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# Intermediate waters in the southwest South Atlantic

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**Abstract**—The density (sigma-theta, $\sigma_\theta$) interval 27.05–27.20 in the Subantarctic Zone of the northern Drake Passage is characterized by two water types with potential temperatures of 3.7 and 4.8°C, respectively, both with salinity of approximately 34.2. These major contributors to the low salinity intermediate water mass are advected northward along the continental slope of South America. The lower density water type enters the Argentine Basin both east and west of Burdwood Bank. Its thermohaline characteristics are modified by winter sea–air interaction near Burdwood Bank and mixing with the surrounding waters further north. The denser water type flows east of Burdwood Bank, undergoing salinity decrease, primarily by isopycnal processes. Low salinity water, derived from the Polar Front, is introduced into a still denser horizon (27.25 $\sigma_\theta$), from along the axis of the cyclonic circulation feature described by the Malvinas Current and its return to the south. The thermohaline structure across the Malvinas Current is similar to the water mass zonation observed in the northern Drake Passage.

In the vicinity of 38°S, the northward-flowing modified subantarctic water converges with subtropical thermocline water at the Brazil–Malvinas Confluence. The less dense subantarctic water spreads under the subtropical thermocline; however, the denser water (27.25 $\sigma_\theta$) of Polar Front origin is not found under the subtropical thermocline in the western South Atlantic. In general the salinity at the salinity minimum increases rapidly across the Brazil–Malvinas Confluence, suggesting that the bulk of the subantarctic water advected into the region by the Malvinas Current turns towards the interior, spreading under the subtropical thermocline along a broader expanse of the South Atlantic.

## INTRODUCTION

THE three Southern Hemisphere oceans are characterized by a layer of low salinity immediately below the thermocline. The feature is near the sea surface in the region north of the Antarctic Polar Front Zone and deepening northward, reaching a depth of about 1000 m in the subtropical gyres. The water mass is known as Antarctic Intermediate Water (AAIW). Based on the property distributions from data collected during the *Meteor* and *Discovery* expeditions, northward flow at intermediate depth has been inferred (WÜST, 1935; DEACON, 1937). In the South Atlantic, the northward extension of low salinity tongues on the salinity minimum layer, primarily along the coast of South America, was interpreted as indicative of more intense northward flow there. From this perspective, the most important northward route of AAIW was along the coast of South America, across the equator and into the North Atlantic (WÜST, 1935).

Later studies (MARTINEAU, 1953; TAFT, 1963; KIRWAN, 1963; BUSCAGLIA, 1971; MOLINELLI, 1981; PIOLA and GEORGI, 1982) have suggested that the AAIW water

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circulation in the South Atlantic is dominated by the wind-driven subtropical anticyclonic gyre. Similar circulation patterns have been proposed in the South Pacific and South Indian oceans (Reid, 1965; Johnson, 1973; Molinelli, 1981; Piola and Georgi, 1982).

Because the properties of AAIW are similar to the surface waters near the Antarctic Polar Front, the traditional mechanism of AAIW formation invoked a significant component of Antarctic surface and subsurface water sinking below Subantarctic Surface Water (Deacon, 1933, 1937; Wüst, 1935). More recently, mixing across the Polar Front by small-scale processes in the Scotia Sea and Drake Passage (Gordon *et al.*, 1977; Joyce *et al.*, 1978) and divergence of geostrophic transport in the southeast Pacific (Molinelli 1981), have been proposed as effective mechanisms responsible for the Antarctic influence on AAIW.

In contrast with these mechanisms, McCartney (1977, 1982) has suggested that deep winter convection in the Subantarctic Zone of the southeast Pacific plays a major role in the formation of AAIW. Due to the convective overturning, large volumes of water with properties similar to the winter outcrop and minimum values of potential vorticity characterize the Subantarctic Mode Water (SAMW). Jacobs and Georgi (1977) pointed out the ". . . . striking differences between the salinity minimum values in the southwest regions of the three southern hemisphere oceans . . .". These differences suggest a stronger influence of Antarctic waters in the South Atlantic sector as suggested by Molinelli (1981). Because of the rather large differences between South Atlantic and Southeast Pacific AAIW varieties, the required cooling and freshening of SAMW along its path through the Drake Passage into the South Atlantic are too large to be explained solely by the heat and freshwater fluxes through the sea surface (Georgi, 1979; Piola and Georgi, 1981). Therefore, an Antarctic water mass component is required.

In this paper, the evolution of intermediate water characteristics flowing through Drake Passage into the Argentine Basin as part of the Malvinas (Falkland) Current is presented. Recent observations, with vertical resolution adequate to describe the details of the vertical thermohaline structure, allow us to trace the input of intermediate waters as they flow into the South Atlantic as part of the Malvinas Current and sink under the subtropical thermocline in the Brazil–Malvinas Confluence.

*Table 1. Hydrographic data used in this study*

| Cruise | Date | Region | Source |
|---|---|---|---|
| *CATO* 6 | Nov.–Dec. 1972 | Argentine Basin<br>Brazil Basin | SIO (1979) |
| *Drake* 75 | Feb.–Mar. 1975 | Drake Passage | Nowlin *et al.* (1977b) |
| *Drake* 76 | Feb.–Mar. 1976 | Drake Passage | Whitworth *et al.* (1978) |
| *Drake* 77 | Jan.–Feb. 1977 | Drake Passage | Worley and Nowlin (1978) |
| *Drake* 79 | Apr.–May 1979 | Drake Passage | Worley and Nowlin (1982) |
|  | Jan.–Feb. 1980 | Drake Passage | Worley (1982) |
| *Atlantis* II 107–3 | Dec.–Jan. 1979/80 | Argentine Basin | Guerrero *et al.* (1982) |
| *Atlantis* II 107–10 | Aug.–Sep. 1980 | Argentine Basin, Scotia Sea and Drake Passage | Georgi *et al.* (1981)<br>Piola *et al.* (1981) |
| *Marathon* 07 | Oct. 1984 | Argentine Basin | Unpublished data |
| *Marathon* 08 | Oct.–Nov. 1984 | Argentine Basin | Roden and Fredericks (1986) |

## THE DATA

The data used in this study include continuous *in situ* temperature and salinity hydrographic stations with high quality water samples collected between 1975 and 1984. The data in the northern Drake Passage were obtained as part of the International Southern Ocean Studies. The data sources are given in Table 1, and the station locations presented in Fig. 1.

