PHYSICAL OCEANOGRAPHIC SETTING OF THE *SIEDLECKI* JANUARY 1987, SOUTH SHETLAND ISLAND DATA SET

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Abstract

In the vicinity of the northern tip of the Antarctic Peninsula, the Bransfield Straits and South Shetland Islands, cold polar waters from the Weddell Sea meet warmer circumpolar water from the Pacific Ocean. A series of fronts form which are collectively referred to as the Weddell-Scotia Confluence. Within the Confluence region the Weddell Gyre water is separated from the Pacific or Scotia Sea water by a zone of varied width (10 to 100 km) of water which can best be considered as continental margin water, advected into the region along the extreme western edge of the Weddell Gyre. It is relatively cold and low in salinity throughout the water column and prone to deep reach convective events, even as far north as the Bransfield Straits. Along the northern boundary of the Weddell-Scotia Confluence (the Scotia Front), where the Pacific water is encountered, there are indications of vigorous mixing processes of Bransfield Straits water (derived from the Weddell, with further local modification): an intrusive layer of Pacific derived relatively warm-salty water near 300 meters depth and deeper intrusions (500-1 500 meters; e.g. *Siedlecki* stations 217, 226, 231, 235, 236 and 250) of Pacific water, as the Scotia Front protrudes to the south, perhaps associated with mesoscale structures.

The Weddell-Scotia Confluence in the Bransfield Straits is associated with abundant krill populations. It is speculated that mixing of Weddell and Pacific waters near the tip of the Antarctic Peninsula is an important environmental feature related to this abundance.

Résumé

Aux alentours de l'extrémité nord de la Péninsule Antarctique, du détroit de Bransfield et des îles Shetland du Sud, les eaux froides polaires de la mer de Weddell rencontrent les eaux circumpolaires plus chaudes venant de l'océan Pacifique. Là se forme une série de fronts connus sous le nom collectif de Confluence de Weddell-Scotia. Au sein de la région de la Confluence, les eaux du courant tourbillonnaire de Weddell sont séparées des eaux du Pacifique ou de la mer de Scotia par une zone d"eau de largeur variée (10 à 100 km) que l'on peut considérer comme une eau continentale marginale dont l'advection dans la région a lieu de long de l'extrême bordure occidentale du courant tourbillonnaire de Weddell. Cette eau est relativement froide et sa teneur en sel est faible dans toute la colonne; elle est également sujette à des mouvements de convection allant en profondeur, et cela même au détroit de Bransfield au nord. Le long de la limite nord de la Confluence de Weddell-Scotia (le Front de Scotia), là où l'on rencontre les eaux du Pacifique, on remarque des indications d'importants processus de mélange de l'eau du détroit de Bransfield (provenant de la mer de Weddell, subissant par la suite

d'autres modifications locales) : une couche intrusive d'eau chaude et salée à près de 300 mètres de profondeur et des intrusions plus profondes (500-1 500 mètres; par exemple les stations de *Siedlecki* 217, 226, 231, 235, 236 et 250) des eaux du Pacifique au fur et à mesure que le Front de Scotia avance au sud - qui sont peut-être en rapport avec des structures à moyenne échelle.

La Confluence de Weddell-Scotia dans le détroit de Bransfield est associée à des populations abondantes de krill. Il est possible que le mélange des eaux de Weddell et du Pacifique près de l'extrémité de la péninsule Antarctique soit une caractéristique écologique importante liée à cette abondance.

Резюме

Невдалеке от северной оконечности Антарктического полуострова, пролива Брансфилда и Южных Шетландских островов холодные полярные заводы моря Уэдделла встречаются с более теплыми циркумполярными водами Тихого океана. Образуется ряд фронтов, которые все вместе называются конфлюэнцией Уэдделла-Скотия. В районе самой конфлюэнции воды циркуляции моря Уэдделла отделяются от вод Тихого океана и моря Скотия зоной различной ширины (от 10 до 100 км.), которую лучше всего рассматривать как континентальные прибрежные воды, перемещенные сюда вдоль самой крайней западной кромки циркуляции моря Уэдделла. Они относительно холодны и отличаются низкой соленостью по всему водяному столбу, и в глубине их часто происходят интенсивные конвекционные явления, даже так далеко к северу, как, например, в проливе Брансфилда. Вдоль северной границы конфлюэнции Уэдделла-Скотия (фронт Скотия), где встречаются воды Тихого океана, прослеживаются признаки интенсивного процесса перемешивания вод пролива Брансфилда (занесенных из моря Уэдделла, но с дальнейшими, возникшими уже здесь изменениями): слой вторгающейся из Тихого океана сравнительно теплой и более соленой воды на глубине около 300 м и, по мере того, как фронт Скотия выступает на юг, - более глубокий слой (500-1500 метров; напр., выполненные на "Седлецком" станции 217, 226, 231, 235, 236 и 250), что, по-видимому, связано с мезомасштабными структурами.

Конфлюэнция Уэдделла-Скотия в проливе Брансфильда ассоциируется с многочисленными популяциями криля. Делается предположение о том, что происходящее у оконечности Антарктического полуострова смешивание вод моря Уэдделла и Тихого океана является важным фактором окружающей среды, с которым связана вышеупомянутая многочисленность.

Resumen

En las proximidades del extremo norte de la Península Antártica, estrecho de Bransfield e islas Shetland del Sur, las frías aguas polares del mar de Weddell confluyen con aguas más cálidas circumpolares del océano Pacífico. Se forma una serie de frentes a los cuales se les llama colectivamente Confluencia de Weddell-Scotia. Dentro de la región de la Confluencia, las aguas de las vórtices de Weddell se separan de las del Pacífico o del mar de Scotia por una zona de agua una amplitud que varía entre 10 y 100 km que se puede considerar como agua del margen continental, llevada a la región, a lo largo del borde extremo occidental de las vortices de Weddell. Es relativamente frío y bajo en salinidad en toda la columna de agua y propenso a casos de convección de alcance profundo incluso extendiéndose hacia el norte hasta el estrecho de Bransfield. A lo largo del límite norte de la Confluencia de Weddell-Scotia (Frente de Scotia), donde converge con aguas del Pacífico, hay señales de vigorosos procesos de mezcla de las aguas del Estrecho de Bransfield (que llega del Weddell, con una mayor modificación local): una capa intrusa del Pacífico dió como resultado aguas relativamente cálidas y saladas cerca de los 300 metros de profundidad. Hubo también intrusiones aún más profundas (500 - 1 500 metros; por ej. estaciones *Siedlecki* 217, 226, 231, 235, 236 y 250) de aguas del Pacífico debido a que el Frente de Scotia sobresale con dirección al sur, esto tal vez esté relacionado con estructuras de media escala.

La Confluencia de Weddell-Scotia en el estrecho de Bransfield supone abundantes poblaciones de krill. Se especula que la mezcla de aguas del Weddell con las del Pacífico cercanas al extremo de la Península Antártica es una característica ambiental de importancia relacionada a dicha abundancia.

1. OCEANOGRAPHY AT THE TIP OF ANTARCTIC PENINSULA

As we obtain more observations of the physical environment of the Southern Ocean, the better we appreciate the extent of its variability, at a variety of scales (Gordon, 1988). The mean climatic condition exists for only brief periods as the ocean stratification and circulation continuously swings between extremes. Certainly the unique biological community of the Southern Ocean responds to these changes in the habitat. Our challenge is to understand the causes of environmental variability and the response of krill to these changes. This is a most difficult task. The ocean-atmosphere-ice coupled system is in itself exceedingly complex. Added to this is the life cycle of krill, which we are only very slowly getting to know.

