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ABSTRACT

During the summer of 1955 work was begun by the Lamont Geological Observatory on Contract AT(30-1)-1808 under the direction of Dr. M. Ewing. The purpose of the contract is a study of the circulation of the deeper oceanic waters.

This report describes results of the first year of study. The approach has been observational, and new tools have been developed to measure ocean parameters. The research has been organized along the lines of a five point program as follows:

1. Analysis and appraisal of a number of radiocarbon sea water samples taken prior to 1955 by the Lamont Geological Observatory.

2. Collection of additional samples in the Atlantic Ocean for radiocarbon analysis.

3. The taking of standard oceanographic observations and the survey of existing data pertinent to the study of deep oceanic circulation.

4. Construction of a neutral buoyancy deep float capable of drifting at a subsurface level and signaling its position to a surface observer for direct measurement of current velocity and direction.

5. Construction of a temperature-recording probe to measure temperature gradients in the ocean water and in the bottom sediment.

The principal effort of the first year has been put into the radiocarbon program. Careful re-examination of water esmples collected from 1951 to 1955 has allowed separation of reliable from doubtful samples. Some 30 samples have been selected for recounting under the improved

gas proportional system pending the outcome of the present sample series. Work has been done in establishing a standard for modern radiocarbon activity in wood and surface water. Dilution of radiocarbon by industrial fuel consumption has been considered. Fairly rapid equilibration has been assumed for ocean surface water and the atmosphere in relation to known changes in the atmosphere in the past 50 years.

New radiocarbon sea water samples were taken and new controls in sampling and processing were effected during 1955. Some 70 new samples were collected, 50 of which provide data for the present report. The distribution of these samples and the values obtained permit significant generalizations about the time scale and circulation of the western North Atlantic. All surface samples show good agreement, their activity being about 4% greater than 1938 wood. Possible intermediate water of Antarctic origin sampled in the western Atlantic has an apparent age of 500 years older than the surface. Average values for North Atlantic deep water are 350 years older than surface. Bottom water in the North Atlantic is diverse in activity with values from 350 to 370 years older than surface. Samples of Caribbean water reveal apparent ages about 400 years older than surface. Sample ages are uniform from basin to basin and uniform below sill depth in the Cayman Trough. The results of radiocarbon dating are in good agreement with other calculations of the general circulation of the Atlantic. The basis of a time scale for the deeper circulation has been provided.

Hydrographic observations have been taken in places and at depths where no data existed previously. Observations have been used

gas proportional system pending the outcome of the present sample series. Work has been done in examining a standard for modern radiocarbon activity in wood and surface water. Dilution of radiocarbon by industrial fuel consumption has been considered. Fairly rapid equilibration has been assumed for ocean surface water and the atmosphere.

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Hydrographic observations have been taken in places and at depths where no data existed previously. Observations have been used

for sample depth control for radiocarbon sample collection. A survey of existing deep temperature observations has been made and the data examined for evidence of periodic oscillations and discontinuities in the deep thermal structure. Results from the study of one well surveyed area in the North Atlantic indicate that extensive seasonal deep mixing takes place. Annual and longer cycle oscillations of temperature in the deep water system have been observed and correlation with climatic variations is suggested.

A neutral buoyancy deep float for the direct measurement of deep current is being constructed. The design is modified after the prcto-type made by the British National Institute of Oceanography in 1955. A system is planned whereby signal strength and instrument depth ranging will be improved over the original device.

A temperature probe for measurement of temperature profiles in the ocean and heat flow in the bottom sediments has been constructed. The device uses all electrical components and features a unique tempera-ture-sensitive oscillator. A frequency signal is sent up to a surface re-corder through conducting hydrographic cable. The use of frequency is seen as a great improvement over former systems using an amplitude signal. Two of these instruments will be in field operation in the Atlantic Ocean during the summer of 1956.

I. INTRODUCTION

Oceanography as a discipline embracing the physical, natural, and biological sciences is a product of the twentieth century. Its progress has depended largely upon direct observation of physical phenomena, with theoretical aspects following rather than preceding the observational. Its late development can be attributed to the remoteness of the oceans themselves and the consequent slow accumulation of information. Progress in recent years has been impressive, especially as applied to the understanding of the upper waters. Yet today very little is known with certainty about the nature of the deeper waters and in particular the time scale of the general circulation. The extent of the uncertainty of this important physical quantity is perhaps greater than in any other case in the natural sciences.

Today the basic tools for the study of ocean waters beneath the mixed layer are not substantially different from those used fifty years ago. The implications of this statement are numerous. It is good testimony that the early methods and tools were soundly conceived. It bears out that the apparent need for new methods develops no faster than the accumulation of data from the ocean. Very recently, military interest in the upper waters and in the measurement of ocean depth has brought forth many advances in instrumentation. Basic and applied interest in the deeper waters has only begun, and it is evident that need for information is increasing.

New basic interests include the measurement of heat flow through the ocean bottom, a study which has important bearing on the structure and thermal history of the earth. New discoveries in marine geology concerning the role of turbidity currents in deep sea deposition have aroused interest in numerous fields from petroleum geology to those interested in biological productivity of the sea. Students of recent earth history have made great progress through study of the record contained in deep sea sediments. The role of the oceans in present climate and in former climatic oscillations is of interest to meteorology and climatology. The study of the radioactive and trace elements in the ocean presents a whole new aspect not available to earlier workers. There is urgent need to survey present natural concentrations of these constituents before contamination takes place. The nature of the deep circulation of the oceans weighs heavily in considerations of disposal of radioactive wastes. The interest in this application has important economic and political bearing. The understanding of the ocean as an acoustical system has obvious military significance.

These are but a few of the basic and applied interests which require an accelerated program of research in the deep-sea. To satisfy this increasing need for information it is obvious that new methods of study need to be developed. It is the purpose of the present research to provide basic information on the nature of the deeper oceanic circulation through the development of new tools and new methods of approach.

II. BACKGROUND

Early interest in ocean current movement was largely descriptive and concerned with gross surface conditions. In the beginning of the present century a number of Scandinavian workers developed dynamic theories which remain the basis for present-day calculations of current movement. More recently results of studies in fluid mechanics and biological science have modified the earlier theories. Most current studies involve the computation of dynamic heights from observations of temperature and salinity. Underlying this procedure is the assumption that forces affecting the water are gravity, the pressure gradients associated with the variations of density, and the geostrophic force due to the earth's rotation. It is further assumed that accelerations are negligible and that currents are more or less steady in time, their magnitude and direction changing only very gradually with distance. Because of the scarcity of observations, greater homogeneity of properties, and smaller velocities involved in the deeper waters, dynamic calculations generally apply to waters no deeper than 2000 meters. Calculations of movement at greater depths lean heavily on the distribution of observed temperatures and chemical concentrations.

Various studies have applied continuity considerations to the mass and volume transport pattern of the Atlantic. As an example, the flow of water at various levels across the Equator in the Atlantic Ocean must be such that, on the average, the net flow from top to bottom of the section is zero. This must be true since the North Atlantic and Arctic oceans

are closed to the north and no appreciable amount of water can be accumulated or removed. Temperature and salinity concentrations are important in the mass continuity scheme. Recent studies have combined dynamic and continuity calculations. In this scheme a grid network is set up for a three-dimensional ocean model. Average oceanographic values are taken for different density levels in the vertical sections. In this way average lateral and vertical transport in and out of each level of each section is determined. Rational adjustments are required to preserve continuity across boundaries of adjoining units. Adjustments are based on the continuity of conservative concentrations of salt and heat. Some adjustment is also made for nonconservative properties of phosphate, oxygen, and nitrogen in accordance with the magnitude of biological processes.

It is noteworthy that calculations of deep currents have often differed greatly among oceanographers even when working with the same data. Certain mass transport calculations differ by 150% among recent studies (Jung, 1955; Riley, 1951; Sverdrup et al., 1942). Some of the difficulty lies in the failure of the geostrophic balance relationship in equatorial regions where the Coriolis effect vanishes for horizontal motion. The assumption that all oceanographic data used in a study of mass transpor. over a wide area is sumultaneous cannot be defended. There is good evidence that conditions are not stable in any one spot in the ocean from season to season and year to year (Iselin, 1936; Seiwell, 1937). Additional uncertainties which have entered into mass transport calculations are the

influence of tidal effects and of friction in the boundary regions of a water mass. There remains some controversy over the choice of a reference surface of no motion in deep water calculations. The subjective choice of a depth for the level of no motion has led to extreme disagreement. There is an instance where the selection of different levels has led workers to calculate not only different velocities, but opposite directions for movement at the same depth and place. Considering the paucity of data very few workers have attempted any comprehensive mass transport and current studies of the Atlantic circulation. Because of the difficulties already outlined none of the existing studies is entirely satisfactory. It is hoped that the simultaneous observations planned for the International Geophysical Year will help clarify many of the uncertainties in the dynamic calculations.

In order to escape the uncertainties of theoretical values of deep circulation or to confirm and supplement them, many workers have been led to experiment with direct observational measurement of water movement. A vast body of data exists for surface current movement obtained from ship's navigation and floating bottles. More recently radio signaling floats have been successfully used for surface current measurement.

Measurements of deep currents have been made in less than 20 areas in the North and South Atlantic (Bowden, 1954). These observations have largely employed some form of rotating current meter suspended from an anchored ship. One other form of direct measuring device has been the current drag which consists of a drag of considerable surface area

suspended from a float by a suitable line. The movement of the float is taken to reflect the movement at the depth of the drag.

The scarcity of direct observations of deep current movement makes it impossible to use them in any comprehensive picture of ocean circulation. There is some agreement with theoretical values as well as disparity. The uncertainties of both methods make them unsuitable to check one another.

Direct measurement values may be masked by periodic and non-periodic motions due to tidal currents and internal waves. Eddies and countercurrents may vary in position and magnitude daily, obscuring the general circulation pattern. Observations would have to be carried out over a period of a week in order to determine the phases and amplitudes of the constituents with sufficient accuracy to determine mean current. The greatest difficulty with such observations has been the problem of ship movement at a deep anchored station. Ship movement becomes a considerable factor when dealing with deep currents where velocities are small.

One new method of direct observation of deep current has been recently put to use. The system involves tracking a neutral-buoyancy float which moves at a subsurface level along with water of a density similar to its own. The float sends out an acoustical signal which enables a surface vessel to track its path. The development of such a device is part of the present research and will be dealt with in a later part of this report. The advantages of this system of direct observation are that a

mean velocity and direction is obtained unaffected by ship movement and the various periodic and non-periodic uncertainties. At the same time the observations provide valuable data in the study of tides and internal waves.

Only two such observations have been made so that the results play no part in understanding the general circulation.

An interesting indirect observational method in the study of deep ocean circulation exists in the measurement of heat flow in the ocean bottom sediment (Revelle and Bullard, 1952). Only a handful of observations have been made but the results have received much attention in that they are contrary to prediction. The value of heat flow through the ocean floor measures 1.2×10^{-6} cal/cm^2/sec or within ten percent of the average value for the continents. This comes as a surprise since it had been assumed that the granitic rocks of the continents held a much higher radioactive content and therefore generated a greater amount of heat than the basic rock beneath the oceans. If the ocean bottom measurements are correct, the heat flow is such that a minimum velocity of bottom water movement is required in order to prevent instability by heating from below. With a current of 0.1 cm/sec the bottom kilometer of water would increase 1 degree centigrade in passage from polar to equatorial regions. If the movement is considerably less than this estimate, some effect should be observed in the heating of bottom water as it moves away from its place of origin. This kind of indirect evidence can be expected to set certain limits in the study of deep ocean circulation. A new device for sensitive

temperature measurement in the ocean bottom and in the water has been developed under the present contract and will be discussed later in this report.

The present concepts of the deep ocean circulation are based largely on descriptive data and dynamic interpretations. The North Atlantic has been more intensively studied than any comparable body. Considering this, and the fact that the new observations of this study apply to the North Atlantic it is well to review the theories of its general circulation.

Five major water masses occur in the North Atlantic Ocean. In the upper levels above 1000 meters the mass identified as Atlantic Central Water has widespread distribution. The water is characterized by relatively high temperature and salinity. Within this mass the great central gyre of surface circulation operates, bounded on the south by the North Equatorial Current, on the west by the Gulf Stream. and around to the north by the North Atlantic Current. Water of the central Sargasso Sea area shows evidence of mixing with Mediterranean water, Deep water from below and Intermediate water of South Atlantic origin (Iselin, 1939). It is of interest that surface current influence has been traced into intermediate depths where it may impart considerable motion to underlying waters (Martineau, 1953).

To the north in the Norwegian Sea and Greenland Sea areas minor subsurface water masses form seasonally due to cooling at the surface but probably do not flow south over the sills to join the major Atlantic circulation. The surface circulation of the northern seas is of greater influence.

Surface Atlantic water flows toward the Arctic to the east of Iceland and flows out through the Denmark Strait west of Iceland. The Arctic Surface Water which flows out is considerably colder and less saline. The renewal time for the Arctic basins is calculated to be about 165 years (Sverdrup et al., 1942). West of Greenland in the Labrador Sea and in an area southeast of Greenland this cold water from the north mixes with Atlantic Water. During the winter this mixing extends to great depths and the sinking of a large volume of water accounts for the formation of the North Atlantic Deep Water. This mass, identified by relatively uniform temperature, exists throughout the North Atlantic between 1500 and 4000 meters and can be traced deep into the South Atlantic by its moderately high salinity. It is calculated that the Deep Water formation in these two areas accounts for two thirds of all the water leaving the surface in the North Atlantic (Sverdrup et al., 1942). Arctic Bottom Water of less than 2°C. may be formed in both of these areas but is difficult to trace as a mass south of about 50° N. Lat.

Across the southern North Atlantic extending to about 20° North a distinctive water mass of South Atlantic origin is present. This lobe of Antarctic Intermediate Water is characterized by low salinity and fairly high oxygen content. It occupies a level centered around 800 meters and can be traced through the Caribbean circulation and into the North Atlantic Central Water where it loses identity. This mass is formed in the South Atlantic at the surface about 55° South and its major axis of movement closely resembles that of the South Atlantic surface circulation (Riley, 1951; Martineau, 1953).

Intermediate water of North Atlantic origin is of little consequence. High oxygen concentrations in the western North Atlantic at about 45°N probably indicate formation of this water but it is lost in the mass of Deep Water.

Another intermediate type is put into the North Atlantic by the sinking of water emerging from the Mediterranean outside Gibraltar. This Mediterranean Water is traceable as a lobe of high salinity for great distances from its place of origin at about 1200 meters depth. It accounts for the remaining third of surface water which sinks in the North Atlantic to become part of the southward moving Deep Water (Sverdrup et al., 1942).

Antarctic Bottom Water forms at the surface along the edge of the Antarctic continent. Water of this origin enters the North Atlantic and is evident in temperature profiles to about 10° North Latitude. Salinity concentrations indicate the presence of this water type beneath the Deep Water to about 35° North.

The total picture of the deeper water masses is that they represent water whose density has become greatly increased when in contact with the atmosphere in high latitudes. Sinking and subsequent spreading has caused this water to fill all the deeper portions of the oceans. In the North Atlantic the Deep and Bottom Waters flow to the south, the Deep Water being reinforced by additions from Mediterranean Water, Antarctic Bottom Water flows northward across the equator along with Antarctic Intermediate Water and surface currents, together equal to the volume transport of the Deep Water. Table 1 from Sverdrup et al. (1942)

illustrates this net transport scheme as worked out through continuity considerations of salinity. Velocity calculations are from Riley (1951).

Table 1

TRANSPORT OF WATER ACROSS THE EQUATOR

Water Mass	Transport in millions m^3/sec		Av. vel. cm/sec
	North	South	
Upper Water	6	--	1.2
Intermediate Water	2	--	.13
Deep Water	--	9	.24
Bottom Water	1	--	.03

Using essentially these same values Jung (1955) has developed a detailed scheme of circulation and mixing in the North Atlantic. The study is based on mass transport considerations for which the chief agent is considered to be the large-scale advection process, with the contributions from eddy and molecular diffusion being several orders of magnitude smaller. Results of this study indicate that in the upper levels the central gyre of North Atlantic Central Water receives horizontal additions from the Caribbean and Labrador Sea area. Losses occur to the Mediterranean and the Labrador Sea. The major sinking areas off Greenland and outside Gibraltar are shown to be the major contributors to the Deep Water but contrary to the earlier estimate, the Mediterranean volume is considered rather larger than the more northerly counterpart.

The greatest part of the Antarctic Intermediate Water is considered to mix with the Central Water in a region about 22°North. A

considerable mass of Deep water is believed to mix upward into Central water about 15 degrees north. A sizeable mass equal to 1/5 the amount which moves south across the equator is withdrawn from the Deep Water to enter the Caribbean. This rather large mass is in agreement with the evidence of rapid turn-over in the Deep water of Caribbean area.

As indicated previously, the velocities involved in these water mass movements have never been satisfactorily established. Only average velocity estimates of levels of the deeper water are available. Riley (1951) has published average values (Table 2) for the North Atlantic considering only the net north-south components in a two-dimensional scheme.

Table 2

Calculated Average North-South Velocities in the North Atlantic in cm per sec.

Latitude	1500M	2000M	2500M	3000M	3500M	4000M
54°N	S .10	S .11	.00	.00	.00	-----
45	S .10	S. 09	N..01	.00	S .01	N .01
36	S .10	S .06	N .01	.00	S .01	N .01
27	S .11	S .05	N .02	N .01	S .02	S .01
18	S .12	S .04	N .02	N .02	S .03	S .02
9	S .12	S .04	N .02	N .01	S .03	S .03
0	S .09	S .04	S .01	S .01	S .03	S .04

These data are highly idealized and do not consider such important influences as bottom topography nor axes of maximum current movement.

Other methods based on special properties of the water have been used to estimate velocities in the deeper levels. Based on volume outflow and salinity of Mediterranean water Iselin (1936) has estimated a flow of this water toward the western Atlantic at about 2.5 cm/sec. By the same reason the flow of Intermediate Water into the North Atlantic from the south is put at 2.7 cm/sec. Seiwell (1934) has used oxygen distribution in a transect through the southern North Atlantic (from 35° to 10° north) as an indicator of velocity. A series of maxima and minima was found in the oxygen-poor level (500-800 meters) which was taken as a yearly variation. From the distance between successive minima a velocity of 1.5 cm/sec south in the northern portion was deduced, while a velocity of 1.3 cm/sec north in the southern portion was assumed. Similar estimates based on oxygen in the South Atlantic have been made (Deacon , 1933) but both can be criticized for the assumption that the observed oscillations represent annual cycles.

III. RADIOCARBON STUDIES

One of the newest tools in the investigation of deep ocean circulation is the study of natural radioactive isotopes found in sea water. In 1950, shortly after the radiocarbon laboratory was set up at the Lamont Geological Observatory, M. Ewing initiated work on the age determination of sea water by the radiocarbon method, together with J. L. Kulp.

The principles of the radiocarbon method are now well known. Carbon-14 is a radioactive isotope formed indirectly by the action of cosmic

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The principles of the radiocarbon method are now well known. Carbon-14 is a radioactive isotope formed indirectly by the action of cosmic

rays in the earth's atmosphere. The nature of this isotope is such that in a given quantity of C-14, spontaneous radioactive disintegration takes place at a rate which reduces the original amount by half in a period of about 5,500 years. This characteristic half life rate has been used to date materials which contain carbon by comparing the present ratio of C-14 to the normal element in the sample with the ratio found in very recent material of the same type. Using this method, dating has been accomplished on suitable material as old as 40,000 years by application of the formula

$$\text{age (in years)} = \frac{-\log \frac{N}{No}}{\log 2} \times 5.568$$

where $\frac{N}{N_o}$ is the fraction of C-14 remaining, and 5,568 is the half-life of C-14 in years.

The principle has been applied to ocean water which at the surface is subject to exchange of gasses with the atmosphere. When water sinks from the surface to become part of a more or less distinct subsurface mass it is effectively sealed from further contact with the atmosphere. If a sample of deep water is taken some distance from its high latitude source, its radiocarbon activity is ideally a measure of the time since it quit the surface. The sample age and present location relative to its source region become measures of the direction and velocity of the water movement. Additional samples along the line of movement of the water mass can be expected to tell something of its history.

In applying the radiocarbon method to the dating of sea water certain basic assumptions are necessary. Based on studies of the stable isotopes of carbon (Craig, 1954), complete equilibrium between surface ocean water and the atmosphere would give the carbon dioxide components in the water a 5% higher concentration of C-14 than the present carbon dioxide in the atmosphere. This effect is due to fractionation. While carbon dioxide from the atmosphere with its C-14 content is imparted to surface ocean water through diffusion, the surface water is continuously being diluted by C-14 deficient water from depth. Considering these opposing processes, unless equilibration is rapid the C-14 concentration in surface water will be considerably less than the predicted value. Our average of five surface samples is 4% higher than a sample of 1938 wood from Palisades, New York.

This picture has been considerably complicated by recent changes in the carbon dioxide content of the atmosphere. During the past 60 years great quantities of CO_2 with no radiocarbon activity have been added to the atmosphere through the burning of industrial fuels. The effect has been a "dilution" in recently formed carbon material which makes it appear older than similar material formed 60 years ago. The quantity of CO_2 added has been estimated at 6×10^{16} grams during this period. This amounts to an increase of 10% in the atmospheric carbon dioxide. A measure of the C-14 activity of woods grown in 1890 and recently should reveal how much of this CO_2 has remained in the atmosphere. Table 3 represents the value of the change as determined in

In applying the radiocarbon method to the dating of sea water certain basic assumptions are necessary. The greatest part of the carbon dioxide content of deeper waters is acquired through diffusion when at the surface in high latitudes. Observation shows that the partial pressure of CO_2 in arctic surface water is 15×10^{-5} atmosphere. The concentration in the atmosphere in the same regions is 33×10^{-5} indicating that CO_2 passes into solution in the water. In equatorial regions the picture may be reversed with higher partial pressure in the ocean surface. It is assumed that the surface water is essentially in equilibrium with the atmosphere with respect to the C-14 ratio. The predictable radiocarbon activity of surface water under these conditions at the present time would be about 5% higher than that of recently grown wood. Our average of five surface samples of the present series from the Atlantic is 4% higher than a 1938 wood sample. This activity gives an apparent age of 80 years to the surface water.

There is, however, a significant change in the atmospheric content of carbon dioxide which must be considered in the choice of a modern standard of activity. During the past 60 years great quantities of CO_2 with no radiocarbon activity have been added to the atmosphere through the burning of industrial fuels. The effect has been a "dilution" in recently formed carbon material which makes it appear older than similar material formed 60 years ago. The quantity of CO_2 added has been estimated at 6×10^{16} grams during this period. This amounts to an increase of 10% in the atmospheric carbon dioxide. A measure of the C-14 activity of woods grown in 1890 and recently should reveal how much of this CO_2 has remained in the atmosphere. Table 3 represents the value of the change as determined in

Table 3

Effect of Industrial Fuel Consumption on Radiocarbon Content of Various Wood Samples

Lab	Sample Location	Age	% Difference (Corr. for Age)
Los Alamos	Lake Geneva	1933-53	-3.0
	Wisconsin	1913-33	-1.7
		1890-1913	.0
	Peonuia	1934-54	.7
	Amazon	1874-1903	.0
		1844-1874	-.2
U.S. Geol. Survey	Moses Pt.	1945-50	-1.9
	Alaska	1874-80	.0
	Petersham	1946-53	-2.7
	Mass.	1936-46	-3.3
		1840-1850	.0
	Yosemite	1950-53	-1.1
	Cal.	1940-44	-1.9
		1895-1900	.0
	Cedrela	1948-53	-1.0
	Peru	1943-46	.0
		1890-1896	.0
Lamont	Palisades	1936-40	-2.1
	N.Y.	1888-1892	.0

various places from the radiocarbon activity of wood samples. The results indicate a 2% change in the Northern Hemisphere and perhaps no change in the Southern Hemisphere. That 80% of the added carbon is missing from the atmosphere lends further support to the idea of rapid equilibration of surface water and atmosphere. Considering that the present top 225 meters of ocean water may have been in contact with the atmosphere during the past half century then one would predict a dilution of 2% in recently grown wood. This calculation does not take account of the influence of the biosphere.

There is, however, some evidence that the absolute amount of CO_2 in the atmosphere over the northeastern Atlantic Ocean has increased to a greater extent than the wood sample analyses indicate. A summary of existing data (Harvey, 1955) indicates an increase or atmospheric CO_2 of 7% over the past 60 years.