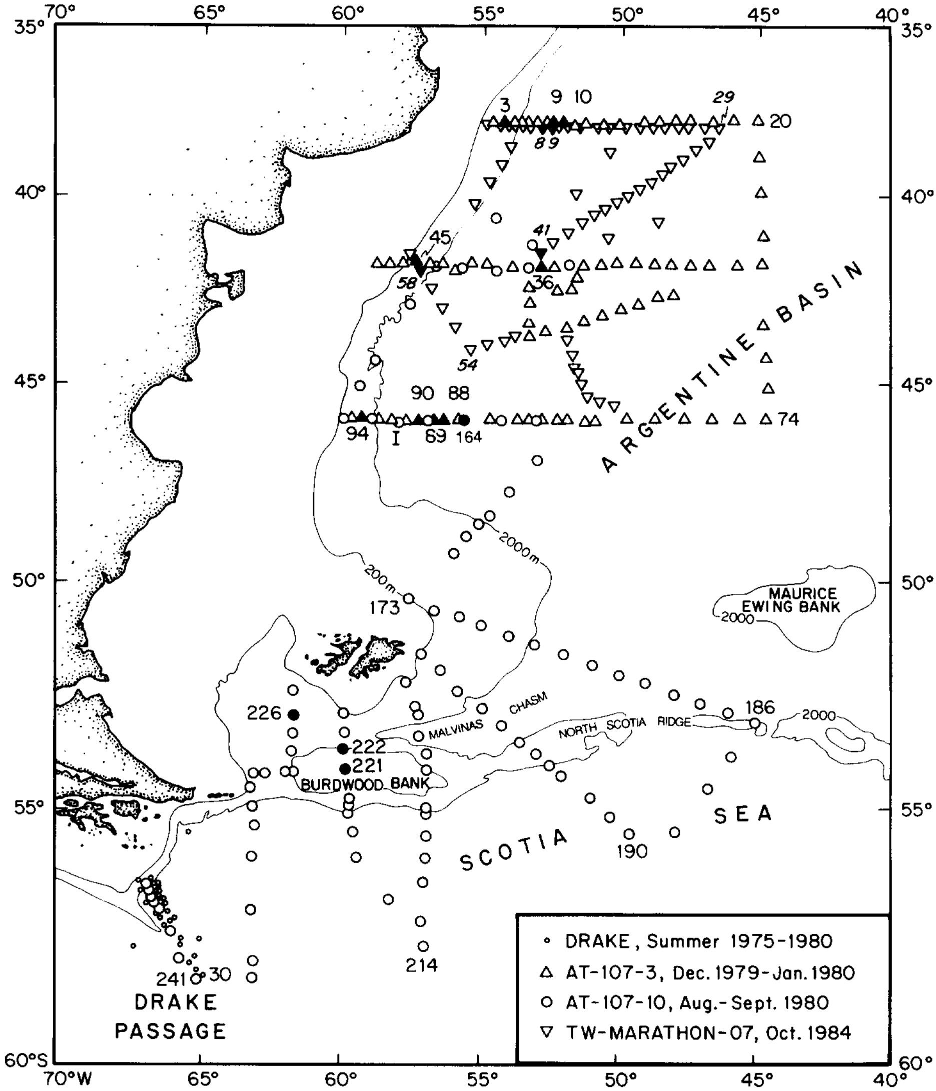

Fig. 1. Positions of the hydrographic data used in this study (see Table 1 for data sources). Solid symbols represent stations explicitly mentioned in the text. Section I (45°S) is shown in Fig. 5.

## SUBANTARCTIC WATER OF THE NORTHERN DRAKE PASSAGE

The southern boundary of the Subantarctic Zone in the Drake Passage is identified by a sharp shallowing of the 3° and 4° isotherms (NOWLIN *et al.*, 1977; NOWLIN and CLIFFORD, 1982). The typical summer potential temperature–salinity distribution of the upper waters within the Subantarctic Zone in the northern Drake Passage is shown in Fig. 2. In order to only include those stations within the Subantarctic Zone, stations in which the 3°C isotherm is shallower than 800 m are not used. The θ–S distribution shown in Fig. 2 is relatively tight for waters of $\sigma_\theta > 27.05$. Two remarkable changes in the slope of the θ–S distribution are evident at about 4.8°C, $S \geq 34.2$ (water type A) and 3.8°C, $S \leq 34.2$ (water type B). These two features are referred to as the end-members of the intermediate water in the northern Drake Passage (Fig. 2).

The less dense water type A shows a small but discernible salinity maximum and is associated with a relatively thick layer of low stability (SIEVERS and NOWLIN, 1984). The θ–S characteristics of this water are similar to the winter outcrop in the Subantarctic Zone in the southeast Pacific, where it is formed by deep winter convection (MCCARTNEY, 1977). The colder and somewhat fresher water type B in the 27.15–27.20 density range is characterized by a relative salinity minimum. Water type A is the coldest variety of SAMW, while water type B must include colder Antarctic water.

