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RADIOTRACER STUDIES OF DEEP WATER FORMATION IN THE NORDIC SEAS

by

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Summary

The distributions of the radiotracers ^{137}Cs , ^{90}Sr , and ^3H which characterized surface and deep waters of the Nordic Seas in the time-period 1979-82 are presented and discussed in the context of regional circulation and deep water formation.

The data indirectly support the view that mid-gyre winter convection is the major process which is driving the transfer of surface water and associated properties into the deep Nordic Seas. Furthermore the deep gyral circulation appears the active process which propagates these properties relatively rapidly within the regional deep water waters.

Introduction

Various anthropogenic tracers have been used to study the processes of deep water formation in the Norwegian and Greenland Seas. Peterson and Rooth (1976) modelled the evolution of bomb-produced tritium and radiocarbon in the Greenland and Norwegian Seas and obtained estimates of about 30 years for the exchange times between surface and deep waters of the Greenland Sea and about 100 years for Norwegian and Greenland Sea deep water. Bullister and Weiss (1983) applied their data for chlorofluoromethanes in a like manner and found similar results for deep convective mixing in the Greenland Sea but a shorter timescale for deep lateral exchange between the Greenland and Norwegian Sea. Smethie and Ostlund (1985) used ^{85}K and tritium data to derive ventilation rates for the region and included exchange between the deep Norwegian Sea and the deep Eurasian Basin of the Arctic Ocean in their model. The evolution of the radiotracers ^3H , ^{137}Cs , ^{90}Sr , and $^{239,240}\text{Pu}$ in the central Greenland Sea between 1972 and 1981 has been discussed in terms of the different input histories of some of these tracers (Livingston, 1985). In the present paper, surface and deep distribution patterns of ^{137}Cs and tritium are compared and viewed in the context of current ideas on the nature of regional

circulation and mixing processes (Aagaard et al., 1985; Swift, 1986; and Johannessen, 1986).

These tracers (and others, including ^{90}Sr) have been initially introduced to the region from global fallout from the 1952-62 atmospheric nuclear weapons tests primarily and subsequently by physical movement of the nuclides into and out of the region. In recent years the region has received a further major input of ^{137}Cs (and minor one of ^{90}Sr) from the advection northward of nuclear wastes discharged to European Shelf seas. It is almost inevitable that a further input of ^{137}Cs (and ^{134}Cs) from fallout of radioactivity introduced to the troposphere from the nuclear accident at Chernobyl in the U.S.S.R. will represent a very distinct and characteristic new surface water signal which will be available for study of deep water formation or other mixing or circulation processes in the Nordic and Arctic Seas.

Methods and Results

The data which are used in this paper and the methods which were applied to obtain them, derive from the work of several laboratories and have been reported in a number of publications. References to many of these appear in papers by Livingston (1985) and Livingston et al. (1985); other data are derived from work of Ostlund (1984) and of Schlosser (1985).

Surface concentrations of ^{137}Cs and ^3H in the Nordic Seas region during 1981-82 are plotted and contoured in Figures 1 and 3. The ^{137}Cs data have been previously reported (Livingston, 1985; Livingston et al., 1985) but are reproduced here to facilitate comparison with the deep water and tritium data. Mean deep water concentrations of both nuclides are plotted and contoured in Figures 2 and 4. These values are obtained by averaging measurements at multiple depths below an upper boundary for the deep water at each location. This boundary, typically at depths in the 1500-2000 m depth range, was selected to be at a depth below which hydrographic and tracer properties showed little or no change with depth.

Tritium/Strontium-90 Ages of Water Masses

It is proposed that some semi-quantitative measurements of deep water mass ages in the Nordic Sea region may be inferred from a measurement of the relative amounts of tritium and ^{90}Sr which characterize a given water mass. The method is

based on the assumption that bomb fallout is the only input of these nuclides contributing to their deep water concentrations and that advective processes dominate in large scale water transport. The basic premise is that the Atlantic Water flowing northwards into the Norwegian Sea bears tracer inprints which reflect their time-history characteristics in the southern source waters. This source function is then viewed as being propagated into deep water in the Greenland Sea by convective mixing from the Greenland Sea gyre.

Some observations have been reported that the proportions of tritium relative to other bomb-derived radiotracers have been increasing with time in the northern North Atlantic Ocean (Livingston et al., 1985; Livingston, 1985). The primary reason for the sharp increase in the relative tritium content of surface water is probably due to the nature of the atmospheric tests conducted in the early 1960's. The production of tritium in the large yield Soviet tests was evidently relatively enhanced compared with earlier phases in atmospheric weapons testing. An additional mechanism for this increase may be a result of the continued, recycling input of tritium which is not applicable to non-volatile fallout radionuclides. Further evidence of these effects can be found from information published by Dreisgacker and Roether (1978) on time-histories of ^3H and ^{90}Sr in North Atlantic surface water (from observational and model data) from 1952-74.

