Antarctic Polar Front Zone in the Western Scotia Sea—Summer 1975

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ABSTRACT

The component of the FDRAKE-75 data obtained by the R/V Conrad in the western Scotia Sea reveals a definite sequence of thermohaline stratification zones encountered on passing from Antarctic to Subantarctic waters. A Polar Front Zone, displaying multiple temperature minima, separates the Antarctic Zone, characterized by a single intense T-min above 200 m, from the Subantarctic Zone with its nearly isohaline layer from 100 m to over 400 m. The Antarctic Zones of the Weddell and the Scotia Seas are separated by a cold, relatively homogeneous zone situated in the southern Scotia Sea called the Weddell-Scotia Confluence.

The boundaries of the Polar Front Zone are highly meandered and isolated eddies of Subantarctic water may occur within the zone. The main axis of the Antarctic Circumpolar Current apparently lies close to the Subantarctic boundary of the Polar Front Zone, while a secondary axis is associated with the southern limit of the Polar Front Zone. Inspection of the Islas Orcadas and Melville data, the western section of the FDRAKE-75 data set, also shows a meandered Polar Front Zone. It further suggests the possibility of eddies of Polar Front Zone water within the Subantarctic Zone.

The thick, nearly isohaline layer of the Subantarctic Zone possesses a weak negative salinity gradient (at least within a few hundred kilometers of the Polar Front Zone). It is proposed that this structure is a remnant of a winter period homogeneous layer, which is altered from above by summer sea-air interaction and from below by upward mixing of Antarctic water introduced into the Subantarctic Zone by cross-frontal isopycnal exchange. This latter process may cool and freshen the overall characteristics of the Subantarctic water in relation to expected characteristics by local sea-air factors.

1. Introduction

From January to March 1975 the first phase of the ISOS (International Southern Ocean Studies) project FDRAKE-75 (First Dynamic Response and Kinematic Experiment, 1975) took place. The objectives of FDRAKE and cruise reports have been published in the ANTARCTIC JOURNAL OF THE U.S. [Neal, 1974; Gordon, 1975 (R/V Conrad); Nowlin et al., 1975 (R/V Melville); Wearn and Park, 1975 (ARA Islas Orcadas)]. This paper describes the position and thermohaline structure of the Polar Front Zone, based primarily upon the R/V Conrad cruise in the western Scotia Sea.

The Conrad program included 58 continuous salinity-temperature-depth (STD) stations (Fig. 1). Twelve Rosette bottles and additional Nansen bottles were used to collect STD standardization and chemistry information. STD salinities were corrected for dynamic errors introduced by temperature and salinity sensor time-constant mismatch (Scarlet, 1975). Subsequently, STD temperatures and salinities were brought into agreement with bottle standardization data. To facilitate the analysis of the multiple cast STD station 364/365 (Section 7), temperature and salinity observations were linearly interpolated to 1 m intervals.

Along with associated surface salinity and silicate, 183 expendable bathythermograph (XBT) observations were taken. An expanded-scale XBT recording system developed at Lamont-Doherty Geological Observatory, similar to that described by Steen et al. (1975), allowed better definition of thermal stratification and greatly increased the usefulness of the XBT traces.

2. Thermohaline stratification zones

Thermohaline stratification is the basis for delineating four zones in the western Scotia Sea [similar to the work of Gordon et al. (1974) for the area south of Australia]. Fig. 2 gives two examples from each zone.

a. The Subantarctic Zone

The Subantarctic Zone is characterized by a thick, slightly negative salinity gradient layer (a "nearly isohaline layer") from approximately 100 m to greater than 400 m. The depth of the lower boundary deepens with increasing distance from the Polar Front Zone. Below this layer the salinity gradient is positive. Associated with the nearly isohaline layer is a negative
temperature gradient, often culminating in a weak temperature minimum (T-min) at or slightly below the salinity minimum (S-min) marking the base of the nearly isohaline layer. Decreased surface salinity induces a subsurface salinity maximum.

b. The Polar Front Zone

Multiple temperature inversions accompanied by density compensating salinity inversions generally are identified with the Polar Front Zone. The interleaving layers extend from approximately 100 to 400 m, with the more pronounced temperature minima in the upper half of this range. The mean salinity gradient is for the most part positive throughout the depth interval.

c. The Antarctic Zone

This zone is characterized by a well-developed T-min embedded in a halocline above 200 m. Thermohaline stratification is relatively weak below the T-min.

