[RADIOCARBON, VOL 31, NO. 3, 1989, P 544–556]

^{14}C PROFILES IN THE CENTRAL WEDDELL SEA

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ABSTRACT. ^{14}C data from stations in the central Weddell Sea are presented and discussed using additional parameters (potential temperature, salinity and ^{3}He). The low ^{14}C concentrations of the surface water (≈–90‰) are explained by suppressed gas exchange due to ice cover during the winter and rapid turnover of the surface layer caused by entrainment of Warm Deep Water (WDW) with low ^{14}C concentrations. A simple time-dependent balance calculated for the Surface Water (SW) and the underlying Winter Water (WW) can reproduce the ^{14}C concentrations observed in these layers for 1985. The pre-bomb ^{14}C concentrations are estimated at ≈–130‰ for SW and –140‰ for WW. A strong deviation of the SW ^{14}C concentration observed in 1973 from the calculated value suggest a change in surface circulation and/or air/sea exchange during the period before the Weddell Polynya in 1974. The observed ^{14}C concentrations of the Weddell Sea Bottom Water (WSBW; –135 to –150‰) are only slightly higher than those of the WDW showing that the uptake of bomb ^{14}C in the Weddell Sea is limited. The ^{14}C profiles show a minimum at intermediate depths (≈1500m) which is caused by radioactive decay and/or penetration of bomb ^{14}C from shallow and deep layers (WDW and WSBW) into intermediate layers.

INTRODUCTION

Bottom water formation in the ocean is restricted to the northern North Atlantic and the area around Antarctica (eg, Warren, 1981). Thus, the polar oceans play an important role in the deep-water circulation of the ocean, and, as deep-water formation leads to an interaction between the cold-water sphere of the ocean and the atmosphere, it also has considerable impact on global climate. In the Southern Ocean, Weddell Sea Bottom Water (WSBW), formed on the southwestern shelves of the Weddell Sea, is an important source of Antarctic Bottom Water (AABW), the southern component of deep water found in the ocean (Brennecke, 1921; Mosby, 1934; Deacon, 1937; Carmack & Foster, 1975a; Foster & Carmack, 1976a). The contribution of other sources like the Ross Sea or the area off Adélie Coast are of minor importance (Gordon, 1974).

Despite the importance of the Weddell Sea for deep circulation, few data exist from this region compared to other parts of the ocean due to the fact that the ice-covered polar oceans are inaccessible. The lack of data holds especially for tracers which, in some cases, require special equipment for sampling large amounts of water only available on a few special research vessels. However, tracers can provide useful information on the time scale of deep-water circulation and on the deep-water formation process and thus have become an important tool in oceanographic studies during the last decades (eg, Broecker & Peng, 1982). Most information on the time scale of deep-water circulation has been derived from ^{14}C measurements of the GEOSECS program (Stuiver & Östlund, 1980, 1983; Östlund & Stuiver, 1980; Broecker, 1981). However, until recently, only near-surface ^{14}C data (depth ≤600m) existed from the Weddell Sea and the ^{14}C concentration of Weddell Sea Bottom Water (WSBW) and Antarctic Bottom Water

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(AABW) was estimated based on mixing considerations (Weiss, Östlund & Craig, 1979). The first profile covering the whole water column was obtained on a cruise of the German research icebreaker, *Polarstern,* to the central Weddell Sea (ANT III/3, Jan–March 1985) using small volume samples measured by accelerator mass spectrometry (AMS) (Schlosser *et al*, 1987). These data showed that in the deep water of the Weddell Sea only small ^{14}C gradients exist and that the ^{14}C concentrations of the waters forming the WSBW are not much changed in the deep-water formation process.

We present here the first large set of high-precision ^{14}C data from three stations in the northern, central and southern Weddell Sea covering the whole water column. Beside determining the ^{14}C concentration of WSBW, the potential of ^{14}C data for studies of the deep-water formation process and ocean/atmosphere exchange is discussed. The data fill the gap in ^{14}C measurements of the southern component of bottom water in the world oceans.

SAMPLING PROCEDURES AND MEASUREMENT

Water samples for ^{14}C measurement by low-level counting were collected on leg two of the fifth cruise of the *Polarstern* to Antarctica (ANT V/2, Winter Weddell Sea Project 86, June–Sept 1986) using stainless steel Gerard-Ewing samplers (volume: 270L; for description of the WWSP program, see Schnack-Schiel, 1987).

Total inorganic carbon and dissolved gases were extracted on board using a vacuum extraction system as follows: The sea water was acidified to pH 2 by addition of hydrochloric acid and sprayed into a vacuum chamber at a flow rate of $\approx$6–8Lmin^{-1}. The pressure in the vacuum chamber was held at water vapor pressure by removing both water and the released gases with pumps. The extracted gases were bubbled through purified NaOH to absorb CO_2 for ^{14}C measurement and, at some stations, the remainder of the gases was collected for ^{39}Ar and ^{85}Kr measurement. Extraction efficiency was $\approx$80–90% for CO_2. Kuntz (1980) described details of the extraction systems.