The ^3H and ^{90}Sr time-histories were calculated from data reported by Dreisgacker and Roether (1978) in the following manner. From their temporal distribution data (their Table 2) for the 20°N to 60°N area, the average values for each year in the 40°N to 60°N area was calculated using the method described in their Figure 1. The concentrations derived were then decay corrected to a standard time (1/1/81) and the ratio of $^3\text{H}/^{90}\text{Sr}$ computed. This ratio was then expressed as tritium units divided by ^{90}Sr concentration (disintegrations per minute per 100 Kg). The resulting ratios were then plotted by year of collection (Fig. 5) - for both the experimental and theoretical data reported by Dreisgacker and Roether (1978). The solid line connects the data for the theoretical results while the solid symbols show the experimental data. Also shown are the mean values for the same ocean area derived from the GEOSecs program in 1972 and the Transient Tracers in the Ocean program (TTO) in 1981 - following Livingston et al. (1985).

The main point of this figure is the sharp increase in the $^3\text{H}/^{90}\text{Sr}$ ratio between 1960 and 1970 - in both theoretical and experimental data. This sharp increase is clearly linked to the arrival of fresh fallout from the ^3H rich

Soviet tests during 1961-62. The increase from 1970-81 is much less steep and is possibly due to the recycling of previously delivered tritium from land or lower latitudes to the 40°-60°N region.

The $^3\text{H}/^{90}\text{Sr}$ age of a deep water sample in the Arctic Ocean or sub-Arctic Seas is then inferred from a comparison of the measured deep water ratio with that which was previously characteristic of inflowing Atlantic surface water at an earlier date. For example, ratios less than 0.2 were not found in surface water after 1963. So deep water values below this value imply that the water mass in question has been isolated from the surface since this date. To illustrate the method, deep water $^3\text{H}/^{90}\text{Sr}$ ratios measured in samples collected in the Norwegian/Greenland Seas during the TTO expedition in 1981 have been plotted against tritium concentration - Figure 6. On the right-hand side of the Y-axis is plotted the year when Atlantic surface water was characterized by the various $^3\text{H}/^{90}\text{Sr}$ values (derived from Fig. 5). Briefly, the high values in the deep Greenland Sea show it to be the youngest water mass amongst those compared. This will be discussed further in the following section.

Discussion

Swift (1986) has reviewed the various possible processes which might form deep water in the Nordic Seas. They include a) classical deep winter convection, b) shelf water cooling following by advective transport, c) subsurface processes not requiring outcropping of the densest isopycnals. He noted recent data which point to the role of deep exchanges through Fram Strait in coupling deep water formation and circulation in the Arctic Ocean basin with those active in the Nordic Seas. In particular he discusses the nature and movement of deep water around the periphery of the Greenland Sea. Broadly speaking, a deep inflow from the Arctic Ocean is believed to move south into the western side of the Greenland Sea basin. Eventually this circulates counter-clockwise around the area of deep winter convection and returns as Norwegian Sea Deep Water flowing towards the Arctic Ocean through the eastern side of Fram Strait. Various inputs and mixing processes may contribute to and modify this deep water during its passage through the deep basins. For example, dense water found in the Barents Sea may be injected sporadically between Bear Island and Spitsbergen.

The deep water patterns of radiotracers and their contrast with surface (or intermediate) water patterns may be viewed in the context of their bearing on the

developing knowledge of the nature of the deep regional circulation. When the surface water concentration patterns of both ^3H and ^{137}Cs in the Nordic Seas in 1981-82 are compared with those of the deep water (Figs. 1-4), a consistent picture can be noted. In the surface waters, higher concentrations characterize the periphery of the Greenland Sea gyre. The concentration gradient between the exterior and interior areas of the gyre is steeper for ^{137}Cs than for ^3H - because of the relatively recent ^{137}Cs input from European nuclear waste sources along the eastern boundary of the region (Livingston et al., 1985). On the other hand, the deep water patterns of both ^3H and ^{137}Cs show an inverse picture to the surface distributions. The tracer concentrations are highest in the deep water underneath the mid-gyre region where surface concentrations are lowest. This dominant feature of the tracer patterns could be taken as indirect evidence of the major role which mid-gyre winter convection must play in regional deep water formation - despite the failure to observe the process in action (Swift, 1986).

