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Temperature-salinity relations and mixing

on the Scotian shelf

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Introduction

The temperature-salinity diagram introduced by Helland-Hansen (1916) has proved a powerful tool in the description of physical processes in the oceans. With it, waters may be identified as belonging to a given water mass (a definite curve on the T-S diagram), or water masses may be identified as being derived from specific water types (points on the T-S diagram). Wust (1935), for example, has shown how the T-S diagram can be used in tracing Mediterranean waters as they flow into the Atlantic Basin, gradually loosing their T-S identity through mixing. Jacobsen (1927) and Stockman (1946) have discussed the theory of T-S curves resulting from the mixture of two or three water types, and have shown how a co-efficient of mixing may be determined.

In most cases where T-S diagrams have been discussed, it has been found convenient to use only observations from deeper than some 100 to 200 metres, as "surface data have to be omitted because annual variations and local modifications lead to discrepancies" (Sverdrup et al 1942, P.142). Analytical treatment has been mostly limited to cases involving the mixing of no more than three water types. Hence the question arises as to what use can be made of this method in the study of an area such as the Scotian Shelf, where the average depth is approximately 150 metres and at least four water types must be invoked to explain the T-S relationships found.

Miller (1950), in a study of mixing processes over the edge of the continental shelf, where most of the observations were from depths less than 100 metres, introduced a modified concept of the T-S theorems and a method of analysis against a quadrilateral grid. Such concepts and analyses may greatly extend the usefulness of the T-S method in coastal regions. The application of T-S analysis to shallow areas will be useful in a limited area where the mixing processes are proceeding rapidly relative to the influence of such local factors as evaporation, precipitation and solar radiation. It is of interest to attempt such an analysis of the waters on the Scotian Shelf during a specific month for the illumination of the mixing processes active in that area.

Method

In the usual study of T-S co-relation each point on the T-S diagram represents a distinct "water type". It is assumed, or argued, that the T-S distribution of the observed water mass is arrived at by the mixing of a finite number of "water types" representative of "source regions". At these "source regions" water masses must exist which are homogeneous in the temperature and salinity displayed by the terminal point of the T-S curve under consideration, and in sufficient supply to maintain the observed system.

The geometry of T-S curves resulting from the mixture of two and three water types has been treated analytically by Jacobsen (1927) and Stockman (1946). It can be demonstrated that when two water types, represented by points on the T-S diagram, mix in any proportions, the resultant water mass is represented by a straight line joining the two points. Similarly, when three types mix, there result initially, two intersecting straight lines which, unless all three types are in

unlimited supply, degenerate as mixing progresses into curves which
can be analytically formulated.

Miller's (1950) method of treating T-S relationships circumvents
the necessity of postulating absolute homogeneity of water types. It
is sufficient that the points representing the T-S correlations within
the water type fall inside a small area on the T-S diagram. The mixing
of two water types, so defined, will result in points which lie within
the envelope of straight lines joining the two areas. If, then, the
points representing data for an area are enclosed by a simple geo-
metrical figure formed by straight lines joining extreme points, and
these lines are then divided into equal numbers of equal sections, a
grid may be constructed which usefully describes all the waters. Sup-
pose that the figure is a quadrilateral ABCD and that the grid is
formed by dividing each side AB, BC, etc. into four equal parts. If
each of the extreme points A,B,C, and D is considered to represent a
fictitious homogeneous water type, then the point A will be touched
by a segment of the grid, all points in which could represent water
derived of at least 75% A and up to 25% B or D. This segment may
now be labelled A and will be termed a water "type" under the less
rigorous definition regarding homogeneity. Similarly there will be
a segment comprised of from 75% to 50% A with from 25% to 50% B, and
this will be labelled "Ab", etc. There will be some ambiguity re-
garding the origin of waters represented by the central segments in
the grid (Abc, acD, etc.), but in many cases this ambiguity will be
dispersed by consideration of the distribution of points within the
central segments.