d. The Weddell-Scotia Confluence

The Weddell-Scotia Confluence (WSC) is observed only in the Atlantic sector of the Southern Ocean and separates the Antarctic Zone of the Scotia Sea from that of the Weddell Sea (Gordon, 1967). It is characterized by a relatively cold, low-stability water column. The WSC water column is distinctive in that the surface water and the T-min are more saline than the

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Fig. 1. Cruise track, showing the positions of the STD hydrographic stations (large symbols) and XBT observations (small dots) of Conrad cruise 18-01, a component of FDRAKE-75. The STD stations were assigned to one of the four thermohaline stratification types described in the text. The 2000 m (the contour broken with 2 dots) and 3000 m (contour with 3 dots) isobaths are taken from the map of Heesen et al. (1972).

Fig. 2. Two examples from each of the four zones of types of thermohaline stratification observed in the FDRAKE area. The patterned areas in the T/S diagram are defined by all of the STD stations shown in Figs. 2, 12, 13 and 14 and the stations in the Weddell-Scotia Confluence.
Each of the Conrad STD stations and XBT traces was assigned to one of the four zones (Fig. 1). The Subantarctic and Antarctic limits of the Polar Front Zone are shown, assuming steady-state conditions (Fig. 3a); since it is probable that the Polar Front Zone is not in steady state, Fig. 3a does not represent a synoptic view and should not be used to determine the spatial scales of meanders or eddies. It does indicate a highly meandered Polar Front Zone, with the possibility that embedded within it are one or more eddies of relatively warm, saline Subantarctic Water.

Traditional definitions of the polar front (see Gordon, 1971, Table 1) would place it within the Polar Front Zone. However, we believe it is more suitable to consider the polar front to be a zone rather than a single line.

A contorted Polar Front Zone was anticipated from the Discovery and William Scoresby data in the western Scotia Sea [Fig. 3b (after Mackintosh, 1946)]. Mackintosh states (1946, p. 180): "At the surface the junction of Antarctic and sub-Antarctic water seldom lies in a straight line, probably because it is an unstable boundary. It forms twists and loops that may extend as much as 100 miles north or south, and it possibly even forms isolated rings. The line is perhaps comparable to the edge of the pack-ice, and may be even more tortuous." He shows (Fig. 3b) that the front frequently (a climatic feature) exhibits a large S-shaped meander as part of a major northward shift near 45°W.

3. Relation of the Polar Front to relative sea surface dynamic topography

The dynamic topography of the surface relative to the 1000 db level (Fig. 3c) shows the major axis of relative geostrophic flow crossing the westernmost Conrad section (58°W) between 56° and 57°S. The axis
then splits into two branches. The northern branch turns northward, reaching the flank of the North Scotia Ridge, and continues eastward until the ridge is breached at the deep topographic passage or gap between 48°–49°W.

The southern branch continues to flow eastward, turning toward the northeast near 47°W. It reaches and apparently crosses the North Scotia Ridge to the east of the gap, then executes a cyclonic pattern over the Malvinas Chasm.

North of the North Scotia Ridge the double axis of flow continues, with the western branch (higher dynamic values) continuing for the most part to the north, crossing the topographic saddle in the Falkland Plateau to enter the Argentine Basin. The eastern axis flows over the southern flank of the Falkland Plateau, as part of the Malvinas Chasm cyclonic pattern. The extent to which this pattern represents a climatic condition is not known; significant variations probably occur.

The patches of Subantarctic Water found within the Polar Front Zone between 50° and 45°W (Fig. 3a) are associated with anticyclonic flow. The density section along 50°W (not shown in this paper) reveals the anticyclonic pattern extending, albeit weaker, to 2000 or 2500 m.

The dynamic topography is based only on STD data, while the Polar Front Zone is defined by both STD and XBT observations. The less precise definition of the baroclinic field does not allow direct comparison with the Polar Front Zone. However, it appears likely that the northern axis of flow tracks immediately to the north of the Polar Front Zone and the southern axis tracks along the southern limit of the Zone. The current axes also trace the many machinations of the Polar Front Zone, including the meanders and eddies. The Polar Front Zone and Antarctic Circumpolar Current apparently are intimately related.

4. Surface water

Surface temperature, salinity, density and silicate were measured at each XBT and hydrographic station. The surface distributions and property diagrams (Figs. 4a and 4b) clearly reflect the positions of the Polar Front Zone and Weddell–Scotia Confluence.

