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DEEP-SEA RESEARCH
PART I

Enrichment of silicate and CO₂ and circulation of the bottom water in the Weddell Sea

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Abstract

Deep and bottom water from the Enderby Basin, which is strongly enriched in silicate, enters the Weddell Sea off Kapp Norvegia parallel to the coast. However, the bottom water in this region originates from the northern Weddell Sea, indicating a southward return flow of bottom water west of the prime meridian. The eastern Weddell Sea margin was identified as the place where a significant silicate enrichment (at least 15 $\mu\text{mol kg}^{-1}$) and a weak CO₂ enrichment of the bottom water occurs, related to a regional recirculation cell. The deep and bottom water continue their course through the Weddell Sea along the base of the continental slope, where further to the west they are underridden by a thin layer of new, silicate-poor bottom water. A silicate maximum and weak TCO₂ maximum are formed at the interface between deep and bottom water at approximately 4000 m. This silicate maximum occurs in the central Weddell Sea as well. This indicates an exchange of the deep water between the boundaries and the interior of the Weddell basin; the northwestern Weddell Sea was identified as an important site for this. Bottom layer enrichment of CO₂ in the central Weddell Sea (3 $\mu\text{mol kg}^{-1}$) is comparable to that in the eastern Weddell Sea, but silicate enrichment in the former is much less than in the latter. The extent of bottom layer enrichment suggests that about 2% of the primary production reaches the seafloor, supporting the view that the biological pump mechanism in this area is effectively transporting downward a significant amount of CO₂. © 1998 Elsevier Science Ltd. All rights reserved.

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1. Introduction

The circulation and hydrography of the Weddell Sea have been relatively well investigated in comparison with other areas of the Antarctic Ocean due to its significant contribution to the formation of globally spreading Antarctic Bottom Water (e.g. Brennecke, 1921; Mosby, 1934; Foster and Carmack, 1976; Deacon, 1979; Orsi et al., 1993; Fahrbach et al., 1994). The water masses of the Weddell Sea obtain their characteristics from advected source waters that are modified by local processes. The principal source water of the Weddell Sea is the Warm Deep Water (WDW), a descendant of the Circumpolar Deep Water (Deacon, 1933; Carmack and Foster, 1975). WDW is entrained into the surface layer, where it is modified through ocean–atmosphere interactions modulated by sea ice formation and melting. Because of regionally different conditions, several types of surface waters are generated, which under special circumstances are dense enough to sink to the bottom after incorporating a certain amount of WDW (Gill, 1973). This Weddell Sea Bottom Water (WSBW) is produced along the southern and western continental shelves, but is found on most of the bottom of the Weddell–Enderby Basin as indicated by its potential temperature $< -0.7^{\circ}\text{C}$ (Carmack and Foster, 1975; Muench and Gordon, 1995; Fahrbach et al., 1995). The bottom and deep waters of the Weddell Sea are the main precursors of Antarctic Bottom Water, which in turn significantly influences the abyssal characteristics of all world ocean basins (Wüst, 1939; Carmack, 1977).

For the distributions of (particulate) silica/ (dissolved) silicate and carbon dioxide (CO_2) the Southern Ocean takes a special position. A major part of the biogenic silica accumulation of the world oceans occurs in the Southern Ocean (DeMaster, 1981), and the dissolved silicate concentration in the surface waters of the Southern Ocean is among the highest of all oceans. The Antarctic Ocean is among the few oceanic regions where through net cooling of surface waters CO_2 can potentially be absorbed from the atmosphere. Through incorporation during bottom water formation, anthropogenic CO_2 is also sequestered in the abyssal world oceans (Anderson et al., 1991).

Silicate enrichment in the sub-surface waters of the Atlantic sector of the Antarctic has been well known (Carmack, 1973; Van Bennekom et al., 1988). The origin of this enrichment, however, has been a matter of debate. Weiss et al. (1979) contend that all mixing steps in the Weddell Sea are associated with non-conservative silicate increases, while Rutgers van der Loeff and Van Bennekom (1989) pointed to regional differences. According to their findings silicate behaves conservatively during the mixing of recent bottom water into the deep water. In the Enderby Basin extensive opaline sediments are present, and it is clear that the bottom water of this basin is strongly enriched in silicate through input from the sediments. Edmond et al. (1979) therefore stated that the main sub-surface enrichment of silicate in the Weddell–Enderby Basin is caused by contact of the bottom water with the opal-rich sediments of the Enderby Basin. Nevertheless, most of the silicate enrichment in the sub-surface waters of the Weddell–Enderby Basin is caused by redissolution in the water column, as argued by Rutgers van der Loeff and Van Bennekom (1989).

Through cooling the saturation level of CO_2 of the surface waters is reduced. In the Antarctic divergence the large-scale upwelling of CO_2 -rich deep water increases the CO_2 concentration (Weiss et al., 1979; Hoppema et al., 1995), tending to cause over-saturation of CO_2 . In the surface layer CO_2 is assimilated by the phytoplankton. Though most of the organic material thus produced is respired again in the surface layer, a part is carried downward in the water column and remineralized at depth or at the seafloor. In fact, CO_2 is being pumped down in this way; this is the so-called biological pump. The effects of the biological pump on the CO_2 distribution in the Southern Ocean are not known in detail (De Baar, 1994). Notably, the net effect of these three processes determines whether the Weddell Sea is a source or a sink for atmospheric CO_2 .

As the characteristics of the Antarctic Bottom Water of the abyssal oceans are significantly influenced by the bottom water formation in the Weddell Sea and ensuing mixing processes in this basin involving this new water mass, it is essential to know the initial state and (chemical) properties of the bottom water of the Weddell Sea. In this study, which is part of an investigation on carbon cycling in the Antarctic Ocean (Hoppema and Fahrbach, 1995), we present property distributions of the WSBW, which will give insight to the near-bottom circulation pattern of the Weddell Sea. This in turn is relevant for the residence times of the water masses. In addition, we investigate the non-conservative behaviour in the bottom water with respect to silicate and CO_2 , and as a reference also to nitrate. As the non-conservative behaviour is usually biologically mediated, it is also useful as an indicator of the efficiency of the biological pump.

2. Sampling and methods

Data were collected during cruise ANT X/7 of FS 'Polarstern' in December 1992/January 1993 (Fahrbach, 1994) and during a previous cruise leg, ANT X/4, in June/July 1992 (Lemke, 1994). During these two cruises the same equipment was used. Temperature profiles were obtained by means of a NBIS, Mark IIIb conductivity-temperature-depth (CTD) instrument with accuracy 3 mK. Water for the determination of TCO_2 , silicate and nitrate profiles was taken from a 24-place rosette sampler coupled to the CTD.

Silicate and nitrate concentrations were measured on board 'Polarstern' using a Technicon Autoanalyzer-II-System. The methods applied were slightly modified standard techniques (see Kattner and Becker, 1991). Samples were collected in 100 ml polyethylene bottles and were generally analysed immediately after sampling. In a few cases the bottles were kept in the dark at 4°C, but never for longer than 6 h. All samples were analysed in duplicate; the analytical precision was estimated at $0.3 \mu\text{mol kg}^{-1}$ for silicate and $0.1 \mu\text{mol kg}^{-1}$ for nitrate. The accuracy was set by running four standards at the beginning and two standards at the end of each run. For nitrate the results indicate that the spread between different stations is considerably higher than the analytical precision. This is probably due to standardization problems. The given precision of $0.1 \mu\text{mol kg}^{-1}$ holds for all individual nitrate depth profiles, which were measured within one run.

