

The Inhomogeneous Distribution of Tritium and Radiocarbon in the Abyssal Southern Ocean

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ABSTRACT

The tritium and radiocarbon measurements taken at the Southern Ocean GEOSECS stations were analyzed. Excess CO_2 for the Atlantic GEOSECS stations 76, 77, 82, 85, 87, 89, 91 and for all the stations of the SOMOV-81 cruise were correlated with the radiotracer data. Radiocarbon and excess CO_2 support the tritium data showing that these tracers are not homogeneously distributed in the deep-water column. The preformed radiocarbon value of the Antarctic Surface water component in the Antarctic Bottom Water was estimated to be -139.3×10^{-3} .

1. INTRODUCTION

The deep and bottom waters around Antarctica have been found to be quite homogeneous in the radiocarbon and excess CO_2 concentrations and to a somewhat lesser extent in the tritium content. The presence of a bottom layer with clearly marked higher tritium values than in the deep water zone (e.g., typical bottom values of $> 0.1 TU$ relative to deep water of about $0 TU$; $1 TU = 10^{18} T/H$) is well documented (Michel, 1978; Weiss *et al.*, 1979 and Jenkins *et al.*, 1983). This situation is interpreted to mean that bottom waters contain significant percentages of relatively young waters (i.e. waters of recent surface origin).

Radiocarbon value, on the other hand, has sometimes been reported to be very uniform regionally in the deep and bottom waters of the Antarctica, below the salinity and potential temperature maxima and the oxygen minimum. Values reported are -163×10^{-3} (Broecker, 1979; Fiadeiro, 1982); -158×10^{-3} (Stuiver, *et al.*, 1983) and -160×10^{-3} (Stuiver, 1976; Broecker, 1981; Bolin, 1983). Excess CO_2 has also been shown to be regionally uniform (Chen, 1982).

These results may suggest that the bottom waters do not contain waters of recent surface origin.

Contrary to these reports, however, our study confirms the results of Weiss *et al.* (1979), Chen and Rodman (1984), Michel and Linick (1985), Chen and Drake (1986), and Poisson and Chen (1987) and shows that radiocarbon and excess CO_2 are also non-homogeneous in deep to bottom waters, similar to the trend observed for tritium.

Radiocarbon values can be used for dating purposes only when both the initial (preformed) and measured values are known. Further, most deep and bottom waters in all major oceans contain some Antarctic Bottom Water (AABW). It is thus important to accurately describe the radiocarbon distribution in the AABW in order to obtain the preformed radiocarbon values.

2. DATA

The radiotracer and hydrographic data used in this study are from the Antarctic GEOSECS stations in the three oceans (Ostlund *et al.*, 1976, 1979, 1980; Stuiver and Ostlund, 1980; Bainbridge, 1981; Broecker *et al.*, 1982; Weiss *et al.*, 1983) and the stations of the Weddell Polynya Expedition (WEPOLEX) (Huber *et al.*, 1983) aboard the SOMOV. The Antarctic GEOSECS stations used were those containing a shallow temperature minimum and deep potential temperatures of less than $0^\circ C$. Neither radiocarbon nor tritium were sampled on SOMOV; however, one GEOSECS station, GS 89 (22 Jan., 1973) at $60^\circ 1' S$ and $0^\circ 1' E$ is very near one SOMOV station, SOMOV 33 (11 Nov., 1981) located at $59^\circ 59' S$ and $0^\circ 19' E$. The next two nearest GEOSECS stations to the SOMOV study area are GS 82 and GS 91. The excess CO_2 results are from Chen (1982, 1984, 1987), Chen and Poisson (1984) and Poisson and Chen (1987).

3. DISCUSSION

In Fig. 1 the vertical structures of tritium, radiocarbon and excess CO_2 are displayed for the three GEOSECS stations nearest the SOMOV cruise track. The gross details are similar among the three variables in each station. For example, GS 89 shows a rapid decrease of tritium, radiocarbon and excess CO_2 from the highest values at the surface to the minimum values near 250 m and then maintaining these generally low values to the bottom. GS 82 shows an increase only in tritium and $\Delta C - 14$ for the bottom sample, but the deepest sample depth for excess CO_2 is well above the bottom. The impression one gets is that below approximately 300 m these tracers are quite uniformly distributed in the water column.