^{14}C was measured by gas counting on the CO_2 set free in the laboratory by addition of acid to the NaOH solution (Schoch *et al*, 1980; Schoch & Münnich, 1981). The ^{14}C blank arising from the NaOH solution was negligible (on the order of 0.2‰ in $\Delta^{14}C$). The samples were usually measured in two counters for 1/2 week each, leading to a statistical error of $\approx\pm$1.4‰. Additional errors of counter background and efficiency leads to an overall 1σ error of the $\Delta^{14}C$ values of $\pm$2‰. The ^{14}C data are reported as age corrected $\Delta^{14}C$, following Stuiver and Polach (1977). The data refer to the 1983 recalibration of the Heidelberg sodium carbonate substandard to NBS oxalic acid (Kromer, 1984).

The AMS ^{14}C data are taken from Schlosser *et al* (1987) and have a precision of $\approx\pm$8‰ (these data are the result of our first attempt to measure ^{14}C on small volume oceanic water samples; the main emphasis was not on ultimate precision. The Zürich AMS facility can reach a precision of $\approx\pm$5‰ ($\approx$30 min counting time, Kromer *et al*, 1987) or better (increased counting time, Bonani *et al*, 1987)). ^{3}He was measured with a precision of $\approx\pm$0.2% using a $^{3}He/^{4}He$ mass spectrometer (Lynch & Kay, 1981) and is reported as $\delta^{3}He$, *ie,* the per cent deviation of the $^{3}He/^{4}He$ ratio of the sample from an air standard.

OCEANOGRAPHIC BACKGROUND

The basic water mass from which all other waters of the Weddell Sea are derived is the Warm Deep Water (WDW; $0°C<\theta<0.8°C$, Foster & Carmack, 1976b). It is advected from the circumpolar flow into the Weddell Sea and is centered at depths of ≈200–500m. Above the WDW is a two-layer hydrographic system. During winter a mixed layer consisting of cold water with temperatures near freezing (Winter Water, WW) and a mean depth of ≈100m (Gordon, Chen & Metcalf, 1984) is formed. This water is separated from the underlying WDW by a weak pycnocline (Gordon & Huber, 1984). During the ice-free period in summer, a layer of Surface Water (SW) overlying the remnant WW is seasonally warmed and slightly fresher. The remnant WW has potential temperatures of –1.6 to –1.8°C (Foster & Carmack, 1976b), which can be detected throughout the summer by a distinct temperature minimum.

Below the WDW, potential temperature and salinity decrease steadily to reach values below –0.7° and 34.65‰ near the bottom. Water with a potential temperature below –0.7‰ is called Weddell Sea Bottom Water (WSBW) and the waters with potential temperatures below 0°C Antarctic Bottom Water (AABW, Carmack & Foster, 1975a). The WSBW is a mixture of waters on the broad shelves of the southwestern Weddell Sea and WDW. AABW is formed by further mixing of the WSBW with warmer and more saline water.

It is not yet clear which specific shelf-water masses are contained in the WSBW and by which processes WSBW is formed. A process directly observed by current meter measurements is the flow of Ice Shelf Water (ISW) across the sill separating the Filchner Trench from the deep Weddell Sea down the continental slope (Foldvik, Gammelsrød & Tørresen, 1985a,b). ISW is a water mass formed by modification of Western Shelf Water (WSW) due to water/ice interaction under the Filchner Ice Shelf with temperatures below the surface freezing point of sea water and salinities of 34.60–34.70‰ (Carmack & Foster, 1975b). WSW on the shelf west of the Filchner/Ronne Ice Shelves is marked by relatively high salinities (>34.70‰, Carmack & Foster, 1975b) resulting from brine release during sea ice formation. Other processes of WSBW formation may be modification of WDW which flows onto the southwestern shelves and subsequent mixing with cold and relative saline shelf water and some WW (Foster & Carmack, 1976a; Foster, Foldvik & Middleton, 1987). Geochemical data presented by Weiss, Östlund and Craig (1979) agree with the hypothesis that WSBW is a mixture of WW, WSW and WDW.

RESULTS

The ^{14}C profiles obtained during ANT V (stations 234, 266, 317; Fig 1) are plotted in Fig 2A. These data represent the first measurements from a section across the ice-covered Weddell Sea under winter conditions.

One main feature of the profiles that was already observed (Weiss, Östlund & Craig, 1979; Schlosser *et al*, 1987) is the remarkably low ^{14}C concentration of the surface layer, which for ANT V at the time of sampling was already homogenized due to the convective processes of ice formation and

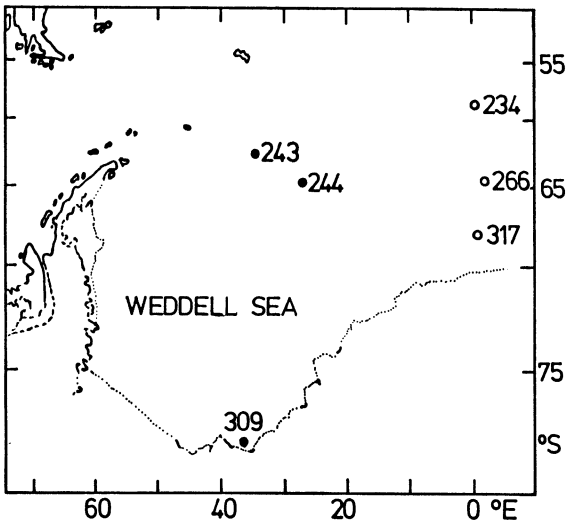

Fig 1. Geographic positions of ^{14}C stations. Open dots: ANT V stations (July–Sept 1986, austral winter); full dots: ANT III stations (Jan–March 1985, austral summer).