Data

The data considered are from the observations of the C.N.A.V. "Whitethroat" cruise WT-5 in November 1950. This was one of the series of seasonal cruises over the Scotian Shelf made by the Atlantic Oceanographic Group, (McLellan and Trites, 1951). Thirty-six stations were occupied in lines over the Nova Scotia banks, across Cabot Strait, and across the Bay of Fundy. The locations of these stations are shown in figure 1. At each station sampling was carried out at standard depths and to the greatest permissible depth, except for the six deep water stations where 800 metres was the greatest depth sampled. Station 24 lay just within the slope water regime and was the only station occupied in the slope water during this cruise.

Figure 2 shows the scatter of points on a T-S diagram for all stations. Salinities ranged from 30.02 ^{o}/oo to 35.18 ^{o}/oo and temperatures from 0.8 C. to 16.9 C. The heavy dashed line to the right of the figure represents the characteristics of Central Atlantic waters after Iselin (1936). This curve normally forms a limiting curve in the T-S pattern of the deeper slope waters (Iselin 1936). Curves of equal density (σ_t) have also been shown in the figure.

Analysis

1. The Grid

Five points were chosen to bound the area occupied by points on the T-S diagram in figure 2. They were as follows:

Point A - Temperature 7.8 C., salinity 29.90 ^{o}/oo, representative of the surface waters flowing from the Gulf of St. Lawrence, out through the western side of Cabot Strait (Sandstrom 1919, P.289) and thence over the Scotian Shelf.

$\underline{Point\ B}$ - Temperature 17.5 C., salinity 35.03 /oo, representative of
the surface slope water at the time of this cruise.

$\underline{Point\ C}$ - Temperature 11.0 C., salinity 35.40 /oo, representative of
the limiting characteristics of slope water at intermediate depths.

$\underline{Point\ D}$ - Temperature -1.7 C., salinity 33.00 /oo, representative of
the coldest waters which come around the Tail of the Grand Banks and
are sometimes found as far as Banquereau Bank, (McLellan and Trites
1951). No waters of these precise characteristics were observed dur-
ing this cruise.

$\underline{Point\ E}$ - Temperature 4.0 C., salinity 34.97 /oo, representative of
the deeper slope waters.

It must be borne in mind that these points will bound the T-S area
only in so far as the results of this cruise are concerned. Points A
and B especially will be subject to seasonal variations. In order that
the method of analysis might be valid it is necessary to postulate
that mixing, both horizontal and vertical, takes place rapidly com-
pared to seasonal variations. This view is supported by the fact that
most of the surface observations fall close to a straight line joining
points A and B.

The lack of observations falling in the region between points
D and E, and the known origins of these water types, one in the deep
slope waters and the other in shallow coastal waters, is sufficient
reason to assume that no direct mixing takes place between these waters.

A grid was constructed in two parts (figure 3) dividing the per-
tinent area on the T-S diagram into twenty-eight segments. One part
of the grid took the form of a quadrilateral ABCD in which each side
was divided into four equal parts and the division points joined in a
quadrilateral grid. On the side CD a triangle CDE was erected, and

each side of this similarly divided into four equal parts.

The segments of the grid were then labelled as shown in figure 3. In each case the large letter indicates the water type chiefly involved in producing the waters belonging to the segment, while the small letters indicate the type or types also required to complete the mixture. There is some ambiguity concerning the origin of waters in those segments requiring a three letter label, but this is in part dispelled by the observed distribution of water types. In the section described below (figures 4 to 9 inclusive) areas where these water types were found, have been indicated by stippling.

2. The Sections

Having constructed the grid and so labelled the water types, the next step in the analysis was to plot the distribution of water types as they occurred in vertical sections. The T-S curve for each station was overlaid with the grid and the distribution of water types with depth recorded. These were plotted in vertical sections in figures 4 to 9 inclusive.