The Bransfield Straits region marks the northwest corner of the Weddell Gyre. Here the cold Antarctic waters, which sweep north along the eastern margin of Antarctic Peninsula, meet the warmer waters carried in from the Pacific Ocean. It is a region of strong contrasts and deep reaching convection (Clowes, 1934, Gordon and Nowlin, 1978) and abundant krill population (Marr, 1962).

The Weddell Gyre is a large, wind-driven cyclonic gyre, with a transport of 70 to 90 Sv (Carmack and Foster, 1975; Gordon, Martinson and Taylor, 1981). The average speed of the surface current in the western boundary of the Gyre, of 8 cm/sec as measured by drifting ships and buoys, extended to the sea floor can easily account for the large transport. The western most rim of the Weddell western boundary current, pressed up against the continental slope, has been modified by convective processes and may be referred to as continental margin water, marking a transition from the deep water open ocean stratification to the colder shelf water masses. The continental margin water follows the continental slope, turning into the Bransfield Straits and becomes strongly coupled to the complex bottom topography of the South Scotia Ridge (including the South Shetland Islands), with some deep water passing into the Pacific Ocean (Nowlin and Zenk, 1988). Ocean dynamics suggests that the circulation would form an isobath contour following current, with shallower topography to the left of the velocity vector.

The merging of the Weddell water with circumpolar waters entering the Atlantic via the Drake Passage, creates a zone of low stability, referred to as the Weddell-Scotia Confluence (Figure 1 presents a schematic of the Confluence structure; Gordon, 1967; Gordon, Georgi and Taylor, 1977; Deacon and Moorey, 1975; Patterson and Sievers, 1980). It displays intense eddy activity, which increases downstream from the initial contact of the two circulation regimes (Foster and Middleton, 1984). The Weddell-Scotia Confluence varies in width from 10's to 100 kms scale, presumably a consequence of mesoscale activity. However, there does seem to be a quasi-stationary form which is related to the topography of the South Scotia Ridge. The fronts marking the northern and southern edge of the Confluence have been called the Scotia Front and the Weddell Front, respectively (Gordon, Georgi and Taylor, 1977). he sea ice edge along this front is investigated with the shuttle imaging radar-B (SIR-B) by Carsey et al (1986). Comiso and Sullivan (1986) compare passive microwave data from satellite with field observations along the ice edge of the region. The sea ice edge also displays irregular patterns responsive to the mesoscale activity.

In summary (see Figure 1): The Weddell-Scotia Confluence brings together waters with very different histories: cold polar Weddell water and warmer circumpolar Pacific water. In between these two large scale water mass or stratification regimes, is an order 100 km wide zone of very cold, generally fresher water. This zone is referred to as the Weddell-Scotia Confluence Zone, includes the water of the Bransfield Strait, and is essentially continental margin water which has migrated along the flanks of Antarctic Peninsula before being injected into the open ocean. This water has a low degree of

stratification, with indications of vigorous vertical exchange processes and local water mass modification. The Weddell Scotia Confluence Zone extends northwest across the Scotia Sea and remnants can be identified as far east as the Greenwich Meridian.

2. *SIEDLECKI*, 1986/87

In 1986/87 the R/V *Professor Siedlecki* obtained oceanographic data within the waters surrounding South Georgia and along the South Shetland Islands from Livingston Island to Elephant Island (Figure 2a, b). The cluster of stations around South Georgia (*Siedlecki* leg 1)is not the focus of this paper. The South Georgia water mass structure varies little from station to station: it is essentially circumpolar water stratification (e.g. Gordon and Molinelli, 1982), with a temperature minimum of 0° to +1.0°C with an underlying pycnocline truncated near the 27.7 σ_0 density.

2.1 57°W Section

The water mass structure along the tip of Antarctic Peninsula does reveal strong spatial variability. A section of potential temperature and for salinity along approximately 57°W passes from the Pacific zone into the continental zone of the Bransfield Strait between Elephant and King George Island (Figure 3a, 3b). The relatively warm-saline deep water of the Pacific circumpolar water is clearly defined to a position just south of station 214. An abrupt change occurs between stations 214 and 217, over the continental slope, which is fairly characteristic of this region. This intense thermohaline front marks the initiation of the Scotia Front or continental water boundary (see Nowlin and Clifford, 1982). Above 100 meters the front separates low salinity colder water of the north from higher salinity warmer water to the south. The opposite is the case for the bulk of the water column, below 100 m. The haline front at the surface between stations 214 and 217 is quite strong, though the temperature expression of the front at the immediate surface is nearly absent.

South of the front a warm-saline layer is observed within the 200-300 meter range. The θ/S properties of this feature indicate that it represents poleward isopycnal spreading of much diluted Pacific deep water. Similar intrusions are often observed poleward of the shelf-slope front around Antarctica, re-enforcing the analogy that the South Shetland Island end of the Scotia Front is similar to a continental shelf-slope front of Antarctica. The *Discovery* data of the 1920's and '30's also shows the invasion of Pacific deep water into the Bransfield Strait through the passages of the South Shetland Islands (Clowes, 1934).

Further south along the section the Pacific intrusion attenuates, replaced by the very cold, but low salinity water filling the Bransfield Basin, fed by inflow from the Weddell Sea. Deep reaching convection is common within this region (Gordon and Nowlin, 1978) with surface winter (freezing point) water of salinity 34.62 responsible for the deep convection. This water is probably derived from the margin of the Antarctic Peninsula.

2.2 Potential Temperature/Salinity Relationship, θ/S

The regional θ/S distribution (from the Southern Ocean atlas data set of Gordon and Molinelli, 1982) for "climatic" January and February is given in figure 4. The θ/S position of the various component water masses are labelled on figure 4. The Pacific Ocean water stands out as an arc marking the warmest/saltiest water. The Weddell deep water θ/S cluster found in the eastern end of the Bransfield Straits falls in the region of 0° to -0.7°C; 34.65, marking the Weddell continental margin water advected into the area. The scatter of points at temperatures below -0.5°C marks the unique water mass filling the Bransfield Basins (see Gordon and Nowlin, 1978). The water within the Weddell-Scotia Confluence is

similar to water of the upper 1 000 m within the Bransfield Strait; deeper than that the Bransfield water seems to be isolated from the open ocean, its only means of "communication" being vertical exchange processes (Gordon and Nowlin, 1978). The θ/S scatter at salinity less than 34.5 is composed of an array of points stretching from the summer surface water values to each of the three basic deep water units (Pacific, Weddell and Bransfield).

Comparison of this large scale water mass structure to that of the *Siedlecki* 1986/87 data provides a guide in identifying the origin of the stratification observed by the *Siedlecki* in the South Shetland Island region (the *Siedlecki* data set is separated into five groupings, shown in Figure 5).

2.3 Group #1 Bransfield Strait

The Bransfield Strait Group #1 (Figure 6) reveals the cold, low salinity water which fills the Bransfield Strait basins (to about 1 200 meters, the depth limits of the *Siedlecki* data). The relatively warm-saline feature observed between σ_0 range of 27.7 to 27.8 is the same water discussed above (Figure 3 a,b). Comparison with the large scale water mass distribution (Figure 4) supports the statement that it is of Pacific deep water origin, which spreads along isopycnal surfaces into the Bransfield Straits.

2.4 Group #2 South of Elephant Island

This area (Figure 7) is similar to Group #1, with two exceptions: A Pacific water column station (214) is included in the northwestern corner of the group and its neighboring station 217 displays a relatively salty bottom water mass, extending to 27.8 σ_0. In addition, the average depth of the stations is less than within group #1 and hence does not attain as low temperatures. The station 217 feature is similar to that observed within the cluster of stations centered at 60° 50'S and 55° 45'W, within group #3. The possible origin of this θ/S feature is included in the discussion section of this paper.