Both ^{137}Cs and ^3H concentrations in deep water masses around the perimeter of the Greenland Sea gyre are relatively constant at levels below those in the central gyre (Figs. 2 and 4). This uniformity of tracer concentration is found in deep water at both sides of Fram Strait so that deep exchanges over the sill between the Eurasian Basin and Nordic Seas basin presently do not indicate net export or import of tracer. Furthermore, the lack of a tracer gradient in deep water around the perimeter of the Greenland Sea gyre suggests that the deep circulation around the gyre center must be rapid enough to have obliterated any gradients which may have been linked to specialized input sources such as the Barents Sea.

On the other hand, the concentrations and characteristics of the radiotracers in deep water in the southern basins of the Norwegian Sea confirm previous estimates of much slower rates of ventilation and circulation referred to in the introductory section. Both ^{137}Cs and ^3H were shown in 1981-82 to have deep water concentrations in the southern Norwegian Sea at about one third or less of those in the center of the Greenland Sea gyre. This is a very similar result to that reported by Bullister and Weiss (1983) for chlorofluoromethanes.

Some sense of the timescales associated with the deep circulation in the Nordic Seas can be derived from the different $^3\text{H}/^{90}\text{Sr}$ characteristics measured in the regional deep water masses. Figure 6 illustrates this approach using data obtained from the 1981 TTO cruise. The data are from two southern Norwegian Sea stations (144 and 145), one Iceland Sea station (159), one Boreas Basin station

(149), and the central Greenland Sea gyre station (148). As noted above, the central gyre station is characterized by the highest tracer concentrations and $^3\text{H}/^{90}\text{Sr}$ ratios. The latter imply relatively young water relative to its isolation from the surface with an average $^3\text{H}/^{90}\text{Sr}$ ratio age of about five or six years. Next in age is the station in the Boreas Basin (149) representative perhaps of water in the periphery of the gyre. Tracer concentrations are about two thirds of the central gyre levels but the average ^{90}Sr age is about 16-18 years. Finally, deep water in the Iceland Sea (station 159) and in the southern Norwegian Seas (144 and 145) have similar $^3\text{H}/^{90}\text{Sr}$ ages (close to 20 years), although the tracer concentrations at the Iceland Sea station are about twice as high as those in the deep southern Norwegian Sea.

There do not appear to be any difficulties in accomodating these deep water radiotracer data with other data being used to develop an understanding of regional circulation processes. The radiotracer data convey at least a sense of the timescales involved and appear to confirm the major role which winter convection plays in pumping surface water with its associated properties into the deep water circulation active in the Nordic Seas.

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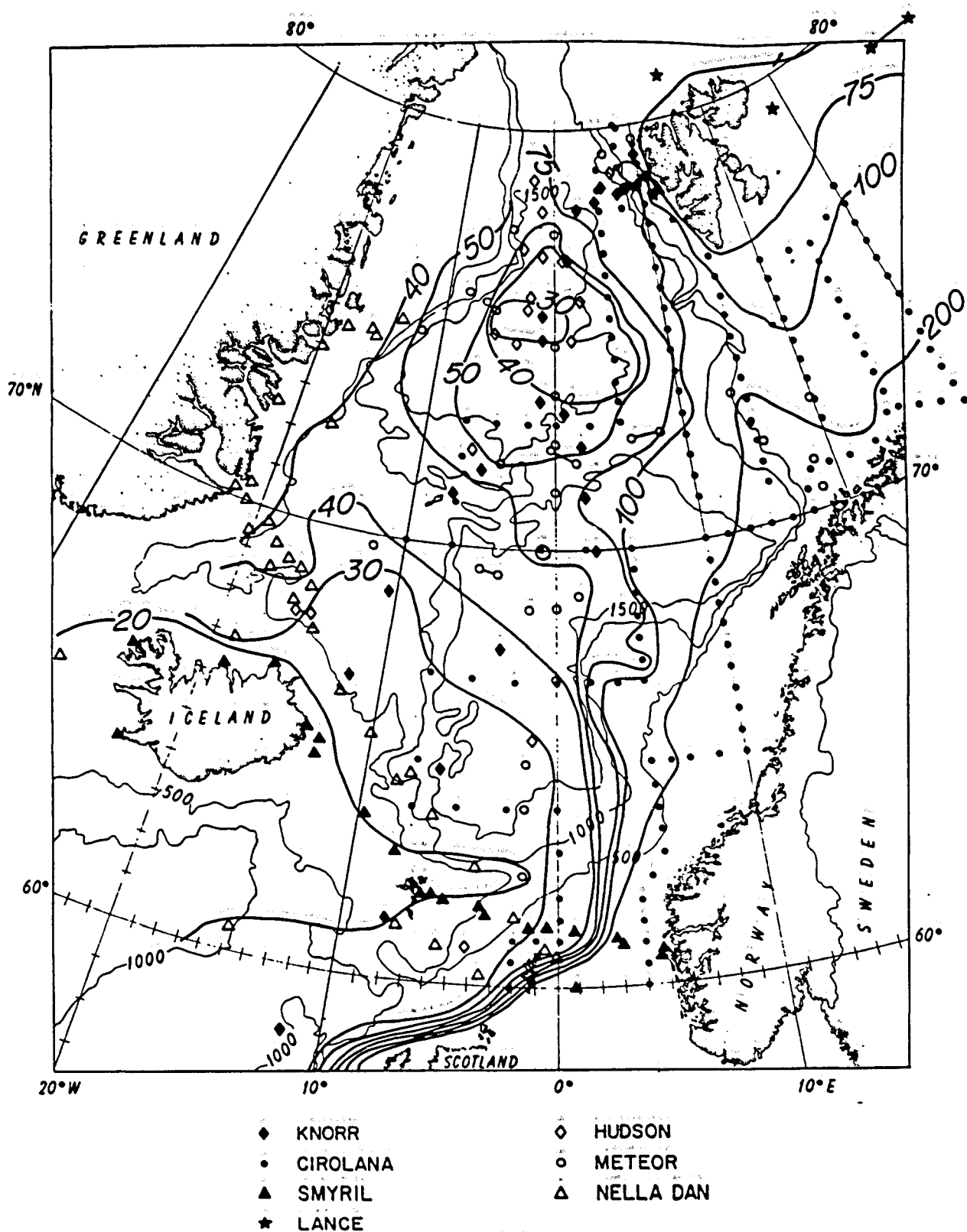


