,5
RRS164	5,0-4,0	1/7,4	4,0-2,0	2/39,0	4,5	3,0
SANAE26	5,0-4,0	1/113,4	6,0-5,0	1/56,7	4,5	5,5
SANAE25	4,0-3,0	1/76,1	4,0-3,0	1/164,0	3,5	3,0
SANAE24	4,0-3,0	1/101,0	4,0-2,0	2/39,6	3,5	3,0
SANAE19	3,0-2,0	1/70,4	5,0-3,0	2/155,3	2,5	4,0
SANAE19^R	5,0-4,0	1/102,2	6,0-4,0	2/71,4	5,0	5,0
SH1970	4,0-3,0	1/166,8	3,0-2,0	1/166,8	3,5	3,0
MARION78	5,0-4,0	1/53,7	4,0-3,0	1/53,7	4,5	3,5
SIBEX126	6,0-4,0	2/45,5	6,0-4,0	2/45,1	5,0	5,0
BOUV-CT	6,0-5,0	1/96,4	6,0-4,0	2/111,2	5,5	5,0
PACK-ICE	4,0-3,0	1/46,3	3,0-2,0	1/46,3	3,5	2,5
MAR-GOU	4,5-4,0	0,5/57,6	4,5-3,5	1/91,0	4,0	4,0
MAR-GOU	4,0-3,0	1/45,0	3,5-2,5	1/53,8	3,0	3,0
KRILL	5,0-4,0	1/64,6	4,5-3,5	1/68,5	4,0	4,0
FIBEX	6,0-5,0	1/64,8	6,0-3,0	3/82,9	5,5	4,5
FIBEX	3,0-3,5	-0.5/89,3	4,0-2,0	2/107,6	3,5	3,0
Mean	1,1	0.02	1,4	0,02	4,4	4,0
Standard deviation	0,4	0.02	0,6	0,01	1,1	0,9

Antarctic Polar Front

The Antarctic Polar Front has been defined as the front that occurs at the northernmost limit of the 2° C isotherm which is part of the sub-surface temperature minimum, according to Joyce and Patterson (1978) (see figure 5.4). At the northern flank of the Kerguelen Plateau, however, the Antarctic Polar Front is defined as the front that occurs at the northernmost limit of the 2,5° C isotherm. Where an isolated cold water cell of 2° C water is found north of the northernmost limit of the contiguous 2° C isotherm water that is part of the sub-surface temperature minimum, the cold cell is regarded as the primary Antarctic Polar Front, and the northernmost limit of the contiguous 2° C isotherm water, that is part of the sub-surface temperature minimum, is regarded as the secondary Antarctic Polar Front (see figure 5.4).

The Antarctic Polar Front is traced from 10,9° W to 64,3° E in the sea surface temperature profile and from 11° W to 65,2° E in the sub-surface temperature profile (see table 5.7). From 10° W to 17° E in the sea surface temperature profile the Antarctic Polar Front moves southward generally, and briefly joining the Sub-antarctic Front at 7° E. From 10° W to 10° E in the sub-surface temperature profile the Antarctic Polar Front moves generally zonally across the eastern South Atlantic Ocean, briefly joining the Sub-antarctic Front at 7° E. From 10° E to 20° E in the sub-surface temperature profile the Antarctic Polar Front moves northeastward as it is guided along the South West Indian Ocean Ridge from 52° S to 48° S. From 20° E to 30° E in the sub-surface temperature profile, the Antarctic Polar Front bends southward in the South Atlantic Ocean, agreeing with the results put forward by Belkin and Gordon (1996) that the Antarctic Polar Front moves southward along 30° E due to the South West Indian Ocean Ridge. In the sea surface temperature profile the Antarctic Polar Front lies northeastward from 17° E, under the influence of the South West Indian Ocean Ridge. It reaches the Sub-antarctic Front at 18° E and then turns abruptly southeastward from 18° E to 27° E. The Antarctic Polar Front then moves northeastward from 58° S to 52° S between the Crozet Plateau and Ob-Lena Rise, in the sea surface temperature profile. This agrees with the results of Belkin and Gordon (1996) as far as the Antarctic Polar Front moving between the Crozet Plateau and Ob-Lena Rise is concerned. In the sub-surface temperature profile the Antarctic Polar Front moves steeply northeastward under the influence of the South West Indian Ocean Ridge from 51° S to 46° S (see figure 6.2). The Antarctic Polar Front does not join with the Sub-antarctic Front east of 40° E. This disagrees with the idea of Belkin and Gordon (1996) that the Antarctic Polar Front joins with the "Crozet Front" to form a quadruple front with the Agulhas Front, Subtropical Convergence and Sub-antarctic Front.

In the nine sections that intersected the Antarctic Polar Front, the front revealed a primary Antarctic Polar Front as well as a secondary Antarctic Polar Front. In 30% of the Antarctic Polar Front cases investigated therefore a separate 2° C isotherm cold water cell below 200 m was found north of the main body of 2° C temperature minimum water.

The detailed geographic locations, widths, middle temperatures, thermal gradients, thermal ranges, and their standard deviations and means, have been determined for the thermal surface and sub-surface expression of the Antarctic Polar Front and are thermal surface and sub-surface expression of the Antarctic Polar Front and are presented in tables 5.7 and 5.8. The average sea surface width is 66 km, but the width varies considerably, with a standard deviation of 42 km. The average sub-surface width is 74 km, but the width also varies considerably, with a standard deviation of 39 km. This high variability in the width of the Antarctic Polar Front both at surface and sub-surface indicates the instability experienced as a result of rings shed from the meandering Antarctic Circumpolar Current behind the Mid-Ocean Ridge (Gouretski and Danilov, 1994). The mean sea surface middle temperature of the Antarctic Polar Front in this study is 2,1° C compared to the 4° C of earlier studies. The mean sea surface temperature range of the Antarctic Polar Front in this study is 0,8° C compared to the 2,9° C of earlier studies.

The fact that many of the sections analysed in this study were not exactly perpendicular to the Antarctic Polar Front has resulted in the calculated widths of this study being greater than previous studies. All sub-surface measurements in this study have not been taken at any specified reference depth as in other studies, but rather between 150 m and 500 m depth. This has resulted in characteristics (gradients, widths, ranges, positions) being obtained at sub-surface during this study, for the Antarctic Polar Front, being different from other studies. Furthermore, this study has averaged the statistics of the Antarctic Polar Front over the entire Southern Ocean south of Africa, and have therefore taken into account the times when the Antarctic Polar Front meanders far southward, dropping in temperature. Lower mean middle temperatures (2,1° C at the surface) have therefore been obtained during this study, compared to earlier investigations (4° C at the surface).

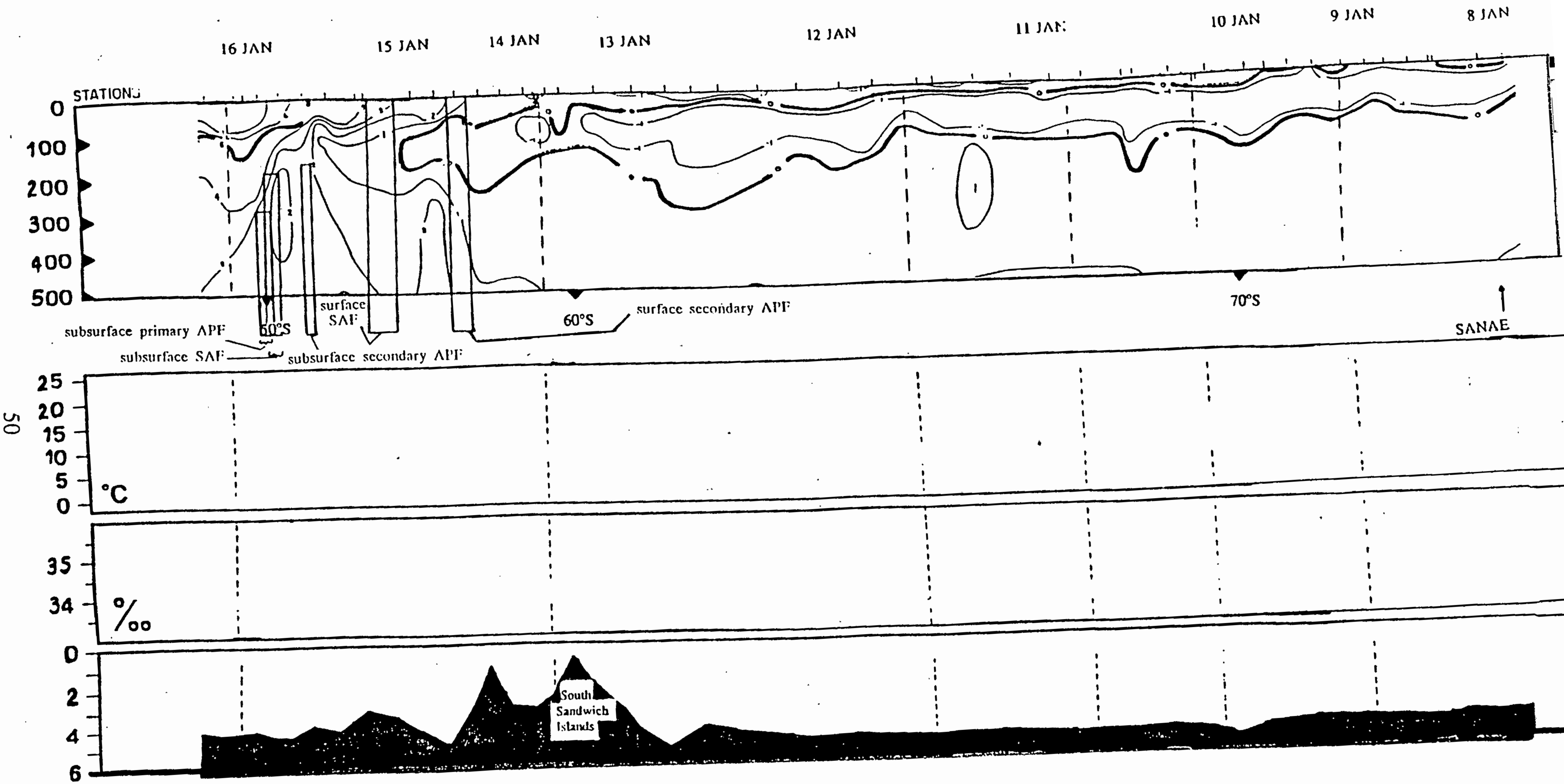

Figure 5.4 A meridional temperature section from the Sanae24 Cruise showing the primary and secondary Antarctic Polar Front and other main Southern Ocean frontal systems.

Table 5.7 The locations and widths of the Antarctic Polar Front.

Cruise	Sea surface latitudinal range(°S)	Sea surface longitudinal range(°E unless otherwise stated)	Sub-surface latitudinal range(°S)	Sub-surface longitudinal range(°E unless otherwise stated)	Sea surface mean position (°S;°E unless otherwise stated)	Sub-surface mean position (°S;°E unless otherwise stated)	Sea surface width (km)	Sub-surface width (km)
KRILL	52,5-52,8	10,6-10,4	51,8-52,5	10,9-10,6	52,7; 10,5	52,2; 10,8	40,8	75,4
FIBEX	57,8-58,4	28,7-29,1	47,4-48,0	23,5-23,7	58,1; 28,9	47,7;23,6	72,8	60,4
FIBEX[R]			47,7-48,2	37,5-36,2		47,9; 36,8		107,6
FIBEX[R]	56,1-56,5	26,6-25,9	50,4-50,6	33,5-32,8	56,3; 26,2	50,5; 33,1	63,4	79,4
CON-RAD			47,1-47,1	40,4-42,1		47,1; 41,2		128,8
PACK-ICE			48,1-48,4	11,1-10,0°W		48,2; 10,5°W		83,5
PACK-ICE	50,0-50,3	10,9-10,9°W	49,4-50,0	11,0-10,9°W	50,2; 10,9°W	49,7; 11,0°W	27,8	72,5
PACK-ICE[R]	49,9-50,4	1,0-1,5°W	49,3-49,9	0,6-1,0°W	50,1; 1,3°W	49,6; 0,9°W	69,1	65,9
TVG	51,4-52,0	20,1-20,1	49,1-49,4	20,0-20,1	51,7; 20,1	49,3; 20,0	68,6	31,6
BOUV-CT	53,3-53,8	8,0-8,0	49,5-49,8	9,0-9,0	53,6;8,0	49,7;9,0	55,6	33,4
AJAX	53,0-53,2	1,4-1,4	49,9-50,4	1,4-1,3	53,1;1,4	50,1;1,4	20,4	55,7
SIBEX			49,5-49,7	42,0-42,2		49,6; 42,1		28,6
SH1970			47,2-47,9	65,0-65,0		47,5;65,0		79,7
SANAE 19	51,4-52,0	3,3-3,3	49,1-49,6	4,2-3,5	51,7;3,3	49,4;3,9	70,4	67,4
SANAE 19[R]			48,1-48,4	20,2-20,1		48,2; 20,1		28,5
SANAE 23	52,9-54,2	44,8-44,8	48,5-49,2	46,1-45,7	53,6; 44,8	48,8;45,9	152,0	84,5
SANAE 24			49,1-50,5	28,2-27,0		49,8; 27,6		175,7
SANAE 24	55,2-56,8	23,3-22,8	51,0-51,6	26,6-25,8	56,0; 23,1	51,3; 26,2	184,8	87,0
SANAE 24[R]			49,3-49,4	28,3-28,1		49,4;28,2		18,3
SANAE 25	50,3-50,5	7,2-7,0	49,6-50,9	7,7-6,6	50,4;7,1	50,3;7,1	28,5	160,6

Table 5.7 The locations and widths of the Antarctic Polar Front (Cont.).

UK1969	58,2-58,7	64,0-64,6	48,3-49,2	65,2-65,2	58,4;64,3	48,8; 65,2	67,3	107,5
SANAE 20	49,4-50,1	18,7-18,8	48,4-48,9	18,7-18,7	49,7; 18,7	48,6; 18,7	78,0	48,2
SANAE 20^R	54,6-54,9	18,2-18,0	48,8-49,3	18,7-18,87	54,8; 18,1	49,1; 18,7	36,1	55,6
SANAE 22	51,1-51,4	19,1-18,9	48,4-48,8	20,6-20,4	51,3; 19,0	48,6;20,5	41,3	52,9
SANAE 22^R	52,3-52,6	3,7-3,5°W	49,2-50,0	6,7-6,0°W	52,4; 3,6°W	49,6; 6,4°W	36,0	97,5
SANAE 21	51,3-51,9	18,7-18,6	48,9-49,4	18,9-18,8	51,6; 18,6	49,2; 18,8	68,6	50,8
SANAE 21^R	52,1-52,8	4,2-3,9	49,4-49,8	6,1-6,4	52,4;4,0	49,6;6,3	81,1	51,1
Mean	0,6	0,2	0,5	0,4	52,7;14,9	49,2; 20,8	66,4	73,6
Standard deviation	0,4	0,2	0,3	0,4	2,3;11,5	11,0;15,5	42,1	39,3

Table 5.8 The thermal characteristics of the Antarctic Polar Front.

Cruise	Sea surface temperature range(°C)	Sea surface temperature gradient (°C/km)	Sub-surface temperature range(°C)	Sub-surface temperature gradient (°C/km)	Sea surface middle temperature (°C)	Sub-surface middle temperature (°C)
KRILL	2,5-2,0	0,5/40,8	2,0-1,5	0,5/75,4	2,0	1,8
FIBEX	2,5-2,0	0,5/72,8	2,5-2,0	0,5/60,4	2,0	2,3
FIBEX^R			4,0-2,0	2/107,6		3,0
FIBEX^R	2,5-2,0	0,5/63,4	2,5-2,0	0,5/79,4	2,0	2,3
CONRAD 17			2,3-2,0	0,3/128,8		2,0
PACK-ICE			2,0-1,8	0,3/83,5		2,0
PACK-ICE	2,0-1,0	1/27,8	2,0-1,8	0,3/72,5	1,5	2,0
PACK-ICE^R	2,5-2,0	0,5/69,1	2,5-2,0	0,5/65,9	2,0	2,3
TVG	2,5-2,0	0,5/68,6	3,0-2,0	1/31,6	2,0	2,5
BOUV-CT	2,5-1,5	1/55,6	2,5-2,0	0,5/33,4	2,0	2,3
AJAX	2,2-2,0	0,2/20,4	3,0-2,0	1/55,7	2,1	2,5
SIBEX			4,0-2,0	2/28,6		3,0
SH1970			3,0-2,0	1/79,7		2,5
SANAE19	3,0-2,0	1/70,4	3,0-2,0	1/67,4	2,5	2,5
SANAE19^R	2,0-1,0	1/102,4	3,0-2,0	1/32,1	1,5	2,5
SANAE23	3,0-2,0	1/152,0	2,5-2,0	0,5/84,5	2,5	2,3
SANAE24			3,0-2,0	1/175,7		2,5
SANAE24	2,0-1,0	1/184,8	2,5-2,0	0,5/87,0	1,5	2,3
SANAE24			2,5-2,0	0,5/18,3		2,3
SANAE25	3,0-2,0	1/28,5	2,0-1,0	1/160,6	2,5	1,5
SANAE20	2,5-2,0	0,5/78,1	2,5-2,0	0,5/48,2	2,3	2,3
SANAE20^R	2,5-2,0	0,5/36,1	3,0-2,0	1/55,6	2,3	2,5
SANAE22	3,0-2,0	1/41,3	3,0-2,0	1/52,9	2,5	2,5
SANAE22^R	2.5-2.0	0.5/36,0	3,0-2.0	1/97,5	2,3	2,5
SANAE21	3,0-2,0	1/68,6	3,0-2.0	1/50,8	2.5	2,5
SANAE21^R	3,0-2,0	1/81,1	3.0-2.0	1/51,1	2,5	2,5
Mean	0,8	0,01	0,8	0,02	2,1	2,3
Standard deviation	0,3	0,01	0,5	0,01	0,5	0,3

Weddell-Scotia Confluence

The Weddell-Scotia Confluence has been identified by its northern boundary, namely the Scotia Front. The Scotia Front has been defined as the front that occurs at the position of the 1° C isotherm in the 300 m to 500 m depth layer (see figure 5.5).

The detailed geographic locations, widths, middle temperatures, thermal gradients, thermal ranges, and their standard deviations and means, have been determined for the thermal surface and sub-surface expression of the Weddell-Scotia Confluence and are presented in tables 5.9 and 5.10.

The Weddell-Scotia Confluence is traced from 1,3° E to 18,6° E in the sea surface temperature profile and from 1,4° E to 18,6° E in the sub-surface temperature profile (see table 5.9). The Weddell-Scotia Confluence lies in a slightly northeasterly direction south of Bouvet Island in the sea surface temperature profile, and joins the Antarctic Polar Front at 10° E. In the sub-surface temperature profile the Weddell-Scotia Confluence moves slightly northeast before continuing zonally south of Bouvet Island (see figure 6.2). This agrees with Belkin's (1996) results which trace the Weddell-Scotia Confluence south of Bouvet Island. These results also do not trace the Weddell-Scotia Confluence downstream of the South Sandwich Island Arc, agreeing with Clifford (1983).

The fact that many of the sections analysed in this study were not exactly perpendicular to the Weddell-Scotia Confluence has resulted in the calculated widths of this study being greater than previous studies. All sub-surface measurements in this study have not been taken at any specified reference depth as in other studies, but rather between 150 m and 500 m depth. This has resulted in characteristics (gradients, widths, ranges, positions) being obtained at sub-surface during this study, for the Weddell-Scotia Confluence, being different from other studies. Furthermore, this study has averaged the statistics of the Weddell-Scotia Confluence over the entire Southern Ocean south of Africa, and have therefore taken into account the times when the Weddell-Scotia Confluence meanders far southward, dropping in temperature.

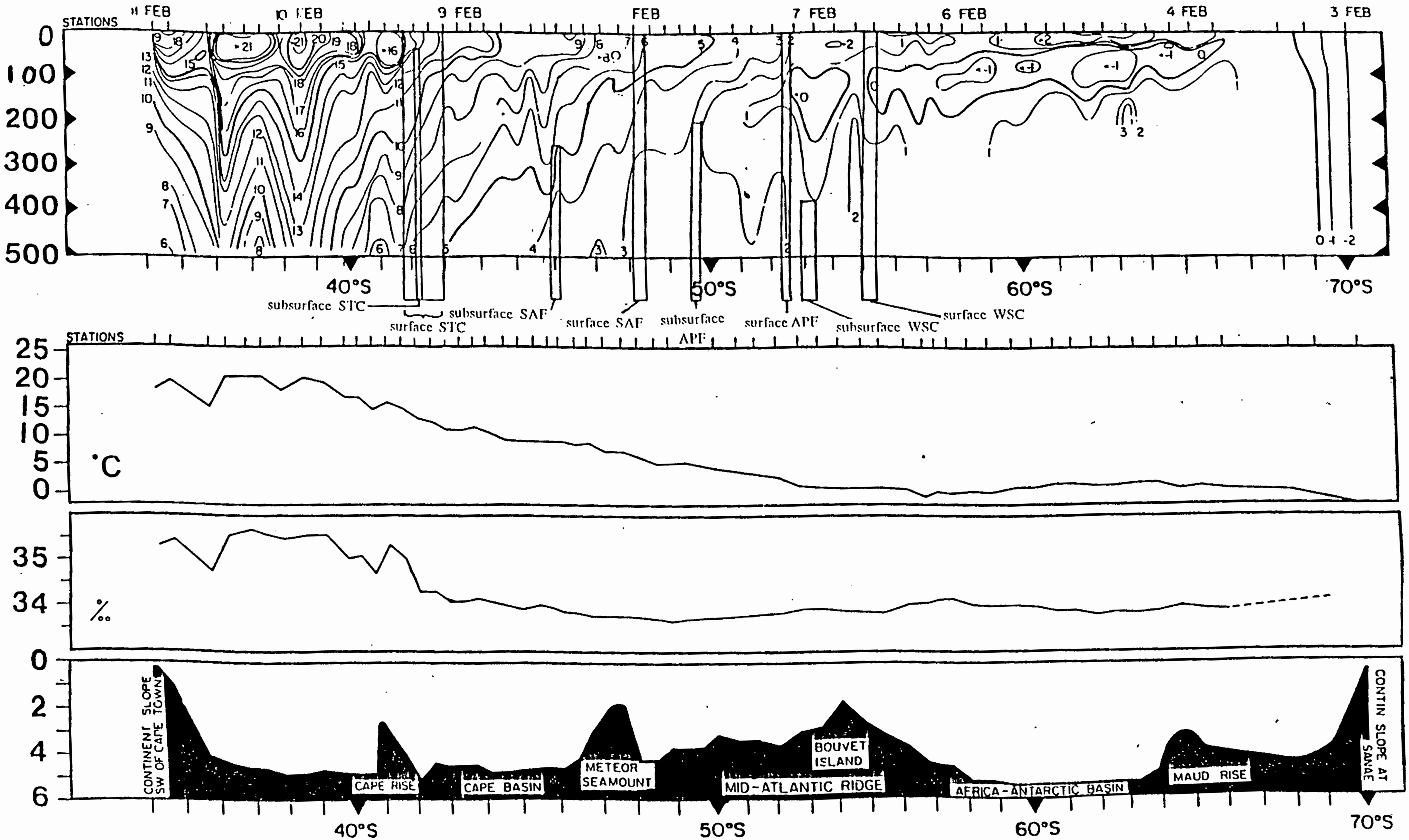

Figure 5.5 A meridional temperature section from the Sanae21 Cruise showing the Weddell-Scotia Confluence and other main Southern Ocean frontal systems.

Table 5.9 The locations and widths of the Weddell-Scotia Confluence.