MOLINELLI (1978, 1981) identifies an isohaline thermocline within the southeast Pacific, east of 85°W. This feature occurs south of the Subantarctic Zone in the Drake Passage, falling within the Polar Front Zone (as defined by NOWLIN and CLIFFORD, 1982). While the warmer end-member of the isohaline thermocline is effectively the same as

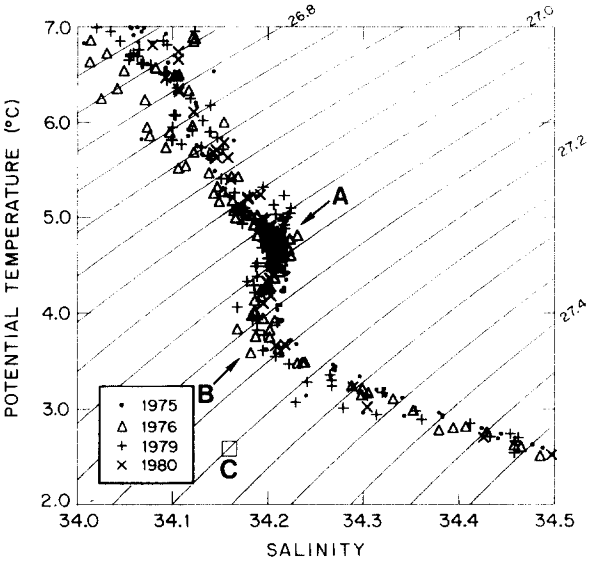

Fig. 2. Potential temperature–salinity distributions in the Subantarctic Zone in the northern Drake Passage. Data collected during the austral summers between 1975 and 1980 as part of the International Southern Ocean Studies. The arrows point to the end-members of the intermediate water in the northern Drake Passage referred to as water types A and B in the text. The square indicated as water type C corresponds to the base of the isohaline thermocline of the southeast Pacific (MOLINELLI, 1978).

water type A (Fig. 2), the cold end-member of the isohaline thermocline is colder than type B. This water type (C in Fig. 2) is not observed in the Subantarctic Zone of the Drake Passage, though water type B can be considered as a 50 : 50 mix of types A and C.

Although there is a suggestion of some interannual variability of the θ–S characteristics, the distribution in the 27.05–27.10 $\sigma_\theta$ range is remarkably tight. The scatter is somewhat larger at $\sigma_\theta > 27.10$, with the 1975 data consistently saltier by 0.02. Given that the water in the Subantarctic Zone is advected eastward at moderate speeds (~6 cm $s^{-1}$ at 150 m; see Tables 1 and 2 in Nowlin *et al.*, 1977a), the small changes in the θ–S distribution suggest equally small changes in the characteristics of the source waters upstream of the Drake Passage during that period.

## THE FLOW DOWNSTREAM OF DRAKE PASSAGE

Because the flow east of Drake Passage and into the Argentine Basin occurs primarily in a narrow band closely following the bottom topography and since the near-bottom currents are probably significant in this region, we have chosen not to calculate relative geostrophic velocities. Instead, maps of the depth of the 27.10 and 27.20 $\sigma_\theta$ surfaces constructed from the winter data collected in 1980 are presented (Figs 3 and 4, respectively). These two density surfaces are representative of water types A and B, respectively. Molinelli (1981) has shown a linear relation between the geostrophic volume transport in the 27.10–27.20 $\sigma_\theta$ range and the depths of this isopycnal range. Buscaglia (1971) noted the similarity of patterns of isopycnals near the AAIW core and the relative acceleration potential at that level in the western South Atlantic. Therefore, the contours of depth on an isopycnal surface can be interpreted as streamlines of geostrophic flow.

The flow on the 27.10 isopycnal is confined to a relatively narrow band between the surface outcrop to the south and east and the ocean bottom to the north and west. East of Drake Passage the flow appears to bifurcate into two branches to the east and west of Burdwood Bank. The flow in the easternmost branch describes an abrupt cyclonic loop north of the Burdwood Bank, closely following the bottom topography of the Malvinas Chasm. Further to the north of Burdwood Bank both branches merge, and the flow continues along the continental slope of South America. At about 43°S the $\sigma_\theta$ isobaths turn east and south adjacent to deeper isobaths associated to the southward extension of the Brazil Current. The winter surface outcrop of the 27.10 isopycnal also curls back, forming a northward loop (to 45°S) of surface water denser than 27.10. Therefore, during the winter, water of 27.10 $\sigma_\theta$ has direct access to the atmosphere within the center of the cyclonic circulation cell in the western Argentine Basin.

The depth of the 27.20 isopycnal shown in Fig. 4, associated with the colder end-member of intermediate water (water type B) indicates that the flow passes east of Burdwood Bank over the North Scotia Ridge. Most of the flow seems to occur through a greater than 1500 m gap situated near 54°S, 54°W. North of Burdwood Bank the flow describes a cyclonic loop over the Malvinas Chasm and then closely follows the continental slope, similar to the flow on the 27.10 isopycnal. The Malvinas Current meets the southward-flowing Brazil Current near 40°S. The 27.20 $\sigma_\theta$ surface does not outcrop at the surface within the western Argentine Basin as does the 27.10 surface. The only evidence of surface outcropping of the 27.20 density surface is in the region of the Polar Front Zone over the North Scotia Ridge east of 50°W.