2.5 Group #3 North of Elephant Island

In the region just north of Elephant Island (area #3; Figure 8), there are various blends of Bransfield Strait and Pacific circumpolar water, associated with the sharp continental front (or western end of the Scotia front) over the continental slope. Labelled on figure 8 are two such features: "A" which is a less salty blend falling along the continental front and "B" which is found within the cluster of stations centered at 60° 50'S and 55° 45'W (as well as station 217 in group #2).

2.6 Group #4 and #5 Western South Shetland Islands

These shallow stations (Figure 9) show the typical Bransfield surface water. These stations are over the South Shetland Islands shelf zone and obviously south of the front with the Pacific water.

3. DISCUSSION

Besides Pacific water intrusions near 300 meters there appears to be Pacific influence within the deep water, below 500 meters.

The *Siedlecki* data within group #3 and at station 217 of group #2 reveal the presence of blends of Pacific deep water with Bransfield Straits water. These water columns have contact only along the front (the westward extension of the Scotia Front, shown in Figure 1) and hence are indicative of cross frontal mixing. Figure 8 shows the end-member water columns (Pacific, represented by station 244 and Bransfield, represented by station 223) and stations representing various stages on mixing, for the blends marked A and B in the group #3 θ/S. The stations with blend B all fall in the 1 000 to 1 500 m bottom depth interval, with the salinity steadily increasing to the bottom. It is possible that this mixture is induced by interaction of the front with the sea floor as the Scotia (or Continental) Front protrudes further south, perhaps associated with meso-scale variability. Stations with blend A (only three stations in the northeast corner of the group #3), are in deeper water, over 3 000 m, and the deepest segment of the θ/S curve follows the Pacific water column. Thus it is not the product of (at least) local interaction with the sea floor.

The abundance of krill swarms, which often are confined to the northern slope of the Shetland Islands, might be related to the presence of mixing of Pacific water with water derived from the Weddell undergoing further modification within the Bransfield Straits. Additionally, in this region the cold waters of the Weddell, with a substantial winter sea ice cover, encounter the much warmer Pacific water. This is particularly the case north of Elephant Island. Rapid melting along the ice edge might enable establishment of an environment conducive to krill development and/or swarming.

The Bransfield Straits, with its unique oceanographic regime and its krill population, make for an ideal area for study of the relationship of krill to its environment.

ACKNOWLEDGEMENTS

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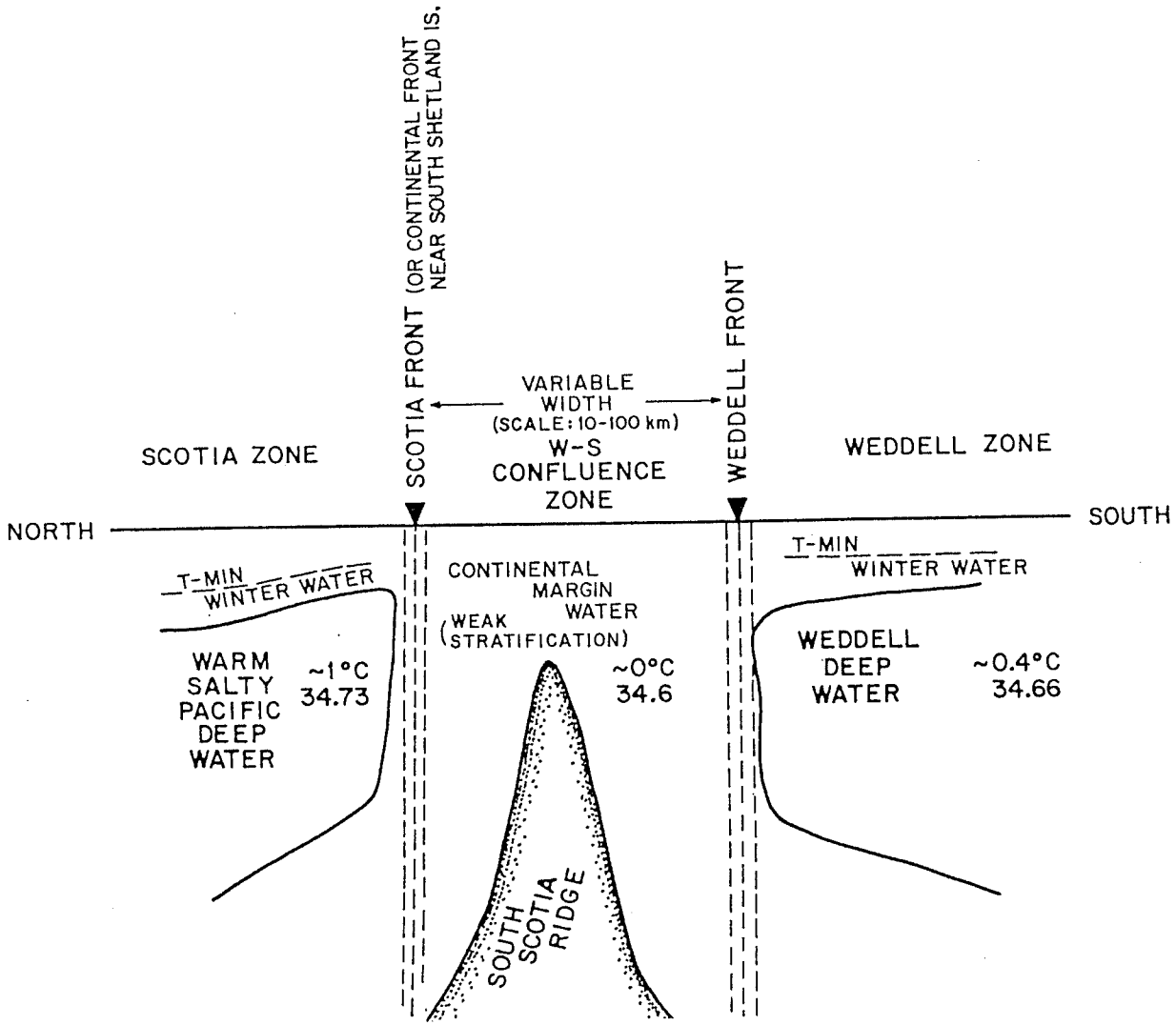

Figure 1: A schematic of water mass zones and fronts associated with the Weddell-Scotia Confluence. A sequence of stratification regimes and fronts encountered from south to north composing the Weddell-Scotia Confluence structure is as follows (Gordon, Georgi and Taylor, 1977) : Weddell Gyre zone; Weddell front; Weddell-Scotia Confluence zone; Scotia front (which along the northern edge of the South Shetlands may be called the continental front); Pacific zone.