If very slow equilibration of surface ocean and atmosphere were assumed then perhaps the age corrected value for 1890 wood should be used as a modern standard. In this case, the surface ocean value would be only 2% higher than the modern standard, equivalent to an age of 250 years for surface water. However, evidence of removal of the industrial carbon, and evidence that surface water activity is quite uniform support the view of rapid equilibration. Clearly, the problem of ocean surface equilibrium, dilution, and fractionation with respect to Carbon-14 needs further investigation.

Throughout this study the activity of the various ocean water samples has been referred to a 1928 wood standard. On this scale surface values are

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There is, however, some evidence that the absolute amount of CO_2 in the atmosphere over the northeastern Atlantic Ocean has increased to a greater extent than the wood sample analyses indicate. Measurements of atmospheric carbon dioxide in this area (Harvey, 1955) show a present concentration of 0.032%, an increase of 7% over sixty years ago.

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Throughout this study the activity of the various ocean water samples has been referred to a 1938 wood standard. On this scale surface values are

uniformly plus 4% of 1938 wood, or apparently 80 years old. Deeper samples are described by their age older than surface.

A further complication attends the relationship of deep to surface water, regarding the extent to which the deeper water has been affected by the atmospheric dilution in the past 60 years. Surface water may have had a 2% higher C-14 content in the past. Water of such initial activity is without doubt still in the system as Deep and Bottom Water. Therefore, ages for deeper water calculated on the basis of present-day surface activity should be considered a minimum. The true age could be as much as 150 years older if a 2% dilution of the surface water-atmosphere has in fact taken place.

A. Methods of Radiocarbon Sea-Water Sampling and Processing.

The procedures for radiocarbon sea-water sampling have been set up to collect large-volume samples from accurately known depths in the ocean, extract the inorganic carbon in the form of carbon dioxide, and return the sample to the laboratory in a suitable form where it is refined and its radioactivity counted. This experiment has had no precedent and it is natural that many modifications of method should have taken place since the initial work was begun.

The main problems which have been encountered in carrying out these procedures can be listed as follows:

1. Securing water samples of sufficient size.

2. Securing samples from known depths free from contamination by water from any other depth.

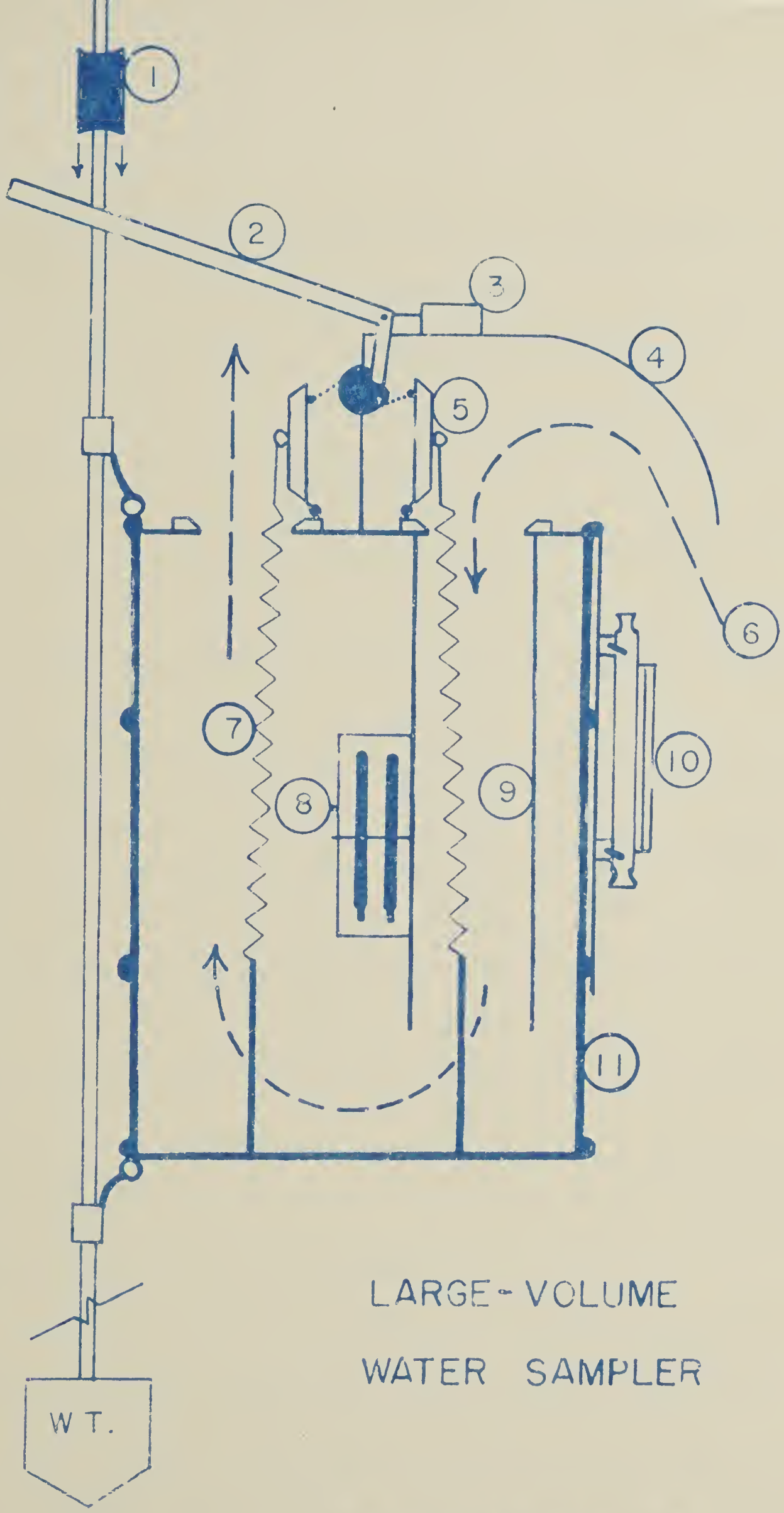
3, Avoidance of contamination by reagents or by exposure to the atmosphere.

4. The efficient extraction of CO_2 from sea water.

5. Increase in the sensitivity and accuracy of the radiometric assay.

All but the last of these problems is peculiar to ocean water sampling techniques. During the course of this work improvements have been made in all of these areas.

Initially no water sampler of sufficient size existed, and a large-volume sampler had to be developed. Figure 1 illustrates the present large-volume water sampler in use. The device is lowered in the ocean by a winch using one-half inch steel wire rope. The barrel is attached to the wire some distance above a 1500-pound weight which hangs on the lower end of the wire. The body of the sampler (11) is a heavy gauge steel barrel of 110 gallons capacity. When the sampler reaches the desired depth a "messenger" (1) in the form of a heavy weight is dropped down the wire from the surface to effect the closing of the sampler. The messenger moves a lever (2) which trips the doors (5) thus sealing the water sample from the desired level. Depth of closing is registered by a pressure-activated recorder (3). Circulation through the vessel while descending is achieved by channeling t he flow through one door and out the other. A sheet-metal scoop (4) funnels the flow of water (6) into the first door. Dashed lines represent the flow which is conducted to the bottom of the barrel by a large tube (9) and thence up and out through the second door. Inside the barrel are two deep sea reversing thermometers (8) which accurately record



LARGE-VOLUME

WATER SAMPLER

FIGURE 1

temperature and, by computation, depth of the water sampled. Outside the barrel is a 2-liter Nansen-type water sampler (10) fitted with thermometers similar to the ones within. The Nansen bottle closes at the same time as the larger sampler. The ehemistry of the water sample taken outside is compared with that of the larger sample for possible leakage into the barrel from levels other than the desired depth. Comparison of temperatures within and without is a check on the circulation and closing of the large sampler. Computed values for depth of closing are compared with indicated values of the predsure recorder (3).

The large-volume water sampler described is the result of considerable evolution. The earliest samplers used were 55-gallon containers which proved too small in volume for the CO_2 extraction methods at the time. Later 250 gallon steel barrels were used which provided a good amount of sample but were slow and difficult to handle. At another time collapsible canvas and rubber types were tried but showed evidence of leakage. The present device has shown signs of contamination less than 3% of the times used, and in most cases leakage or malfunction is easily detectable through the control system which is employed.

The method of extraction of carbon dioxide aboard ship has also undergone a series of refinements. In practice the water collected in the large-volume sampler is pumped out into a processing tank immediately upon being brought to the surface. The processing tank is a permanently-mounted monel metal container fitted so that sample water can be introduced without contact with the atmosphere. When the sample has been transferred to the processing tank about one liter of concentrated sulfuric acid is added.

A strong acid must be added to the sea water in order to displace the equilibria of the carbonate and bicarbonate toward free CO_2. At the bottom of the tank is a coil of pipe having many perforations through which nitrogen is introduced with extensive bubbling. An outlet at the top of the tank leads the gas to a caustic absorbing medium.

At first, tank nitrogen was used to sweep the sample and a solution of NaOH and $Ca(OH)_2$ was the absorber. This system proved troublesome and the absorbent easily contaminated. Later, air was used to sweep the sample and a dry material, Ascarite, was the absorber. Corrections necessary for the CO_2 content of the air and the impure Ascarite made this undesirable. The present system employes tank nitrogen which sweeps the CO_2 into a purified KOH solution. The caustic medium is a 8 N solution especially prepared to eliminate CO_2. Starting with USP KOH, a 14 N solution is prepared. Then a solution of $BaCl_2$ is added, precipitating the carbonate of the reagent as $BaCO_3$. The suspension is filtered through glass filter paper and the filtrate immediately capped. The 14 N KOH is then diluted to 8 N using boiled distilled water and put into specially designed bubblers. The CO_2 content of this solution is less than 0.08 mg per ml.

The absorbing bubblers used in the shipboard process are rugged steel cylinders capable of being used together in series as absorbers, and also as shipping containers. The cartridges have an inlet and an outlet tube which are stoppered except when in use. The containers are filled half way with 500 ml of solution. The inlet tube extends to near the bottom

SHIPBOARD SEA WATER

PROCESSING FOR

RADIOCARBON

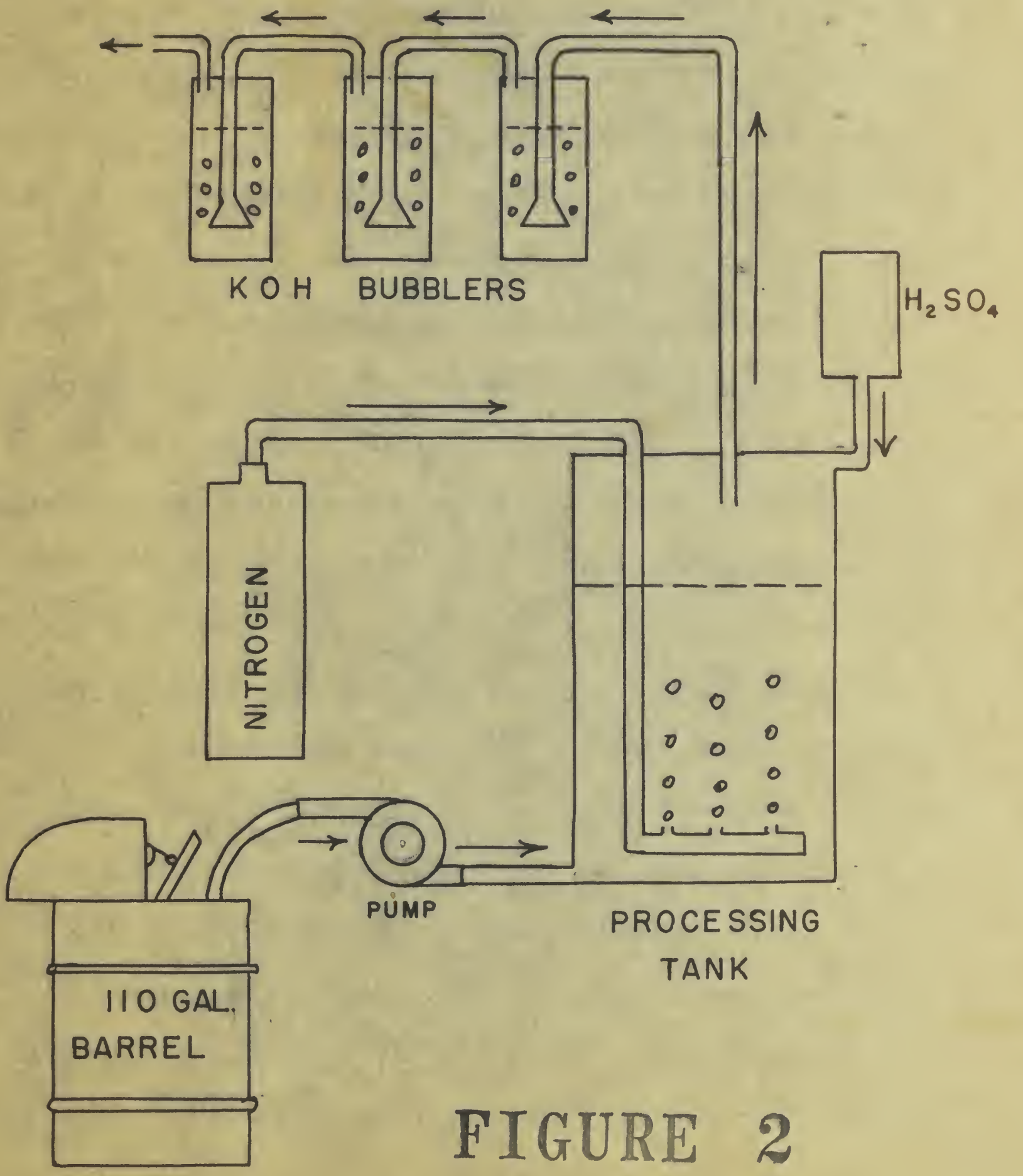


FIGURE 2

where it terminates in an inverted funnel perforated to cause incoming gas to break up into numerous small bubbles. The outlet near the top accommodates a fitting which permits connection to the inlet of the following bubbler. In operation three bubblers are used in series. The mixture of N_2 and CO_2 from the processing tank passes through the train of bubblers where the CO_2 is absorbed, the nitrogen passing out into the air. Figure 2 illustrates the shipboard processing system. One component not shown is a filter of 200 mesh wire cloth between the pump and the processing tank. This has been used to eliminate particulate carbonate material which might contaminate the normal C-14 content of the sample. Under these processing conditions nitrogen is passed through the sea water for about four hours at a flow rate of 12 to 15 liters per minute. This amount of nitrogen is equal to about eight times the volume of water being processed and is calculated to remove nearly all the CO_2. A flow meter is placed in the line as it emerges from the nitrogen tank and another meter after the last bubbler, These indicate the flow rate and also, by comparison, reveal any possible leaks in the system. At the end of a run the bubblers are disconnected from each other, immediately sealed and eventually shipped back to the laboratory. The spent sea water sample is allowed to drain from the processing tank, its volume being replaced by nitrogen to avoid having air in the tank at any time.

When the sample returns to the laboratory it is transferred to a glass flask in which it is acidified with 50% H_3PO_4. The KOH is first neutralized then the carbonate is decomposed, releasing the CO_2, which is collected by freezing it in a cold trap, then expanded into a solution of

ammonia, where it is absorbed. The ammoniacal solution is bubbled with oxygen to oxidize any sulfite present, then a solution of $CaCl_2$ added to precipitate the carbonate as $CaCO_3$. The precipitate is recovered by filtration and dried. 50-60 grams of the dried $CaCO_3$ is hydrolized with 50% phosphoric acid, again releasing the CO_2 which is collected in a cold trap, passed through a drying column of phosphoric anahydride and allowed to pass into a reservoir of very pure calcium oxide, inside a furnace which is at a temperature of 800°C, where it is absorbed forming $CaCO_3$. The temperature of the furnace is dropped to 450°C at which point the vapor pressure of CO_2 over $CaCO_3$ is zero, and the CaO reservoir pumped on to remove any lingering impurities still associated with the CO_2. After pumping, the temperature of the furnace is raised to 950°C, the $CaCO_3$ in the reservoir decomposes, releasing the CO_2 which is collected as a solid. The CO_2 is now in a very pure condition, suitable for the detection of C^{14} in a proportional counter.

B. Radiocarbon Samples Prior to 1955.

From 1950 to 1955 workers from the Lamont Geological Observatory collected ocean water samples for radiocarbon analysis during eight research cruises. Figure 3 shows the sample locations. Various processing techniques already described were used in this work. The earliest C-14 assays were made using the solid-carbon counting method (Kulp, 1952). In 1954 the laboratory converted to the proportional carbon dioxide method which has allowed higher precision and eliminated fission product contamination.

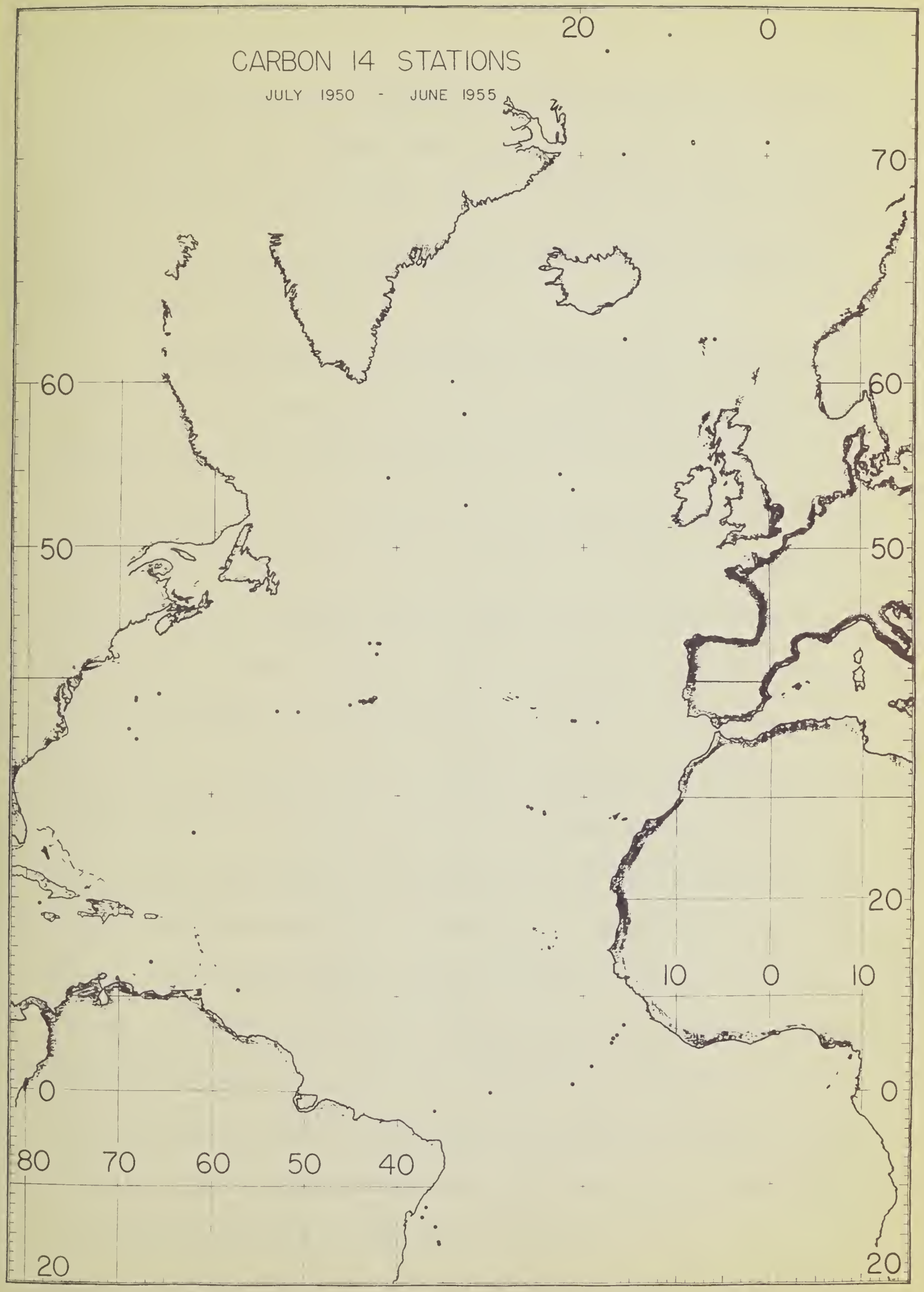

CARBON 14 STATIONS
JULY 1950 - JUNE 1955
20
0
70
60
50
20
10
0
10
0
20
80
70
60
50
40
20

FIGURE 3

A few preliminary results have been published on the earlier samples (Kulp, 1952 ; Kulp, 1953). Apparent ages as great as 1900 years were indicated for bottom water. More recently, in the light of results from improved techniques these ages have been revised downwards (Kulp and Broecker, 1956).

As part of the present research careful reappraisal has been made of 78 samples obtained up to June 1955. A number of samples previously counted by the solid-carbon method were recounted by the proportionate carbon dioxide method. Experiment with reagents used for processing of certain samples has revealed an amount of contamination which must be corrected for in the apparent age. This effort has allowed separation of reliable from doubtful samples. Table 4 lists those samples which are considered reliable within known limits of error. These samples are being held for recounting until additional sampling under newer methods can be done in the same areas as a check on the older samples. Another 15 older samples not listed in Table 4I may be considered potentially worth while in that known malfunction of the counters makes the previous counts invalid. Most of the samples in Table 4 were counted under the solid carbon system and the average error for the group may be considered $\pm .2$ with correction. Count rates have been corrected for contamination due to the amount of CO_2 contained in the absorbing medium. Using the value for surface water obtained in later sampling, the surface value of this group should equal about 6.4 counts per minute.

Table 4

RADIOCARBON SEA WATER SAMPLES 1950-1955

Surf

Sample No.	Lat.	Long.	Depth Meters	CPM Corrected
136A	58.26N	28.5W	Surface	6.4
136B	63.45N	27.5W	3182	6.1
172B	60.02N	34.12W	Surface	6.4
172C	62.17N	15.30W	1463	6.6
172D	62.17N	15.30W	2195	6.35
172E	62.17N	15.30W	1045	6.4
172H	70.04N	15.24E	1062	6.25
172I	73.22N	17.15E	Surface	6.3
172K	70.29N	07.57E	1453	6.5
172M	73.53N	10.26W	2335	6.3
172N	73.53N	10.26W	777	6.15
172O	73.53N	10.26W	Surface	6.3
172P	70.25N	00.08E	305	6.2
174F	14.09S	35.55W	2834	5.6
174G	02.00S	35.59W	4120	5.5
174H	10.33N	57.20W	3890	5.6
183D	42.30N	42.00W	Surface	6.2
183K)			4025	5.7
183L)	W. N. Atlantic		Surface	6.1
183T)			1737	6.0

20 Samples of which 6 are Surface.

Series 136 samples were taken in 1952 in the North American Basin of the Atlantic. The samples were collected in a 250-gallon container and CO_2-free air was used to sweep the sample while Ascarite was used to absorb the carbon dioxide. The deeper sample has an apparent age of 350 years older than surface with a rather large uncertainty of ± 200 years.

The 172 series includes samples from the North Atlantic and the Norwegian Sea area. Ascarite corrections were necessary but the samples were sufficiently large (200 gallons) so that the Ascarite CO_2 contribution was relatively slight. It is interesting that none of the activities are significantly different from the surface. This would be in accord with oceanographic theory which applies to the northern seas. In certain areas in this region deep mixing in winter is believed to bring dense surface water nearly to the bottom. A number of additional 172 samples are on hand for possible recounting when the correlation with newer samples becomes definitely established.

Samples of the 174 series were collected in the fall of 1952. The samples shown in Table 4 are from the Deep water near the Equator. The original samples were of smaller volume than some of the earlier ones which causes the Ascarite correction to be relatively greater. The apparent age difference from surface is 800 to 1,000 years. This seems to be a reasonable age for the lower Deep water in the South Atlantic which should fall amont the oldest values we have. Four additional samples of this series are on hand for recount, awaiting the results of the present VEMA cruise samples collected in the same area January-April, 1956.

The 183 series was collected using the collapsible sampler and because of possible leakage many of the deep samples may be considered unreliable. The corrected surface values appear older than later samples in the same area. If the surface ages are made to agree with newer figures the deeper samples fall in line with the newer ages as well. Further sampling in the area should show whether this practice would be justified. Only a few other samples of this series are potentially usable.

The progress of this research to 1955 was marked by accumulating experience in technique. The results of the sampling have produced age values for ocean water which are in general accord with those arrived at through present improved methods. The results obtained through research under the present contract have enabled the earlier values to be corrected in the light of more precise observations.

C. Radiocarbon Samples, 1955.

In June, 1955 under the present research program, radiocarbon sea-water sampling was begun using the latest methods. Since then more than 70 individual samples have been collected, of which about 50 have been completely processed and counted, while work on the remainder is nearly completed. Preliminary results indicate the highest order of precision thus far achieved. All of the results are on hand for samples taken on VEMA Cruise 7, June-September, 1955. Most of the results are completed for VEMA 8 samples taken during September-December, 1955. Only a few samples have been received from VEMA 9 cruise and laboratory processing has just begun.