consisted of WW (for a description of ice conditions during the cruise, see Casarini & Massom, 1987). The ANT V ^{14}C concentrations of the surface layer vary between ≈–80‰ (stations 234 and 266) and ≈–125‰ (station 317) and span the full range of ^{14}C concentrations of SW and WW at station 243 (Fig 2B) which was occupied on leg 3 of the third cruise of *Polarstern* to Anarctica in austral summer (ANT III/3, Jan–March 1985; for geographic position, see Fig 1).

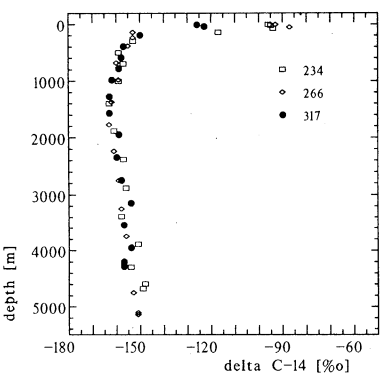

Fig 2A. ^{14}C profiles from ANT V stations.

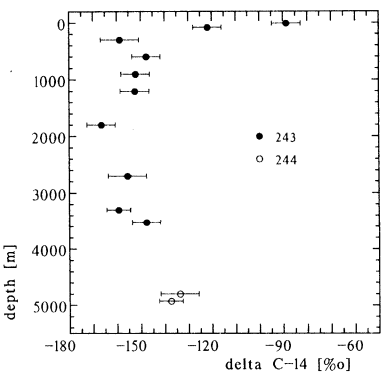

Fig 2B. AMS ^{14}C profile from ANT III station 243 (lower two data points taken from station 244 to extend the profile into WSBW). Samples were measured at the Zürich AMS facility and taken from Schlosser *et al* (1987).

Below the WW, the ^{14}C concentrations decrease to reach an intermediate minimum at depths of ≈1500m (Fig 2A; the ANT III data in Fig 2B agree with this picture but the precision and depth resolution are not high enough to resolve the effect). The difference in ^{14}C concentration between the WDW (≈400–500m) and this minimum is ≈12‰. Below 1500m, ^{14}C concentrations increase steadily to values of ≈–150‰ in the bottom water (max: –149‰ at station 234; min: –156‰ at station 317). At station 243, closer to the source region, ^{14}C concentration of bottom water is ≈–135‰.

The low ^{14}C concentration of WSBW is the second remarkable feature of the ^{14}C distribution in the Weddell Sea. There is a distinct modification of most of the parameters of the shelf-water masses if compared to WDW caused by the ocean/atmosphere exchange and water/ice interaction on the shelves of the southwestern Weddell Sea; this signal is clearly reflected in the WSBW which, to a considerable degree, consists of shelf water. For ^{14}C, concentrations of WSBW fall into a range ≈–135‰ to –150‰ (potential temperature of bottom water at station 317 is above –0.7°C and so it is, by definition, AABW), *ie,* concentrations of WSBW are higher by only 3–18‰ compared to WDW (–153‰ at ≈300m depth), and lower than the value estimated by Weiss, Östlund and Craig (1979) from mixing considerations (–119‰ for WSBW with a potential temperature of –0.9°C).

DISCUSSION

^{14}C distributions will be discussed mainly with respect to the processes leading to the low concentrations in the Weddell Sea. As these data are the first measurements from a large sample set, we will concentrate on qualitative aspects; quantitative treatment will follow once the complete data set is available.

^{14}C in the Surface Layer

The difference in ^{14}C concentration between SW and WW (Fig 2B) is related to the entrainment of WDW into the winter mixed layer due to convective processes caused by brine release during sea ice formation. The entrainment rate is on order of 15–35m year^{-1} (Gordon, Chen & Metcalf, 1984; Schlosser, Roether & Rohardt, 1987) which leads to a turnover time of the mixed layer due to entrainment of WDW of ≈3–7yr. During entrainment, the ^{14}C concentration is decreased due to the low ^{14}C content of WDW. Only after the ice is melted in summer does the ^{14}C concentration of the newly formed SW increase by exchange with the atmosphere, leading to a difference in $\Delta^{14}C$ between SW and WW on the order of ≈30‰ (see below). Variations of the ^{14}C concentrations of the WW at the ANT V stations might be due to the different duration of ice cover at the time of sampling and related variable entrainment rates.