Surface isotherms and isohalines suggest the proximity of 6°C and 34.0‰ to the Subantarctic limit of the Polar Front Zone, though north of the North Scotia Ridge it seems to be associated with surface temperatures above 6°C. Relatively strong temperature and salinity gradients occur across this boundary, although these gradients are significantly reduced north of the North Scotia Ridge.

The Antarctic limit of the Polar Front Zone occurs near 4°C and 33.8‰. South of this the surface salinity remains below 33.8‰ until the Weddell–Scotia Confluence is reached. Within the Weddell–Scotia Confluence the surface salinity increases very rapidly to maximum values above 34.3‰. The surface salinity again decreases south of the Weddell–Scotia Confluence on encountering the Antarctic Zone of the northern Weddell Sea.

The source of the low-salinity band of the Antarctic Zone is most likely the residue of sea ice melt water which has been warmed by solar radiation. The high-salinity band of the Weddell–Scotia Confluence may be associated with relatively vigorous vertical mixing between surface and deep layers, perhaps the product of deep winter convection, which would also account for the low level of thermohaline stratification in the Weddell–Scotia Confluence water column (Deacon and Moorey, 1975).

Surface density gradients are small across the Polar Front Zone indicating that the salinity and temperature surface gradients are partially compensating. The Weddell–Scotia Confluence is marked by a significant maximum in surface density (about 0.6 sigma-t units above the Antarctic Zone values).

The surface silicate distribution shows a spectacular increase within the Weddell–Scotia Confluence, attaining values above 80 μmol l⁻¹ (an order of magnitude above the Polar Front Zone values). The source of the high surface silicate can be deep water which reaches the surfaces as a result of enhanced vertical interaction within this zone (Deacon and Moorey, 1975). Surface
silicate also shows a marked change across the Subantarctic limit of the Polar Front Zone, though this is more apparent on the silicate vs distance plots accompanying the XBT/STD thermal sections, discussed below.

The surface temperature and salinity vs silicate plots (Fig. 4b) reveal the intensity of the increase of silicate with distance south of the Polar Front Zone, particularly within the Weddell-Scotia Confluence.

5. Thermal structure across the Polar Front Zone

A number of sections of the thermal structure of the upper 500 m, with surface salinity and surface silicate (not included for section A-A') were constructed for the lines shown in Fig. 3a.

a. Section A-A' (Fig. 5)

This section extends along the North Scotia Ridge and crosses the only deep gap (about 3700 m) in the

Fig. 4a. Surface distribution of salinity, temperature, silicate and density (sigma-t) determined from the Conrad STD and XBT water sample data.
ridge between South America and South Georgia. The thermal section reveals a very sharp polar front directly over the gap in the ridge. The sharp front is manifested by a depth change and abrupt termination of the T-min, as well as a rapid change of surface salinity. The T-min increases in depth and temperature from approximately 100 m and 1.5°C at the XBT observation between STD stations 313 and 315, to 500 m and 2°C between STD station 313 and 314, within a distance of approximately

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**Fig. 4b.** Property distributions using Conrad XBT water sample data.

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**Fig. 5.** Thermal section for the upper 600 m and surface salinity constructed from XBT, STD and water sample data along Section A-A' (see Fig. 3a). Also shown is bottom topography. SAZ, PFZ and AZ refer to Subantarctic Zone, Polar Front Zone and Antarctic Zone, respectively.

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**Fig. 6.** As in Fig. 5 except for upper 500 m along Section A''-A' (Fig. 3a).
The surface salinity and silicate do not undergo significant changes along this track, as is the case for the sections south of the North Scotia Ridge. In fact the surface silicate is minimally higher in the Subantarctic Zone, in variance with the conditions to the south. The impression is that the Polar Front Zone over the Falkland Plateau is less intense than that within the Scotia Sea, especially in the sea surface expression.

**c. Section B-B’ (Fig. 7)**

The T-min layer terminates abruptly near STD station 330 and is accompanied by a strong surface salinity gradient. A silicate gradient is suggested, though

25 n mi. The surface salinity increases from 33.95 to 34.15% in this distance.

The thermal gradient across the Polar Front Zone at depths below the surface mixed layer (below 50 m) is substantially greater than the gradients within the mixed layer. The subsurface thermal expression is larger than the surface thermal expression during the summer period, when surface heating masks the front, though the surface salinity expression remains (Gordon, 1971). This is seen to be true for all of the following sections. Deacon (1933, 1937) notes a frequent separation between surface and subsurface expression.