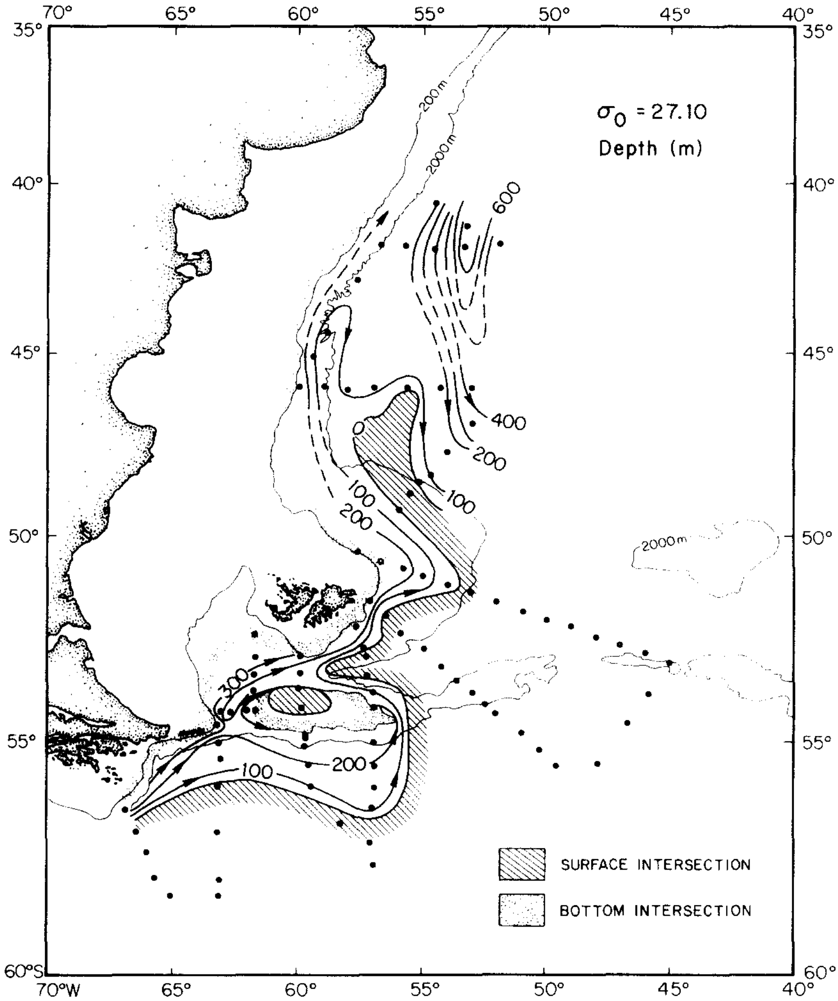

Fig. 3. Depth of the 27.10 $\sigma_\theta$ surface in the western South Atlantic. Data collected in the austral winter of 1980 (R.V. *Atlantis* II, Cruise 107, Leg 10). The hatched area indicates the region where surface water is denser than 27.10 and the light shading the intersection with the ocean bottom.

## THE θ-S CHARACTERISTICS ALONG THE CONTINENTAL SLOPE OF SOUTH AMERICA

A composite θ–S diagram of stations taken in December 1979 along the continental slope of South America (Fig. 5) shows that the water within the 27.05–27.10 $\sigma_\theta$ range is fresher (0.02) and colder (0.3°C) than the water within the same density range (water type A) in the northern Drake Passage. The salinity in the 27.05–27.10 $\sigma_\theta$ range is further decreased towards the north (Fig. 5), from about 34.18 at 46°S (Sta. 94, 46°S) to 34.16 at 38°S (Sta. 3, 38°S). Therefore, the salinity in the vicinity of the 27.10 isopycnal has decreased from an averaged value greater than 34.20 in the northern Drake Passage to

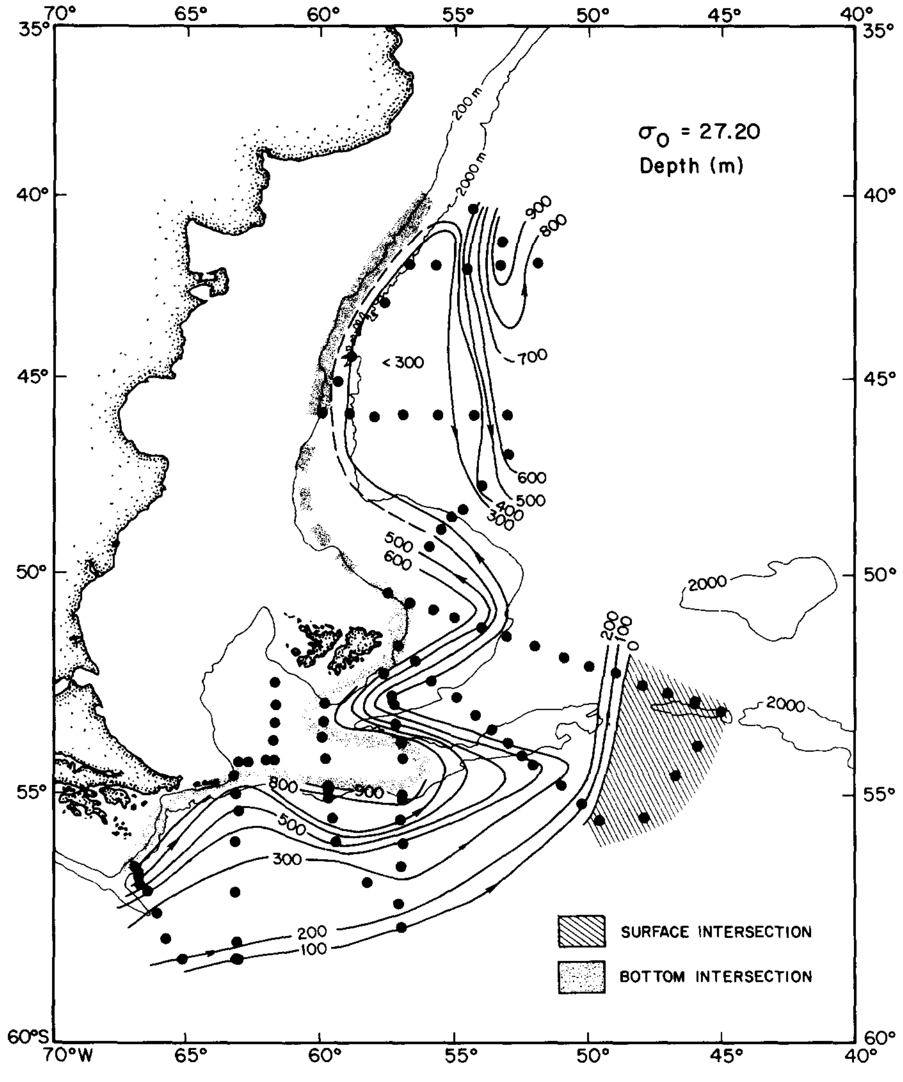

Fig. 4. Depth of the 27.20 $\sigma_\theta$ surface in the western South Atlantic. Data collected in the austral winter of 1980 (R.V. *Atlantis* II, Cruise 107, Leg 10). The hatched area indicates the region where surface water is denser than 27.20 and the light shading the intersection with the ocean bottom.

