

The Weddell-Scotia Confluence

STEVEN L. PATTERSON¹

Department of Oceanography, Texas A&M University, College Station 77843

HELLMUTH A. SIEVERS²

Instituto Hidrografico de la Armada, Valparaiso, Chile

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ABSTRACT

The Weddell-Scotia Confluence is the zone separating the waters of the Weddell Sea from those of the Scotia Sea. Available historical hydrographic station data were examined to improve the description of this boundary zone from its western limit near the northern tip of the Antarctic Peninsula (~55°W) to 20°W. Vertical sections of potential temperature, salinity, oxygen and density, as well as horizontal property distributions, confirm that the waters in the western part of the Weddell-Scotia Confluence are more homogeneous in the vertical than the surrounding waters and that, at depth, this zone is characterized by relatively low temperatures and salinities and high oxygen values. Near the sea surface, on the other hand, the confluence is characterized by relatively high salinities and low oxygen values. The distinguishing characteristics attenuate toward the east. Previous speculation has been that the relative homogeneity of this zone is due to vertical convection driven during winter by ice formation and air/sea interaction. Here we propose that the unusual properties of this zone may be due instead to vertical mixing processes occurring within the oceanic lateral boundary layer which, while acting to homogenize the water column, incorporate into the water column cold, fresh meltwater from the ice (principally that of continental origin) which is nearly always present in this area. The influence of such a process would not be restricted to the winter season.

1. Introduction

The boundary zone separating the eastward flowing waters of the northern Weddell Sea from those of the southern Scotia Sea has been referred to as the Weddell-Scotia Confluence (WSC) by Gordon (1967). He described this boundary as a discontinuity or a sharply defined line separating deep water masses of Weddell Sea origin from those of southeast Pacific origin. He shows this line to extend from the South Shetland Islands, near the Antarctic Peninsula, in a generally northeastward direction across the southern Scotia Sea, and he speculates that the boundary may extend as far as 30°E. The deep waters on either side of the boundary are distinguishable on the basis of their temperature and salinity properties, the deep waters from the southeast Pacific being warmer and slightly more saline.

Such a description of this feature might lead one to expect the deep waters in and near the WSC to exhibit properties which are intermediate between

those of the deep waters of the Scotia and Weddell Seas as in a simple transition zone or front. However, observations made during the early *Discovery* and *William Scoresby* cruises (Deacon, 1937) showed that the typical Circumpolar Deep Water (CDW) core layer characteristics, that is, the deep temperature and salinity maxima and the dissolved oxygen minimum, are either weakly expressed or absent in the region over the South Scotia Ridge between the South Shetland Islands and the South Orkney Islands. Hence, in this area, the vertical property distributions are unusually homogeneous with deep waters that are anomalously cold, fresh and oxygen-rich. These early observations have been confirmed by more recent meridional sections across the South Scotia Ridge in the vicinity of 50°W (Deacon and Moorey, 1975; Deacon and Foster, 1977; Gordon *et al.*, 1977).

The anomalous properties of the deep waters in the western part of the WSC suggest that these waters are not merely a mixture of the adjacent Weddell and Scotia deep water types, but are instead the result of water mass modifications being imposed upstream or by local processes. Previous researchers (Deacon, 1937; Deacon and Moorey, 1975; Deacon and Foster, 1977; Gordon *et al.*,

¹ Current affiliation: Science Applications, Inc., McLean, VA 22102.

² Current affiliation: Departamento de Oceanologia, Universidad de Chile, Vina del Mar, Chile.

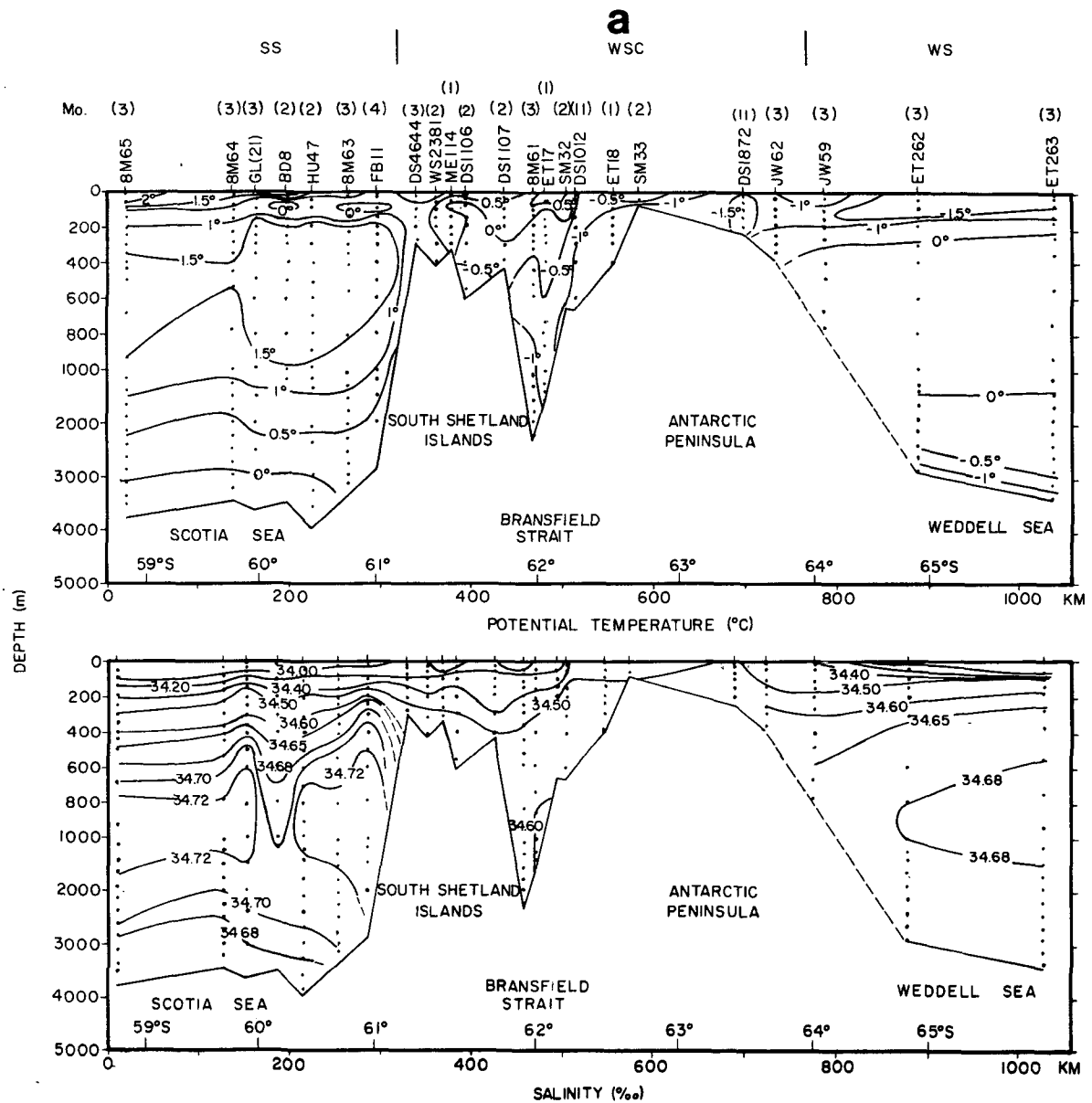


FIG. 2a. Vertical section of potential temperature (top) and salinity (bottom) along Section I shown in Fig. 1.

that at least the gross features of the property distributions associated with the WSC are quite persistent. The individual stations used in each vertical section are identified by the appropriate two-character NODC ship code, as listed in Table 1, followed by the originator's station number. In a few cases (e.g., *Glacier* station 21 in Section I, Fig. 2), the originator's station number was unavailable and the NODC assigned consecutive number was used instead. In these cases the station number is enclosed in parentheses. The month during which each station was occupied is indicated by the appropriate number enclosed in parentheses above the identifier. There is a scale change on the depth axis at 1000 m to afford better resolution of features in the upper part of the water column.

Oxygen data from *Discovery*, *Discovery II*, and *William Scoresby* have been "corrected" by adding 0.4 mL L^{-1} to each observation as suggested by Gordon and Goldberg (1970). The potential density anomaly parameters displayed in the vertical sections are those explained by Lynn and Reid (1968). The values presented between the sea surface and 1000 m are of σ_0 which is the potential density anomaly computed relative to the sea surface; those presented between 1000 and 3000 m are of σ_2 , the anomaly relative to 2000 m; and those presented below 3000 m are of σ_4 , the anomaly relative to 4000 m.

The distribution of temperature, salinity and dissolved oxygen concentration on horizontal surfaces at 20 and 500 m are also presented (Figs. 14 and

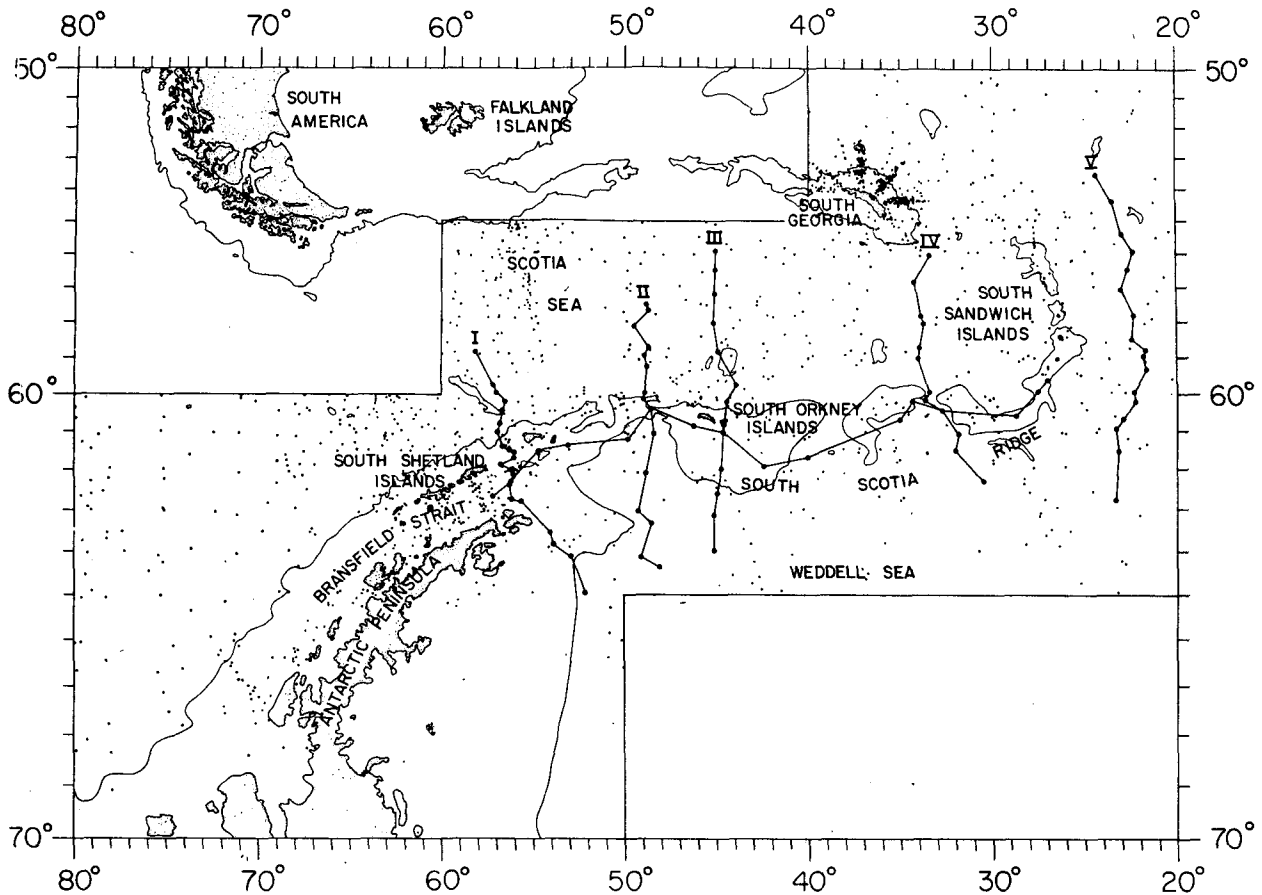


FIG. 1. Distribution of historical hydrographic stations considered in this study. Lines of stations used to construct vertical sections and the 2000 m isobath are shown.

1977; Gordon and Nowlin, 1978) have concurred that the vertical homogeneity of the water column in this region is due to extensive vertical convection which is driven by air/sea/ice interactions occurring during the austral winter.

In this paper we examine the available historical hydrographic station data from the region outlined in Fig. 1 in an effort to refine and expand our description of the vertical and horizontal property distributions in and near the WSC. The zone is described from its western limit near the northern tip of the Antarctic Peninsula to 20°W and an alternative explanation for the observed distributions is proposed.

2. Data

Historical hydrographic station data from the region outlined in Fig. 1 were obtained from the National Oceanographic Data Center (NODC) and the Instituto Hidrografico de la Armada de Chile. Recent data obtained during the First Dynamic Response and Kinematics Experiment (FDRAKE) of the International Southern Ocean Studies (ISOS) were available at Texas A&M University. The

original sources of the data, acquired during the period from 1911 to 1975, are listed in Table 1. From a total of 2087 available hydrographic stations, 1535 were selected for inclusion in this analysis.

Five lines of hydrographic stations that are roughly meridional in orientation and one that is roughly zonal (Fig. 1) were selected to construct vertical sections of potential temperature (θ), salinity (S), dissolved oxygen concentration (O_2) and potential density anomaly (σ). The meridional lines, numbered I–V in Fig. 1, are approximately perpendicular to the WSC and the vertical sections show how the water mass properties change in the cross-stream direction. A comparison of the five meridional sections also reveals how the WSC changes in the downstream direction. The zonal line of stations is approximately parallel to the direction of flow and is located near the “axis” of the WSC.

In spite of the non-synoptic nature and the sometimes questionable quality of the data used, the distributions shown in the vertical sections do present a reasonably consistent picture suggesting

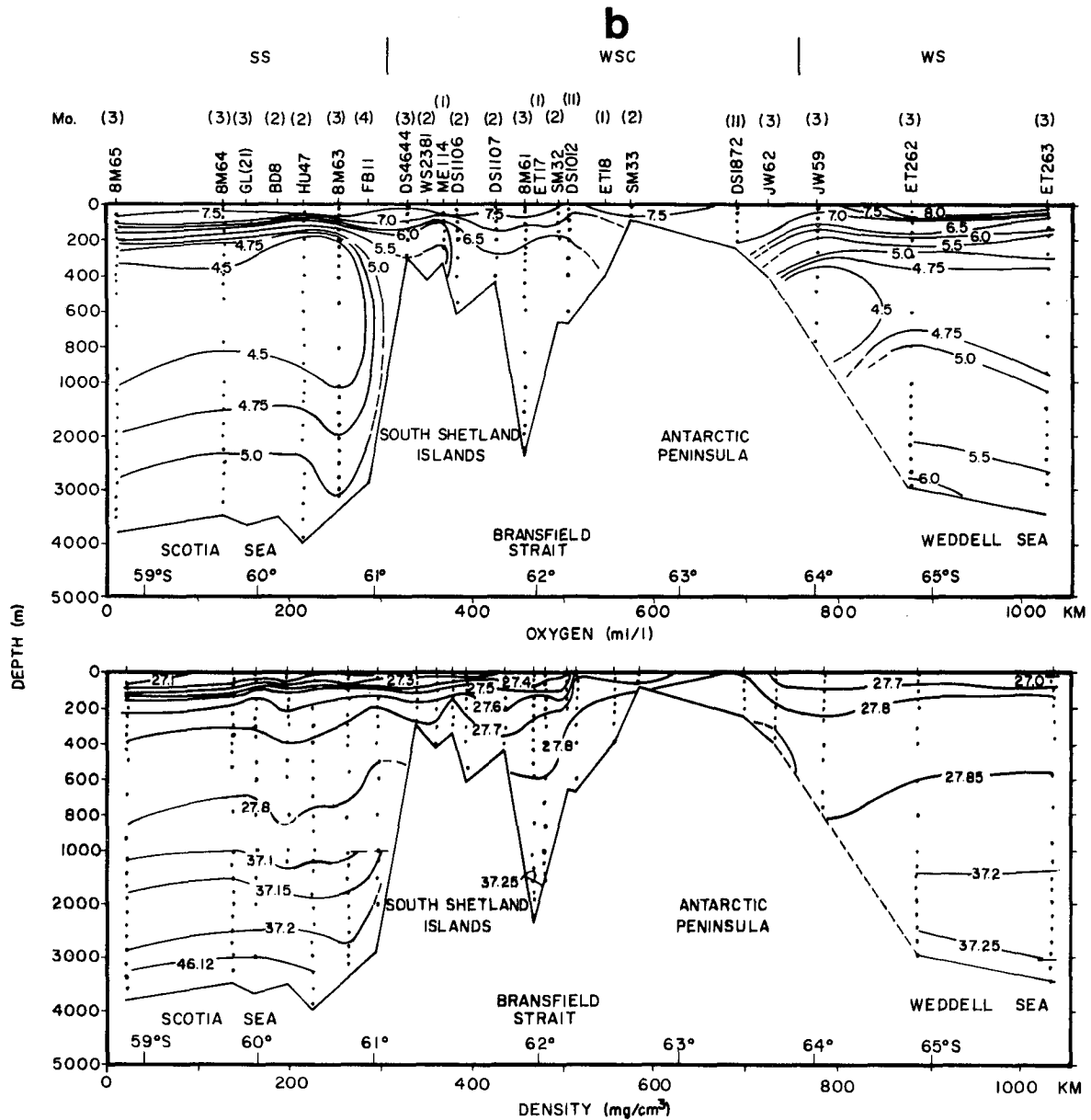


FIG. 2b. Vertical section of dissolved oxygen concentration (top) and potential density anomaly (bottom) along Section I shown in Fig. 1.