To check if the observed ^{14}C concentrations can be reconstructed based on atmospheric ^{14}C concentrations and present oceanographic knowledge on the dynamics of near-surface water layers, a simple time-dependent balance is calculated. We treat the upper water layer from the surface down to the mean depth of the WW (≈100m) as a reservoir containing ≈215mols total inorganic carbon (TIC)/m^2. The ^{14}C concentration of this reservoir is changed by

exchange with the atmosphere in summer (assuming a 6 month ice-free period) and by entrainment of WDW in winter under ice cover. For the exchange process in summer, we assume partial re-equilibration of a 50m thick layer of SW with the atmosphere by exhange at ≈25mols CO_2 m^{-2} $year^{-1}$ (Weiss, Östlund & Craig, 1979; Broecker *et al*, 1985) leading to a TIC renewal time in the water layer by atmospheric CO_2 of ≈4yr. The entrainment rate of WDW is chosen as 33m yr^{-1} (Gordon, Chen & Metcalf, 1984; Schlosser, Roether & Rohardt, 1987), and the ^{14}C content of the WDW is assumed constant (–158‰). The atmospheric $\Delta^{14}C$ concentration as a function of time for the period 1959–1979 is taken from Levin, Münnich and Weiss (1980). The 1985 value of 200‰ is taken from Levin *et al* (1987) and 1979–1985 data are obtained by linear interpolation. For the period before 1959 a linear interpolation between –20‰ (1949) and 150‰ (1959) is applied (Fig 3A). As the calculation is a rough estimate, a constant value for TIC in different water masses is assumed (the same holds for mixing, discussed below).

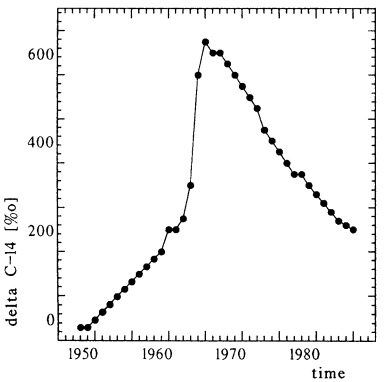

Fig 3A. Atmospheric ^{14}C data used in calculating the ^{14}C concentration of SW and WW as a function of time. For explanation, see text.

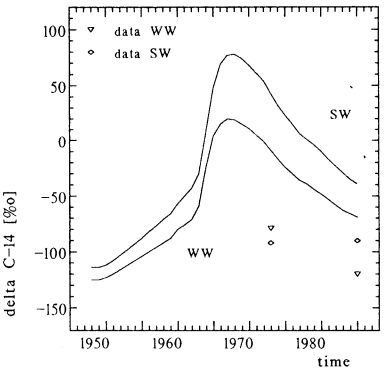

Fig 3B. Calculated ^{14}C concentration of SW and WW as a function of time. The time constant for carbon exchange of the SW is set to 4 yr and the entrainment rate of WDW into the winter mixed layer to 33m yr^{-1}.

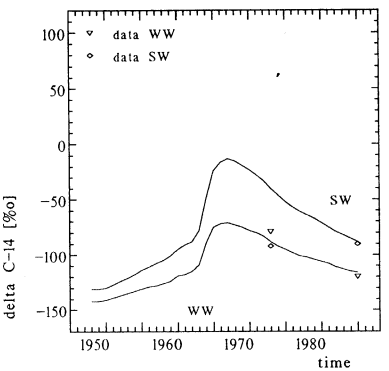

Fig 3C. Same calculation as for Fig 3B using a carbon exchange time constant of 5 yr and an entrainment rate of 50m yr^{-1}.

Calculation results show the influence of bomb ^{14}C on both SW and WW (Fig 3). Calculations with a time constant for carbon exchange of 4 yr and an entrainment rate of 33m yr^{-1} (Fig 3B) yield ^{14}C values for 1985 that are too high compared to the measurements (–39‰ for SW compared to –90‰ observed at station 243; –69‰ for WW compared to –120‰; see Fig 2B). The calculated values can be adjusted by varying both the atmospheric ^{14}C input and the entrainment rate of WDW. The time constant for CO_2 exchange is sensitive on the absolute ^{14}C concentration of the SW and the entrainment rate adjusts the difference in ^{14}C concentration between WW and SW. Taking values of 5yr for the CO_2 exchange time constant and increasing the entrainment rate to 50m yr^{-1} leads to calculated ^{14}C concentrations of SW and WW which fit the 1985 data reasonably well (–88‰ for SW and –116‰ for WW; Fig 3C). The required increase of the entrainment rate is interpreted as consequent to the fact that parts of the Weddell Sea are perennially ice covered resulting in lower ^{14}C concentrations of SW due to suppressed gas exchange. Lateral mixing with such water would result in an addition of water with low ^{14}C concentration, for which we have compensated by an increased WDW entrainment rate.

The calculated data cannot fit ^{14}C data from SW samples collected in 1973 (Weiss, Östlund & Craig, 1979). The calculated value for WW (–88‰) reasonably agrees with the data (–79‰) but the calculated value for SW (–40‰) is higher by 52‰ compared to the experimental data (–92‰). As atmospheric ^{14}C concentrations are well known and ^{14}C content of WDW has not changed (–158‰ in 1973; Weiss, Östlund & Craig, 1979; –153‰ (300m depth) to –158‰ (500m depth) in 1986), the explanation might be a change in circulation pattern of upper water layers and/or air/sea exchange rate. This change may be related to the appearance of the Weddell Polynya (1974–1976) which was accompanied by a cooling of the WDW (Gordon, 1982) indicating changes in the circulation pattern of upper water layers.