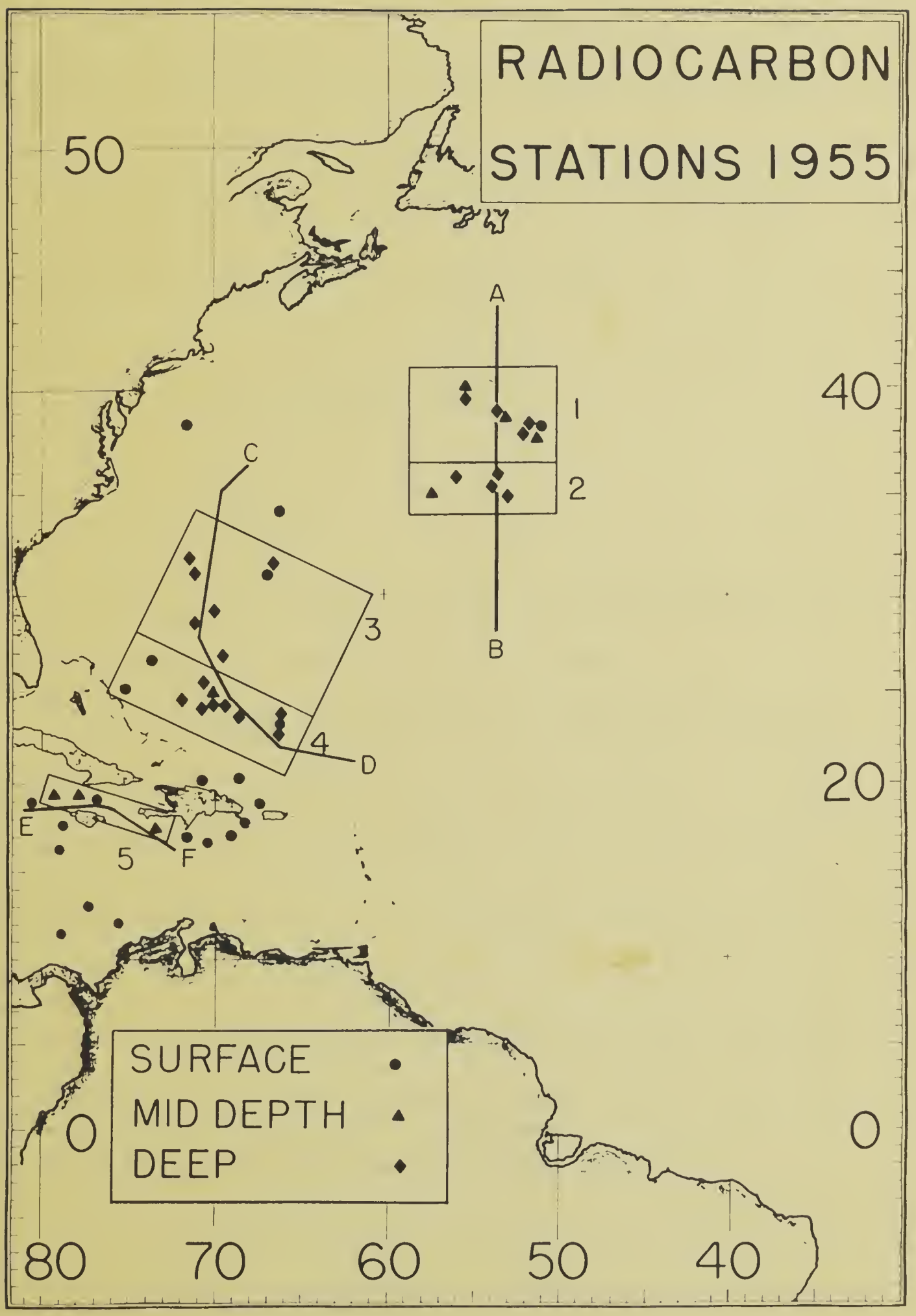

RADIOCARBON
STATIONS 1955
50
40
20
0
80
70
60
50
40
A
B
C
D
E
F
1
2
3
4
5
SURFACE
MID DEPTH
DEEP

FIGURE 4

During VEMA Cruises 7 and 8 samples were taken in the western Atlantic in places indicated in Figure 4. For ease of discussion blocks of samples have been set off in sections numbered one through five. The samples were collected and processed in the manner already described. Table 5 lists the data pertinent to the VEMA 7 cruise samples. The columns in that table are organized in the following way:

No. 1. Ocean depth in meters.

No. 2. Sample depth in meters.

No. 3. Latitude.

No. 4. Longitude.

No. 5. Equiv. amount of carbonate extracted from KOH (in most cases CO_2 evolved was measured in gas phase).

No. 6. Amount of KOH from which CO_2 was extracted. A train of five bubblers each containing about .5 liter of KOH. When 0.8 normal KOH was used the first 3 or 4 bubblers were processed and with the 8 normal KOH only the first 1 or 2. Normally 100 gm or more $CaCO_3$ should be collected. For the VEMA 7 samples insufficient N_2 was used and the yields were low (approx. 30%). On the VEMA 8 cruise the correct amount of N_2 was used and the yields were quite high (greater than 75%) giving more than sufficient material for the most sensitive analysis.

No. 7. Counter No. Two counters (C and D) were used to make these measurements. The two differ slightly in their characteristics.

No. 8. The raw count rate for one overnight run (approx. 1000 min. duration). The error quoted is a combination of statistical error (approx. 2 CPM) and uncertainty in efficiency (approx. 2 CPM).

No. 9. The average background for counter during period of the given run (measured about once per week). Error is from deviations of bgd. about mean value.

No. 10. Difference between (8) and (9). Error sq. root of sum of sq. on errors for 8 and 9.

No. 11. When samples were too small to fill counter to usual pressure (1 atm. for these samples) the sample was diluted with CO_2 free of C^{14} activity to bring it up to suffiicient size. The number given is the fraction of sample CO_2.

No. 12. Net count corrected to 1.00 dilution.

No. 13. Meson count rate during run. Remains constant to within one percent except at times of extreme atmospheric pressure variation. Tests have shown that the C^{14} efficiency is very nearly a linear function of meson efficiency. For small deviations the C^{14} efficiency changes may be considered to be equal to the meson efficiency change. Hence the meson count is used as a crude check on counter efficiency which may vary slightly due to residual impurities in the CO_2. Subsequent to the measurement of these samples a Co^{60} gamma ray source has been adapted for more rapid and accurate efficiency monitoring. Also the purification techniques have been developed to the point where variations in purity are very small in most cases.

No. 14. As explained above the meson count was used to estimate the slight efficiency variations. The corrections involved are small in most cases (i.e. less than 1%);where larger, the error has been increased correspondingly.

No. 15. Average of values obtained in C.

No. 16. " " " " " D.

No. 17. The efficiency difference of 2% between C and D is used to normalize the D average to C and then these two numbers are averaged.

No. 18 - No. 19. The KOH used for the 282 and 287 series was found to have about 1000 times more CO_2 than specified by the manufacturer. The amount of impurity per liter was measured together with the C^{14} activity of this impurity. The amount was .86 gm of $CaCO_3$/liter of 0.8 N KOH and 4.3 gm $CaCO_3$/ liter of 8 N KOH. This amounts to a percent contamination of 3 to 9%. The activities of this contamination were 78% modern wood for the 0.8 N and 87% modern wood for the 8N. The correction was made as follows:

$$A_{water} = \frac{A_{total} - f_{con.} A_{con.}}{f_{water}}$$

In most cases this was less than 1% and never exceeded 2%. The error due to this correction is certainly not more than 20% of the correction itself.

Since then we have prepared CO_2-free KOH ourselves and for the VEMA 8 and 9 cruises, the amount of contamination is less than .1%.

No. 20. The results are expressed in % difference from our 1938 Oak standard. The value predicted for surface ocean water on the basis of C^{12}/C^{13} measurements should be approx. 5%.

No. 21. Ages are indicated in number of years older than surface age. Very good agreement has been obtained among all surface samples

TABLE 5

Computation of 282 Series Samples VEMA Cruise 7

	#1	#2	#3	#4	#5	#6	#7	#8	#9	#10
Sample No.	Ocean Depth	Sample Depth	Lat.	Long.	GM $CaCO_3$	Liters KOH	Counter	Total Count	BGD	Net Count
282 K	5403	1829	26.05	69.58	29	2.2	C C	47.4±.3 46.3±.3	21.9±.3 21.8±.3	25.5±.4 24.5±.4
L	5203	5363	25.05	69.58	33	2.2	D	43.5±.3	14.3±.4	29.2±.5
M	5683	896	23.26	65.67	32	2.2	C	50.7±.3 52.8 45.5	21.9±.3	28.8±.4
N	5683	5640	23.33	65.56	33	2.3	C	50.8±.3	21.9±.3	28.9±.4
O	5653	4681	23.18	66.09	—	2.1	D	36.8±.3	14.3±.4	22.5±.5
P	5548	5500	23.57	68.20	39	2.1	D	43.6±.3	14.5±.3	29.1±.4
R	5440	5390	24.27	70.22	42	2.1	C D	51.3±.3 44.0±.3	22.0±.3 14.6±.3	29.3±.4 29.4±.4
S	5428	5376	25.55	70.26	44	2.1	D	42.6±.6	14.2±.3	28.4±.6
T	5296	5245	27.22	69.20	34	3.2	D	42.6±.6	14.2±.3	28.4±.6
U	5370	5320	28.36	70.56	31	3.0	C D	44.0±.3 36.4±.3	22.0±.3 14.5±.3	22.0±.4 21.9±.4
V	5392	5340	28.36	70.56	29	3.0	D C	43.9±.3 51.2±.3	14.3±.3 22.0±.3	29.6±.4 29.2±.4
W	5385	5340	31.17	71.02	—	3.0	C D	50.8±.3 44.0±.3	22.0±.3 14.4±.3	28.8±.4 29.6±.4
Y	5378	5333	31.46	71.73	43	3.0	D C	43.4±.3 50.9±.3	14.6±.3 22.0±.3	28.8±.4 28.9±.4
Z	4934	4890	31.22	66.39	44.5	3.0	D D	43.6±.3 44.0±.3	14.6±.3 14.6±.3	29.0±.4 29.4±.4

#11 Dilution Factor	#12 Cor. for D.F.	#13	#14 Eff. Cor.	#15 Aver. C	#16 Aver. D	#17 Aver.	#18 p Con.	#19 Cor. Aver.	#20 %D M.W.	#21 D Surf. Age
.852	29.8	430	29.9±.5							
.838	29.3	427	29.5±.5	29.7±.4		29.7±.4	6.0	30.1±.4	+8±1.3	260
1.00	29.2	436	29.4±.6		29.4±.6	28.7±.6	5.7	29.1±.6	-2.5±2.0	540
1.00	28.8	431	28.8±.4	28.8±.4		28.8±.4	5.9	29.2±.4	-2.2±1.3	520
1.00	28.9	432	28.9±.4	28.9±.4		28.9±.4	5.7	29.3±.4	-1.8±1.3	480
.760	29.6±.7	435	29.9±.7		29.9±.7	29.9±.7	6	29.6±.7	- .8±2.3	400
1.00	29.1	440	29.1±.4		29.1±.4	28.4±.4	4.6	28.7±.4	-3.8±1.3	650
1.00	29.3	438	29.3±.4	29.3±.4	29.4±.4	29.0±.3	4.4	29.3±.3	-1.8±1.0	480
1.00	29.4	442	29.4±.4							
1.00	28.4	429	29.5±.9		29.5±.9	28.8±.9	4.1	29.1±.9	-2.5±3.0	540
1.00	28.4	429	29.5±.9		29.5±.9	28.8±.9	8.1	29.3±.9	-1.8±3.0	480
.748	29.4±.5	434	29.3±.5	29.3±.5	29.3±.5	29.0±.4	8.2	29.5±.4	-1.2±1.3	430
.748	29.3±.5	440	29.3±.5							
1.00	29.6	435	29.9±.5	29.2±.4	29.9±.5	29.2±.4	8.9	29.7±.4	-5±1.3	370
1.00	28.8	430	28.9±.4	28.9±.4	29.7±.4	29.0±.3	6	29.4±.4	-8±1.3	400
1.00	29.6	438	29.7±.4							
1.00	28.8	441	28.8±.4	28.9±.4	28.8±.4	28.5±.3	6.0	28.9±.3	-3.2±1.3	600
1.00	28.9	432	28.9±.4							
1.00	29.0	442	29.0±.4		29.1±.3	28.7±.3	5.8	28.9±.3	-3.2±1.0	610
1.00	29.4	444	29.3±.4							

Table 5

Computation of 287 Series Samples

VEMA Cruise 7

Sample No.	#1 Ocean Depth	#3 Sample Depth	#3 Lat.	#4 Long.	#5 GM $CaCO_3$	#6 Liters KOH	#7 Counter	#8 Total Count	#9 BGD	#10 Net Count
287 A	5235	4150	39.52	55.21	38	1.6	D	44.3±.3	14.5±.3	29.8±.4
B	5223	5163	39.49	54.46	18	1.6	D	35.1±.3	14.3±.4	20.8±.5
							D	34.4±.3	14.3±.4	20.1±.5
C	5302	4960	38.57	53.22	30	1.6	C	50.5±.3	21.9±.3	28.6±.4
							D	44.3±.3	14.6±.3	29.7±.4
D	5359	3530	38.38	52.46	22	1.6	D	37.4±.5	14.6±.3	22.8±.6
E	5401	0	37.57	50.57	50	.47	D	46.5±.3	14.7±.3	31.8±.4
							C	52.8±.3	22.0±.3	30.8±.4
F	5401	2109	37.57	50.57	33	1.6	D	45.2±.3	14.6±.3	30.6±.4
							C	51.0±.3	21.7±.3	29.3±.4
G	5381	732	38.00	51.24	33	1.6	D	45.7±.3	14.5±.3	31.2±.4
							D	45.8±.3		
							C	52.9±.3		
H	5381	5335	38.00	51.29	33	.53	C	50.9±.3	21.7±.3	29.2±.4
I	5490	5445	34.39	52.41	32	.53	C	49.7±.3	21.8±.3	27.9±.4
							D	43.4±.5	14.5±.3	28.9±.6
							D	43.8±.3	14.6±.3	29.2±.4
K	5463	5423	34.43	53.15	38	.52	C	49.6±.3	21.9±.3	27.7±.4
							D	44.0±.3	14.8±.4	29.2±.5
L	5383	5347	37.23	53.22	35	.44	C	50.1±.3	21.9±.3	28.2±.4
							C	50.1±.3	21.8±.3	28.3±.4
M	5427	5390	35.28	55.45	60	1.05	D	43.2±.3	14.4±.4	28.8±.5
N	3667	3485	34.56	57.10	35	.52	D	44.8±.3	14.6±.3	30.2±.4
							D	45.2±.3	14.8±.4	30.4±.5
							C	50.7±.3	21.9±.3	28.8±.4

[illegible] Correction Factor	#12 Cor. for D.F.	#13	#14 Eff. Cor.	#15 Aver. C	#16 Aver. D	#17 Aver.	#18 % Con.	#19 Cor. Aver.	#20 %D M.W.	#21 D Surf Area
[illegible]	29.8	441	29.8±.4		29.8±.4	29.1±.4	3.5	29.5±.5	-1.2±1.7	430
.723	28.7±.7	432	29.3±.9		29.0±.7	28.3±.7	7.7	28.5±.7	-4.5±2.3	720
.723	27.8±.7	428	28.6±.9							
1.00	28.6	433	28.6±.4	28.6±.4	29.6±.4	28.8±.3	4.5	29.1±.3	-2.5±1.0	540
1.00	29.7	443	29.6±.4							
.763	29.9±.8	445	29.7±.8	29.7±.8		29.7±.9	6.1	30.0±.8	+.5±2.7	280
1.00	31.8	442	31.8±.4	30.7±.4	31.8±.4	30.9±.3	4.0	31.1±.3	+4.2±1.0	- -
1.00	30.8	434	30.7±.4							
1.00	30.6	440	30.6±.4	29.5±.4	30.6±.4	29.7±.3	4.1	30.0±.3	+5±1.0	280
1.00	29.3	428	29.5±.4							
1.00	31.2	439	31.3±.4		31.3±.4	30.6±.4	4.1	30.9±.4	+3.5±1.3	30
1.00	29.2	429	29.3±.4	29.3±.4		29.3±.4	6.9	29.5±.4	-1.2±1.3	430
1.00	27.9	429	28.0±.4	28.0±.4	29.1±.4	28.2±.3	7.1	28.4±.3	-4.8±1.0	740
1.00	28.9	439	29.0±.6							
1.00	29.2	441	29.2±.6							
1.00	27.7	430	27.8±.4	27.8±.4	29.2±.5	28.1±.4	5.8	28.3±.4	-5.2±1.2	780
1.00	29.2	442	29.2±.5							
1.00	28.2	431	28.2±.4	28.3±.3		28.3±.3	5.5	28.5±.3	-4.5±1.0	720
1.00	28.3	428	28.5±.4							
1.00	28.8	436	29.0±.6		29.0±.6	28.3±.6	7.1	28.5±.6	-4.5±2.0	720
1.00	30.2	440	30.2±.4	28.8±.4	30.2±.3	29.2±.3	6.5	29.4±.3	-1.5±1.0	450
1.00	30.4	448	30.1±.5							
1.00	28.8	431	28.8±.4							

and the activity of 4.2% different from 1938 wood is taken for all surface areas. This gives surface water an apparent age of 75-80 years.

The data for VEMA Cruise 8 is summarized in Table 6. The computations are much simplified over the previous series. More efficient extraction of CO_2 has eliminated the need to bring up the size of the sample with "dead" carbon dioxide. The calculation for reagent impurity is also eliminated by using nearly pure KOH.

Table 6

VEMA 8 Cruise, 1955

Sample No.	North Lat.	West Long.	Ocean Depth M.	Sample Depth M.	% Diff. from mod. Wood	Appar. age yrs. diff. from surface avg.
326C	30.56	67.00	4970	0	+3.5	---
326F	19.58	70.51	1796	0	+3.7	---
326H	19.07	67.07	4864	0	+4.5	---
326R	19.04	80.48	----	0	+4.0	---
326S	19.14	79.29	over 5000	4450	+0.5	300±
326T	19.09	78.01	5194	4755	-0.9	410±
326U	19.09	76.58	3704	1097	-1.7	480±
326W	17.31	73.22	4225	4190	-1.9	500±

RADIOCARBON SEA WATER SAMPLE AGES

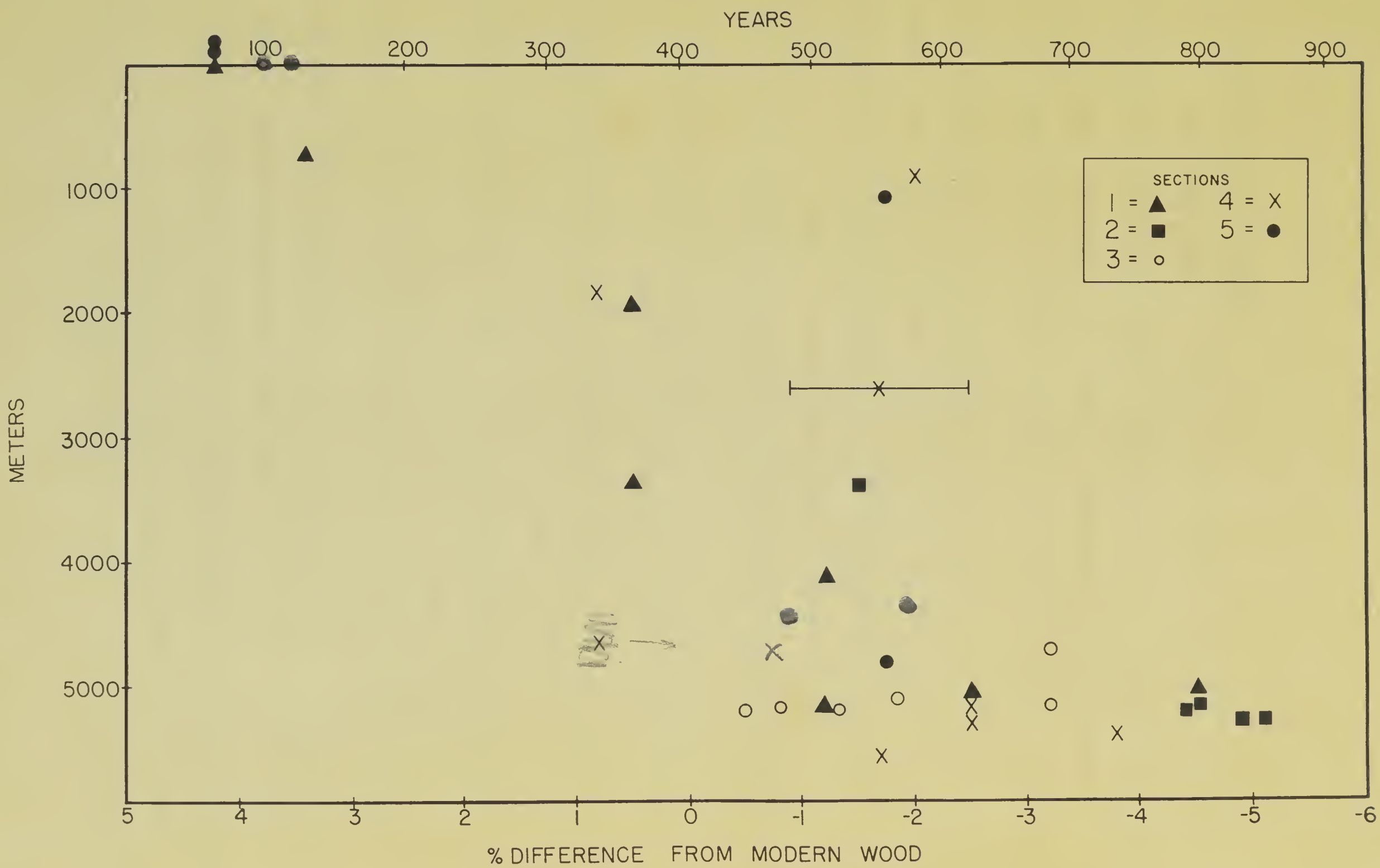


FIGURE 5

D. Analysis of 1955 Samples

Considering these Atlantic and Caribbean samples as a group, certain general features stand out. Figure 5 illustrates a plot of the age-depth relationship for the entire group. This presentation is in no way meant to infer age as a function of depth. The water masses represented in this sampling may be considered as North Atlantic Central Water in the surface levels, with some modification in the case of the Caribbean samples. Centered at 800 meters, Antarctic Intermediate Water is considered to enter part of the area. Between 1500 and 4000 meters Atlantic Deep Water is prevalent. Bottom water of both sub-Arctic and Antarctic origin probably is represented though its distribution is uncertain. Located near the center of Figure 5 is a sample point having a horizontal line through it. The extremes of this line represent the error limitations of the samples. This error averages $\pm$ 1.5% for all the samples shown. It is expected in the future to keep the error within $\pm$ 1%, the equivalent of $\pm$ 80 years.

Figure 6 represents cross sections through the regions sampled. Profiles A-B, C-D, and E-F cut across the various sections as indicated in Figure 4. The vertical scale in the profiles has been extremely exaggerated. The sample points in this figure bear the same coded markings as those in Figure 5. The numbers beside the points represent percentage difference of the sample from the activity of 1938 wood. Surface samples falling outside the section limits of Figure 4 are not shown in the profiles.

Surface samples in the profiles have an average activity of 4% different from modern wood. Over a range of 20 degrees of latitude surface samples agree very well. In section 1 near 40°N, the activity of the 800 meter sample (±3.47) is not significantly different from surface. In section 4 in the Atlantic and section 5 in the Caribbean, samples from near the 800 meter level agree well with each other, 500 and 530 years older than surface. They are significantly older than the sample to the north from the same depth. The evidence suggests that the two samples below 23° S are from Antarctic Intermediate Water. The fact that the sample from 18°N in the Caribbean appears slightly younger than the Atlantic sample at 23°N may indicate that the former is from a greater depth and perhaps represents the lower portion of the Intermediate water which has mixed with younger water below. Numerous studies show that Antarctic intermediate water extends to about 23° N in this area. If our assumption is correct, a rough estimate for velocity from place of origin can be made. Using the path indicated by Martineau (1953), an average velocity of .12 cm/sec is indicated.