Cruise	Sea surface latitudinal range(°S)	Sea surface longitudinal range(°E unless otherwise stated)	Sub-surface latitudinal range(°S)	Sub-surface longitudinal range(°E unless otherwise stated)	Sea surface mean position (°S;°E unless otherwise stated)	Sub-surface mean position (°S;°E unless otherwise stated)	Sea surface width (km)	Sub-surface width (km)
AJAX	53.8-54.6	1,3-1,3	54,9-55,8	1,3-1,5	54,2;1,3	55,3;1,4	89.1	100.6
SANAE 22	53,1-54,0	17,6-17.3	54,6-54,8	16,8-16,2	53,6; 17,4	54,7;16,5	53.0	104.6
SANAE 21	53,2-54,0	18,7-18,8	52,6-53,2	18,6-18,7	53,6;18,7	52,9; 18,6	80,1	81,6
SANAE 21^R	55,0-55.5	3,3-3,5°W	52,8-53,5	3,9-3,6	55,3; 3,4	53,1;3,7	71,2	78.9
Mean	0.7	0.2	0,6	0,3	54,2; 10,2	54,0; 10,1	73,3	91.4
Standard deviation	0.2	0,1	0,3	0,3	0,8;9,1	1,2;8,8	15,4	13,1

Table 5.10 The thermal characteristics of the Weddell-Scotia Confluence.

Cruise	Sea surface temperature range(°C)	Sea surface temperature gradient (°C/km)	Sub-surface temperature range(°C)	Sub-surface temperature gradient (°C/km)	Sea surface middle temperature (°C)	Sub-surface middle temperature (°C)
AJAX	1,5-1.0	0.5/89.1	1.6-1.0	0.6/100.6	1,3	1.3
SANAE24	2.0-1.0	1/83.6	2,0-1.0	1/83.6	1,5	1,5
SANAE22	1.5-1.0	0.5/53.0	1.0-0,5	0,5/104.6	1.3	0.8
SANAE21	1.5-1.0	0,5/80,1	1.5-1.0	0.5/81.6	1,3	1.3
SANAE21^R	1.5-1.0	0.5/71.2	1.5-1.0	0.5/78.6	1.3	1.3
Mean	0.5	0.01	0.5	0.01	1.3	1.1
Standard deviation	0	0	0.1	0.01	0	0,3

Antarctic Divergence

The Antarctic Divergence has been defined as the front that occurs where the upwelled, warm deep waters are thought to break the cold surface layer of -1° C water at roughly 65° S (see figure 5.6).

The detailed geographic locations, widths, middle temperatures, thermal gradients, thermal ranges, and their standard deviations and means, have been determined for the thermal surface and sub-surface expression of the Antarctic Divergence and are presented in tables 5.11 and 5.12.

The Antarctic Divergence is traced from 0,5° W to 18° E in both the sea surface temperature profile and the sub-surface temperature profile. Both temperature profiles are very similar, with the Antarctic Divergence running fairly zonally across the Southern Ocean at roughly 65° S (see tables 6.1 and 6.2). These profiles compare well with the results of Deacon (1982) that reveal the Antarctic Divergence between 63° S to 68° S. This result therefore suggests that an Antarctic Divergence does exist.

The fact that many of the sections analysed in this study were not exactly perpendicular to the Antarctic Divergence has resulted in the calculated widths of this study being greater than previous studies. All sub-surface measurements in this study have not been taken at any specified reference depth as in other studies, but rather between 150 m and 500 m depth. This has resulted in characteristics (gradients, widths, ranges, positions) being obtained at sub-surface during this study, for the Antarctic Divergence, being different from other studies. Furthermore, this study has averaged the statistics of the Antarctic Divergence over the entire Southern Ocean south of Africa, and have therefore taken into account the times when the Antarctic Divergence meanders far southward, dropping in temperature.

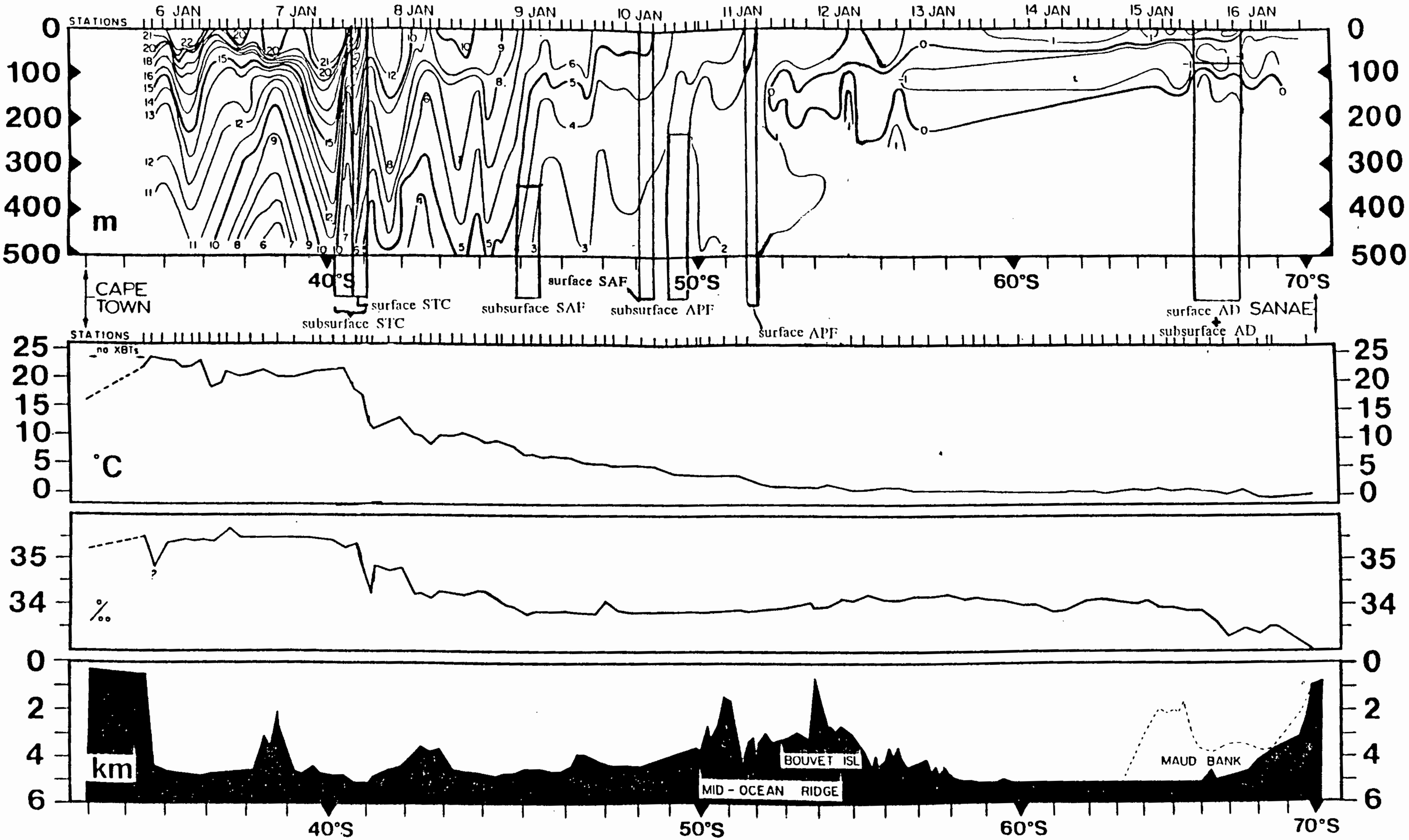

Figure 5.6 A meridional temperature section from the Sanae19 Cruise showing the Antarctic Divergence and other main Southern Ocean frontal systems.

Table 5.11 The locations and widths of the Antarctic Divergence.

Cruise	Sea surface latitudinal range(°S)	Sea surface longitudinal range(°E unless otherwise stated)	Sub-surface latitudinal range(°S)	Sub-surface longitudinal range(°E unless otherwise stated)	Sea surface mean position (°S:°E unless otherwise stated)	Sub-surface mean position (°S;°E unless otherwise stated)	Sea surface width (km)	Sub-surface width (km)
SANAE 19	66.1-67,7	3.2-3,3	66,1-67,7	3,2-3,3	66,9;3,3	66,9;3.3	146,6	146,6
SANAE 19[R]	65.2-65.7	5,5-4,8	65,2-65.7	5,5-4,8	65,5;5,2	65,5;5,2	64,3	64,3
SANAE 20	64.6-65.1	18,0-18,0	64.6-65.1	18,0-18.0	64,9;18.0	64,9;18,0	55,6	55,6
SANAE 22	65.4-65.8	0.7-0,4°W	65.4-65.8	0,7-0,4°W	65,6; 0,5°W	65,6; 0,5°W	46,6	46,6
Mean	0,8	0.3	0.8	0,3	65,7;6,7	65,7;6,7	78,4	78,3
Standard deviation	0,6	0,3	0.6	0,3	0,9;7,8	0,9;7,8	46,1	46,1

Table 5.12 The thermal characteristics of the Antarctic Divergence.

Cruise	Sea surface temperature range(°C)	Sea surface temperature gradient (°C/km)	Sub-surface temperature range(°C)	Sub-surface temperature gradient (°C/km)	Sea surface middle temperature (°C)	Sub-surface middle temperature (°C)
SANAE19	1.0-0	1/146.6	-1.0-(-1.0)	-	0.5	-1.0
SANAE19[R]	2.0-1.0	1/64.3	-1.0-(-1.0)	-	1.5	-1.0
SANAE20	-1.0-0	1/55.6	-1.0-(-1.0)	-	-0.5	-1.0
SANAE22	3.0-2.0	1/46.6	-1.0-(-1.0)	-	2.5	-1.0
Mean	1.0	0.02	0	-	1.0	-1.0
Standard deviation	0	0.01	0	-	1.3	0

Continental Water Boundary

The Continental Water Boundary has been defined as the front that occurs at the southern boundary of the warm, deep Upper Circumpolar Deep Water (see figure 5.7).

The detailed geographic locations, widths, middle temperatures, thermal gradients, thermal ranges, and their standard deviations and means, have been determined for the thermal surface and sub-surface expression of the Continental Water Boundary and are presented in tables 5.13 and 5.14.

The Continental Water Boundary has been traced zonally from only 3,1° W to 30° E in the sub-surface temperature profile (see figure 6.2). The sparse data coverage in this data set south of 60° S is probably the reason for the limited latitudinal range of the Continental Water Boundary in this study.

The fact that many of the sections analysed in this study were not exactly perpendicular to the Continental Water Boundary has resulted in the calculated widths of this study being greater than previous studies. All sub-surface measurements in this study have not been taken at any specified reference depth as in other studies, but rather between 150 m and 500 m depth. This has resulted in characteristics (gradients, widths, ranges, positions) being obtained at sub-surface during this study, for the Continental Water Boundary, being different from other studies. Furthermore, this study has averaged the statistics of the Continental Water Boundary over the entire Southern Ocean south of Africa, and have therefore taken into account the times when the Continental Water Boundary meanders far southward, dropping in temperature.

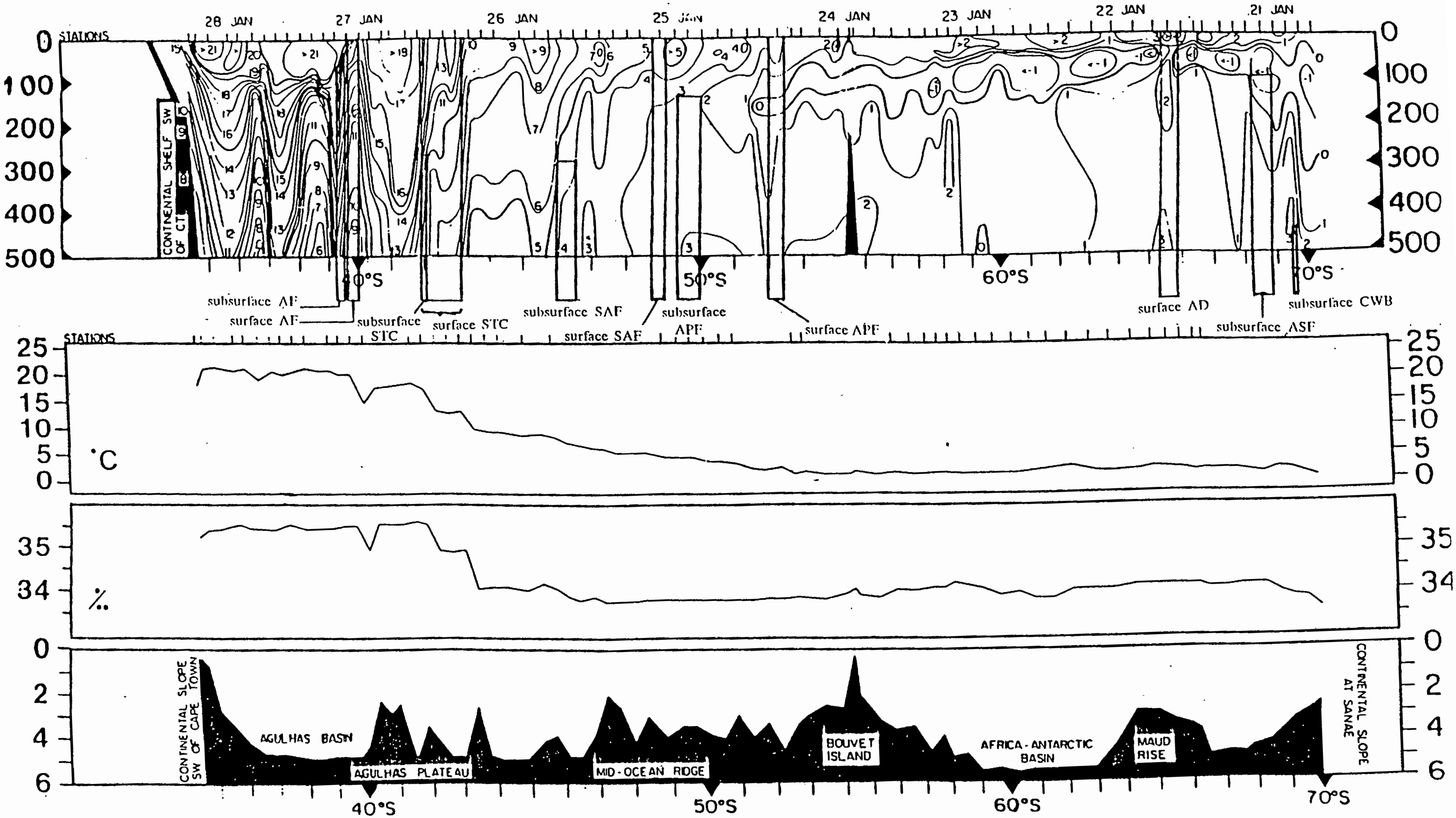

Figure 5.7 A meridional temperature section from the Sanae22 Cruise showing the Continental Water Boundary, Antarctic Slope Front and other main Southern Ocean frontal systems.

Table 5.13 The locations and widths of the Continental Water Boundary.

Cruise	Sub-surface latitudinal range(°S)	Sub-surface longitudinal range(°E unless otherwise stated)	Sub-surface mean position (°S;°E unless otherwise stated)	Sub-surface width (km)
SANAE 22	69,8-70,0	1,3-2.7	69,9;2.0	55,5
ANTX3	68,1-70,0	3,3-2,9°W	69,1; 3,1°W	209,9
FIBEX			68,5; 30,0	
Mean	0,7	0.6	69,2; 11,7	132,7
Standard deviation	1,0	0.7	0,7:15.9	109,2

Table 5.14 The thermal characteristics of the Continental Water Boundary.

Cruise	Sub-surface temperature range(°C)	Sub-surface temperature gradient (°C/km)	Sub-surface middle temperature (°C)
SANAE22	3.0-2.0	1/55.5	2.5
ANTX3[R]	1.0-0.5	0.5/209.9	0.8
FIBEX	-	-	1.0
Mean	0.5	0.01	1.4
Standard deviation	0.5	0.01	1.0

Antarctic Slope Front

The Antarctic Slope Front has been defined as the front that occurs where the 0° C isotherm dips sharply beneath the sub-surface temperature minimum layer in the vicinity of the shelf break at Antarctica (see figure 5.7).

The detailed geographic locations, widths, middle temperatures, thermal gradients, thermal ranges, and their standard deviations and means, have been determined for the thermal surface and sub-surface expression of the Antarctic Slope Front and are presented in tables 5.15 and 5.16. The Antarctic Slope Front is traced from 12,2° W to 61° E in the sub-surface temperature profile. It dips south at about 0° E and joins the Continental Water Boundary before moving northwards and separating from the Continental Water Boundary. So although the Continental Water Boundary and Antarctic Slope Front briefly join, the Antarctic Slope Front is a single and separate front of the Continental Water Boundary (see figures 6.1 and 6.2). On all four sections of the Antarctic Slope Front no V-shaped double Antarctic Slope Front as proposed by Jacobs (1991) and Foster and Carmack (1976) was observed, presumably as the result of the narrow continental shelf of the Antarctic continent at these four sections.

The fact that many of the sections analysed in this study were not exactly perpendicular to the Antarctic Slope Front has resulted in the calculated widths of this study being greater than previous studies. All sub-surface measurements in this study have not been taken at any specified reference depth as in other studies, but rather between 150 m and 500 m depth. This has resulted in characteristics (gradients, widths, ranges, positions) being obtained at sub-surface during this study, for the Antarctic Slope Front, being different from other studies. Furthermore, this study has averaged the statistics of the Antarctic Slope Front over the entire Southern Ocean south of Africa, and have therefore taken into account the times when the Antarctic Slope Front meanders far southward, dropping in temperature.

Table 5.15 The locations and widths of the Antarctic Slope Front.

Cruise	Sub-surface latitudinal range(°S)	Sub-surface longitudinal range (°E unless otherwise stated)	Sub-surface mean position (°S:°E unless otherwise stated)	Sub-surface width(km)
CONRAD	68,3-69,0	61.0-61.0	68,6;61,0	70,4
ANTX3	68,2-68,3	4,3-4.2°W	68,2;4,3°W	12,0
ANTX3^R	68,8-69,0	12.0-12.3°W	68,9;12,2°W	20.6
SANAE22	68,4-68.8	1.6-0.7	68,6;1,2	62,0
AJAX			69,4:0.3	
Mean	0,3	0,3	68.7:15.8	41,2
Standard deviation	0,3	0.4	0,4:25,7	29,2

Table 5.16 The thermal characteristics of the Antarctic Slope Front.

Cruise	Sub-surface temperature range(°C)	Sub-surface temperature gradient (°C/km)	Sub-surface middle temperature (°C)
CONRAD	1.5-0.0	1.5/70.4	0.8
ANTX3	0.5-(-1.0)	1.5/12.0	-0,3
ANTX3^R	0.5-(-1.0)	1.5/20.6	-0.3
SANAE22	0-(-1.0)	1/62.0	-0.5
Mean	1.4	0.1	-0.1
Standard deviation	0.3	0.1	0.6

CHAPTER 6

CONCLUSIONS

Past research using regular hydrographic surveys (Deacon, 1937; Mackintosh, 1946; Jacobs and Georgi, 1977 and Lutjeharms and Valentine, 1984) have revealed certain specific elements of the thermal nature of the main oceanic frontal systems at the sea surface of the Southern Ocean south of Africa. Sub-surface investigations into the nature of these main thermal oceanic fronts in the Southern Ocean south of Africa (Gordon, 1967; Emery, 1977 and Lutjeharms, 1985a) have started to increase the knowledge of these frontal systems. By using a newly gathered and assembled high-quality , closely spaced, sub-surface temperature data set of the Southern Ocean south of Africa, stretching over a decade, detail of the thermal nature and characteristics of these fronts over time and space has now been established.

What are the thermal nature and characteristics of these oceanic fronts?

Front	Mean surface position	Mean sub-surface position	Mean surface width (km)	Mean sub-surface width (km)	Mean surface middle tempera-ture (°C)	Mean sub-surface middle tempera-ture (°C)
AF	39,3°S; 22,7° E	39,1° S; 22,7° E	84	37	17,8	12,6
STC	41,8° S; 21,9° E	41,7° S; 22,0° E	146	79	14,3	8,4
SAF	48,7° S; 18,9° E	46,8° S; 19,9° E	73	77	4,4	4,0
APF	52,7° S; 14,9° E	49,2° S; 20,8° E	66	74	2,1	2,3
WSC	54,1° S; 10,2° E	54,0° S; 10,0° E	73	91	1,3	1,1
AD	65,7° S; 6,7° E	65,7° S; 6,7° E	78	78	1,0	-1,0
CWB	-	69,2° S; 11,7° E	-	133	-	1,4
ASF	-	68,7° S; 15,8° E	-	41	-	-0,1

Table 6.1 Mean nature and thermal characteristics of the main oceanic frontal systems in the Southern Ocean south of Africa determined during this study. The main fronts

are the AF (Agulhas Front), STC (Subtropical Convergence), SAF (Sub-antarctic Front), APF (Antarctic Polar Front), WSC (Weddell-Scotia Confluence), AD (Antarctic Divergence), CWB (Continental Water Boundary) and ASF (Antarctic Slope Front).(see figure 6.1 and 6.2)

Earlier investigations have consistently presented higher mean sea and sub-surface middle temperatures than this study. The mean sea surface temperature across the Subtropical Convergence is 14,3° C for this investigation, compared to earlier results of 15,5° C; across the Sub-antarctic Front from this investigation is 4,4° C, compared to 8° C; and across the Antarctic Polar Front is 2° C, compared to earlier results of 4° C.

These fronts meander greatly as they cross the Southern Ocean south of Africa. Previous estimates have either looked at these fronts between longitudes where the front remained fairly zonal or over a shorter longitudinal range, where the front's extensive north to south meandering was not observed. During this study however, the effects of the fronts meandering southward, and therefore decreasing in temperature, have been taken into account. The lower observed values of this study therefore are a function of averaging over a greater longitude than previous authors.

What is the longitudinal range of the Agulhas Front?

An Agulhas Front, separate from the Subtropical Convergence is only observed from 18,2° E to 24,7° E in the sea surface temperature profile and from 18,2° E to 24,6° E in the sub-surface temperature profile. The continual northward leakage of warm, salty water out of the Agulhas Return Current along its path removes the measurable identity of the Agulhas Front east of 25° E.

How often are the Agulhas Front and the Subtropical Convergence joined?

In 44% of the temperature sections investigated as part of this study the Agulhas Front had coalesced with the Subtropical Convergence to form a united front.

Does the Subtropical Convergence have a double frontal structure in the Central South Atlantic Ocean?

Although the Subtropical Convergence is present in the Central/South East Atlantic Ocean as a broad zone, no identifiable and separate North Subtropical Front and South Subtropical Front, was evident in this data set.

Is there a united STC/SAF north of the Crozet Plateau?

The Sub-antarctic Front is pressed northward from 45° S to 43° S by the Mid-Ocean Ridge in the South West Indian Ocean, causing it to converge with the Subtropical Convergence at about 60° E to form a united STC/SAF at the Crozet Plateau.

Does the united STC/SAF become the "Crozet Front" by confluencing with the Agulhas Front at 65° E.

No "Crozet Front" is evident in this data set, since the Sub-antarctic Front separates from the Subtropical Convergence east of 63° E, and no Agulhas Front is observed east of 25° E.

How often does the Antarctic Polar Front split into a primary and secondary Antarctic Polar Front?

In 30% of the temperature sections studied a separate 2° C isotherm, designating an isolated cold water cell, was found north of the main body of 2° C contiguous water. In these cases one could talk of a primary and a secondary Antarctic Polar Front.

Does the Antarctic Polar Front join the "Crozet Front" north of Kerguelen to form a quadruple front.

In neither the surface nor the sub-surface thermal expression of the front, does the Antarctic Polar Front join the Sub-antarctic Front in the vicinity of the Kerguelen Plateau. No quadruple front (AF/STC/SAF/APF) therefore is seen in this data set.