15) for the area outlined in Fig. 1. These two surfaces were chosen as suitable ones to show the lateral extent and configuration of both the deep and near-surface signatures of the WSC and also to be directly comparable to the property distributions presented by Gordon and Goldberg (1970). In many cases direct measurements at these specific depths were not available and interpolated values were used. In the 20 m distributions the few available winter (June–November) data have been omitted. On the horizontal plots the distribution of *in situ* temperature is presented rather than potential temperature. This is because on such shallow surfaces, the adiabatic temperature change will be small and essentially constant.

3. Vertical sections

a. Section I

The westernmost meridional section, Section I in Fig. 1, extends from the Scotia Sea southeastward across the South Shetland Island arc, the eastern Bransfield Strait, the continental shelf at the northern tip of the Antarctic Peninsula and into the Weddell Sea. This section (Fig. 2) shows the property distributions near the point where Scotia Sea and Weddell Sea waters initially “meet.” The relatively warm, saline and oxygen-poor deep waters present in both the Scotia and Weddell Seas are not present over the island arc or over the continental shelf of the peninsula, nor are they

TABLE 1. Available historical hydrographic station data.

Country	NODC ship code	Ship name	Years
Argentina	CC	<i>Capitan Canepa</i>	1958-67
	SM	<i>General San Martin</i>	1955-69
	GZ	<i>General Zapiola</i>	1963
	IO	<i>Islas Orcadas</i>	1975
Canada	HU	<i>Hudson</i>	1970
Chile	YE	<i>Yelcho</i>	1963-64
Germany	DE	<i>Deutschland</i>	1911-12
	JW	<i>Jan Wellen</i>	1936-37
	ME	<i>Meteor</i>	1926
Japan	UT	<i>Umitaka Maru</i>	1962
Norway	NO	<i>Norvegia</i>	1928
U.S.S.R.	KN	<i>Akademik Knipovich</i>	1965-70
	BD	<i>Boris Davidov</i>	1968
	FB	<i>Faddei Bellingshausen</i>	1968
	AK	<i>Kovalevskii A.O.</i>	1955
	MK	<i>Miksun</i>	1963-64
	OB	<i>Ob</i>	1958
	VZ	<i>Professor Viese</i>	1969
U.K.	AN	<i>Anglo Norse</i>	1927
	DI	<i>Discovery</i>	1926-27
	DS	<i>Discovery II</i>	1930-51
	WS	<i>William Scoresby</i>	1925-31
U.S.A.	CT	<i>Canisteo</i>	1947
	RD	<i>Conrad</i>	1975
	ED	<i>Edisto</i>	1959
	ET	<i>Eltanin</i>	1962-70
	GL	<i>Glacier</i>	1959-75
	GN	<i>Knorr</i>	1973
	8M	<i>Melville</i>	1975
	NW	<i>Northwind</i>	1959
	SI	<i>Staten Island</i>	1956
	WT	<i>Thomas Washington</i>	1969
	VE	<i>Vema</i>	1959-62
	WE	<i>Westwind</i>	1958

present within the eastern Bransfield Strait. Instead, the deep waters in these areas are considerably colder, fresher and more highly oxygenated. They are clearly not the result of mixing Scotia and Weddell Sea waters, but are significantly affected by nearshore processes. The properties shown here are consistent with the distributions in Bransfield Strait reported by Gordon and Nowlin (1978). The deep density distribution (Fig. 2b), on the other hand, shows no such remarkable contrast, but instead undergoes a simple transition from the Scotia Sea into the Weddell Sea with the isopycnals exhibiting a general rise toward the south indicating a predominantly eastward flow.

On the basis of the deep property distributions, the meridional sections are subjectively divided into three zones: the Scotia Sea zone (SS) to the north, the Weddell Sea zone (WS) to the south, and the intervening WSC zone. These zones are de-

lined across the top of each section. In Section I, the WSC is considered to include the region from the South Shetland Island arc to the southeastern slope of the Antarctic Peninsula.

In contrast to the deep signature of the western WSC (i.e., low temperature and salinity and high oxygen relative to the surrounding waters at the same depth), the surface property distributions exhibit, at least in part, the reverse relationship. While there is no obvious surface temperature signature, the surface salinity values, and hence the surface density values, within the WSC are high relative to those within the Scotia or Weddell Seas. This observation is in agreement with surface property distributions reported by Gordon *et al.* (1977) who also report that the confluence is characterized by high surface silicate values relative to those farther north. In Fig. 2 there also appears to be a weakly expressed minimum in the surface dissolved oxygen concentration within the WSC.

To examine the variations in water properties in more detail, the potential temperature-salinity (θ - S) relations for stations in Section I are presented in Fig. 3. Although the θ - S relations along this section exhibit significant differences, the section can be divided into five segments, each containing stations with similar θ - S characteristics.

A pronounced CDW core layer is evident in both the Scotia Sea (Fig. 3a) and the Weddell Sea (Fig. 3e), but the differences between these two areas are also readily apparent. The curves from the Scotia Sea exhibit a broad subsurface temperature maximum (T -max), i.e., the portion of the curve near the T -max encompasses a large range in salinity. Temperatures at the T -max are in excess of 1.5°C. Salinities at the subsurface temperature minimum (T -min) are near 34.2‰. In contrast, the curves from the northern Weddell Sea (Fig. 3e) exhibit a sharp T -max with maximum temperatures generally <0.5°C. Salinities at the T -min are higher than those in the Scotia Sea, being near 34.5‰.

The portion of this section between the Scotia and Weddell Seas is divided into three segments, each corresponding to a specific area: the South Shetland Island arc (Fig. 3b), the Bransfield Strait (Fig. 3c), and the continental shelf of the Antarctic Peninsula (Fig. 3d). Over the South Shetland Island arc, the water column is more homogeneous than that in the Scotia Sea, exhibiting only a weak expression of a T -min layer and no T -max layer. Within the Bransfield Strait (Fig. 3c) the θ - S relation becomes more nearly linear with potential temperature decreasing almost monotonically with depth while salinity increases. Waters over the continental shelf of the Antarctic Peninsula (Fig. 3d) are colder, more saline and somewhat more homogeneous than the near-surface waters within

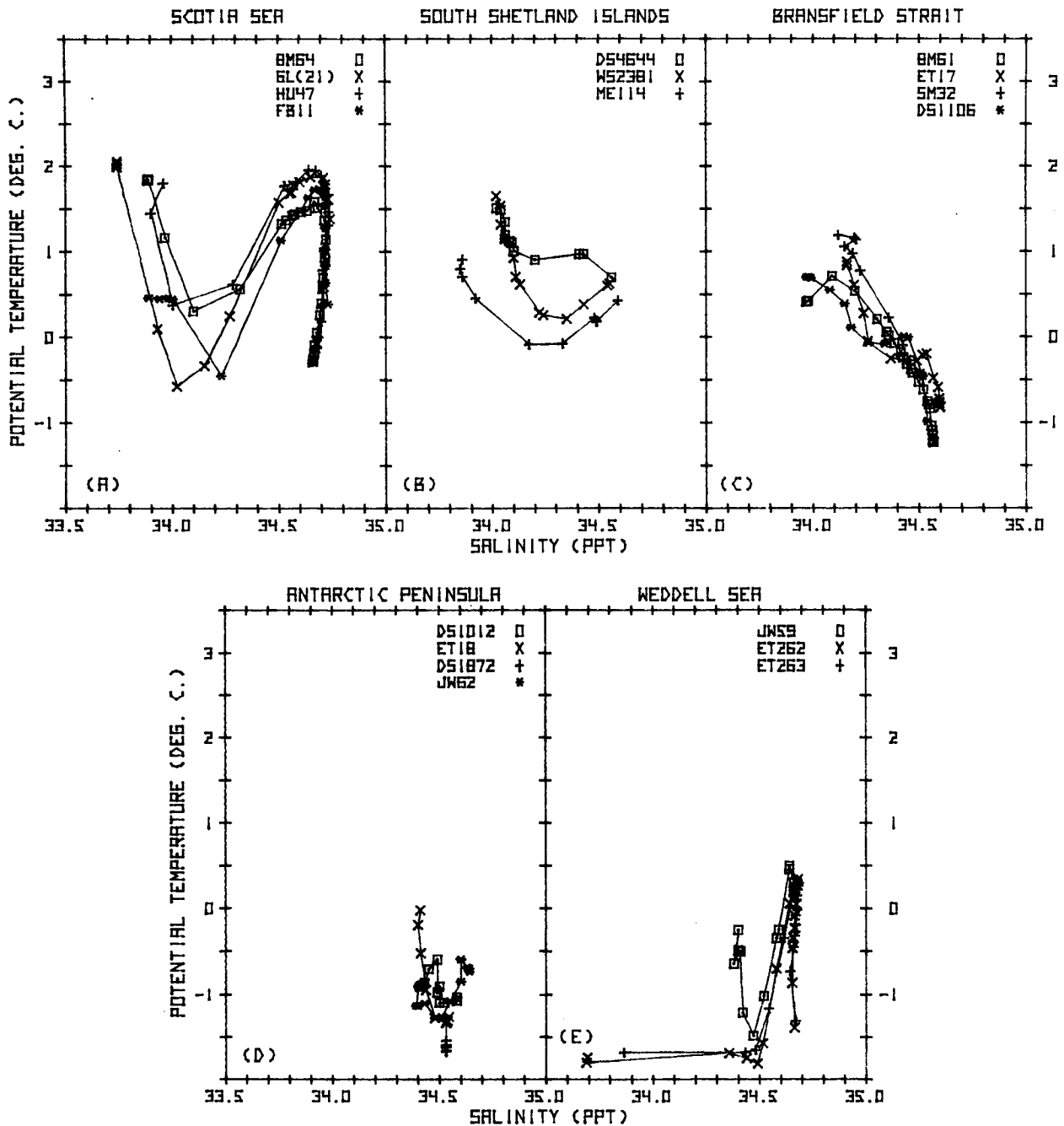


FIG. 3. Potential temperature versus salinity relations for representative stations along Section I (a) within the Scotia Sea, (b) over the South Shetland Island arc, (c) within Bransfield Strait, (d) over the continental shelf at the northern end of the Antarctic Peninsula, and (e) within the Weddell Sea.

the Bransfield Strait or the Weddell Sea and, in fact, are quite similar to the bottom waters in the strait.

b. Section II

Section II extends from the Scotia Sea into the Weddell Sea approximately along 49°W (Fig. 1).

This section is near those reported by Deacon and Moorey (1975), Deacon and Foster (1977) and Gordon *et al.* (1977). As before, the continuity of the warm, saline and oxygen-poor deep waters of the Scotia and Weddell Seas, seen in Fig. 4, is interrupted by a zone of relatively cold, fresh and oxygen-rich deep water. However, the magnitude of

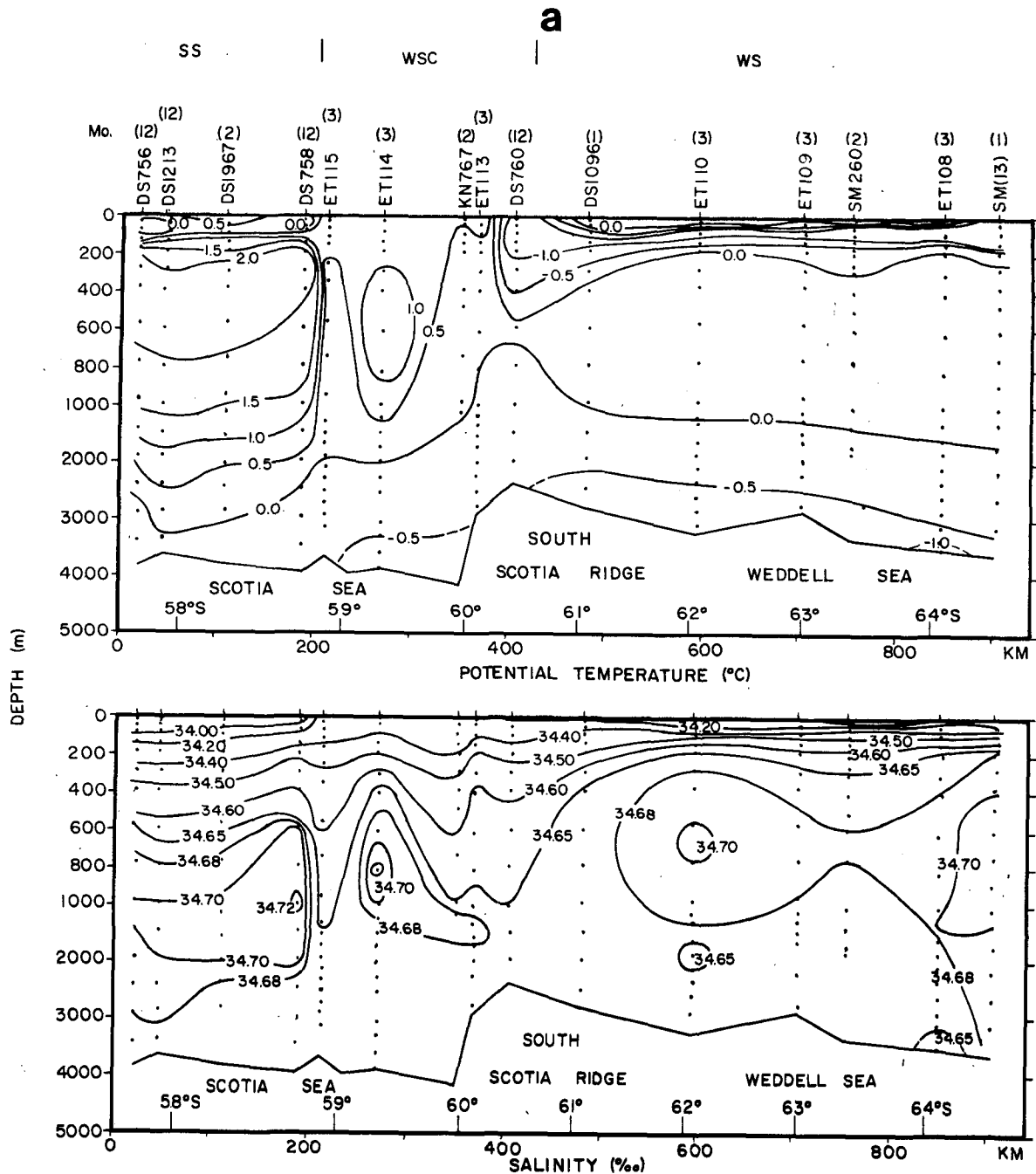


FIG. 4a. As in Fig. 2a except along Section II.

this signal is not as great as that seen in Section I (Fig. 2). The placement of the boundaries of the WSC in this study is quite subjective and arbitrary, being based primarily on the temperature of the deep water. It is expected that subsequent studies will refine the definition of WSC limits. The northern boundary of the WSC in Section II is placed at the southern terminus of the Scotia Sea variety of CDW as delineated by the 1.5°C isotherm.