TCO_2 , which is the sum of all inorganic carbonate species dissolved in seawater (identical to DIC, ΣCO_2 and Total Carbonate), was analysed with a slightly modified standard coulometric technique (Johnson et al., 1985; Stoll, 1994: Chap. 2). Saturated mercury-(II)-chloride was added as a preservative to samples from the upper 250 m. All analyses were performed within 24 h, but most within 12 h of sampling. Prior to analysis, samples were stored in the dark. The precision, determined from all duplicates, amounted to $0.85 \mu\text{mol kg}^{-1}$. Standardization of the data of cruise ANT X/7 was done with certified reference seawater (DOE, 1994). For further details on the TCO_2 measurements refer to Stoll (1994).

3. Large-scale distributions

The circulation of the Weddell Sea is dominated by a large, elongated cyclonic gyre. In the west the gyre is bounded by the Antarctic Peninsula and in the east it extends to about 30°E (Orsi et al., 1993). In the latter region the gyre is supplied with Circumpolar Deep Water of the Antarctic Circumpolar Current, which circulates within the gyre in a depth range of about 150 m to 1000–1500 m as the Warm Deep Water. In the southern limb of the Weddell gyre, water is transported westwards in almost all depths (except the near-bottom layers directly affected by bottom topography), turning northwards as it meets the Antarctic Peninsula (Fig. 1). From the tip of the Peninsula, part of it leaves the Weddell Sea to the north, and another part flows to the east, forming the northern limb, which is constrained by topographic features, i.e. South Scotia Ridge and the North Weddell Ridge. The volume transport of the Weddell gyre is 30 Sv, 90% of which is transported by the boundary current (Fahrbach et al., 1994). In the centre of the gyre currents are weak and variable, although some persistent circulation features are reported (Orsi et al., 1993; Fahrbach et al., 1994).

Weddell Sea Bottom Water (WSBW) with $\theta < -0.7^\circ\text{C}$ (Carmack and Foster, 1975), produced along the southern and western margins of the Weddell Sea, is transported towards the east within the northern limb of the gyre, where it can be found at least until 15°E (Orsi et al., 1993). From there it appears to return towards the Weddell Sea in the west, at some point joining the southern limb of the gyre. Orsi et al. (1993) suggest a southward flow of WSBW west of 20°W . Such a feature is also apparent in the water mass lying above the WSBW, the Weddell Sea Deep Water (WSDW), which is present everywhere within the gyre. WSDW is lifted through large-scale upwelling and mixing and has the characteristics of a mixture of the underlying WSBW and the overlying WDW. The circulation of the WSDW is similar to that of the underlying bottom water, but due to its shallower depth it is able to leave the gyre circulation.

A quasi-zonal vertical section between Joinville Island and Kapp Norvegia, closing off the Weddell embayment, is shown in Fig. 2 for potential temperature, salinity, silicate and TCO_2 . General features that are similar for all parameters are revealed, such as the doming of the isolines due to the large-scale cyclonic gyre circulation, and the contrast between surface and deep waters. In the central Weddell Sea (500–1500 km, contoured from the western end of the transect; Fig. 2) the bottom layer

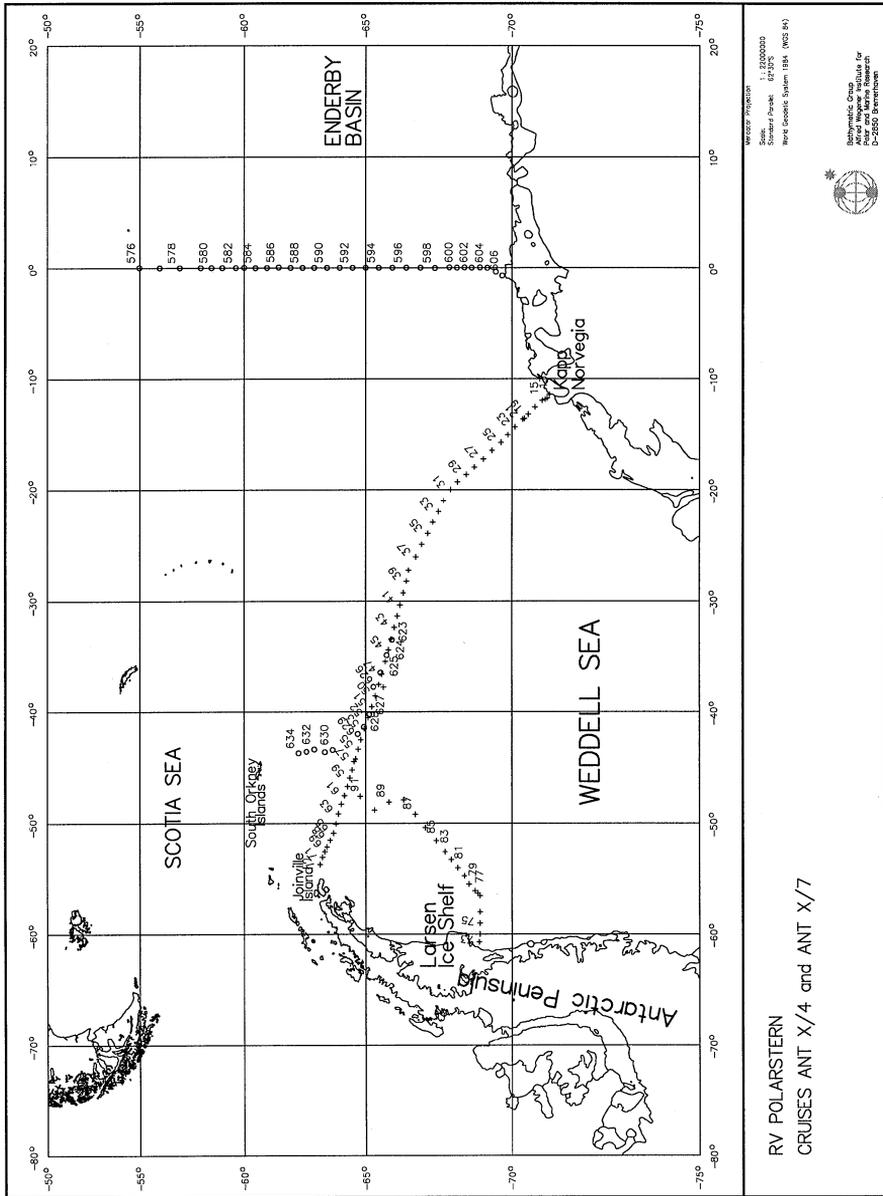


Fig. 1. Map of the Weddell Sea with location of stations and geographical names used in the text. Station numbers > 500 from winter cruise ANT X/4 and numbers < 100 from summer cruise ANT X/7.