34.16 at 38°S near the continental slope of South America. As the water on the 27.10 $\sigma_\theta$ surface flows eastward along the northwestern edge of Burdwood Bank, it is capped by a layer of low salinity ($S < 33.9$, see Sta. 226, Georgi *et al.*, 1981) with typical vertical gradients in the upper waters of ~0.5/100 m. With fresher water both above and below this layer, its freshening can be due to vertical mixing. However, winter outcropping of the 27.10 isopycnal north of Burdwood Bank indicates that local modification at this density by sea–air interaction is possible downstream of the Drake Passage.

Along the northern edge of Burdwood Bank there is evidence of deep winter convection (Table 2) that appears to be confined to a very limited density range close to

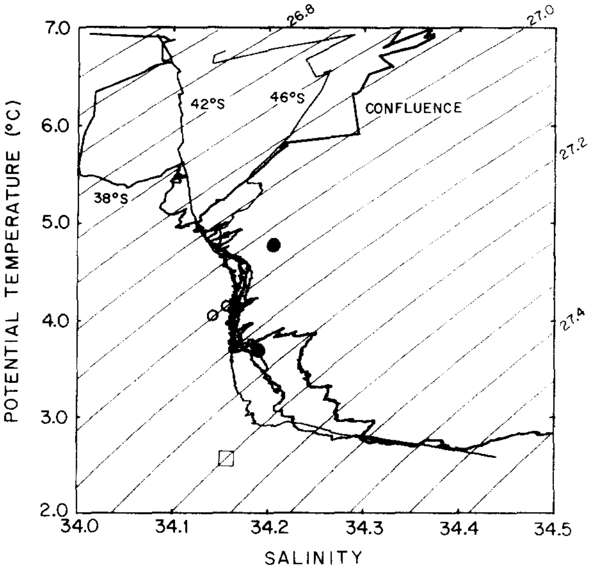

Fig. 5. Potential temperature–salinity distribution of stations along the core of the Malvinas Current from 46°S to the Brazil–Malvinas Confluence (see Fig. 1 for station locations). Data collected in the austral summer of 1979–1980 (R.V. *Atlantis* II, Cruise 107, Leg 3). Stations 94 (46°S), 45 (42°S), 3 (38°S) and 36 (confluence). Large dots indicate the prominent inflections in the potential temperature–salinity distribution from the northern Drake Passage (see Fig. 2). Open circles indicate the θ–S characteristics of winter mixed layers observed north of Burdwood Bank.

the 27.10 isopycnal (Fig. 5). Station 222, for instance, shows a well-mixed water column from the surface to nearly 450 m, with characteristics: 4.16°C, 34.17, 27.10 $\sigma_\theta$. The coldest and freshest mixed layer, found on top of the Bank (Sta. 221, Table 2), is actually the densest, with $\sigma_\theta$ 27.12. Thus, the winter mixed-layer water introduced by isopycnal spreading into the surrounding water column could account for the regional decrease of salinity relative to water type A. It is noted that although surface water fresher than 34.10 is readily available in the region of Burdwood Bank, deep winter convection of these characteristics would be inhibited by the higher stability of the surface layer.

The extension of water types A and B from northern Drake Passage into the Argentine Basin does not occupy the entire cyclonic circulation feature associated with the Malvinas Current (Fig. 3). These waters are confined to the outer edge of the

*Table 2. Mixed-layer characteristics in the region of Burdwood Bank in the austral winter of 1980*

| Station | θ(°C) | Salinity | $\sigma_\theta$ | Depth (m) |
|---|---|---|---|---|
| 207 | 4.26 | 34.166 | 27.10 | 200 |
| 208 | 4.30 | 34.120 | 27.06 | 150 |
| 221 | 3.61 | 34.144 | 27.12 | 85* |
| 222 | 4.16 | 34.168 | 27.11 | 450 |
| 223 | 4.17 | 34.165 | 27.11 | 175 |

* Station 221 taken over Burdwood Bank, bottom depth 85 m.