Figure 1: Surface distributions of ^{137}Cs (d.p.m./100 Kg as of 1/1/81) in the Norwegian/Greenland Seas in 1981-82. Solid symbols are stations occupied in 1981 by the ships indicated; open symbols are for 1982.

SURFACE TRITIUM 1981-82 (T.U. 1981)

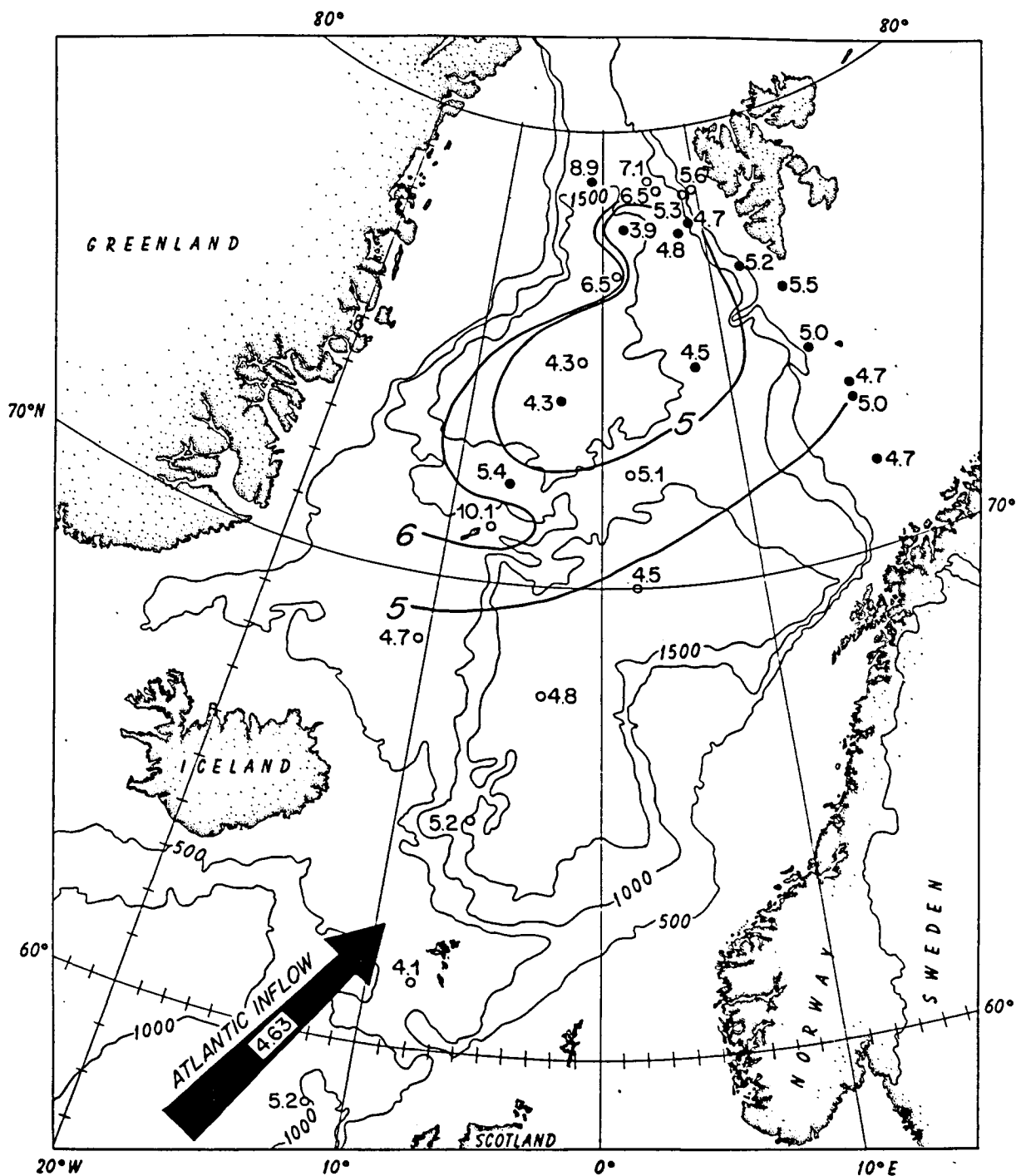


Figure 2: Surface distributions of ^3H (tritium units as of 1/1/81). Open circles are for stations occupied by R/V KNORR in 1981; solid circles by R/V HUDSON in 1982.