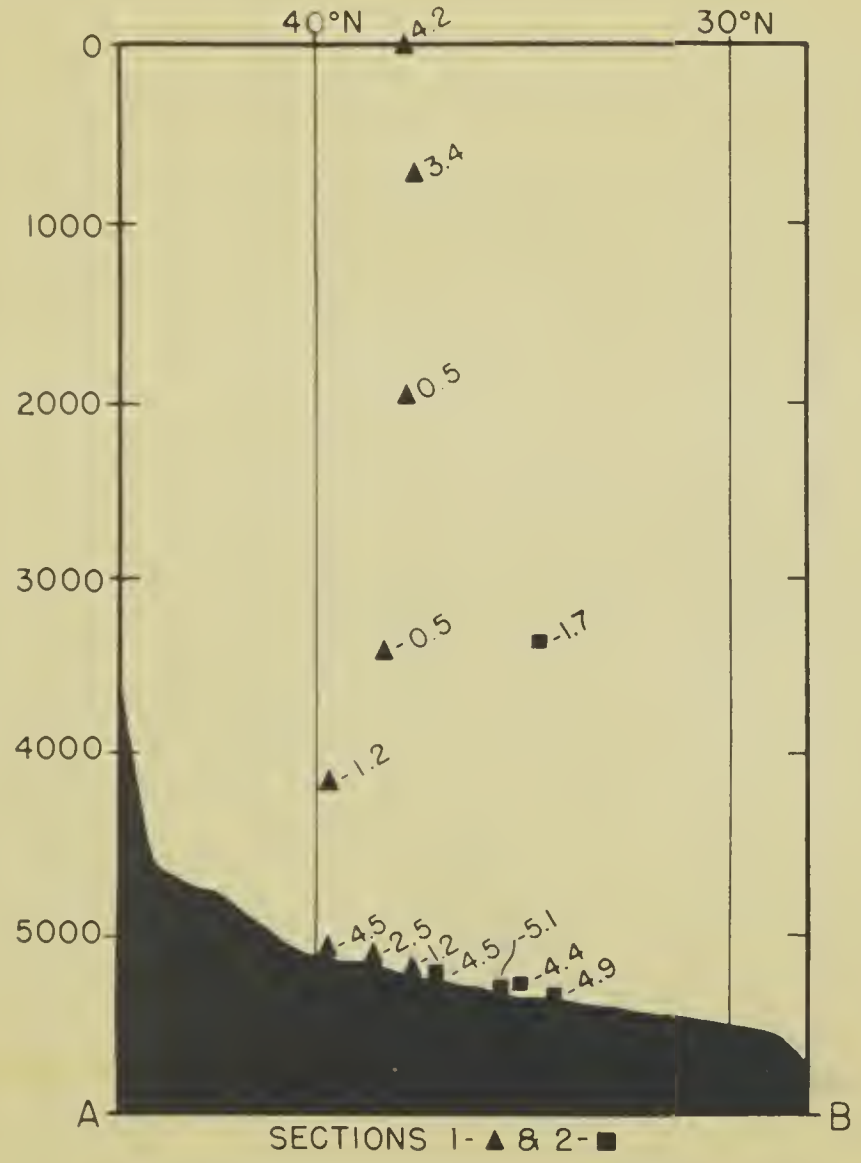
Age values for the Deep water range from 260 to 440 years older than surface but no areal or depth pattern is indicated. The error in these calculations averages ± 1.5% so that the differences are not significant. Two samples from the 2000 meter depth, one near 40° N and the other at 25° N have activities of 0.5 and 0.8 respectively. At greater depth in the Deep Water the remaining Atlantic samples average -1.2% different from modern wood. Thus there is a suggestion that the upper Deep Water

moves at a greater velocity than the deeper levels. It is also expectable that mixing in the upper levels should take place with younger waters above just as mixing with Bottom water must take place. It is of interest that the oldest Deep water sample (-1.8%) at 25°N lies at about 2500 meters depth, a level close to the level of no motion set by Riley (1951) for the area. Figure 7 illustrates the topographic confines affecting Deep Water circulation below 2500 meters, together with the locations of radiocarbon samples below this level exclusive of bottom samples.

No satisfactory velocity computations for Deep Water can be made from the present data. Accepting the radiocarbon ages as real would require that the average southward movement of Deep Water from its northern source be considerably slower than the estimates of Sverdrup (1942) and Riley (1951) based on volume transport considerations. There is, according to Jung (1955), some basis for considering the mass transport involved to be less than the earlier estimates.

Age values for the Caribbean samples bear out certain existing concepts of circulation in the area according to Parr (1937) and Seiwell (1938). From the observed distribution of oxygen, salinity, temperature and density, it can be shown that the surface levels are a mixture of North and South Atlantic water. A considerable amount of Antarctic Intermediate Water is present in the salinity minimum level about 800 meters deep. Below 1200 meters, distribution of temperature, salinity and density is remarkably uniform throughout the basins of the Caribbean. From the uniformity of the deep values it is believed that the replenishment of deeper

RADIOCARBON PROFILES 1955



TIME EQUIVALENT

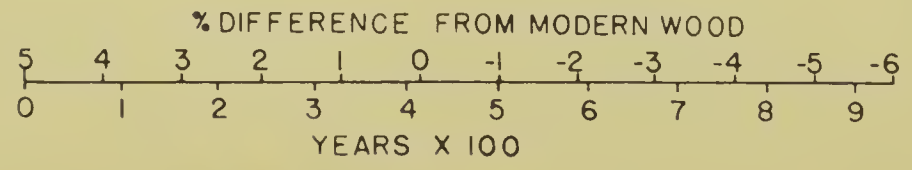


FIGURE 6

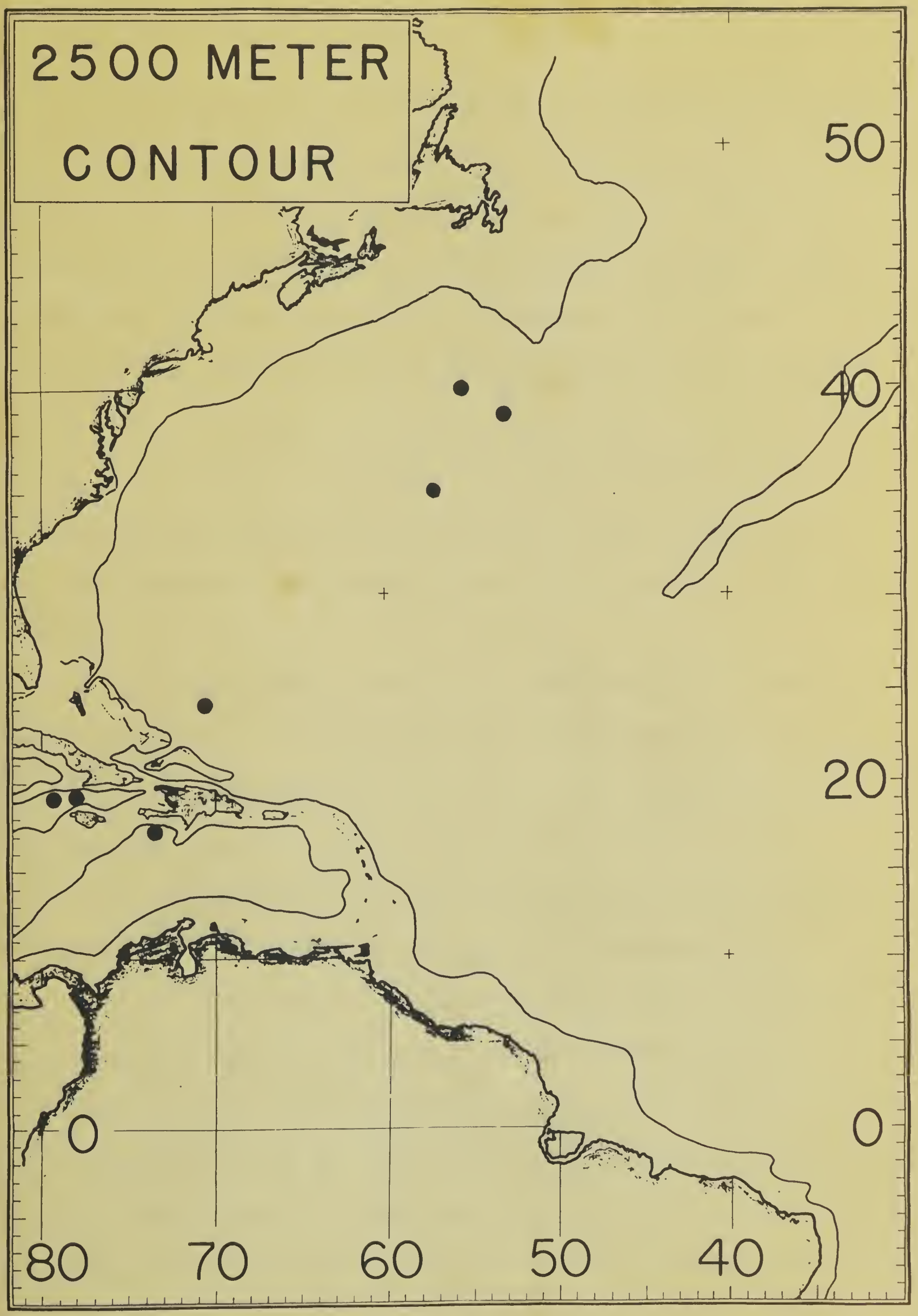


FIGURE 7

Caribbean water takes place from the Atlantic Deep Water over various sills which bound the Caribbean to the east and north. On the Atlantic side, water below the sill depths of about 1600 meters is denser than Caribbean water. Oscillations in density levels on the Atlantic side are believed to cause Atlantic water to spill over the sills and fill the Caribbean basins from below. The water throughout the basins closely resembles the character of Atlantic water at sill depth. That the refilling process is fairly rapid can be shown by the concentration of oxygen which increases downward in the bottom 1500 meters of the Caribbean (Seiwell, 1938). A slight decrease in temperature is also observed toward the bottom (Parr, 1937).

One new theory (Worthington, 1955) proposes that refilling is a periodic process, the last occurrence of which is believed to have taken place at the end of the eighteenth century. This concept fails to explain the increased oxygen concentration with depth.

In Figure 6 the E-F profile cuts through the Cayman Trough, across the Jamaica Rise and into the northern Colombian Basin. As already mentioned, the sample at 1000 meters has been assumed to represent Antarctic Intermediate water. In the Cayman Trough samples at 4400 and 4700 meters have activities different from modern wood of 0.5 and -0.9% respectively. These ages (from Table 6) supercede those shown in Figure 6 and are the result of additional counting of the samples. The deep Cayman samples have essentially the same activity and show apparent age 350 years older than surface. This is in accord with the age of the Deep Water in the

Atlantic from which the Caribbean water is derived. A single sample from the bottom of the Colombian Basin (off the south coast of Haiti) of the Caribbean shows an apparent age of 500 years older than surface average. Errors of ± 1% apply to these samples and thus the difference is not significant. However, if the age difference is assumed to be real a somewhat different history for the two waters is indicated. Seiwell (1948) has suggested that the refilling of the eastern Caribbean is less rapid than in the Cayman Trough. Therefore a slight age difference is in order. Alternatively, shallower sill depths in the eastern passages might allow for the presence of older intermediate water in depths of the eastern Caribbean basins.

Preliminary results from other surface radiocarbon samples in the Caribbean show an average age somewhat older than surface values from the North Atlantic. If these ages hold up under further counting they may point to differences in the activity of North and South Atlantic surface waters.

A larger number of radiocarbon samples have been collected from bottom water than from any other depths in the recent series. Bottom samples have all been collected within 50 meters of the ocean bottom in the deep basin of the Western Atlantic. Figure 8 represents the distribution of these samples within the topographic bounds of the 4500 meter contour. Considering the apparent ages of these samples, it is evident in Figure 5 that the range is greater than at any other level. The spread is from 350 to 770 years older than the surface average. This diversity may be due to the statistical fact that so many bottom samples are represented. However

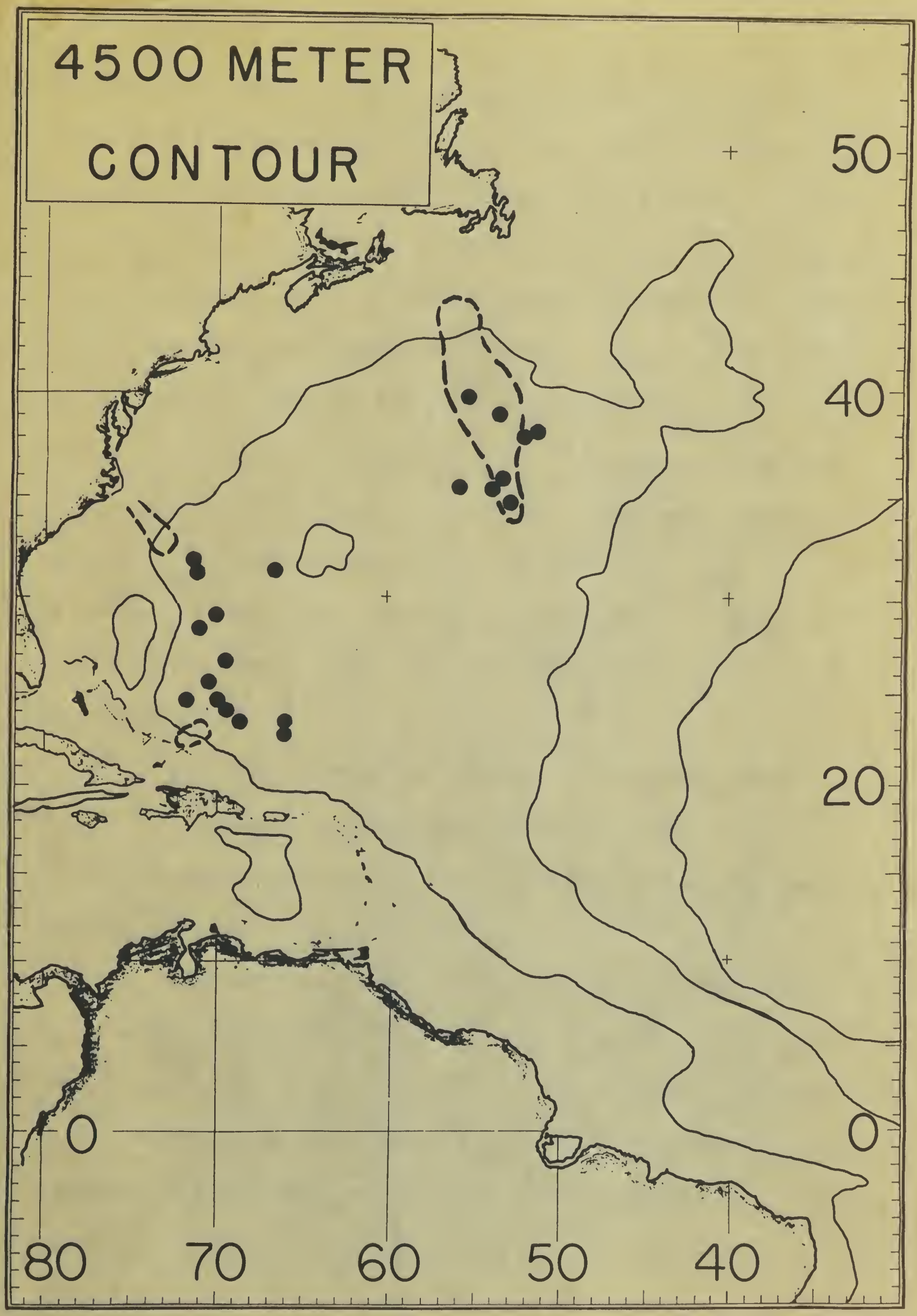


FIGURE 8

the good repeatability and close agreement of the surface ages lends confidence that the bottom spread is not random. Figure 8 illustrates the two general areas where fairly intensive sampling has been done. The age distribution within these areas is shown in the profiles of Figure 6. The average sample age in the northern area amounts to 670 years older than surface average. In the area to the south the ages average 520 years older than surface. It would appear that both of the areas are dominated by bottom water of Antarctic origin. If this is the case an average velocity of something like .05 cm/sec is called for from the source region. While the velocity is reasonable under this assumption, it is difficult to reconcile the extreme values within the sampling areas. The apparent absence of such diversity in other depths leads to a consideration of possible bottom sediment influence.

With each water sample a bottom sediment core sample was obtained. From these and other cores taken by the Lamont Geological Observatory in the area, a good idea of the submarine geology has been worked out.

A feature of the submarine geology which may have influenced the apparent age of the bottom water is the disturbing influence of turbidity currents in the areas sampled. Heezen and Ewing (1951, 1954) have shown that an earthquake in 1929 near the Grand Banks caused great quantities of sediment to be dislodged from the slope south of Newfoundland. This material was deposited over the abyssal plain to the south through the agent of turbidity currents. The area affected by this deposition lies within the dotted line which can be seen among the northern samples in Figure 8.

Similar disturbances have occurred in recent times in the Hatteras area off the U.S. east coast and an area near the Bahamas, both areas shown with dotted lines in the figure. Evidence for turbidity currents in all of these areas comes from submarine cable breaks and from the nature of the sediment deposited. The effect of this type of deposition is to bring calcareous sediment from a shallower environment into a deeper water environment where solution of carbonate may take place. In such a way quantities of old carbon may be put into the bottom water.

Bottom sediments in areas 1 and 2 contain sand and coarse silt in their upper layers as evidence of turbidity current deposition. Below the silt and sand layers, foraminiferal lutite having 16% calcium carbonate is found. This sediment contains shell material 30% broken and dissolved. In this and other deep sea areas where there is evidence of turbidity current deposition, shells are frequently found belonging to bottom-dwelling organisms whose natural environment is in relatively shallow water. In the southern area considerably more calcium carbonate is present in the bottom sediments. One sample at 31°22' N, 66°39'W was taken over a bottom of globigerina ooze, nearly 100% calcium carbonate. The degree to which bottom water in the deep ocean is saturated with CO_2 is not accurately known. It is believed that water overlying highly calcareous bottoms will be supersaturated, while water over red clays will be undersaturated. Bottom calcium carbonate exposed to undersaturated water must go into solution. A number of samples of shell from the top few centimeters of the bottom sediment at locations in the Atlantic have been measured for C-14

activity. Average apparent age has been about 5000 years for these samples. All sea water is probably younger than 1400 years. A slight contamination from carbonate material of the bottom, age 5000 years, will have a far greater effect in the apparent age of a water sample than will mixing of two water types whose activities cannot be relatively so different. If contamination from bottom sediments has affected the bottom water ages, then the youngest samples must be considered the most accurate. Using a few of the youngest samples in each of the areas an average of 440 years older than surface is shown for the southern area and 500 years for the northern samples. Under these conditions the bottom water would be largely Antarctic in both areas but probably much diluted with northern water.

The absolute amount of carbonate recovered from the samples has been compared with apparent age but a correlation of only .09 was found. Other chemical properties have been studied to see if correlation can be found with apparent age. Table 7 represents values for chemical concentrations found in the ocean water samples in the 282-287 series. Units for phosphorus, nitrogen and silicon are in microgram atoms per liter; for oxygen in mililiters per liter. Aside from the normal distribution of these substances with depth, and their correspondence with the age-depth relationship already indicated for the samples, no meaningful correlations with radiocarbon ages have been found.

Table 7

CHEMICAL DETERMINATIONS SERIES 282, 287

Sample No.	P Inorg.	P Org.	No. $\overline{3}$	No. $\overline{2}$	SiO_2	O_2
SERIES 282 K	0.91	0.19	10.9	0.13	8.2	5.28
L	1.29	0.08	17.1	0.15	34.0	5.14
M	1.08	0.10	16.0	0.12	34.9	2.68
N	1.40	0.01	21.0	0.15	24.7	4.17
P	1.25	0.05	14.95	0.12	36.7	4.83
R	0.99	0.04	12.85	0.10	15.5	5.06
S	1.06	0.12	14.50	0.14	30.4	4.58
T	1.21	0.05	14.00	0.11	33.5	4.98
U	0.87	0.15	8.70	0.11	9.9	4.58
W	0.99	0.13	13.45	0.14	11.9	4.86
X	1.18	0.48	0.16	3.8	39.1	4.81
Y	1.00	0.26	13.35	0.10	32.3	5.04
Z	0.97	0.17	12.00	0.12	25.0	5.04
SERIES 287 A	0.95	0.11	0.01	3.5	12.9	5.00
B	0.59	0.66	0.06	4.4	20.8	5.01
C	1.21	0.00	.14	0.9	20.7	4.85
D	1.10	0.87	.02	4.7	11.2	5.25

Table 7 (cont.)

Sample No.	P Inorg.	P Org.	No. $\bar{3}$	No. $\bar{2}$	SiO_2	O_2
237 E	.28	0.02	.01	0.00	1.0	4.07
F	.72	0.54	.08	3.8	7.6	5.23
G	.05	0.10	.04	1.9	2.1	2.79
H	1.16	0.05	.13	2.5	23.1	5.00
I	.87	0.41	.12	3.8	23.7	4.83
K	1.04	1.19	.17	6.5	30.0	4.91
L	1.07	1.72	.07	5.5	24.0	4.94
M	1.07	0.15	.03	9.0	30.5	4.89
N	.36	0.95	.09	5.8	20.8	5.33

One new radiological study of the ocean waters by Lamont workers has recently become available (Kulp and Giletti, 1955). Use is being made of tritium, a natural isotope of hydrogen to study short term characteristics of ocean circulation. The half life of this isotope is 12.3 years and its maximum useful limits extend to 75 years. Tritium has the advantage of being part of the water itself rather than a dissolved constituent. However, concentrations in the surface waters appear to be seriously affected by rains following thermonuclear tests. The present work has been done largely to establish what are the normal ocean surface concentrations of tritium.

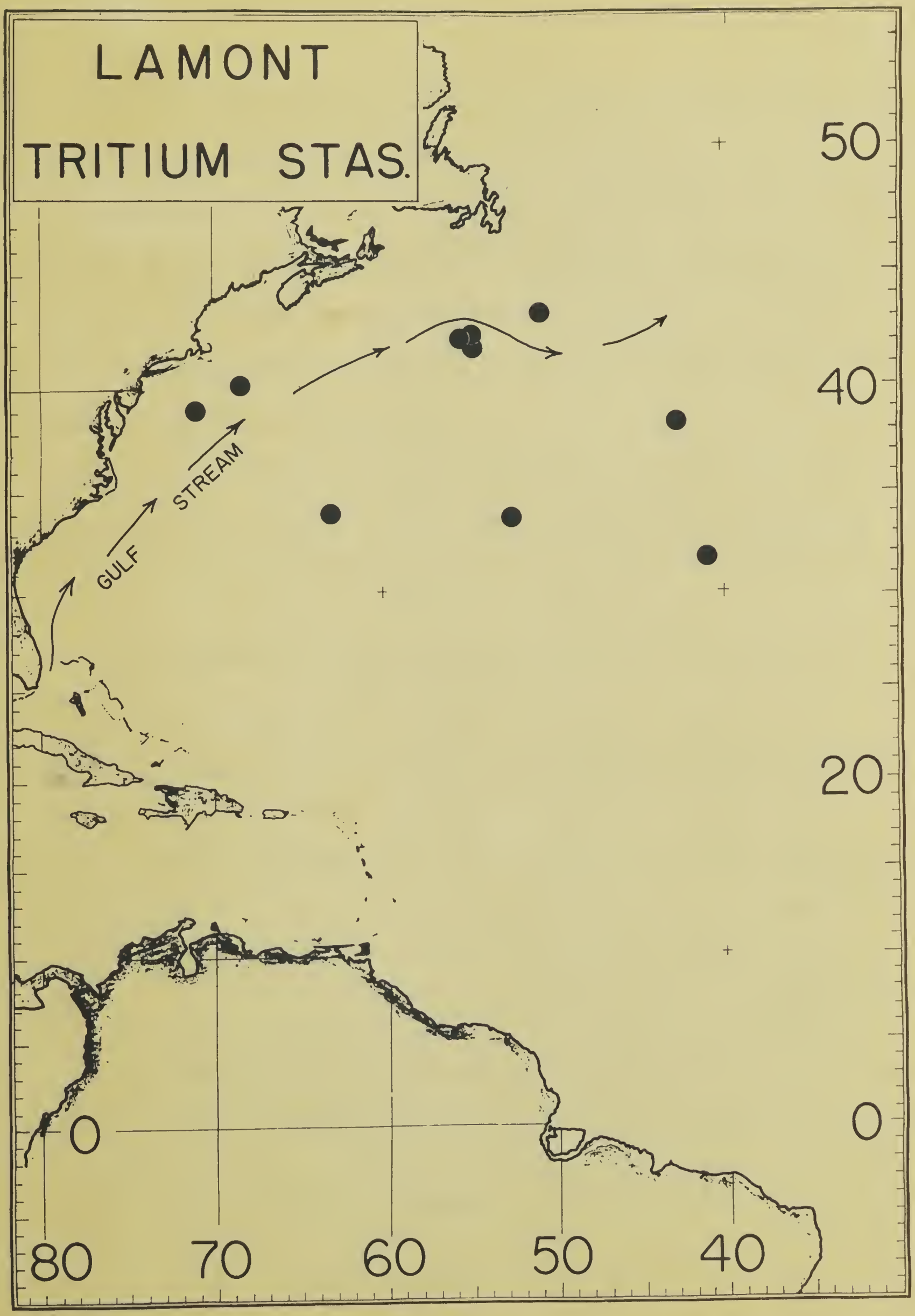


FIGURE 9

The collection methods for tritium are simple and consist merely of bringing back a suitable quantity of sea water sample to the laboratory, uncontaminated by other water. The sample is isotopically enriched, the heavier isotopes remaining in the liquid. The enrichment of tritium is monitored by following the duterium enrichment with the mass spectrometer. The activity of the enriched water is then counted by the gas proportionate method as hydrogen, H_2.

