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^{14}C IN THE DEEP WATER OF THE EAST ATLANTIC

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ABSTRACT. The renewal of east Atlantic deep water and its large-scale circulation and mixing have been studied in observed distributions of temperature, silicate, ΣCO_2, and ^{14}C. ^{14}C variations in northeast Atlantic deep water below 3500m depth are small. $\Delta^{14}C$ values range from −100‰ to −125‰. ^{14}C bottom water concentrations decrease from $\Delta^{14}C = -117$‰ in the Sierra Leone Basin to $\Delta^{14}C = -123$‰ in the Iberian Basin and are consistent with a mean northward bottom water flow. The characteristic of the water that flows from the west Atlantic through the Romanche Trench into the east Atlantic was determined by inspection of $\theta/\Delta^{14}C$ and θ/SiO_2 diagrams. A mean potential temperature of $\theta = 1.50 \pm .05$°C was found for the inflowing water. A multi-box model including circulation, mixing, and chemical source terms in the deep water has been formulated. Linear programing and least-squares techniques have been used to obtain the transport and source parameters of the model from the observed tracer fields. Model calculations reveal an inflow through the Romanche Trench from the west Atlantic, which predominates over any other inflow, of (5 ± 2) Sv (potential temperature 1.50°C), a convective turnover of (150 ± 50) years and a vertical apparent diffusivity of (4 ± 1) cm^2/s. Chemical source terms are in the expected ranges.

INTRODUCTION

Classical methods of physical oceanography (geostrophy, current meters, floats, etc) yield only crude estimates for the mean, large-scale circulation rates because of the small velocities and considerable temporal and spatial variability. The utility of radioactive tracers for the determination of residence times and the large-scale circulation of the deep water has repeatedly been demonstrated. Although the half-life of tracers like ^{39}Ar ($T_{1/2} = 269$ yr), ^{32}Si (101 yr) or ^{226}Ra (1600 yr) are more favorable for the study of processes with time scales of a few hundred years, ^{14}C ($T_{1/2} = 5600$ yr) is still the most important tracer for deep-water studies. The sampling procedure is comparatively simple, the $^{14}C/^{12}C$ ratio can be measured with high precision and, in contrast to ^{226}Ra, the source strength of ^{14}C in the deep water is small compared with radioactive decay.

The renewal of west Atlantic deep water has been thoroughly studied through the GEOSECS project (Stuiver, 1976; Broecker, 1979; Stuiver, Quay & Östlund, 1983), but for the east Atlantic rather few ^{14}C measurements existed until a cruise of the German R V *Meteor* in 1981. During this cruise, 120 ^{14}C deep-water samples from 10 stations in the equatorial west Atlantic, the Romanche Fracture Zone (0°N/20°W) and along a south-north section in the northeast Atlantic were taken (Fig 1).

The deep east Atlantic is an enclosed water basin (Fig 1). The deep water of this basin is a relatively uniform water mass, as can be seen from the small variations in potential temperature (θ) and salinity (S) (Levitus, 1982). From the uniformity and the analysis of temperature/salinity diagrams it is known that the east Atlantic deep water is fed from the west Atlantic by deep water flowing through gaps in the Mid-Atlantic Ridge at equatorial latitudes, and filling the Angola Basin in the south and the entire northeast Atlantic (Wüst, 1936). More recent current meter measurements (Vangriesheim, 1980) suggest that the inflow through the Vema Fracture Zone (11°N/42°W) is small and that the inflow through the Romanche Fracture Zone (0°N/20°W) dominates.