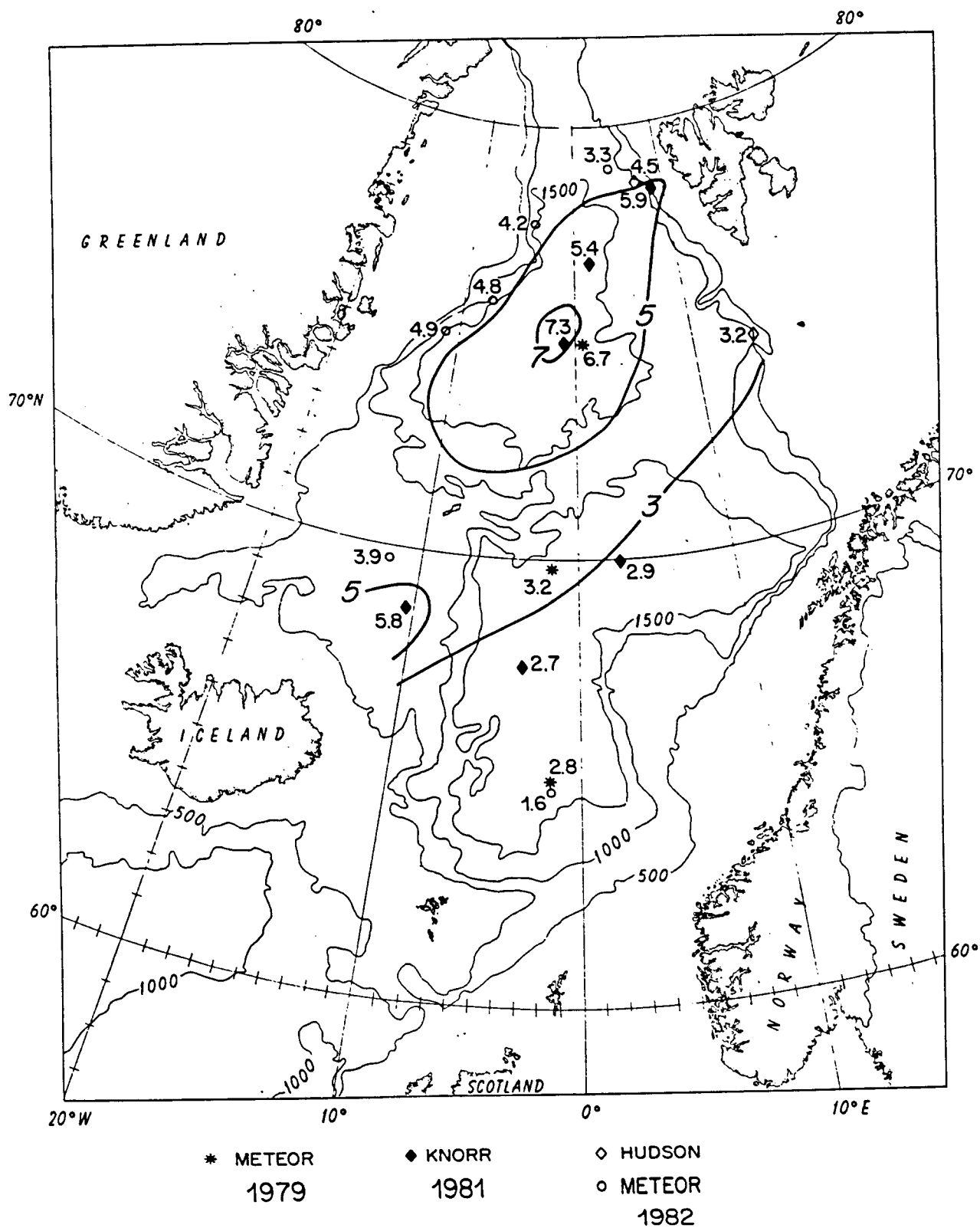


Figure 3: Average ^{137}Cs concentrations (d.p.m./100 Kg as of 1/1/81) in deep water. Symbols denote ship and year of collection.