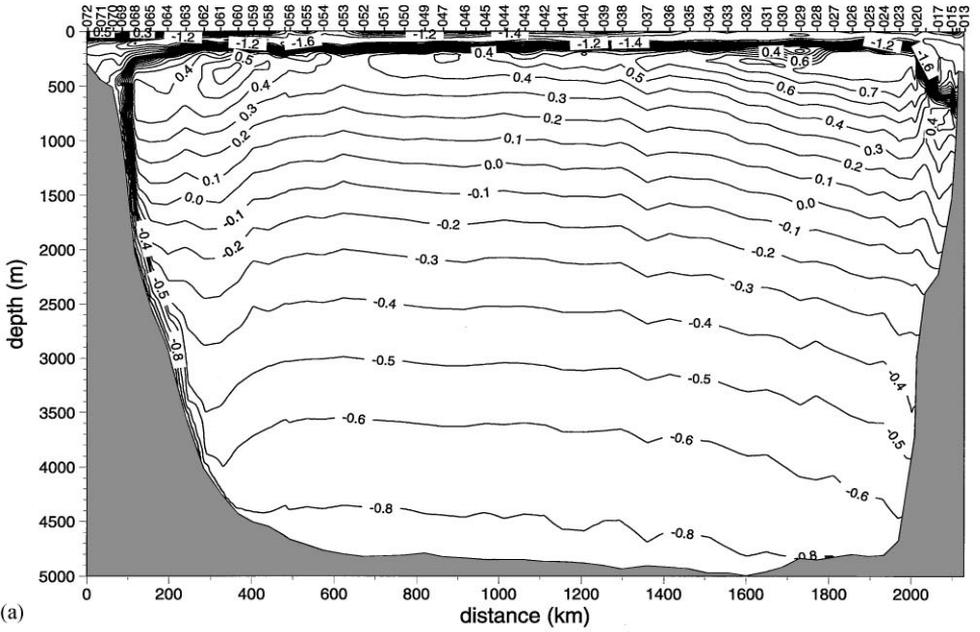
consists largely of Weddell Sea Bottom Water. On the western continental slope some relatively recently produced WSBW can be identified by the coolest temperatures (Fahrbach et al., 1995), also recognizable by its low values of silicate, down to $82 \mu\text{mol kg}^{-1}$, and TCO_2 , down to $2232 \mu\text{mol kg}^{-1}$. The WSBW is relatively low in silicate and TCO_2 because it partly derives from shelf waters, which have the low silicate and TCO_2 concentrations of surface waters (Weiss et al., 1979; Anderson et al., 1991). Underneath the surface layer the WDW is found to a depth of 1000–1500 m, approximately corresponding to the 0.2°C isotherm (Hoppema et al., 1997).

In spite of the general similarity in the distributions of the various properties, there are also some striking differences. Some of these result from the different dynamic ranges in the source water masses (Table 1), e.g., the largest percent change of the silicate values implies that the injection of newly formed bottom water is most evident in the silicate distribution (Fig. 2C). Pronounced differences are also present in the vertical position of the property extrema on the level of the WDW. The shallowest is the temperature maximum, and the salinity, TCO_2 and silicate maxima are deeper in certain areas, although last three maxima do not necessarily correlate with each other. This separation is caused by both physical and biological processes. The WDW stems from the Lower Circumpolar Deep Water, which is characterized by a salinity maximum. Upon entrance into the Weddell Sea this salinity maximum is maintained, where it is found underneath the temperature maximum, the latter forming the upper boundary of the WDW. During the course of the deep water through the Weddell gyre the temperature and salinity maxima weaken due to turbulent mixing. This process would also weaken the TCO_2 and silicate maxima of the WDW, but we observe that these maxima are maintained or even enhanced due to the decomposition of sinking organic material. As the remineralization rates vary for different compounds, the vertical distribution of these compounds will also be dissimilar. Especially, for silicate the processes related to its biological cycling produce conspicuous features in its distribution. Due to accumulation of diatom tests extensive opal layers are formed on the seafloor of the Enderby Basin (DeMaster, 1981), which also causes the bottom water of that area to be much richer in silicate than the bottom water of the remainder of the Weddell gyre (Edmond et al., 1979). The location and magnitude of the silicate maximum is probably also significantly affected by advective processes between the Weddell Sea and the Enderby Basin (Whitworth and Nowlin, 1987; Rutgers van der Loeff and Van Bennekom, 1989).

The deep water layer between 1000 and 4000 m is essentially a mixture of newly formed bottom water and WDW. Surface waters have a low temperature and salinity, and low concentrations of TCO_2 and silicate, whereas the WDW is characterized by considerably higher values of these constituents. In spite of the large range of silicate values in the Weddell Sea water column, its vertical gradient in the deep water is relatively small (Fig. 2C), because the slow remineralization of silicate (Nelson and

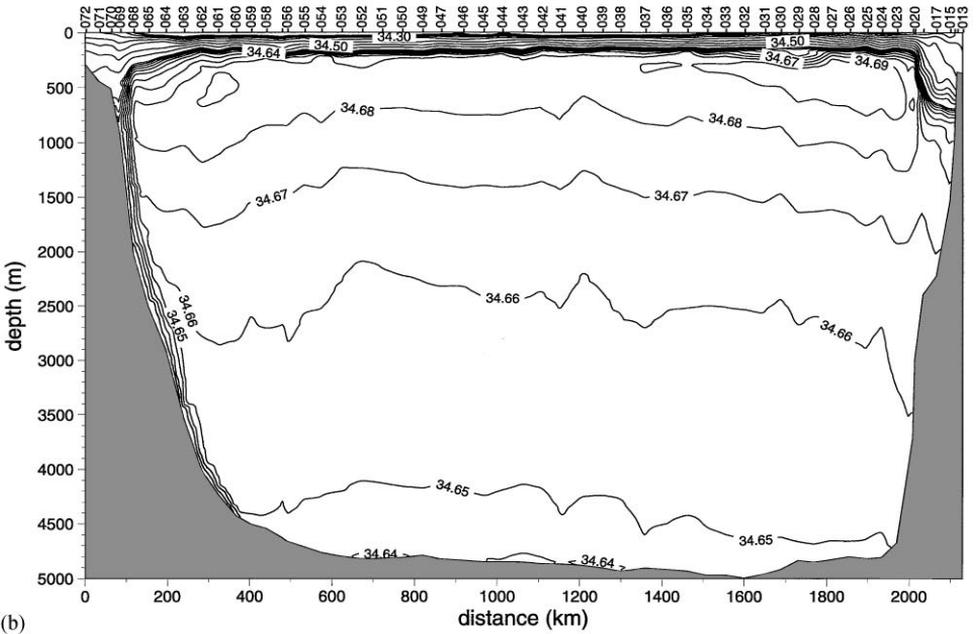
Fig. 2. Sections contoured for (a) potential temperature, (b) salinity, (c) dissolved silicate and (d) TCO_2 across the Weddell Sea between Kapp Norvegia (right) and Joinville Island near the tip of the Antarctic Peninsula (left). Data from summer cruise ANT X/7. In (c) and (d) two areas along the continental slope with high silicate and TCO_2 concentrations in the bottom layer are shaded.

Potential Temperature



(a)

Salinity



(b)