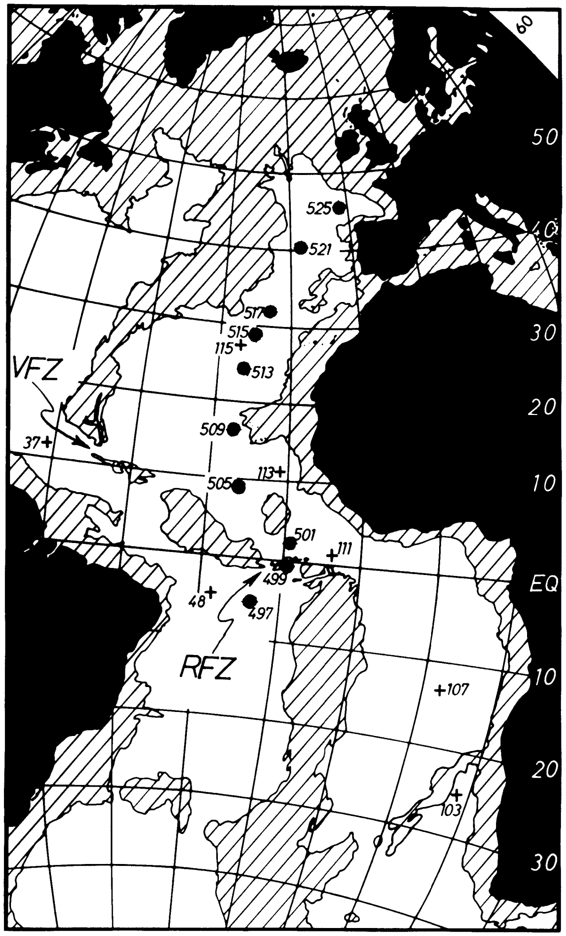

Fig 1. Map of *Meteor* (cruise 56, leg 5) – (●) and selected GEOSECS (+) ^{14}C stations. Water depth in the hatched areas is <4000m. RFZ and VFZ indicate the Romanche and Vema Fracture Zones.

The *Meteor* ^{14}C samples are from the source region of east Atlantic deep water (Stas 497, 499) and from a south-north section in the northeast Atlantic (Stas 501–525, see Fig 1), thus following the expected path of the bottom water.

METEOR ^{14}C SECTION

The contour diagram in Figure 2 shows the Δ^{14}C distribution along the *Meteor* track. It summarizes the results of 120 high-precision ^{14}C measurements ($\sigma \pm 2$‰).

In the west Atlantic and the Romanche Fracture Zone, low ^{14}C concentrations typical for Antarctic Bottom Water (AABW) are found at the bot-

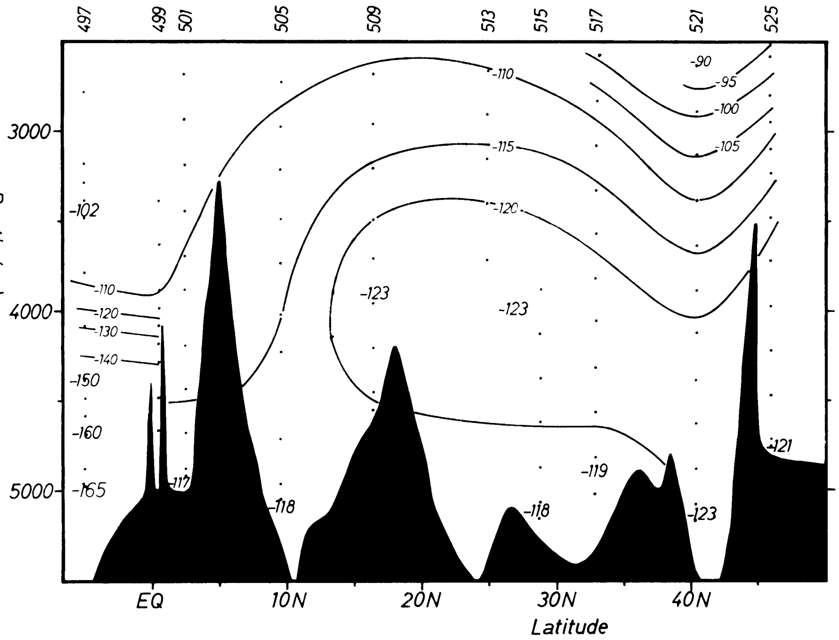

Fig 2. The $\Delta^{14}C$ distribution along the *Meteor* track below 2500m depth (from Schlitzer *et al,* 1985). Dots indicate the position of the actual data points. Bottom topography is along the track and often does not correspond to the deepest south-north connection.

tom, and ca 60‰ higher ^{14}C concentrations were measured in ca 3000m which indicate North Atlantic Deep Water (NADW).