South of this line the temperature at the T -max decreases to a minimum of 0.08°C at *Discovery II* station 760 (DS760). The boundary between the WSC and the Weddell Sea is placed just south of this station. Beyond this boundary the temperature at the T -max increases toward the central Weddell Sea. As in Section I the WSC exhibits a surface signature of relatively high salinity and density and low oxygen. The distributions shown agree with the

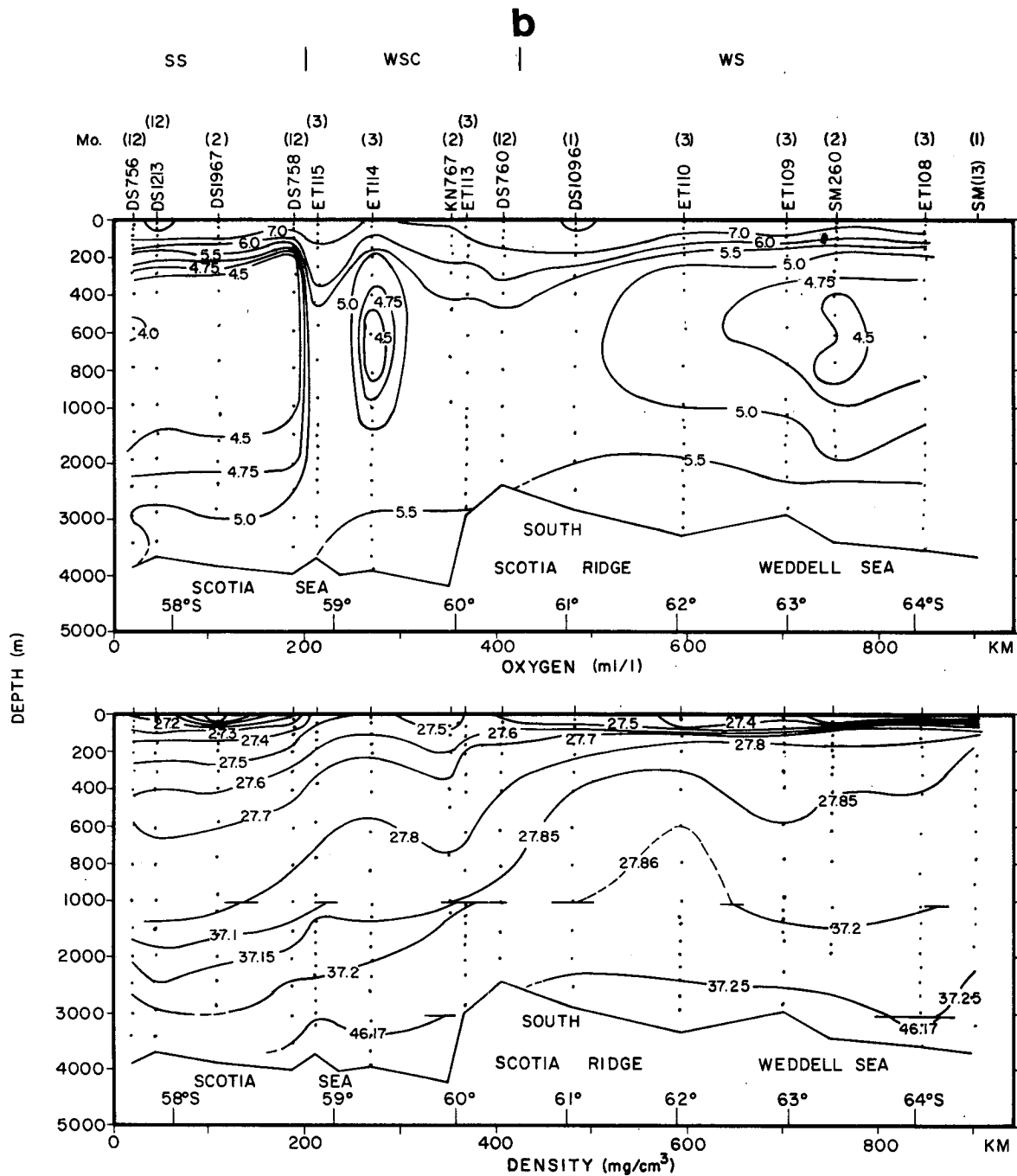


FIG. 4b. As in Fig. 2b except along Section II.

synoptic distributions presented by Deacon and Moorey (1975), Deacon and Foster (1977) and Gordon *et al.* (1977).

As seen in Fig. 4 the properties at *Eltanin* station 114, isolated within the WSC, show some CDW influence suggesting that the waters at this station are in close proximity to, or have been contaminated by, the deep waters outside the WSC. Since the *Eltanin* data that define this feature (stations

113–115) were obtained during a 3-day period and on a single crossing of the WSC, the property distributions are probably due to a meander within the general eastward flow. Evidence for a similar meander in this area has also been seen in the sea surface property distributions of the synoptic data reported by Gordon *et al.* (1977).

The θ - S relations for the stations in Section II are presented in Fig. 5. These curves are separated

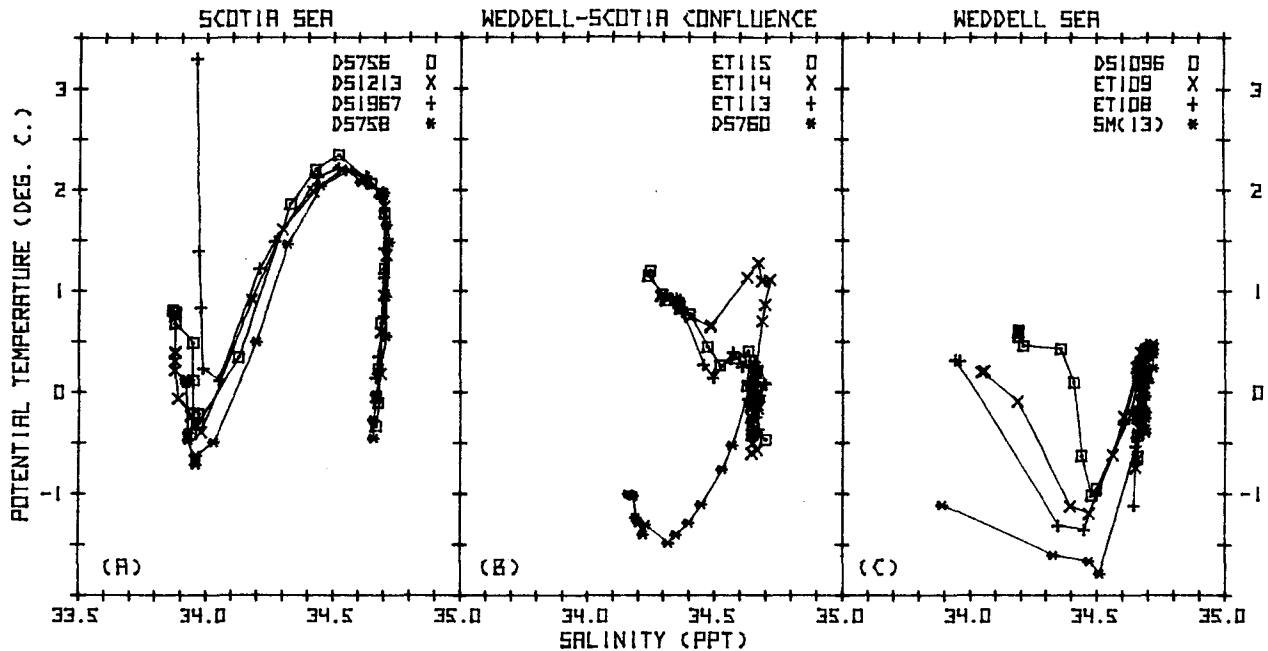


FIG. 5. Potential temperature versus salinity relations for representative stations along Section II (a) within the Scotia Sea, (b) within the Weddell-Scotia Confluence, and (c) within the Weddell Sea.

into three groups corresponding to the three zones indicated in Fig. 4. The curves for stations in the Scotia Sea zone (Fig. 5a) exhibit a broader and warmer T -max and a fresher T -min than those seen in Section I (Fig. 3a). This is because the Scotia Sea stations of Section II sampled a more northerly band of CDW than that sampled by the stations in Section I. In the Southern Ocean, water mass properties are relatively constant within bands parallel to the direction of flow of the Antarctic Circumpolar Current, which is nominally zonal, but these properties change in the cross-stream or meridional direction. In some areas these changes occur abruptly at sharp zonal fronts (Nowlin *et al.*, 1977). The colder band of CDW sampled in Section I appears to become quite narrow in the vicinity of Section II.

The θ - S curves for stations within the WSC (Fig. 5b) exhibit a variety of shapes indicating that there is no "characteristic" θ - S relation for this zone. The deep waters here are warmer and more saline than those in Bransfield Strait (Fig. 3c). Hence, if the cold, fresh and oxygen-rich waters of Bransfield Strait are advecting eastward within the WSC, they are contaminated rather quickly by lateral mixing with the surrounding water masses. The surface waters within the WSC, except at *Discovery II* station 760 (DS760), have characteristics similar to the waters around the South Shetland Islands (Fig. 3b). As mentioned earlier, the deep waters at *Eltanin* station 114 show evidence of mixing with Scotia Sea CDW. Since the core layer character-

istics of CDW are weakest at DS760 (Fig. 4), this station is within the WSC. However, because of the well-developed T -min layer, the water column here is not as vertically homogeneous as it is farther north. The shape of the θ - S curve at DS760 is quite similar to that of stations in the Weddell Sea (Fig. 5c) suggesting that the water column here may have attained its properties within the Weddell Sea along the east coast of the Antarctic Peninsula.

Although the θ - S curves within the Weddell Sea are rather tightly grouped, it is noted that the temperature at the T -min decreases while that at the T -max increases toward the central Weddell Sea. Hence the thermal homogeneity of the water column decreases with distance from the confluence.

c. Section III

Section III extends from the Scotia Sea over the broad plateau of the South Orkney Islands and into the Weddell Sea along $\sim 45^\circ\text{W}$ (Fig. 1). The property distributions presented in Fig. 6 indicate that CDW core layer characteristics attenuate on approaching the South Orkney plateau from either the north or the south. As in the preceding sections, the northern boundary of the WSC is placed at the southern terminus of the deep 1.5°C isotherm in the Scotia Sea and the southern boundary is over the southern slope of the South Orkney plateau in the Weddell Sea. Once again the surface salinity and density reach a local maximum within the WSC. However, this surface signature is interrupted at the

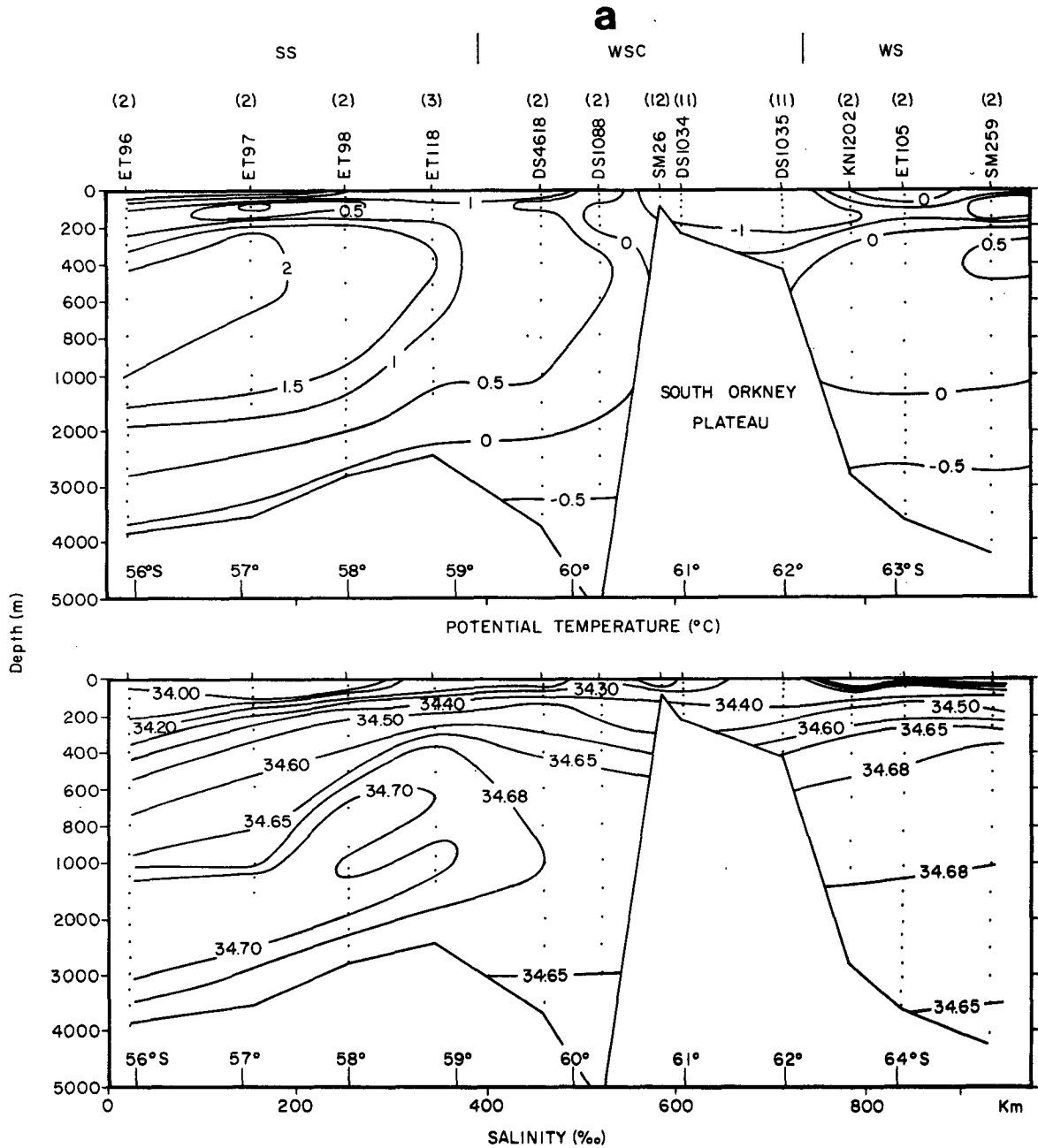


FIG. 6a. As in Fig. 2a except along Section III.

shallowest part of the plateau, near the islands, by a patch of relatively fresh and less dense water.