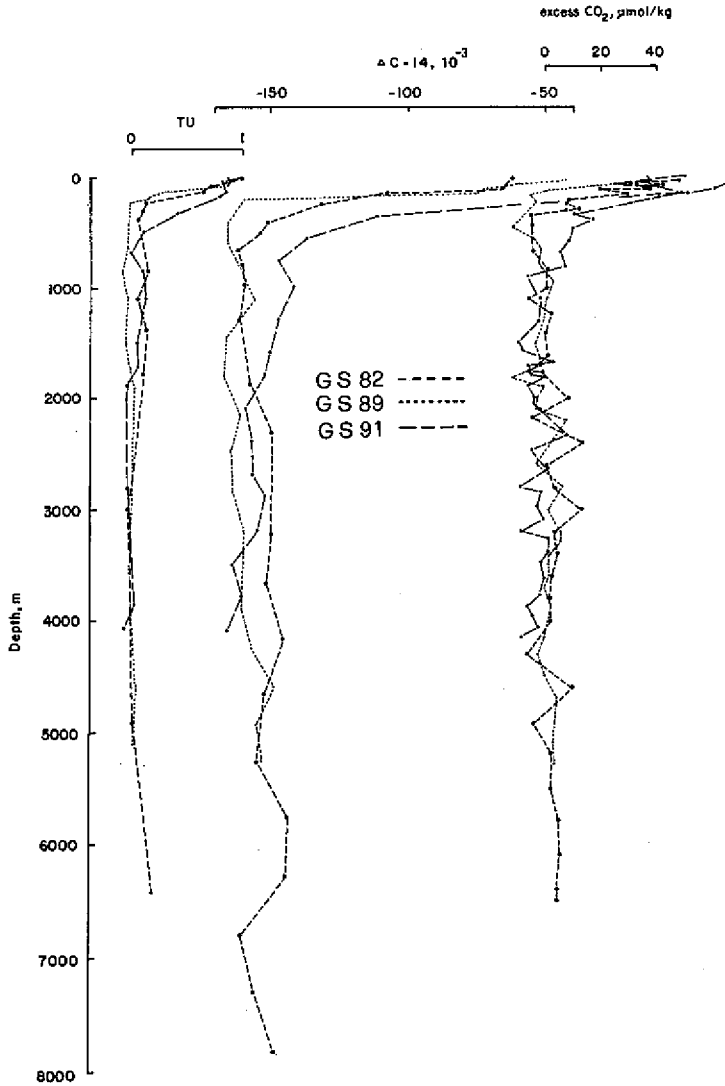


Fig. 1. Vertical distributions of tritium, ($1 TU = 10^{18} T/H$), $\Delta C - 14$ and excess CO_2 near the SOMOV study area based on data from three GEOSECS stations, GS 82, GS 89, and GS 91.

In Fig. 2, the same stations as Fig. 1 are plotted but with potential density ($\sigma\theta$) rather than depth as the ordinate, and the SOMOV 33 excess CO_2 results are also included. When potential density rather than depth is used, the structures of tritium and excess CO_2 profiles are similar. Tritium and excess CO_2 decrease to a minimum value at a $\sigma\theta$ of about 27.86 and then both parameters as well as $\Delta C - 14$ show a gradual increase to the bottom.

Station 89 has anomalously higher tritium and radiocarbon at densities less than roughly 27.80 $\sigma\theta$. This effect is not seen on the depth plot but is noticeable in other figures discussed later. We have no explanation for this phenomenon.

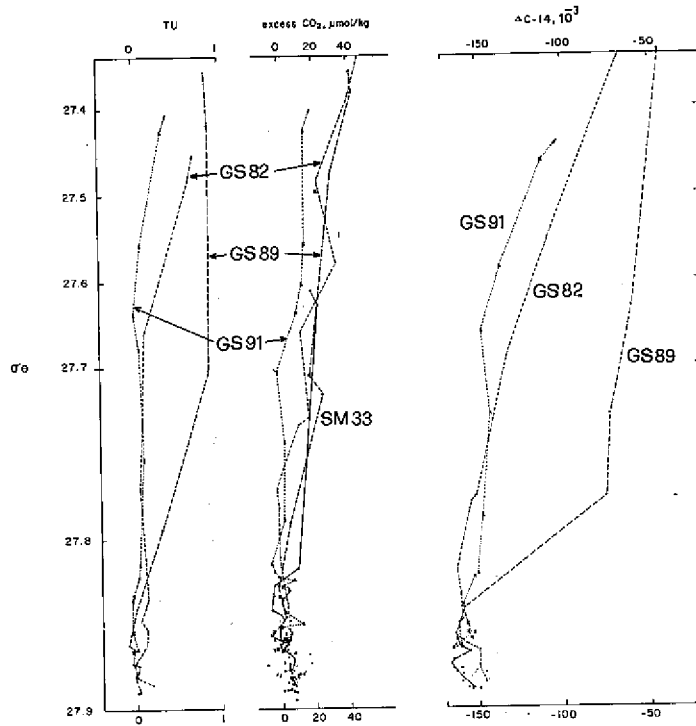


Fig. 2. Potential density vs tritium, ($1 \text{ TU} = 10^{18} T/H$), $\Delta C - 14$, and excess CO_2 from GEOSECS stations GS 82, GS 89, and GS 91. Excess CO_2 for SOMOV 33 is also shown.

Excess CO_2 at SOMOV 33 (Fig. 2) appears at relatively less dense layers than at GEOSECS stations. This difference, however, was found to be an artifact caused by the use of different equations of state for the GEOSECS data and for the SOMOV data. GEOSECS density values are systematically higher by $0.03 \sigma_\theta$ units and $0.02 \sigma_4$ units than values obtained by using the international equation of state at one atmosphere and higher pressures (Millero *et al.*, 1980; Millero and Poisson, 1981). Density data from SOMOV agreed to within 0.0002σ units of the international equation. Figs. 3, 4, 5 and 6 have the GEOSECS data scaled by subtracting $0.03 \sigma_\theta$ ($0.02 \sigma_4$).

The poorer precision of radiocarbon and excess CO_2 relative to tritium may obscure some information on the abyssal environment. We investigated this possibility by combining all the Antarctic GEOSECS and SOMOV stations in Figs. 3, 4, 5 and 6 where tritium, radiocarbon and excess CO_2 are plotted against potential density as the ordinate. Note that GEOSECS density in these figures has been scaled. The bottom values are clearly higher than the deep water values for all three parameters. Surface values are the highest and decrease to a broad minimum centered at about $\sigma_\theta = 27.85$, which is the density near, or just below the S_{max} layer (Carmack and Foster, 1975). The bottom