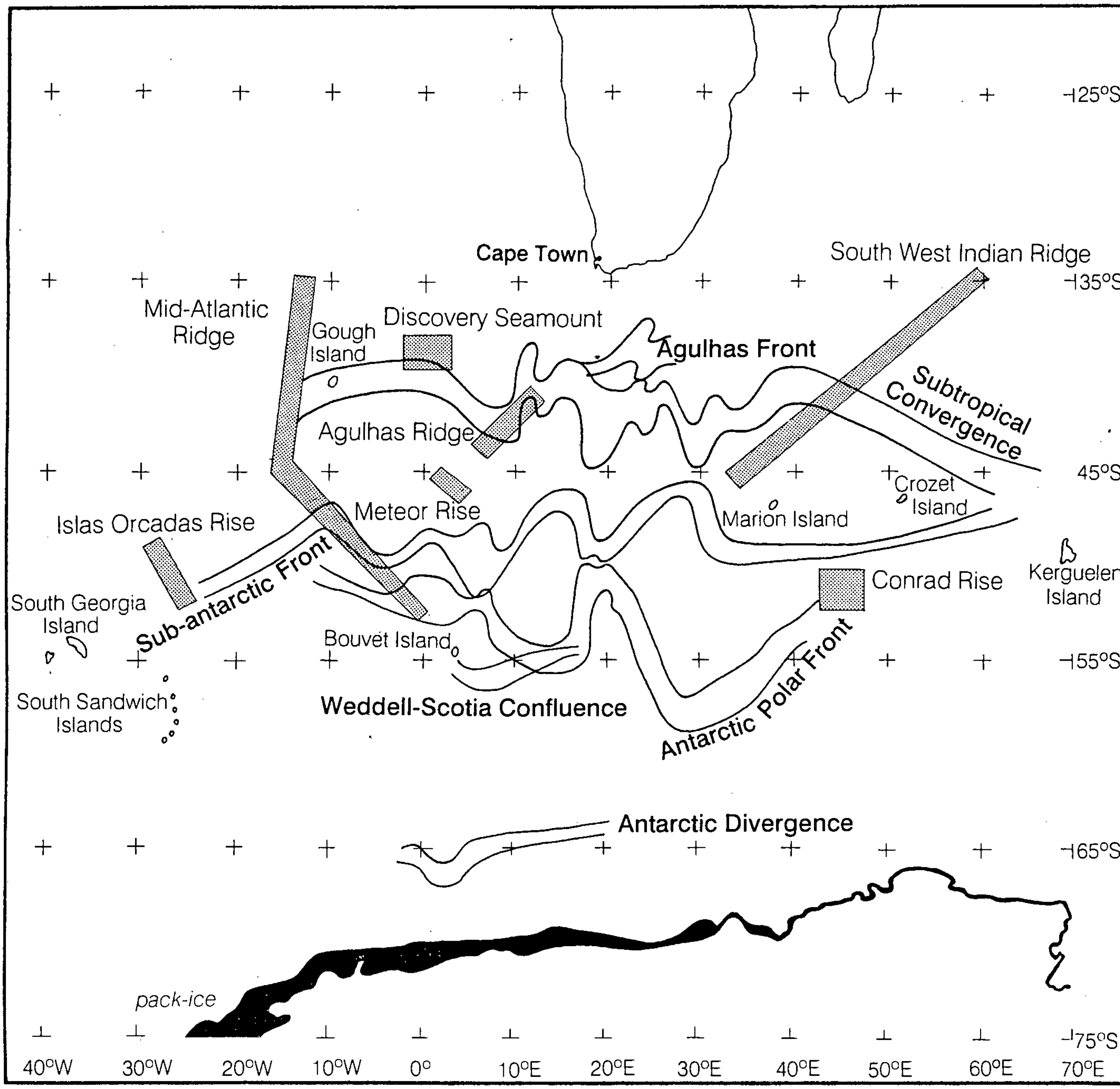

Figure 6.1 Geographic positions of the thermal expressions of all the fronts studied at the sea surface.

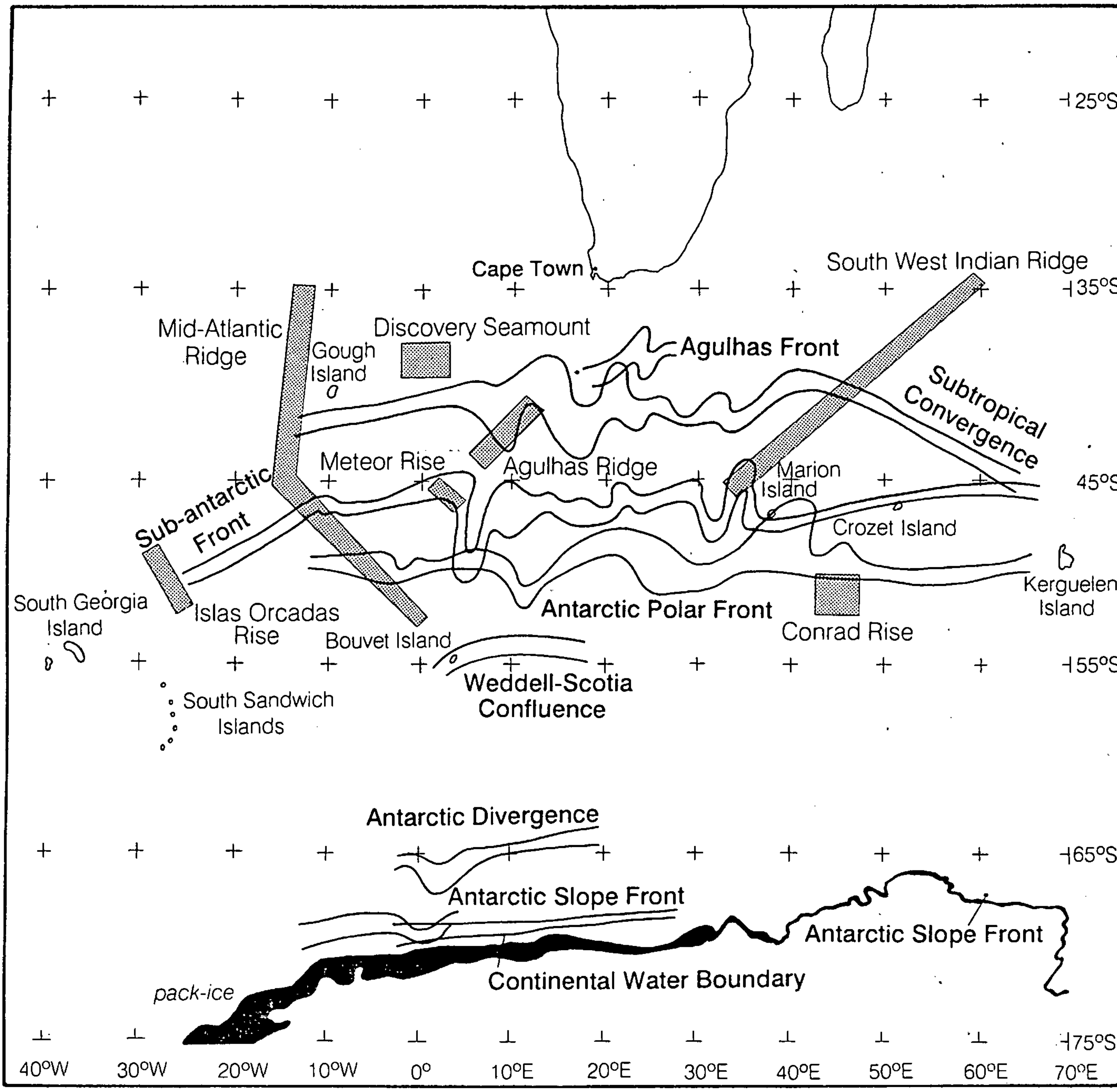

Figure 6.2 Geographic positions of the thermal expressions of all the fronts studied at the sub-surface.

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ADDENDUM

This addendum contains a representative temperature diagram from each of the remaining forty-three cruises used for this investigation which best depict the main thermal oceanic frontal systems in the Southern Ocean south of Africa.

Temperature diagrams

The information on the temperature diagrams of each cruise refer to the following:

The dates: The dates of specific stations given in day-month format.

The letters: The legs of the cruise.

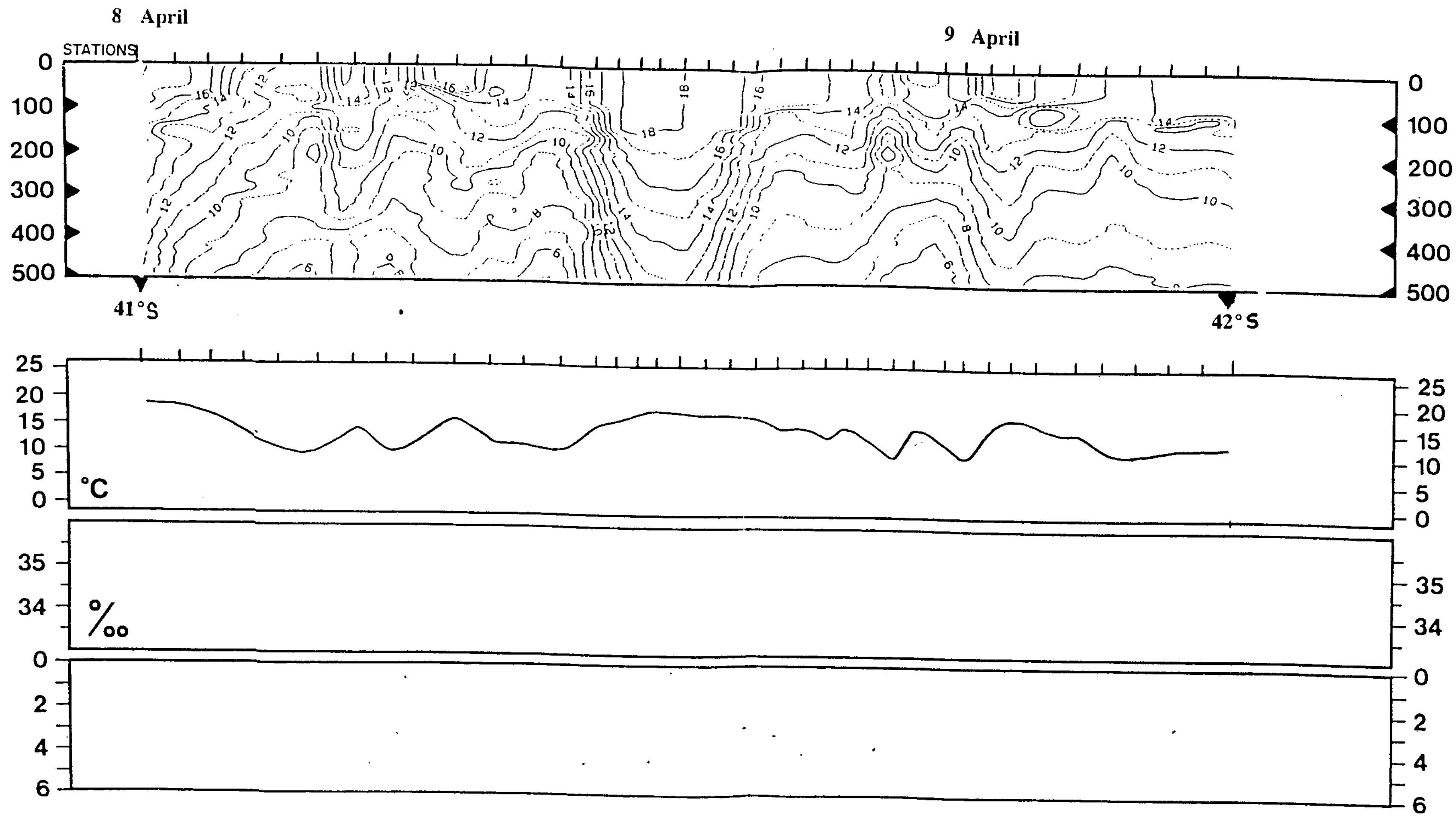
The broken vertical lines across the diagram: A new cruise leg.

The upper panel: The temperature section to 500 m depth.

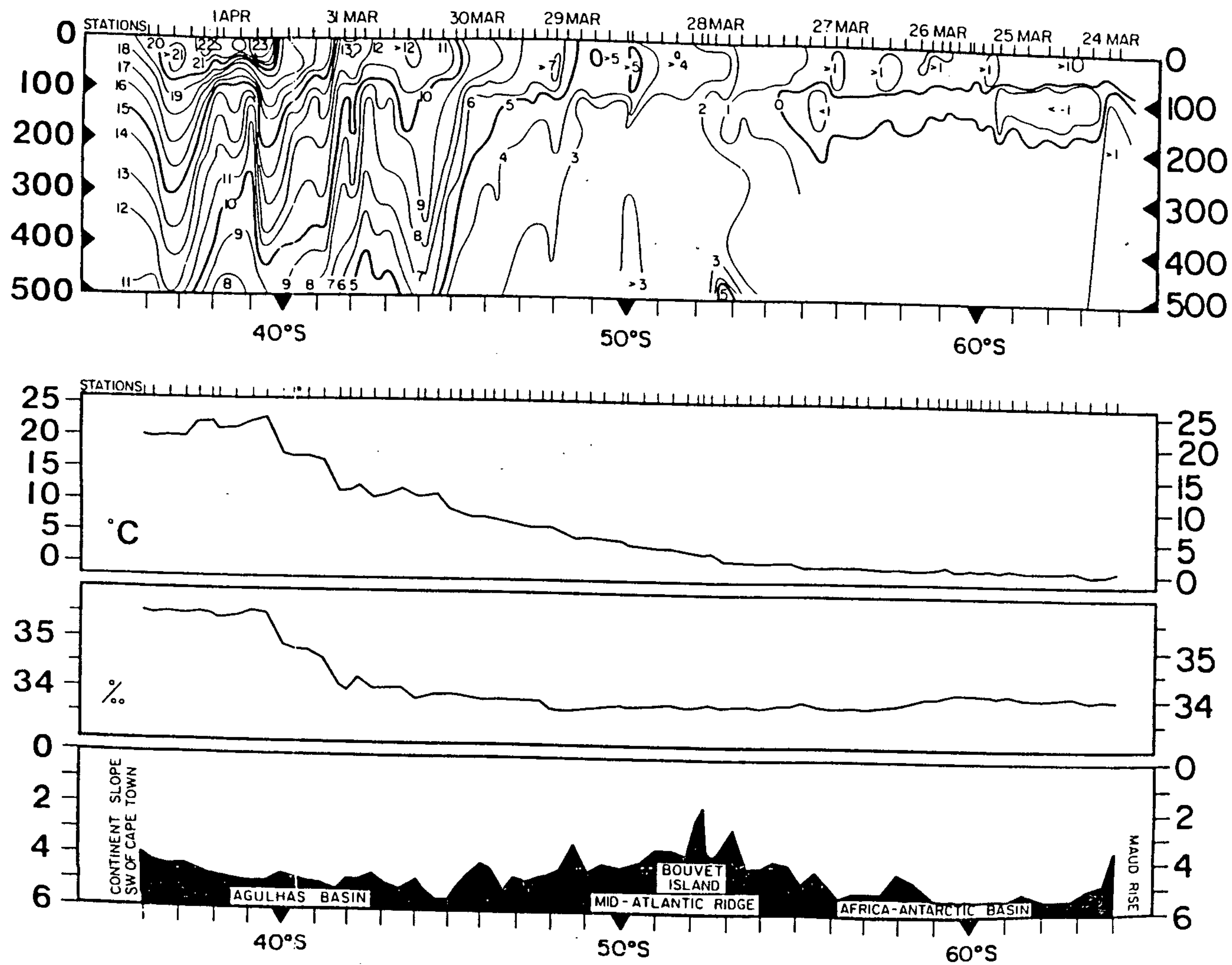
The second panel: The sea surface temperature trace (where available).

The third panel: The sea surface salinity trace (where available).

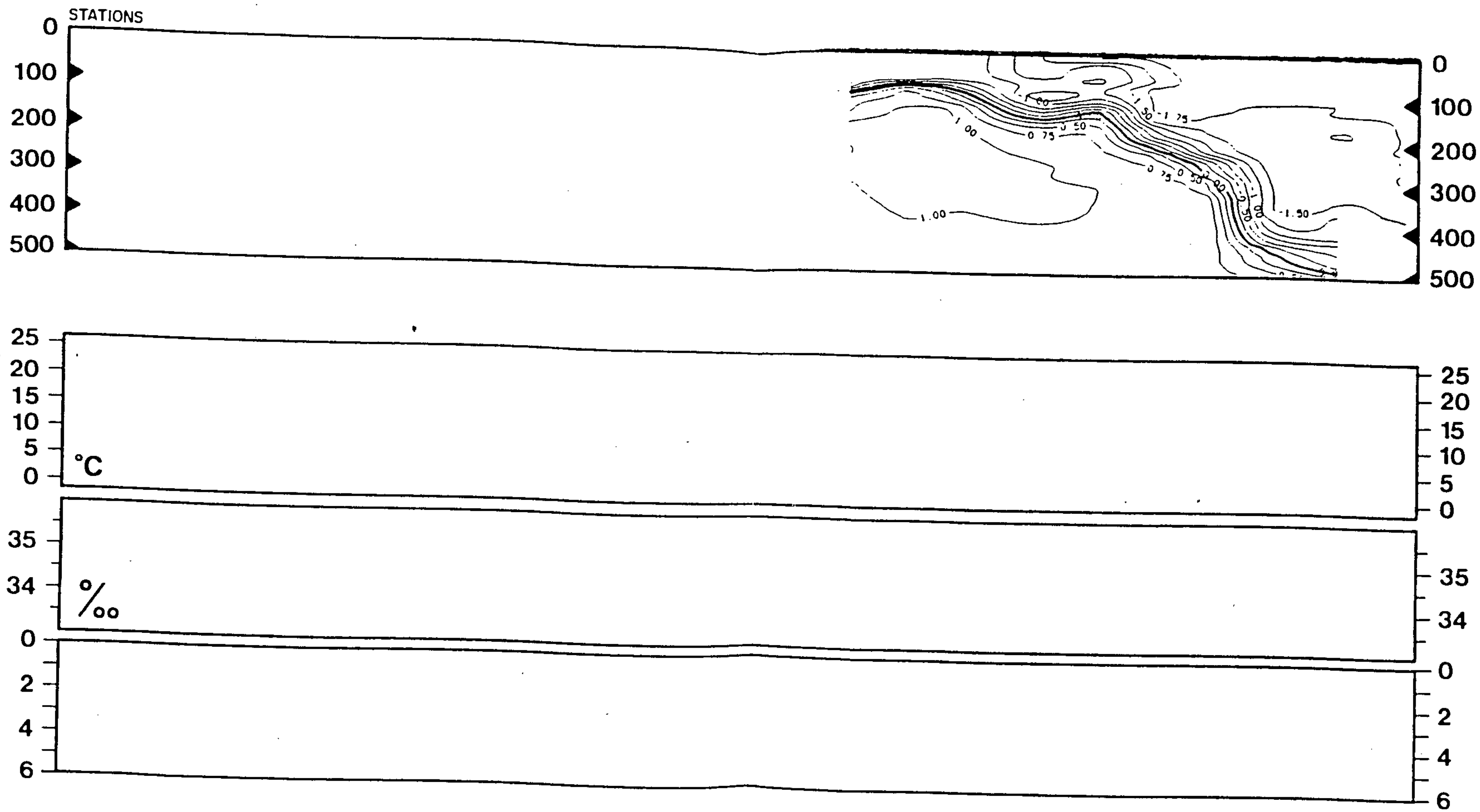
The bottom panel: The bathymetry (where available).



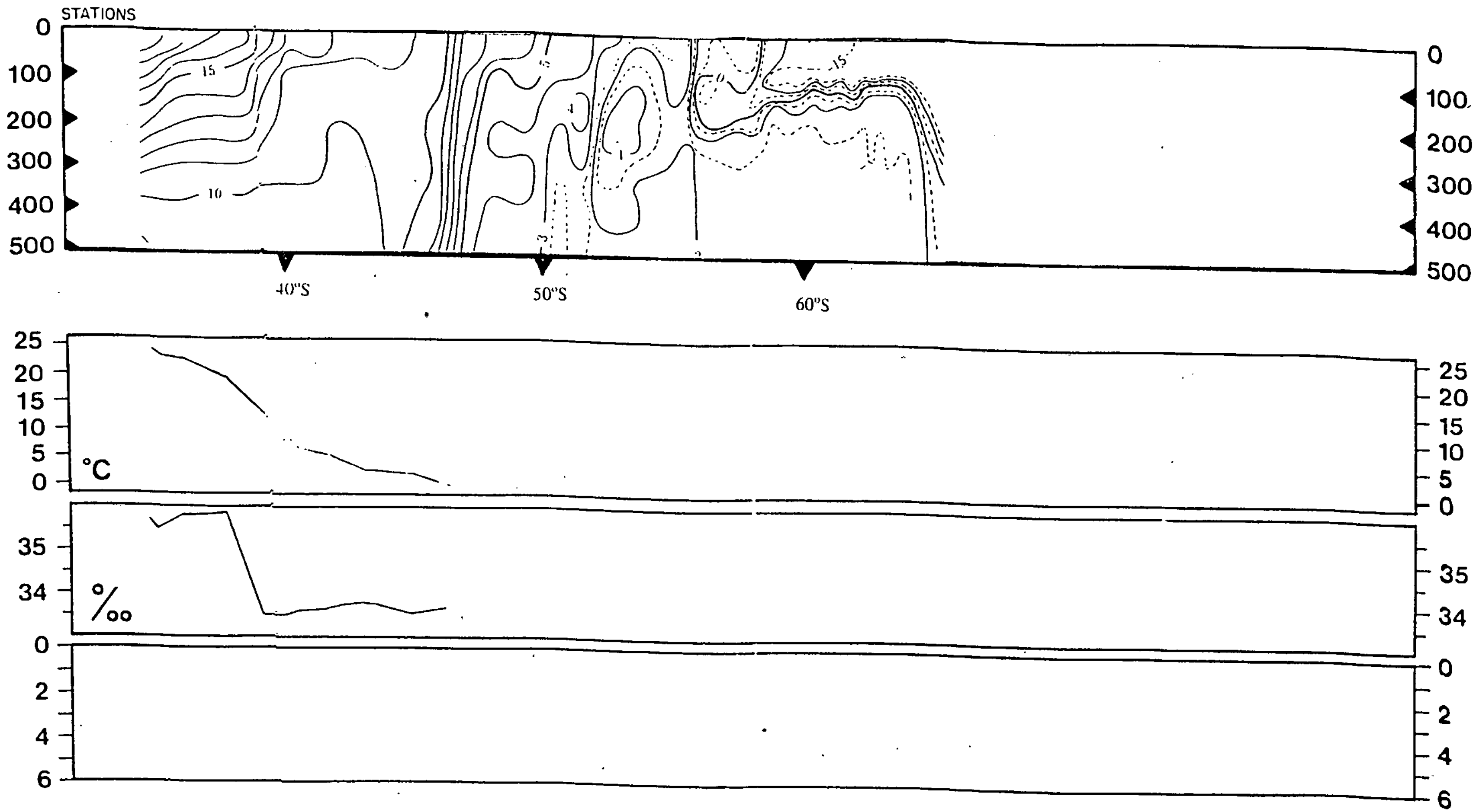
A meridional temperature section from the Saames 1 Cruise (5 April - 8 May 1991)