The θ - S relations for this section are presented in Fig. 7. The curves from the Scotia Sea are not as tightly grouped as in the previous sections. They undergo a transition from those showing a broad, warm T -max to those showing a sharper and cooler T -max. Within the WSC this trend continues until it is interrupted by the anomalously cold and fresh patch of water at *General San Martin* station 26. South of this station the waters over the plateau

become warmer and more saline until typical Weddell Sea stratification is encountered south of the plateau. As in the previous section, the temperature at the T -min decreases as that at the T -max increases toward the central Weddell Sea.

d. Section IV

Section IV runs from the Scotia Sea, through a gap in the South Scotia Ridge at $\sim 33^\circ W$, and into the Weddell Sea (Fig. 1). The property distributions in

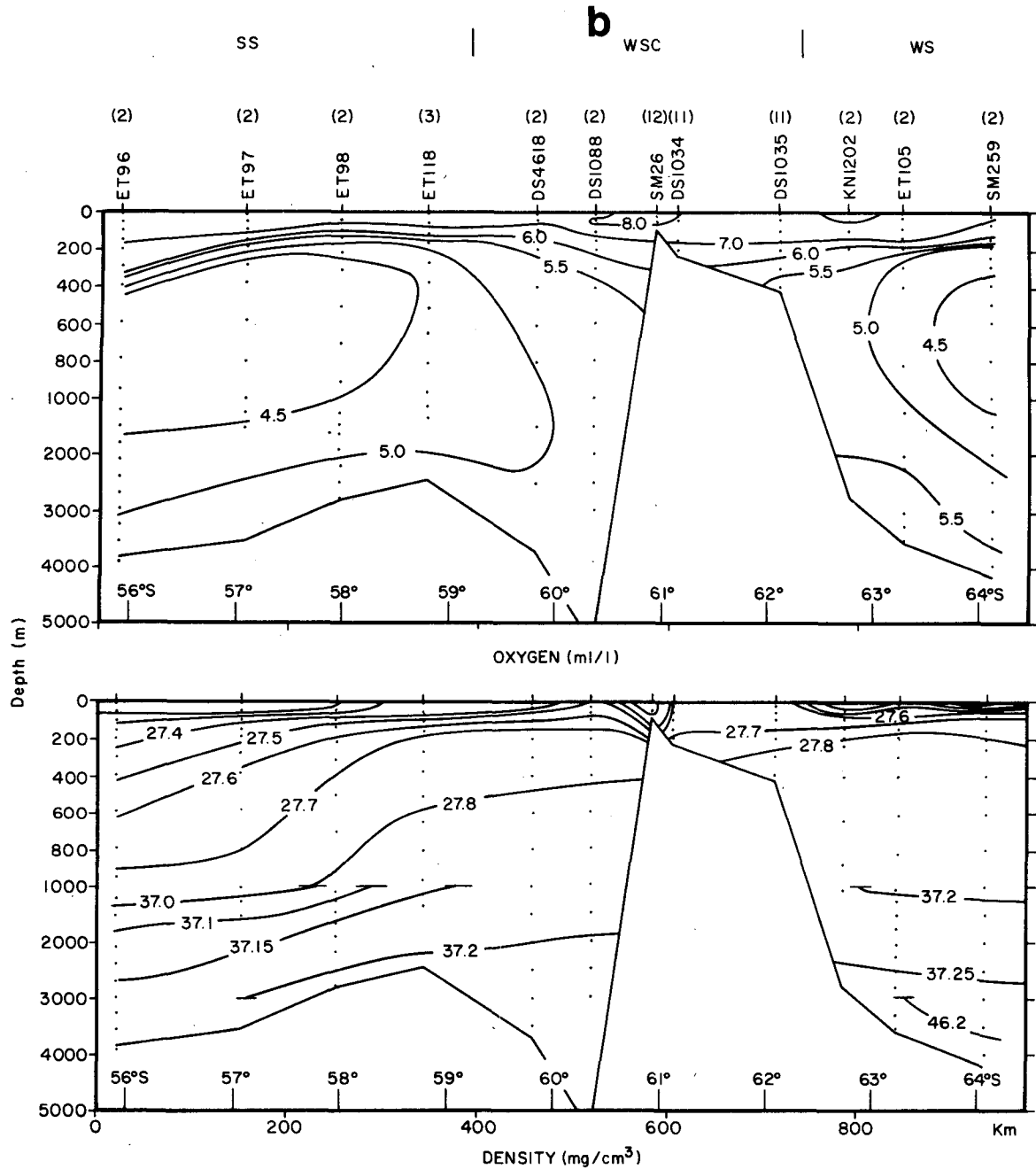


FIG. 6b. As in Fig. 2b except along Section III.

Fig. 8 show that CDW core layer characteristics are weakest near the gap. Although the weakening of CDW characteristics within the WSC is not as pronounced here as it is in the sections farther upstream, it is still a readily identifiable feature. However, there is no clear surface signature of the WSC in this section.

The θ - S relations in Fig. 9 show that along Section IV water mass characteristics undergo a steady transition from those typical of the Scotia Sea to

those observed at *Deutschland* station 114 (DE114) within the WSC, and then to those typical of the Weddell Sea. Everywhere along this section a well-developed T -max layer is evident and there are no stations that exhibit the same degree of vertical homogeneity as that observed upstream.

e. Section V

Section V, which runs approximately along 23°W (Fig. 1), is east of the South Sandwich Island arc.

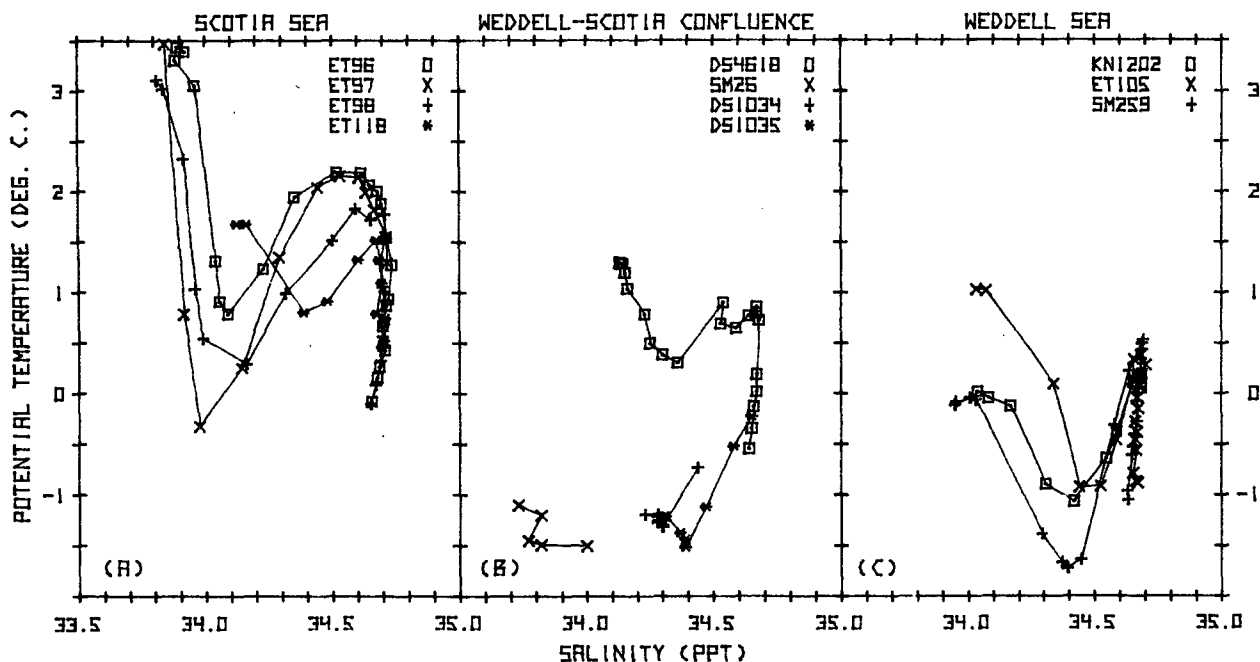


FIG. 7. As in Fig. 5 except along Section III.

The deep water properties along this section (Fig. 10) are patchy and cannot be easily divided into three zones as in the previous sections. This patchiness may not be real, but merely the result of using non-synoptic data to describe a flow field which experiences significant temporal and/or spatial variability downstream of the island arc. The θ - S curves from this section, shown in Fig. 11, suggest that the boundary between the Weddell and Scotia Seas has, at this point along its path, evolved into a simple transition zone containing waters with properties intermediate between those to the north and south. It is this transition zone which Gordon (1967) contends may extend as far as 30°E. Although the patchiness does impose some reversals on the otherwise orderly progression of curves from those characteristic of the Scotia Sea to those characteristic of the Weddell Sea, no consistent evidence of an eastward continuation of the zone of weak CDW core layer characteristics can be seen in this section. Such a continuation might be observable in a synoptic section in this area, though its signal strength is expected to become progressively weaker with distance toward the east.

f. Zonal section

The series of meridional vertical sections across the WSC has shown that the region of diminished CDW core layer characteristics which separates the deep waters of the Scotia and Weddell Seas has its lowest temperature and salinity values and highest

oxygen values within Bransfield Strait, near the tip of the Antarctic Peninsula, and over the South Orkney plateau. This deep signature attenuates toward the east probably as a result of lateral mixing with the adjacent deep water masses. East of the South Sandwich Island arc, the deep signature has been eroded to such an extent that it cannot be detected in this analysis.

The eastward attenuation can be more easily seen in the zonal vertical section shown in Fig. 12 which runs approximately along the axis of the WSC as defined by the line of weakest expression of CDW core layer characteristics. The position of this section is indicated in Fig. 1.

As noted earlier the meridional sections suggest that the WSC has no "typical" or "characteristic" θ - S relation, but as seen in Fig. 13, the curves within certain segments of zonal section along the WSC axis are similar. Figs. 12 and 13 show that there is a significant change in the characteristics of the water column in the western part of the WSC between Bransfield Strait and the South Orkney plateau. In the eastern basin of the Bransfield Strait temperature decreases almost monotonically with depth. Toward the east this type of stratification is replaced by one which exhibits a weakly expressed T -min and T -max just to the west of the South Orkney plateau. East of the plateau the vertical property distributions are only slightly more homogeneous than those of the northern Weddell Sea. The waters here may have attained their properties along the east coast of the Antarctic Peninsula.

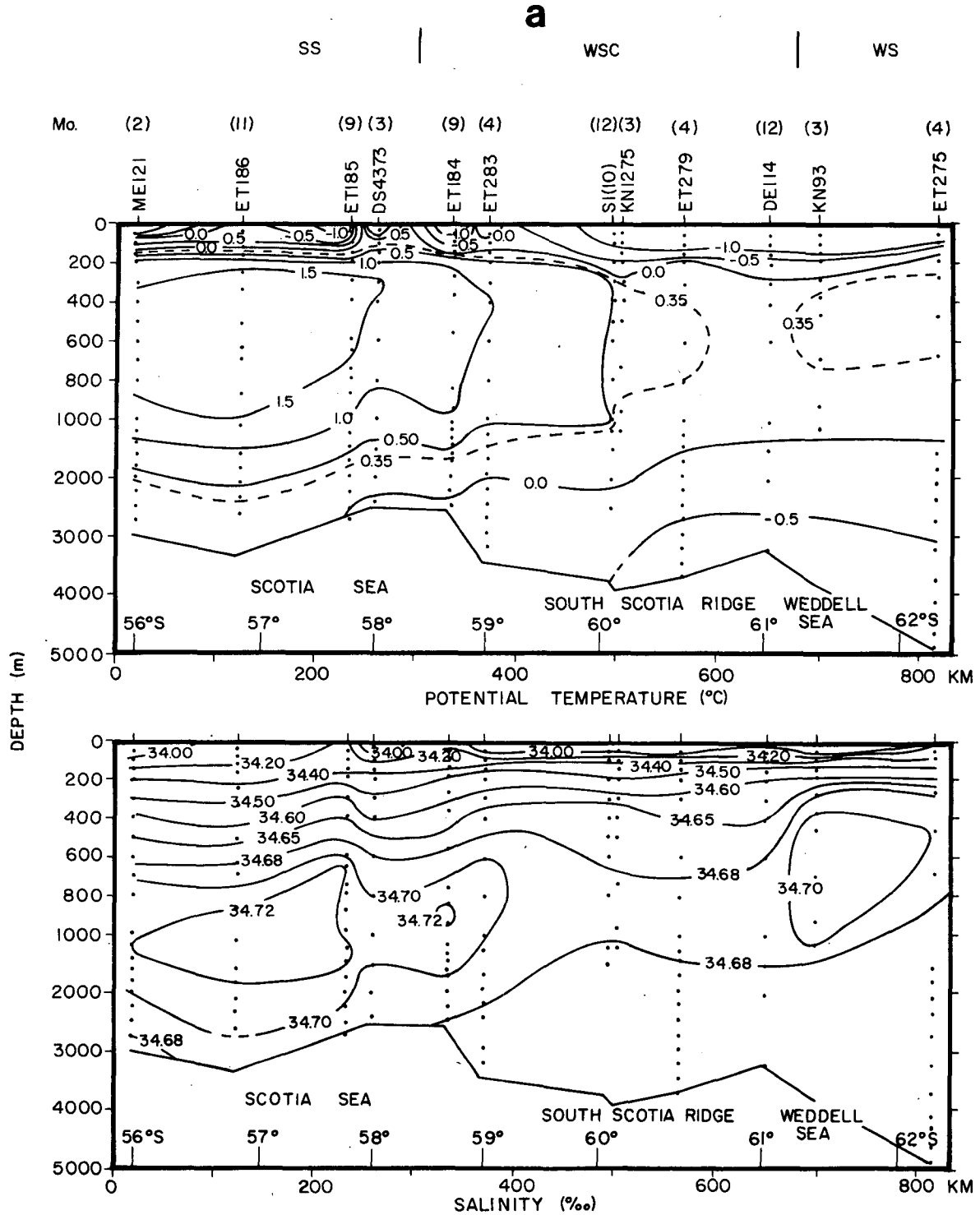


FIG. 8a. As in Fig. 2a except along Section IV.