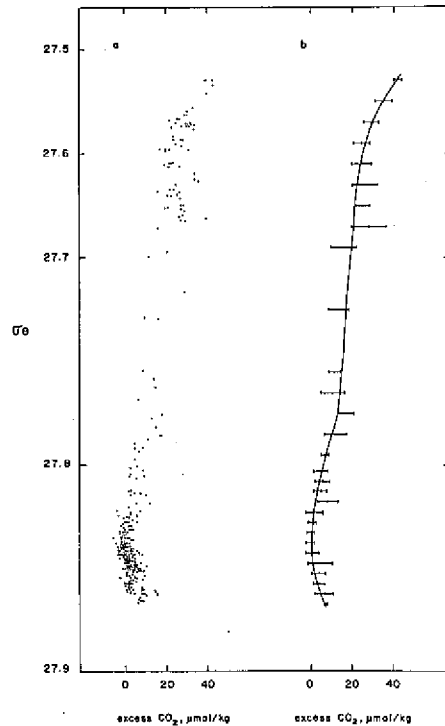


Fig. 3. (a) Composite GEOSECS potential density vs tritium for Atlantic (GS 76, 77, 78, 82, 89, 91), Pacific (GS 287) and Indian (GS 430, 431, 432, 433) Antarctic stations. (b) Curve fit by eye resulting from averaging data of *Fig. 3a* in density bands. Points with no error bars indicate single-datum points.

layer increases by about 0.16 for tritium and 8×10^{-3} for radiocarbon relative to their minima (Figs. 3, 4). An increase near bottom for excess CO_2 may exist in the GEOSECS data (Fig. 5). The increase is more clearly shown in the more precise SOMOV data (Fig. 6; Chen, 1984).

Shown also on Figs. 3, 4, 5, 6 are averages (and standard deviations) calculated for density bands with curves fit by eye through the averages. Averaging within density bands is justifiable because of the isopycnal spreading of water masses below the pycnocline (Reid *et al.*, 1977). The choice of density bands was based on the number of data points contained therein and thus is somewhat arbitrary. The averaging intervals are as follows: for tritium and radiocarbon, 0.02 density units at $\sigma_\theta \leq 27.7$ and 0.01 density units at $\sigma_\theta > 27.7$; for excess CO_2 , 0.02 density units at $\sigma_\theta \leq 27.7$, 0.01 density units at $27.7 < \sigma_\theta \leq 27.8$ and 0.005 density units at $\sigma_\theta > 27.8$. The curves for tritium, radiocarbon and excess CO_2 are remarkably similar and show increases for waters denser than $\sigma_\theta = 27.85$. The precision and methodology for excess CO_2 are apparently improved for the SOMOV data because of the tighter scatter of data points. The SOMOV excess CO_2 data also indicate a break in slope near $\sigma_\theta = 27.78$ which

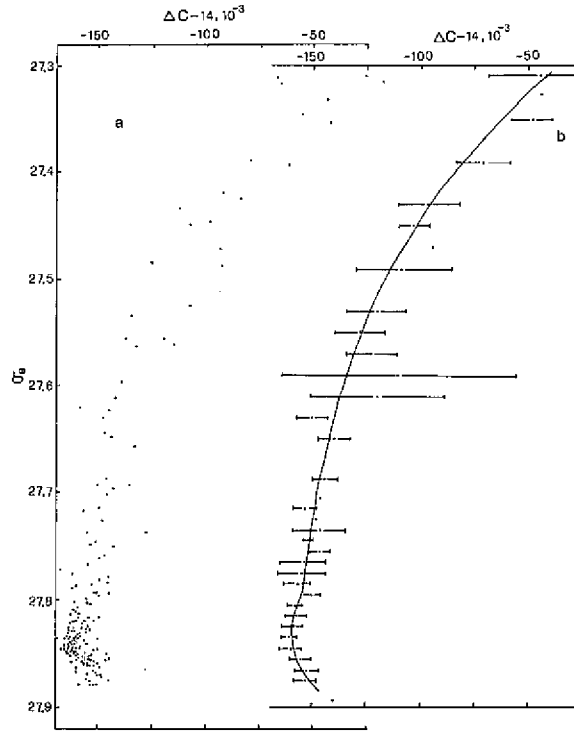


Fig. 4. (a) Same as Fig. 3a but for radiocarbon. (b) Same as Fig. 3b but for radiocarbon.

may be present in the GEOSECS tritium and radiocarbon data. It is interesting to note that this density surface lies near the base of the pycnocline for the SOMOV data and is also the isopycnal displaying some interleaving (Gordon and Huber, 1984; their Figs. 7 and 8). Wisegarver *et al.* (1989) also reported that chlorofluoromethanes in the southeast Pacific Ocean south of 55S show a minimum at $\sigma\theta = 27.8$ with concentrations increasing toward the bottom.

Excess CO_2 data from SOMOV are again plotted in Fig. 7 but with σ_4 as the ordinate. Only data below the S_{max} are plotted because σ_4 undergoes a minimum near the θ_{max} , as warmer water is less compressible than colder water (Lynn and Reid, 1968; Reid and Lynn, 1971). Using σ_4 effectively expands the deep water density scale compared to $\sigma\theta$ and confirms the results found from previous figures. An increased slope occurs near $\sigma_4 = 46.156$, and some indication of an offset to increased values exists at $\sigma_4 = 46.056$. These isopycnal surfaces have been investigated by Chen (1984). Briefly, breaks in scatter plots, in particular θ/pH , at these two strata may indicate that surface to near-surface components are exerting an influence at these depths, perhaps through isopycnal interleaving (Carmack and Kilworth, 1978; Jacobs and Georgi, 1977) or deep vertical convection (Gordon, 1978; Martinson *et al.*, 1981). Three linear