In the east Atlantic ^{14}C variations are small. The biggest vertical gradient is found in the Iberian/West European Basin where in 2500m the highest and at the bottom the lowest ^{14}C concentration in the northeast Atlantic were measured. In the Cape Verde/Canary Basin minimal concentration is obtained at ca 4000m depth.

The bottom water ^{14}C concentration in the northeast Atlantic decrease from the equator to the Iberian Basin by 6‰. This concentration difference can be converted into a travel time of 50 years, or a mean northward velocity of 3mm/s (Schlitzer *et al,* 1985).

THE CHARACTERISTIC OF INFLOWING WATER

The characteristic of the deep water flowing into the east Atlantic is an important parameter for tracer budgets. In particular the potential temperature and the silicate, ΣCO_2, and ^{14}C concentrations of the inflowing water are input data for the box models of the east Atlantic which are described below. Whereas the origin of the east Atlantic deep water has been discovered by analysis of temperature/salinity diagrams, the characteristic of the inflowing water cannot be determined with temperature and salinity measurements.

Figure 3 is a combined $\theta/\Delta^{14}C$ and θ/SiO_2 plot for the *Meteor* stations 497 west of the Mid-Atlantic Ridge, 499 in the Romanche Fracture Zone and station 501 in the east Atlantic. While the θ/S curves of east and west Atlantic deep water coincide, for the nonconservative tracers ^{14}C and silicate distinct linear relationships for the west and east Atlantic deep water are obtained. Due to radioactive decay and dissolution of particulate silicate east Atlantic $\Delta^{14}C$ values are lower than west Atlantic values at a given temperature and silicate concentrations are higher.

The east Atlantic deep water can be interpreted as a mixture of west Atlantic deep water flowing across the Romanche Fracture Zone and of eastern water from about the depth of the sill (4000m, point "C" in Figure 3, $\theta \cong 2.1°C$) which is entrained by the inflowing water along its downflow path into the basin. The characteristic of the inflow water is defined by the intersection of the extrapolated eastern line with the west Atlantic line (point "B" in Figure 3). The extrapolation of the $\theta/\Delta^{14}C$ and θ/SiO_2 curves yields consistent results. It is found that the inflowing water has a mean potential temperature of 1.50 ± .05°C, and is thus considerably colder than the bottom water (point "A" in Figure 3) formed from it. The $\Delta^{14}C$ value of the inflowing water is $-122 \pm 3‰$ (Schlitzer *et al,* 1985).

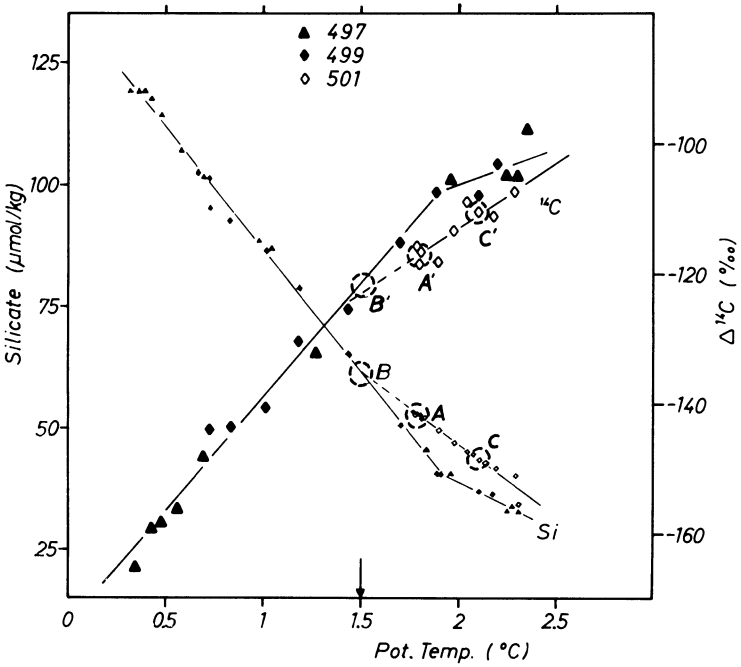

Fig 3. Combined SiO_2 and ^{14}C *vs* potential temperature plots for Stas 497 and 499 representing Western Basin water, and Sta 501 representing the Eastern Basin (from Schlitzer *et al,* 1985). Arrow at abscissa marks the deduced potential temperature of the inflow across the Romanche Fracture Zone (for explanation see text).