4. Horizontal property distributions

Deacon and Foster (1977) showed that the shape of the WSC, as defined by the potential temperature distribution on the *T*-max surface, conforms to the

shape of the South Scotia Ridge in the region extending from the tip of the Antarctic Peninsula to the South Orkney plateau. This relationship with the bottom topography is also evident in the horizontal distributions of temperature, salinity and

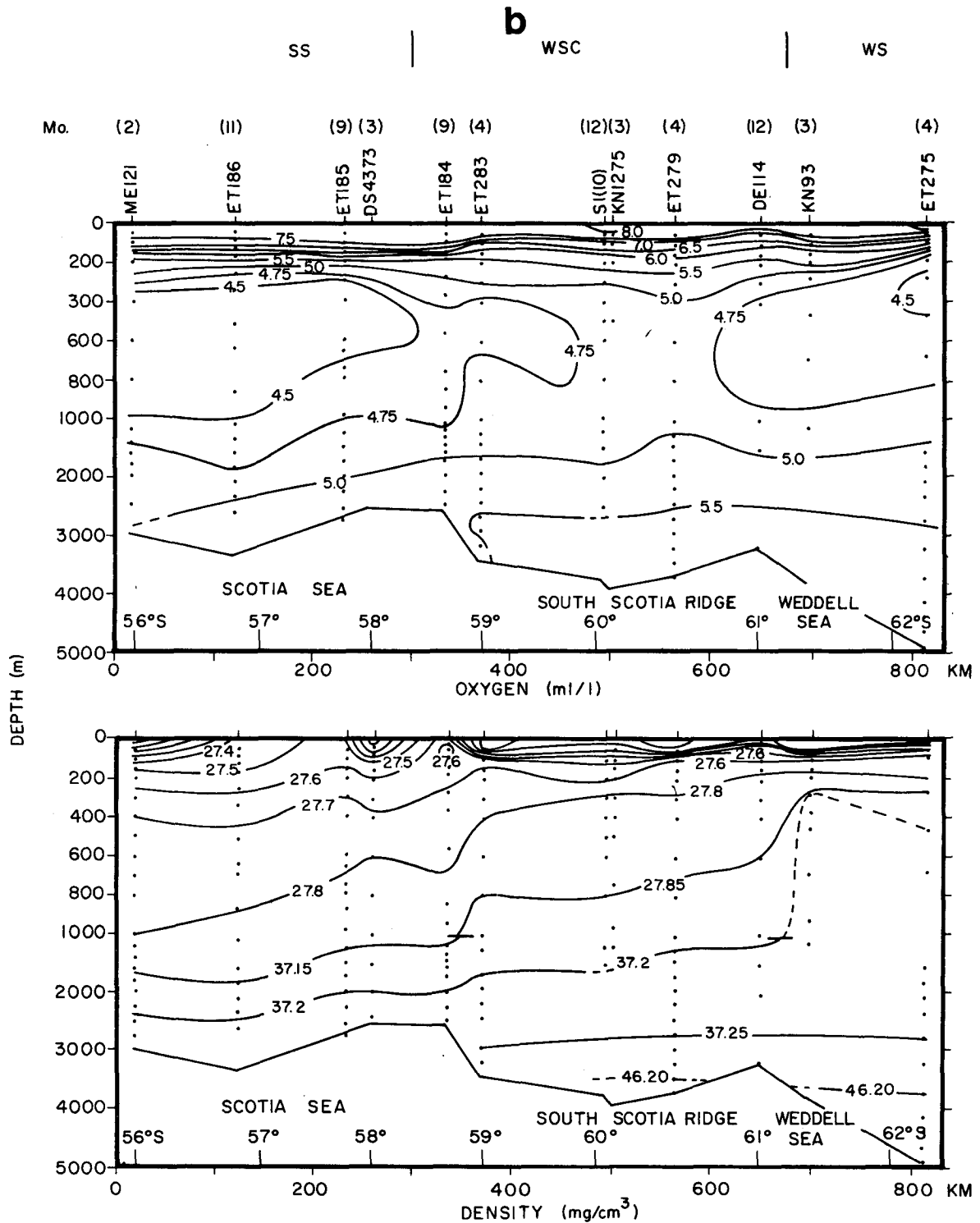


FIG. 8b. As in Fig. 2b except along Section IV.

dissolved oxygen concentration at 20 and 500 m presented in Figs. 14 and 15. As in the vertical sections, the attenuating signal strength of both the deep and shallow signature of the western WSC

can be traced eastward along the South Scotia Ridge at least as far as the South Sandwich Islands. The northward deflection of the general eastward flow in the vicinity of the South Sandwich Island

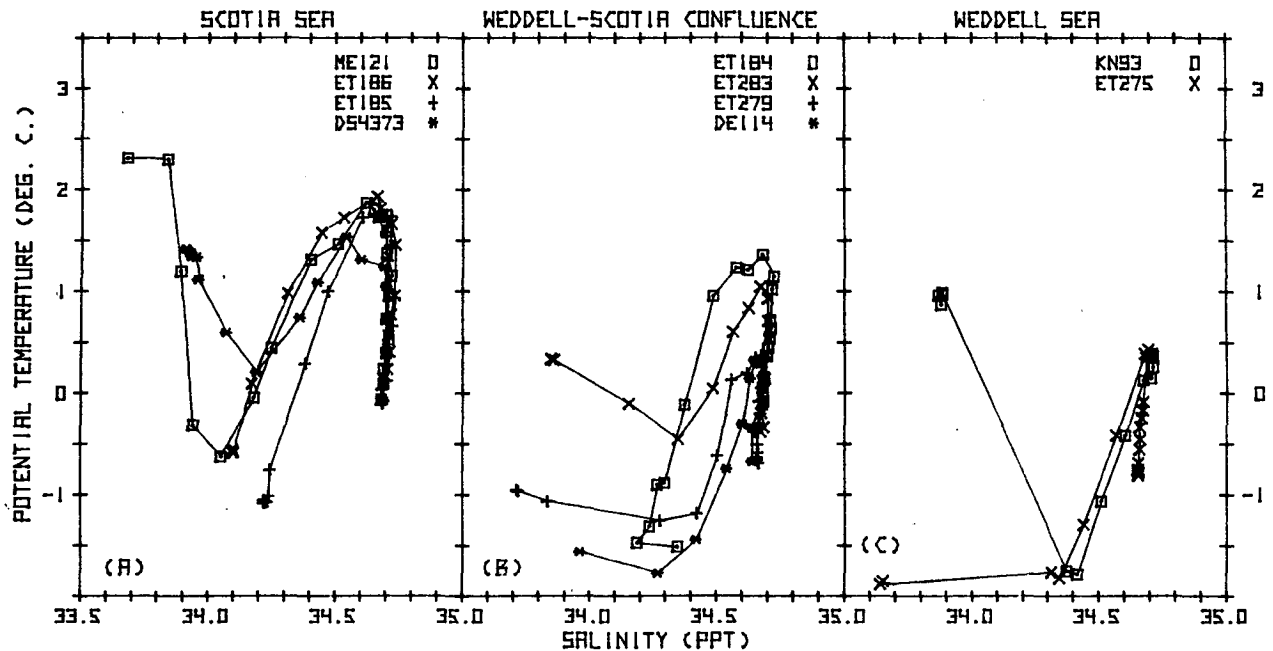


FIG. 9. As in Fig. 5 except along Section IV.

arc is evident to varying degrees in all the property distributions. The patchiness in the distributions is due in part to temporal variability of the flow configuration.

As noted earlier, these two surfaces were selected as being suitable ones to show the horizontal extent and configuration of both the deep and the near-surface signatures of the WSC and to be directly comparable to the distributions presented by Gordon and Goldberg (1970). The earlier work shows neither the deep signature of the WSC in the salinity distribution at 500 m nor the near-surface signature in the summer property distributions at 20 m. Except for the addition of a few recent observations, the data base used in both studies is essentially the same. The differences in the resulting distributions are due principally to the differences in the way the data were analyzed. Gordon and Goldberg (1970) were examining the large-scale circumpolar characteristics of the Southern Ocean, whereas in the present study, we are focusing specifically upon the WSC. By Southern Ocean standards the data distribution between 20 and 80°W is quite dense. To simplify the task of describing this sector, Gordon and Goldberg (1970) averaged the data over areas 1° latitude by 2° longitude before contouring. This procedure obscured the WSC to such an extent that it is not revealed in some of their distributions.

a. Distributions at 500 m

The temperature at 500 m (Fig. 14a) decreases from north to south until it reaches a local

minimum within the cold tongue of the WSC above the South Scotia Ridge. South of the ridge the temperature increases slightly toward the central Weddell Sea. The lowest temperatures ($< -1.0^{\circ}\text{C}$) are observed within Bransfield Strait. Temperatures below 0°C extend eastward from Bransfield Strait and the tip of the Antarctic Peninsula to the broad plateau of the South Orkney Islands. Beyond this point the tongue of low temperatures warms, but a narrow band of temperatures below 0.4°C can be traced eastward as far as the South Sandwich Islands. Note that the low temperatures within the cold tongue of the WSC are not observed to the west of Bransfield Strait. In fact, temperatures along the continental slope on the western side of the Antarctic Peninsula are generally above 1°C . Hence, the cold waters within the WSC do not originate west of Bransfield Strait. Although it is clear that the temperatures along the continental slope on the eastern side of the peninsula are significantly lower than those on the west side, there are insufficient data to determine if they are as low as those within the WSC.

The salinity at 500 m (Fig. 14b) increases from north to south until it reaches a local maximum just north of the continental slope of the Antarctic Peninsula and the South Scotia Ridge. This is due to the general southward rise of the saline CDW. South of this band of high salinity, the values decrease until they reach a relative minimum above the South Scotia Ridge. South of this relative minimum the salinity values once again increase toward the central Weddell Sea. Within the WSC the lowest

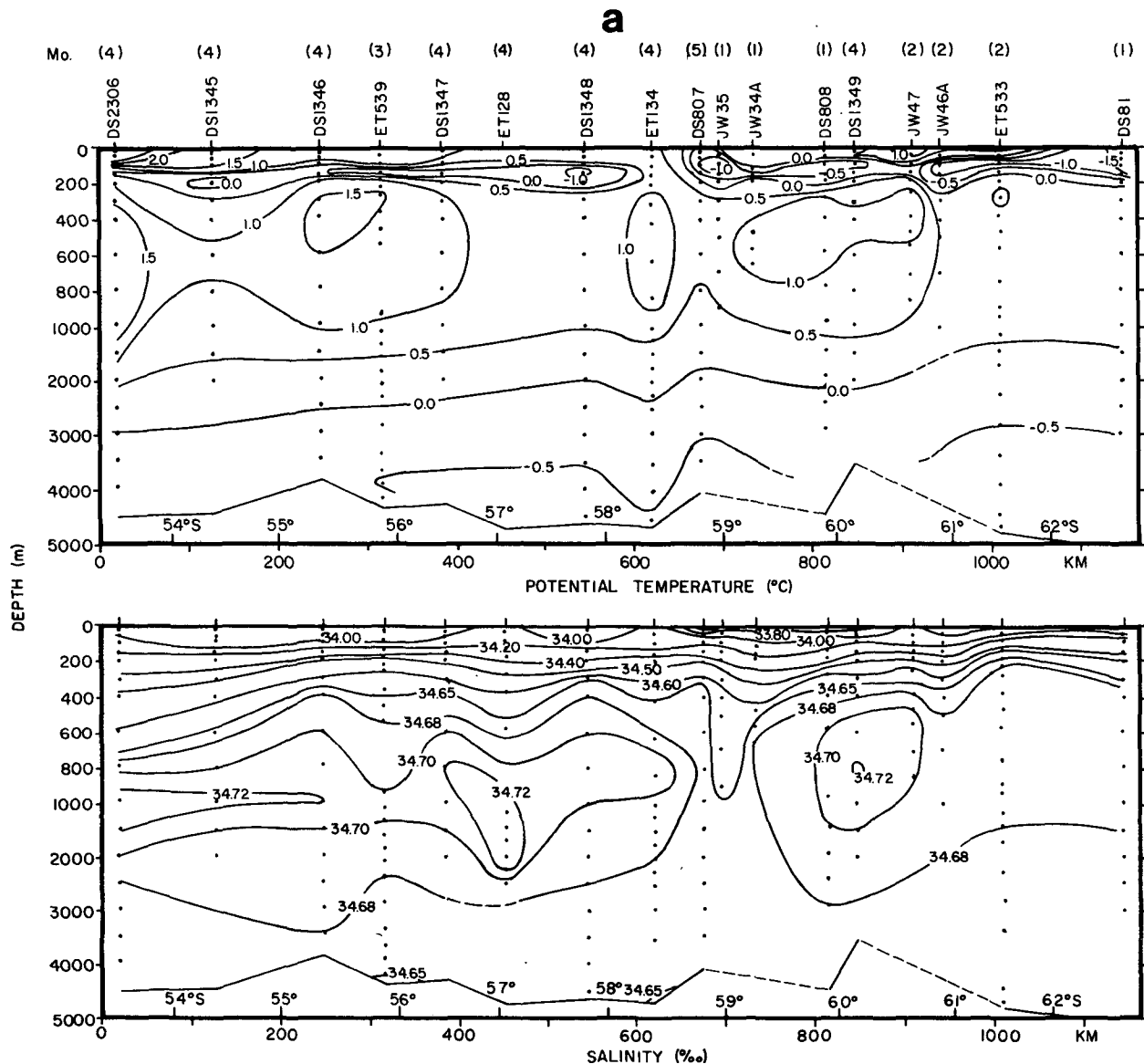


FIG. 10a. As in Fig. 2a except along Section V.

salinities (<34.6‰) are observed in a band following the South Scotia Ridge from Bransfield Strait eastward to the eastern boundary of the study area (20°W). As in the case of the temperature distribution at this level, the low salinity values observed within the western WSC (i.e., those <34.6‰) are not observed with any consistency upstream of Bransfield Strait along the continental slopes on the western side of the Antarctic Peninsula. In fact, the sparse data available suggest that these very low salinities are also absent on the eastern side of the Antarctic Peninsula.

The dissolved oxygen distribution at 500 m (Fig. 14c) is essentially the inverse of the salinity distribution at this level. That is, bands of relatively

high oxygen roughly correspond to bands of relatively low salinity. Oxygen values decrease from north to south until they reach a local minimum in a band just north of the continental slope. Once again this is due to the general southward rise of the oxygen-poor CDW. Over the South Scotia Ridge the oxygen values attain a relative maximum and then they decrease again toward the central Weddell Sea. In agreement with the earlier distributions, the highest oxygen values (>6.0 mL L⁻¹) are observed in Bransfield Strait. Oxygen values above 5.0 mL L⁻¹ are confined to the area from Bransfield Strait to the South Orkney plateau. Values above 4.5 mL L⁻¹ extend from both sides of the Antarctic Peninsula eastward at least as far as 20°W.

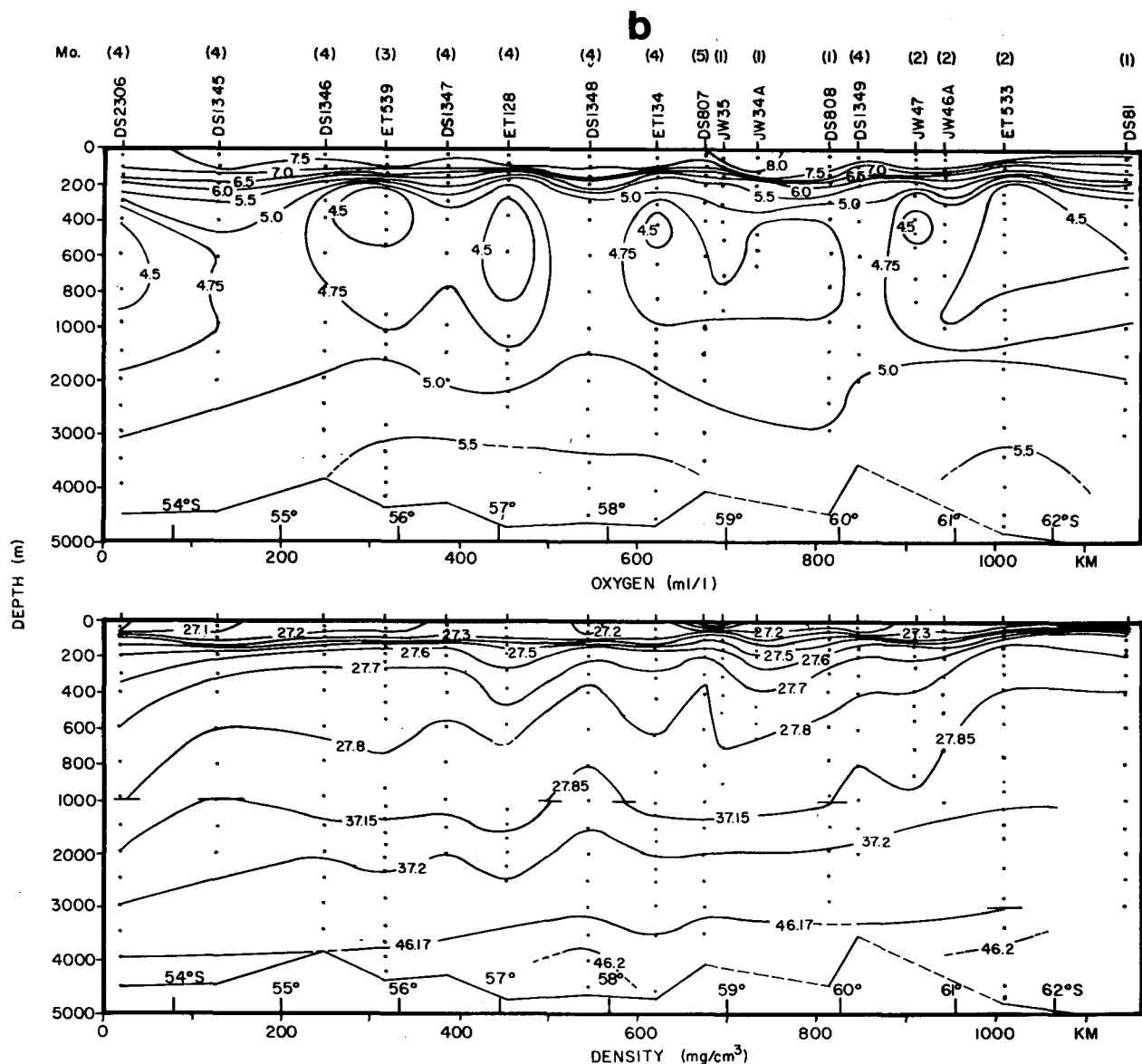


FIG. 10b. As in Fig. 2b except along Section V.

b. Distributions at 20 m

The summer (December–May) property distributions at 20 m are somewhat more patchy than the 500 m distributions. This is due in part to the increased influence of air/sea/ice interactions.