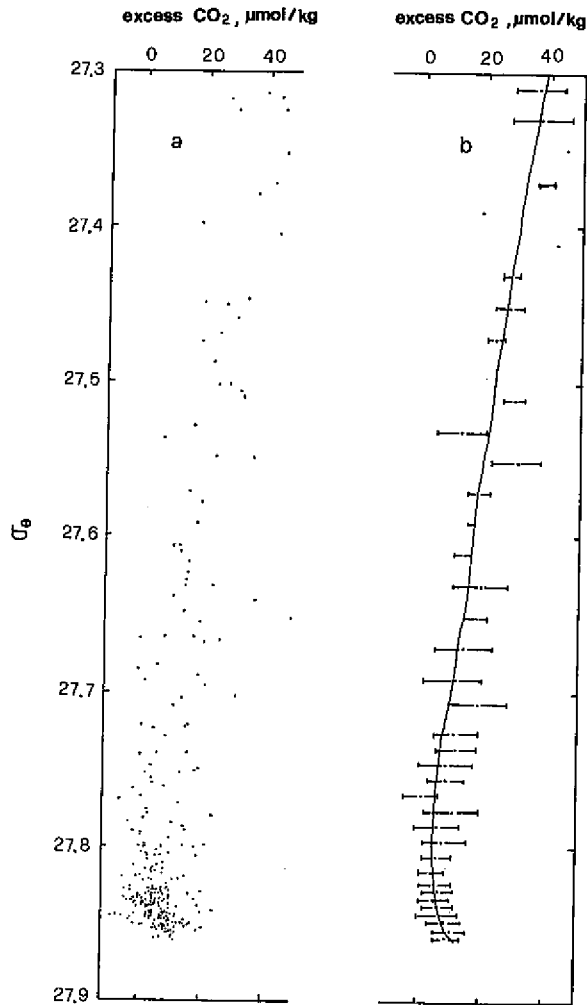


Fig. 5. (a) Composite potential density vs excess CO_2 for Atlantic GEOSECS stations. (b) Curve fit by eye resulting from averaging data of *Fig. 5a* in density bands. Points with no error bars indicate single-datum points.

regression lines were fit to these data, a) between $\sigma_4 = 46.000$ and 46.056 the slope is $7.3 \text{ kg}^2/\mu\text{mol}/\text{m}^3$, b) between $\sigma_4 = 46.056$ and 46.156 the slope is $1.1 \text{ kg}^2/\mu\text{mol}/\text{m}^3$, c) and below $\sigma_4 = 46.156$ the slope is $49.8 \text{ kg}/\mu\text{mol}/\text{m}^3$. Three regimes, therefore, are indicated, with the deepest regime having the most significant slope. As was done for σ_θ , averages (and standard deviations) were calculated (the interval was 0.01 density units). Instead of a curve two linear relations were fitted. The deeper short segment (for data below $\sigma_4 = 46.14$) shows a well-defined increase, and the overall trend shows a general increase with depth.

Composite scatter of potential temperature, tritium and radiocarbon vs.

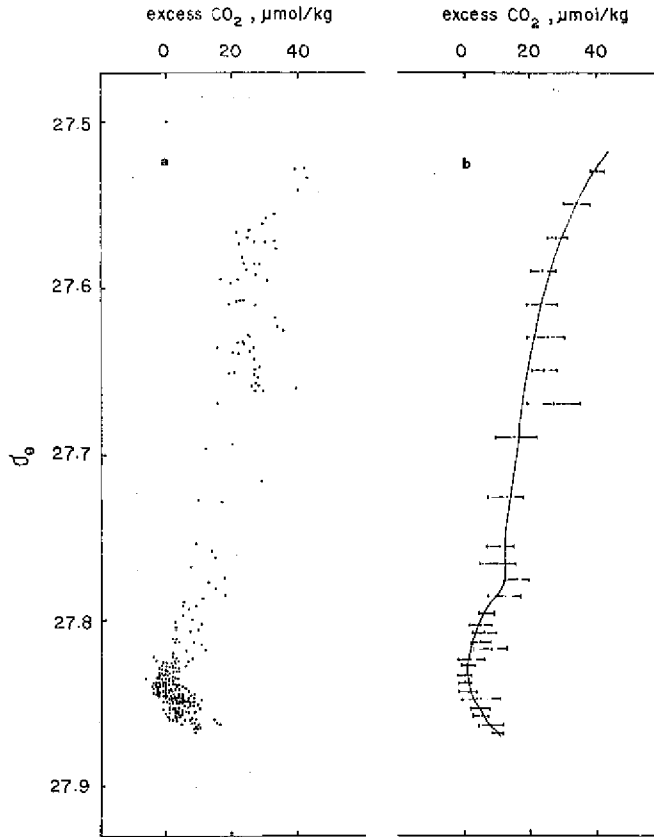


Fig. 6. (a) Same as *Fig. 5a* but using SOMOV data. (b) Same as *Fig. 5b* but using SOMOV data.

salinity for all Antarctic GEOSECS data, separated into Atlantic, Indian and Pacific sectors, are shown in Figs. 8a, 8b, 8c. The scatter of the deep-water data for tritium and radiocarbon is obvious (Figs. 8b, 8c); these waters, therefore, may appear homogeneous in tritium and radiocarbon content. Salinity as a conservative tracer was chosen for one of the axis so that temporal effects on mixing can be investigated. Overall, the scatter of the radiotracers makes decay determinations difficult, although there is a slight indication of decay in the radiocarbon data. Neither salinity nor temperature is strictly conservative at the very important air-sea interface. Also, mixing and stirring are enhanced near the surface, and surface and pycnocline waters can have large variabilities. Establishing well-defined surface values (except for the freezing curve temperature) is not easy.