(a) The Cabot Strait section. This section (figure 4) shows "A" type water flowing out of the Gulf of St. Lawrence on the Cape Breton side of the Strait. On the Newfoundland side the surface waters are colder and more saline ("Ad"). A layer of "D" water with average thickness of the order of one hundred metres covered the whole section at intermediate depths. Below this layer, the sequence of water types was "cD", "Cde", and "cE" showing the combination of "E" water with water formed by a mixture of "D" and "C" waters. The occurrence of "Cde", "cE", and "E" water at depths less than 500 metres in the slope waters and coastal waters has been interpreted as the result of up-welling of Central Atlantic waters against the continental slope

(Iselin 1936, McLellan et al 1952).

(b) _The Banquereau section_. The section shown in figure 5 ran from the Cape Breton shore out over Banquereau Bank and beyond the edge of the continental shelf. A surface layer of type "A" water covered all but the outer part of the section to a depth of over forty metres, and a fairly sharp transition lay between this and the "D" water which covered the banks. The "D" water extended more than forty miles beyond the outer edge of Banquereau. At station 32A, the influence of warm "B" water was shown in the sequence "Ab", "Abd", "acD". In the water deeper than 150 metres, beyond the Shelf, the sequence was "cD", "Cd", "Cde", "cE", "E" showing that "D" and "C" waters mix and there is a deep water addition of "E" water.

(c) _The Emerald Bank section_. The section in figure 6 ran from Sambro Bank over Emerald Bank and beyond. Inside, and over Emerald Bank, the influence of slope water ("B" and "C" waters) was marked in the sequence "Ab", "Abd", "acD", "cD", and the bottom water was a layer of "Cd", which extended slightly beyond the outer bank. Moving outward, the transition to a pure slope water type is seen in a narrow band with sequence "aB", "aBc", "bCd", "Cd", "Cde", "cdE", "E", "E", beyond which the sequence is that of the usual slope water. A tongue of surface slope water ("B") was observed to extend in, under the "aB" water, as far as station 22.

(d) _The Roseway, LaHave section_. The section running out over Roseway and LaHave banks (figure 7) showed a greater coastal influence than had appeared in the Emerald Bank section. The occurrence of "Ad" and "aD" water at stations 15 to 18 is indicative either of a flow along the coast which is confined inshore of station 19, or a flow which, having been more general, has been interrupted by the intrusion

of warmer waters in the Emerald Bank section. Hachey (1942) has in-
dicated such a continuity in his illustrations of temperature and salin-
ity distributions. This section did not extend to the slope water al-
though stations 12 and 13 showed high proportions of waters with "slope"
characteristics. Below 200 metres, station 13 showed the slope water
sequence, but a more coastal characteristic was observed at station 12
between 200 and 475 metres. These waters ("Cde" and "cdE") are no
doubt continuous with those found close against Emerald Bank and would
indicate that these waters flow westward against the trend of the slope
water.

(e) The Brown's Bank section. The section shown in figure 8 ran
from Cape Sable, over Brown's Bank to the eastern extremity of Georges
Bank. The waters in this section are generally well mixed, especially
over Brown's Bank. The general sequence of water types is "Ab", "Abd",
"acD", with more slope-like waters pressing in at stations 10 and 11.
The bottom water inside Brown's Bank ("aBc") appears to be derived
from the Bay of Fundy.

(f) The Bay of Fundy section. All of the water in the section across
the Bay of Fundy (figure 9) belongs to categories about whose origin it
is difficult to be specific. Along the coast of Nova Scotia a surface
layer of "Ab" water extends down to the mouth of the Bay, while the
deep Fundian Channel, is fed by "Cd" and "C" type waters through the
channel between Brown's Bank and Georges Bank (station 10, figure 8).
The intense tidal mixing in the Bay of Fundy converts these to "Abd",
"aBc", and "bCd" waters with "Abd" predominant. Consideration of the
density (σ_t) lines on figure 3, will show that due to this mixing
surface waters are produced which are heavier than surface waters out-
side the Bay, while bottom waters in the Bay are less dense than those

at similar depth outside. The result must be an outward flow at mid-depths, which accounts for the thick layer of "Abd" water shown in figure 8, and calls generally for a flow of waters into the mixing system both at the surface and along the bottom. Such a system has been remarked upon by Bigelow (1924 and 1928) and by Watson (1936).