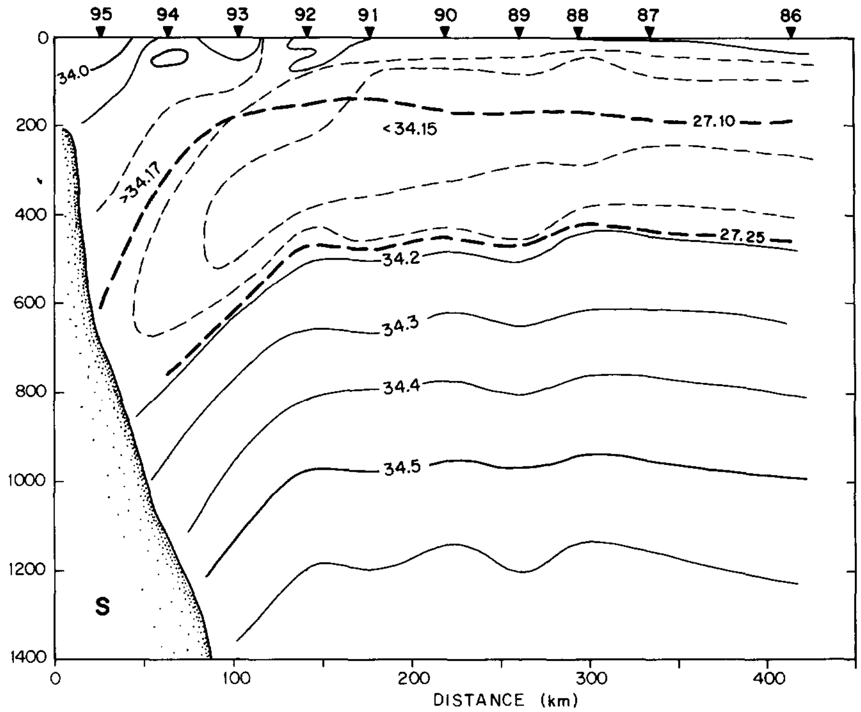

Fig. 6. Salinity section across the Malvinas Current at 46°S. Section location is shown in Fig. 1. Also shown are the 27.10 and 27.25 isopycnals. Data collected in the austral summer of 1979–1980 (R.V. *Atlantis* II, Cruise 107, Leg 3).

cyclonic cell in both the northward- and southward-flowing limbs. A distinct water type is found in the center of the cyclonic feature. For example, over the continental slope the 27.10 isopycnal is associated with a weak salinity maximum ($S > 34.17$; Fig. 6). This water represents slightly modified (freshened) water type A derived from the Drake Passage, as discussed above. Below this feature a salinity minimum derived from water type B is evident. The vertical salinity structure over the slope is similar to, but slightly fresher than, the water type A and B sequence observed in the Subantarctic Zone of the northern Drake Passage.

Further offshore, within the center of the cyclonic circulation cell, the salinity minimum is still evident but it is associated with water of $\sigma_\theta$ 27.10. Thus, the salinity minimum occurs at lower density within the cyclonic trough than it does at the edges of the Malvinas Current. This feature is apparent as a tongue of low salinity and high dissolved oxygen concentration in the property distributions on the 32.0 $\sigma_1$ surface (Buscaglia, 1971) and the 27.18 $\sigma_\theta$ surface (Reid *et al.*, 1977).

The θ–S distribution within the cyclonic trough (Fig. 7) reveals a structure distinct from that found over the continental slope and in the northern Drake Passage. Two water types are apparent (open symbols in Fig. 7): the densest and saltiest lies near the 27.25 isopycnal and is identical to water type C (Fig. 2); while a shallower salinity minimum, found on the 27.05 isopycnal, also is observed south of the Subantarctic Front in the northern Drake Passage.

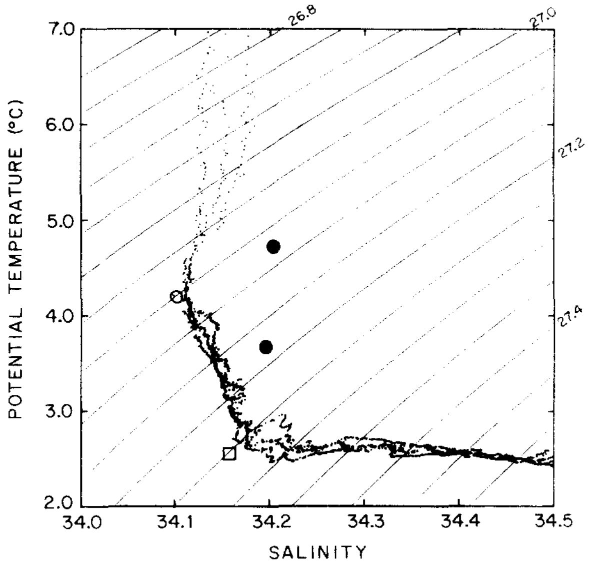

Fig. 7. Potential temperature–salinity distribution of stations within the cyclonic trough of the Malvinas Current at 46°S (Stas 88, 89 and 90, R.V. *Atlantis* II, Cruise 107, Leg 3, see Fig. 1 for station locations). Large dots indicate the prominent inflections in the potential temperature–salinity distribution from the northern Drake Passage (see Fig. 2). Open circle indicates the θ–S characteristics of the local winter outcrop at Sta. 164 (R.V. *Atlantis* II, Cruise 107, Leg 10) Square indicates the θ–S characteristics of the base of the isohaline thermocline of the southeast Pacific described by Molinelli (1978).

The shallower salinity minimum has θ–S characteristics that are found in the vicinity of the Polar Front in the Drake Passage and are virtually identical to the local surface outcrop during winter (Sta. 164, see Fig. 7). Therefore, this water is attributed to locally modified Polar Front water. Further evidence of recent ventilation at this level comes from the relative oxygen maximum observed at or near the local salinity minimum. Lateral mixing of this water with water type A leads to the freshening on the 27.10 isopycnal observed along the edges of the Malvinas Current north of 50°S. Interleaving of temperature, salinity and dissolved oxygen at this level (see Sta. 93, Guerrero *et al.*, 1982), which is often taken as evidence for lateral mixing, supports this concept.

Water type C is not found in the Subantarctic Zone of the northern Drake Passage. However, it is observed within the Polar Front Zone of the Drake Passage, and flows east of Burdwood Bank, into the axis of the cyclonic trough. Thus, one can visualize a "folding" of the zonation of the Drake Passage into the Malvinas cyclonic cell within the Argentine Basin.

## INTERMEDIATE WATERS UNDER THE SUBTROPICAL THERMOCLINE

The Brazil and Malvinas Currents converge (Brazil–Malvinas Confluence) over the continental slope between 35° and 40°S, and then flow seaward (Reid *et al.*, 1977; Gordon and Greengrove, 1986). There is some evidence suggesting that the currents diverge further offshore (Fig. 14 in Reid *et al.*, 1977; Roden, 1986; Olson *et al.*, 1988). In August 1980 the separation of subantarctic water from the boundary (Figs 3 and 4) occurs near 40° to 43°S. At the separation a strong thermohaline front is induced. Changes in the θ–S structure across the front are obvious at densities less than 27.20 (Fig. 8); these differences are somewhat reduced for higher densities. In the density range from 27.05 to 27.15, the water on the subantarctic side of the confluence is characterized by the modified (freshened) northern Drake Passage stratification. Above this layer, fresher and warmer water is found marking the influence of shelf water (Sta. 3, Fig. 8). The subtropical water within the southward-flowing Brazil Current is characterized by a warm and salty thermocline and a somewhat saltier intermediate water (e.g. *Atlantis* II Sta. 9 in Fig. 8).