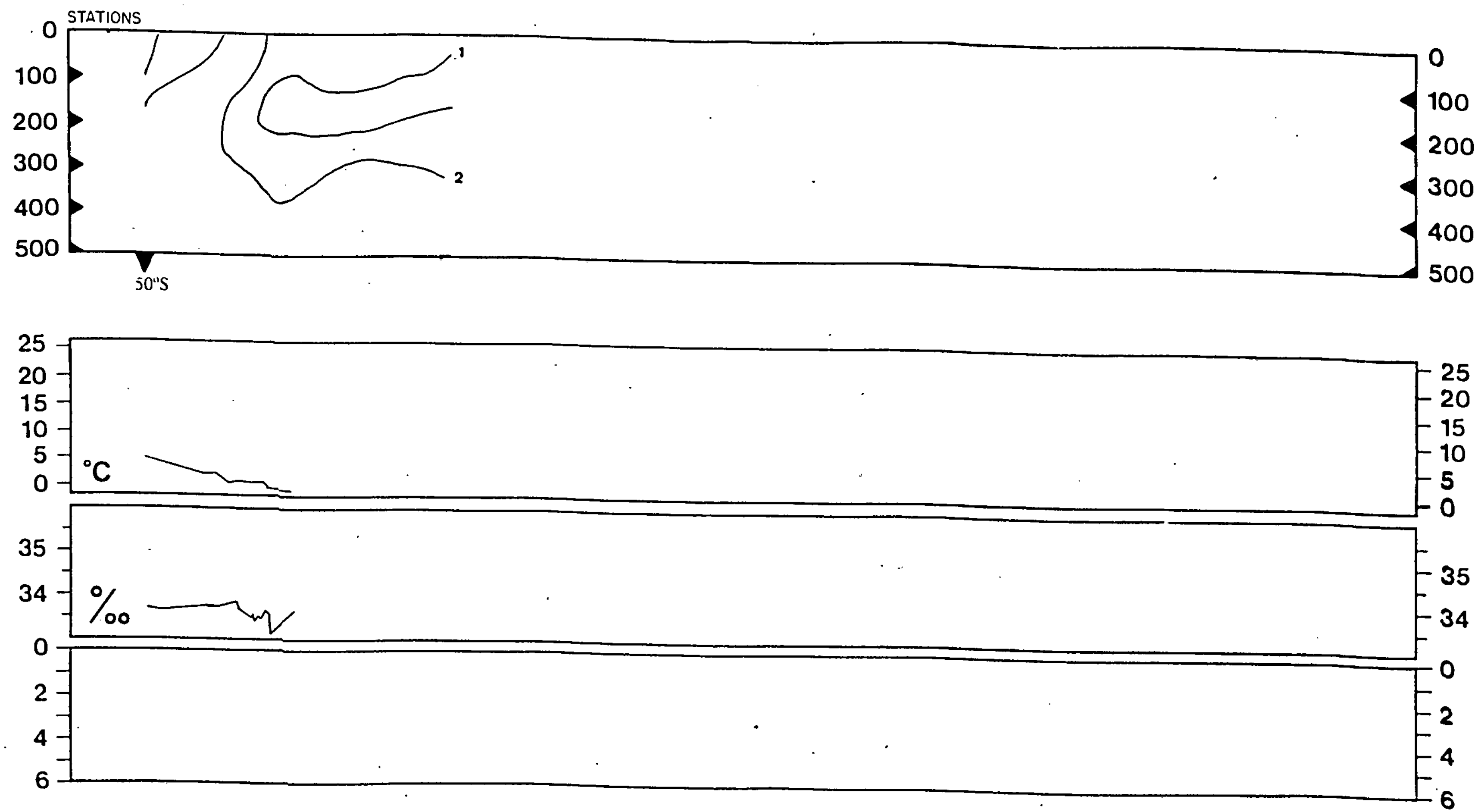
A meridional temperature section from the Krill Cruise (28 February - 2 April 1980)



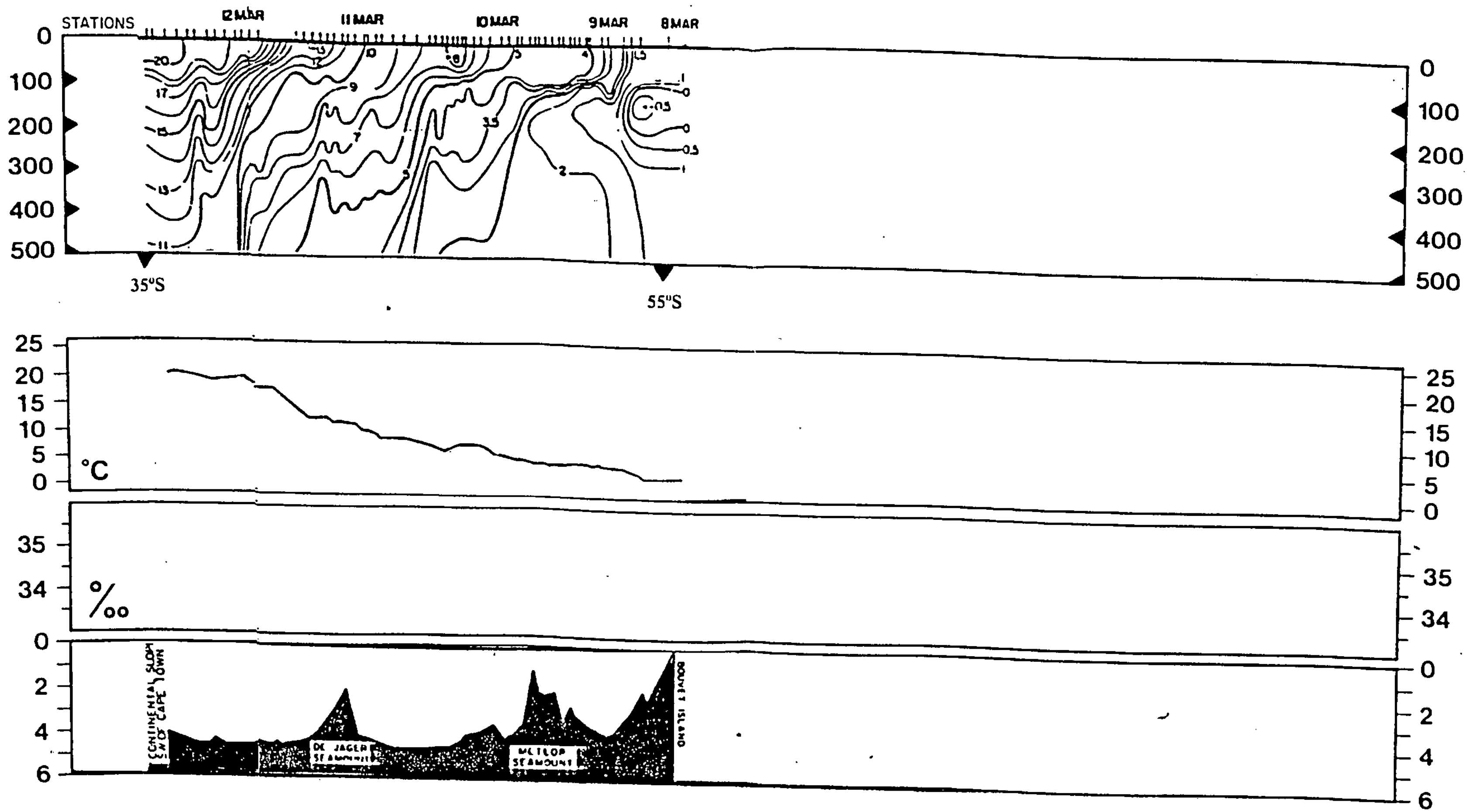
A meridional temperature section from the AntX3 Cruise (27 March - 19 May 1992)



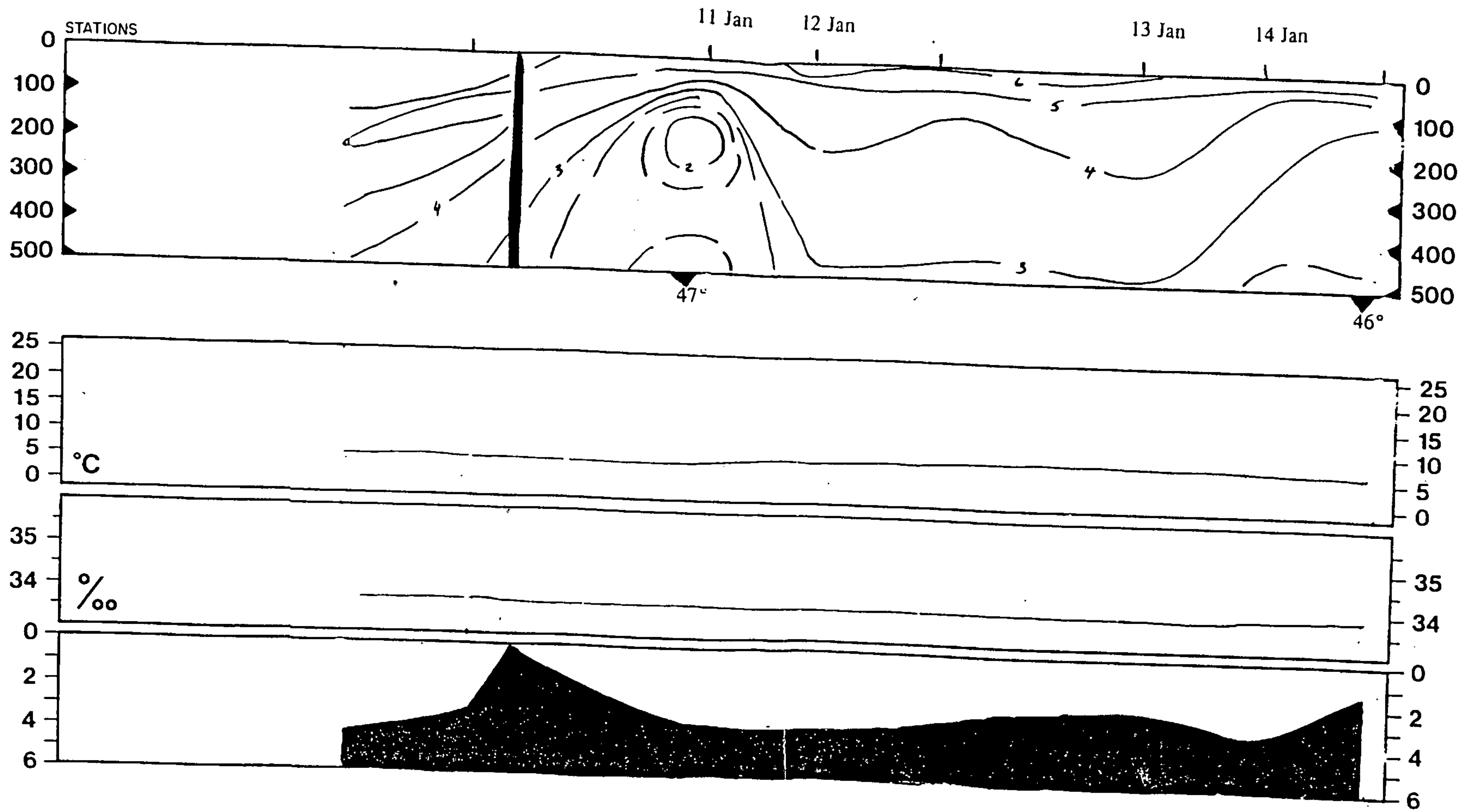
A meridional temperature section from the Jare 27 Cruise (November - April 1986)



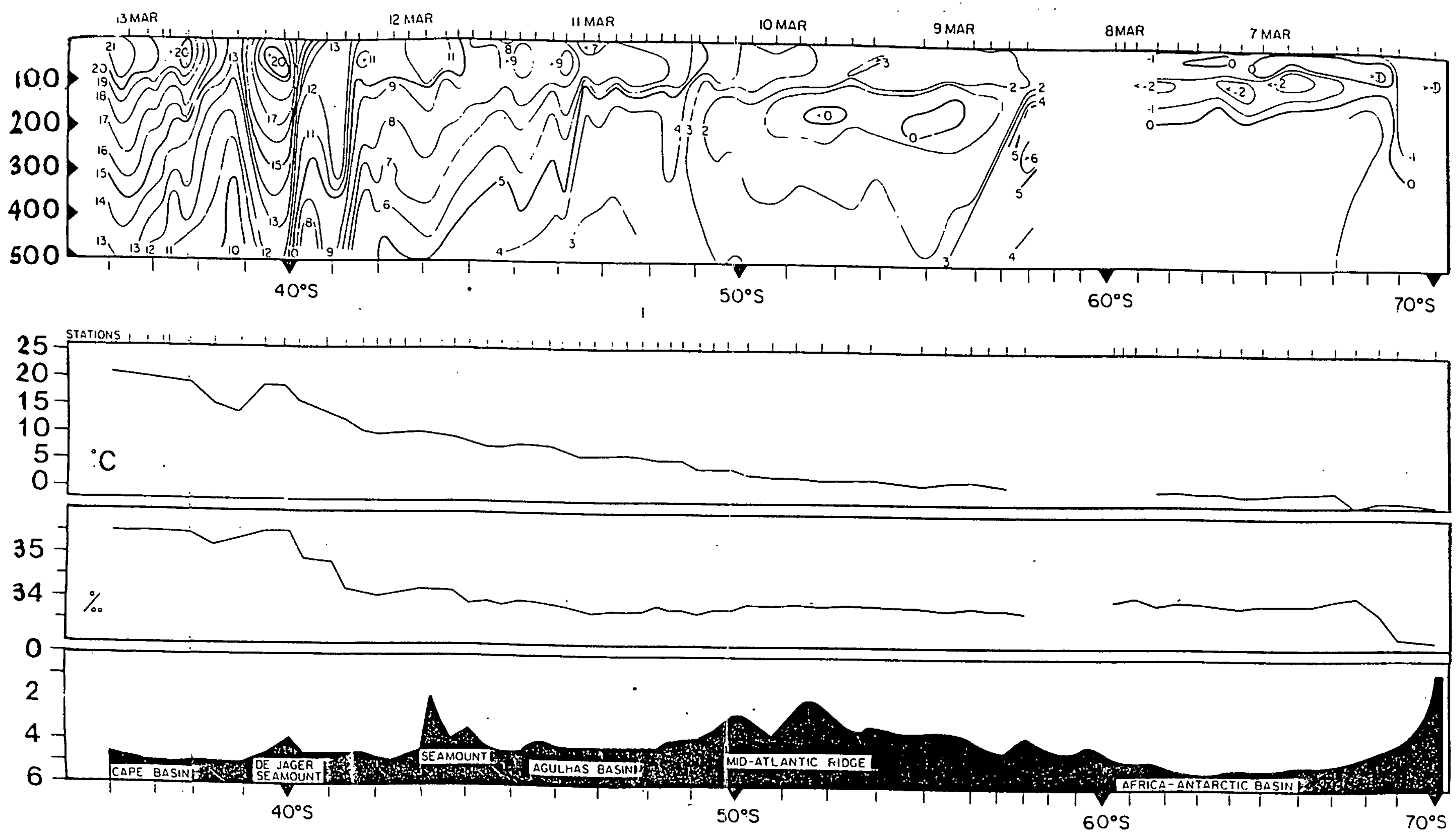
A meridional temperature section from the Jare 29 Cruise (November - March 1987)



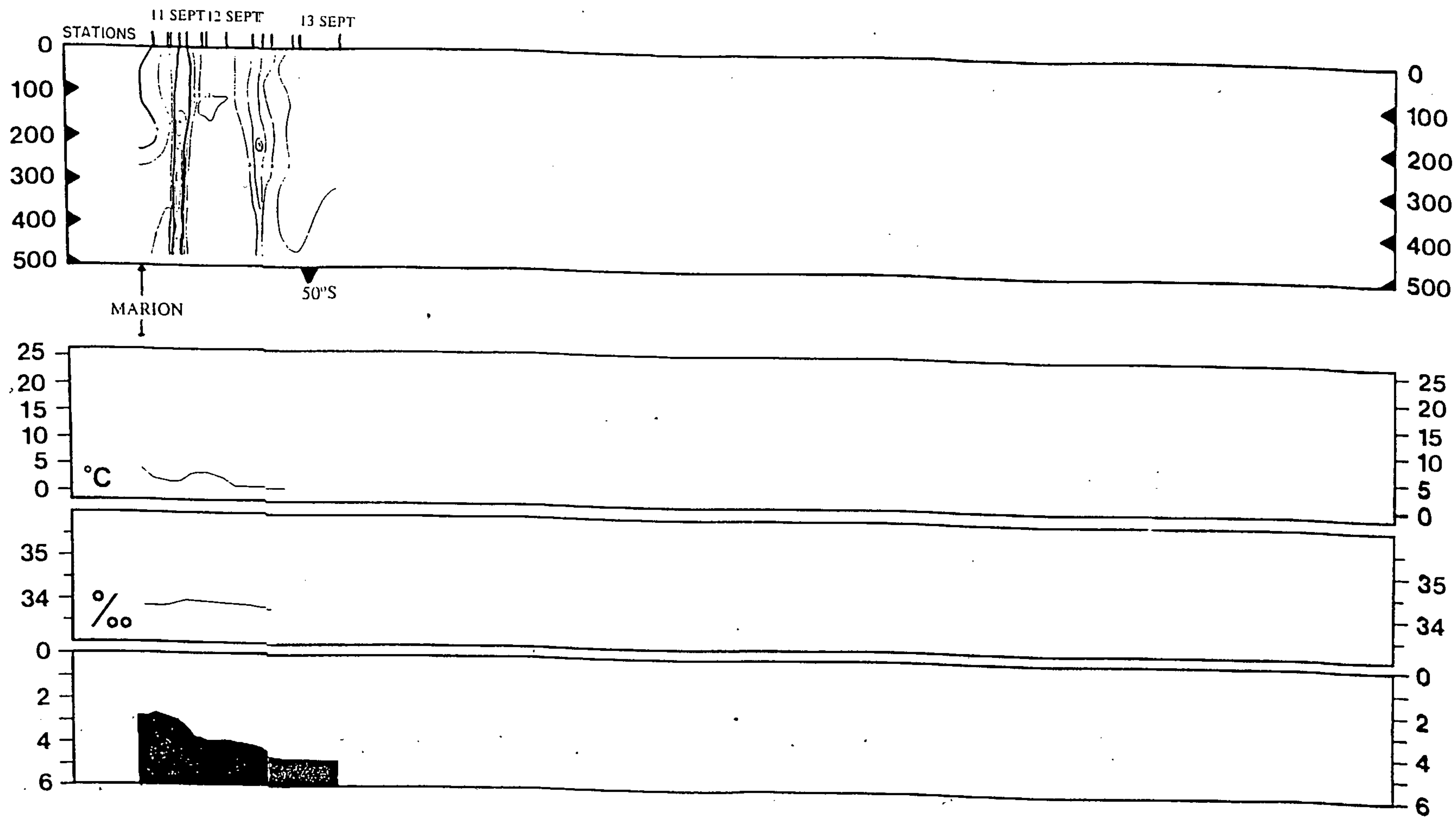
A meridional temperature section from the Bouvet-Cape Town Cruise (8 March - 13 March 1979)



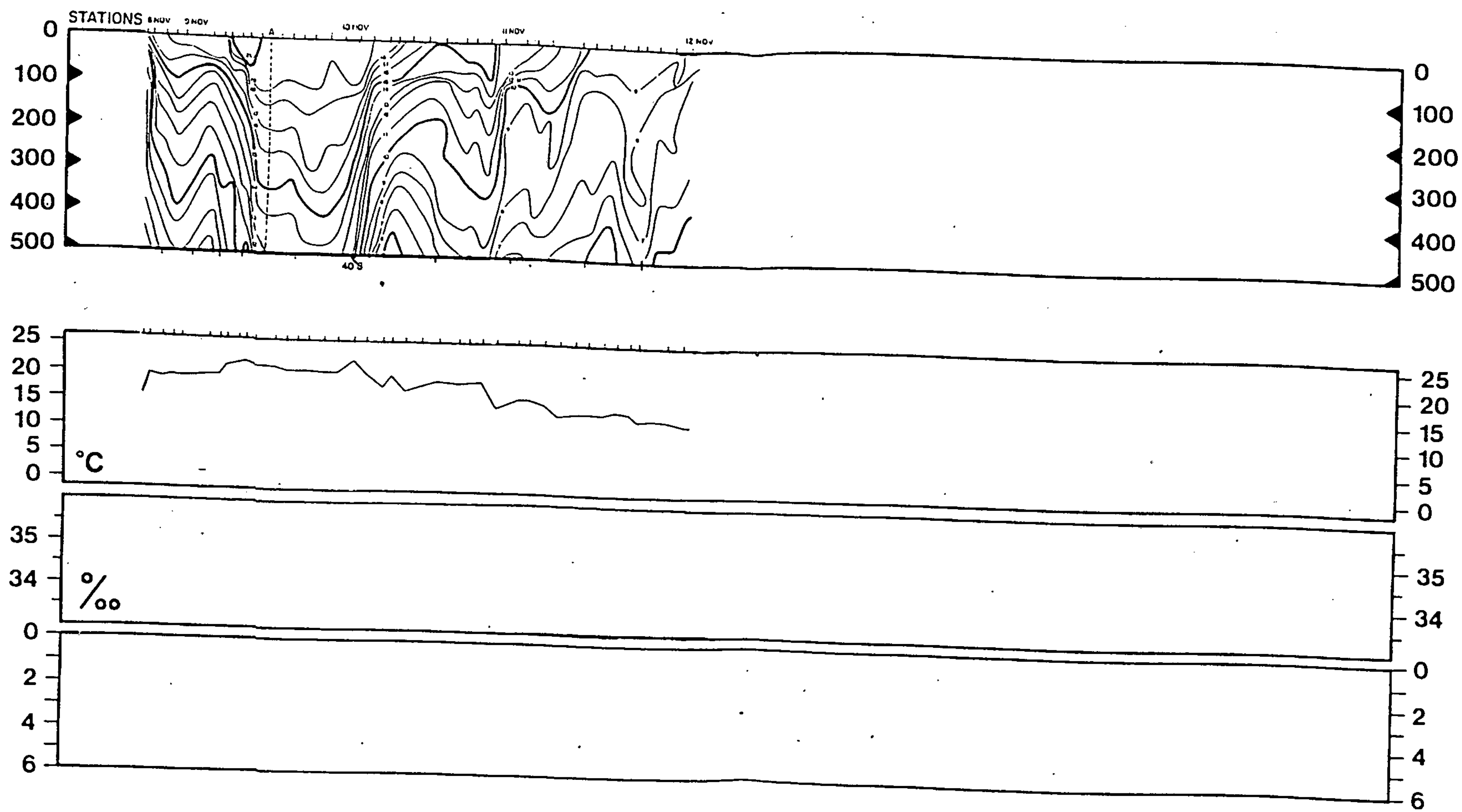
A meridional temperature section from the Conrad 17 Cruise (5 January - 11 April 1974)



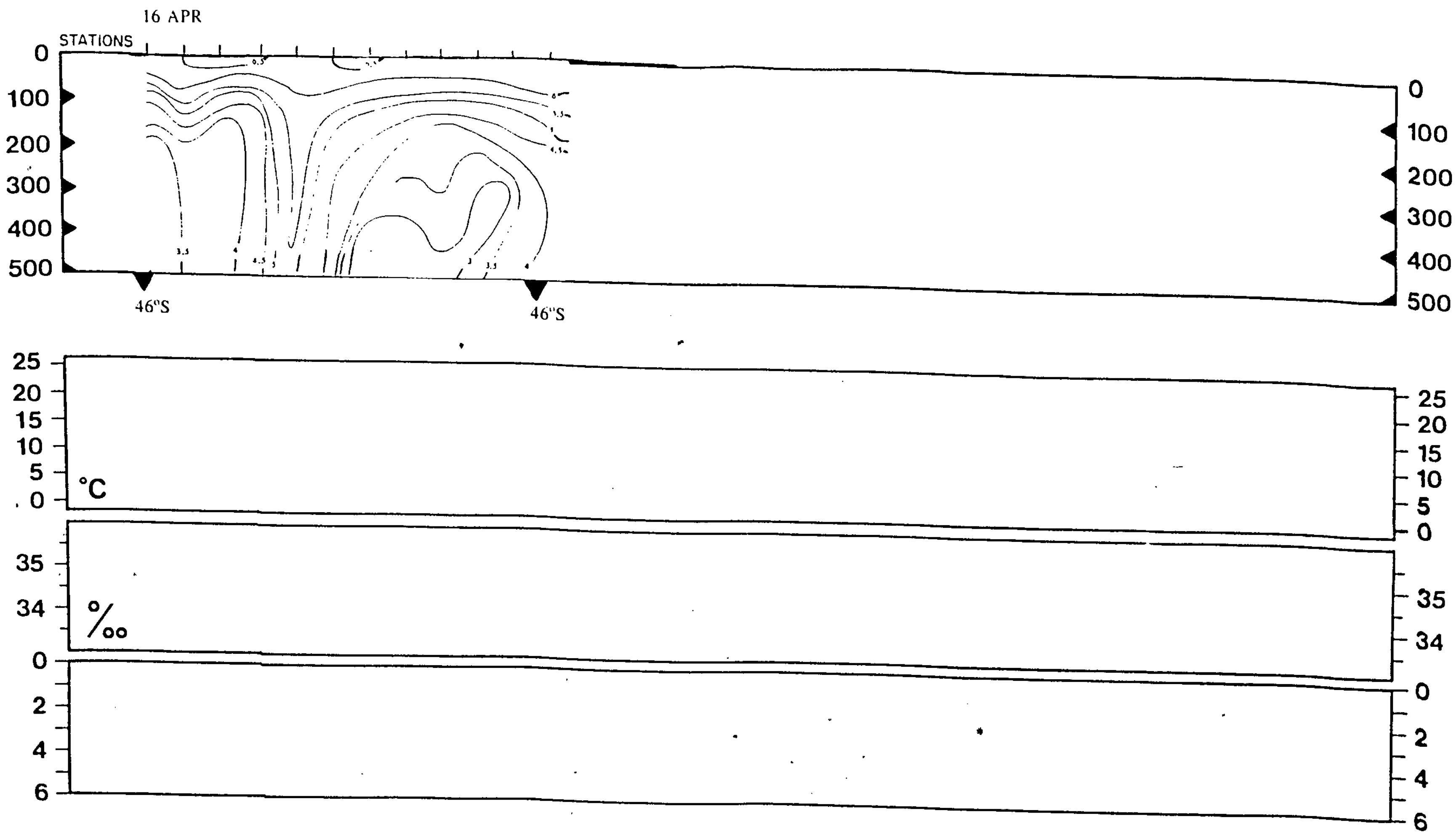
A meridional temperature section from the Marathon Cruise no. 3 (20 February - 26 March 1985)