The tritium plot (Fig. 8b) indicates that the surface Atlantic and Pacific have significantly higher tritium values than the surface Indian Ocean. The lower value in the Indian Ocean is the result of decay and more reduced atmospheric input in 1978 than in 1972-74. The Atlantic expedition was undertaken in 1972 and the Pacific in 1973-74, while the Indian Expedition took place in 1978 so that in the six-year interim between the Atlantic and Indian expe-

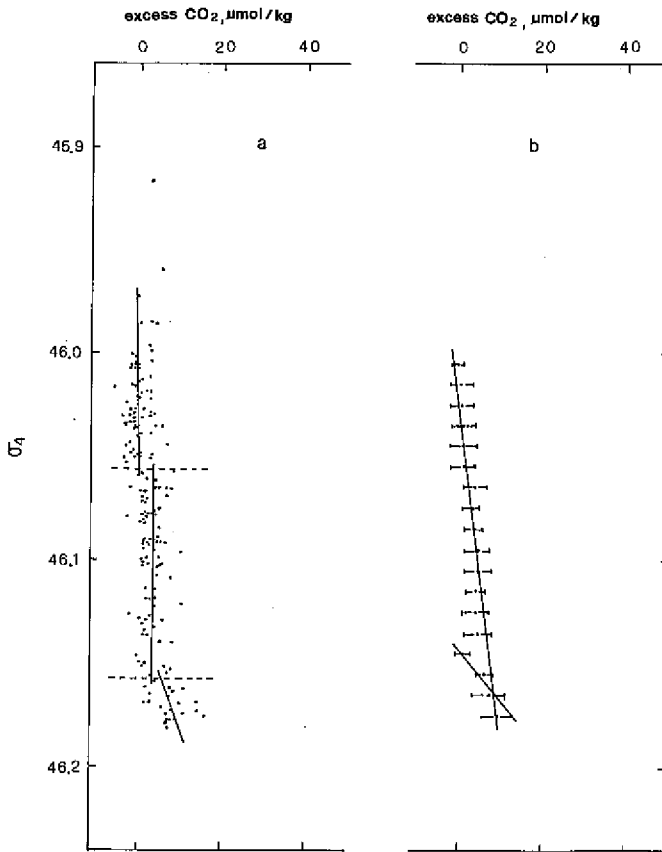


Fig. 7. (a) Composite σ_4 vs excess CO_2 for SOMOV data below the salinity maximum. Upper dashed line is at 46.056 and lower one is at 46.156. See text for linear regression lines. (b) Curves fit by eye to average data of Fig. 7a.

ditions, tritium could decrease by 30 %. The anomalously high tritium and radiocarbon in the salinity range between 34.10 and 34.50×10^{-3} is from GS 89 mentioned earlier with respect to Fig. 2.

The one Antarctic Pacific station (GS 287) shows a bottom layer of increasing salinity (Fig. 8a). This increase results from input from the Ross Sea Bottom Water (RSBW) (Jacobs, *et al.*, 1970; Gordon, 1972). When salinity, tritium and radiocarbon are plotted against depth (Figs. 9a, 9b) for station GS 287, tritium and radiocarbon appear to increase in the deep water column. This salinity maximum near the bottom can be used as a tracer for relatively young bottom water only in the Southeast Indian/Southwest Pacific sector (Gordon, 1972; Rodman and Gordon, 1982).

Silicate, on the other hand, can be used circumpolarly as a tracer for recently formed bottom waters. Excess CO_2 data from SOMOV and all Antarctic GEOSECS stations are plotted against silicate in Figs. 10a, 10b. Fig. 10b shows the expanded boxed region of Fig. 10a. Silicate increases from near

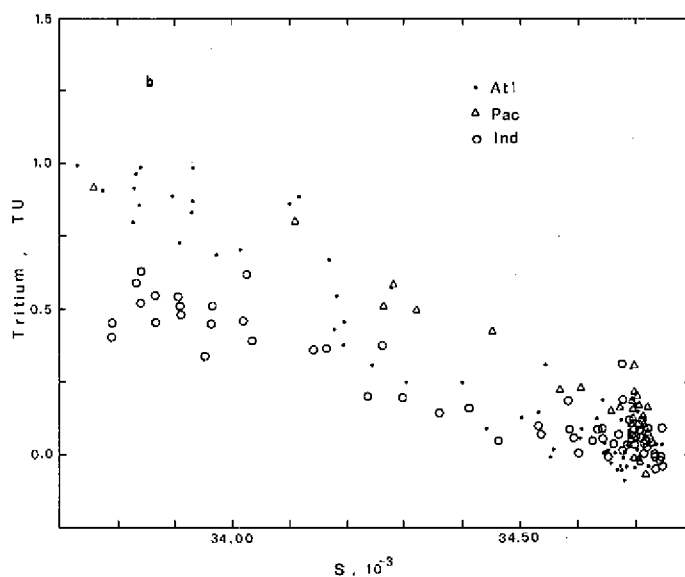
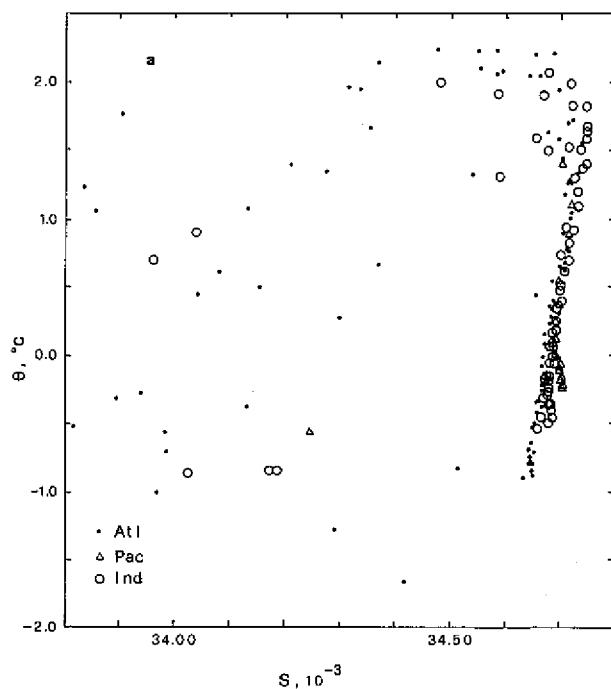


Fig. 8. (a) Potential temperature vs salinity for GEOSECS Antarctic stations: Atlantic (GS 76, 77, 78, 82, 89, 91 - "•"); Pacific (GS 287 - "Δ"); Indian (GS 430, 431, 432, 433 - "o"). (b) Tritium vs salinity for stations in *Fig. 8a*. (c) Radiocarbon vs salinity for stations in *Fig. 8a*.

zero at the surface to a maximum of about $125 \mu\text{mol}/\text{kg}$ then decreases again.