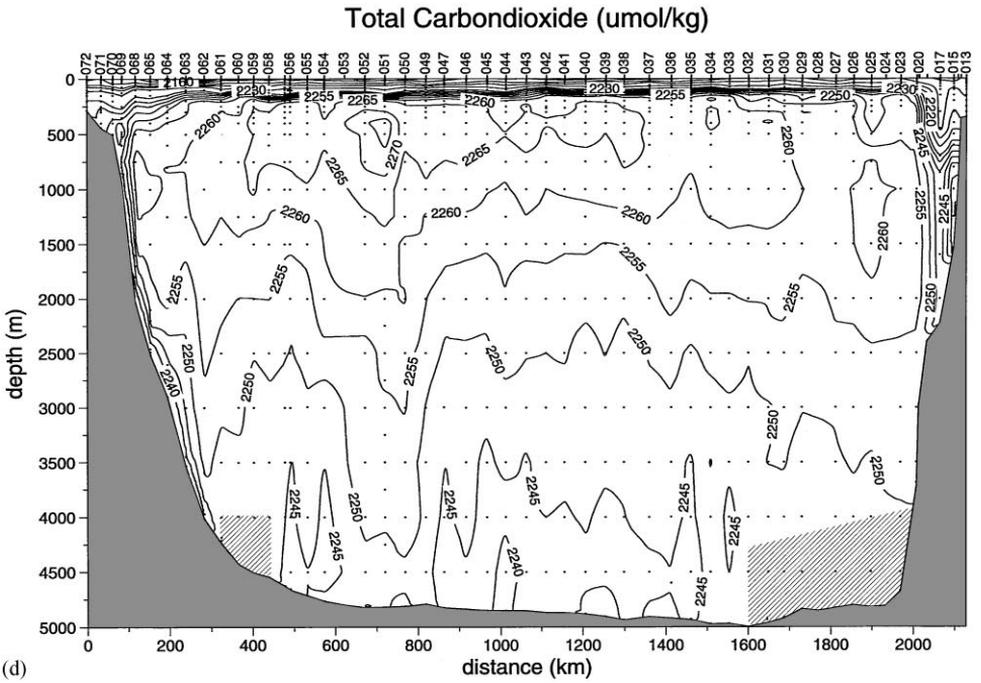
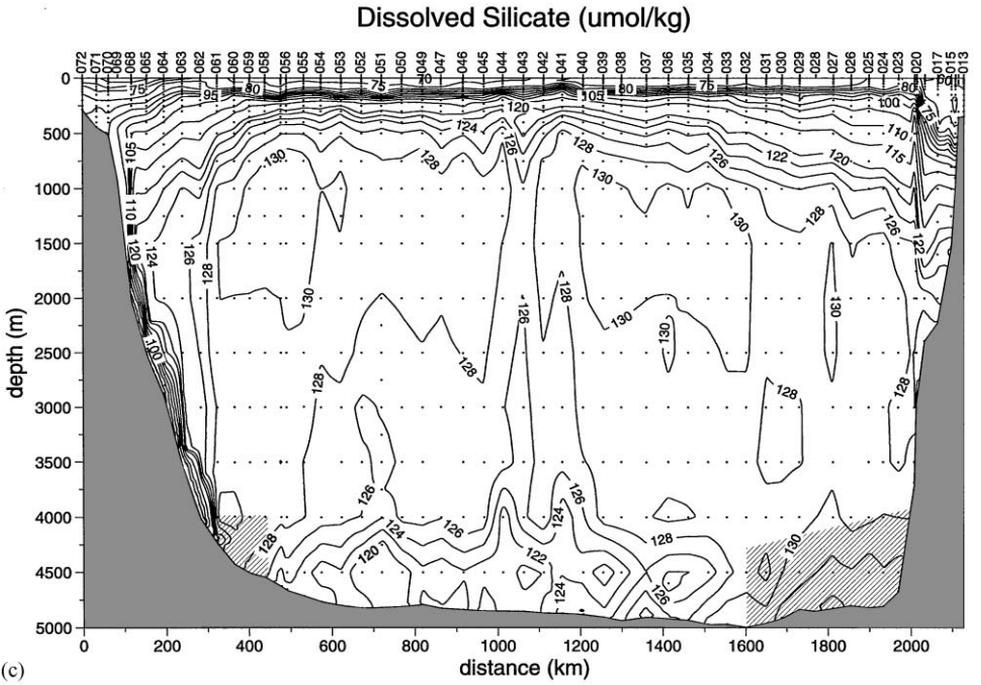


Fig. 2 (continued)

Table 1

Ranges of various parameters in the Weddell Sea. The first part of the table gives the differences between WDW-core and surface layer, and the second part the differences between the maximum and the surface layer

	Surface	WDW-core	Δ absolute	$\Delta\%$	Maximum	Δ absolute	$\Delta\%$
θ ($^{\circ}\text{C}$)	– 1.8	1	2.8	1.0	1	2.8	1.0
Salinity	33.7	34.7	1.0	2.9	34.7	1.0	2.9
Silicate ($\mu\text{mol}/\text{kg}$)	55	100	45	45	130	75	57.7
TCO_2 ($\mu\text{mol}/\text{kg}$)	2100	2255	155	6.9	2275	175	7.7

Gordon, 1982) diminishes the enrichment of it in the shallower layers in proportion to the enrichments in the deeper layers.

4. Bottom water off Kapp Norvegia

In the bottom layer (>4000 m) the silicate concentrations are strikingly higher in the eastern (1600–2000 km; Fig. 2C) and in the western (300–500 km; Fig. 2C) Weddell Sea (shaded regions) as compared to the central part. Also, TCO_2 appears to be higher on these stretches than in the centre (Fig. 2D). In the easternmost bottom water off Kapp Norvegia, silicate attains the highest concentration of the entire section. The θ -silicate scatter plot of these two stretches in the margins of the basin (Fig. 3A) exhibits the fact that all deep and bottom waters have higher silicate values than the source water mass WDW ($\theta > 0.2^{\circ}\text{C}$). The data points of the bottom layer form a separate mixing sequence, with high silicate values, which branches off the deep Weddell mixing sequence at $-0.5/-0.6^{\circ}\text{C}$.

In the θ -property plots for TCO_2 and nitrate for the stretch 1600–2000 km (from the western margin) off Kapp Norvegia (Fig. 3B and C), neither the deep nor the bottom waters comply with the usual linear structure as observed in θ -S diagrams. In fact, the TCO_2 and nitrate data can be described by a similar, though weak, structure as the silicate data. Nevertheless, the interpretation of these diagrams may be quite different than that for silicate. There are two processes that could explain the structure. First, nitrate and TCO_2 enrichment of the bottom water and second, the injection of an additional deep water mass that is low in TCO_2 and nitrate. Which one of the two processes is responsible for the shape of the mixing diagrams (Fig. 3B and C) cannot be established unambiguously due to the lack of the surface water end-member of mixing. (The surface water in the diagrams does not represent the real endmember, because the actual formation of bottom water occurs in another region with other surface water.) The first process can be visualized by drawing a line from the base of the WDW (at about 0.2°C) through the apparently linear part of the diagrams (the thin line in Fig. 3B and C). In this case the bottom water appears to