**b. Section A’-A” (Fig. 6)**

The T-min terminates near XBT-26, and this is marked as the Antarctic limit of the Polar Front Zone.

**Fig. 7.** As in Fig. 6 except along Section B-B’ (see Fig. 3a).

**Fig. 8a.** As in Fig. 6 except along Section B”-B’ (see Fig. 3a).
a problem in the sampling procedure leads to a discontinuous data set, with a twofold increase in the surface silicate from north to south across the frontal zone.

d. Section B'-B'' (Fig. 8)

An indication of a meandered Polar Front Zone, or of an isolated eddy, is found in this section. The Polar Front Zone has been subjectively interpreted as a meander (Fig. 3a) rather than an eddy. The intense T-mins attaining subzero temperatures occur on either side of a warmer section observed between XBT-50 and STD 327 (a distance of 150 km), with rather abrupt termination at the northern end of each of the T-min segments.

In the warm section, the surface salinity is nearly 0.3‰ higher and surface silicate lower by a factor of 5 relative to the surface water across the Polar Front Zone.

The entire structure is similar to the double Polar Front Zone frequently observed in the Pacific sector of the Southern Ocean (Gordon, 1971), which may be a product of eddy generation at the Macquarie Ridge (Gordon, 1972). However, the temperature contrast between the cold and warm sections observed in 1975 within the Scotia Sea is more intense; thus the Scotia Sea feature could not simply be the Pacific Ocean feature described earlier, which has advected through the Drake Passage, but is more likely locally generated.

Temperature, salinity and chemistry are shown for the upper kilometer along B'-B'' to illustrate the relationship of salinity and chemistry to the thermal field across the warm section (Fig. 8b). The warm section possesses a weak temperature minimum near 475 m and a thin salinity minimum layer near 450 m (these features are also shown in the STD profiles discussed in Section 6). The nearly isohaline layer characteristic of the Subantarctic Zone is found between stations 323 and 326 from 100 to 400 m.

The chemistry distribution shows that the isolines of nutrient and oxygen conform to the thermohaline field, i.e., the isolines are depressed between stations 323 and 326 due to the deeper reaching influence of the Subantarctic Surface Water.

e. Section C-C' (Fig. 9)

This section extends into the northern Weddell Sea across the Weddell-Scotia Confluence (see Fig. 1). The vertical stratification is weak between XBT's 96 and 103 (about 300 km) which coupled with the extremely high surface salinity and silicate identifies this band as the Weddell-Scotia Confluence. The Weddell-Scotia Confluence at the time of the Conrad crossing near 50°W was quite broad. Mackintosh (1972) identifies a
Scotia Sea Divergence and Weddell Sea Divergence, which appear to form the northern and southern limit of the Weddell-Scotia Confluence, respectively. We prefer the terms Scotia Front and Weddell Front.

The T-min layer associated with the Antarctic and Polar Front Zones is reestablished quite abruptly north of XBT-103, but is divided by a warmer section, XBT-106 to STD station 354 (about 150 km), similar to Section B'-B"'. Again surface salinity and silicate reveal a surface expression of the Polar Front Zone.

It is possible that the structure observed along Section C-C' is the same feature observed along B'-B'', but advected eastward. In view of the time separation of the two sections, a velocity of 0.5 kt would be required to accomplish the necessary advection. While this is possible, the Polar Front Zone shown in Fig. 3a is drawn from a steady-state point of view.

f. Section D-D' (Fig. 10)

This XBT section extends across the gap in the North Scotia Ridge (near XBT 162-166).

The warm section observed along the previous two sections is also observed along this section, with the expected surface salinity and silicate expression, between XBT 143 and 149 (again 150 km wide). The section does not enter the Subantarctic Zone, though judging from the 2°C T-min and surface chemistry it must pass close to the Subantarctic limit of the Polar Front Zone over the gap, suggesting little change in position as compared to Section A-A'.

g. Section E-E' (Fig. 11)

This section is similar to B'-B'', C-C' and D-D' in that the T-min is separated by a 150 km warm segment, associated with increased surface salinity and decreased surface silicate.

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Fig. 9. As in Fig. 6 except along Section C'-C (see Fig. 3a). WSC refers to Weddell-Scotia Confluence.
6. STD profiles

The STD profiles along Sections A-A', B'-B'' and C-C' are shown by the temperature and salinity vs depth traces for the upper kilometer and on T/S diagrams (Figs. 12–14) in order to further study the continuity of the zones encountered in transversing from Antarctic to Subantarctic Waters.