Discussion

Presentation of the data in this form has some advantages in the formulation of a movement pattern for the area. This is so since a more or less definite region may be designated as the source of each of the five basic categories of water. "A" water flows out the western side of Cabot Strait and covers the surface as far as station 31. As it moves westward along the coast considerable mixing with "B" waters takes place, probably localized in the region of Middle Ground Bank, so that only "Ab" water is found in the three western sections. The "B" and "C" waters are representative of slope water from the surface and mid-depths and have their greatest influence in the Emerald Bank section, and, in the case of "C" water, again in the Fundian Channel. "D" water appears as a strong layer across Cabot Strait and over the banks in the Banquereau section. Its influence is felt in all sections but is considerably modified by "C" waters in the more westerly sections. "E" water appears only below 450 metres beyond the edge of the continental shelf. Its greatest influence inshore is observed in the bottom waters of the Cabot Strait section, which is indicative of a flow inward along the Laurentian Channel. The efficient mixing brought about by tidal action in the Bay of Fundy is evidenced by the fact that mixture of at least three of the basic water types is required to explain the origin of any water found here. "A", "B", "C", and "D" waters are all necessary for explanation

of the complete column.

The grid used in this analysis will of course only be applicable to the single cruise and the water movements inferred do not necessarily hold for all seasons. It is implicit in the method that a condition of simultaneous observations be approximated and that the dynamics be inferred from a static distribution.

Summary

1. A method essentially similar to that used by Miller (1950) makes it practical to use T-S relationships in studies of mixing and circulation of shallow waters.

2. A five pointed grid was necessary to classify the waters found on the Scotian Shelf in November 1950. The five points were representative of:

(a) surface water flowing out of the Gulf of St. Lawrence on the west side of Cabot Strait.

(b) surface slope water.

(c) slope water from intermediate depths.

(d) cold Labrador water which enters the area by rounding the Tail of the Grand Banks.

(e) deep slope water.

3. Vertical sections showing water types as designated on the T-S grid show several features of the dynamics of Scotian Shelf waters:

(a) The surface water from the Gulf of St. Lawrence floods the eastern portion of the Shelf as far offshore as Banquereau Bank but undergo significant mixing with surface slope water before appearing in the section to the west of this.

(b) Cold water of Labrador characteristics appears as a thick layer in Cabot Strait and over the Banquereau section where it reaches to the bottom, but it also is considerably modified by slope water as it moves towards the southwest.

(c) The deep slope water has a significant influence in the waters beyond the Shelf and in the deep waters of Cabot Strait.

(d) The efficiency of Bay of Fundy tides as a mixing mechanism is shown by the need to evoke at least three primary water types to explain any of the waters found here.

(e) There is evidence of an outflow of mixed waters from the Bay of Fundy at mid-depths.