Figure 9 plots the Lamont tritium stations to date, the data is presented in Table 8. Sample T-271 is overly high in activity and believed

Table 8

TRITIUM CONTENT OF ATLANTIC OCEAN WATERS

July-September 1953

Sample No.	Lat. N.	Long. W.	Depth (fms)	Date Collected	T:H x 10^{-18}	Comment
T-1	40°10'	71°10'	Surface	7/21/53	0.92	Continental shelf
T-4	42°28'	55°02'	50	7/30/53	1.04	Slope water, lower portion of thermocline
T-5	42°28'	55°00'	25	7/30/53	0.94	Slope water, upper portion of thermocline
T-8	40°05'	55°00'	Surface	8/1/53	1.09	Gulf Stream
T-15	43°28'	51°05'	Surface	8/9/53	1.19	On Grand Banks of Newfoundland
T-16	48°51'	50°10'	Surface	8/24/53	approx 0.4	Northern Grand Banks
T-25	34°00'	52°35'	Surface	9/7/53	1.22	Sargasso Sea
T-28	34°00'	62°50'	Surface	9/10/53	1.64	Sargasso Sea

Table 8 (cont.)

July-September 1954

Sample No.	Lat. N.	Long. W	Depth (fms)	Date Collected	T:H $\times 10^{-18}$	Comment
T-271	39°05'	70°45'	Surface	7/10/54	4.75	Slope water
T-356	31°58'	40°48'	Surface	9/9/54	1.31	

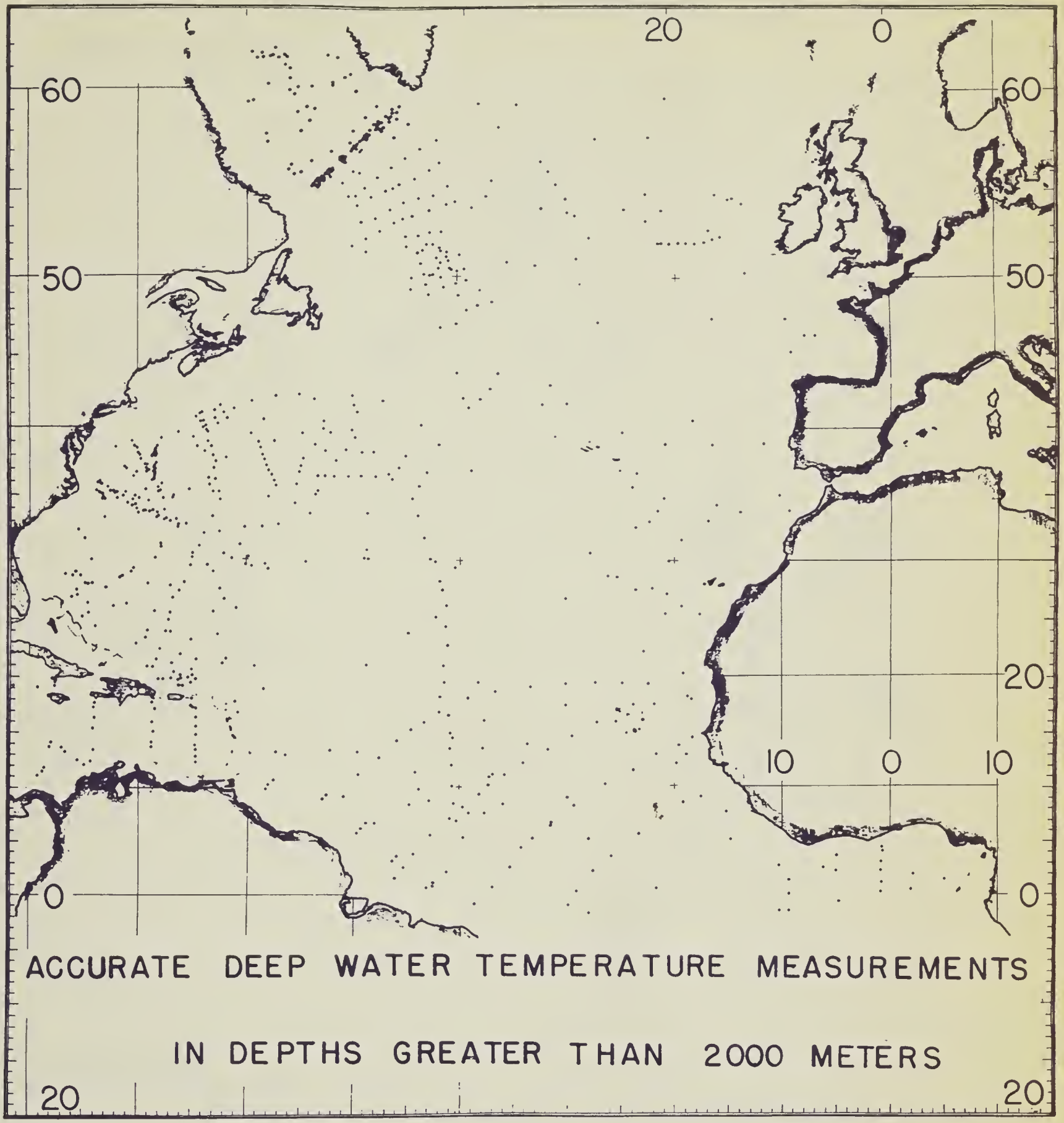
to be the result of "hot" rain. Values to the southeast of the Gulf Stream appear slightly higher than those northwest of the Stream, but the difference may not be significant. The average surface value is 1.3×10^{-18}. Two samples beneath the surface indicate that seasonal mixing does in fact extend to 100 meters, or at most a three-year lag may occur. The possibilities of using the tritium method alongside the radiocarbon method show promise. The former could be ideal to establish minimum ages in that the best accuracy of the radiocarbon method is ± 80 years. There is obviously a very important use for the tritium method in establishing the maximum depth of seasonal and short term mixing of surface water downward. Good use could be made of the tritium method in following the inttial movement of a water mass from its high-latitude surface source. It is hoped that some coordinated experiment using the two radiological methods can soon be made.

E. Summary of 1955 Sampling

Radiocarbon samples from various levels have been taken in the western Atlantic Ocean. New measurements of higher precision indicate ages for sea water somewhat younger than values previously published. Fairly rapid equilibration is assumed for ocean surface water and the atmosphere. Surface samples agree well averaging about 4% greater activity than 1938 wood. Water of surface age extends to nearly 1000 meters in some in part of the area studied. At the same depth water believed to be of Antarctic origin shows an apparent age of 500 years older than the surface. Between 1500 and 4500 meters depth North Atlantic water averages 350 years older than the surface. In the Caribbean, results support the theory of fairly rapid refilling from the Atlantic at sill depth through the Windward Passage and other passages in the area. Bottom samples taken within 50 meters of the ocean bottom show diverse ages. Apparent ages from 350 to 750 years older than surface have been recorded. It is suggested that influence from the bottom sediments may be a factor in the observed variance. Bottom ages are considered reliable as maximum ages. Velocities for the average movement of certain water masses have been suggested. Water sample ages have been compared with various chemical distributions in the sea but no meaningful correlations have been found. The tritium method of age determination has been described and shown to be a valuable supplement to the radiocarbon studies.

F. Hydrographic Studies

The taking of standard hydrographic observations coincident with radiocarbon sampling is necessary to establish the identity of the water mass sampled. The use of chemical and temperature observations as controls on contamination has already been described. In this regard, temperature-salinity diagrams (Iselin, 1939) have proved most useful. In addition to standard observations of salinity, temperature, nitrogen, phosphorus, oxygen and silicate, work has begun on sampling carbon dioxide components, namely, free CO_2, carbonic acid, carbonate, and bicarbonate. The concentration of carbon dioxide in the ocean has not been surveyed nearly as intensively as other chemical concentrations. Determination of carbon dioxide is commonly made from computations involving temperature, depth, salinity, alkalinity, pH, and partial pressure of CO_2. Calculations of this sort have shown considerable variation, making it difficult to compare results obtained by different workers. Some results show a large CO_2 increase immediately over the bottom. Now that the system for extraction of CO_2 in radiocarbon sampling has been standardized it is planned to compare absolute amounts obtained in this way with computed values for the same initial sample. Such measurements are desirable in view of the possible effect of bottom carbonate on radiocarbon ages of water. Furthermore, the comparison may permit some critical evaluation of the method of calculating carbon dioxide. Reference has already been made to the paucity of deep hydrographic observations. Figure 10 shows locations of all the reliable published temperature observations taken since 1872 in the North Atlantic in depths greater than 2000 meters. Fewer than


20
0
60
50
60
50
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10
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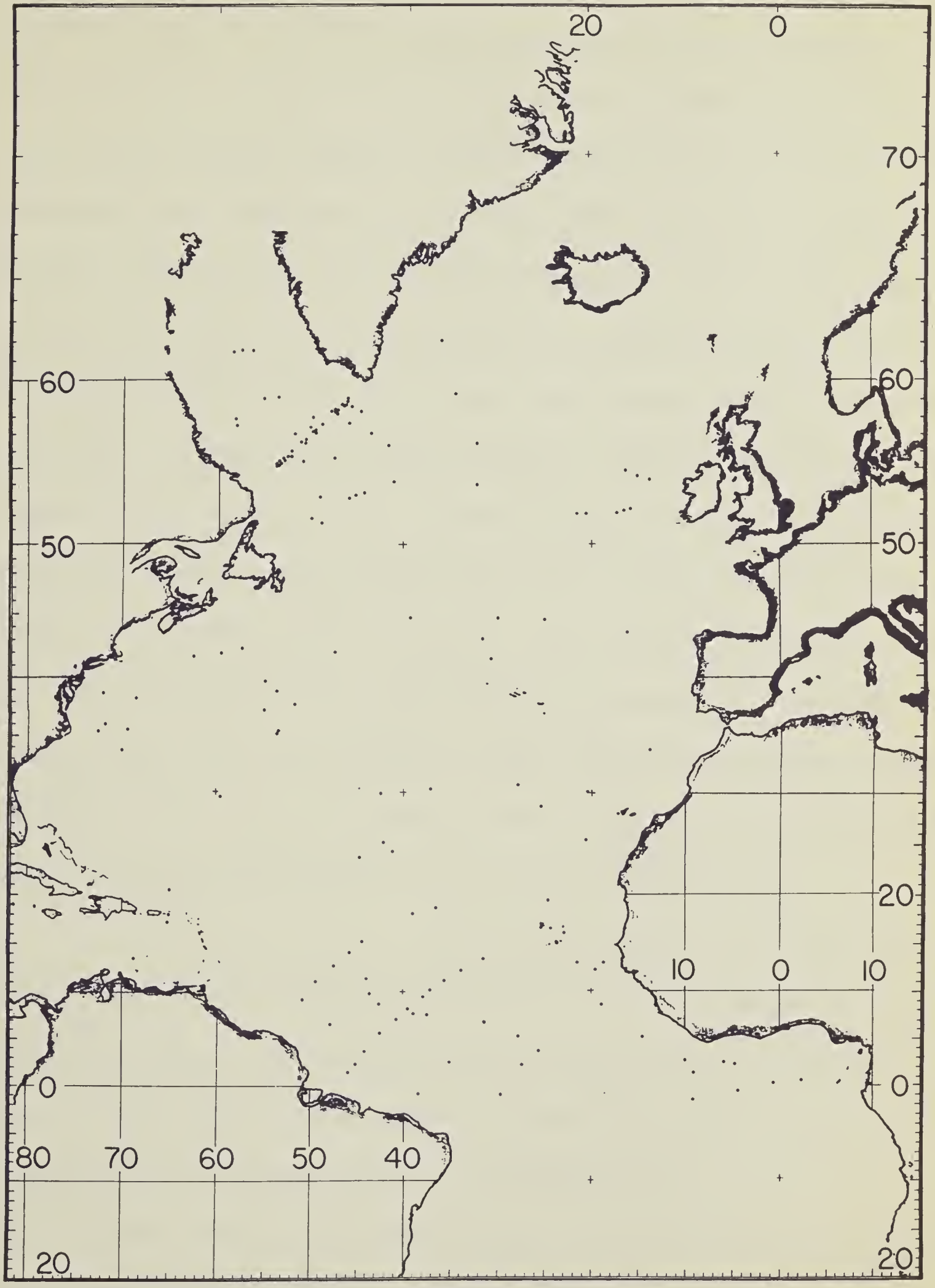
ACCURATE DEEP WATER TEMPERATURE MEASUREMENTS
IN DEPTHS GREATER THAN 2000 METERS
20
20

FIGURE 10

ACCURATE NEAR BOTTOM TEMPERATURE MEASUREMENTS



ALL OBSERVATIONS WITHIN 100 METERS OF BOTTOM IN DEPTHS GREATER THAN 2000 METERS

FIGURE 11

800 observations make up our entire knowledge of this vast region. Even more striking is the small number of deep observations which have extended nearly to the bottom. Figure 11 plots the mere 155 stations which have sampled depths within 100 meters of the ocean bottom in deep water. The present work has added about 30 new bottom observations to this total during the past year. A number of these new observations of temperature and salinity have been listed in a previous report on this contract issued Dec. 15, 1955. One important feature of our new data besides near-bottom depth is the extreme accuracy with which depth is known. Bottom samples have all been taken within 50 meters of the ocean floor and our devices register direct contact with the bottom. The remaining information needed for accurate depth control is the measure of ocean depth. This need is supplied admirably by the Precision Depth Recorder developed at Lamont Geological Observatory (Luskin and Roberts, 1955). With this instrument ocean depths can be measured to one meter in 1000 meters.

We are continuing our deep observations and at the same time have under taken a study of existing deep temperature data in order to learn in what areas information is most needed. In many ways temperature measurements are the most valuable observations available from the deeper waters for the purposes of the present study.

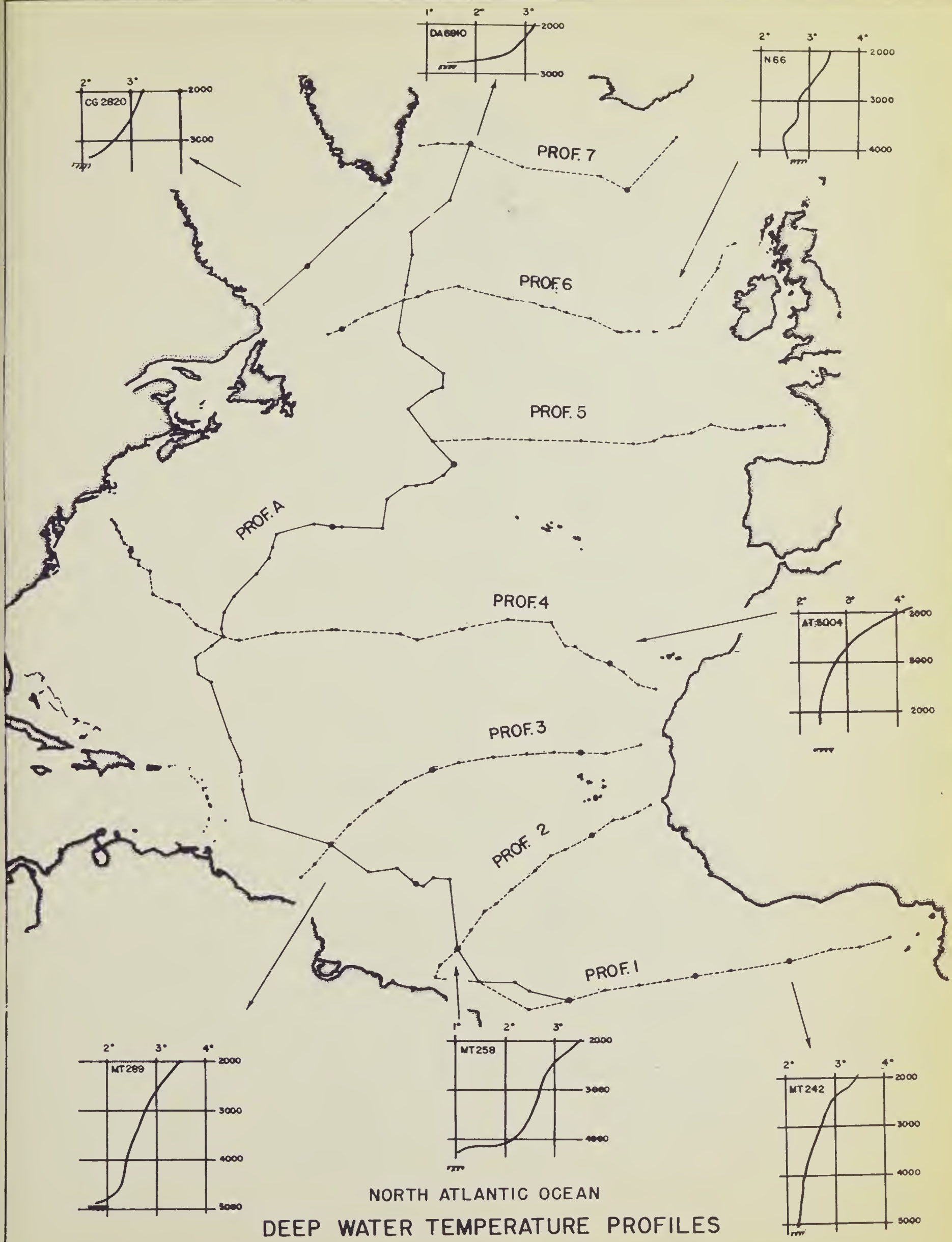
More temperature measurements are on hand from these depths than measurements of salinity and other chemical properties. Better comparability exists among temperature measurements than other observations taken by various observers over a period of more than fifty years.

The system of temperature measurement using deep sea reversing thermometers has remained essentially unchanged throughout the period in question, whereas various methods have been used for other determinations. Relatively greater precision attends the measurement of temperature than the determination of chemical concentrations.

The purpose of our deep temperature studies can be summarized as follows:

> To observe discontinuities in the deep thermal structure of the ocean basins for indications of bottom current movement.
>
> To examine the temperature gradient in the bottom water layers for indication of earth heat flow.
>
> To delimit the areal extent of bottom water masses.
>
> To examine the practice of extrapolation of bottom ocean temperatures from gradient observations which end some distance above the bottom.
>
> To investigate possible temperature anomalies in the bottom waters from various causes including the introduction of quantities of sediment and water from warmer and shallower environments through the agent of turbidity currents.
>
> To observe the variations of temperatures in areas where there is evidence of periodic oscillations.

Figures 10 and 11 show locations of temperature observations used in the temperature survey. The sources for data are indicated in the references at the end of this report. Figure 12 illustrates the transects along which profiles of deep water temperature have been prepared. In these profiles *in situ* temperatures are plotted. Figure 13 shows the north-south profile in the western North Atlantic. In the northern section, bottom water of less than $2^{o}C$ extends no farther south than about 50^{o} N La



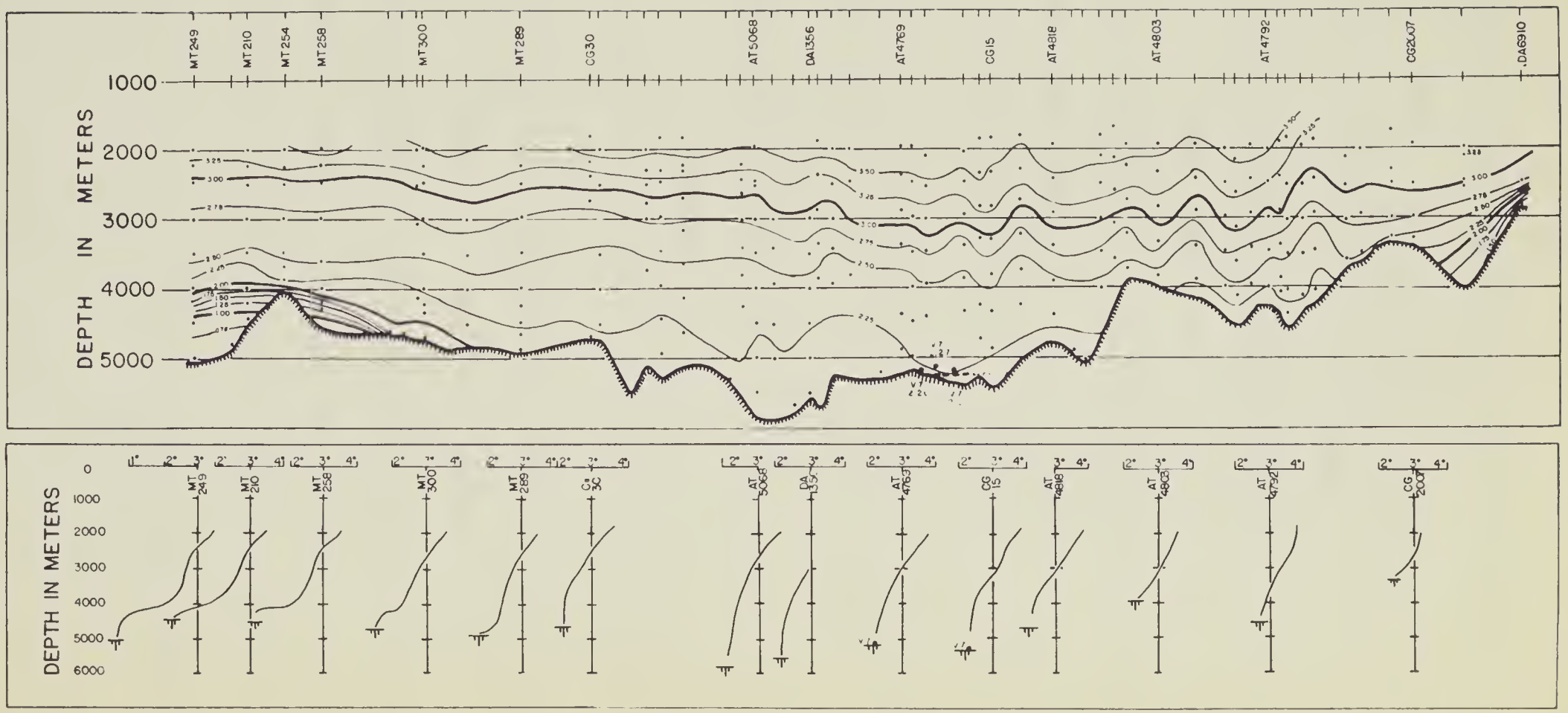
NORTH ATLANTIC OCEAN

DEEP WATER TEMPERATURE PROFILES

(GREATER THAN 2000 METERS)