Stations 312, 313 and 314 straddle the gap in the North Scotia Ridge (Fig. 12). Station 312 is in the Subantarctic Zone. The base of the nearly isohaline layer (slightly negative salinity gradient), which occurs near 350 m, is a very abrupt feature in T/S space, i.e., nearly a right-angle turn.

Station 313 is to the east of the gap and in the Polar Front Zone. The thermal stratification at this station shows the temperature inversions typical of the Polar Front Zone; the coldest T-min is near 175 m, occurring at the base of a 100 m thick, nearly isohaline layer. This layer has a slightly positive salinity gradient, in the opposite sense from the thicker nearly isohaline layer of the Subantarctic Zone. The 27.1–27.3 sigma-t interval thickens from the Polar Front Zone to the Subantarctic Zone.

Station 314, about midway between stations 312 and 313, reflects both the Subantarctic and Polar Front Zone characteristics. Its thermohaline stratification above the base of the isohaline layer (near 300 m at both stations) closely follows that of station 312 (Subantarctic). Below this T/S point, station 314 has a 250 m layer which stands out in the depth traces as a series of relative cold-fresh filaments, more characteristic of the Polar Front Zone, though generally not as cold as that of station 313. At 550 to 600 m the characteristics return to Subantarctic Zone T/S space, indicating that a segment of Polar Front Zone water has "invaded" the otherwise Subantarctic character of station 314.

This type of T/S feature, representing the superposition of zones within one water column, suggests the presence of differential motion (shear) within the water column. The station 314 intrusion is direct evidence of cross-frontal exchange of water masses. Superposition of water of neighboring zones is found at

Fig. 10. As in Fig. 6 except for XBT and water sample data along Section D'-D (see Fig. 3a).
a number of STD stations (314, 318, 323, 351, 359). Differential motion near the boundaries of zones would be an effective transfer mechanism of water.

The STD sequence 322 to 329 (Fig. 13) crosses a warm cell (Section B'-B'”, Fig. 7) and is interpreted as a broad meander of the Polar Front Zone (Fig. 3a). Stations 322 and 327 are similar, both being within the Polar Front Zone. Stations 328 and 329 belong to the Antarctic Zone, as is evident by the intense, single T-min layer. Stations 324, 325 and 326 are from the Subantarctic Zone. At these stations the T-min and S-min (at a depth of 400–500 m at stations 324 and 325, and 300–400 m at station 326) are more intense than on other Subantarctic Zone stations (also see Fig. 8b).

Station 323 is Subantarctic in character above 200 m and becomes Polar Front Zone stratification below 300 m; the transition is marked by a significant negative salinity gradient with an S-min at its base. The Subantarctic waters apparently override Polar Front waters at station 323.

The 27.1–27.3 sigma-t interval is clearly thicker within the Subantarctic Zone segment than within the Polar Front Zone. This density interval, traced into the Antarctic Zone, is found within the strong thermocline directly above the T-min layer. Therefore the T-min of the Antarctic Zone and that of the Subantarctic Zone occur at the same density, sigma-t 27.3, indicative of potential interaction by isopycnal processes.

Fig. 13b demonstrates this relation further: the T-min is nearly horizontal when sigma-t is used as the vertical coordinate, though large thermal gradients occur along the T-min layer. The boundary of the Subantarctic Zone is marked by relatively large thermohaline gradients along density surfaces.

The presence of isopycnal processes is strongly supported by tritium distribution. Tritium concentration was measured at a number of levels at station 365, which is located within the Polar Front Zone (Fig. 17). Present day surface water concentrations of tritium (approximately 0.6 T.U.) occur at a depth of 300 m, below which the concentration drops rapidly to less than 0.3 T.U. The discontinuity in the tritium profile occurs at the 27.3 density horizon marking both the T-min in the Antarctic Zone and base of the nearly isohaline layer of the Subantarctic Zone. The significant density gradient above this density horizon within the Polar Front Zone does not suggest local winter period convection to the 27.3 level. Therefore it is reasonable to conclude the surface water tritium concentration to the 27.3 density level is not a product of local convection, but rather induced by “communication” with the winter convective layer to the north and south of the polar front zone.

The sequence of stations along 50°W from 54° to 58°S (Section C-C’, Fig. 14) transverses a warm Subantarctic cell (stations 352 and 353), and a cold cell of Polar Front Zone water (station 354 and XBT’s 109 and 110).