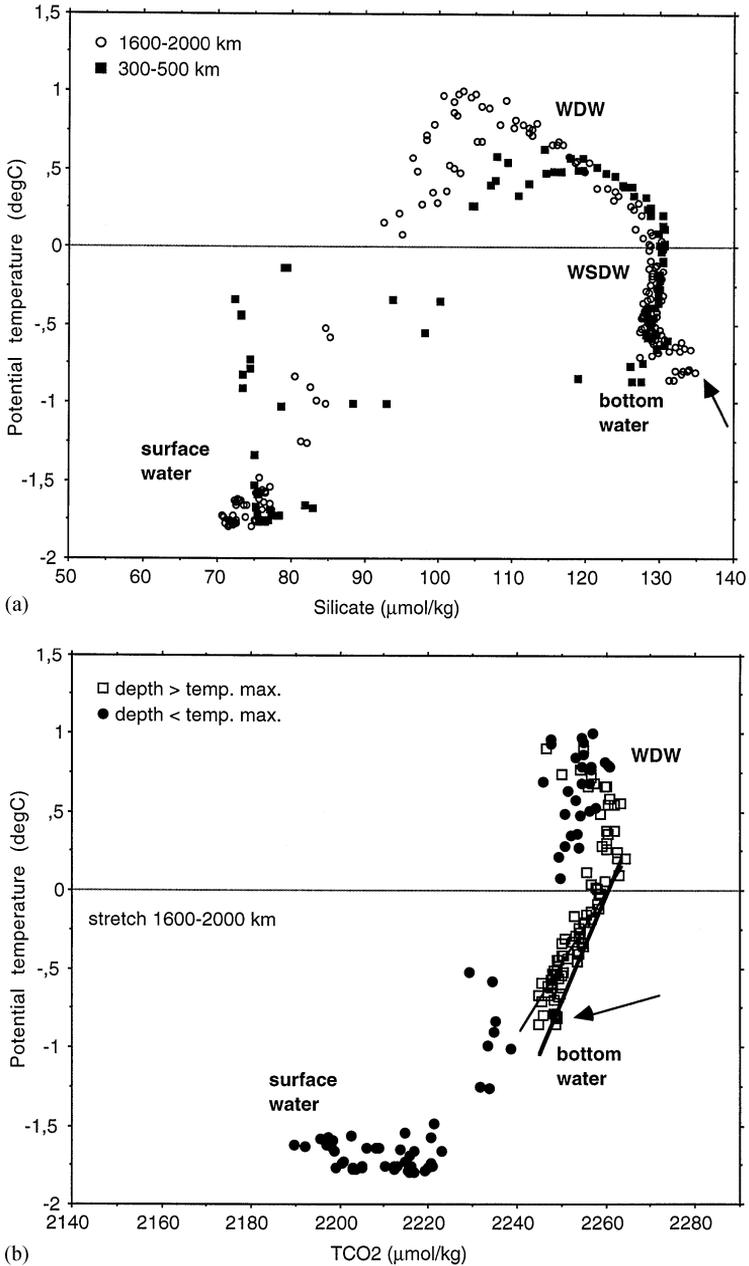


Fig. 3. Scatter plots: (a) Silicate vs potential temperature for two stretches at the base of the continental slope, i.e. over the distances 1600–2000 km (stations 23–32) and 300–500 km (stations 58–61) as shown in Fig. 2. (b) As in (a) except TCO_2 vs potential temperature and only for the stretch 1600–2000 km. (c) As in (a) except nitrate vs potential temperature and only for the stretch 1600–2000 km. Arrows point to the anomalously high property values in the bottom layer, corresponding to the shaded areas in Fig. 2. In (b) and (c) for the thin and the thick line, see the text Section 4.

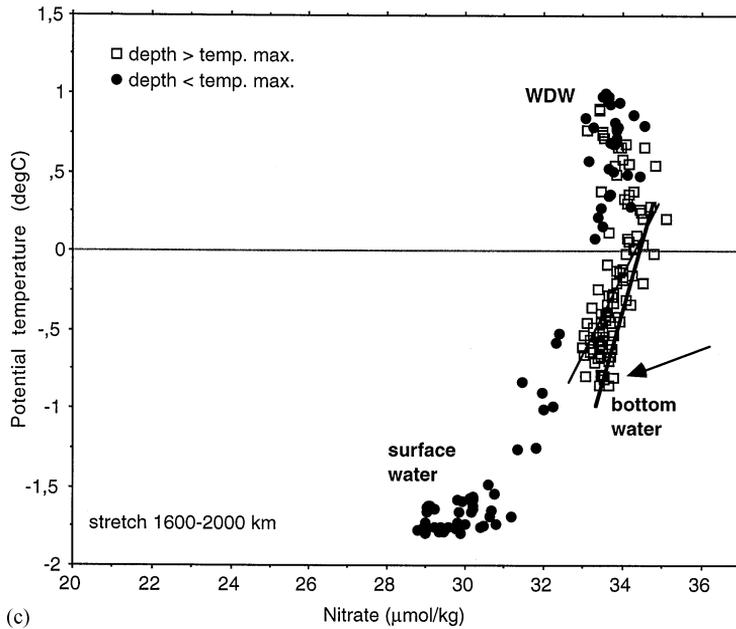


Fig. 3 (continued)

deviate from the mixing line by approximately $5 \mu\text{mol kg}^{-1}$ for TCO_2 and $0.8 \mu\text{mol kg}^{-1}$ for nitrate. The second process is visualized through the assumption that the observed WSBW characteristics should lie on the mixing line between the WDW and a surface water endmember (the thick line in Fig. 3B and C), which represents the usual situation in θ - S diagrams for the Weddell Sea. Then water relatively high in TCO_2 /nitrate is required as the surface water endmember, and an additional water mass with low TCO_2 /nitrate centred at about -0.6°C must be present. This interpretation would be in line with the suggestion by Orsi et al. (1993) of an additional source of deep water, which these authors placed along the continental margin east of the prime meridian. This newly formed WSDW would then have moved parallel to the continent towards the Weddell Sea. If both processes play a role, then the TCO_2 and nitrate enrichments in the bottom layer must be lower than the figures given above.

Bottom water with high silicate values in these regions is usually associated with the Enderby Basin (Edmond et al., 1979). As the Weddell and Enderby circulation are coupled through the cyclonic Weddell gyre, the bottom water of the Enderby Basin can indeed enter the Weddell Basin (Deacon, 1979). The southern limb of the Weddell gyre has principally westward flow and is thus deemed to transport water from the Enderby Basin. The flow is parallel to the Antarctic coastline and enters the Weddell Basin off Kapp Norvegia. This is illustrated in Fig. 4 by high current speeds at this location directed towards the southwest (Fahrbach et al., 1994). That the water with high silicate concentration originates in the east is corroborated by a section further

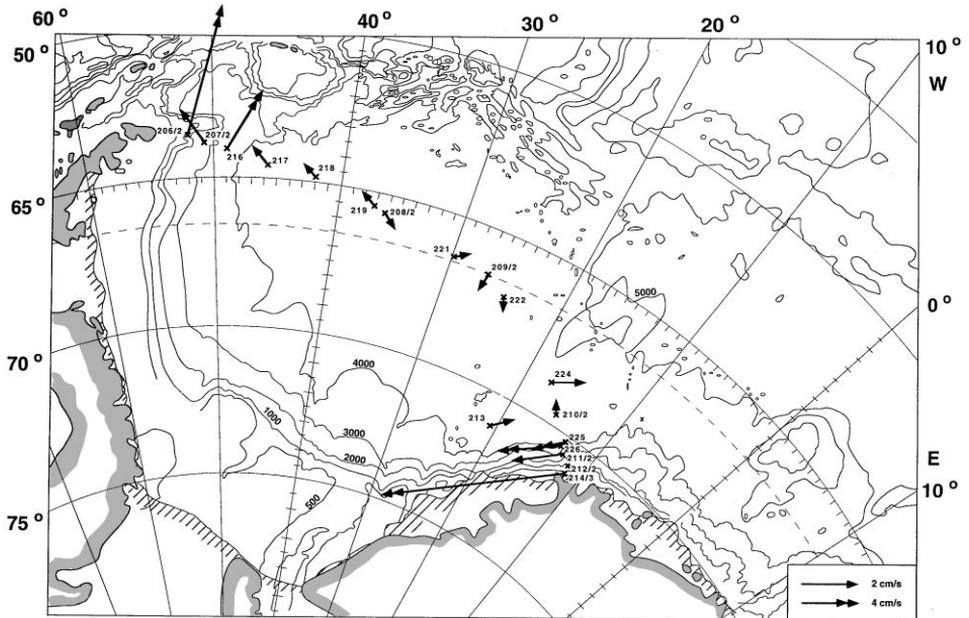


Fig. 4. Mean current vectors about 50 m from the bottom on a transect between Kapp Norvegia and Joinville Island as obtained from current meter moorings. The transect is coincident with that of Fig. 2. Taken from Fahrbach et al. (1994), with permission from Springer-Verlag.

east on the prime meridian (data from the winter cruise ANT X/4; see Fig. 1 for positions), of which the θ -silicate scatter plot is displayed in Fig. 5. In this figure the data are split according to the magnitude of their temperature maxima, whereby the warm regime is the southern limb of the Weddell gyre with westward flow and the cold regime the northern limb with mainly eastward flow. The θ -silicate fields in the bottom range are very different for the northern and southern limbs. On the other hand, the θ -silicate relationships of the warm regime, southern limb stations on the prime meridian and of the high silicate stretch off Kapp Norvegia are very similar, the branching to high silicate values occurring at the same θ of about -0.5°C (compare Figs. 3A and 5).