IN SITU TEMPERATURES IN DEGREES CENTIGRADE

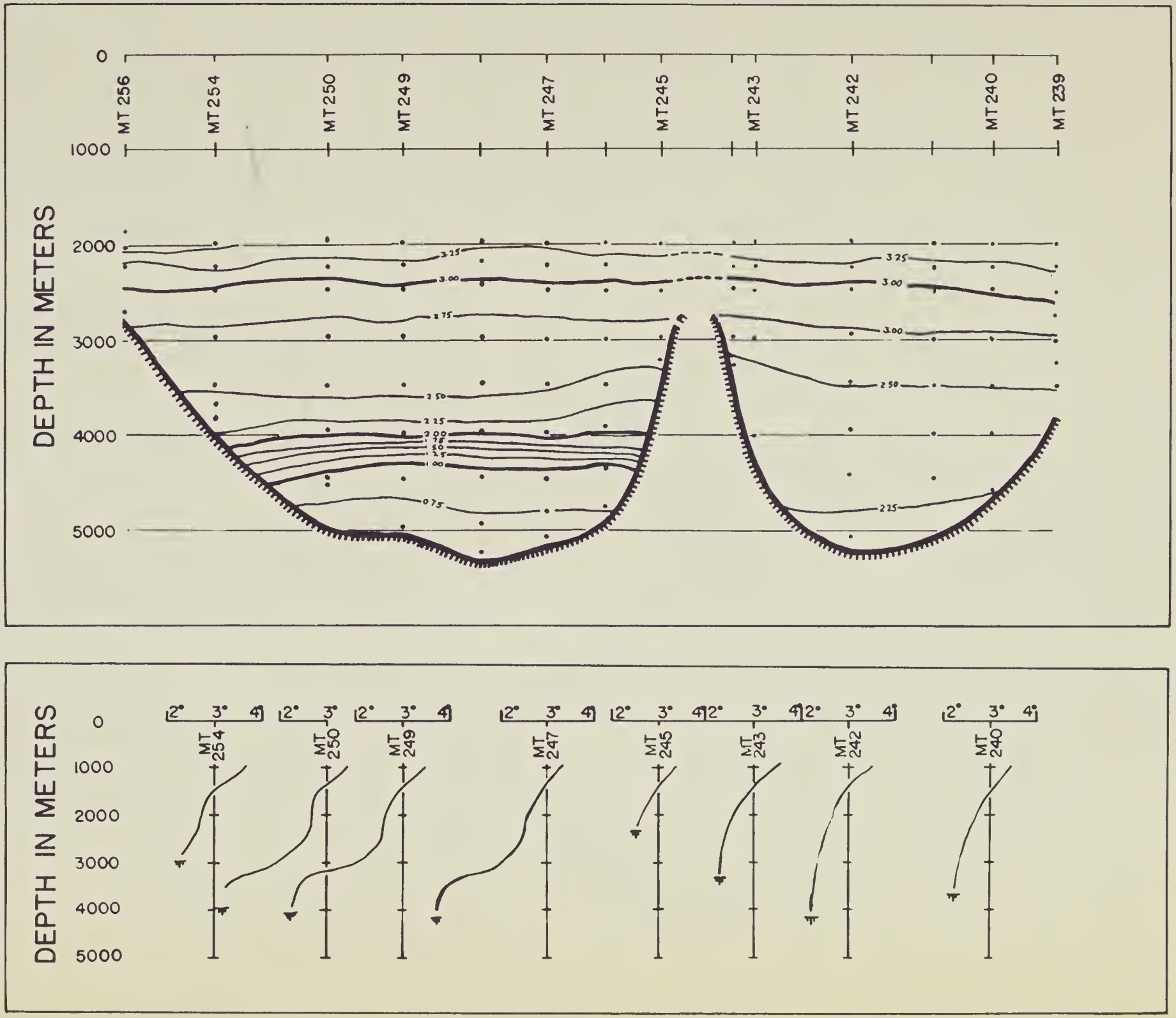
FIGURE 12



PROFILE A. EQUATOR TO DENMARK STRAIT WEST OF MID ATLANTIC RIDGE

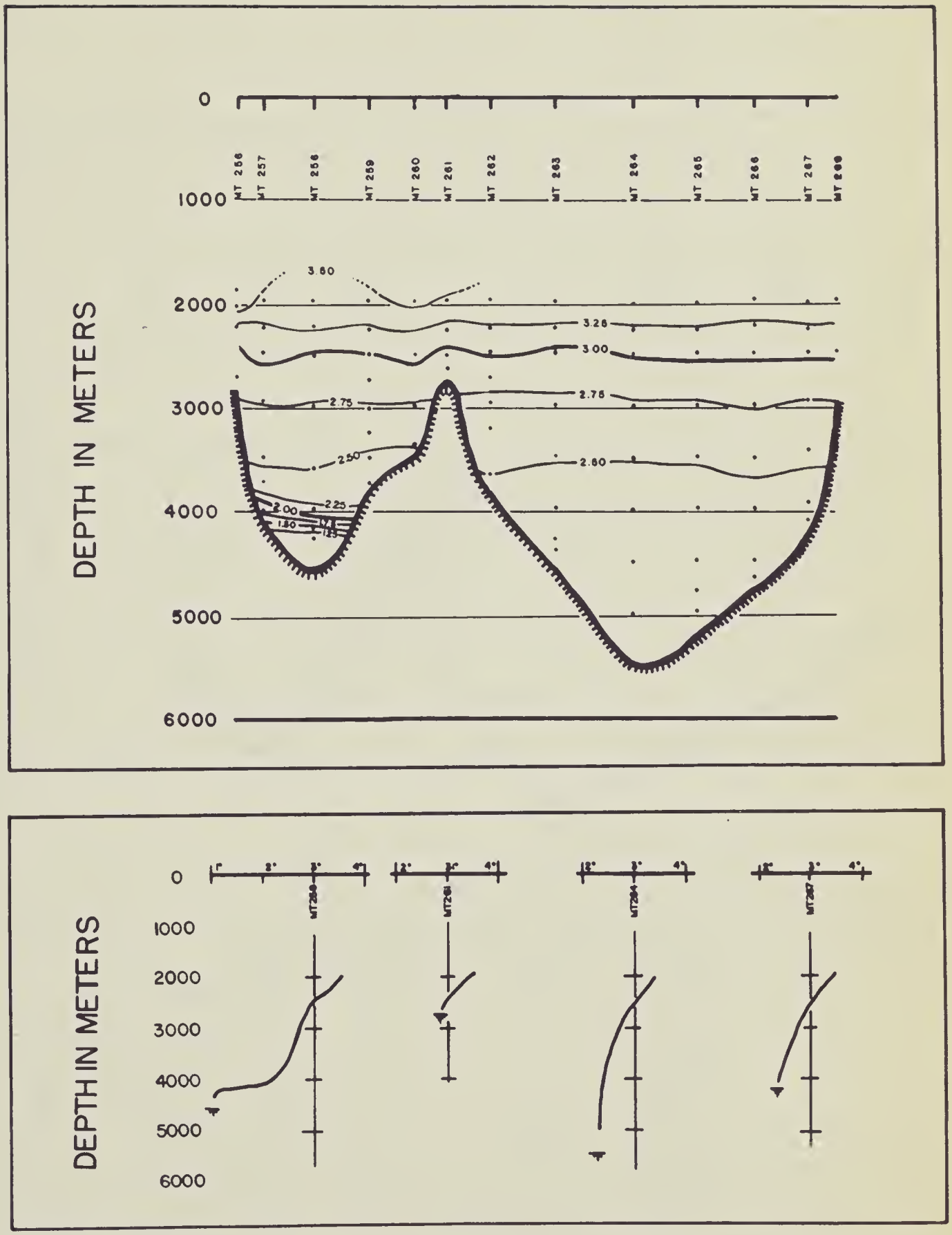
FIGURE 13

At this latitude the 2° water is but a thin layer against the western side (Figure 19) of the Labrador Basin. It is not known whether this water extends farther south in the Mid-Ocean Canyon through the Newfoundland Basin or not. The westernmost stations in Figures 17 and 18 show that the colder bottom water has merged with water above, the temperature gradient sloping gradually to the bottom. In the southern part of the long profile in Figure 13 bottom water from the South Atlantic less than 2°C reaches about 10° N. Lat. in the Guiana Basin. Beyond this area the gradient curves extend to the bottom without the inflection characteristic of the boundary with colder bottom water. Between 10° and 50° north the coldest continuous isotherm is about 2.25°C. Temperature observations from VEMA Cruise 7 have helped establish the position of this contour in the region about 40° N. (Figure 13). It is apparent that the bottom waters of Arctic and Antarctic origin lose identity in the North American Basin through mixing with overlying water. The east-west profiles trace the progressive modification of the deeper waters and contrast the characteristics east and west of the Mid-Atlantic Ridge. Figures 14, 15, and 16 trace the northward thinning of the Antarctic Deep Water moving northward. At the same time it can be seen that the eastern basins of the Atlantic are effectively cut off from the deeper water in this area. Probably the passage of water into the eastern Atlantic takes place at about the 3500 meter level. Figure 16 shows pockets of water having warmer in situ temperature in the southern Canary Basin. The inversion here appears real and probably indicates much reduced circulation.



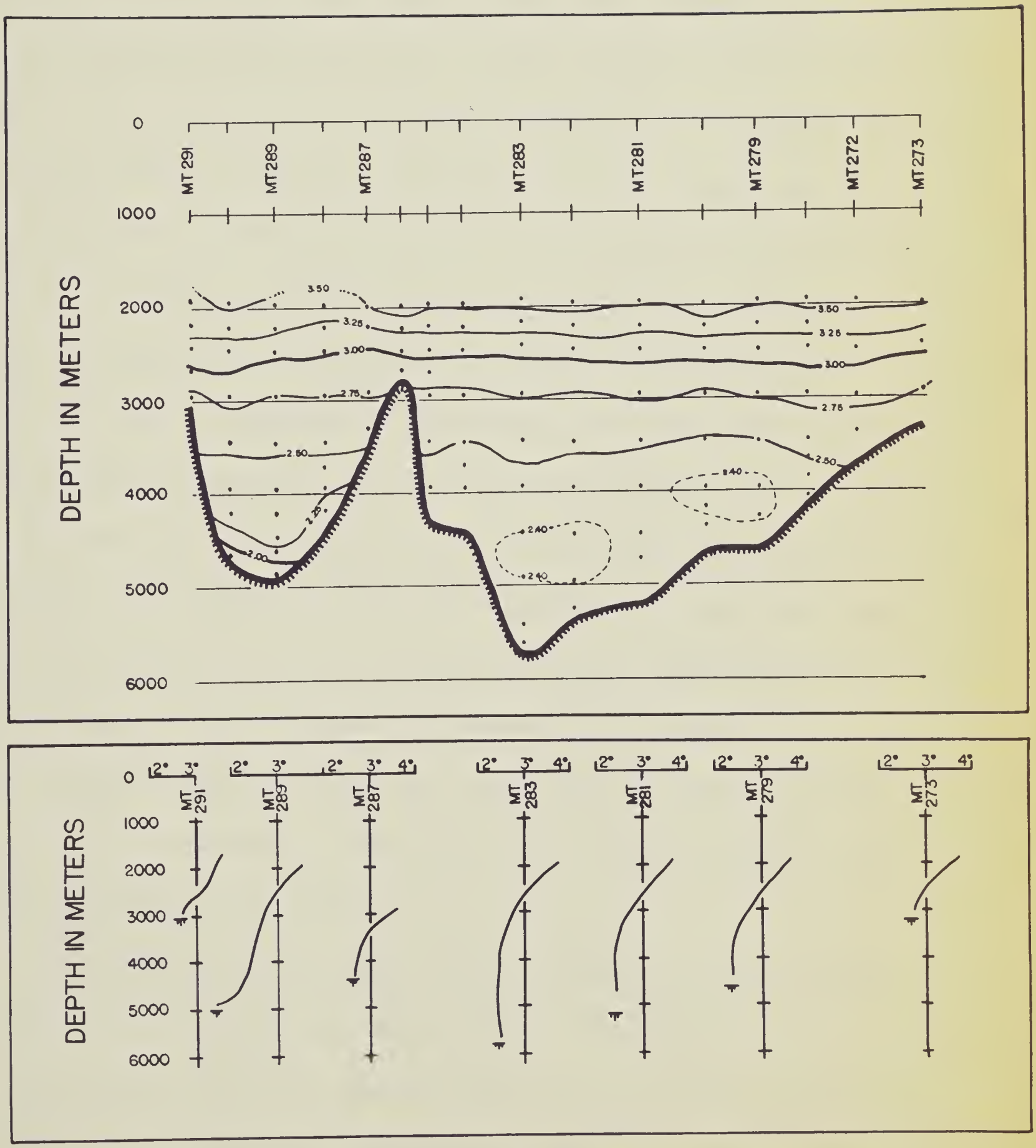
PROFILE I. NORTHEAST BRAZIL TO GULF OF GUINEA

FIGURE 14



PROFILE 2. NORTHEAST BRAZIL TO DAKAR

FIGURE 15



PROFILE 3. SURINAM TO MAURETANIA

FIGURE 16

In the Western Atlantic recent observations very closely spaced near the bottom (Worthington, 1955) reveal inversions of in situ temperature which do not show up in older measurements more widely spaced in the vertical. All of the apparent inversions have been examined for potential temperature and found to have only the adiabatic increase, but minimum stability is indicated. The slight stability of the Caribbean deeper water is well known. Additional areas in the western North Atlantic where minimum stability in the bottom 200 meters occurs lie at 35° N, 65° W and 30° N, 50° W. In the next profile to the north (Figure 17) water below 3800 meters in the western Atlantic is quite uniform in temperature. In the eastern Atlantic, however, 2° C water is found close to the bottom north of the Cape Verde Basin. The presence of this bottom water nearly 30° north indicates a deep passage through the Mid-Atlantic Ridge between 5° and 10° N. Lat. Figures 18, 19, and 20 contrast the colder water and steeper bottom gradients in the western North Atlantic with the warmer water to the east. Figure 20 shows the extremely cold bottom water which emerges through Denmark Strait while comparison with Figure 19 shows that this water is modified by bottom water in the Labrador Sea area, the latter being of greater consequence.

The preparation of these profiles has brought up-to-date a picture of the general distribution of deep temperatures in the North Atlantic Ocean. This picture provides a valuable guide for future measurements concerning the general circulation. A similar survey of reliable salinity observations is being prepared.

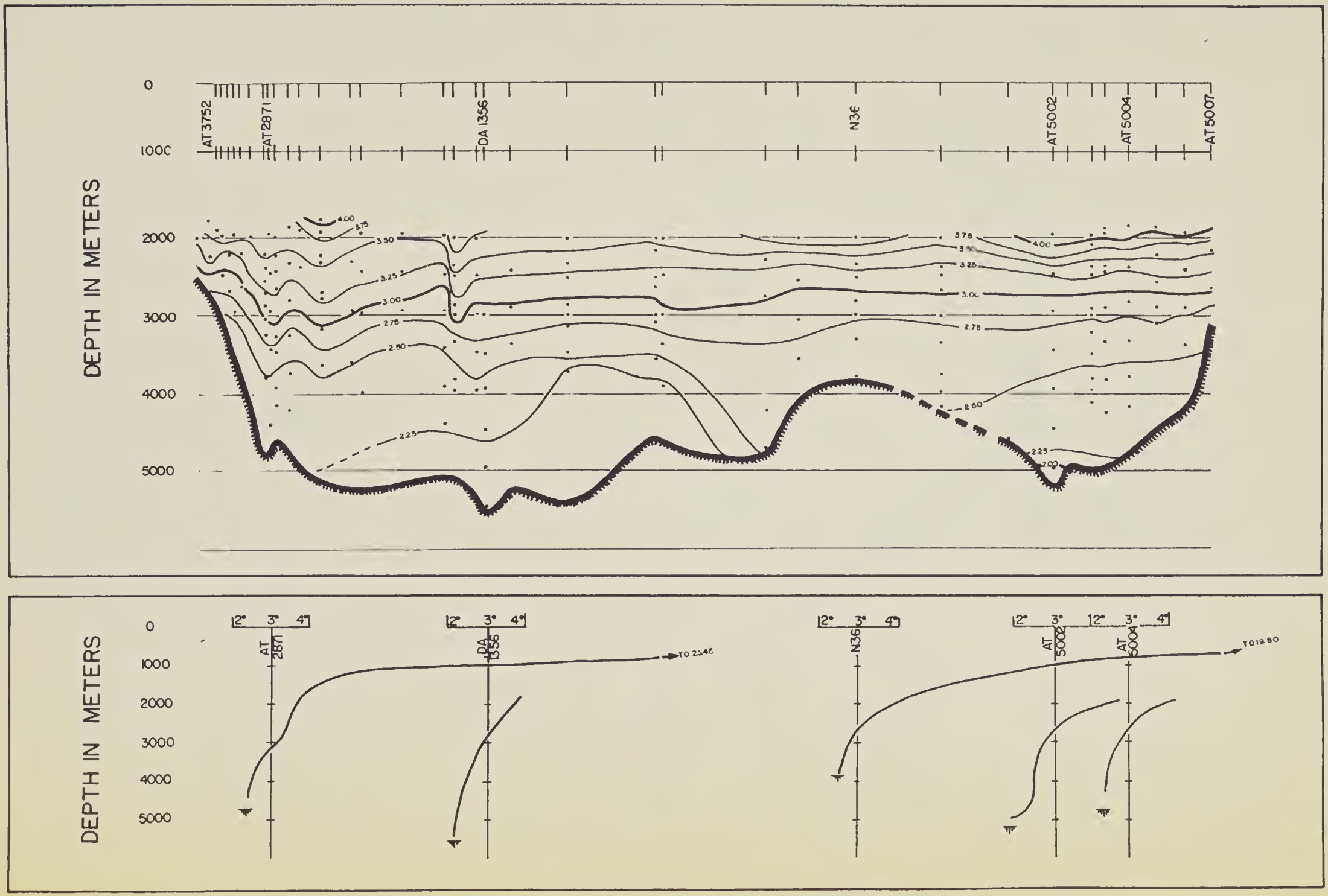
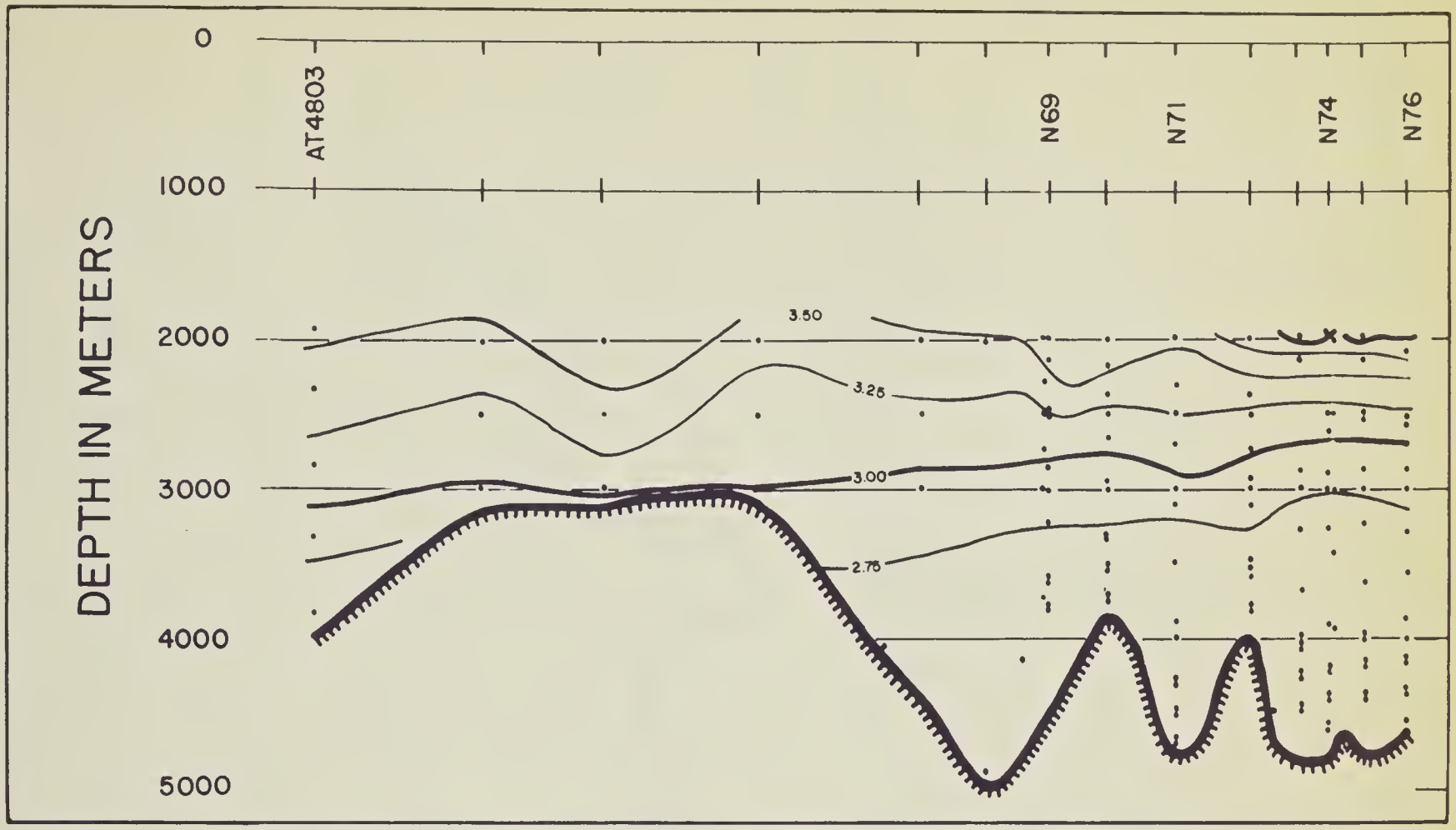
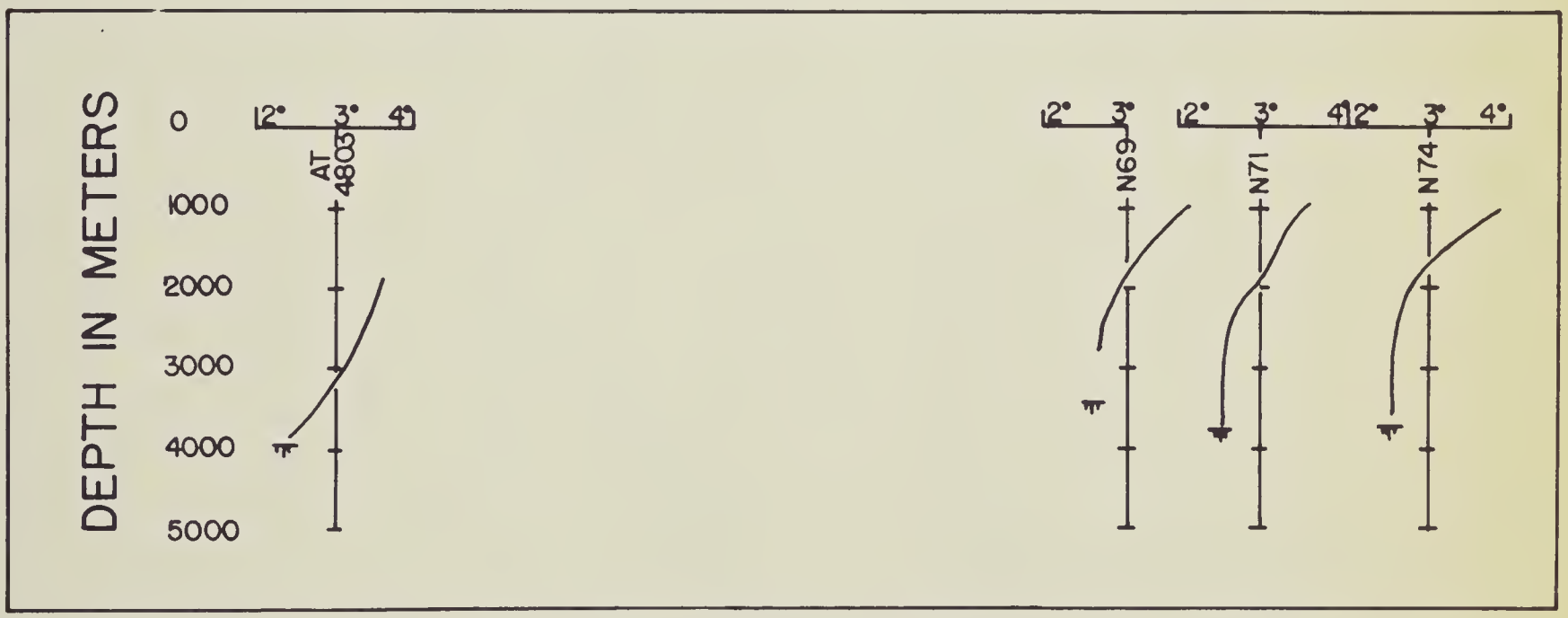