The near-surface temperatures (Fig. 15a) generally decrease toward the south. There is, however, a narrow tongue of water with temperatures below 0°C extending eastward from the Antarctic Peninsula to the South Orkney Islands. In general, the isotherms appear to be quite contorted and there is no clear near-surface signature of the WSC in the temperature distribution.

The salinity distribution, on the other hand, exhibits (Fig. 15b) a pronounced near-surface signature of the WSC, namely, a band of salinities in excess of 34.0‰ which extends from the northern tip of the Antarctic Peninsula eastward to the South Sandwich Island arc where it turns northward. The highest salinities within the band (>34.4‰) occur over the continental shelf at the tip of the Antarctic Peninsula. Isolated within this zone are patches of lower salinity water (<34.0‰) extending eastward from some of the islands. These are presumably due to runoff. The high salinity water is not observed upstream of Bransfield Strait. In fact, the lowest salinities on the 20 m surface (<33.2‰) are

seen to occur along the west coast of the Antarctic Peninsula southwest of Bransfield Strait. North of the WSC is a broad band of relatively low salinity ($<34.0\text{‰}$) water extending from the Bellingshausen Sea across the Scotia Sea to South Georgia Island and into the South Atlantic. This band is flanked on the north by the more saline surface waters of the subantarctic. South of the WSC there is a band of low salinity water ($<34.0\text{‰}$) extending across the northern Weddell Sea. This band is flanked on the south by the higher salinity surface waters of the central Weddell Sea.

As at the 500 m level, the oxygen values at 20 m (Fig. 15c) exhibit a distribution that is roughly the inverse of the salinity distribution; however, there is substantially more patchiness in the oxygen distribution. Over the South Scotia Ridge the near-surface oxygen values are generally lower than those to the north and south, but because of the patchiness of the distribution, this near-surface oxygen signature of the WSC is not as clearly defined as the salinity signature. [Although the variations in the oxygen values shown in Fig. 15c are affected to some extent by changes in oxygen saturation level, that is, the saturation level increases with decreasing temperature and salinity (Green and Carritt, 1967), the magnitudes of the variations due to this effect are small compared to those actually observed. Hence the surface oxygen distribution is not merely the result of variations in the saturation level.] The lowest oxygen values associated with the WSC ($<7.0 \text{ mL L}^{-1}$) occur over the continental shelf of the Antarctic Peninsula. Around the South Shetland Islands and downstream of Bransfield Strait there are several patches of water with oxygen values lower than 7.5 mL L^{-1} embedded within waters of higher oxygen content. Farther downstream the oxygen values become higher both inside and outside the WSC. Hence, the near-surface oxygen signature continues to be a relative minimum and can be traced from the South Orkney Islands to the South Sandwich Islands as a band with oxygen values below 8.0 mL L^{-1} .

The position of the deep signature of the WSC in all three properties follows the South Scotia Ridge quite closely. The near-surface signature, on the other hand, begins to deviate from the ridge position east of $\sim 33^\circ\text{W}$. This may mean that the processes which maintain the integrity of the WSC upstream are no longer active in this area and that differential flow between the 20 m level and the 500 m level cause the two signatures to diverge and dissipate as they advect downstream.

Although the horizontal property distributions strongly suggest that the anomalous properties of the waters of the western WSC have their source near the tip of the Antarctic Peninsula, the

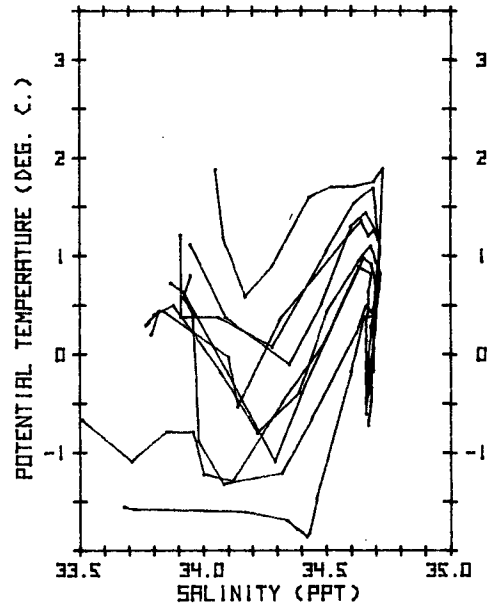


FIG. 11. Potential temperature versus salinity relations for representative stations along Section V.

patchiness in the distributions and the observed spatial variability of the θ - S relations within these waters suggest that the anomalous properties of the WSC may be reinforced at various sites along the ridge such as over the South Orkney plateau.

5. Formation mechanisms

It is the general consensus that vertical homogeneity of the water column within the western WSC is probably due to vertical mixing that is active during at least part of the year. It has been suggested (Deacon, 1937; Deacon and Moorey, 1975; Deacon and Foster, 1977; Gordon *et al.*, 1977) that this vertical mixing is convectively driven during the winter by cooling, evaporation and ice formation at the sea surface. These processes cause the surface waters to become colder and saltier, and therefore, denser. The resulting density instability leads to convective overturning and the formation of a homogeneous mixed layer which, in the shallower areas, may extend to the bottom. The homogeneous column created by this wintertime convection then presumably persists through the summer which is the season during which most observations in this zone have been made.

Clearly, any mechanism which is proposed to explain the homogeneity of the water column in the western WSC and in Bransfield Strait must also explain the anomalous properties observed within this zone during the summer. In particular, it must explain how the zone acquires and maintains the

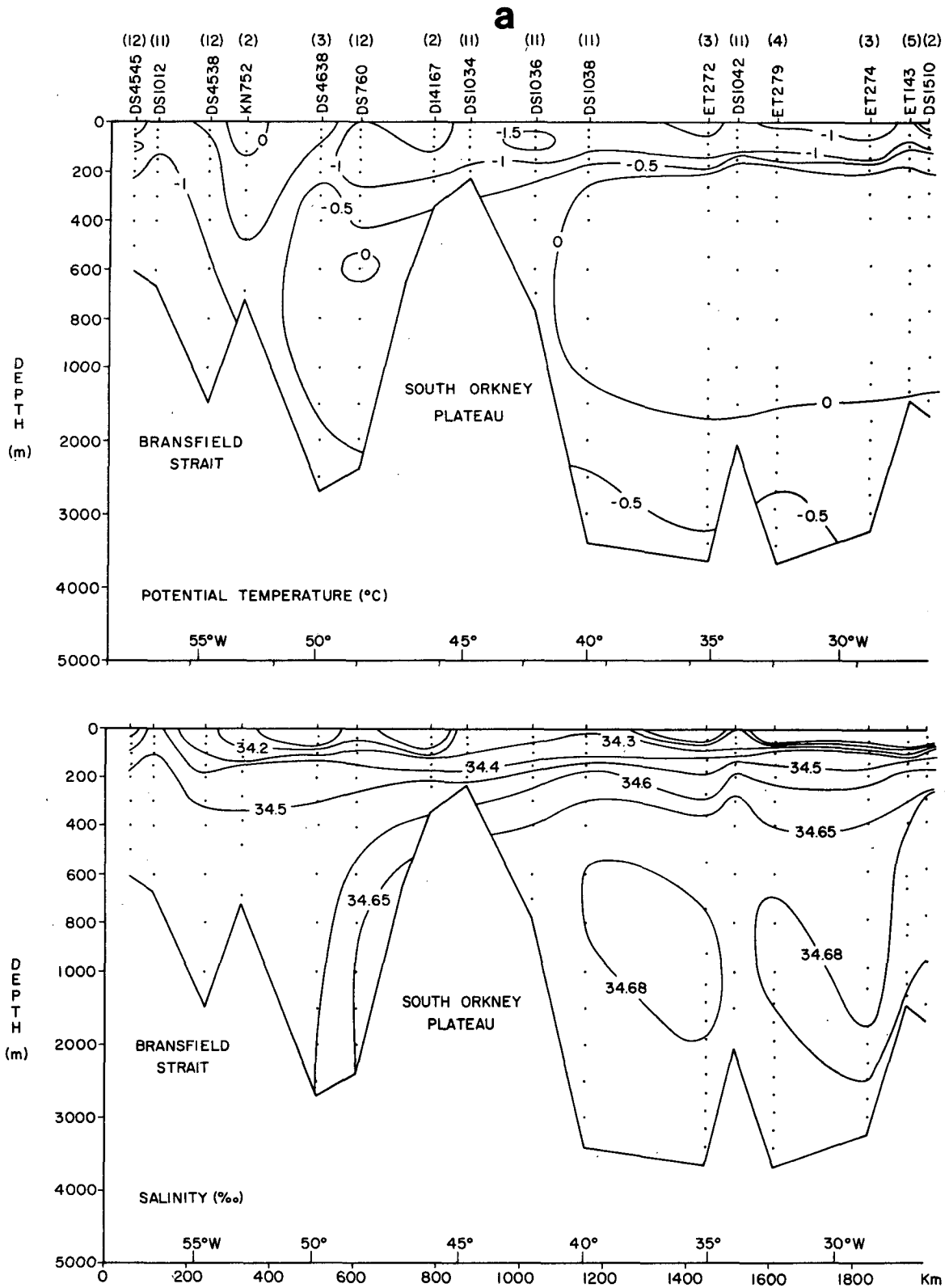


FIG. 12a. As in Fig. 2a except along the axis of the Weddell-Scotia Confluence.

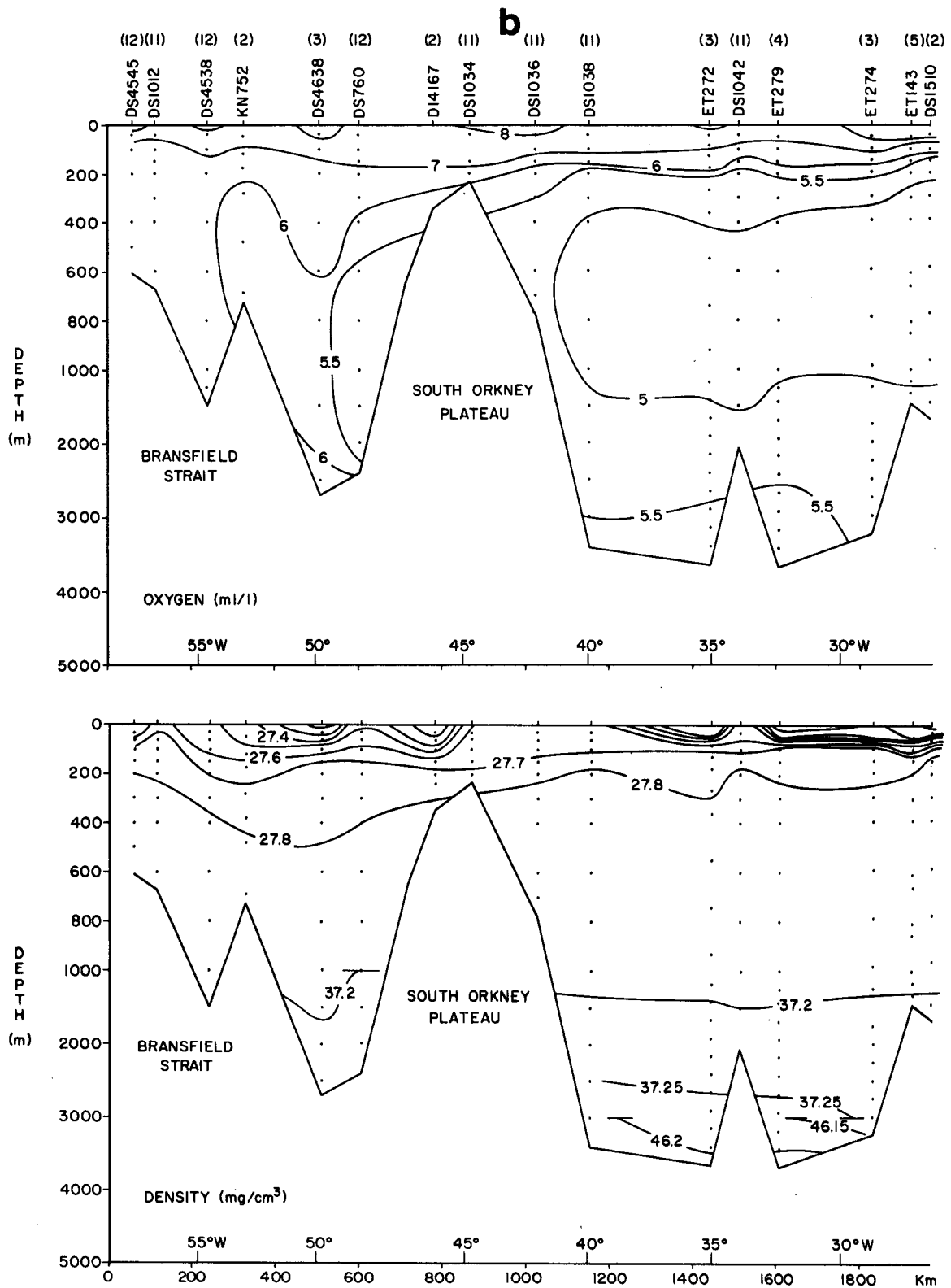


Fig. 12b. As in Fig. 2b except along the axis of the Weddell-Scotia Confluence.

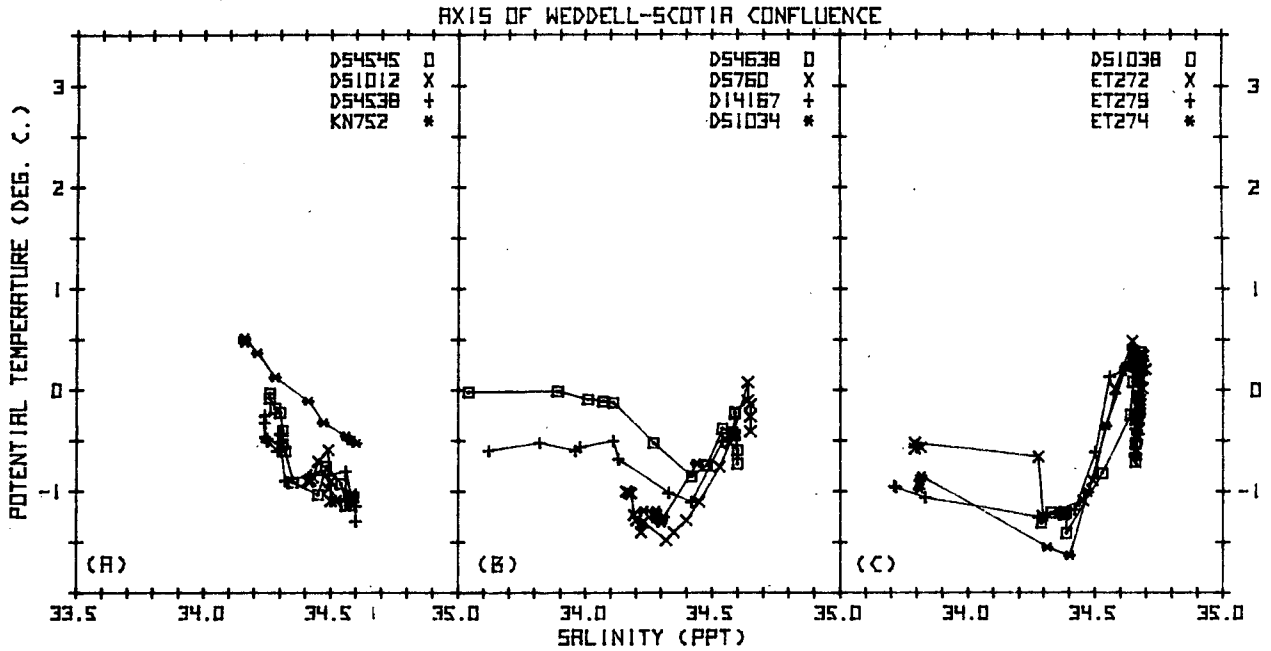


FIG. 13. Potential temperature versus salinity relations for representative stations along the axis of the Weddell-Scotia Confluence (a) within the Bransfield Strait, (b) eastward to the South Orkney plateau, and (c) over the South Scotia Ridge east of the South Orkney plateau.