Despite these similarities (Figs. 3A and 5) the very bottom layer is colder off Kapp Norvegia (about -0.8°C ; marked in the figure) than on the prime meridian (about -0.7°C). This implies that off Kapp Norvegia the bottom water from the southern limb on the prime meridian has been overridden by an additional, colder bottom layer. There are two possible sources of this colder (about -0.8°C) bottom water. Either it is relatively recent bottom water from the Filcher–Ronne ice shelf in the southern Weddell Basin, as conjectured by Fahrbach et al. (1994), or it is bottom water from the northern limb of the gyre, which indeed is colder than -0.8°C . A possible southward flow of this northern limb bottom water is indicated by Orsi et al. (1993: their Fig. 8B) as part of a cyclonic sub-gyre. Based on the regional

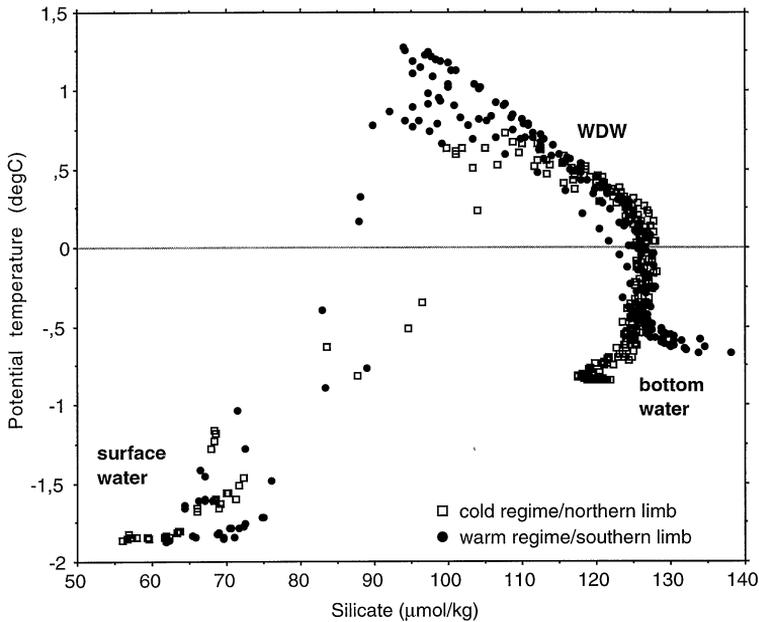


Fig. 5. Scatter plot of silicate vs potential temperature for stations on the prime meridian during ANT X/4. Warm and cold regime was split based on the magnitude of the WDW temperature maximum, i.e. higher and lower than 0.8°C . The cold regime is situated north of the warm regime.

temperature distribution (Fig. 2A), the bottom water off Kapp Norvegia most likely derives from the northern limb of the gyre.

The northern limb derived bottom water flows southwestwards off Kapp Norvegia, but there is also a noticeable bottom current (centred around 1700 km, Fig. 4) with opposite flow direction. This implies that there exists a bottom recirculation cell in this area, which may follow a submarine channel with southwest to northeast orientation. The southwestward flowing bottom water might meet denser bottom water originating from the Filchner–Ronne ice shelf, which to some extent might get admixed. The spatial extent of the recirculation cell is at least 275 km, as inferred from additional current meter data south–southwest of the section (Fig. 4: mooring 213), which are consistent with the northeastward backflow.

Our observation of a markedly high silicate concentration in the bottom layer off Kapp Norvegia, where the highest values of the whole transect were observed, stands in sharp contrast to the relatively low silicate concentration of both of the possible sources of this bottom layer (compare the northern limb stations in Fig. 5). Hence, a strong local source of silicate to the bottom layer in the Kapp Norvegia region is invoked. Measurements and calculations of silicate fluxes from the sediments by Rutgers van der Loeff and Van Bennekom (1989) could support our conclusion. If the bottom water of -0.8°C off Kapp Norvegia is compared with that of the central Weddell Sea with the same temperature, the silicate enrichment in the Kapp Norvegia

area is estimated to be at least $15 \mu\text{mol kg}^{-1}$. The high bottom water enrichment is probably caused by relatively high fluxes from the seafloor but may well be reinforced by the bottom recirculation cell in the Kapp Norvegia region, which may lead to a prolonged residence time of the bottom water in the area.

As touched upon earlier, near the base of the western continental slope another area of high silicate bottom water (300–500 km, Fig. 2C) was observed, being surrounded by WSBW with lower temperature and lower silicate further up the slope and on the abyssal plain. In the θ -silicate field this patch occupies the same space as the high silicate bottom water off Kapp Norvegia, while, in contrast with the deep and bottom water of the central Weddell Basin, the typical high silicate tail is also present (Fig. 3A). This suggests that the water at the base of the western continental slope is an extension of the high silicate water off Kapp Norvegia following the base of the continental slope all through the basin. Note that the bottom water in the west is not as cold and not as silicate-rich as in the Kapp Norvegia region (Fig. 3A). Instead, as seen in Fig. 2C, the high silicate water in the west had been underridden by a thin layer of water with lower silicate concentration, inducing a silicate maximum at 4000 m depth. A weak expression of this silicate maximum is also observed at most other stations in the central Weddell Sea (see Section 5), suggesting that the lower part of the deep water of the Weddell Sea originates from the Enderby Basin (see Figs. 3 and 5), where it is separated from the Weddell Sea long enough to be chemically modified.

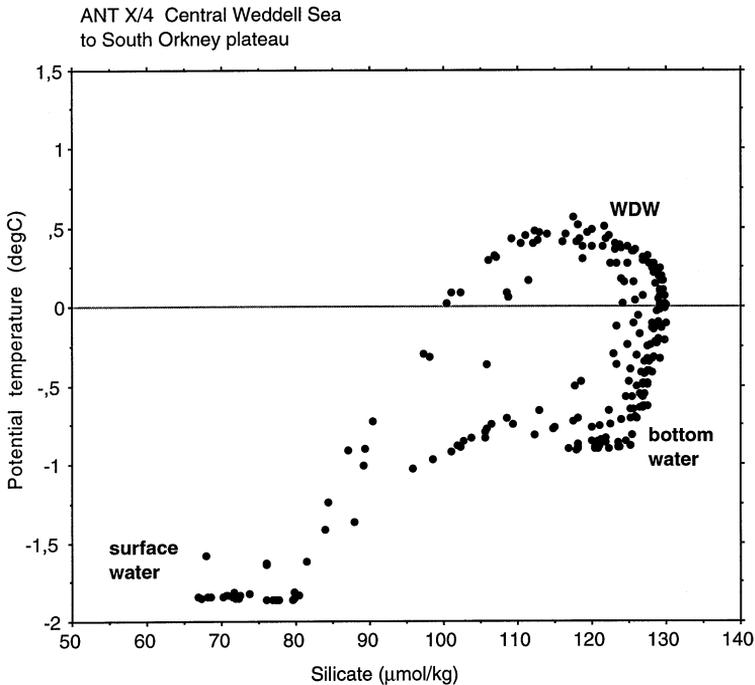


Fig. 6. Scatter plot of silicate vs potential temperature for the winter transect between the central Weddell Sea and the South Orkney plateau (stations 623–632).