Stations 352, 353 and 355 are Subantarctic Zone stations, station 354 is Polar Front Zone and 349 and 350 are Antarctic Zone. Station 351 is another example of superimposition of two zones: the upper layer (150 m) is Antarctic and the deeper water is Polar Front Zone. The transition is extremely abrupt, occurring in as little as 10 m. It is probable that the shear, responsible for carrying Antarctic Water over an otherwise Polar Front Zone column, occurred shortly before station 351 was occupied.
The 27.1–27.3 sigma-τ interval displays a similar relation across stratification zones as discussed above. The 27.3 level appears to be continuously associated with single or multiple T-mins, and consequently is a significant junction in T/S space.

7. Repeated STD station (yo-yo station)

To further investigate the nature of the multi-T-min layers observed in the Polar Front Zone, a series of STD casts was carried out while the ship drifted 9 n mi to the west at an average speed of 0.6 kt (Fig. 15). The ship's drift during the yo-yo station is roughly perpendicular to the temperature section presented in Fig. 11. After the completion of the first lowering, STD station 364-1 and upcast 364-2, repeat profiles were obtained hourly. The series of lowerings spanned approximately 14 h. There was little wind and the weather was extremely mild. The 14 individual traces (Fig. 16) reveal numerous temperature inversions with a typical amplitude of 0.25°C and 25–50 m thick. Mean salinity and temperature traces (Fig. 17) were obtained by arithmetically averaging the individual traces. Most of the structures evident on the individual traces are not coherent throughout the yo-yo station and do not appear in the mean temperature and salinity traces. However, large-scale curvature on a scale of 100–200 m is evident on the mean traces. A weak T-min occurs at 300 m at the base of a 200 m, nearly isohaline layer. The sigma-τ profile (Fig. 17) calculated from the mean salinity and temperature traces shows very little structure; the gradient of sigma-τ with depth is nearly constant.
By subtracting the mean temperature and salinity profiles from the 14 individual traces, temperature and salinity difference pairs ($\Delta T, \Delta S$) were obtained. The temperature differences were contoured (Fig. 18). Because of large temperature variations associated with depth changes of the thermocline, the upper 100 m difference data have not been contoured. The contours reveal a strong horizontal trend. Between 300 and 400 m the differences on the first nine lowerings tend to be negative, forming a 100 m thick layer. This layer remains between the 27.3 and 27.4 sigma-t isopycnals until lowering 364-9, when it appears to dive abruptly (although the contouring is not unique). Some features persist for four to five lowerings, while others are evident only on a single cast. The isopycnals (Fig. 18) remain horizontal throughout the yo-yo station, demonstrating that the temperature and salinity features are density compensating.

Pingree (1972) and others have shown that, if the temperature and salinity are density compensating, then

$$\Delta \rho = A \Delta T + B \Delta S = 0,$$

$$\frac{\Delta T}{\Delta S} = -B/A,$$

where $\Delta \rho$, $\Delta T$, $\Delta S$ are the density change and observed temperature and salinity differences, respectively, and

$$A = \frac{\partial \rho}{\partial T} \bigg|_{S, \text{pressure}}, \quad B = \frac{\partial \rho}{\partial S} \bigg|_{T, \text{pressure}}.$$

On the other hand vertical motions will result in a $\Delta T/\Delta S$ relationship determined by the local $T/S$ slope.

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**Fig. 13a.** As in Fig. 12 except along Section B′-B′. Cast hydrographic stations for GESECS and the Scorpio Expedition are added to the $T/S$ diagram (see text). The 27.1-27.3 $\sigma_t$ interval is indicated by arrowheads.
Shown in Fig. 19 are the $\Delta T = \Delta S$ pairs every 20 m for the 14 traces between the depths of 80 and 800 m. Prior to plotting, the bias in $\Delta T$ and $\Delta S$ for each station was removed. The slopes $-B/A$ for the pressures of 0 db and 1000 db are shown as well as the local $T/S$ slope determined from the average station properties (Fig. 17). Between the sigma-$t$ and sigma-1 $-B/A$ slopes is the regression line for the difference pairs $[\Delta T/\Delta S=9.2\pm0.5^\circ C (\%/1)]$. The local $T/S$ slope indicates that the differences are not due to vertical displacements. The effect of internal waves will be to distort the interleaving. Individual isopycnals vary in depth by up to 15 m, which probably accounts for some of the scatter observed in Fig. 19.