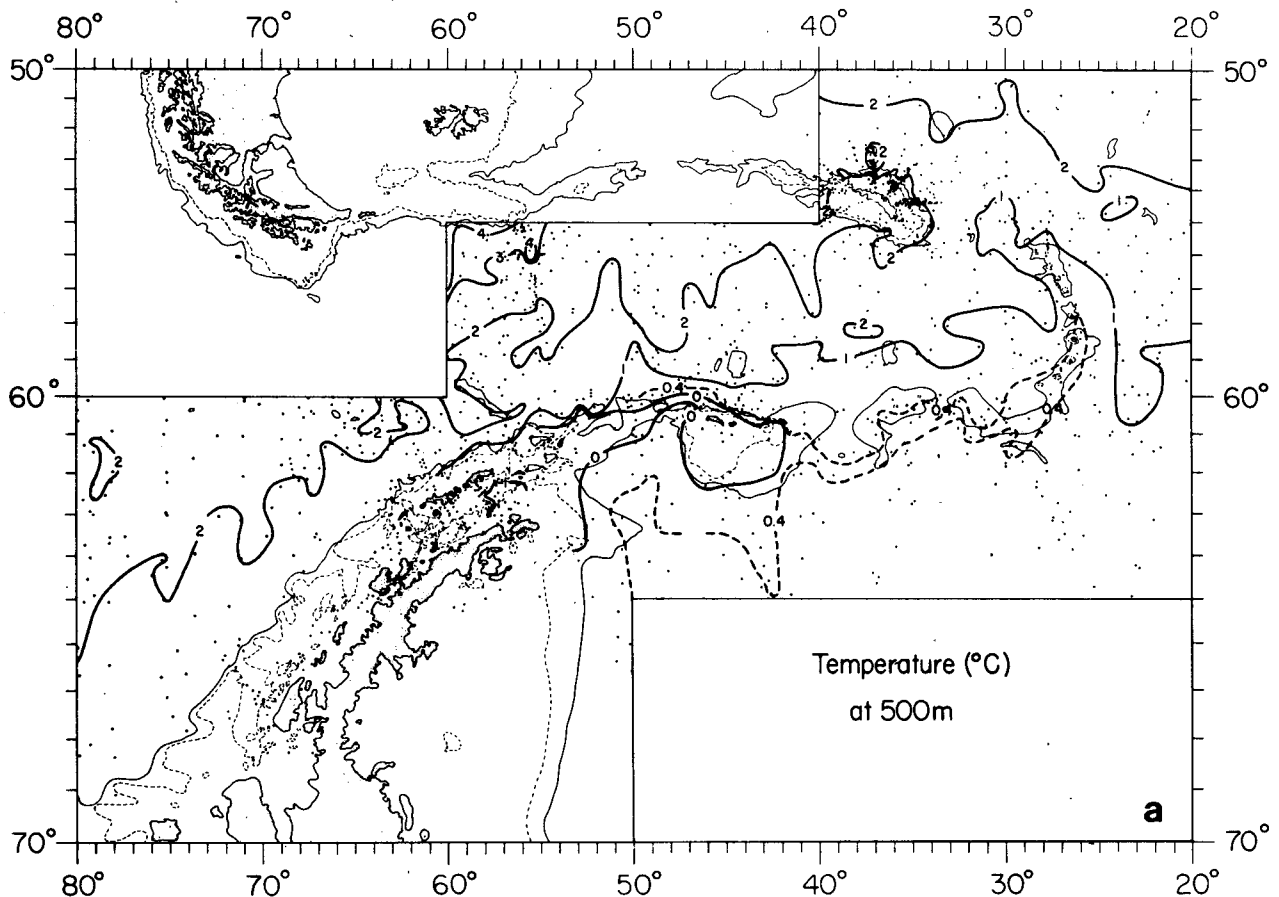


FIG. 14a. Distribution of temperature (°C) at 500 m. The 500 m isobath (dashed line) and the 2000 m isobath (solid line) are also shown.

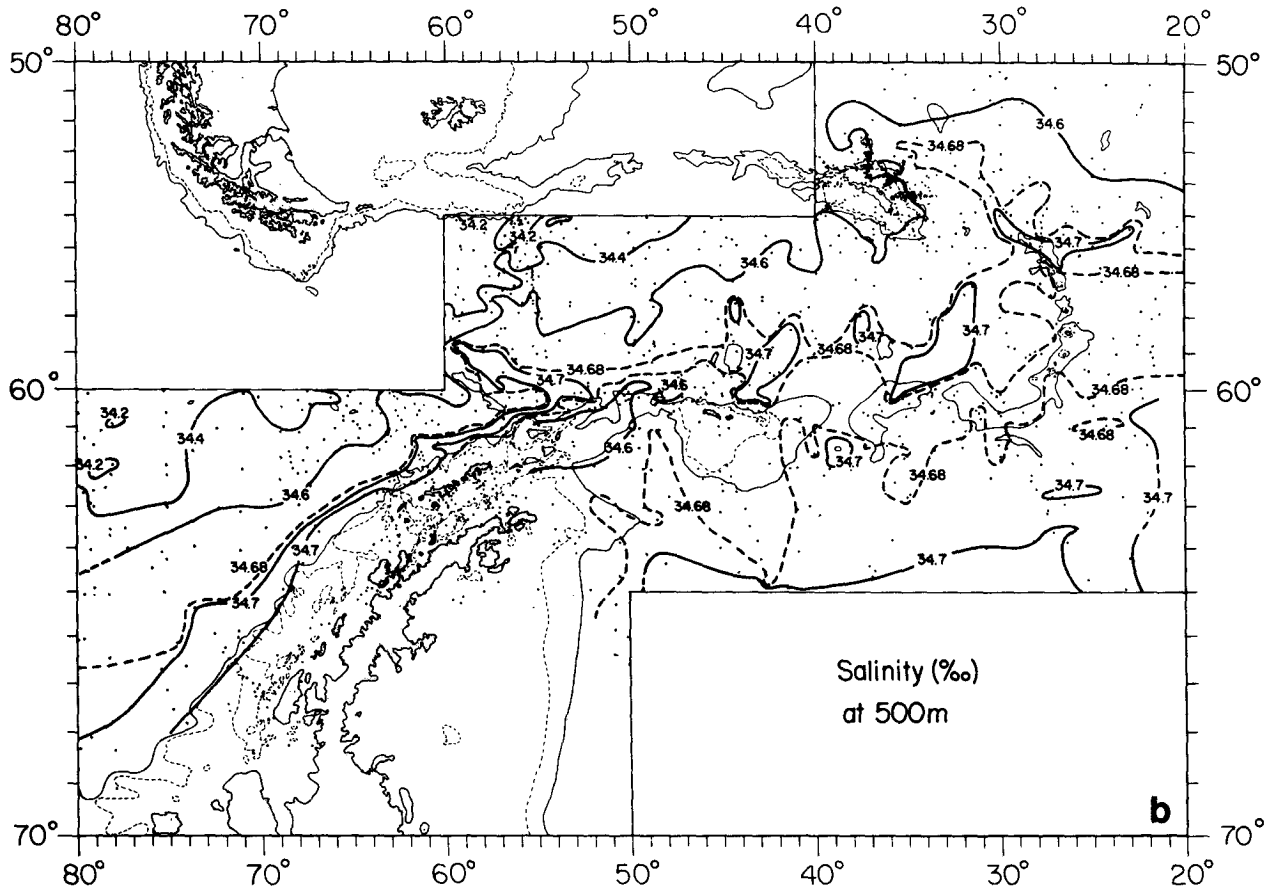


FIG. 14b. Distribution of salinity (‰) at 500 m.

relatively low salinity values that it exhibits throughout all but the upper portion of the water column. The wintertime convection process described above is one which necessarily tends to increase the salt content of the water column in which it is active. Furthermore, a near-surface signature of relatively high salinity is observed in the summer sections across the WSC presented by Deacon and Moorey (1975), Deacon and Foster (1977) and Gordon *et al.* (1977). As noted earlier, a signature in both salinity and oxygen is also readily apparent in the non-synoptic distributions presented in Figs. 15b and 15c. These signatures were probably produced by vertical mixing which introduces higher salinity and lower oxygen values from below into the surface waters. It seems improbable that the near-surface signature of a wintertime convection could persist through the summer, especially in view of air/sea interaction and the large amount of ice melting that occurs. Hence wintertime vertical convection is, in itself, an inadequate explanation of the property distributions observed during summer in the vicinity of the WSC. Some process which is active during the summer must be invoked.

Two questions need to be resolved. What mechanism maintains the vertical homogeneity of

the water column in the western WSC during the summer? And, how does the deep water in the Bransfield Strait and western WSC acquire and maintain its exceptionally low salinities?

The demonstrated coincidence of the homogeneous water column with the South Scotia Ridge, and the rapid restoration of more typical deep ocean stratification downstream of the South Orkney plateau, where the ridge is deeper and interrupted by gaps, strongly suggest that interaction with shallow bathymetry is important to the maintenance of the homogeneity. In fact, all around the Antarctic Continent the water column near the continental shelf tends to be more homogeneous than farther off shore. This homogeneity is due in part to vertical mixing or stirring induced by frictional effects within the lateral boundary layer at the continental margin. Such mixing does not require a vertical density instability and hence can be active during any season of the year. The homogeneity observed within the western part of the WSC may be the result of vertical mixing induced by interaction of the local currents with the lateral and bottom boundaries provided by the Antarctic Peninsula and Scotia Ridge and the numerous islands and shoal areas associated with each. Near-surface

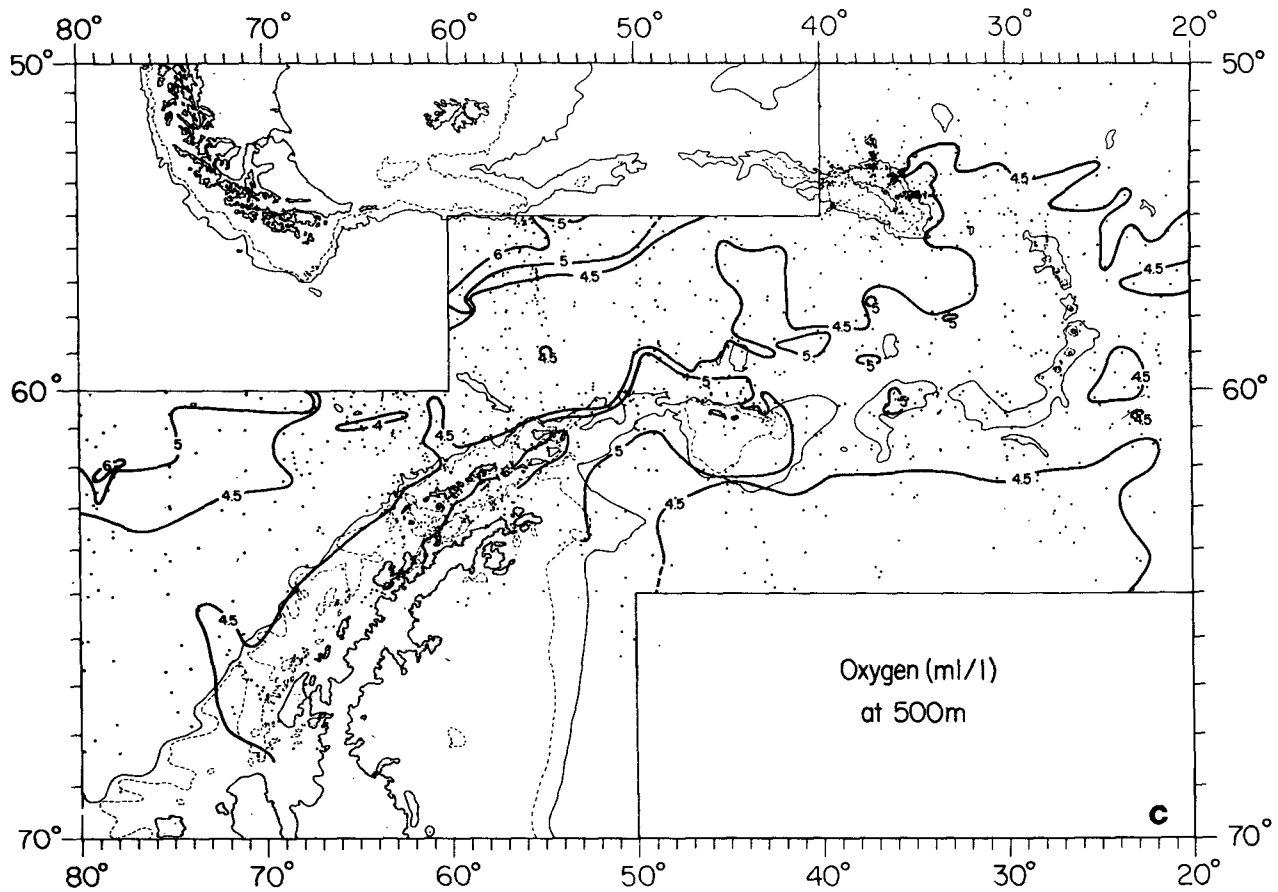


FIG. 14c. Distribution of dissolved oxygen concentration (mL L^{-1}) at 500 m. Values reported by the United Kingdom have been corrected as described in text.

stirring may even be induced by interaction of currents with the massive tabular icebergs which are always present in this area.

The very low salinities ($<34.6\%$) which characterize the deep waters of the western WSC and the Bransfield Strait are not observed upstream on either side of the Antarctic Peninsula. This indicates that there is a significant local input of freshwater into the deep layers. The source of this freshwater may be the meltwater from ice, especially the deep-reaching tabular icebergs. It is well known that prevailing currents cause so much ice to accumulate in the western Weddell Sea that even during summer the area is seldom ice-free. Throughout the summer melting sea ice and icebergs are continuously drifting into the general eastward flow of the WSC zone. Deacon and Moorey (1975) noted the presence of many icebergs in the WSC while they were collecting their data. Actually, the melting that occurs at the bottom of icebergs is not restricted to the summer season, but is a continuous process. It is likely that this melting process will

accelerate somewhat once the ice leaves the cold confines of the Weddell Sea and merges with the warmer waters of the Scotia Sea.

Hence, relatively homogeneous water columns are produced all around the Antarctic Continent by vertical mixing induced in part by frictional effects within the lateral boundary layer. (Of course, during winter, thermohaline circulation must also contribute to the vertical homogeneity, at least in some locations.) The physical characteristics of the final mixture at any location around the continent will depend on the physical characteristics and relative properties of the local constituent water types. The homogeneous water columns formed near the northern tip of the Antarctic Peninsula, especially within Bransfield Strait, are exceptionally fresh. This is probably due to the injection of meltwater.