In an attempt to track the high silicate water further downstream in the Weddell gyre flow, the θ -silicate plot of a transect between the central Weddell Sea and the South Orkney plateau (stations 623–632 of cruise ANT X/4; see positions in Fig. 1) is presented in Fig. 6. As there is little trace of the characteristic high silicate tail in the bottom water sequence, the lower part of the high silicate water either turned into the central Weddell Sea or was mixed away into the WSDW-layer. This indicates that in the northwestern Weddell Sea the injection of water from the margins into the central part may take place.

5. Bottom water of the central Weddell Sea

In the central Weddell Sea the bottom water is characterized by relatively low concentrations of silicate, TCO_2 and nitrate (Fig. 2). This reflects the low-property signal from the surface water endmember of the WSBW. The fine structure of the bottom water layer is investigated for regional differences by means of vertical profiles of silicate, TCO_2 and nitrate (Fig. 7). On all stations the three properties showed a mutually high degree of conformity in the lower portions of the profiles. This is especially disclosed by the observation that even faint extrema, which are not visible in the vertical sections (Fig. 2), are generally encountered in all property profiles. The discussion of the bottom layer structure will again be based mainly on silicate, because this property is most distinct in this layer (see Table 1).

In the western Weddell Sea (station 83) the influence of newly formed bottom water is evident through sharp gradients in all properties (Fig. 7). In the east off Kapp Norvegia, in contrast, this strong decrease to the bottom is not present (station 29). Silicate even increases monotonically to the bottom, causes of which were discussed in Section 4. In the central Weddell Sea (stations 37 and 55) the transition from the deep water to the bottom water layer at the 4000 m level is identified by a significant decrease of the properties (Fig. 7). It should be added that the fine-structure shown for stations 37 and 55 was observed for almost all stations in the central Weddell Sea. Thus, though weak, these structures appear to be real and permanent. The transition at 4000 m is also evident in the corresponding temperature and salinity profiles (Fig. 8). As a rule, a weak silicate maximum occurs at that depth, accompanied by an even weaker maximum of TCO_2 or nitrate, suggesting that a property-poor bottom layer overrides the deep water layer (possessing characteristics such as observed on station 29). Below 4500 m the vertical gradients in all profiles are reversed (except for temperature and salinity). The fine structure in the bottom layer below 4000 m could be caused by superimposing of different layers of bottom water with a different history, or alternatively, by supply of silicate, TCO_2 and nitrate through the seafloor. Support for water-type layering in the bottom ranges is found in the temperature and salinity profiles (Fig. 8), in which, due to the higher vertical resolution, changes of vertical gradients are discernable. Three different layers of bottom water can be distinguished. Similar bottom layer fine structure has been reported by Carmack and Foster (1975). These authors conjectured that such structures are due to interleaving between bottom water that had been mixed thoroughly over the rugged topography of the South

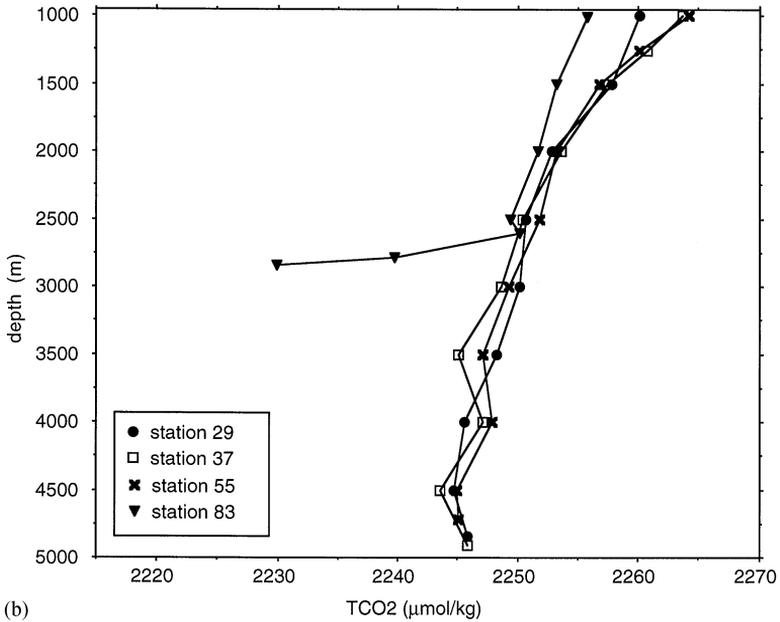
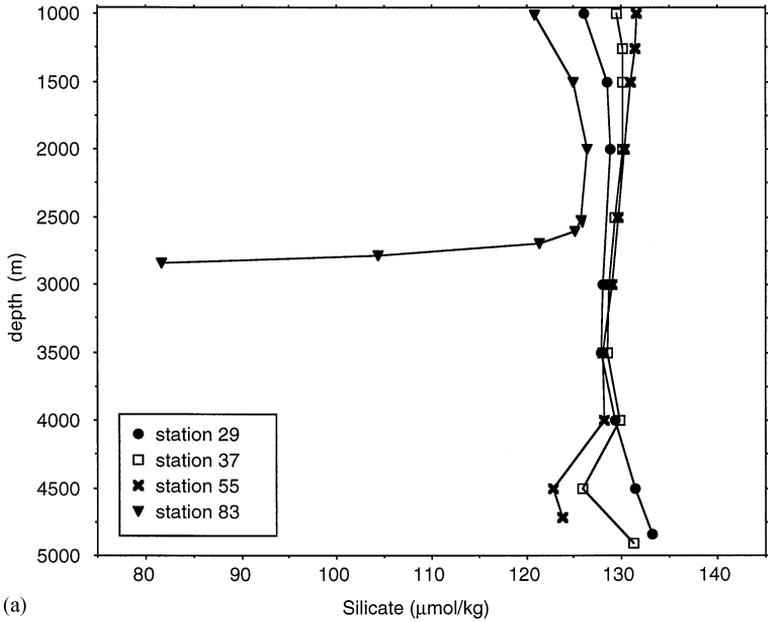


Fig. 7. Vertical profiles for (a) silicate, (b) TCO_2 and (c) nitrate of some stations typical of different regimes in the Weddell Basin.

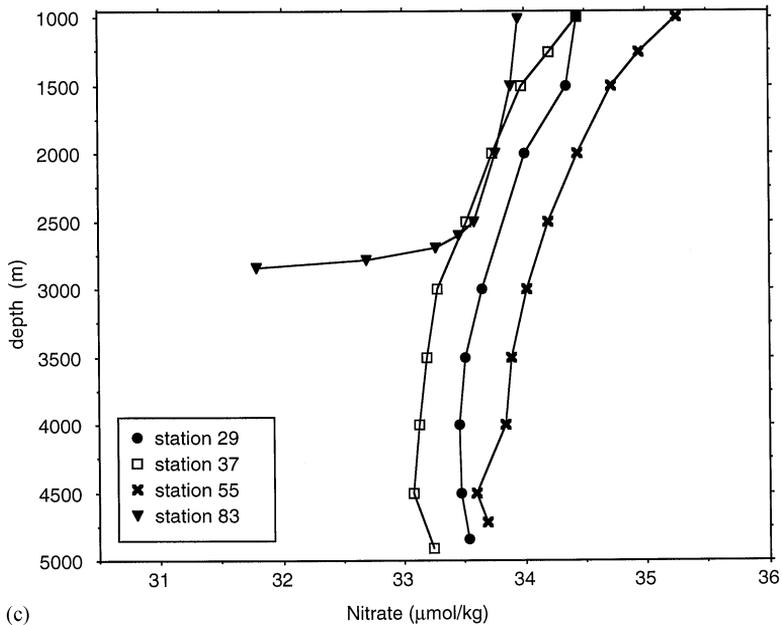


Fig. 7 (continued)

Scotia Ridge and the bottom water of the central Weddell Sea. However, layering is hardly able to explain the inversion of the θ /silicate relation as observed in the deepest layer, where θ and salinity still decrease (Fig. 8), whereas silicate increases. Thus, we conclude that the increases of silicate, TCO_2 and nitrate are predominantly brought about by local contact with the sediments of the central Weddell Sea. Assuming that constant gradients between 4000 m and the bottom would exist when no enrichment through the sediments would occur, the enrichment in the very bottom layer (>4500 m) can be estimated. We have done this for all stations in the central Weddell Sea. The bottom water enrichments thus obtained amount to $7 \pm 3 \mu\text{mol kg}^{-1}$ for silicate ($n = 20$), $3 \pm 2 \mu\text{mol kg}^{-1}$ for TCO_2 ($n = 18$) and $0.3 \pm 0.1 \mu\text{mol kg}^{-1}$ for nitrate ($n = 18$).