It is not possible to distinguish between time and space variations with this experiment since the two changes are convoluted. However, if we neglect time variability we can calculate a horizontal dimension for the patches of differing $T/S$ properties. Using STD station 364 and 363 we calculate a geostrophic shear of 4 cm s$^{-1}$ (surface to 300 m). Thus a feature observed on five lowerings would have a spatial dimension of 0.7 km. Using STD station 365 and 366 we calculate a
geostrophic shear of 1.6 cm s\(^{-1}\) (300 m)\(^{-1}\) and a horizontal spatial dimension of 0.3 km. This compares favorably with a Rossby radius of deformation \(N\Delta D/f\) of 0.5–1 km (\(N=2.42\times10^{-3} \text{ s}^{-1}, f=1.18\times10^{-4} \text{ s}^{-1}\), \(\Delta D=25–50 \text{ m}\)).

8. The Polar Front over the entire FDRAKE-75 area

The ARA Islas Orcadas XBT data and the R/V Melville XBT and STD data were inspected to locate the Polar Front Zone in the western half of the FDRAKE-75 area. Fig. 20 shows a meander pattern with significant variability in the area of frequent crossing near 65°W. In addition, there appear to be cold eddies well north of the Polar Front Zone.

Two large meridional shifts of the Polar Front Zone occur to the west of the major shift associated with the gap in the North Scotia Ridge at 48°–49°W. These are near 54 and 59°W. This latter shift is well represented by the Discovery data (Fig. 3b) and Mackintosh (1946, p. 183) makes specific reference to its apparent permanence.

The Melville STD data reveal the same zonation pattern as the Conrad data, though the degree of interleaving within the Polar Front Zone is lower. The division between the Polar Front and Antarctic Zones stands out more by the warm-broad T-min found in the Polar Front Zone than by a dramatic increase in the number of T-min layers.

The areal extent of the Subantarctic Zone covered by the Melville data set is larger than that of the Conrad.
9. Discussion

The STD stations and XBT observations indicate a sequence of thermohaline stratification zones on passage from the Antarctic to the Subantarctic region. This sequence is continuous along the meandered Polar Front Zone. Similarly such a sequence of thermohaline stratification zones would enclose isolated eddies of Antarctic, Polar Front or Subantarctic Zone waters. Some STD stations near zonal boundaries indicate differential motion or shear within the water column, which induces superposition of segments from neighboring zones in a single water column.

The nearly isohaline layer of the Subantarctic Zone is of particular interest, since Antarctic Intermediate Water (marked by S-max core layers) found within the Argentine Basin (GEOSECS station 66 of Fig. 13a) and the southeast Pacific Basin (SCORPIO station 76 in Fig. 13a) has similar properties.

How does the thermohaline stratification of the Subantarctic Zone come about? Is cross-frontal transfer of Antarctic characteristics important?

McCartney (1977) proposes that a circumpolar, deep, homogeneous surface layer is formed in the Subantarctic region during the winter and, as the surface layer is warmed, remains as a thermostad and spreads northward. He calls this thermostad Subantarctic Mode Water following the lead of Worthington’s work dealing with Subtropical Mode Water. Presumably the nearly isohaline layer of the Subantarctic Zone in the western Scotia Sea is the product of winter convection. However, the salinity gradient is not zero (an S-max and an S-min occur at its upper and lower boundary, respectively), and the thermal gradient is significant. If winter convection initiated the structure, some alterations have occurred which are not simply a product of sea-air heating and freshening.

The relation of oxygen and silicate to salinity (Fig. 22) shows that oxygen decreases and silicate increases on progressing from the S-max to the S-min, across the nearly isohaline layer of the Subantarctic Zone. The Antarctic and Polar Front Zones do not show such a high oxygen/low silicate anomaly. The Subantarctic anomaly suggests localized generation, but the occurrence of the S-min/O_2 and S-min/Si Subantarctic data points within the general trend of the Antarctic and Polar Front Zone scatter indicates the presence of some communication between Antarctic and Subantarctic water at the base of the nearly isohaline layer. This hypothesis is further supported by the following
evidence:

1) The close similarity in density of the $T$-min/$S$-min found at the base of the nearly isohaline layer with the $T$-min of the Antarctic Zone as discussed above (see Figs. 13a and 14).

2) Surface value tritium concentrations to the 27.3 sigma-$t$ level within the Polar Front Zone (Fig. 17).