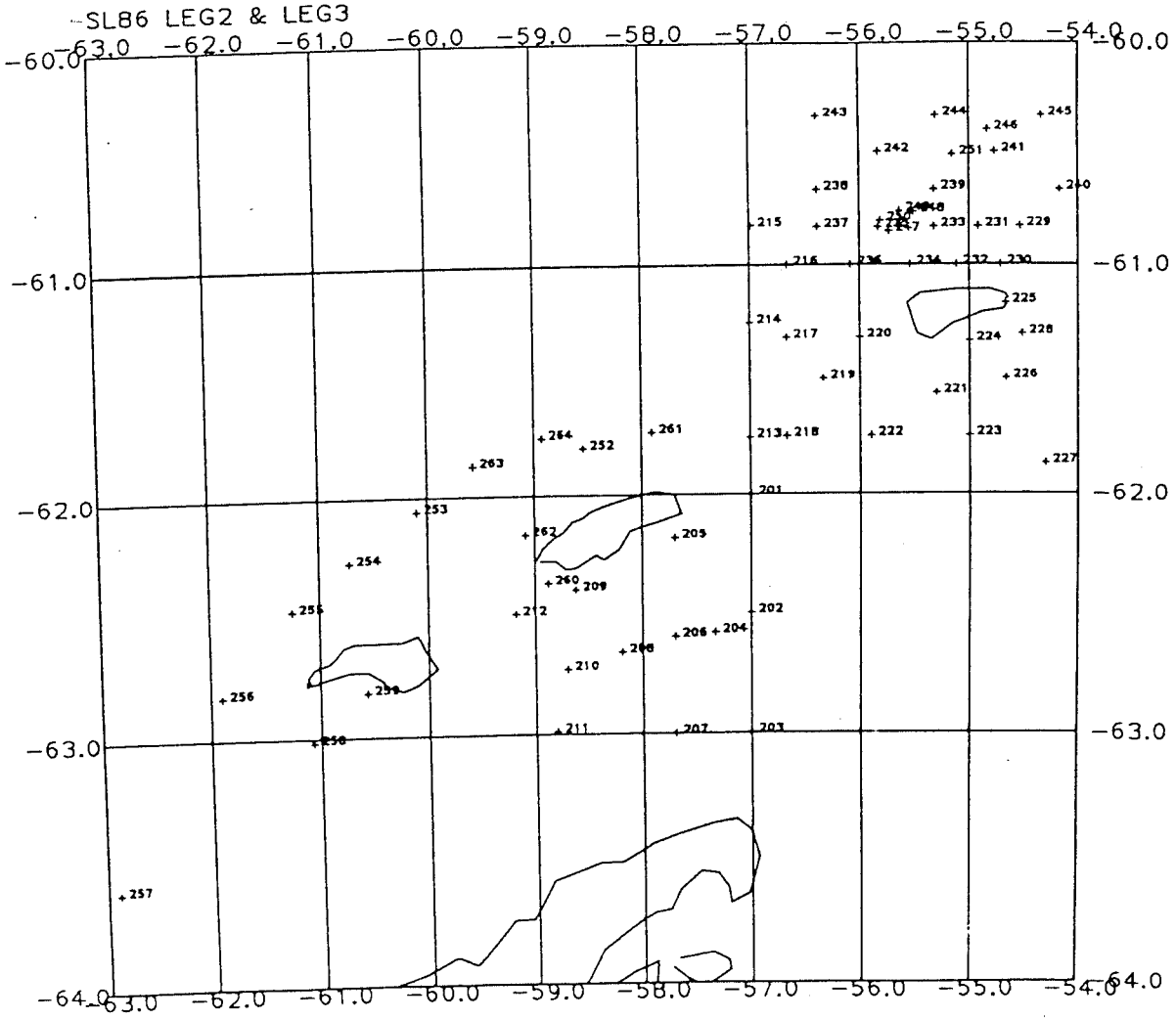

Figure 2a: Station map of *Siedlecki* hydrographic stations 1986/87

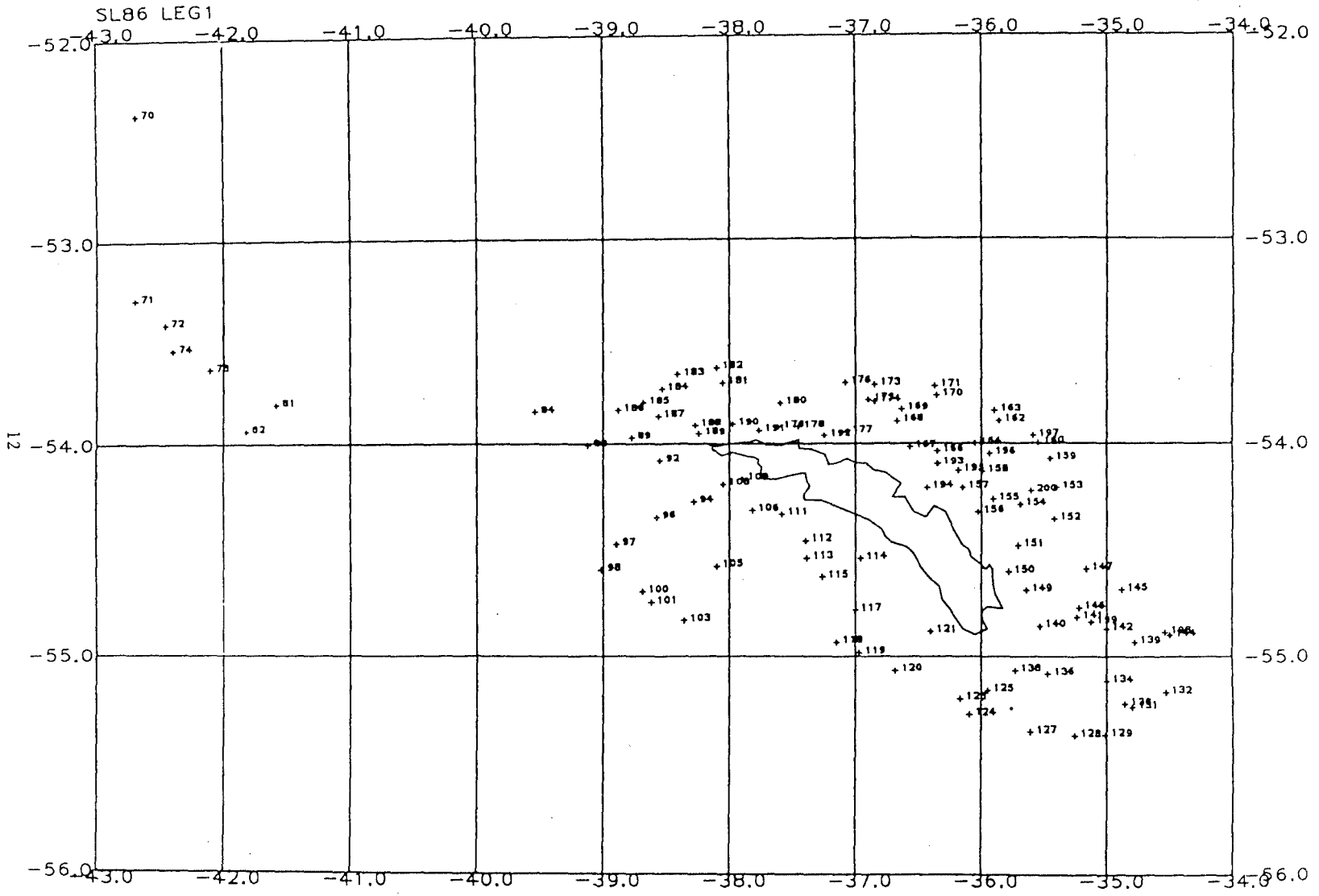

Figure 2b: Station map of *Siedlecki* hydrographic stations 1986/87

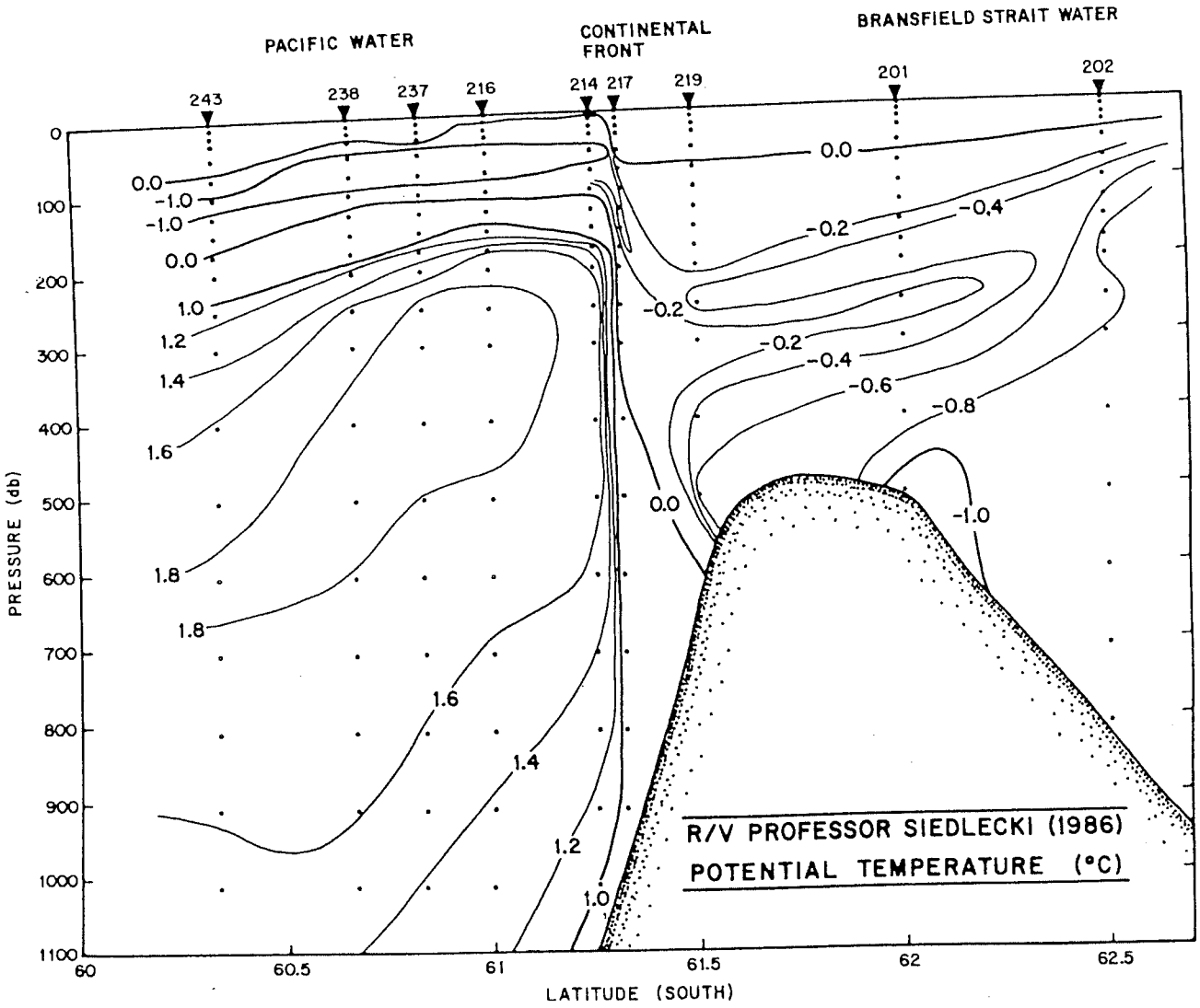