The ^{14}C balance can be used to estimate the pre-bomb ^{14}C concentrations of SW and WW. Assuming the parameters of the calculations in Fig 3C, $\Delta^{14}C$ values of ≈–131‰ for SW and –142‰ for WW are obtained. These values are calculated for a constant atmospheric $\Delta^{14}C$ concentration of –20‰ and for steady-state conditions of the circulation pattern which are an oversimplification of the system. The real ocean is much more complicated, but the calculations give a rough first-order estimate of ^{14}C concentrations found in the upper water layers of the Weddell Sea in the pre-bomb era. Although a comparison of the estimated values with the measurements of Rafter and O'Brien (1973) is difficult due to the different hydrography, there is reasonable agreement with the pre-bomb values measured in the South Pacific (≈60°S) and those estimated here for the Weddell Sea. This shows that in the Southern Hemisphere the high latitude surface ^{14}C concentrations are relatively low due to oceanic circulation patterns.

^{14}C in the Deep and Bottom Water

The intermediate ^{14}C minimum (Fig 2A) has not been observed in the profiles of the 'stable tracers' potential temperature (Fig 4), salinity (Fig 5) and ^{3}He (Fig 6). All these tracers have maxima in WDW. Therefore, the

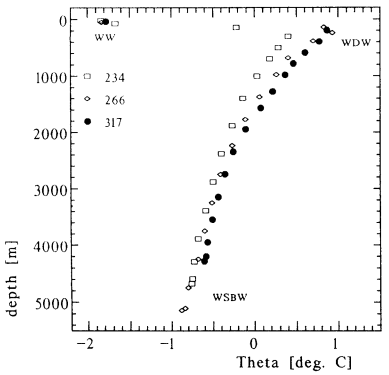

Fig 4A. Potential temperature profiles – ANT V stations

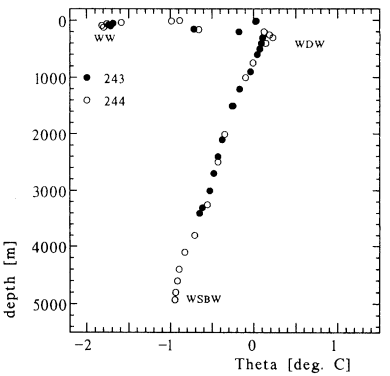

Fig 4B. Potential temperature profiles – ANT III stations

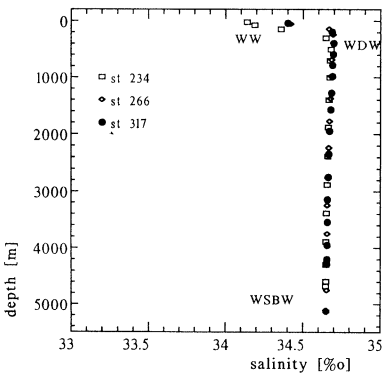

Fig 5A. Salinity profiles – ANT V stations

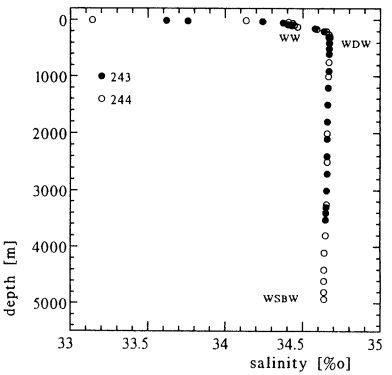

Fig 5B. Salinity profiles – ANT III stations

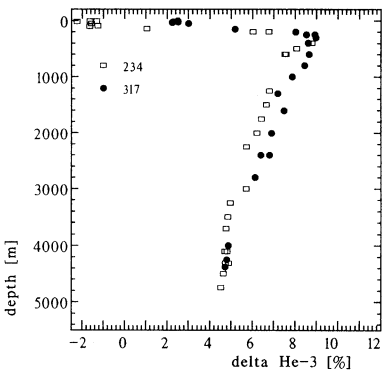

Fig 6. ^{3}He profiles of the ANT V stations 234 and 317

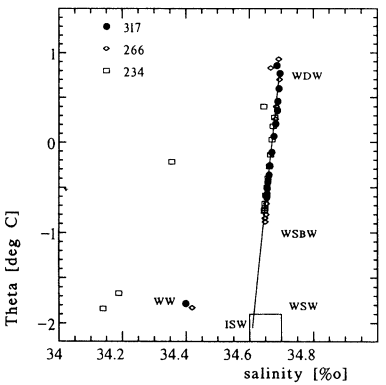

Fig 7A. Potential temperature *vs* salinity plots – ANT V stations. The mixing line between WDW and WSBW is extrapolated to a temperature of –2.05°C. WSW marks the θ/S characteristic of WSW. The θ/S characteristic of ISW is indicated.