3) The prevalence of isopycnal processes within the Polar Front Zone as revealed by the yo-yo station.

4) The observation of an intrusion event of Polar Front Zone water into the Subantarctic Zone, as seen on STD station 314 (Fig. 12).

The high oxygen/low silicate associated with the $S$-max layer is investigated with the aid of early winter hydrographic stations in the Drake Passage [USNS Eltanin cruise 8 (June 1963), Antarctic Zone station 157 and Subantarctic Zone station 158 (Fig. 22)]. The deep surface homogeneous layer of this winter Subantarctic station is similar to the summer $S$-max water but is still higher in salinity and oxygen than the subsurface $S$-min layer at 576 m. It is probable that the early winter period $S$-min layer also results from northward spreading (cross-frontal exchange) of relatively low temperature, low salinity Antarctic water.

We believe that during spring and summer the winter period homogeneous layer is isolated from the sea-air interface by surface warming and surface freshening. We further propose that the $S$-max and the negative temperature gradient from the $S$-max to the $S$-min of the nearly isohaline layer are induced by vertical mixing of Antarctic temperature minimum water intro-

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**Fig. 18.** Contours of the difference (0.10° intervals) between individual temperature traces (shown in Fig. 16) and the mean temperature traces (shown in Fig. 17). Also shown are the 27.2, 27.3, 27.4 and 27.5 sigma-$t$ isopycnals.
Fig. 19. Temperature-salinity difference pairs, 1 pair per 20 m. The two lines 
\[ -\frac{B}{A} = 9.72^\circ C \left( \frac{\%}{\%} \right) \] 
and 
\[ -\frac{B}{A} = 7.33^\circ C \left( \frac{\%}{\%} \right) \] 
define the envelope for salinity-temperature differences due to an isopycnal process. The local T/S slope was determined from the average temperature and salinity traces in Fig. 17.

Fig. 20. Polar Front Zone (patterned area), constructed from Conrad STD and XBT data (taken from Fig. 31), Islas Orcadas XBT data and the Melville STD and XBT data. The STD stations of Conrad (taken from Fig. 1) and Melville are shown with the symbols referring to stratification type. The bars refer to the width of the Polar Front Zone, determined by the XBT data of Islas Orcadas (solid) and Melville (open) along the ships’ tracks. Surface salinity is shown as constructed from water samples taken with XBT observations. The numbers 16–26 in the Subantarctic Zone refer to the Melville stations used for Fig. 21.

duced by cross-frontal exchange into the Subantarctic Zone at the S-min level. Hence the S-max represents the least contaminated or remnant layer of the winter convective layer. The source of relatively saline water which is represented by the remnant S-max layer and which must exist to balance the effect of cross-frontal exchange of polar water may lie to the north.

While it is an attractive possibility to relate formation of Antarctic Intermediate Water to the Subantarctic Zone, as mentioned by McCartney (1977), this does not imply that the process is solely a Subantarctic event. The evidence suggests that cross-frontal exchange occurs and that such an exchange would cool and freshen the Subantarctic Water in relation to what its characteristics would be if it resulted solely from local sea-air effects. To what degree this exchange determines the characteristics and thickness of the Subantarctic, nearly isohaline layer and hence of Antarctic Intermediate Water is unknown. Winter data are necessary, as well as an accurate determination of the annual cycle of sea-air heat and water exchange.

Wüst (1936) and Deacon (1937) have noted the existence of a temperature inversion below the main S-min marking the Antarctic Intermediate Water. It is possible that this inversion is related to the T-min observed at the base of the nearly isohaline layer of the Subantarctic Zone. However, the Melville data (Fig. 21) show that the salinity and particularly the temperature gradients in the nearly isohaline layer weaken 100–200
Fig. 21. Family of temperature and salinity vs depth curves for the set of Mawson stations in the Subantarctic Zone. These STD data are preliminary, therefore absolute temperature or salinity scales are not used. This is sufficient since it is the form of the curve which is relevant here.

Fig. 22. Salinity vs oxygen and silicate diagrams constructed from the Conrad STD station water bottle data (station number and zones are indicated on figure). Early winter oxygen data (Eltanin stations 157 and 158, June 1963) in the Subantarctic and Antarctic Zones of the FDRAKE area are added for comparison.

km north of the Polar Front Zone. This suggests that the Antarctic influence may not extend far to the north, at least in the Drake Passage in the summer of 1975.

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