Figure 3a: Potential temperature section along 57°W

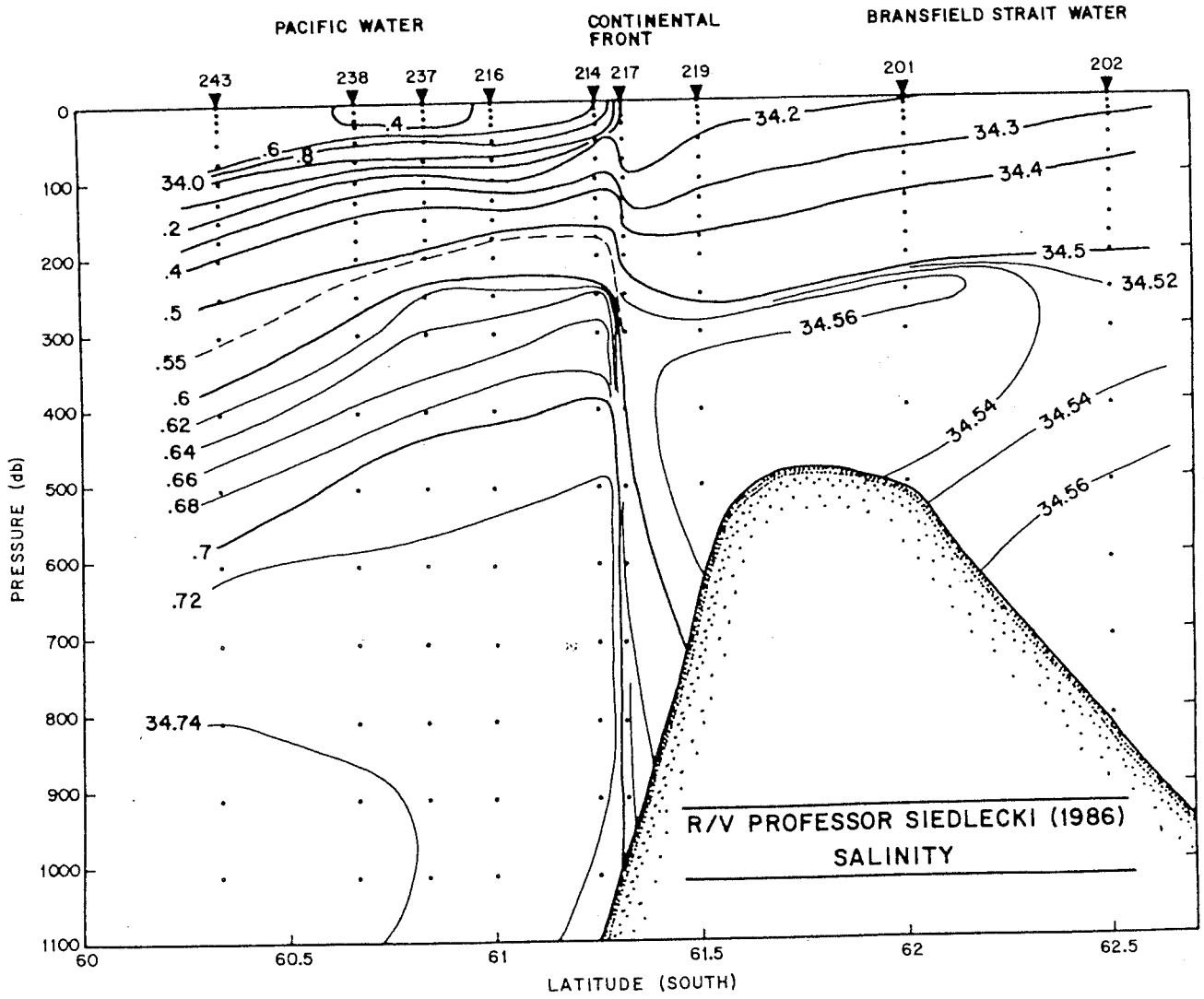

Figure 3b: Salinity section along 57°W

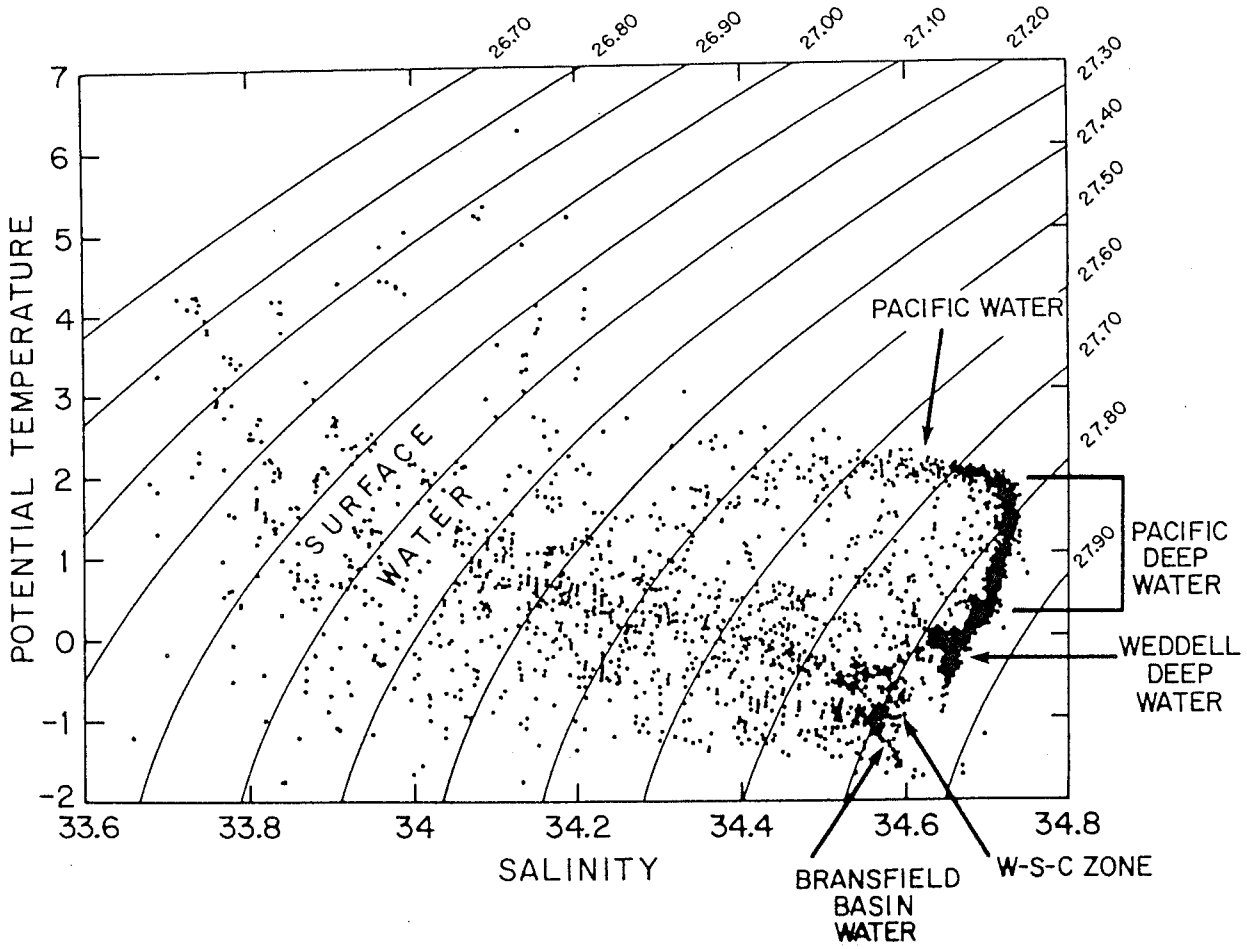

Figure 4: Potential temperature/salinity distribution for the January and February