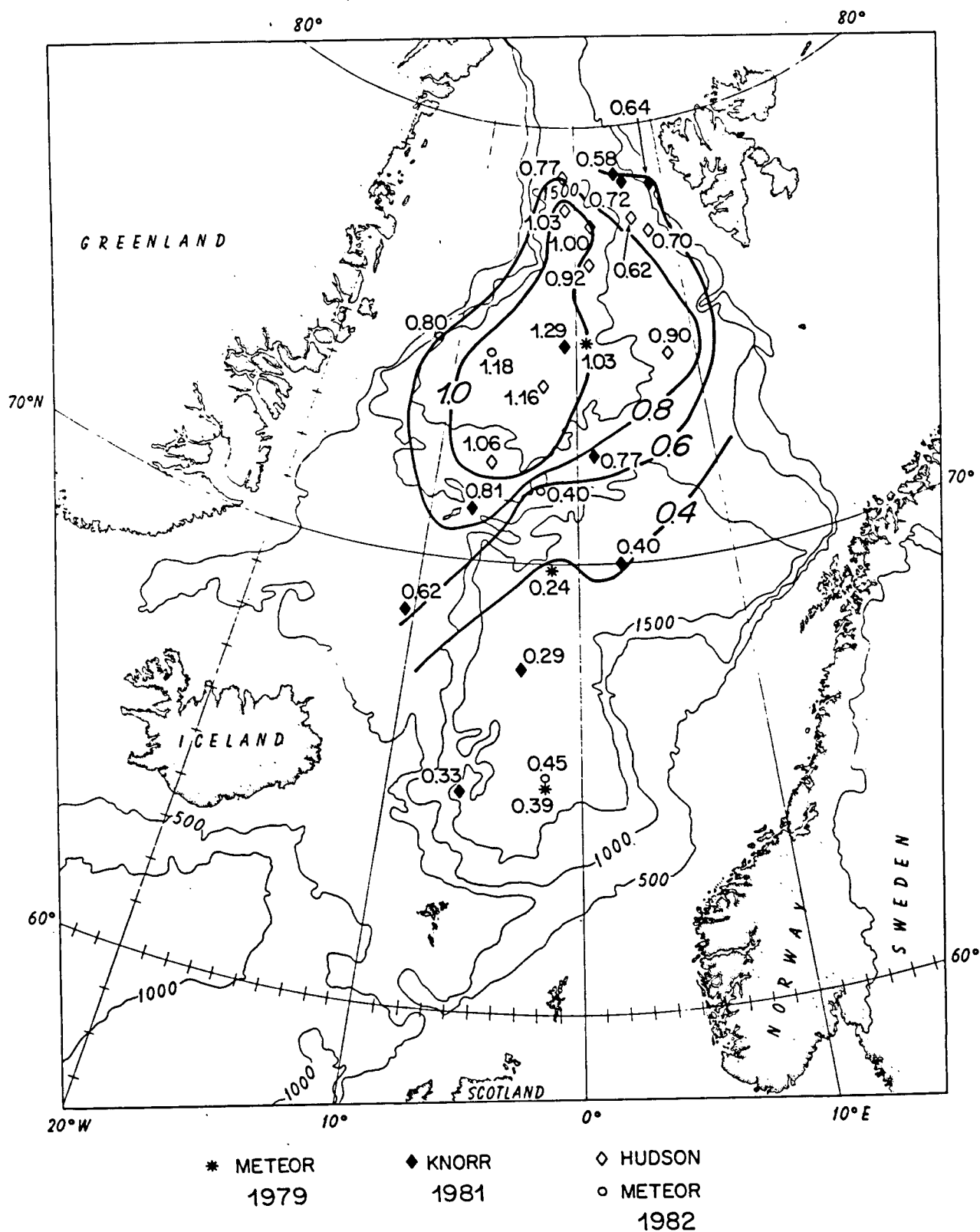


Figure 4: Average tritium concentrations (tritium units as of 1/1/81) in deep water. Symbols denote ship and year of collection.