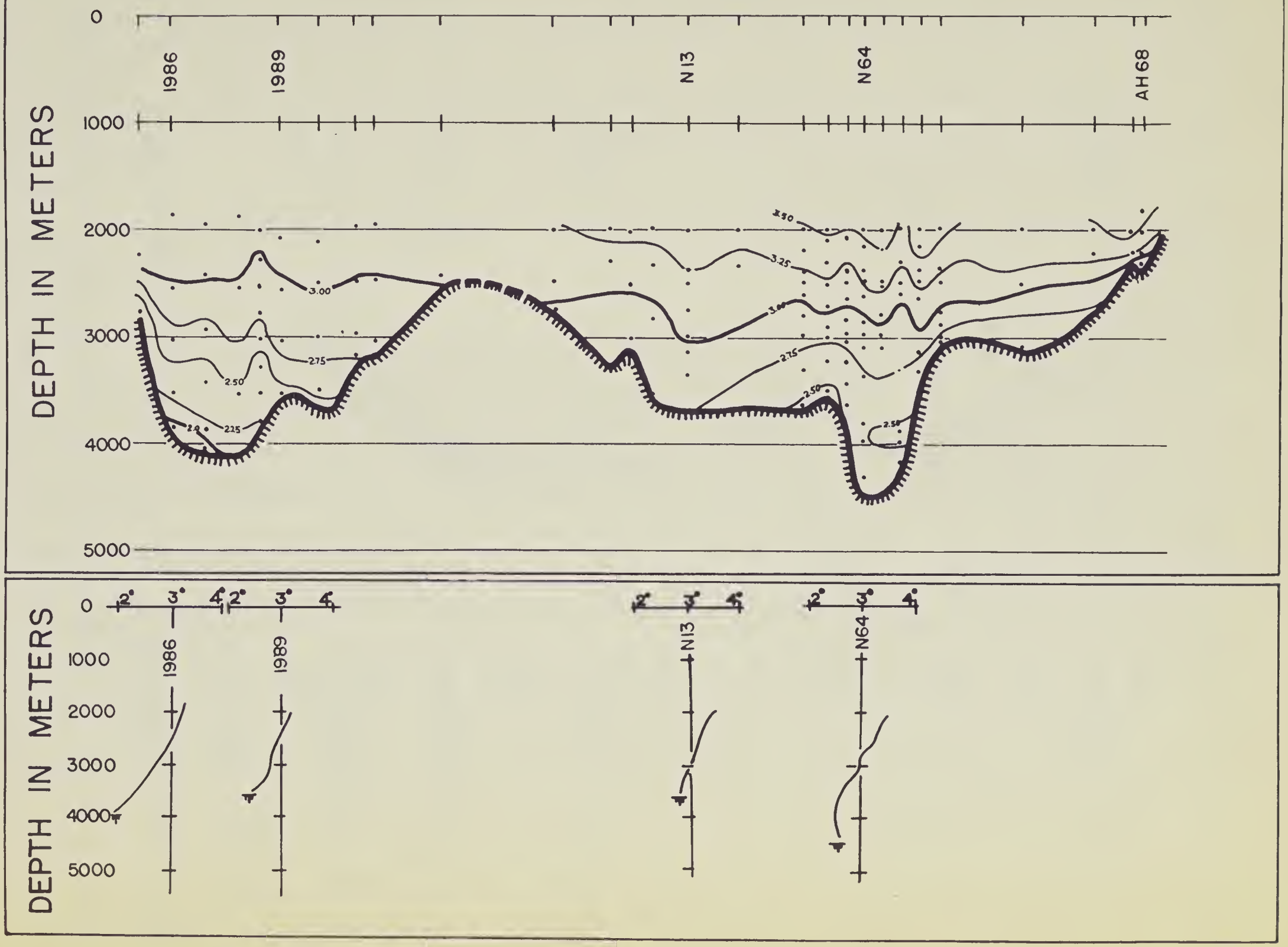
FIGURE 17 PROFILE 4. NEW YORK TO SPANISH SAHARA





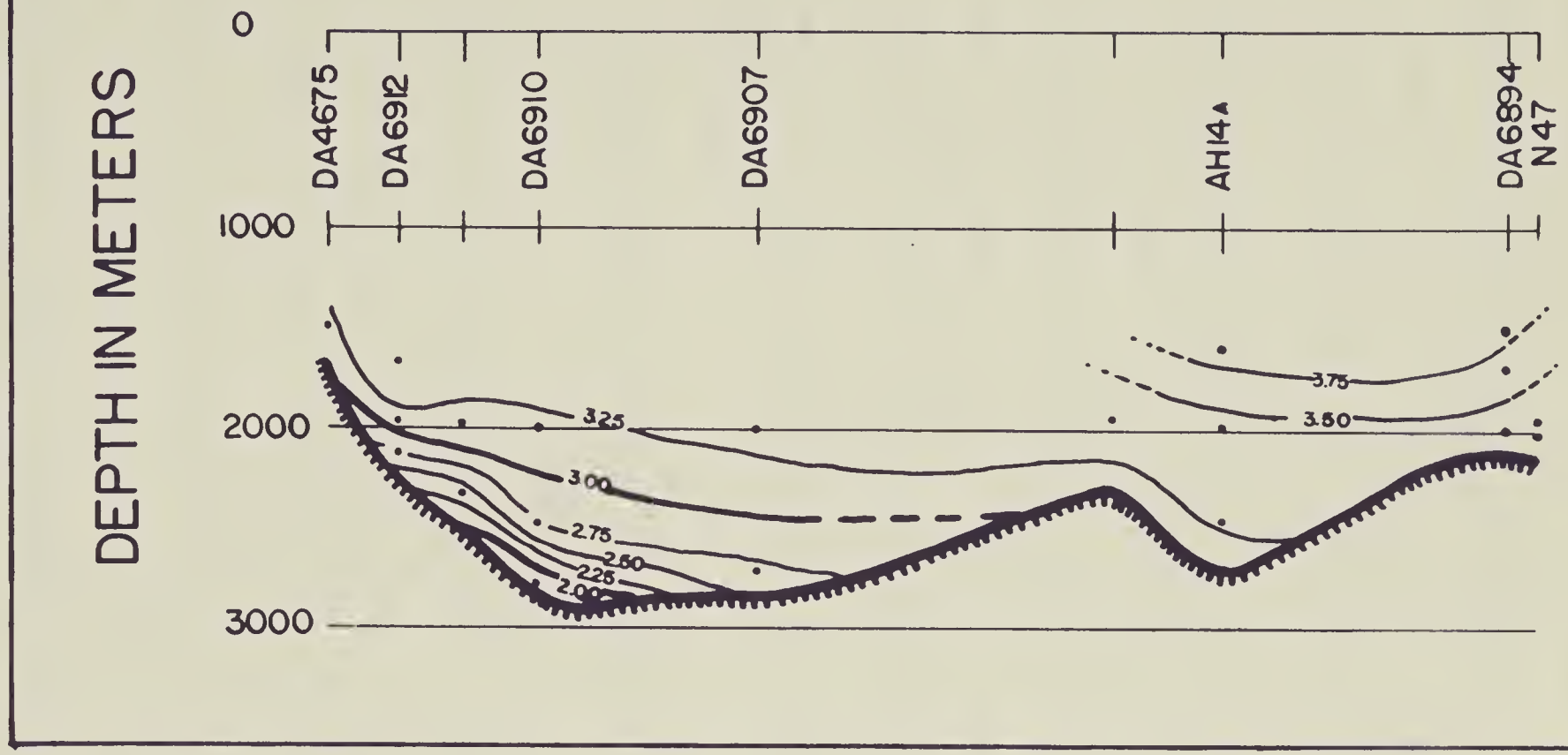
PROFILE 5. GRAND BANKS TO BAY OF BISCAY

FIGURE 18



PROFILE 6. GRAND BANKS TO SCOTLAND

FIGURE 19



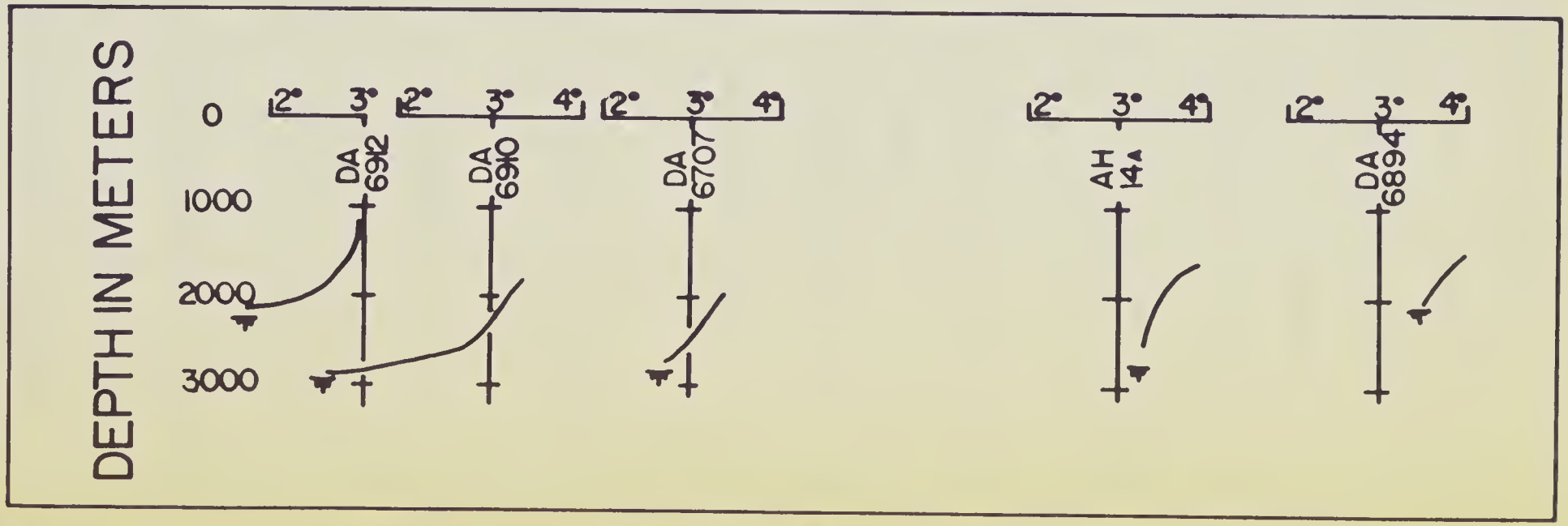
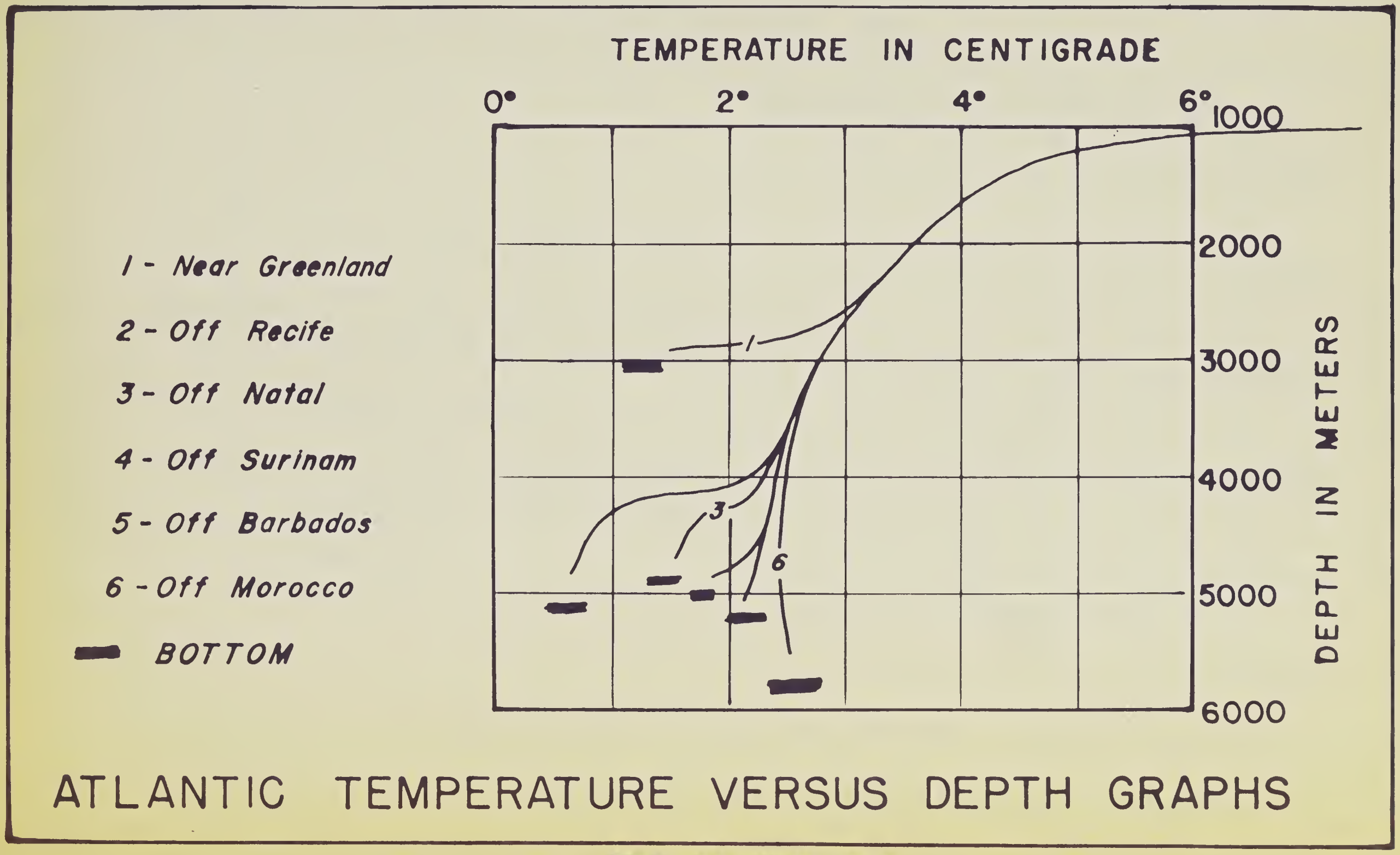


FIGURE 20 PROFILE 7. GREENLAND TO ICELAND

The problem of extrapolation of bottom temperatures from shallower observations has been considered. It is common practice to extend the slope of temperature curves to the bottom from observations which end several hundred meters above bottom. Figure 21 emphasizes the importance of the lowest few hundred meters in certain areas where bottom water masses may occur. Near-bottom temperature measurements which we obtained in 1955 in areas northeast and south of Bermuda have verified that extrapolations of 500 meters from earlier data could be made in the area with good accuracy. Figure 22 represents the extreme curves which might have been drawn for bottom temperature, the probable curve which was constructed, and the verification of that gradient through the new observations.

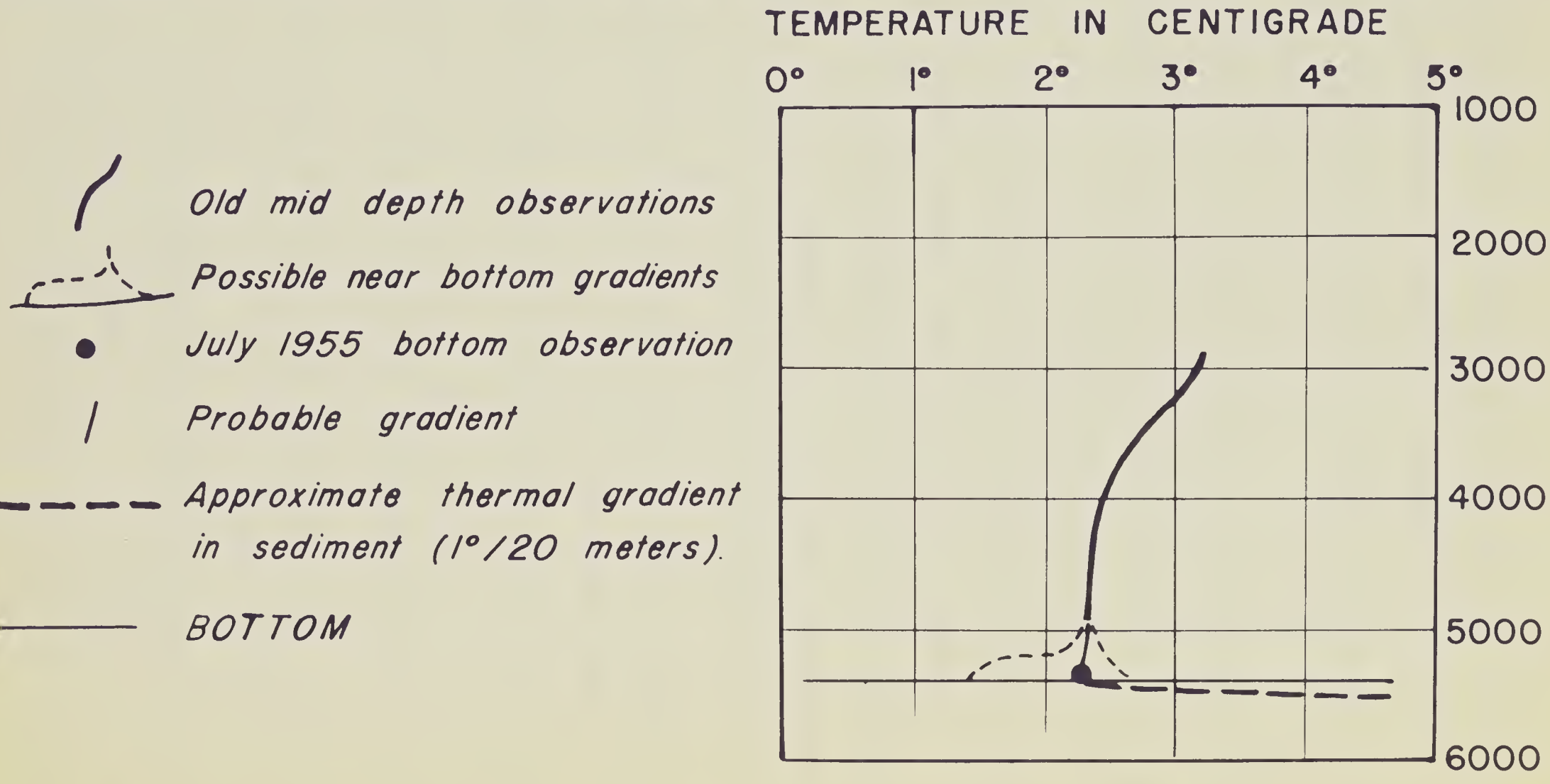
Having examined the general temperature distribution, a study of finer temperature structure is underway in the one area in the Atlantic Ocean where sufficient data is available to show the seasonal and annual variation in recent years. From 1928 to the present almost yearly hydrographic profiles have been run between Cape Farewell on the south tip of Greenland, and South Wolf Island, Labrador by the International Ice Patrol. Figures 10 and 11 illustrate the remarkable concentration of deep observations along this line which crosses the Labrador Current, the Labrador Sea, and the West Greenland Current. Preliminary results of this study show that temperature variations in the Labrador Sea correlate with the changes in air and surface water temperatures in the area.



ATLANTIC TEMPERATURE VERSUS DEPTH GRAPHS

FIGURE 21

FIGURE 22



BOTTOM TEMPERATURE OBSERVATION

SOUTH OF THE GRAND BANKS

Studies of climatic variation in recent time reveal that temperatures in the Northern Hemisphere showed a general increase from 1890 to 1940. The greatest increases have been noted in the Greenland-Iceland area particularly during the winter (Lysgaard, 1950; Willet, 1950). Marked changes in the distribution of herring and cod in these northern areas have made it clear that the climatic change has affected the surface waters (Ahlmann, 1953). The general structure of the water in the Labrador Sea shows a surface zone down to 200 meters having considerable seasonal variability in temperature and salinity. Below this zone is a deep layer of very uniform temperature extending to about 2000 meters. Beneath this level colder, more saline water extends to the bottom. Vertical mixing in winter must extend throughout the deep water. A trend in the temperature of this mass can be shown for the past 25 years. In 1928 a temperature of 3^{o}C was measured for the deep water. In 1937 it had reached a temperature of 3.3^{o}, and by 1949 was 3.6^{o}. A reversal after 1949 had brought the temperature of the deep water to 3.2^{o}C in 1954. These changes coincide with the trend and with the yearly variation of air temperature in the area during this time (Ahlmann, 1953). The boundary between the deep and bottom water has varied through the period by 500 meters in depth. The Bottom Water below 2000 meters has shown large erratic changes in temperature from 1.3^{o} to 2.4^{o}C during this same period which bear no apparent relation to surface temperature changes. The results of this preliminary study suggest that surface conditons may vary the rate of formation of deep and bottom water over short periods and

that the water thus formed may bear identifiable characteristics of temperature useful in determining the rate of flow away from the source.

IV. NEUTRAL-BUOYANCY FLOAT

During 1955 work was begun on a device for direct observation of deep ocean currents. The initial instrument was designed to be put into the ocean and float freely at a predetermined subsurface depth by means of delicate density adjustment. As a neutral-buoyancy float it would move along with water having the same density and signal its position periodically by releasing explosive charges. The explosions were to have been monitored by hydrophones on the mother ship and at one or more shore stations. Calculations from the signals received would establish the depth and mean lateral movement of the float over a period of about one week. Certain limitations were recognized in the inttial scheme. Test areas would naturally be restricted to areas where shore SOFAR stations were set up. The depth zone or "channel" in the ocean where optimum conditions exist for the transmission of sound is not necessarily the depth of greatest interest for observation of deep current. Furthermore some danger existed in setting free an explosive-laden unit in the sea.

In 1955 work was suspended on the original float when it was learned that a somewhat similar device was successfully tested by the National Institute of Oceanography in England. It was decided to modify our instrument after the British device. We have established contact with the English workers and good cooperation has been effected. The

The results of the tests made by the National Institute of Oceanography have been published by J. C. Swallow (1955). The neutral-buoyancy float which was used consisted of two lengths of aluminum tube filled with electric components for signaling to the surface. The units were adjusted to stabilize themselves at given depths. They were fitted with acoustic transmitters capable of sending out a short pulse every few seconds for two or three days. The tubes were chosen from stock material having low compressibility characteristics, high compressive strength, and made with enough spare buoyancy to carry the transmitter. The transmitter was a nickel scroll resonant at 10 kc/s, wound toroidally and energized by discharging a capacitor through a flash tube. Tracking the floats was accomplished by taking bearings on the float signal from a ship using two hydrophones. Several positions would be occupied by the ship to establish the bearings, and the vertical angle of the signal was used to measure depth of the float. The results of the British tests showed current movement of 5.7 cm/sec at a depth of 800 to 1500 meters, in the eastern Atlantic Ocean. Some uncertainty enters into the depth calculations.

Work is under way at the Lamont Geological Observatory on a modified version of this type of neutral buoyancy float. We plan to use a magnetostriction transducer similar to the British design but with greater power output for detection at greater distances. An improved depth control system is planned whereby depth of the float will be established using an echo sounder recorder on a ship traveling directly over the float. Our instruments are expected to be ready for testing in the fall of 1956.

V. PRECISION TEMPERATURE RECORDER

During the course of work on the present contract an instrument for high precision sensing and recording of temperature has been constructed. The device uses all electrical and electronic components. It has been designed to make temperature observations in continuous profile in the deep sea and to record temperature difference at depths in the bottom sediment for the purpose of heat flow studies. Another possible use for the instrument may be internal wave investigation by recording continuously at a fixed intermediate depth in the ocean. With these three purposes in mind, the Precision Temperature Recorder has been designed to the following specifications:

1. To measure temperature over a range of 0^{o} to 30^{o} C with precision of $\pm$ .01^{o}C.

2. To record ocean depth (pressure) with good precision simultaneously with temperature.

3. To record at the surface the data from the sensing unit in the ocean so as to obtain a continuous line graph of temperature against time or temperature against depth.

4. To send the information from the sensing unit to the recorder in the form of frequency change in order to avoid the variations and uncertainties which attend the sending of an amplitude signal under the conditions which prevail at sea.

The precision temperature recorder consists of a temperature-sensitive oscillator which is lowered on a single-conductor hydrographic wire connecting it to a recorder which converts the frequency signal into a line graph on board ship. An exploded view of the temperature-sensitive oscillator unit is shown in Figure 23.