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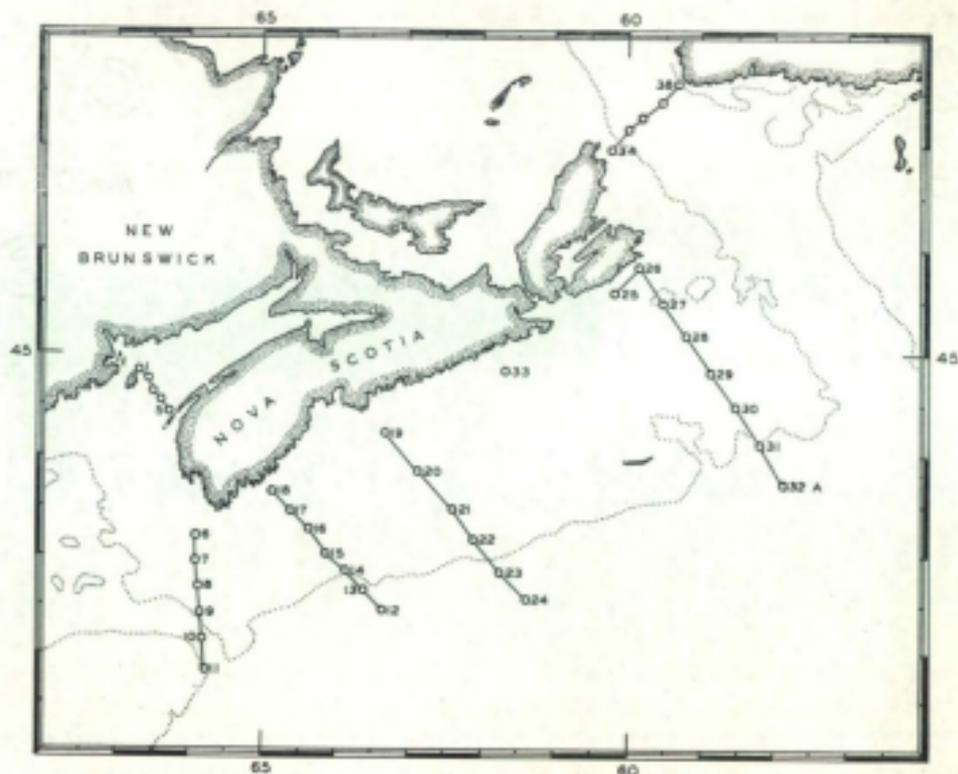　　　Meteor. 1925-1927, Wiss. Eng. 6, 1, 2, 288 pp. 1935.

Figure 1

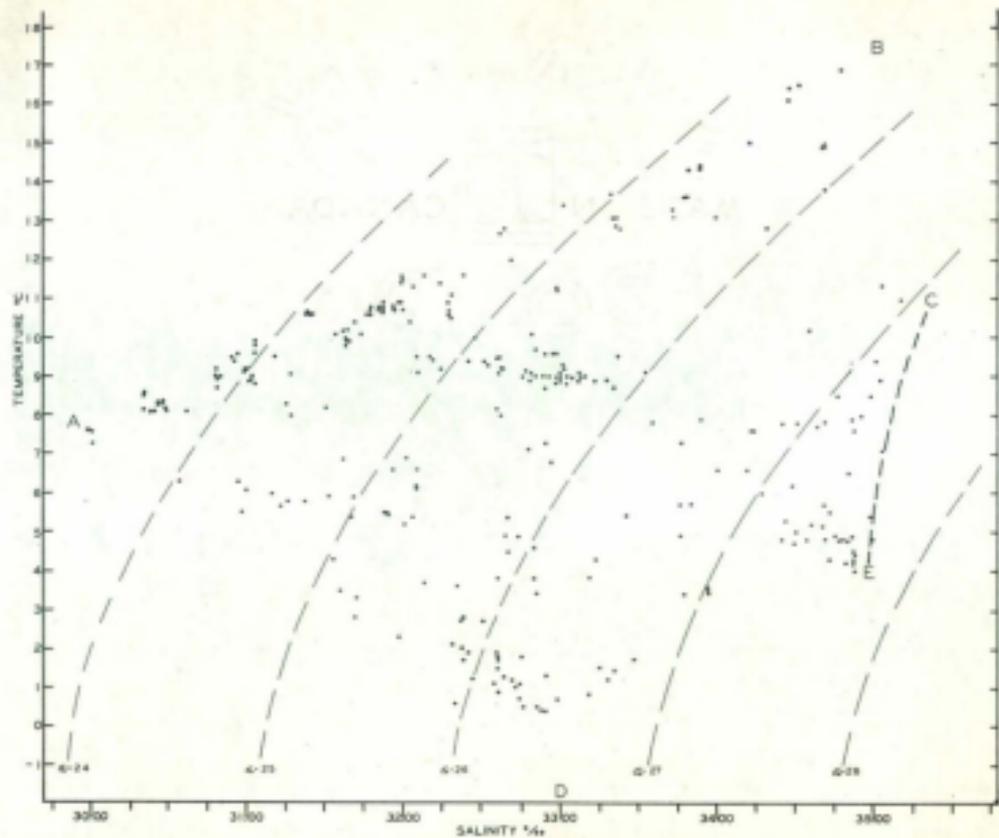Location of stations on the Scotian Shelf occupied during cruise WT-5, November 1981.