data from the Southern Ocean Atlas for the region : 50°-65°S and 20°-90°W. Various water mass regimes are labelled.

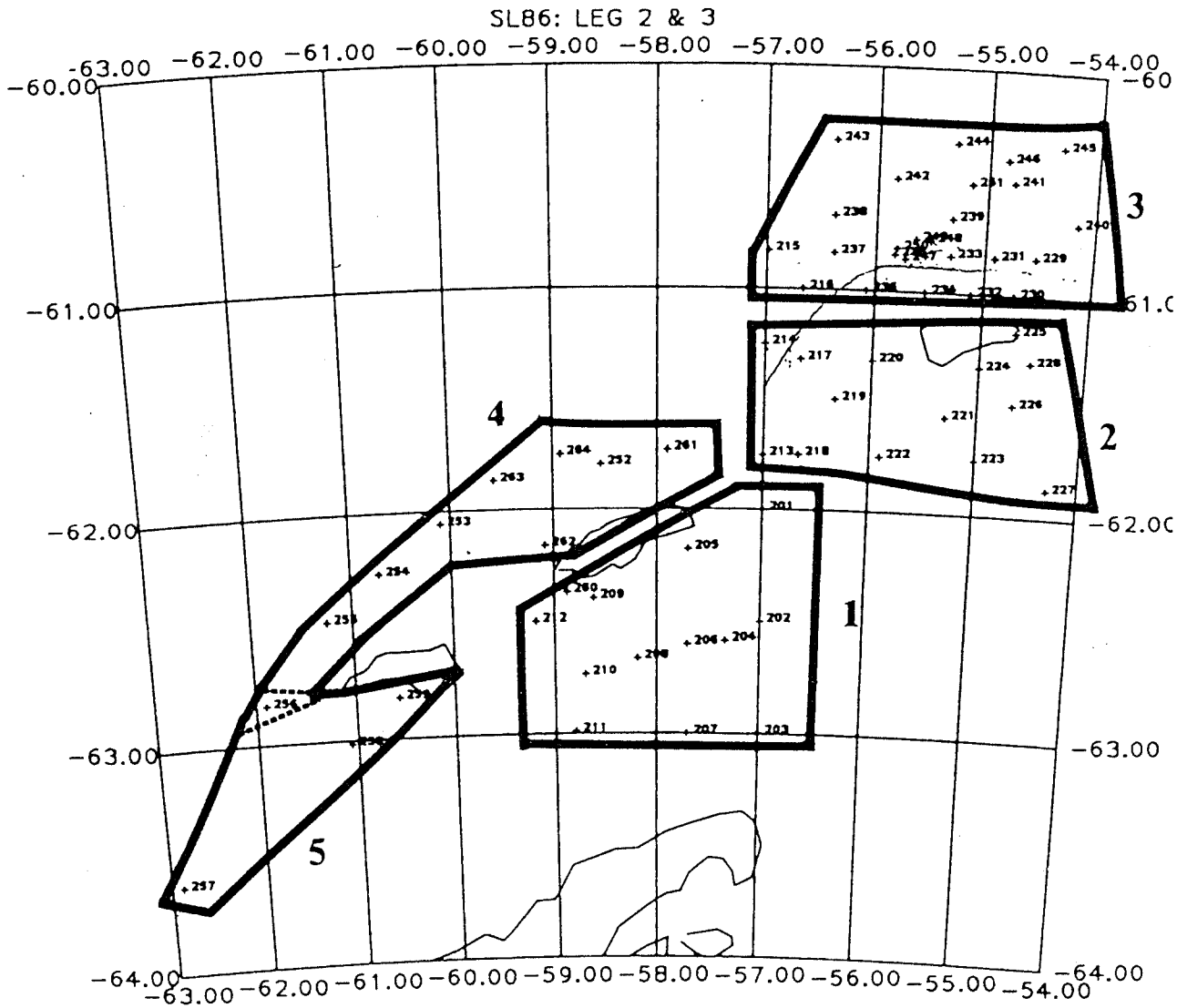

Figure 5: Five groupings of the R/V *Professor Siedlecki* 1986 data in the South Shetland Island region