A meridional temperature section from the Marion Cruise (September 1982)



A meridional temperature section from the Marion 83 Cruise (8 November - 21 November 1983)



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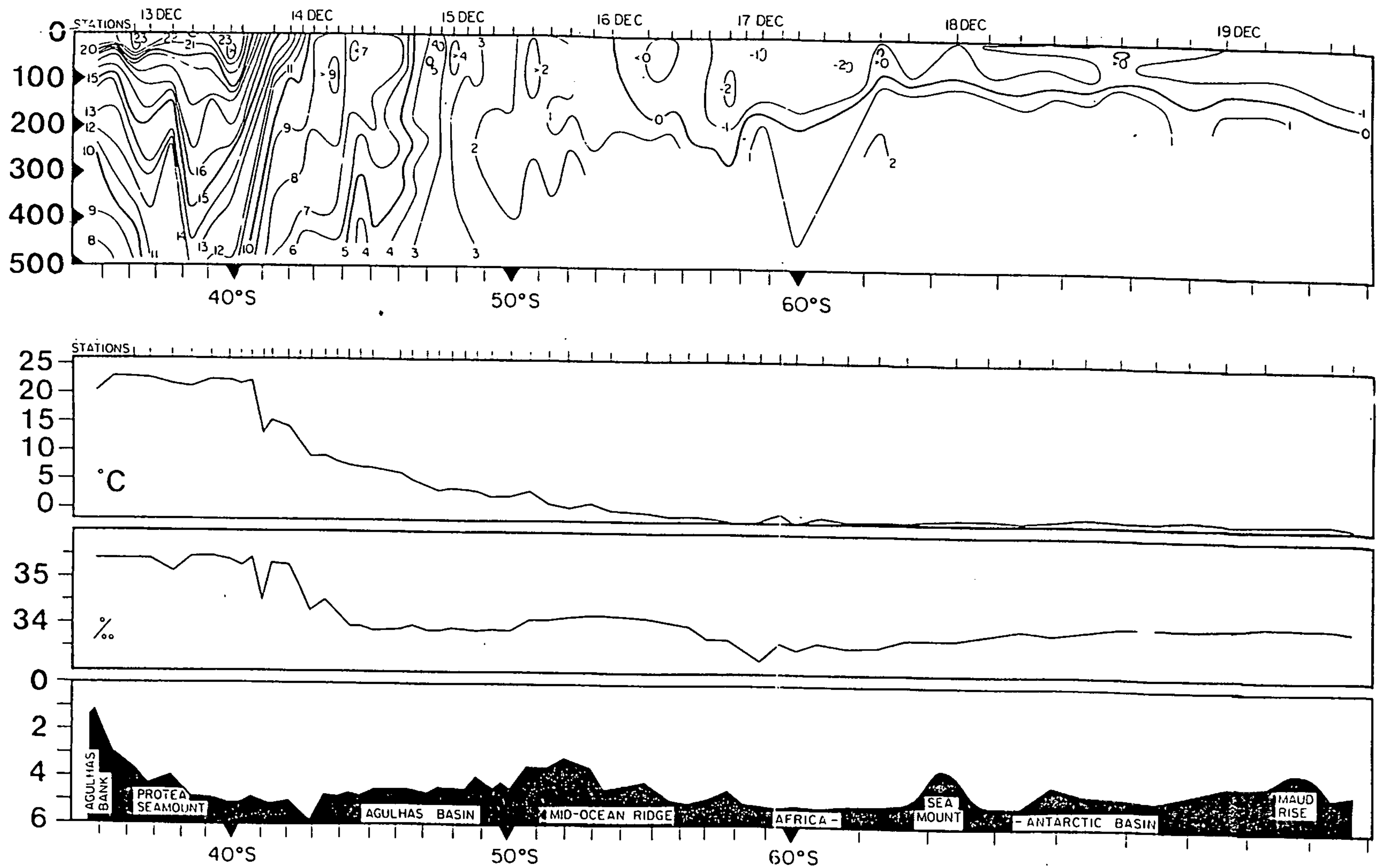
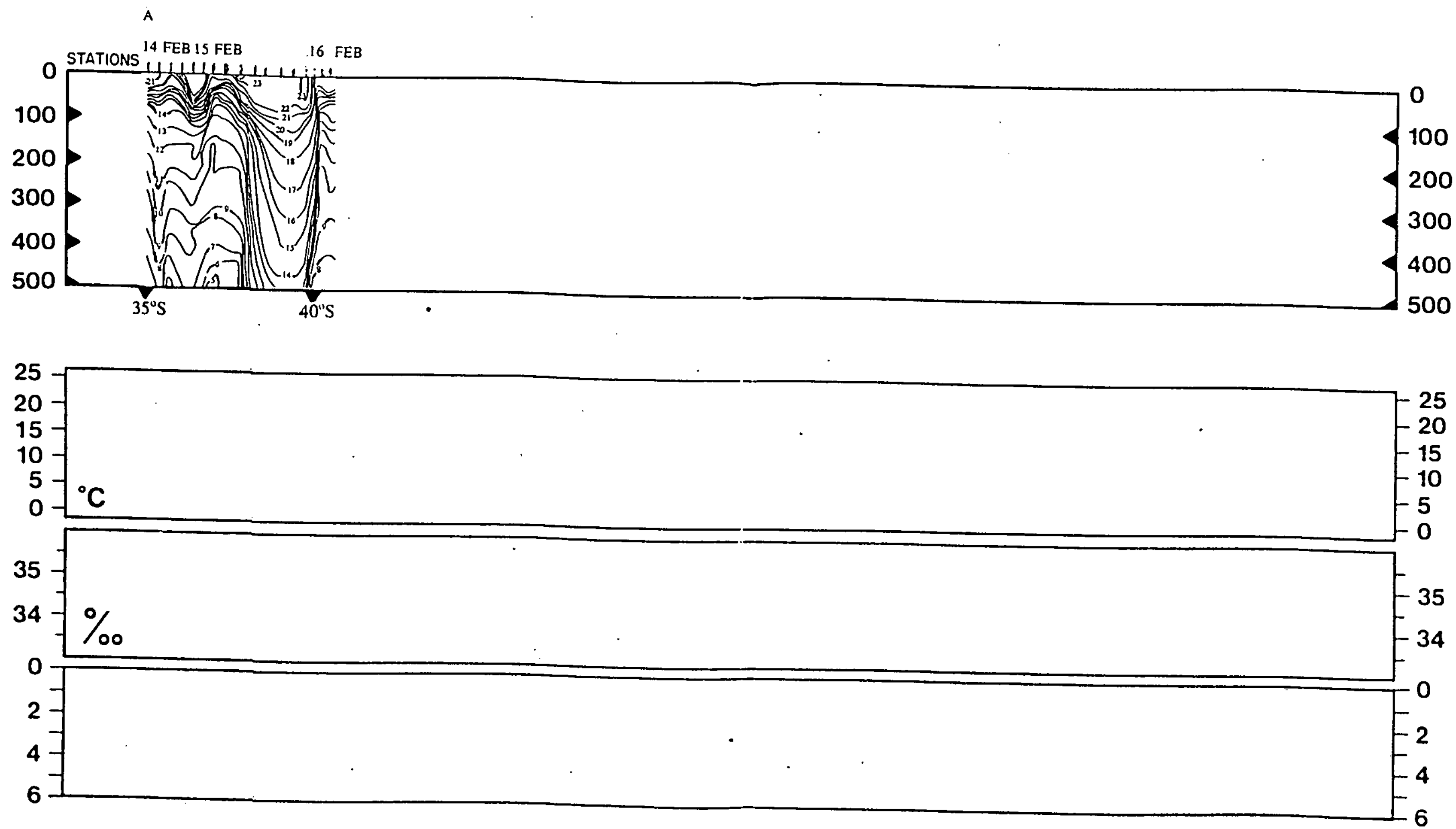
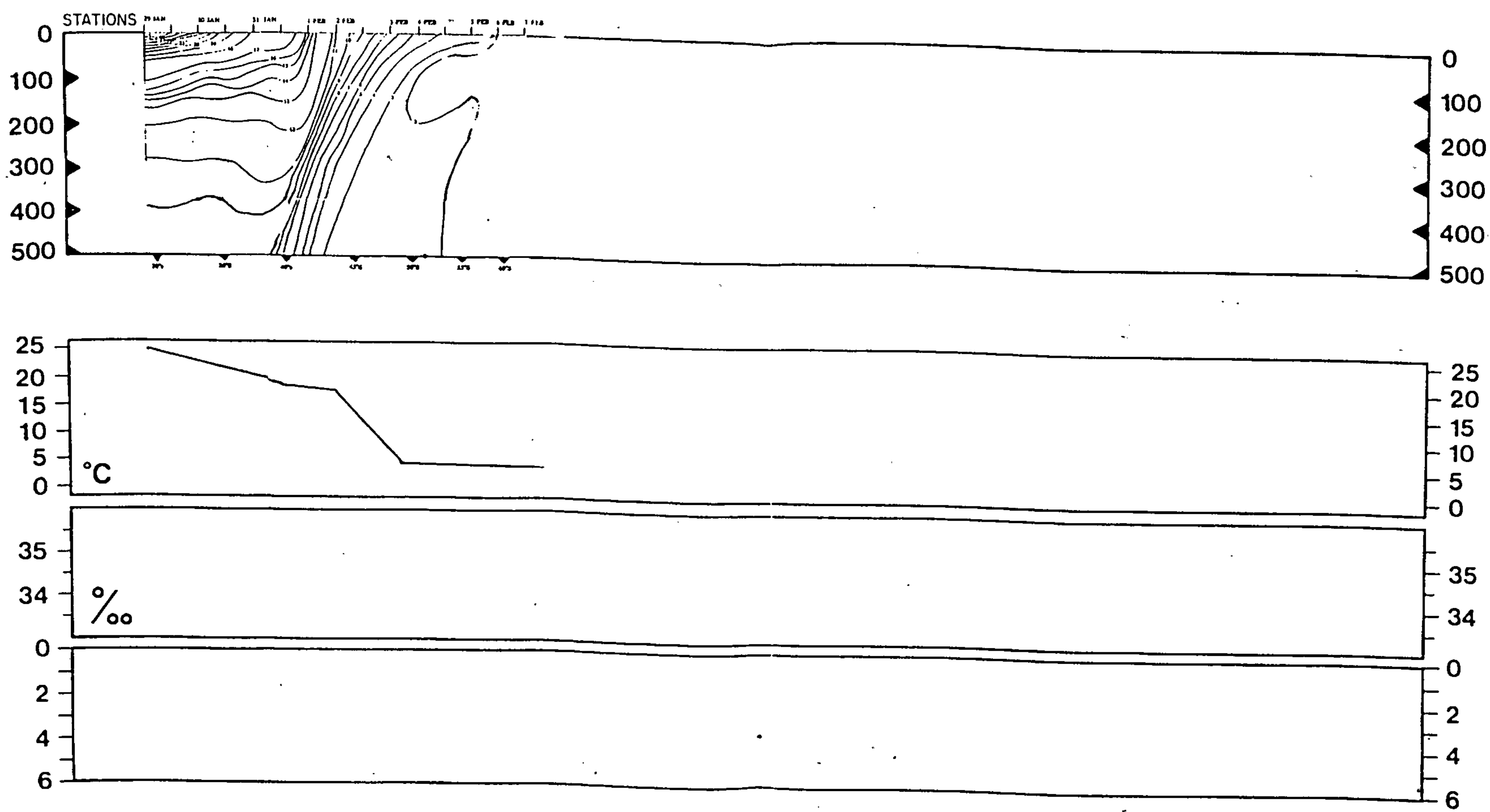


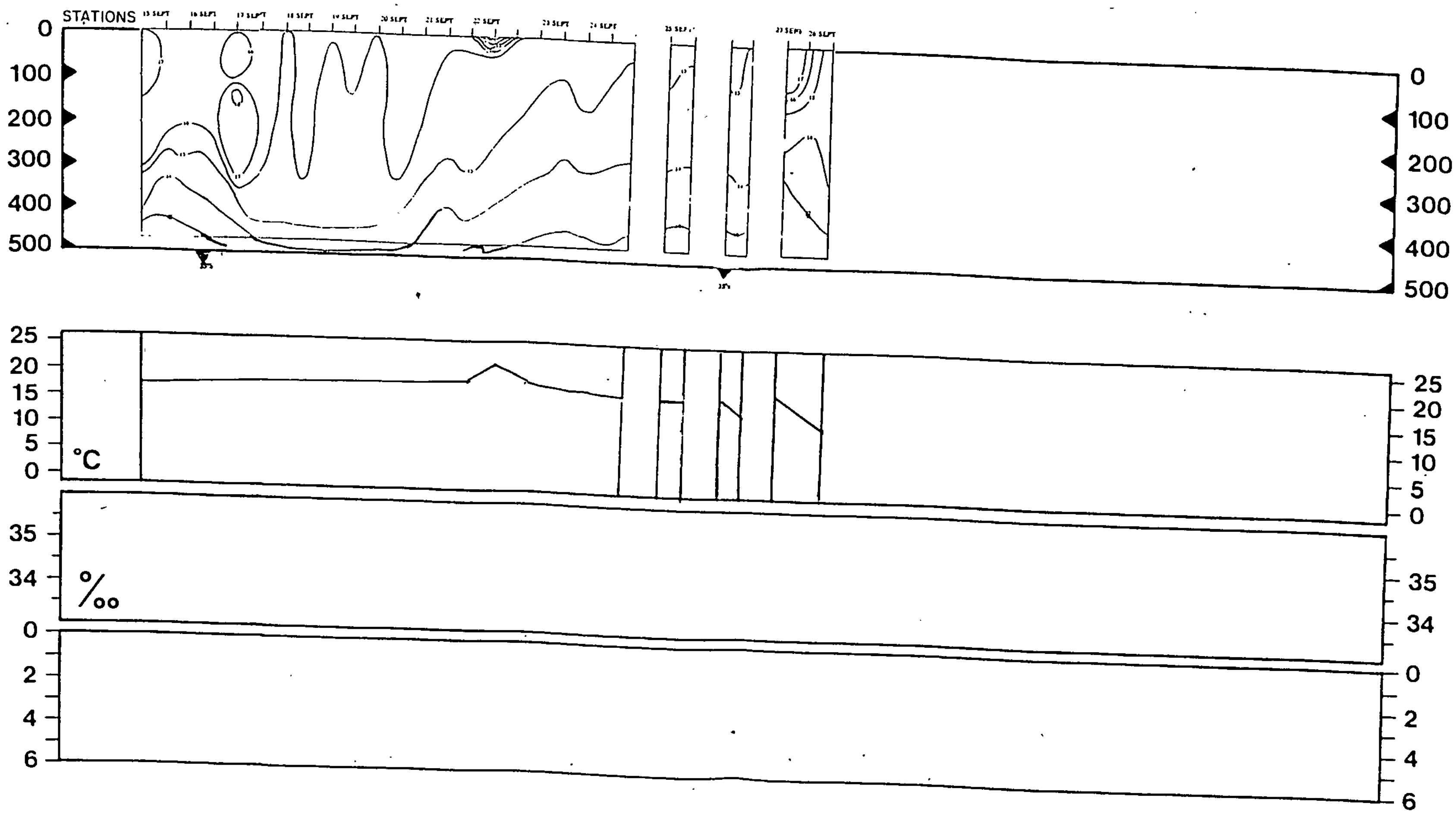
A meridional temperature section from the Sanae 20 Cruise (12 December - 13 March 1979)



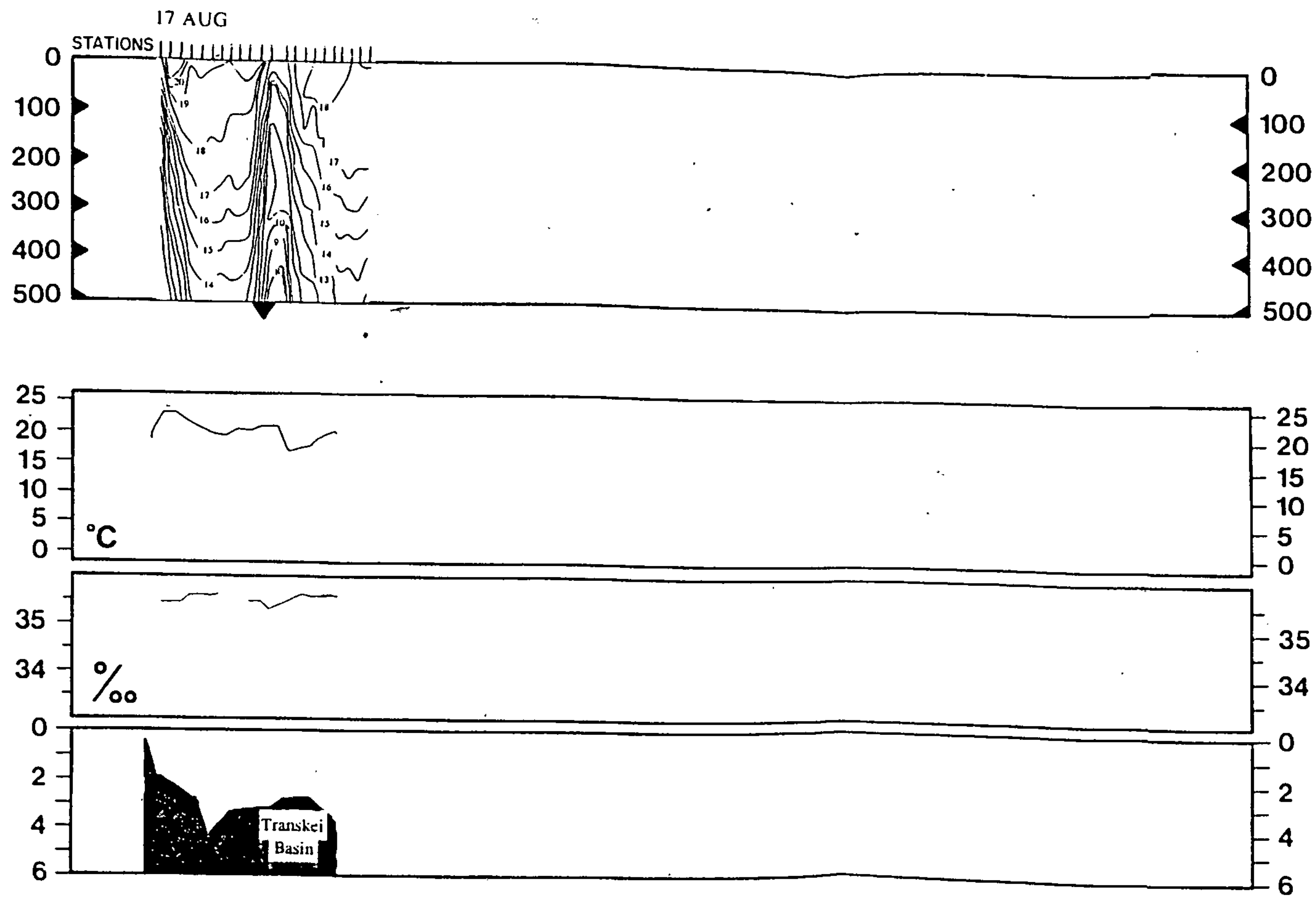
A meridional temperature section from the Sanae 86 Cruise (January - March 1986)



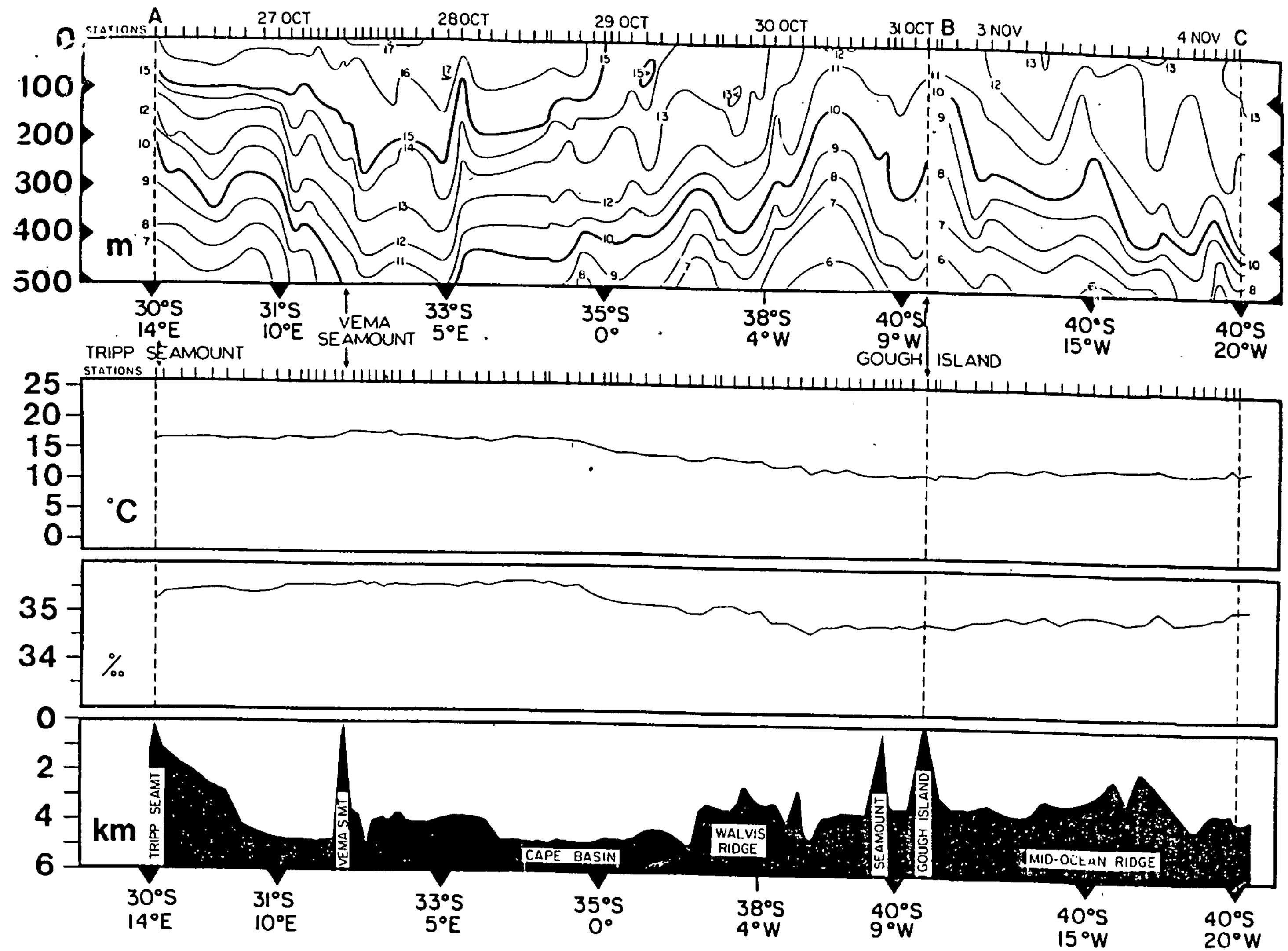
A meridional temperature section from the UK1969 Cruise (29 January - 7 February 1969)