Figure 2

T-S diagram showing all samples collected on the Scotian
Shelf during cruise WT-5.
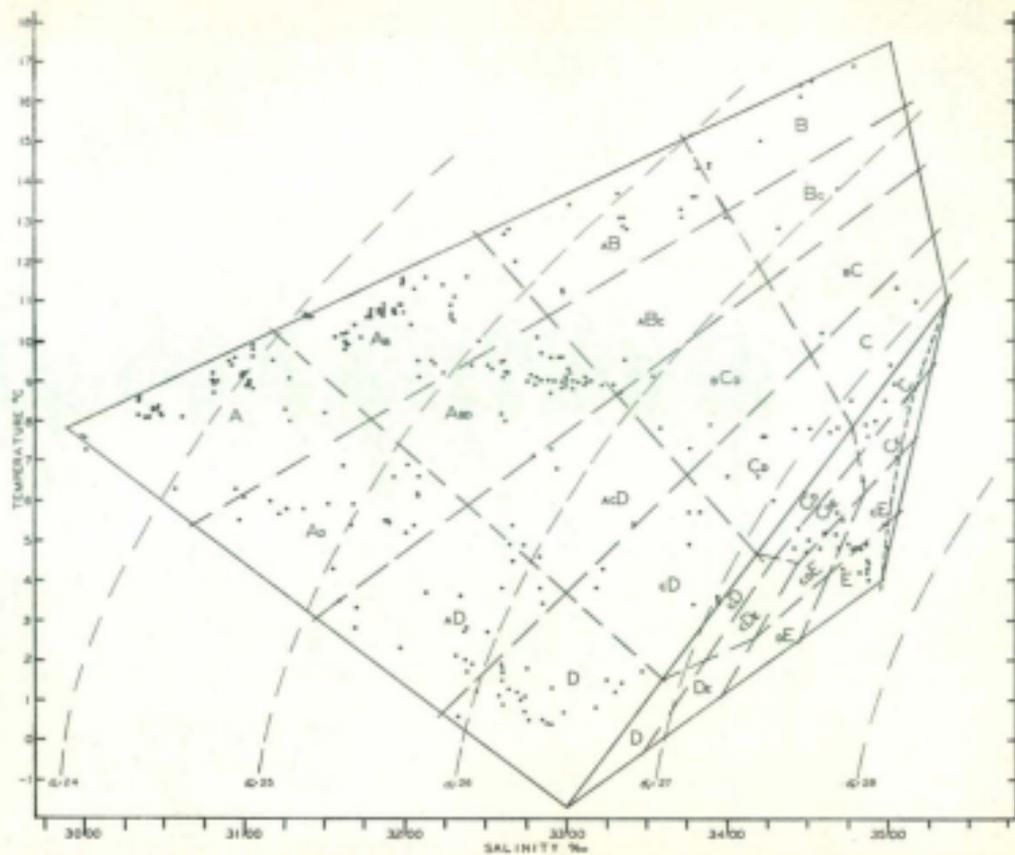
Figure 5