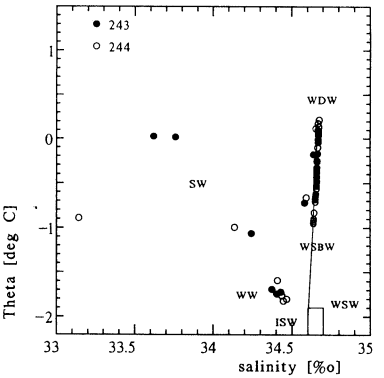

Fig 7B. Same as Fig 7A for ANT III stations

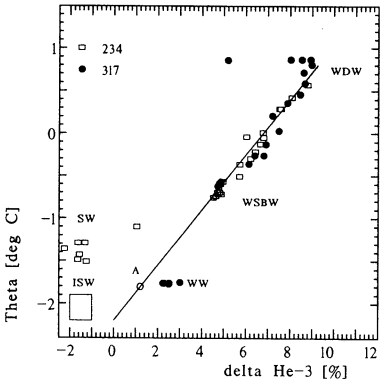

Fig 8. δ^3He *vs* potential temperature plot for ANT V stations 234 and 317. The values for ISW are taken from Schlosser (1986). A indicates the shelf water necessary to produce WSBW by mixing with WDW.

higher ^{14}C concentrations observed in the WDW, if compared to the depth range centered at ≈1500m, must be caused by downward penetration of bomb ^{14}C or by radioactive decay. The two processes cannot be separated without using tritium as indicator for the bomb ^{14}C component. Our first tritium measurements show similar depth profiles indicating that at least part of the structure of the ^{14}C profiles is caused by the bomb component. A final evaluation of the ^{14}C distribution with respect to its potential to derive mean residence times for the intermediate waters has to wait until the final tritium data are available.

From property *vs* property plots of the stable tracers, it is evident that the deep waters found in the depth range between WDW and WSBW are a mixture of WDW and a second end member which was not sampled for ^{14}C but which is known to be a cold water mass originating in the southwestern shelf region (θ/S plot: Fig 7; θ/^{3}He plot: Fig 8). This end member is a mixture of different water masses formed and/or modified on the shelf, and this relatively complicated and poorly understood process seems to produce waters with similar θ/S and θ/^{3}He characteristics near those of ISW (Fig 7,8).

The θ/^{14}C plots (Fig 9) do not show a linear mixing line between WDW and WSBW but a deviation to lower ^{14}C concentration for the intermediate depth range with lowest values for potential temperatures of ≈–0.2°C (Fig 9A). This deviation is caused by the transient bomb ^{14}C component or by radioactive decay, as all the intermediate waters below WDW are formed in the Weddell Sea (the potential temperatures observed in Drake Passage, the source region for the water advected into the Weddell Sea are above 0°C throughout the water column; Nowlin & Clifford, 1982). To evaluate this signal the ^{14}C concentrations of the end members involved in the formation of WSBW and the bomb contribution to the observed ^{14}C distribution have to be known. As almost no ^{14}C data from the southwestern shelf are available, the following is more a discussion of ideas than facts.

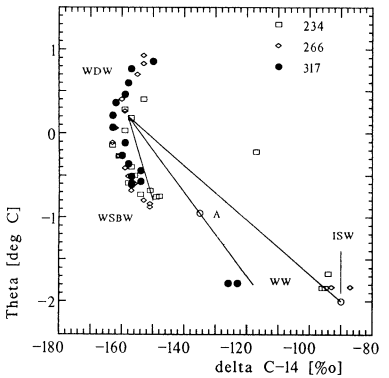

Fig 9A. $\Delta^{14}C$ *vs* potential temperature plots – ANT V stations. The data point for ISW is taken from ANT III station 309 located at the front of the Filchner Ice Shelf (see Fig 1). A indicates the ^{14}C concentration of the WSBW found at ANT III station 244.

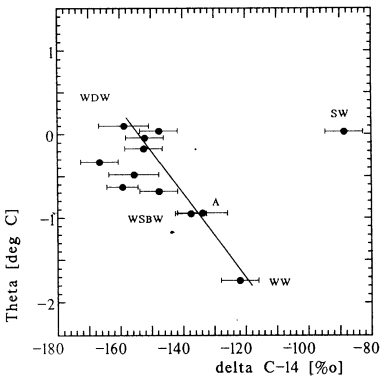

Fig 9B. Same as Fig 9A for ANT III data

We assumed that the bottom water is renewed on a short time scale of some years and that the admixed WDW is relatively cold (0.2°C) as observed at stations 243 and 244 in the northwestern Weddell Sea (Fig 4), *ie,* closer to the source region than the ANT V stations (234, 266, 317; Fig 1). In this way, the extrapolated mixing line in the θ/^{14}C plot (Fig 9B) drawn between WDW and the WSBW found at station 244 (indicated by A) leads to a ^{14}C concentration of the required shelf water component of ≈–120‰, which is lower than the ISW concentration observed so far (Fig 9A). This indicates that ISW

is not the only shelf water mass involved in the formation of WSBW, as could be derived from θ/S considerations (Fig 7). This view is consistent with the ^{3}He data. The θ/^{3}He plot suggests that the shelf water component should have somewhat higher ^{3}He concentrations as those observed in ISW (Fig 8).