Although there is a strong thermohaline contrast in the 27.05–27.15 $\sigma_\theta$ interval where subtropical and subantarctic waters first meet, the θ–S distributions from stations taken downstream of the separation reveal a substantial freshening under the subtropical thermocline. *Thomas Washington* Sta. 41, taken in October 1984, reveals fine structure with alternate layering of subantarctic and subtropical water, indicative of mixing across the confluence. Such mixing processes in the western South Atlantic are apparent throughout the thermocline (Gordon, 1981) and deep water (Georgi, 1981).

Potential temperature–salinity distributions from stations taken during the CATO Expedition (SIO, 1979) across the Brazil Current near 33°S show that in the 27.05–27.30 density range the salinity is close to 34.29, or 0.1 higher than that observed in the confluence region. Moreover, at 33°S there is no evidence of water types A or B. Thus, the salinity minimum layer under the thermocline in the vicinity of the confluence is significantly fresher than that found within the Brazil Current farther north. The changes

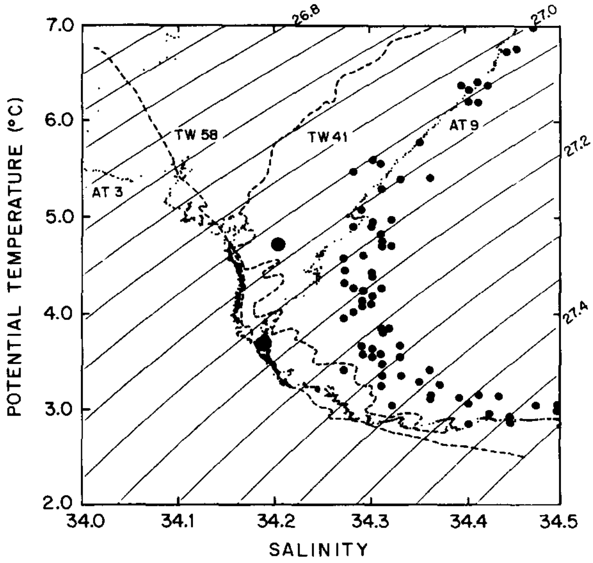

Fig. 8. Potential temperature–salinity contrast at intermediate depths across the Brazil–Malvinas Confluence. Stations indicated AT correspond to the 1979 data from R.V. *Atlantis* II, Cruise 107, Leg 3 and those indicated TW correspond to the 1984 data from R.V. *Thomas Washington* Marathon Expedition, Leg 7. Station locations are shown in Fig. 1. Large dots indicate the prominent inflections in the potential temperature–salinity distribution from the northern Drake Passage (see Fig. 2). Small dots indicate the θ–S distribution of stations near the continental slope at 33°S (CATO Expedition, Leg 6).

in the θ–S distributions along the western boundary suggest that the bulk of the newly formed AAIW observed below the thermocline does not flow northward as a continuous western boundary current. Rather, it must spread northward within the interior region as suggested by Buscaglia (1971) and Reid *et al.* (1977), though it may rejoin the western boundary near 23°S to account for the northerly flowing intermediate water observed by Evans and Signorini (1985). Additionally, both McCartney and Reid (personal communication, 1988) show evidence of a very narrow band of northward-flowing AAIW pressed against the continental slope near 30°S.

Some differences are apparent in the θ–S characteristics in the intermediate waters under the subtropical thermocline between December 1979 and October 1984. In the potential temperature range from 3.5 to 4.5°C the 1979 data show salinities lower than 34.20, while in 1984 salinities in the same density range are 34.25 (Fig. 9). The lower salinity observed in 1979 suggests a greater influence at that time of the denser end-member (water type B) from the northern Drake Passage.

The θ–S differences found under the subtropical thermocline can be attributed to changes in the properties of the source or to differences in the circulation and mixing across the Brazil–Malvinas Confluence. Typical θ–S distributions for 1979 and 1984 (Fig. 9) indicate that no significant changes of the input characteristics have occurred (Stas 45 from *Atlantis* II and 58 from *Thomas Washington*). Therefore, the observed changes in the AAIW below the thermocline must be associated with changes in the circulation and mixing patterns.

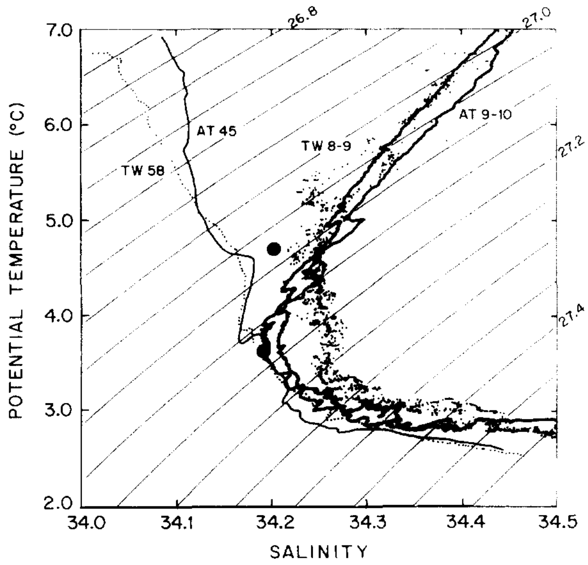

Fig. 9. Comparison of the potential temperature–salinity distributions within subtropical waters between the data collected in the austral summer of 1979–1980 (full line, Stas AT9 and 10) and data collected in the austral spring of 1984 (dotted line, Stas TW8 and 9). Stations indicated AT correspond to the 1979 data from R.V. *Atlantis* II, Cruise 107, Leg 3 and those indicated TW correspond to the 1984 data from R.V. *Thomas Washington* Marathon Expedition, Leg 7. Also shown are Stas AT45 and TW58 characteristic of the northward-flowing waters along the continental slope at 42°S. Station locations are shown in Fig. 1. Large dots indicate the prominent inflections in the potential temperature–salinity distribution from the northern Drake Passage (see Fig. 2).