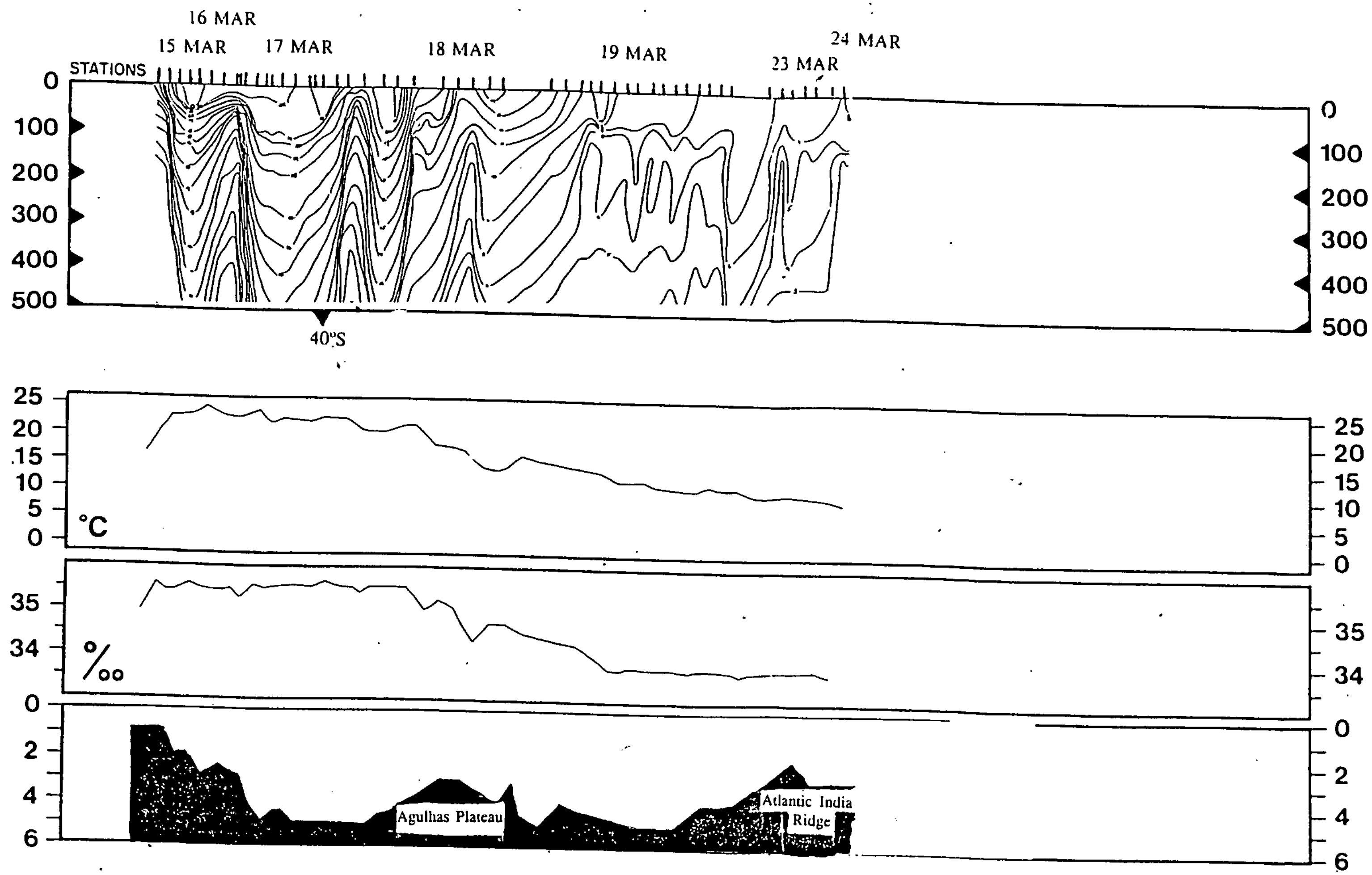
A meridional temperature section from the GL1972.2 Cruise (15 September - 27 September 1972)



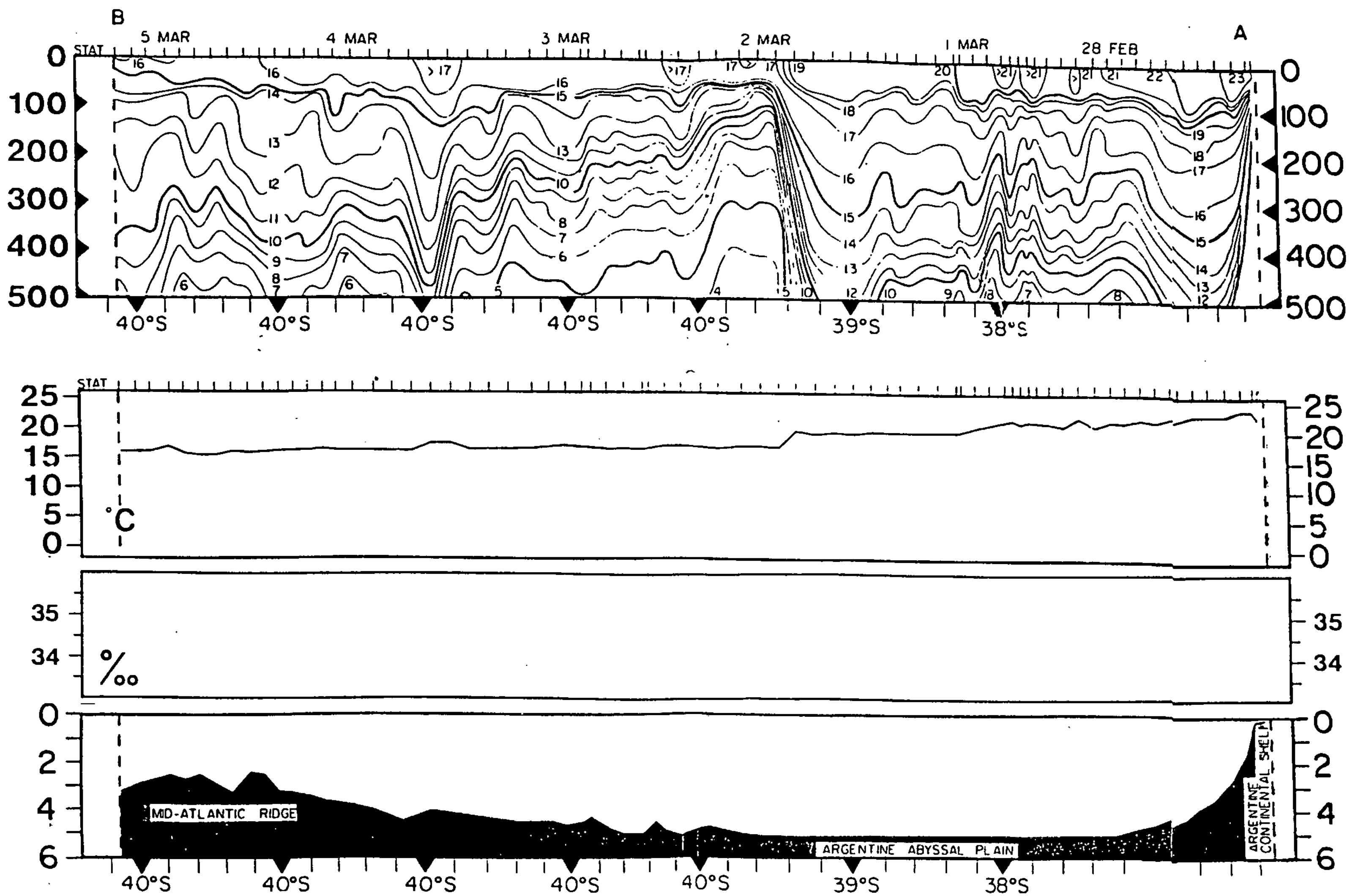
A meridional temperature section from the Mar85.1 Cruise (16 August - 1 September 1985)



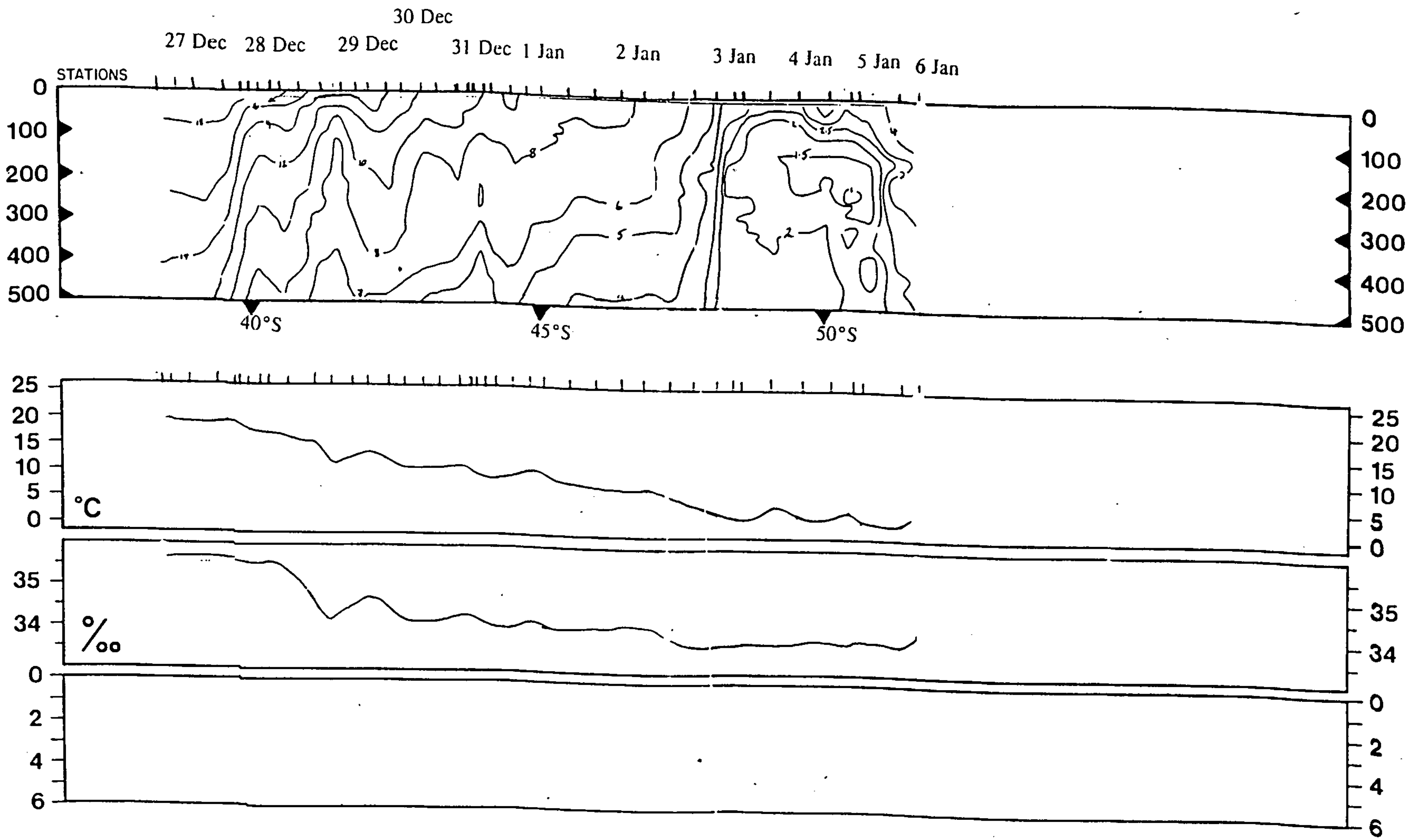
A meridional temperature section from the Gough Cruise (26 October - 12 November 1978)



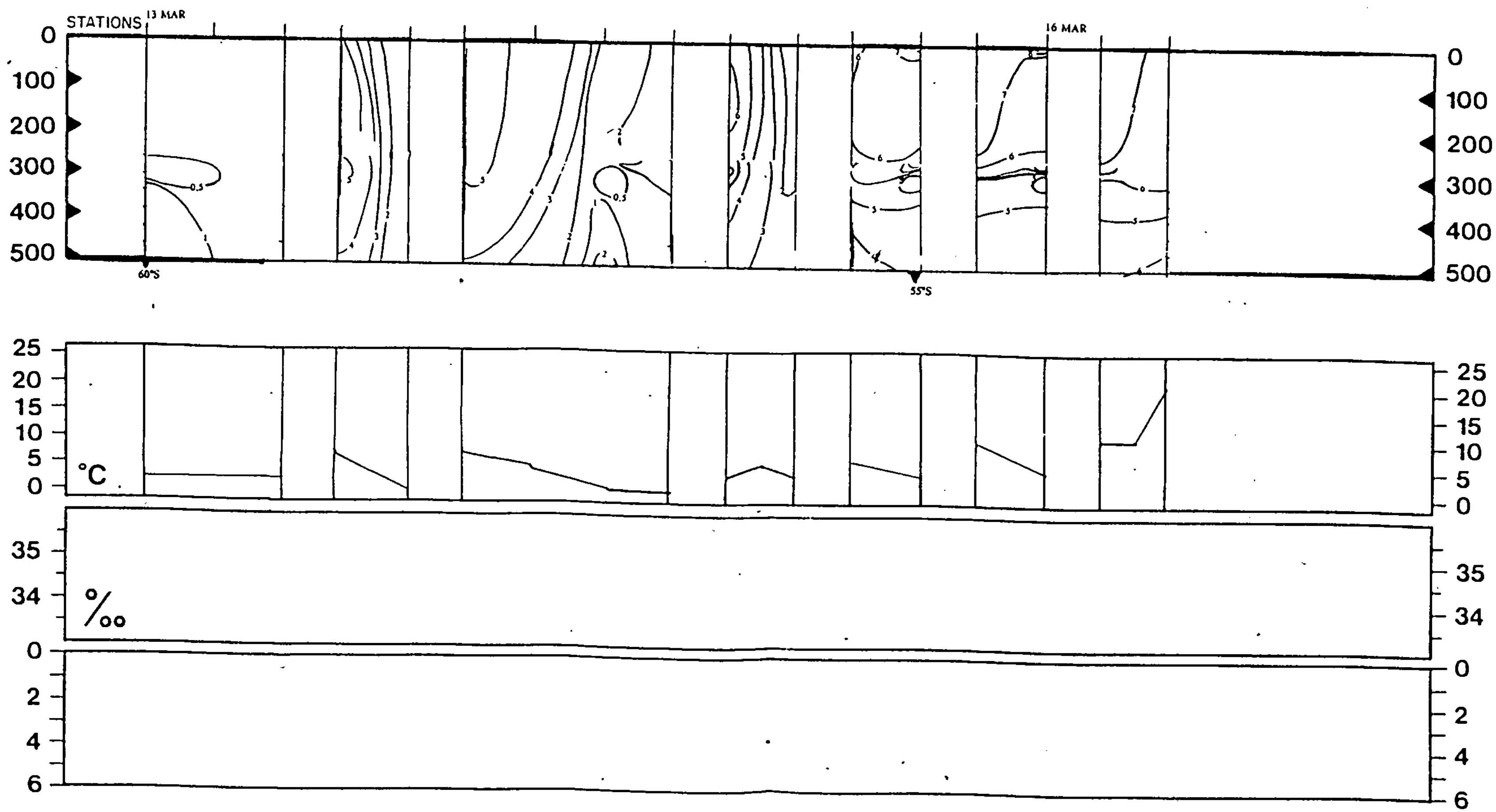
A meridional temperature section from the Sibex126 Cruise (March - May 1984)



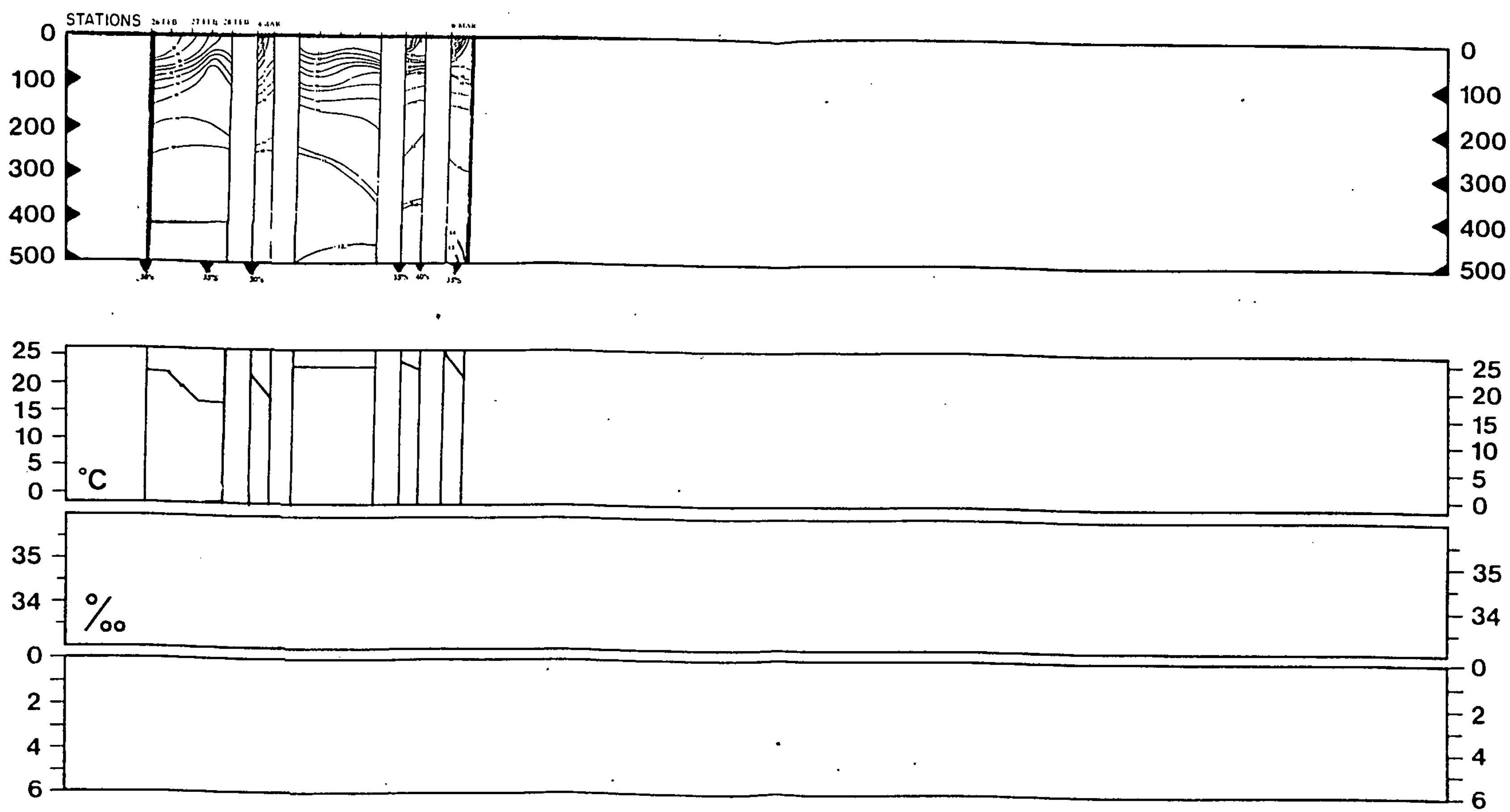
A meridional temperature section from the Montevideo-Cape Town Cruise (27 February - 10 March 1979)



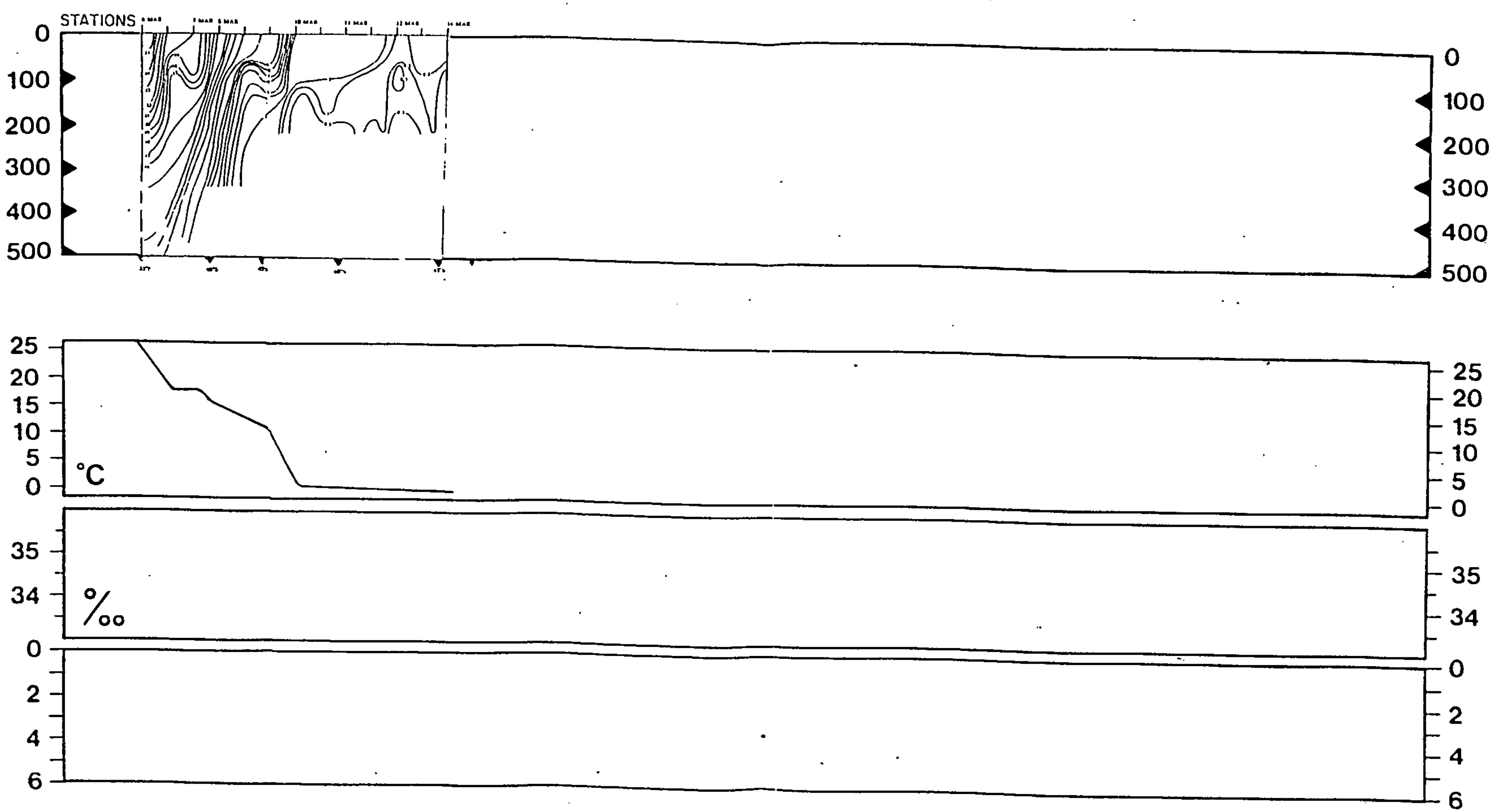
A meridional temperature section from the Discovery Cruise (19 December - 21 January 1987)



A meridional temperature section from the OB1970 Cruise (13 April - 16 April 1970)



A meridional temperature section from the UN1979 Cruise (26 February - 6 March 1979)