The ^{14}C concentrations of the WSBW at stations 234 and 266, *ie,* further east in the Weddell Sea are even lower than those as station 244. This could be caused by different shelf water masses involved in the WSBW formation with relatively low ^{14}C concentrations due to formation/modification of water under partial ice cover which allows helium loss and modification of temperature and salinity but almost no re-equilibration of ^{14}C. An alternative process could be aging or admixture of bottom water from regions outside the Weddell Sea. A definite answer to this question cannot be reached with the present data set.

CONCLUSIONS

Our ^{14}C data show that characteristic effects of the Weddell Sea (low concentrations in the surface layer and WSBW) can be related to oceanographic processes and ice conditions. At present, a rough picture of ^{14}C distribution can be drawn but many features are still unresolved and need further specific sampling, especially in shelf regions where WSBW is formed. We must interpret ^{14}C data together with classical (T/S) and/or geochemical parameters (beside tritium and ^{3}He a suite of other tracers could be applied). ^{39}Ar measurements, which are presently made at the University of Bern (Loosli & Weppernig, pers commun, 1989), should be a most valuable parameter in a more detailed discussion of measured ^{14}C distribution. On the basis of adequate data sets, ^{14}C is a valuable tracer for studies of oceanographic processes and air/sea exchange processes.

ACKNOWLEDGMENTS

The contribution of the following individuals is gratefully acknowledged: Wolfgang Roether was responsible for the coordination of the ANT V/2 tracer program; the crew of RV *Polarstern* gave technical assistance during ANT III and ANT V; the Alfred-Wegener-Institut für Polar- und Meeresforschung, Bremerhaven, provided logistical support for the Ant III and Ant V cruises; Hans Georg Junghans was in charge of the CO_2 extraction on ANT V; Reiner Fletterer and the members of the institute's workshop prepared the equipment for water sampling and gas extraction; Gerd Rohardt provided the ANT III hydrographic data, and Hannelore Witte and Raul Guerrero measured the ANT V salinity samples. Stan Jacobs gave helpful comments on the manuscript. The major part of this work was funded by the Deutsche Forschungsgemeinschaft.

REFERENCES

Bonani, G, Beer, J, Hofmann, H, Synal, HA, Suter, M, Wölfli, W, Pfleiderer, C, Kromer, B, Junghans, C and Münnich, KO, 1987, Fractionation, precision and accuracy in ^{14}C and ^{13}C measurements: Nuclear Instruments & Methods, v B29, p 87-90.

Brennecke, W, 1921, Die ozeanographischen Arbeiten der Deutschen Antarktischen Expedition 1911–1912: Archiv Deutschen Seewarte, v 39, 214 p.

Broecker, WS, 1981, Geochemical tracers and ocean circulation, *in* Warren, BA & Wunsch, C, eds, Evolution of physical oceanography (Scientific surveys in honor of Henry Stommel): Cambridge, Massachusetts, MIT Press, p 434–460.

Broecker, WS and Peng, TH, 1982, Tracers in the sea: Palisades, New York, Eldigio Press, 690 p.

Broecker, WS, Peng, TH, Östlund, HG and Stuiver, M, 1985, The distribution of bomb radiocarbon in the ocean: Jour Geophys Research, v 90, p 6953–6970.

Carmack, EC and Foster, TD, 1975a, On the flow of water out of the Weddell Sea: Deep–Sea Research, v 22, p 711–724.

———— 1975b, Circulation and distribution of oceanographic properties near the Filchner Ice Shelf: Deep–Sea Research, v 22, p 77–90.

Casarini, PM and Massom, R, eds, 1987, Winter Weddell Sea Project sea ice observations: Leg 1: June–September 1986: Rept, Scott Polar Research Inst.

Deacon, GER, 1937, The hydrography of the Southern Ocean: Discovery Repts, v 15, 124 p.

Foldvik, A, Gammelsrød, T and Tørresen, T, 1985a, Physical oceanography studies in the Weddell Sea during the Norwegian Antarctic Research Expedition 1978/79: Polar Research, v 3, p 195–207.

———— 1985b, Hydrographic observations from the Weddell Sea during the Norwegian Antarctic Research Expedition 1976/77: Polar Research, v 3, p 177–193.

Foster, TD and Carmack, EC, 1976a, Frontal zone mixing and Antarctic Bottom Water formation in the southern Weddell Sea: Deep–Sea Research, v 23, p 301–317.

———— 1976b, Temperature and salinity structure in the Weddell Sea: Jour Phys Oceanog, v 6, p 36–44.

Foster, TD, Foldvik, A and Middleton, JH, 1987, Mixing and bottom water formation in the shelf break region of the southern Weddell Sea: Deep–Sea Research, v 34, p 1771–1794.

Gordon, AL, 1974, Varieties and variability of Antarctic Bottom Water, *in* Processus de formation des eaux océaniques profondes: Colloques Internationaux CNRS no. 215, p 33–47.

———— 1982, Weddell Deep Water variability: Jour Marine Research, v 40, p 199–217.