TRITIUM/STRONTIUM-90 IN SURFACE WATER NORTH ATLANTIC NORTH OF 40°N

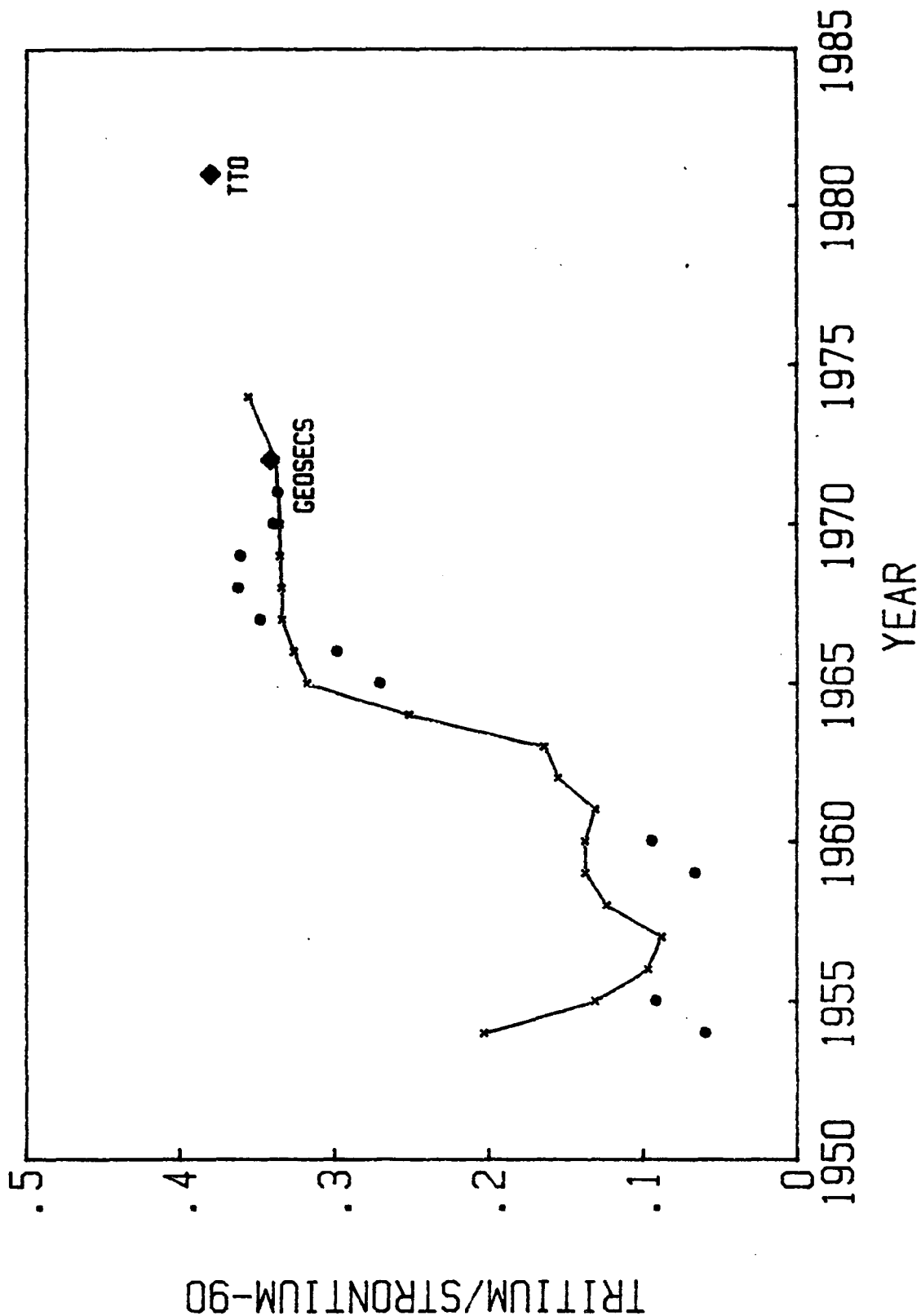


Figure 5: $^3\text{H}/^{90}\text{Sr}$ versus time, activities as of 1/1/81, in North Atlantic surface water. Solid symbols are experimental data; crosses and solid line denote theoretical data (after Dreisigacker and Roether (1978)).