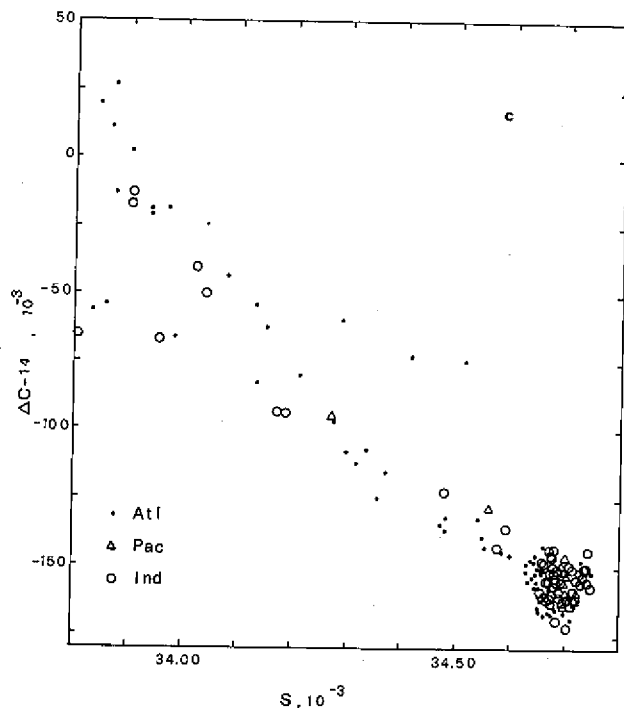


Fig. 8. (Continued)

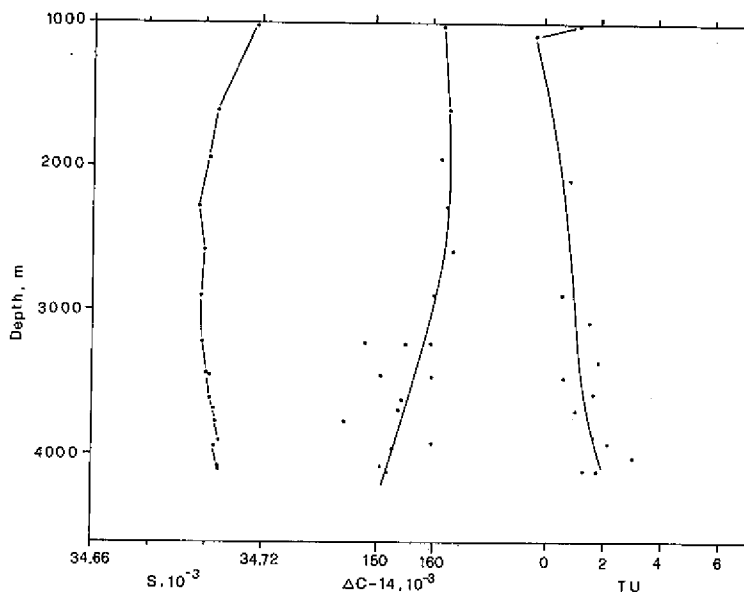


Fig. 9. Salinity, $\Delta C - 14$ and tritium below 1000 m for GEOSECS Pacific station GS 287.

The lowest silicate (Fig. 10a) is associated with the highest excess CO_2 , and the general trend shows silicate increasing as excess CO_2 decreases; however, near a silicate value of approximately $90 \mu mol/kg$ (excess CO_2 of 0), there is a

break in the slope. Silicate values of $80 - 90 \mu\text{mol}/\text{kg}$ lie just above the S_{max} , or within the oxygen minimum layer (see plates 112, 113, 114, Gordon *et al.*, 1982). Waters having silicate values greater than $80 - 90 \mu\text{mol}/\text{kg}$ contain large portions of Circumpolar Deep Water, Weddell Sea Bottom Water and AABW (Rutgers van der Loeff and van Bennekom, 1989), are markedly more aged and contain little or no excess CO_2 (Fig. 10a). The deep silicate maximum has been investigated in the Western Weddell Sea by Carmack (1973) and its distribution circumpolarly and globally as an advective feature by Edmond *et al.* (1979). They were unable, however, to resolve the relative importance of *in situ* and sea-floor dissolution. Silicate was one of many chemicals Weiss *et al.* (1979) investigated in their exhaustive study on the geochemistry of the Weddell Sea. Their work indicated that bottom dissolution rather than solution of sinking particulates was probably responsible for the deep silicate enrichment. Nelson and Gordon (1982) in their study south of New Zealand indicate that during the austral spring, *in situ* dissolution dominates. Rutgers van der Loeff and van Bennekom reported that Weddell Sea contributes little to silicate enrichment in AABW. Although the data in Fig. 10b shows scatter, the resolution is sufficient to show that excess CO_2 increases below the silicate maximum. The average increase is $6.3 \pm 1.2 \mu\text{mol}/\text{kg}$. Reduced silicate below the maximum in Antarctic waters is taken to mean relatively younger bottom waters (Carmack, 1973; Weiss *et al.*, 1979), that is, those containing a larger component of surface and/or shelf waters. The somewhat higher excess CO_2 values support this assumption. (Poisson and Chen, 1987)

The scatter diagram for tritium vs. excess CO_2 is shown in Fig. 11. High tritium is associated with high excess CO_2 , and tritium also decreases as excess CO_2 decreases. The slope of the linear regression line is $0.018 \text{ TU}/\mu\text{mol}/\text{kg}$. Since both tritium and excess CO_2 are highest in the surface waters and decrease with depth, this distribution is not surprising.