In October 1984, the Brazil–Malvinas Confluence was located approximately over the 1000 m isobath at 38°S (Gordon, 1989). Thus, there was a narrow band (<50 km) of subantarctic water located between the front and the shelf break. In December 1979 the front was found some 200 km further east and there was a region of southward-flowing mixed subantarctic and subtropical water (Gordon, 1989). Therefore, in 1979 there was an extensive region of mixed water at 38°S. A time series of the frontal position at 37°30′S derived from inverted echo sounders reveals that the front oscillates with an amplitude of about 80 km, with its more westward location in November 1984 and its most eastward location in June 1985 (Garzoli and Bianchi, 1986; Garzoli and Garraffo, 1989). Thus, there is evidence for frontal displacements and circulation variations at the Brazil–Malvinas Confluence. Associated with such changes there may be alterations in the subduction process of intermediate water under the subtropical thermocline that would lead to the observed changes in the θ–S distribution at the base of the thermocline in October 1984.

## DISCUSSION

The intermediate water from the northern Drake Passage is characterized by two end-members (water types A and B, Fig. 2) that flow into the western Argentine Basin within the northward-flowing Malvinas Current (Figs 3 and 4). In the 27.05–27.15 $\sigma_\theta$ range there is evidence of effective ventilation by deep winter convection in the region of the Burdwood Bank. The salinity of the mixed layers in this region is generally lower than 34.17. Consequently, water type A becomes fresher by mixing with the local winter water as it flows northward around Burdwood Bank. The flow of the densest component (water type B) is confined to the east of Burdwood Bank and is only exposed to the atmosphere south of the Antarctic Polar Front (Fig. 4).

North of 46°S there continues to be a progressive downstream salinity decrease of water type A that leads to values close to 34.16 at the northernmost extension of the Malvinas Current. Direct contact with the winter atmosphere in principle could be responsible for the observed freshening. However, estimates of the annual averaged net freshwater flux through the sea surface (Baumgartner and Reichel, 1975) indicate that north of 48°S there is excess evaporation rather that excess precipitation along the axis of the Malvinas Current. Therefore, sea–air interaction in the western Argentine Basin would act to increase rather than decrease the salinity north of that latitude.

It is most likely that the downstream freshening of water type A is a result of vertical and isopycnal mixing, since it is surrounded by lower salinity water (Fig. 6). The 27.10 $\sigma_\theta$ surface extends to the axis of the cyclonic trough formed by the Malvinas Current and its southward return. This region is characterized by low salinity water advected from the Polar Front Zone (Figs 6 and 7). Lateral mixing with water type A could lead to the observed salinity decrease with latitude within the Malvinas Current.

The salinity decrease on the 27.20 $\sigma_\theta$ surface (water type B) is somewhat less pronounced than that observed on the 27.10 $\sigma_\theta$ surface. Since the 27.2 isopycnal only outcrops within the Polar Front Zone, the freshening at this level can only be induced by lateral mixing with the waters found within the trough of the Malvinas Current.

From the θ–S distributions in the subtropical water (north of the Brazil–Malvinas Confluence) there is evidence of the low salinity waters of the Malvinas Current spreading under the subtropical thermocline along density surfaces (Fig. 8), as suggested by MCCARTNEY (1982). This exchange appears to decrease somewhat the cross-frontal salinity gradients at intermediate depths further east (RODEN, 1986).

The intermediate water within the cyclonic trough (Fig. 7) does not appear to be in direct contact with the subtropical water at the confluence (Fig. 8). It is unlikely that spreading below the subtropical thermocline can occur at the confluence. The influence of the Polar Front Zone water seems to occur upstream of Drake Passage, in the southeast Pacific, where it contributes to form water type B, as pointed out by MOLINELLI (1981). Further influence of Polar Front water is through modification of the less dense intermediate water of the northern Drake Passage (types A and B) along the cyclonic trough described by the Malvinas Current. These processes can continue further downstream along the northern edge of the Polar Front.

Based on the property distributions of TAFT (1963), JACOBS and GEORGI (1977) have pointed out the large differences between the salinity values in the southwest regions of the three southern hemisphere oceans. These differences suggest a stronger influence of high latitude waters (e.g. low salinity and high dissolved oxygen concentration) in the western South Atlantic than in the Indian and Pacific Oceans. The existence of two sources of low salinity water in the 27.0–27.3 $\sigma_\theta$ range leads to a thicker layer of lower salinity in the South Atlantic than found in the Pacific and Indian Oceans (see Plates 10, 12 and 14 of GORDON and BAKER, 1982). The northward flow of this thick layer within the Malvinas Current in the western South Atlantic is responsible for the lower salinity and higher dissolved oxygen observed below the thermocline.

In the Indian Ocean, there is no northward-flowing western boundary current of low salinity water. The AAIW water of the Indian Ocean is relatively salty and poorly ventilated (see Fig. 6 in PIOLA and GEORGI, 1982). A source of intermediate water of subantarctic origin is found in the southeast Pacific (the SAMW, MCCARTNEY, 1977, 1982). Although intermediate water of Antarctic origin is also found in the southeast Pacific south of the Polar Front (MOLINELLI, 1978), this water appears to be advected into the South Atlantic. Thus, the intermediate water in the South Pacific is mainly of subantarctic origin.

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