BOX MODELS

In order to use ^{14}C and other tracer data to determine the inflow rate of deep water into the east Atlantic and the residence time of this water mass, two box models were established, which are described in detail elsewhere. In this paper the models are outlined briefly and the importance of the ^{14}C data is emphasized.

For Model A the deep water of the east Atlantic was represented by a single box extending from the Walvis Ridge in the south to the continental rise in ca 50°N and from the continental rise in the east to the mid-Atlantic Ridge in the west. The isopycnal surface $\sigma_4 = 45.85$, which lies at ca 3500m depth, was chosen as the top of the box. Deep water inflow through the Romanche Fracture Zone and upwelling through the top of the box are permitted. Turbulent mixing and dissolution of particulate matter are included in the model. The indicated flows and diffusion and dissolution parameters are treated as free model parameters and are to be calculated.

The tracer balance equations, including advective and diffusive transport, source terms, and radioactive decay, for the four tracers θ, SiO_2, ΣCO_2, and ^{14}C serve as constraint equations for the unknowns. Using the "Simplex-Algorithm" the minimal value of the inflow rate into the east Atlantic which is consistent with the constraint equations has been calculated. The impact of the ^{14}C data on the results was studied in two independent calculations. In the first case all constraints were used; in the second case the ^{14}C constraint was omitted. The results are given in Table 1.

The calculations show that the heat, silicate, and ΣCO_2 constraints alone could be satisfied with a rather small value for the inflow (0.1Sv). Obviously, the ^{14}C constraint is inconsistent with such a small inflow rate which would result in a turnover time of east Atlantic deep water of 7500 years and in much smaller ^{14}C concentrations than those actually observed. Addition of the ^{14}C constraint to the other constraints raises the minimal inflow rate considerably (3Sv).

For Model B the single box of Model A was subdivided along the sills between the individual basins of the east Atlantic and along the isopycnal surfaces $\sigma_4 = 45.865$ and $\sigma_4 = 45.88$, into 11 boxes. In addition to the horizontal and vertical water flows into and out of the deep east Atlantic that were introduced in Model A horizontal advection between the individual basins and vertical advection within the basins are investigated.

For each of the 11 boxes the balance equations for the tracers ^{14}C, ΣCO_2, SiO_2, and potential temperature were formulated in the manner indicated above. The equations form a set of linear equations for the unknown water flows. Values between 1 and 10Sv were prescribed for the

TABLE 1

Minimal amount of inflowing water into the east Atlantic using different sets of constraints (for explanation see text, 1Sv = 10^6 m^3/s)

Without ^{14}C constraint	With ^{14}C constraint
0.1Sv	3Sv

Romanche Fracture Zone inflow and the set of linear equations was solved for the water flows in the interior by "least squares" techniques. Once the water currents are calculated the theoretical tracer concentrations in the boxes which result from the specified currents can be determined. The deviations between measured and calculated tracer concentrations have been studied.

While the deviations of calculated and measured temperatures and silicate concentrations are independent of the inflow rate, for ΣCO_2 and ^{14}C satisfying agreement between calculated and measured concentrations is obtained only for inflow rates between 3 and 7Sv. With these inflow rates the residence time of the east Atlantic deep water turns out to be 150 ± 50 years. An inflow of 5Sv into the east Atlantic amounts to 25% of the total input of Antarctic Bottom Water (AABW) and North Atlantic Deep Water (NADW) into the deep west Atlantic (Stuiver, Quay & Östlund, 1983).

CONCLUSIONS

The measured distribution of ^{14}C in the northeast Atlantic deep water confirms the idea of deep water inflow in equatorial regions and mean northward flow of the bottom water. Together with silicate data, ^{14}C was used to determine the characteristics of the inflowing water. Two box models of the east Atlantic deep water using different mathematical methods yield consistent results for the inflow rate and the turnover time of east Atlantic deep water. The model calculations show that ^{14}C is the essential tracer for the determination of flow rates. The qualitative argument that the inclusion of ^{14}C data to data sets of conservative tracers like temperature and salinity provides additional information and that ^{14}C data can successfully be used to determine flow rates has been verified numerically.

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