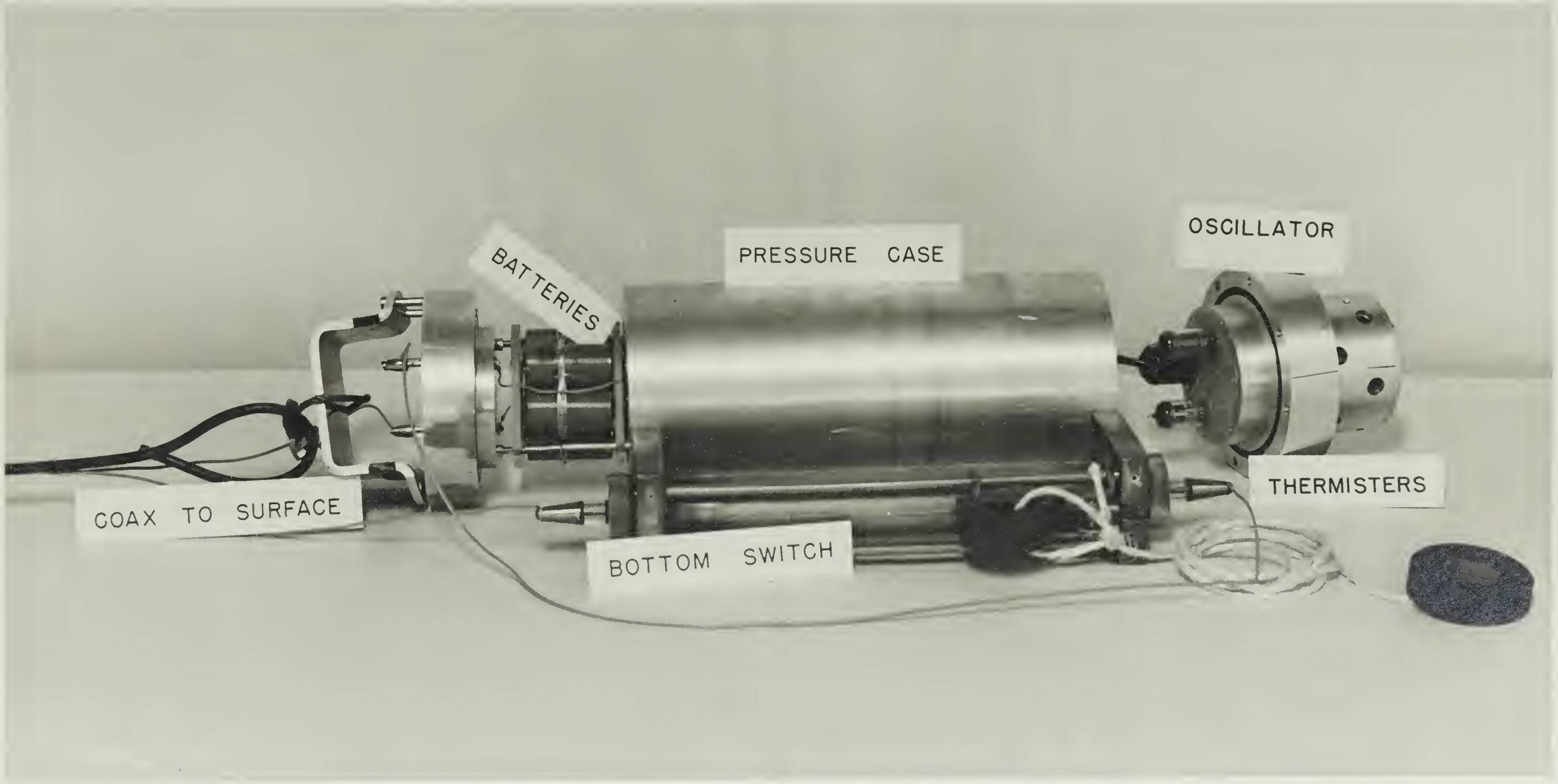

BATTERIES
PRESSURE CASE
OSCILLATOR
COAX TO SURFACE
THERMISTERS
BOTTOM SWITCH

FIGURE 23

The pressure case which houses the unit is an aluminum alloy cylinder 13 inches long with an outside diameter of 6 inches and a wall thickness of one inch. End plates are fitted with "0" ring seals and the unit has been tested to withstand 10,000 pounds per square inch pressure with probable safety to 15,000 pounds. Most of the space inside the case is occupied by batteries some of which can be seen projecting from the pressure case on the left side in the photo. The electronic components are mounted in the end plate seen on the right of the photograph. Two thermistors are fitted to the outer side of the same plate beneath the perforated housing (far right) and lead through the end plate to the oscillator circuit by means of a high pressure electrical pass-through. Similar pass-through fittings can be seen on the left cover plate in the figure which lead from the sensing unit to the conducting hydrographic wire. One of these leads passes through a switch which is triggered by contact with the ocean bottom. When the unit reaches bottom a D.C. signal is sent up the wire to indicate contact.

The oscillator is a conventional RC phase-shift type employing two thermistors in the frequency determining phase-shift network. Figure 24 illustrates the circuit diagram of the oscillator. The choice of components was made so that the frequency of the oscillator is

$$f = \frac{1}{2\pi RC}$$

where R is the thermistor resistance and C is equal to 500 micromicrofarads In the range of temperature 0° to 30° C the oscillator frequency varies from about 1200 to about 3800 cycles per second. The frequency range was chosen since it corresponds with a range of frequencies which will be

TEMPERATURE-SENSITIVE OSCILLATOR

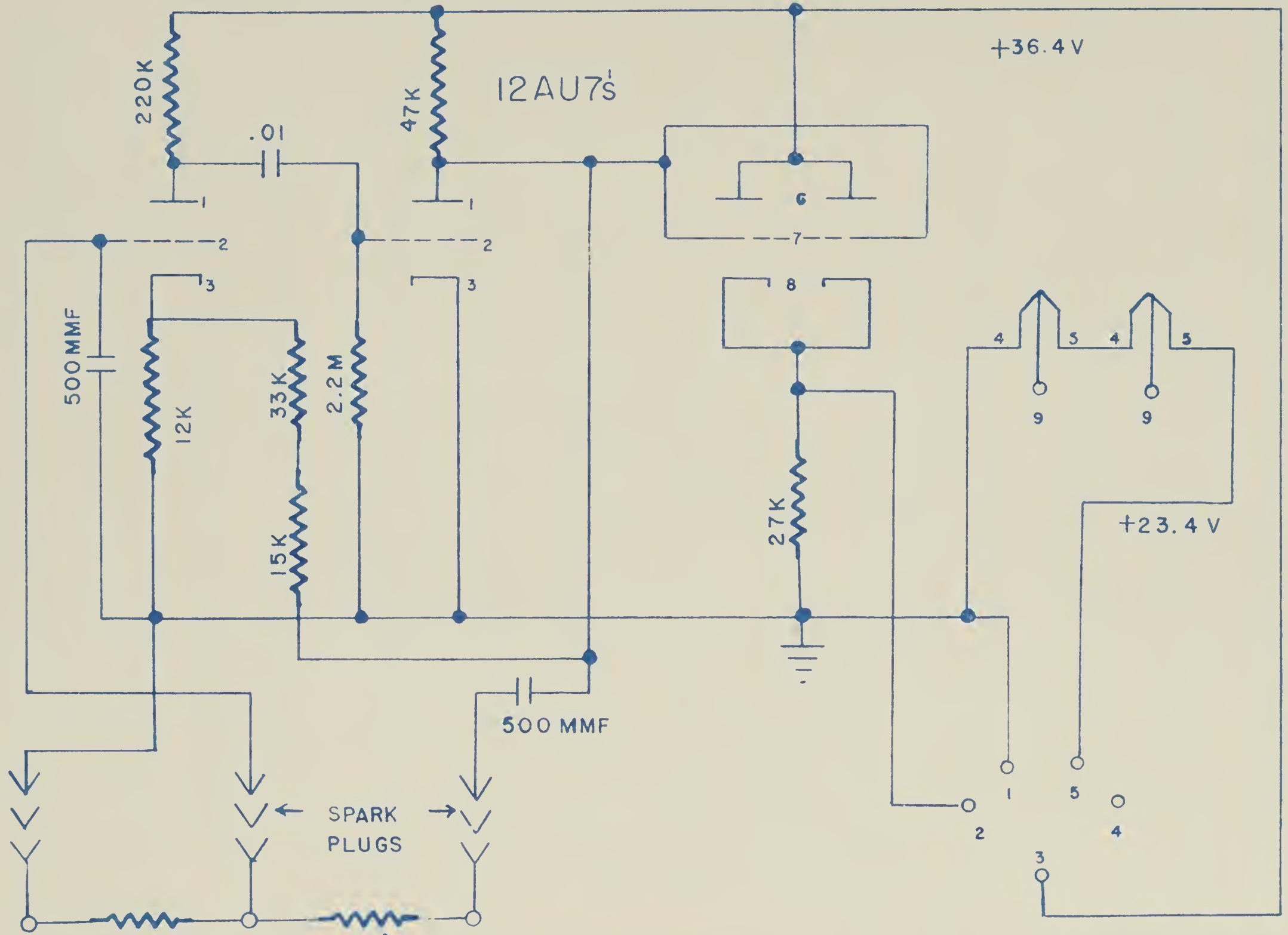


FIGURE 24

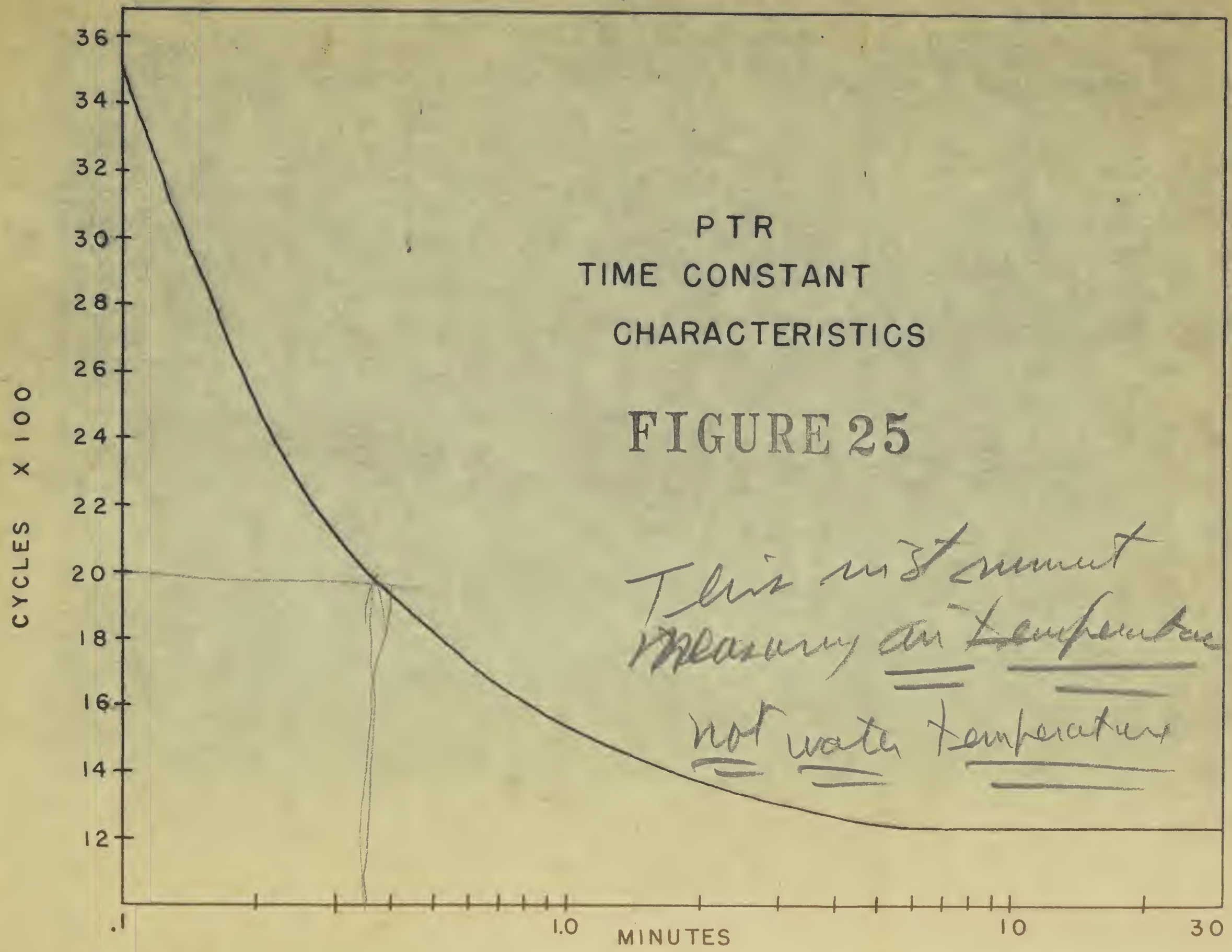
delivered by a new magnetometer instrument now under development, thus both instruments may use the same recorder. The oscillator circuit employs a substantial amount of degenerative feedback for frequency stability. Allowance has been made for drop in battery output due to lowered temperature. The frequency of the oscillator changes less than one part in 10,000 when the battery voltage is reduced by one-third. The response time of the sensing unit is illustrated in Figure 25. The curve is based on tests in air where the oscillator was stabilized in a temperature environment of 25° C and suddenly(within 10 seconds) immersed in an environment of 0°C. The frequencies at which the oscillator was stable for these extremes were 3,500 cycles and 1,200 cycles respectively. Considering the time required to come within 35% of the final stabilized reading the time constant of the sensing unit is seen to be about 15 seconds.

The recorder unit which will be used to handle the oscillator frequency is shown in Figure 26. Its development has been partly supported by other government contract funds. The functions of the recorder are:

1. To count the incoming frequency with high precision.

2. To make a digital-analog conversion so that the frequency count is presented as a line graph on a highly expanded scale.

A functional diagram of the recorder is presented in Figure 27. The frequency which is sent up the wire from the oscillator is led through an audio amplifier into an adjustable filter. This provides a noise-free signal for the audio-counter. The audio-counter consists of a chain of binary units gated by a program device which permits a count lasting about


PTR
TIME CONSTANT
CHARACTERISTICS
FIGURE 25
This instrument measures air temperature not water temperature
CYCLES X 100
36
34
32
30
28
26
24
22
20
18
16
14
12
.1
1.0
MINUTES
10
30

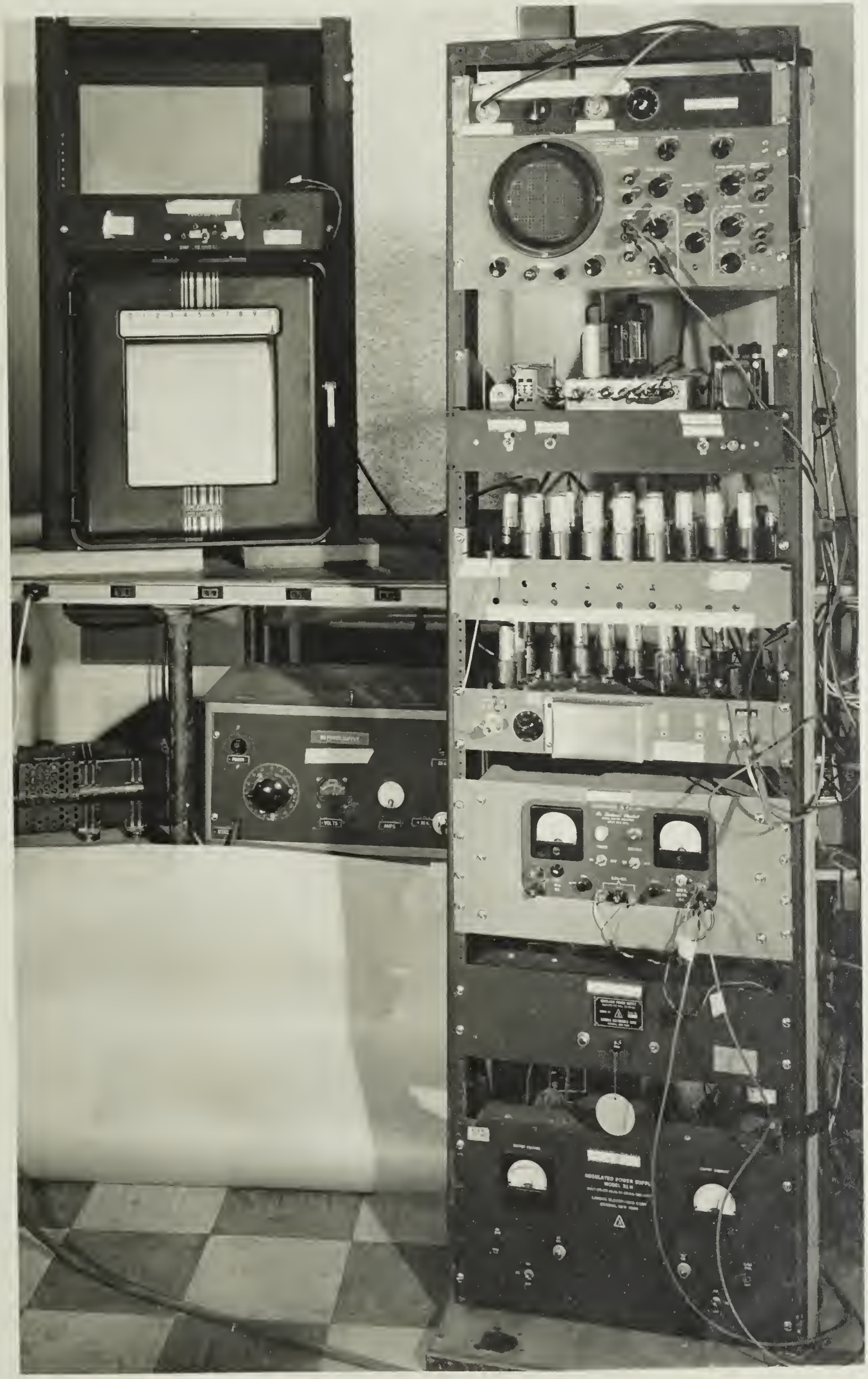


FIGURE 2C

TEMPERATURE SENSITIVE OSCILLATOR AND RECORDER

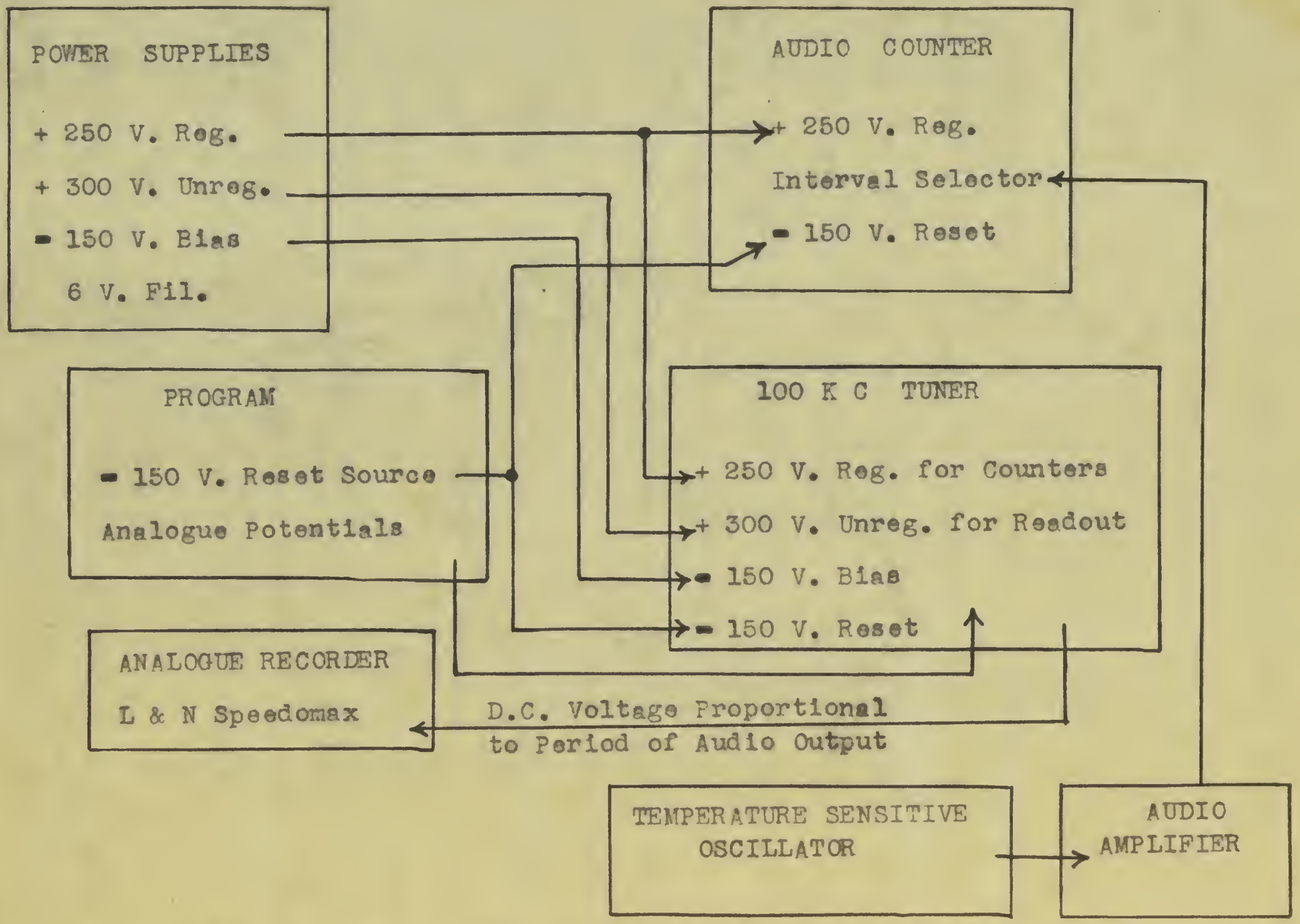


FIGURE 27

2.5 seconds to be made every 6 seconds. The operation of the audio counter can be summarized as follows: When the program device gates it on, it counts to 16, resets itself while sending out an ON pulse to a 100 KC timer, counts to 2048, and sends an OFF pulse to the 100 KC timer. The 100 KC timer is therefore operative for 2048 cycles of the temperature signal and the usual ± 1 count error of frequency counting is eliminated. The 100 KC timer unit is a chain of binaries fed by an over-controlled 100 KC crystal oscillator during its operative period determined by the audio counter gating pulses. It provides a highly accurate count of the period of the temperature-sensitive oscillator. The digital-to-analog conversion is accomplished by a set of binary read-out tubes which decouple the counting binaries from a set of read-out relays. The two positions of the read-out relays correspond to the 0 and 1 positions of each binary unit. The relays in turn control the connection of a matrix of small batteries, the sum of whose voltages is fed into a Leeds and Northrop Speedomax recorder. This recorder balances the input voltage to it and provides a continuous recording of the count on an expanded scale. The precision of the analog readout is one part in 500 and full scale on the Speedomax recorder is $1^{\circ}C$.

The Precision Temperature Recorder is being test-calibrated at the present time. Sea tests will follow, and will include the comparison with standard deep reversing thermometers at various depths in the ocean. When these tests are concluded it is planned to add a pressure transducer for the recording of depth. In addition a suitable probe will be provided

for penetrating into the ocean bottom sediment so that temperature difference may be read between two thermistor units spaced a considerable vertical distance apart on the probe.

Reference has already been made to certain measurements of heat flow through the floor of the ocean in the Pacific. The fact that the observations show values the same as for the continents may require drastic changes in present theory of the composition of the earth's crust and mantle, and in the thermal history of the earth. Previously it was assumed that the heat flow through the ocean floor was considerably less than on the continents, largely because of the increased radioactivity in granitic rocks. It does not seem possible to account for more than 50% of the observed value by assuming a "Fossil" heat effect in the ocean sediments as a consequence of warmer ocean temperatures in the past. Considering the observed ocean bottom heat flow of 1.2 to 1.5 x 10^{-6} cal/cm^2 /sec it is believed that only 35% of this value can come from activity in the crust and sediment plus the amount due to conduction from the earth's interior (Revelle and Bullard, 1952). The remaining 65% can be explained by assuming either increased radioactivity in the outer part of the mantle or convection heat transport in the mantle under the ocean. It is expected after initial field tests are completed, that the Precision Temperature Recorder will be adopted for heat flow observations and to put to use in this important [illegible] research.

The Precision Temperature Recorder described here is considered to have decided advantages over other instruments used for temperature measurement in the ocean. The advantage of being able to follow the trace of temperature at the surface from an instrument in situ cannot be overemphasized. Surface recording is made possible by the use of a frequency signal rather than amplitude or phase. The variability of wire impedance while handling the hydrographic wire as well as other variables preclude the use of other systems where high precision is desired.

Using this surface recording instrument, the search for discontinuities in the vertical thermal structure of the oceans could become a precise activity. Complete bathythermograph profiles from surface to bottom could be obtained in far less time than present serial hydrographic observations which almost never reach the bottom, and which secure temperatures from no more than 20 points in depth. Not only will the new depth trace be continuous, but two profiles will be available for each station, one ascending and one descending.

Considering the importance which the Precision Temperature Recorder may have to oceanographic sampling, work has gone on in the development of a suitable water sampling bottle for use with the recorder in taking complete hydrographic stations. A polyethelene container has been developed which is suitable for all water sampling including trace elements. It is planned to use a battery of such bottles attached close to the temperature recorder. The bottles would automatically trip at predetermined depths and their tripping depths would be accurately monitored

and correlated with temperature through a D.C. pulse sent to the surface with the closing of each bottle. It is believed that the Precision Temperature Recorder has great potential value in oceanography. The temperature unit if used with the water sampling unit described could take highly accurate and far more complete oceanographic observations in much less time than the instruments now in general use which were developed 50 years ago.

It is planned to have two Precision Temperature Recorders operating at sea during the summer of 1956.

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