It is possible to estimate the radiocarbon value of surface and near-surface water components in the formation of AABW. The time dependence of radiocarbon is neglected, and conservative mixing is assumed. An average radiocarbon value for all Antarctic GEOSECS stations was calculated in the following manner:

When there existed a bottom silicate gradient, all $\Delta C - 14$ values from the top of the gradient down were averaged to give a bottom water value of $(-151.9 \pm 4.9) \times 10^{-3}$, which agrees well with the pre-bomb values reported for Weddell Sea Bottom Water and Antarctic Bottom Water of -150×10^{-3} and 153×10^{-3} respectively (Michel and Linick, 1985). Between the S_{max} and the top of this silicate gradient, or to the bottom if no silicate gradient was present, all values were averaged to give a Circumpolar Deep Water (CDW) value of $(-160.3 \pm 4.2) \times 10^{-3}$. It appears, therefore, that AABW may be

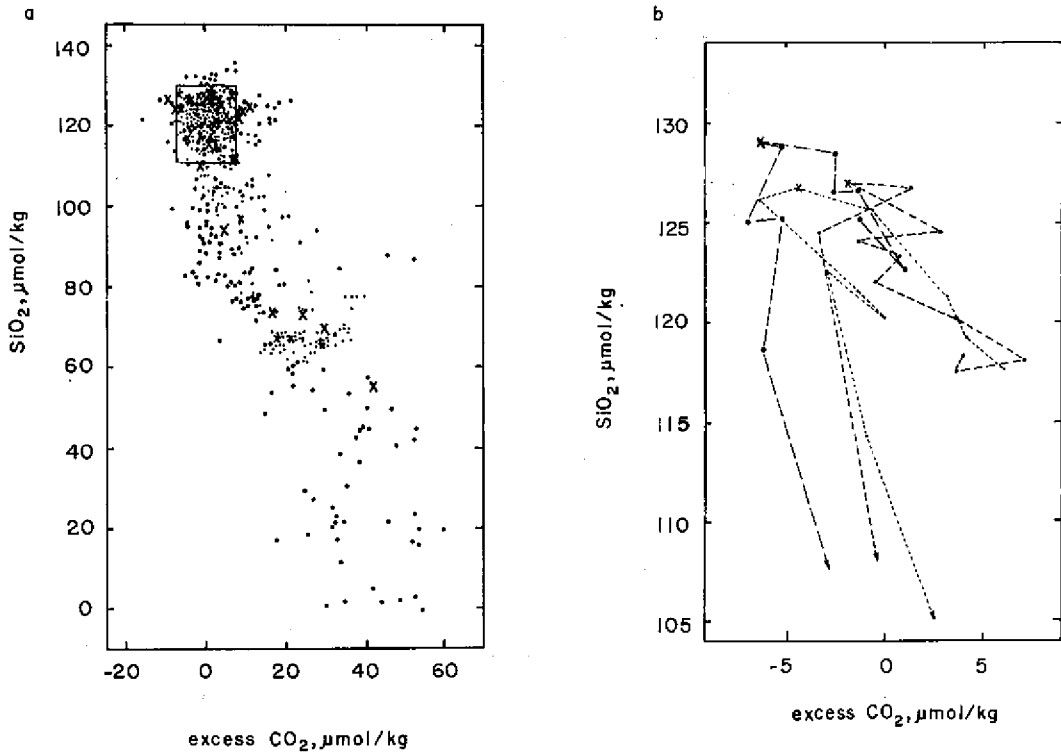


Fig. 10. (a) Silicate vs excess CO_2 for the Antarctic GEOSECS and SOMOV stations (The X's are for GS 89). (b) Expanded scale of the "boxed" region in Fig. 10a for near-bottom waters of three SOMOV stations which contain a silicate maximum marked by X on b plot only.

slightly younger than CDW, or AABW may contain a little bomb-produced $C - 14$. (Note the precision of each $C - 14$ determination is 3.5×10^{-3} (Stuiver *et al.*, 1983)). This deep water value agrees well with other work (Fiadeiro, 1982; Stuiver *et al.*, 1983; Bolin, 1983; Broecker, 1979). The nature of this silicate gradient vs. potential temperature, with respect to θ/S and $\theta/\Delta C - 14$ is shown in Figs. 12a, 12b, 12c where the two Southern Ocean GEOSECS stations (82, 89) having deep radiocarbon values associated with a potential temperature less than $0^\circ C$ are plotted.

Depending on one's choice of end-members, different proportions of deep and shelf-surface water combinations are possible in a complex sequence of mixing processes. Foster and Carmack (1976), however, simplified these processes considerably and arrived at the proportions of 37.5 % near-surface components (12.5 % Winter Water and 25 % Western Shelf Water) and 62.5 % deep-water components. For classical AABW-CDW mixtures the proportion is about 30 % surface components and 70 % CDW, and classical AABW-Weddell Deep Water ratios are 45 % surface and 55 % WDW. As Chen (1984) and Poisson and