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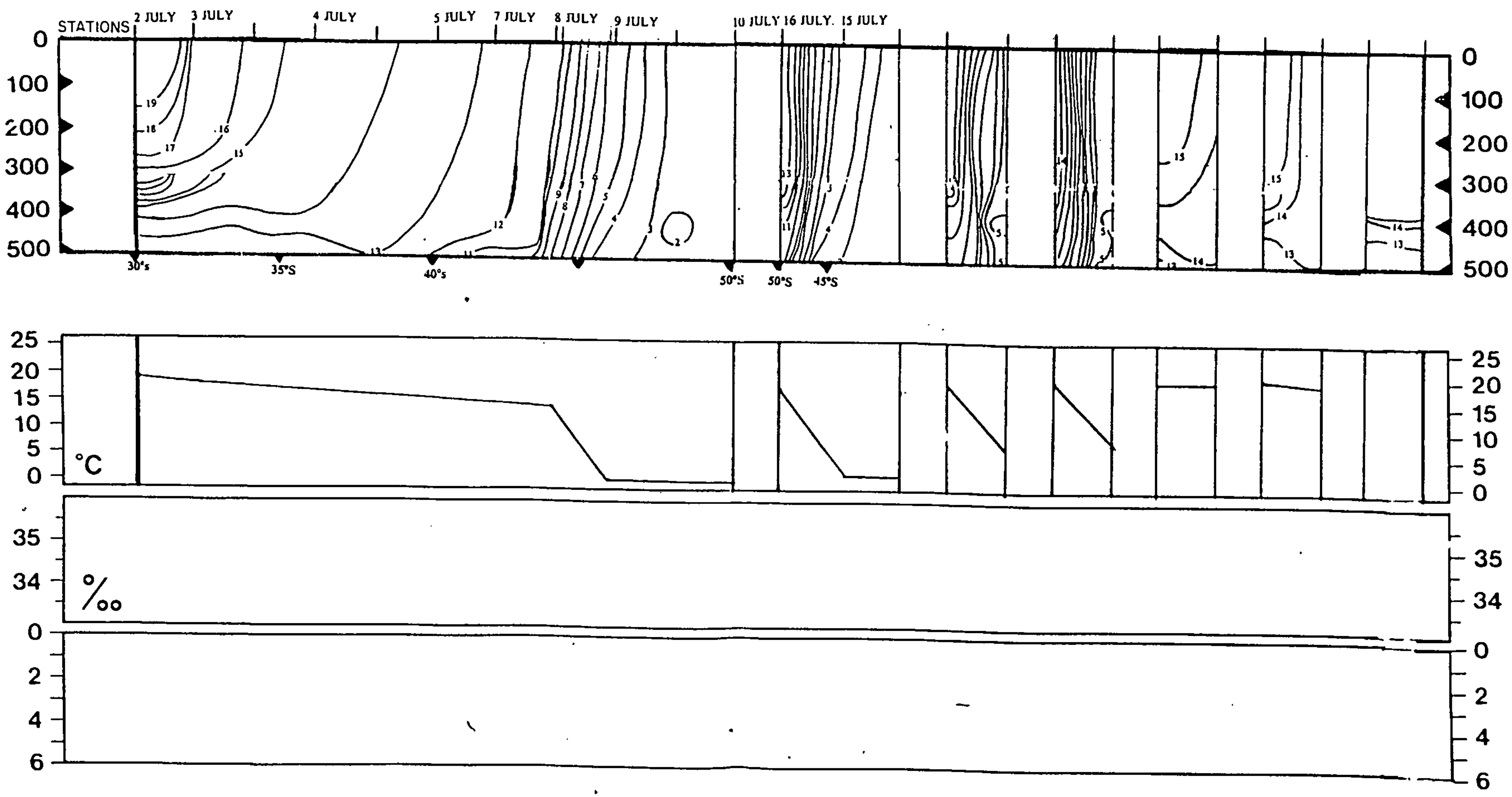

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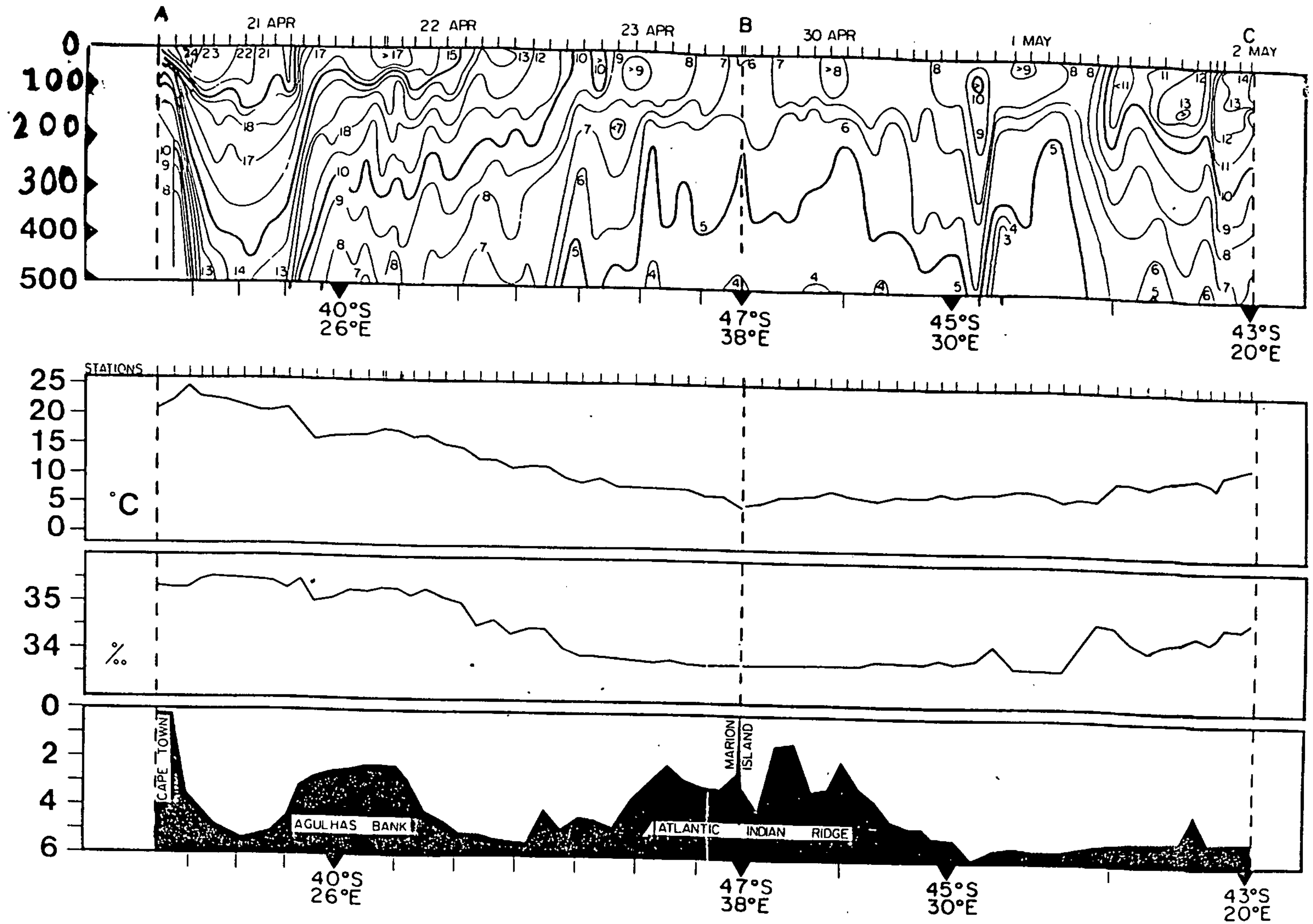
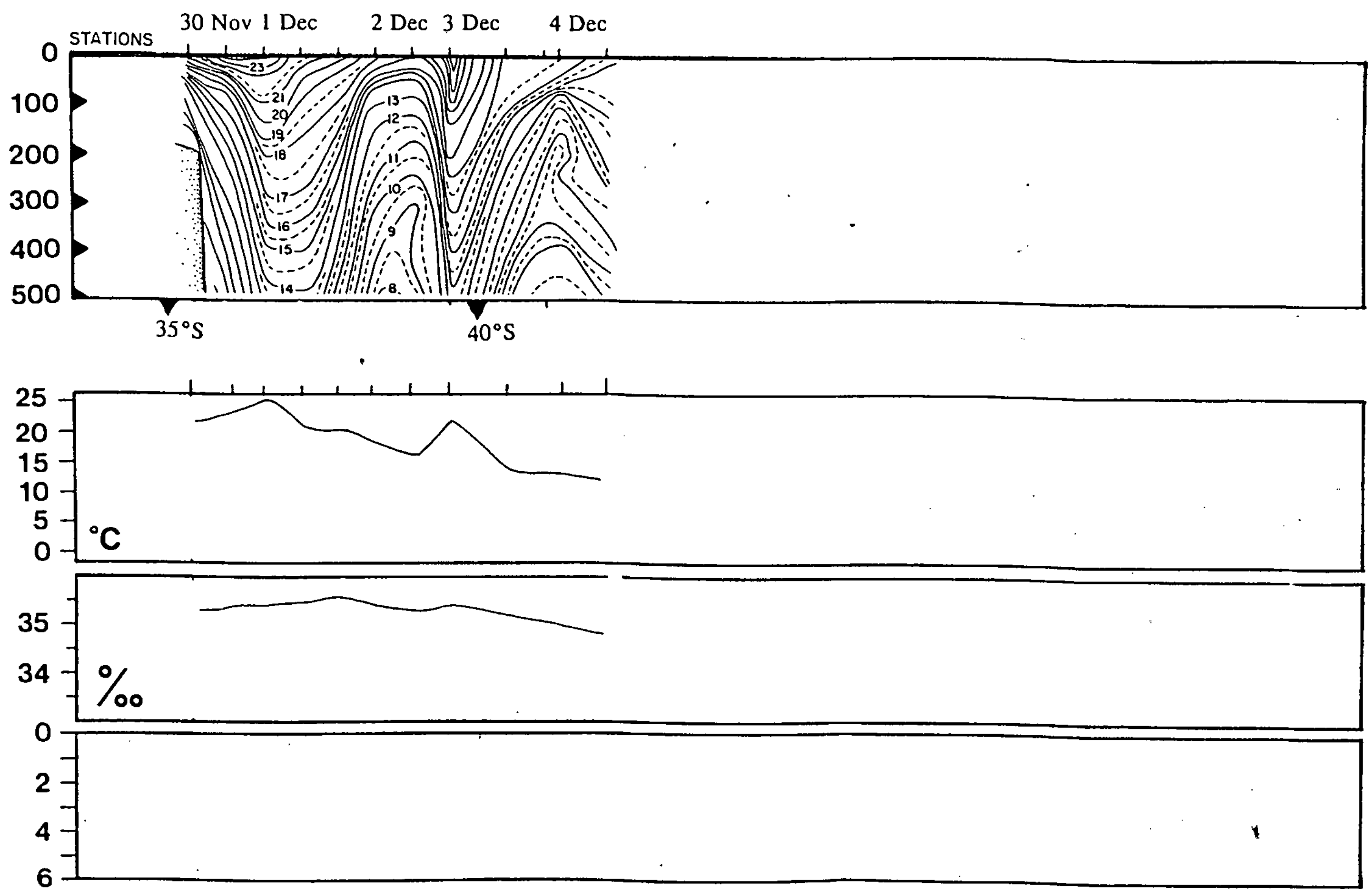
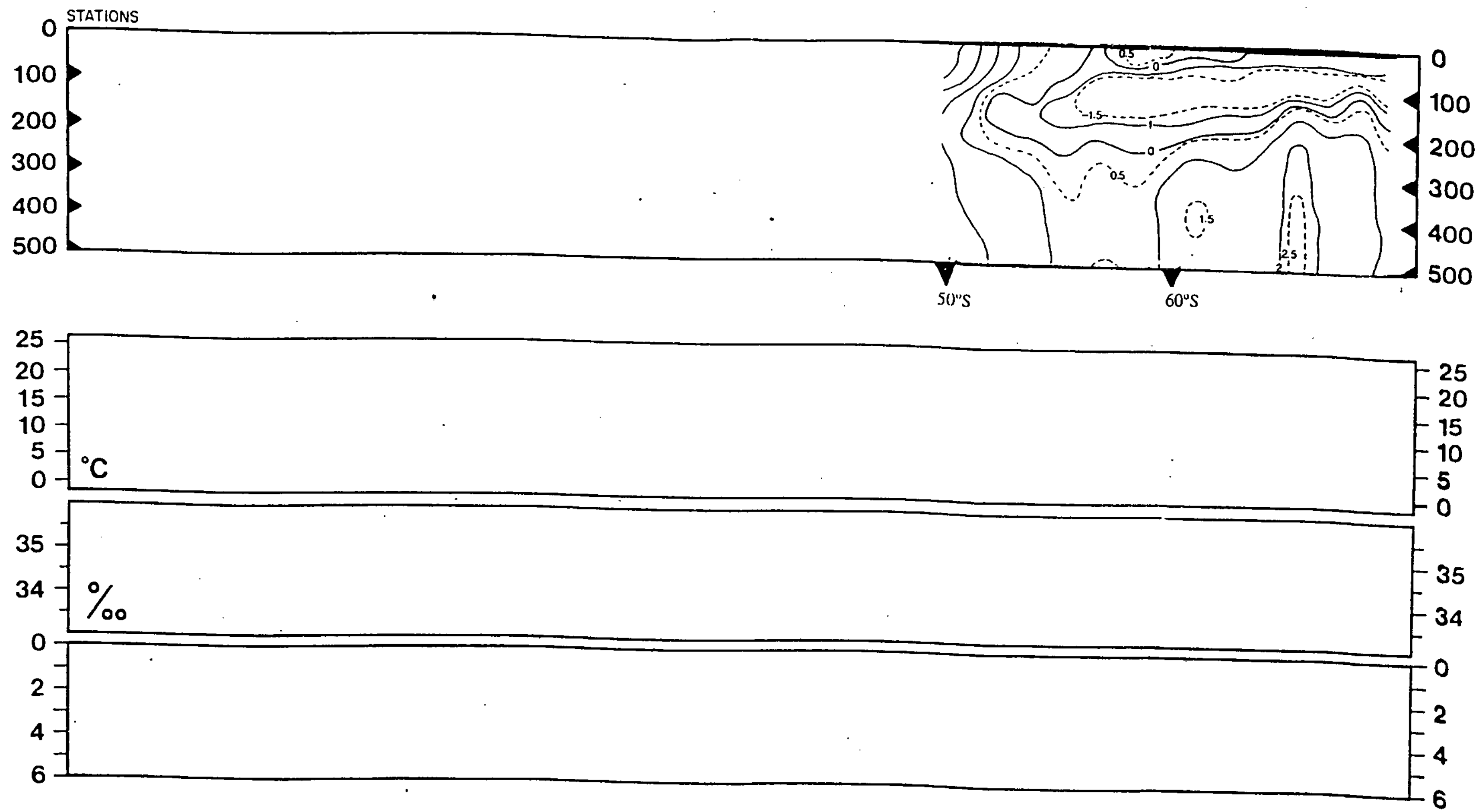


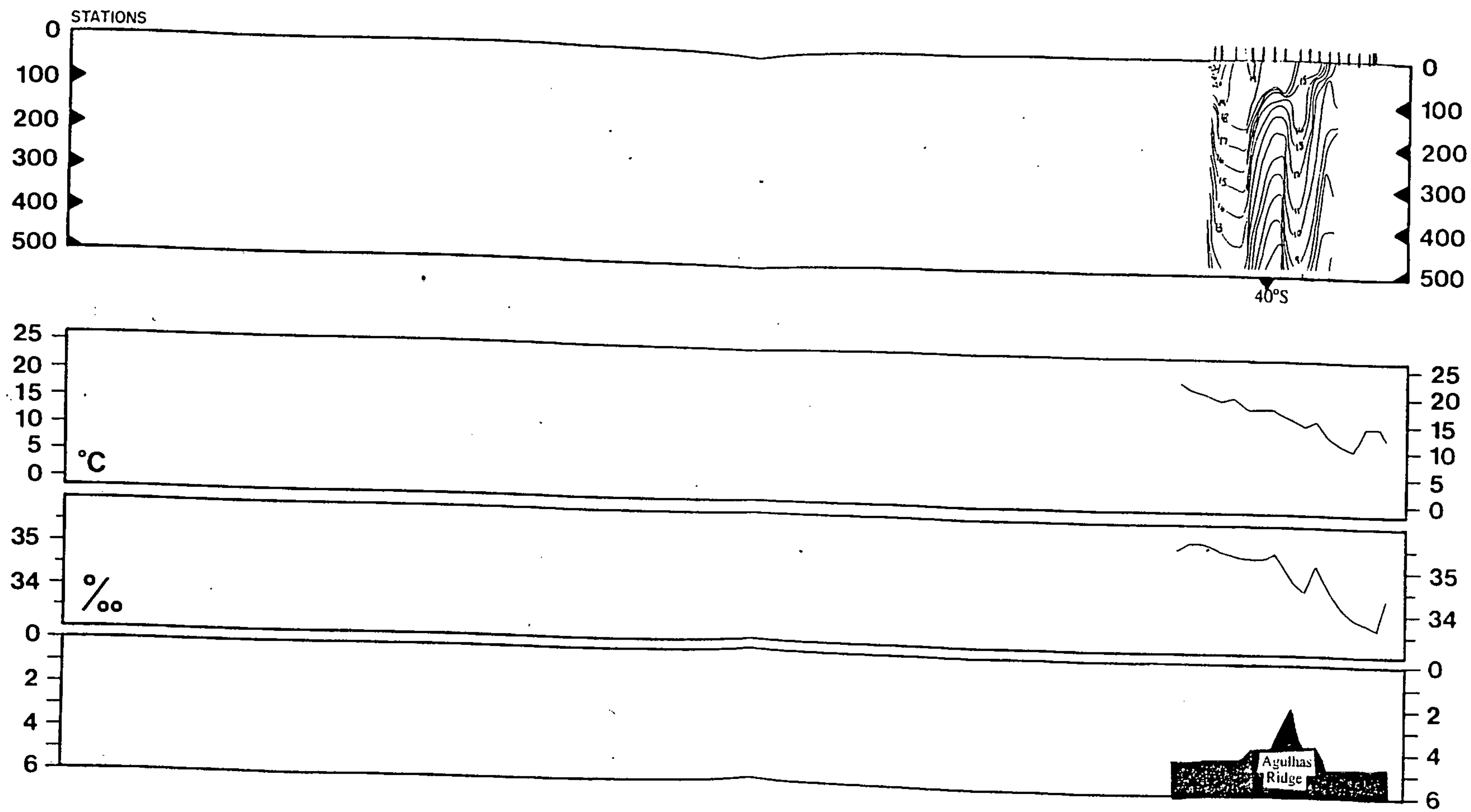
A meridional temperature section from the Mar-Gou (20 April - 14 May 1979)



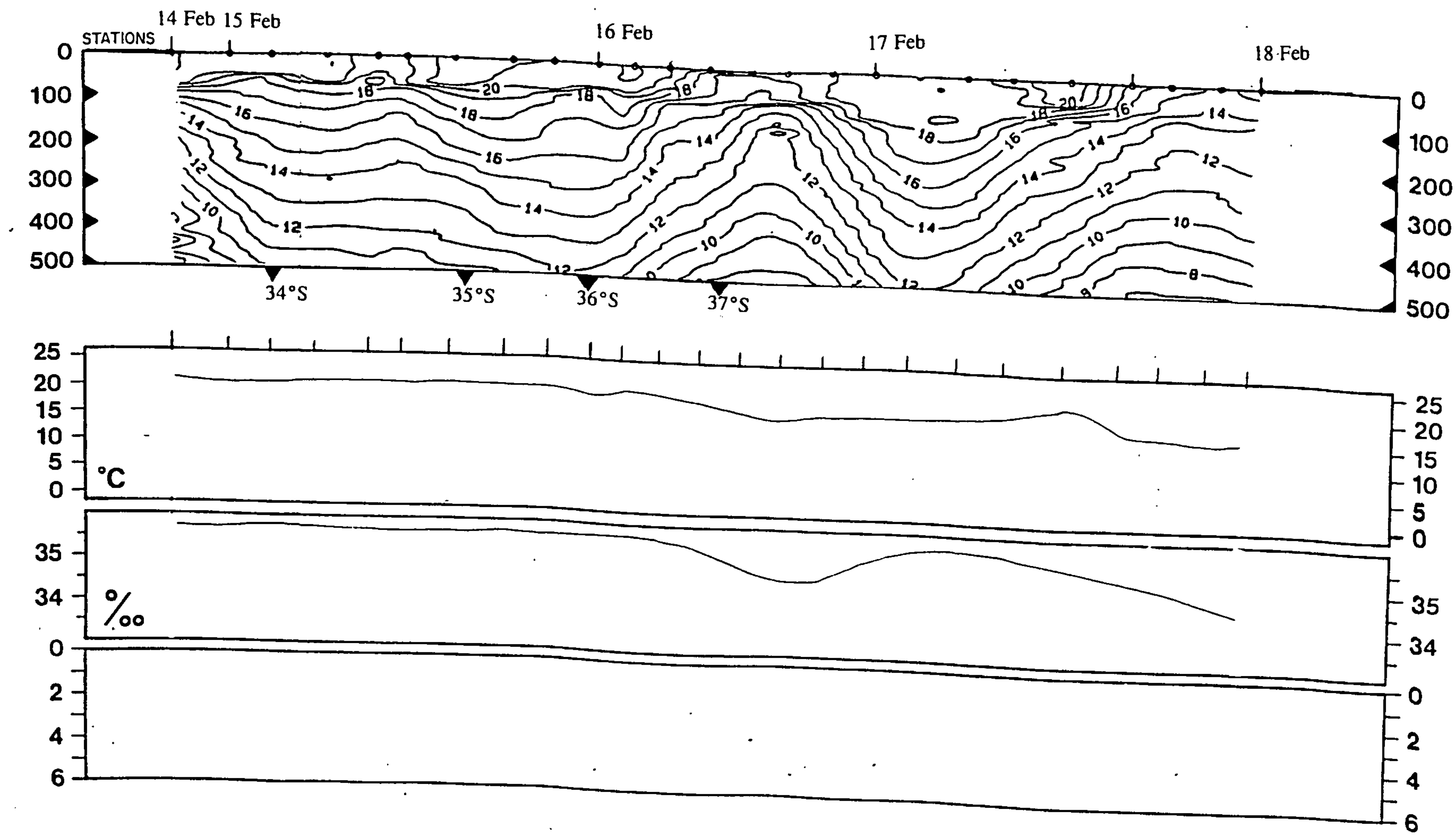
A meridional temperature section from the ARC Cruise (November - December 1983)



A meridional temperature section from the Jare 30 Cruise (November - March 1989)



A meridional temperature section from the Mar86 Cruise (April - May 1986)



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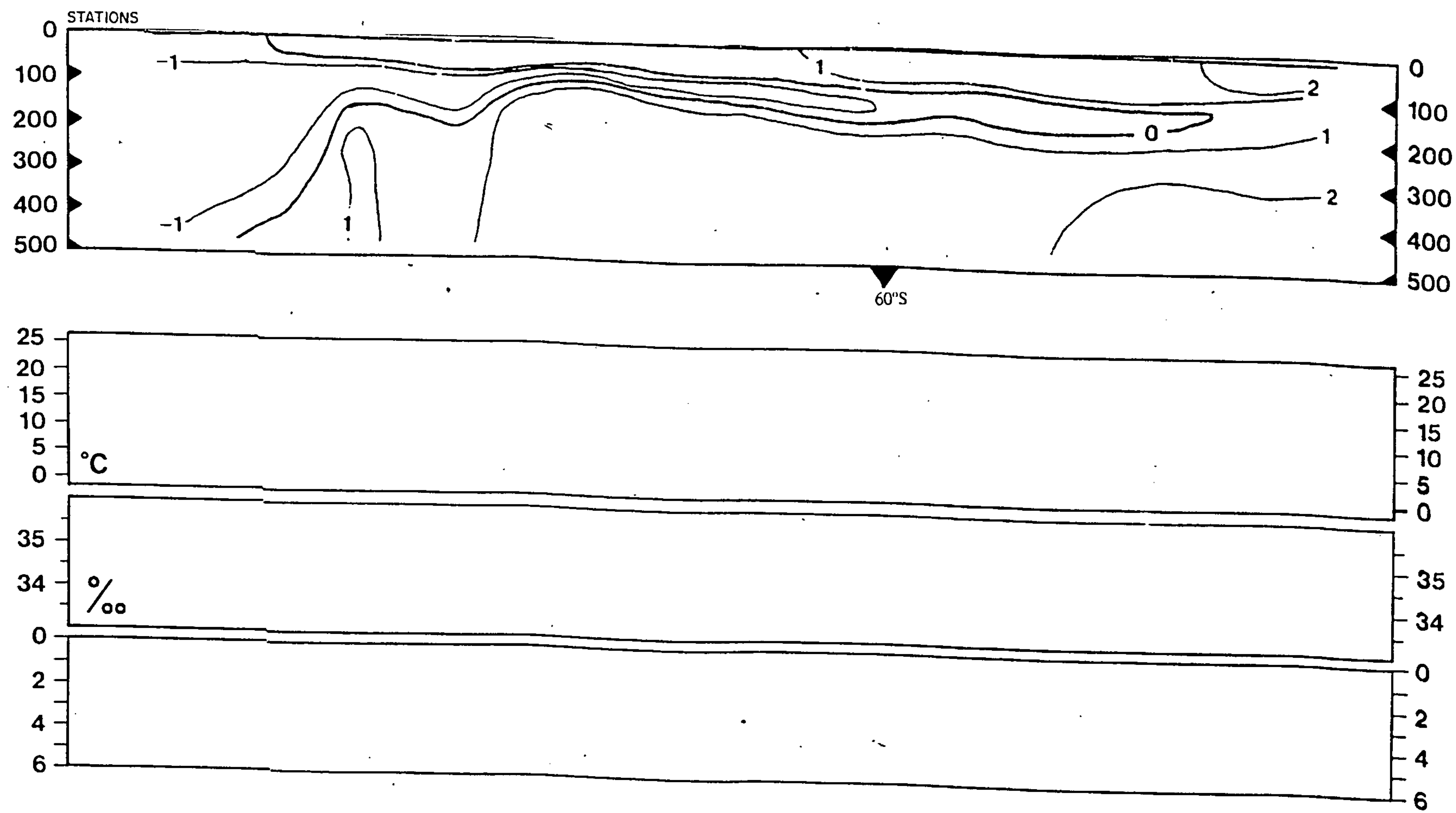