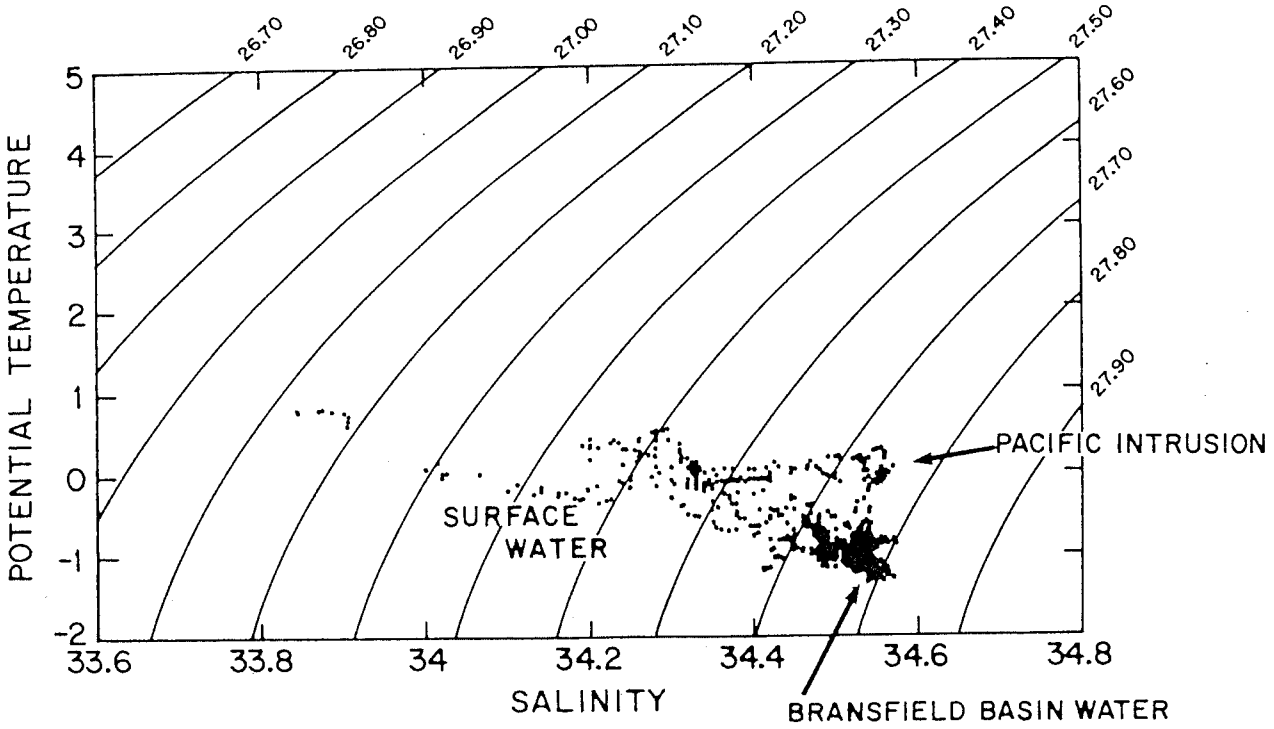

Figure 6: Potential temperature/salinity for area #1 (see Figure 5)

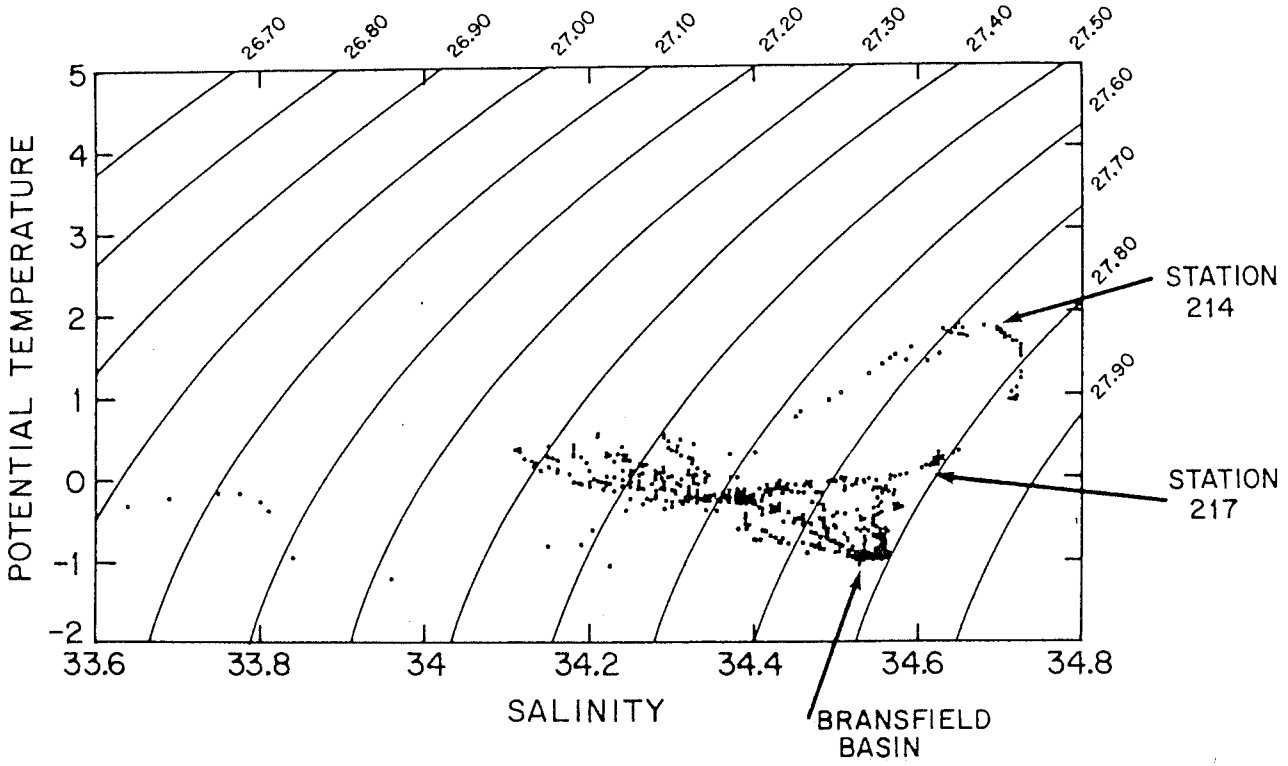

Figure 7: Potential temperature/salinity for area #2 (see Figure 5)