As the homogeneous water columns from each side of the Antarctic Peninsula are advected downstream, they merge to form the WSC. The properties of the various columns immediately begin to blend together due to lateral mixing. Within a fairly

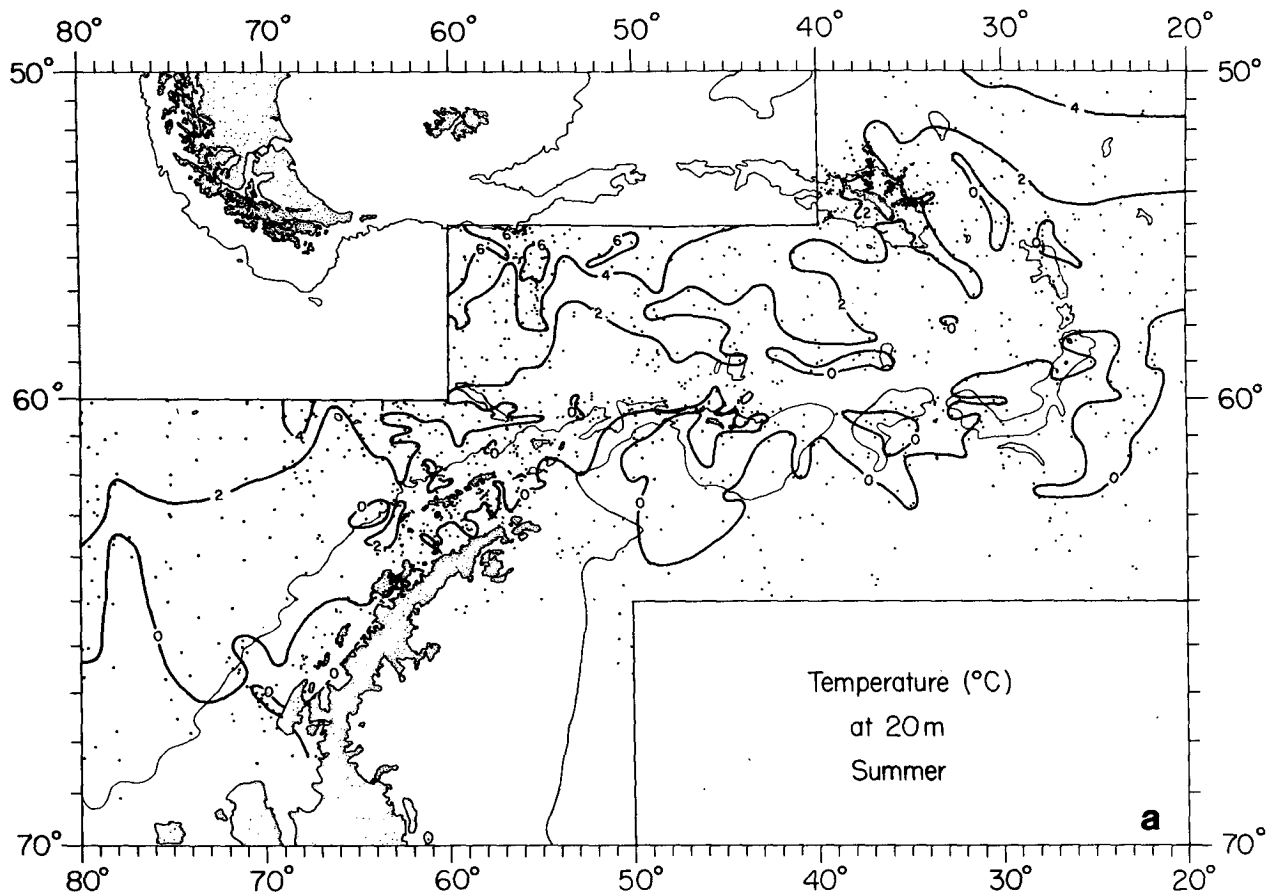


FIG. 15a. Summer (December–May) distribution of temperature ($^{\circ}\text{C}$) at 20 m.

short distance the unique characteristics of Bransfield Strait water are contaminated. The WSC becomes wider to encompass the broad South Orkney plateau. Interaction of the flow with the plateau probably induces additional mixing. Downstream of the South Orkney plateau stratification more typical of the deep ocean is restored and east of the South Sandwich Island arc, the WSC has become a simple transition zone. Hence the θ - S characteristic along the axis of the WSC undergoes a continuous evolution.

It is interesting to speculate on how the properties within Bransfield Strait are maintained. The strait is unique in that it is ideally located to receive a continuous supply of ice from the Weddell Sea and the Antarctic Peninsula. The basins of the strait act as reservoirs in which the cold, fresh meltwater may accumulate and be sheltered to some extent from contamination by the surrounding waters. Being at the northernmost extremity of the Antarctic Continent, this region experiences a somewhat more moderate climate than other parts of the continent.

During the autumn, sea ice which forms farther south along the Atlantic sector of the Antarctic coastline advects westward and accumulates in the northwestern Weddell Sea where local currents carry some of it into the eastern Bransfield Strait (Clowes, 1934). This protective covering of ice may shield the underlying waters from the increasingly harsh winter environment and thereby inhibit to some extent the formation of new ice and the associated increase in salinity of the water column. In this way the low-salinity characteristics of the deep waters in the area can be at least partially preserved during winter.

6. Temporal versus spatial variability

Significant temporal variability of the water properties of the WSC and Bransfield Strait has been reported (Deacon and Foster, 1977; Gordon and Nowlin, 1978). However, the large changes that can occur in property values over relatively short horizontal distances due to the steep slope of the

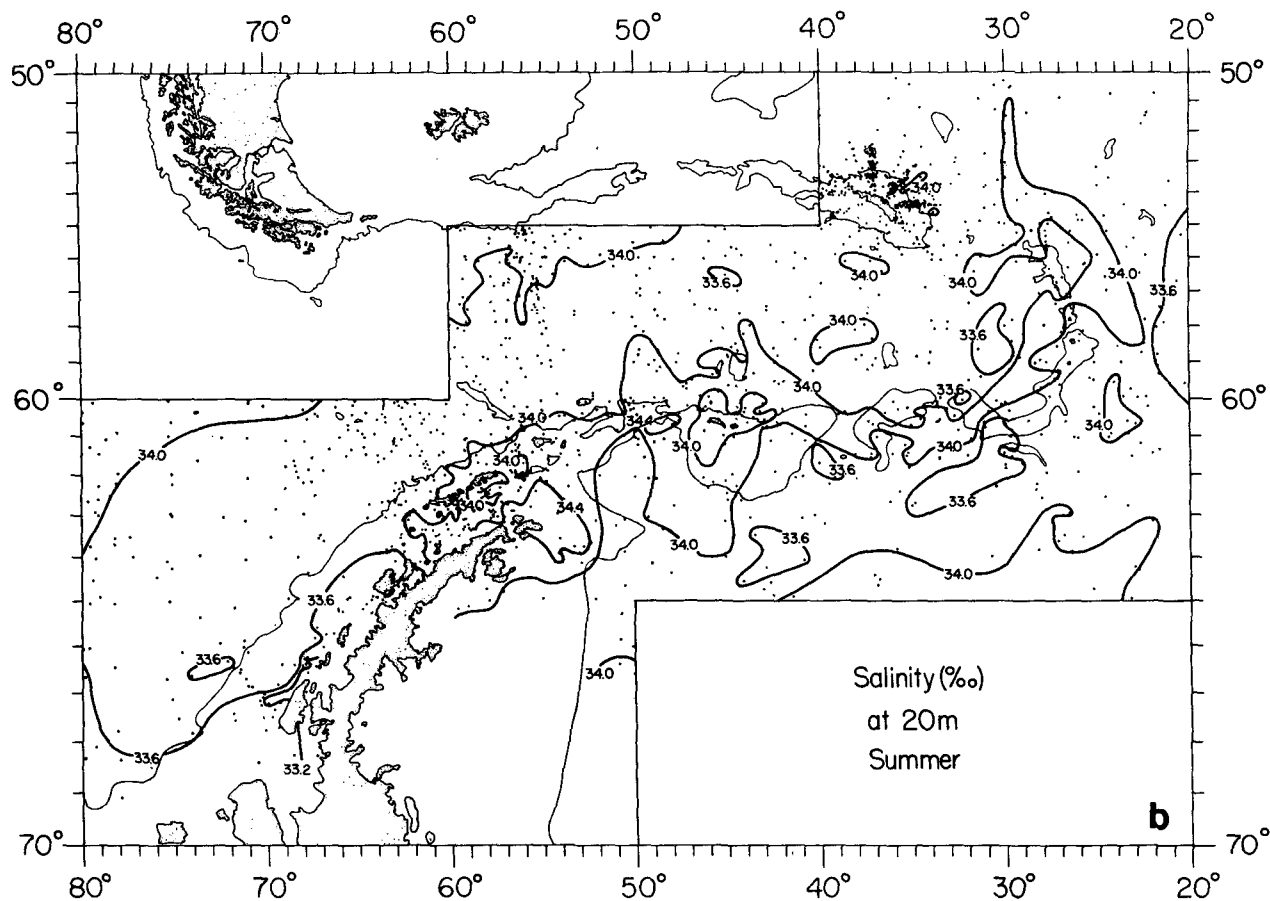


FIG. 15b. Summer distribution of salinity (‰) at 20 m.

isopleths (cf. Fig. 2) and the patchiness and complexity of the horizontal property distributions shown in Figs. 14 and 15 suggest that much of the reported temporal variability may be due to lateral oscillations of the WSC. For example, a meander is probably responsible for the apparent variation in width of the WSC indicated by the reported sections at 50°W. In the vertical section presented by Gordon *et al.* (1977), the confluence appears to have a width of ~300 km, whereas Deacon and Moorey (1975) and Deacon and Foster (1977) show it to be less than 100 km wide in the same area. Although some variation in width with time is expected, the surface property distributions presented by Gordon *et al.* (1977) indicate a northward deflection of the WSC along the section occupied by Conrad. Hence, the large width of the WSC as shown in Gordon *et al.* (1977) is probably due to the shallow angle at which the confluence was crossed. As mentioned earlier, a meander in this area was also evident in data obtained by *Eltanin* in 1963 (Fig. 4).

7. Summary

The anomalous properties of the waters in the western part of the WSC suggest that they are not merely a mixture of the adjacent Weddell and Scotia Sea water masses, but are instead the result of water mass modifications being imposed upstream or by local processes. Both the near-surface and the deep signatures of the western WSC are most intense within Bransfield Strait and attenuate toward the east due to lateral mixing with the surrounding waters. These signatures are not observed upstream of Bransfield Strait. East of the South Sandwich Island arc the boundary between the waters of Scotia and Weddell Sea origin evolves into a simple transition zone containing waters with properties intermediate between those to the north and south. The WSC does not have a single "characteristic" θ - S relation, although within limited areas the curves are similar. The position of the WSC follows the South Scotia Ridge quite closely indicating that interactions with bottom topography are important

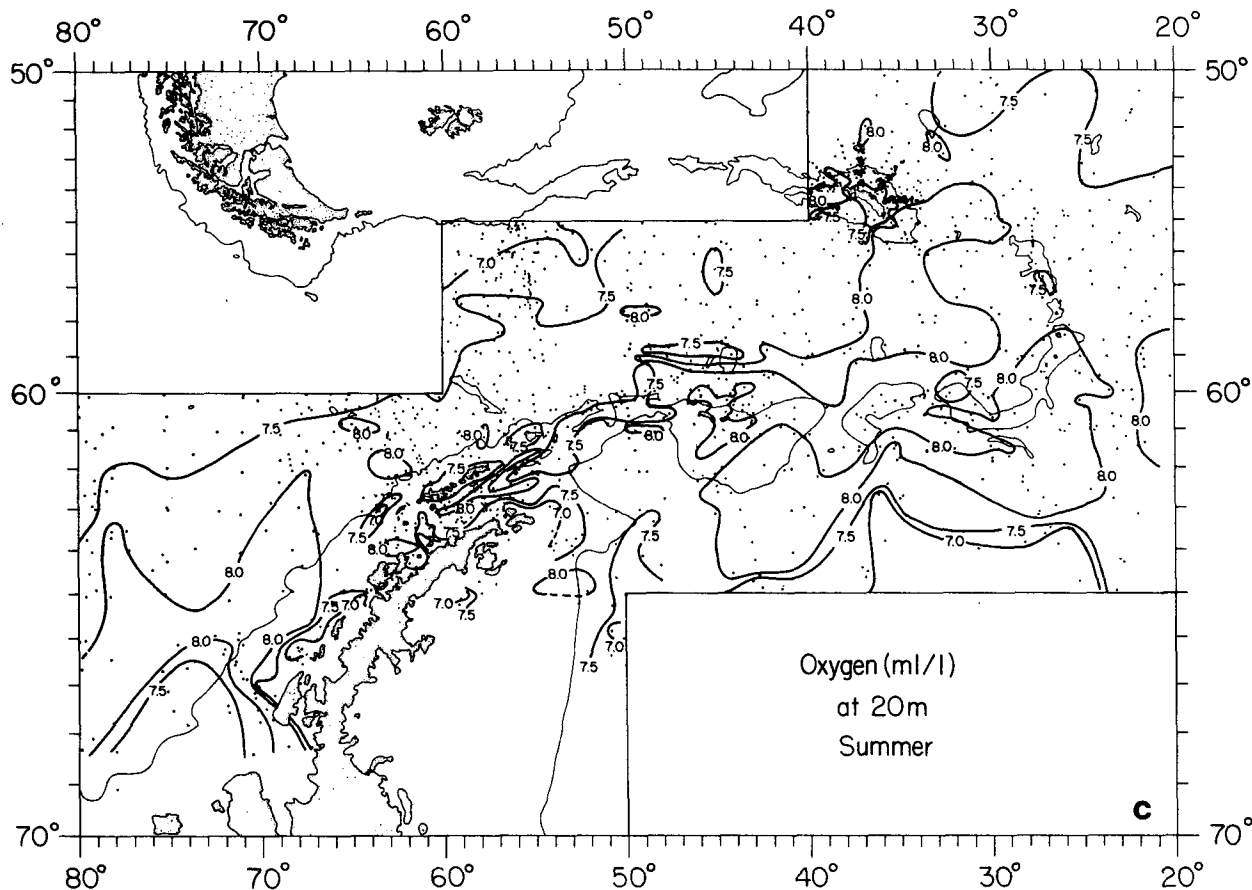


FIG. 15c. Summer distribution of dissolved oxygen concentration (mL L^{-1}) at 20 m.

to the formation and maintenance of the homogeneous zone.

It is generally agreed that the homogeneity of the water column in the western WSC is due to vertical mixing. The summer salinity and oxygen distributions at 20 m indicate that this mixing is active during the summer, contrary to earlier speculation. The low salinity of the deep waters of the WSC and Bransfield Strait is inconsistent with the idea that the homogeneous zone is produced and maintained by deep convection driven by surface cooling, evaporation, and the formation of sea ice during winter. Homogeneous water columns observed near the continental margins all around Antarctica are produced in part by vertical mixing induced by frictional effects within the lateral boundary layer. The physical characteristics of these homogeneous columns depend on the characteristics and relative proportions of the constituent water types. The low salinities observed in the water column in Bransfield Strait may be due to the injection of meltwater from ice which is continu-

ously flowing into the area. As waters from the east and west coast of the Antarctic Peninsula advect downstream, they flank the waters of Bransfield Strait origin to form the western WSC. The characteristics of these waters immediately begin to blend together through lateral mixing. The θ - S characteristics along the axis of the WSC undergo continuous evolution in the downstream direction until ultimately typical deep water stratification is restored.

8. Suggestions for further research

We have attempted to describe the WSC from its western limit near the tip of the Antarctic Peninsula to 20°W using the available hydrographic station data and to suggest hypotheses to explain the observed property distributions. Confirmation will require suitably designed field observations. Numerous questions related to the WSC remain unanswered. What is the eastern limit of the WSC, or in other words, how large is the so-called Weddell Gyre? How do the properties in the WSC

and Bransfield Strait change during the winter? What are the effects of large amounts of ice on the ocean environment? The region is clearly an important one for the study of air/sea/ice interactions. The potential importance of this region for the study of oceanic convective processes and the controlled exploitation of krill has been noted by Deacon and Foster (1977). We believe the WSC zone to be one of the most interesting and least understood areas in the Southern Ocean.

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