Gordon, AL, Chen, CTA and Metcalf, WG, 1984, Winter mixed layer entrainment of Weddell Deep Water: Jour Geophys Research, v 89, p 637–640.

Gordon, AL and Huber, BA, 1984, Thermohaline stratification below the Southern Ocean sea ice: Jour Geophys Research, v 89, p 641–648.

Kromer, B, 1984, Recalibration of Heidelberg ^{14}C laboratory data: Radiocarbon, v 26, no. 1, p 148.

Kromer, B, Pfleiderer, C, Schlosser, P, Levin, I, Münnich, KO, Bonani, G, Suter, M and Wölfli, W, 1987, AMS ^{14}C measurement of small volume oceanic water samples: experimental procedure and comparison with low-level counting technique: Nuclear Instruments & Methods, v B29, p 302–305.

Kuntz, R, (ms) 1980, Bestimmung der Parameter einer Vakuumextraktionsapparatur zur parallelen Aufbereitung ozeanischer C-14 und Kr-85 Proben: Masters thesis, Inst f Umweltphysik, Univ Heidelberg.

Levin, I, Kromer, B, Wagenbach, D and Münnich, KO, 1987, Carbon isotope measurements of atmospheric CO_2 at a coastal station in Antarctica: Tellus, v 39B, p 89–95.

Levin, I, Münnich, KO and Weiss, W, 1980, The effect of anthropogenic CO_2 and ^{14}C sources on the distribution of ^{14}C in the atmosphere, *in* Stuiver, M and Kra, RS, eds, Internatl ^{14}C conf, 10th, Proc: Radiocarbon, v 22, no. 2, p 379–391.

Lynch, MCF and Kay, DJ, 1981, Performance of a mass spectrometer for determining low tritium levels from $^{3}He/^{4}He$ measurements, *in* Methods of low-level counting and spectrometry: Vienna, IAEA-SM-252/47, p 511–523.

Mosby, H, 1934, The waters of the Atlantic Antarctic Ocean: Scientific results of the Norwegian Antarctic Expeditions 1927–1928, v 1, no. 2, 131 p.

Nowlin, WD, Jr and Clifford, M, 1982, The kinematic and thermohaline zonation of the Antarctic Circumpolar Current at Drake Passage: Jour Marine Research, v 40, p 481–507.

Östlund, HG and Stuiver, M, 1980, GEOSECS Pacific raduicarbon: Radiocarbon, v 22, no. 1, p 25–53.

Rafter, TA and O'Brien, BJ, 1973, ^{14}C measurements in the atmosphere and in the south Pacific ocean – a recalculation of the exchange rates between the atmosphere and the ocean, *in* Rafter, TA and Grant-Taylor, T, eds, Internatl conf on ^{14}C dating, 8th, Proc: Wellington, New Zealand, Royal Soc New Zealand, p 241–267.

Schlosser, P, 1986, Helium: a new tacer in Antarctic oceanography: Nature, v 321, p 233–235.

Schlosser, P, Pfleiderer, C, Kromer, B, Levin, I, Münnich, KO, Bonani, G, Suter, M and Wölfli, W, 1987, Measurement of small volume oceanic ^{14}C samples by accelerator mass spectrometry: Radiocarbon, v 29, no. 3, p 347–352.

Schlosser, P, Roether, W and Rohardt, G, 1987, Helium-3 balance of the upper layers of the northwestern Weddell Sea: Deep-Sea Research, v 34, p 365–377.

Schnack-Schiel, S, ed, 1987, The winter-expedition of RV *Polarstern* to the Antarctic (ANT V/1–3), Alfred-Wegener Institut für Polar- und Meeresforschung, Bremerhaven, FRG: Repts Polar Research, v 39, 259 p.

Schoch, H, Bruns, M, Münnich, KO and Münnich, M, 1980, A multi counter system for high precision carbon-14 measurements, *in* Stuiver, M and Kra, RS, eds, Internatl ^{14}C conf, 10th, Proc: Radiocarbon, v 22, no. 2, p 442–447.

Schoch, H and Münnich, KO, 1981, Routine performance of a new multi-counter system for high-precision ^{14}C dating, *in* Methods of low-level counting and spectrometry: Vienna, IAEA, p 361–370.

Stuiver, M and Östlund, HG, 1980, GEOSECS Atlantic radiocarbon: Radiocarbon, v 22, no. 1, p 1–24.

———— 1983, GEOSECS Indian Ocean and Mediterranean radiocarbon: Radiocarbon, v 25, no. 1, p 1–29.

Stuiver, M and Polach, HA, 1977, Discussion: Reporting of ^{14}C data: Radiocarbon, v 19, no. 3, p 355–363.

Warren, BA, 1981, Deep circulation of the World Ocean, *in* Warren, BA and Wunsch, C, eds, Evolution of physical oceanography (Scientific surveys in honor of Henry Stommel): Cambridge, Massachusetts, MIT Press, p 6–41.

Weiss, RF, Östlund, HG and Craig, H, 1979, Geochemical studies of the Weddell Sea: Deep-Sea Research, v 26, p 1093–1120.