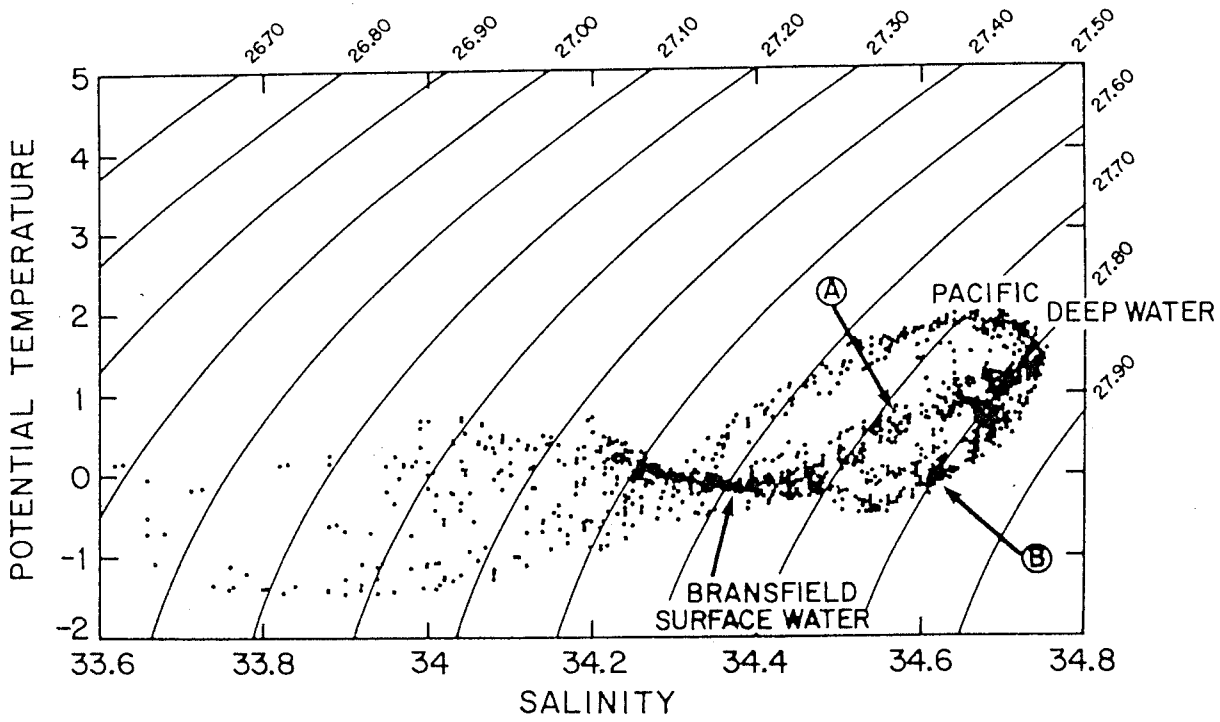

Figure 8: Potential temperature/salinity for area #3 (see Figure 5)

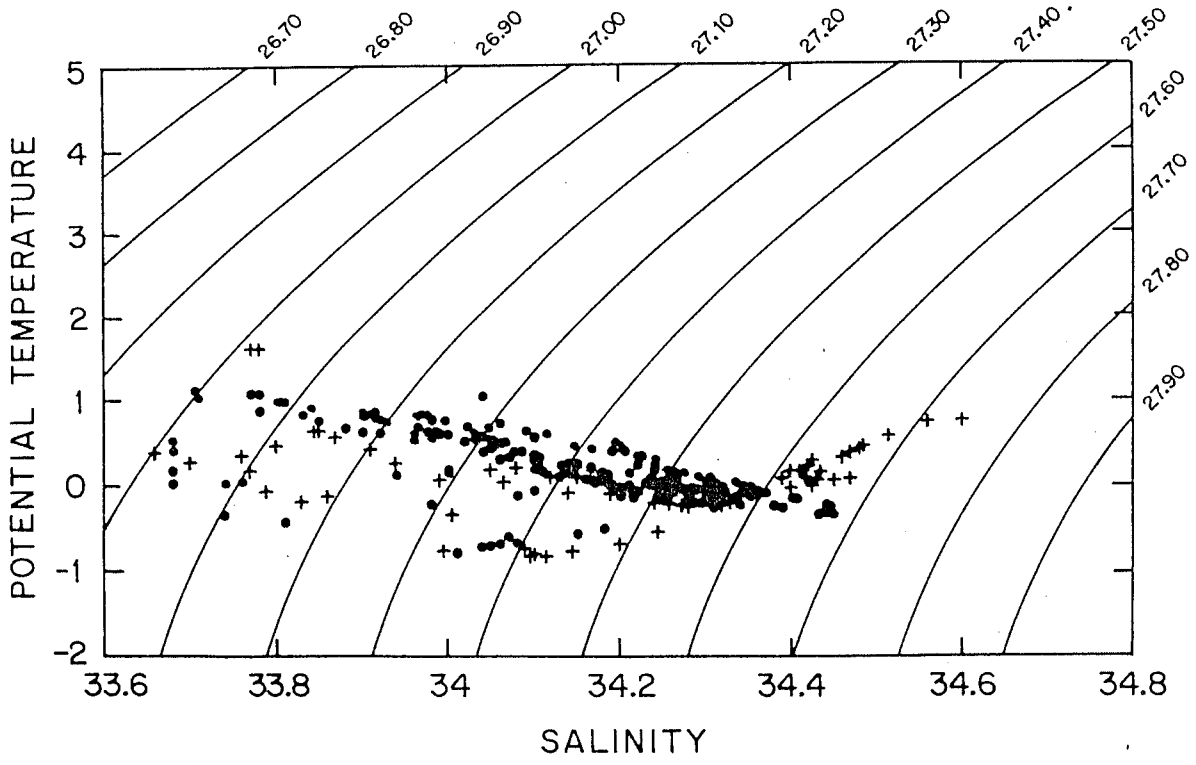

Figure 9: Potential temperature/salinity for area #4 and 5 (see Figure 5).

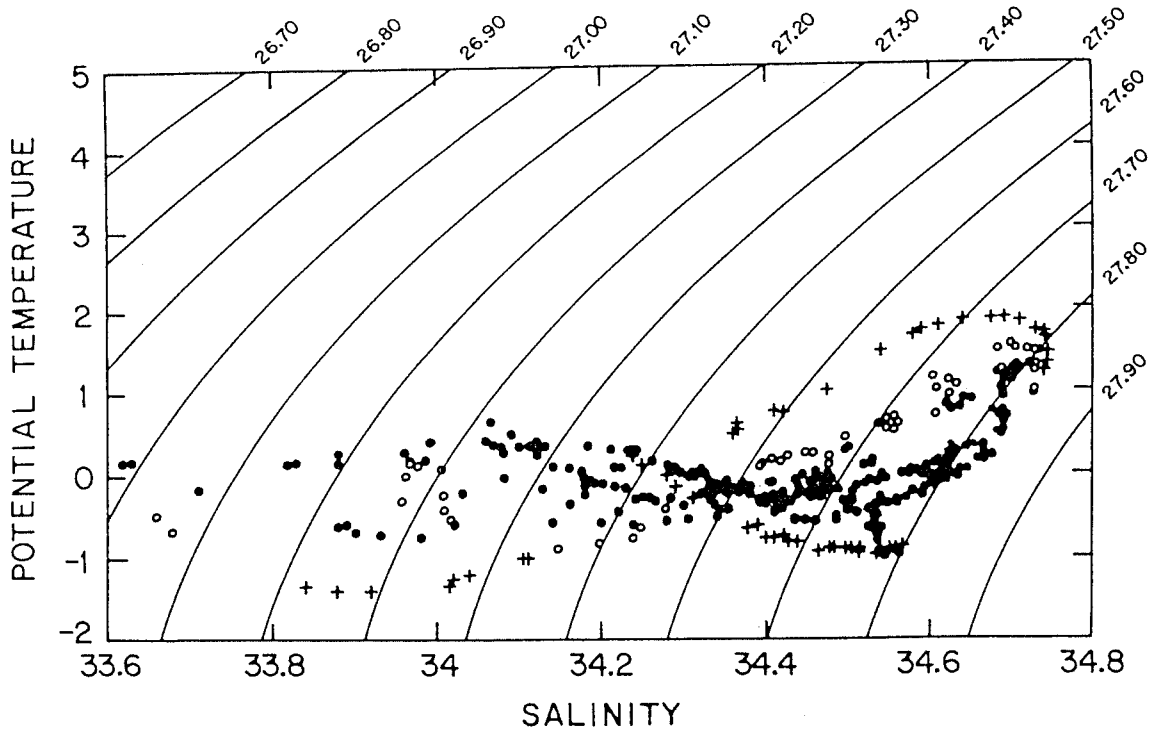

Figure 10: Potential temperature/salinity for stations 217, 226, 231, 235, 236 and 250 (representing stations with the mixture labelled "B" on Group #3 θ/S) shown by •; Stations 223 (Bransfield Strait station) and 244 (Pacific water column station), represented by +; and station 241 (with mixture "A" labelled in group #3 θ/S) represented by ∘ . The type A and B blends appear to be mixtures of Bransfield and Pacific water, products of mixing across the Scotia Front (see Figure 1).

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