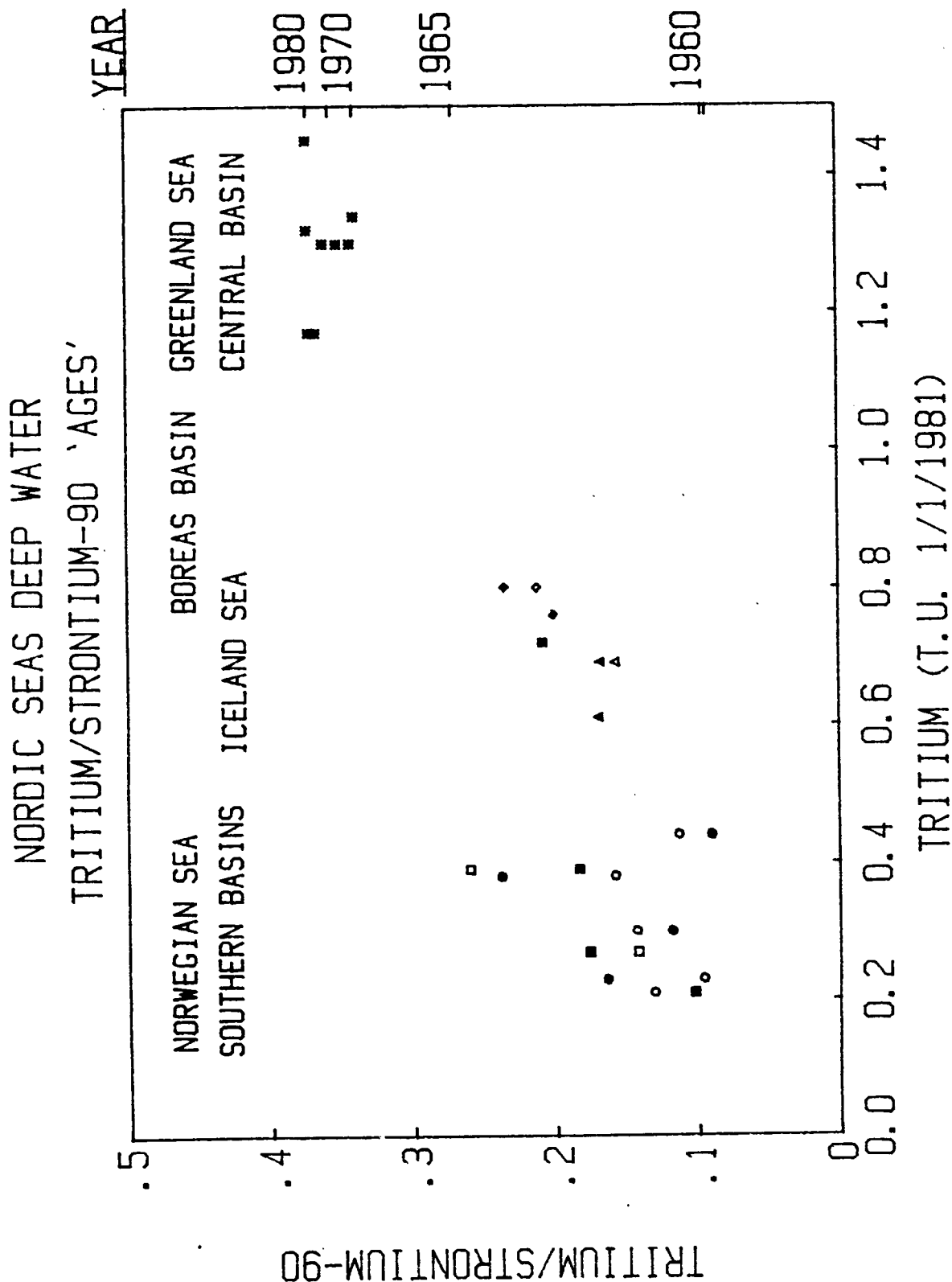


Figure 6: $^3\text{H}/^{90}\text{Sr}$ against ^3H concentration in Nordic Sea deep water - from TTO stations in 1981. Scale on right-hand side of Y-axis is the $^3\text{H}/^{90}\text{Sr}$ "age" from Figure 5. Symbols: stars = TTO-148; diamonds = TTO-149; triangles = TTO-159; squares = TTO-145; circles = TTO-144. (Solid symbols are derived by converting measured ^{137}Cs values to ^{90}Sr by multiplication by 1.5).