T-S diagram with grid superimposed.
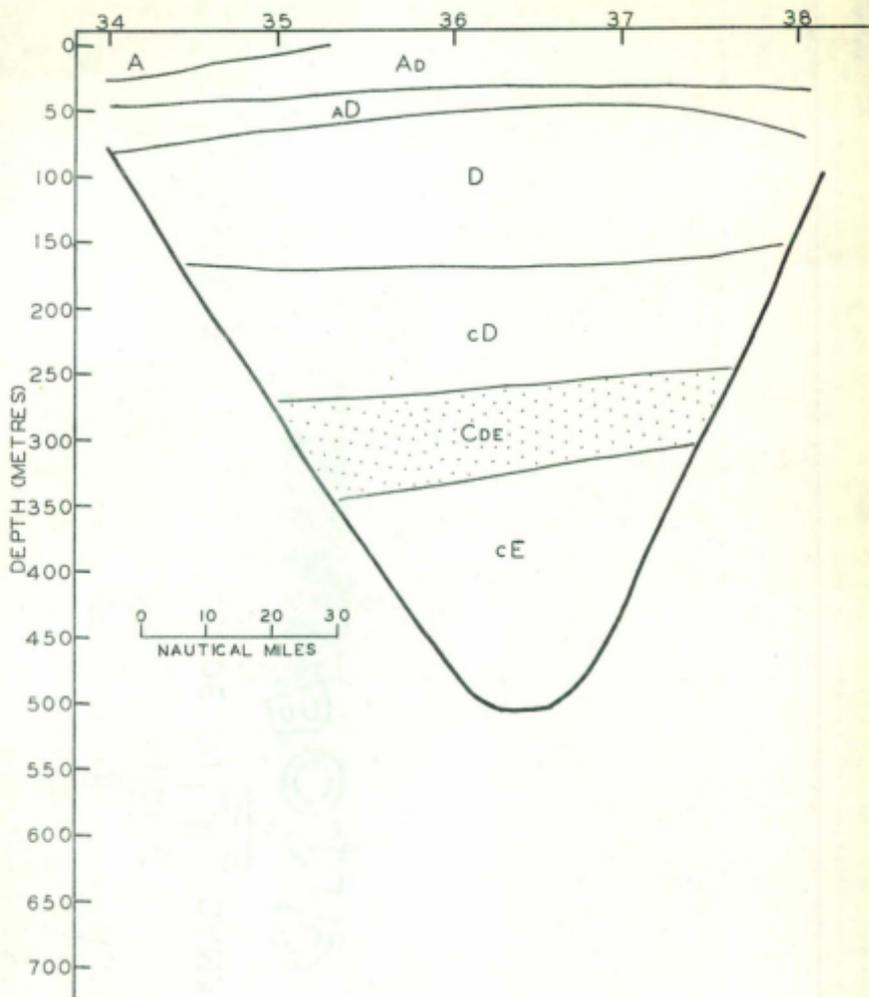
Figure 4