6. Discussion and conclusions

The silicate distribution along the margins of the eastern and western Weddell Basin (Figs. 2C and 3A) strongly suggests that there exists an uninterrupted flow of deep and bottom water in a cyclonic sense at the base of the continental slope. Any new plume of bottom water from the southern or western Weddell margins is incorporated into the relatively strong cyclonic boundary current of the Weddell Sea, which reaches to the bottom (Fahrbach et al., 1994). The recently formed bottom

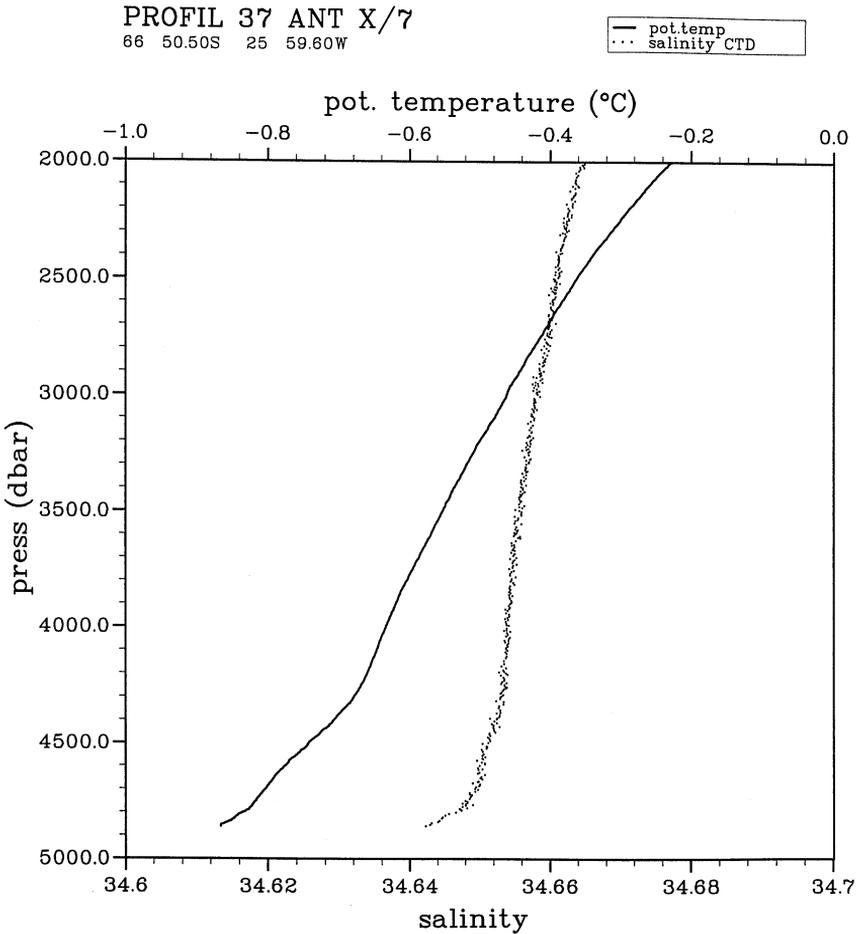


Fig. 8. Near-bottom part of temperature and salinity profiles of the central Weddell Sea showing fine structure.

water, hugging the continental slope and rise well beyond the Antarctic Peninsula, continues its course at the base of the South Scotia Ridge. Part of this recent bottom water turns southwards, thus replenishing the central Weddell Basin. Our data suggest that a branch of this bottom water also reaches the eastern boundary of the Weddell Basin off Kapp Norvegia.

The marked enrichment of nutrients in the bottom water implies relatively large amounts of organic material falling through the water column without being remineralized. A tentative calculation conveys the relative importance of this effect. The mean enrichment in the bottom layer of 400 m thickness being $3 \mu\text{mol C kg}^{-1}$, the total enrichment is $1200 \text{ mmol C m}^{-2}$. Rutgers van der Loeff and Berger (1993) estimated the mean residence time of the water in the Weddell gyre to be 35 years (for the water

in the bottom layer this will likely be less). This residence time yields an annual remineralization rate in the bottom layer of $34 \text{ mmol C m}^{-2} \text{ yr}^{-1}$ (thus to be considered as a lower boundary). The Antarctic primary production being of order $2 \text{ mol C m}^{-2} \text{ yr}^{-1}$ (Smith, 1991), this suggests that at least 2% of the production reaches the bottom layer. The relatively high percentage of organic material reaching the seafloor is indicative of the effectiveness of the biological pump in the Weddell Sea.

The significant enrichment of the bottom layer implies that the organic matter either sinks fast or is relatively resistant to decomposition. Nelson and Gordon (1982) reported that a much larger part of the biogenic silica (opal) leaves the surface layer in Antarctic waters than elsewhere. These authors conjectured that this could be due to the low temperatures in Antarctic waters causing a slow dissolution of biogenic silica. Indications for fast sinking of organic material are found in the observation of the highly episodic character of the vertical fluxes in the Weddell Sea, as documented by Fischer et al. (1988). This means that much organic material produced in the surface layer falls out in one event. Supporting this is the observation of distinct and high maxima of total organic carbon at great depths in the Weddell Sea (Wedborg et al., in press). This suggests that larger amounts not only of siliceous material but also of soft organic matter, i.e. containing carbon and other nutrients, could reach the seafloor. It should be realized that, although a significant part of the organic material may reach the seafloor, a large part will still be remineralized in the water column. This holds especially for opal, through which the silicate maximum in the deep Weddell gyre is shaped (Rutgers van der Loeff and Van Bennekom, 1989). But it also holds for other nutrients and TCO_2 , as expressed in the enhanced maxima of these properties in the Central Intermediate Water (Whitworth and Nowlin, 1987; Hoppema et al., 1997).

As argued above, we expect that a significant remineralization of soft organic material occurs not only in the bottom layer but also in the water column of the Weddell Sea. Considering the extent of these enrichments and the vertical extent of the water column, we conclude that the biological pump is a major agent for redistributing carbon and nutrients through the Weddell Sea. This conclusion is of special relevance for Antarctic waters, because the CO_2 that is brought into the surface layer through upwelling of CO_2 -rich Warm Deep Water would otherwise be released to the atmosphere. It is worth adding that the biological pump of the Weddell Sea is effective in sequestering CO_2 in the deep oceans. This is due to the fact that the CO_2 -enriched deep and bottom waters of the Weddell Sea are transported to the bottom layers of the world oceans, which restrains them from contact with the atmosphere for many hundreds of years.

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