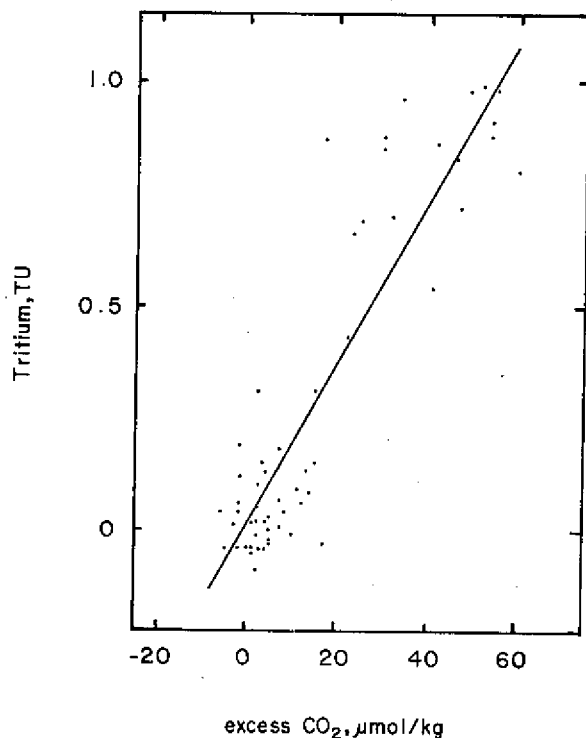


Fig. 11. Tritium vs. excess CO_2 for Antarctic GEOSECS data.

Chen (1987) pointed out, the near surface waters in turn have a deep-water component and they reported a 32:68 mixture of WDW to surface water. Gordon *et al.* (1984) reported a 1:3 ratio and Schlosser *et al.* (1987) reported a 31:69 ratio of WDW to surface water. Weiss *et al.* (1979) using a large array of chemical tracers to check the internal consistency of their results estimated that classical AABW was composed of 62 % WDW and 12 % Winter Water and 26 % Western Shelf Water mixtures which supported the earlier work of Foster and Carmack (1976) based on θ/S analysis. Thus as a first approximation we have used 60 % WDW and 40 % surface components. This proportion yields an estimate for the surface water radiocarbon content of -139.3×10^{-3} . Broecker and Peng (1982), instead, used a 60 % surface water to 40 % deep water ratio and arrived at an estimate of -146×10^{-3} . Had we used this 60-40 surface-to-deep-water mixing ratio, we would have also obtained an estimate of -146.3×10^{-3} . But we believe that our estimate of -139.3×10^{-3} for the radiocarbon value is more realistic because the 60 % WDW and 40 % surface water components estimation is more reliable.

4. CONCLUSION

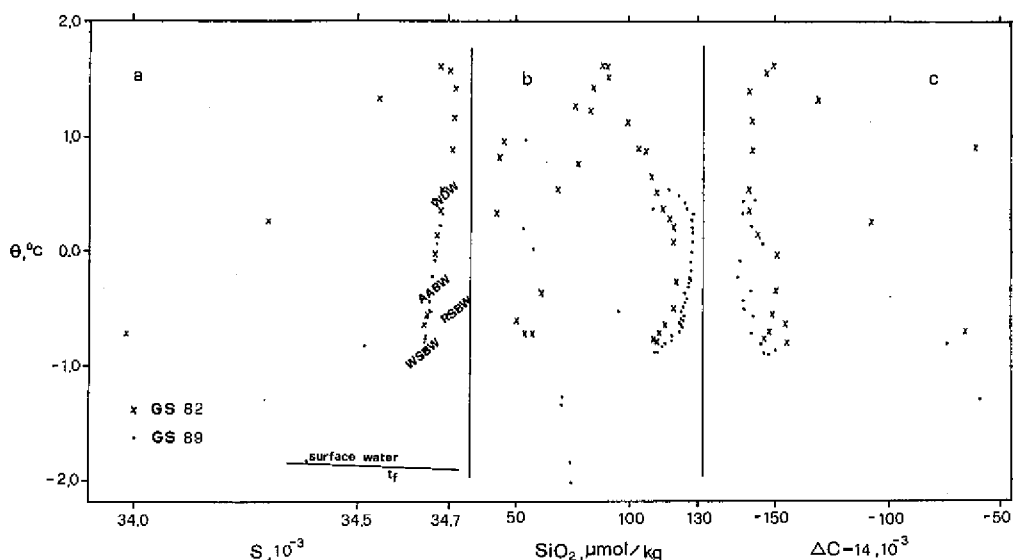


Fig. 12. (a) Potential temperature vs salinity for GEOSecs stations GS 82 ("X") and GS 89 (".") in the Southwest Atlantic. The following water masses have been approximately shown: WSBW (Weddell Sea Bottom Water), AABW (Antarctic Bottom Water), RSBW (Ross Sea Bottom Water), and WDW (Weddell Deep Water). The freezing curve, t_f , is also shown. (b) Same as *Fig. 12a* but for potential temperature vs silicate. (c) Same as *Fig. 12a* but for potential temperature vs radiocarbon.

The tritium data have consistently supported the existence of a young component in the bottom waters of the Southern Ocean. The radiocarbon and excess CO_2 data as reported in the literature, however, have not provided similar evidence for the existence of a relatively young bottom-water component. Our investigation of the distribution of radiocarbon and excess CO_2 with respect to density shows that both parameters have a deep-water-to-bottom-water signal which correlates with the tritium/density distribution. The discrepancy in distribution between tritium and radiocarbon as well as excess CO_2 , therefore, has been removed. We have also been able to estimate the surface preformed radiocarbon value at -139.3×10^{-3} based on a 60 % WDW and 40 % surface water mixing scheme.

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南冰洋深層水中氬及碳14之不均衡分佈

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摘 要

本文分析GEOSECS 計畫中取得之南冰洋氬及碳14 數據。將GEOSECS 於大西洋之測站 76, 77, 82, 85, 87, 89, 91 及 SOMOV-81 航次之所有測站所得之過量二氧化碳與碳14 資料作對比後發現, 這些資料與氬一樣, 均顯示於深水中之分佈不平均。本文最後計算出南極底層水當形成時, 其中所含表層水中碳14 之原始值為 -139.3×10^{-3} 。