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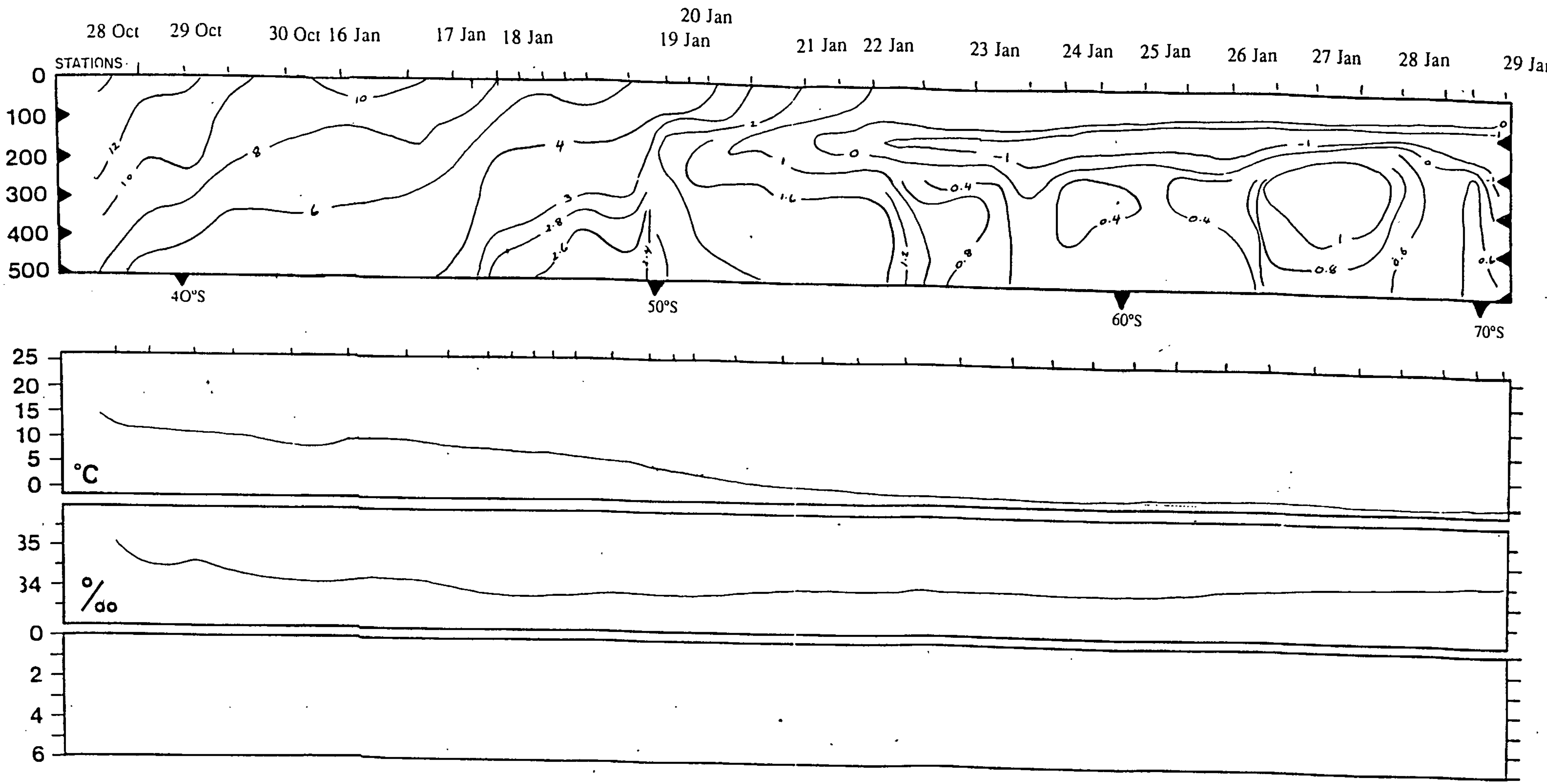
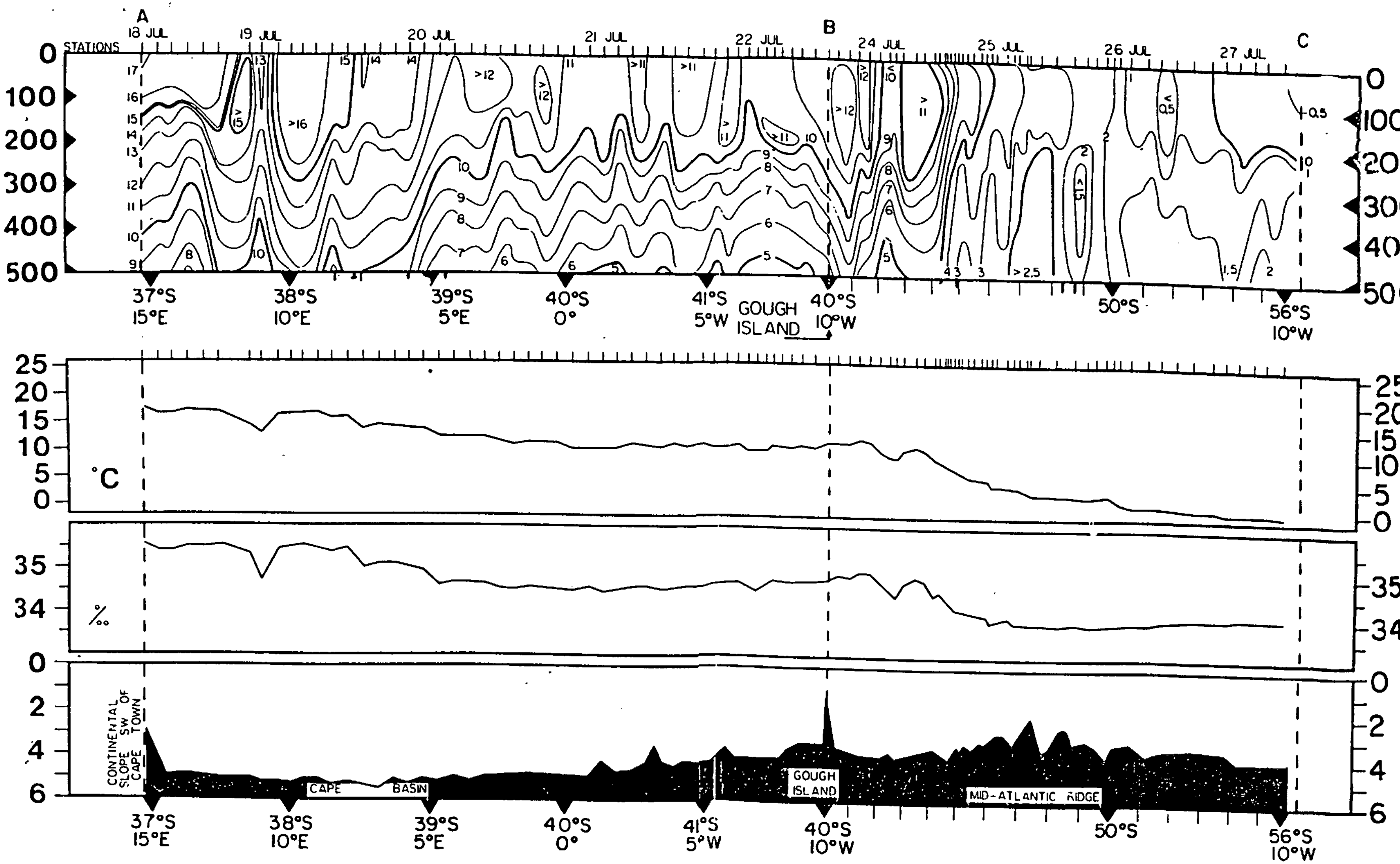
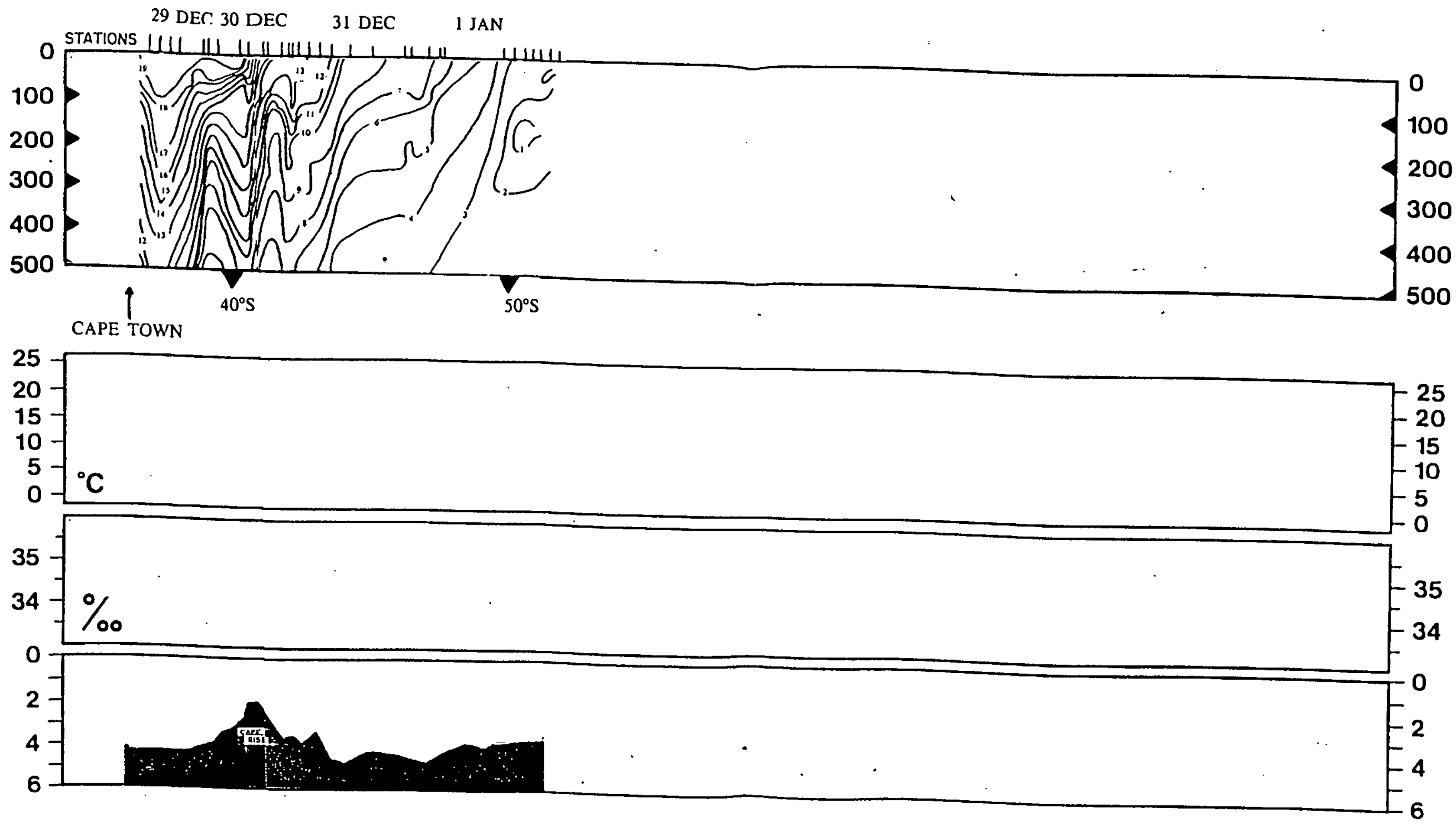


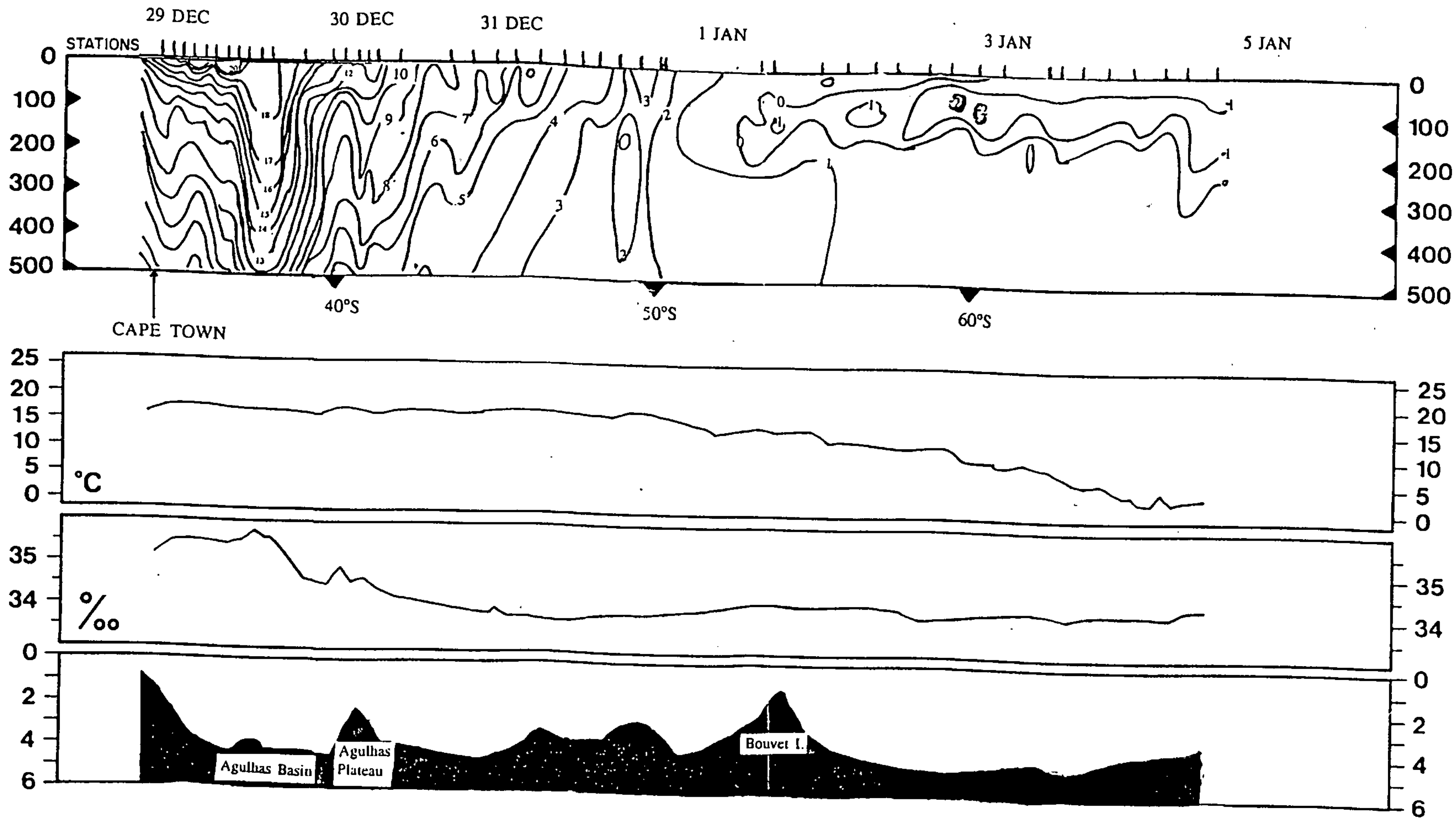
A meridional temperature section from the Ajax Cruise (7 October - 19 February 1984)



A meridional temperature section from the Pack-Ice Gough Cruise (17 July - 6 August 1979)



A meridional temperature section from the Sanae 26 Cruise (29 December - 1 February 1985)



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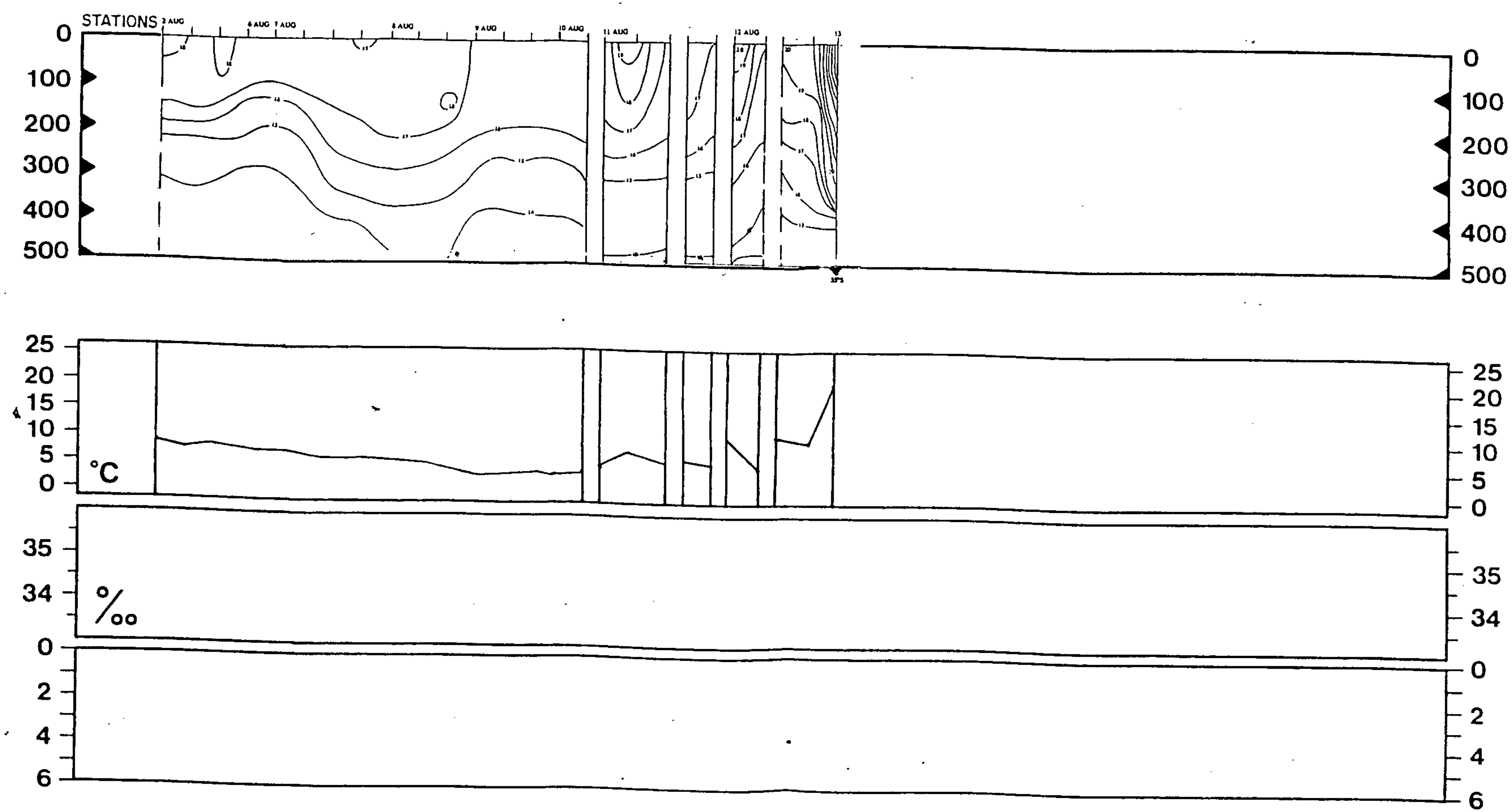
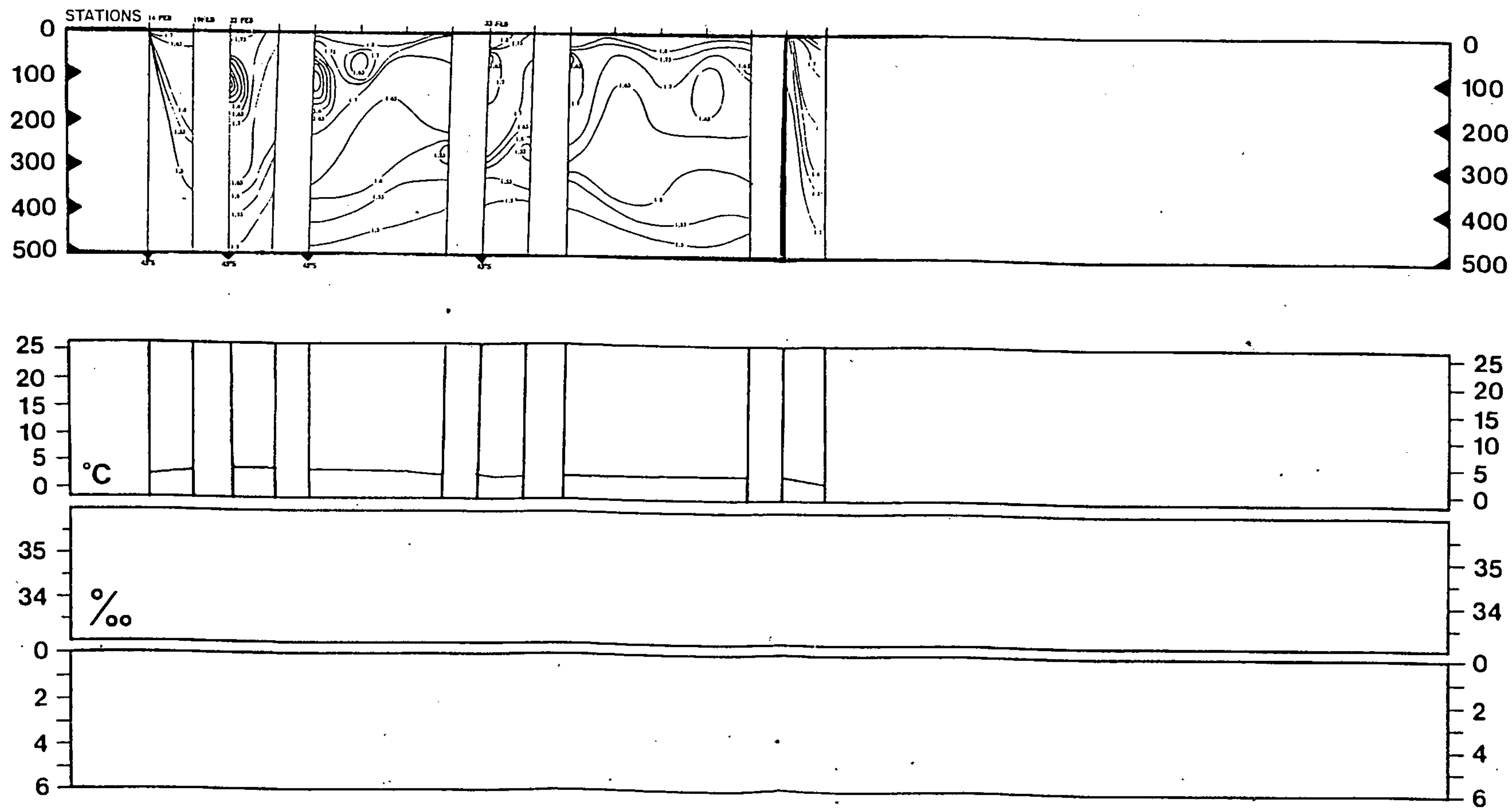


A meridional temperature section from the GL1972 Cruise (2 August - 13 August 1972)



A meridional temperature section from the OB1963 Cruise (14 February - 24 February 1963)