Vertical distribution of water types in the Cabot Strait section.
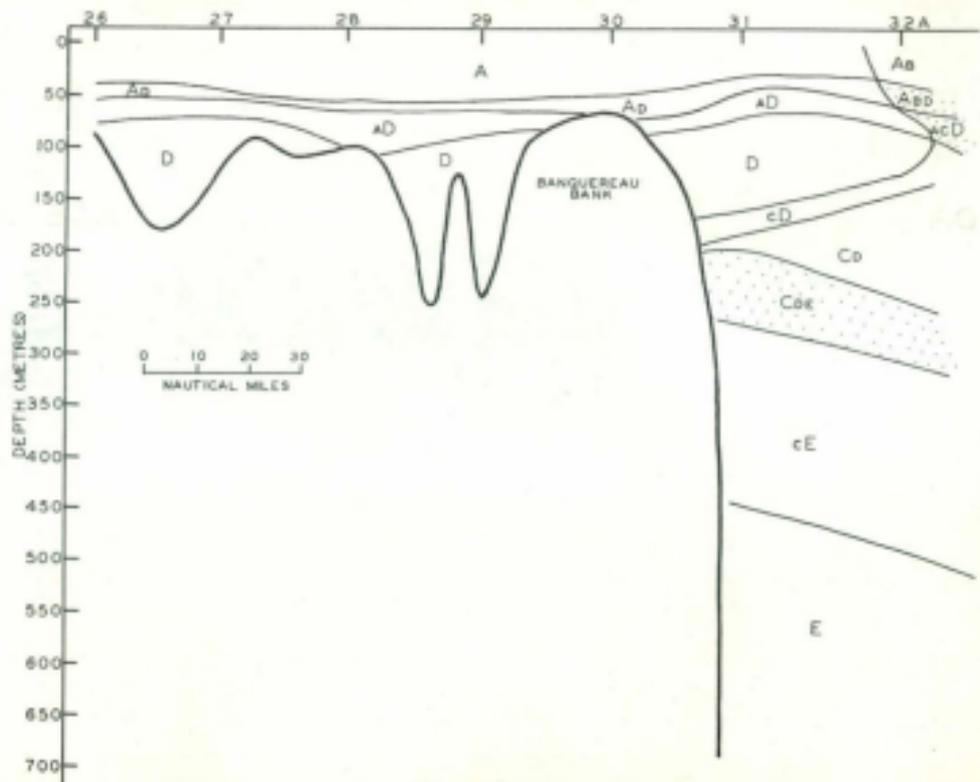
Figure 5

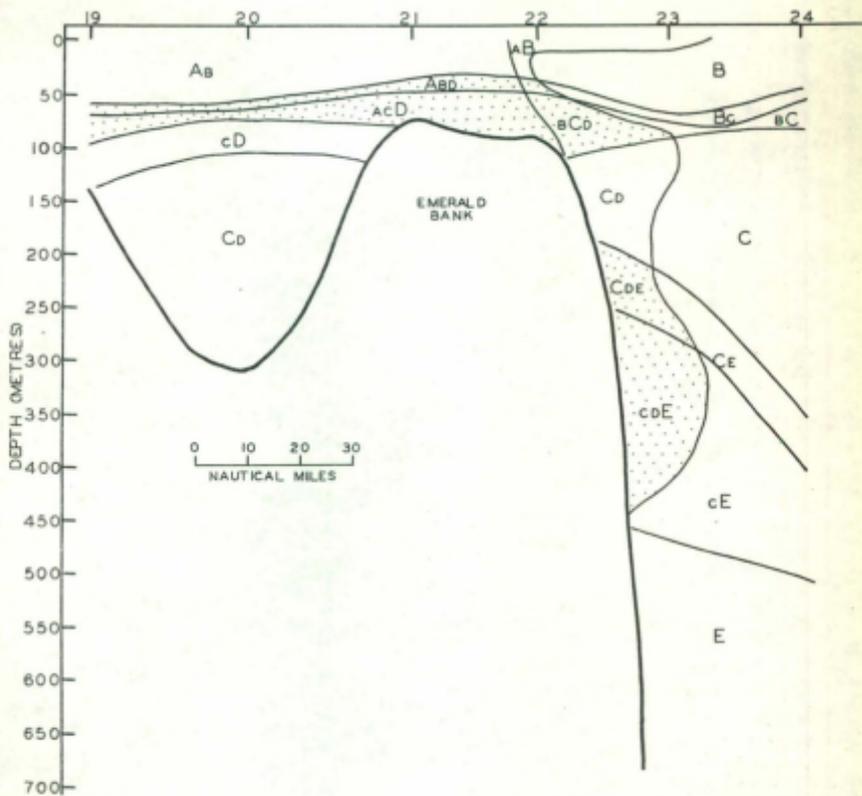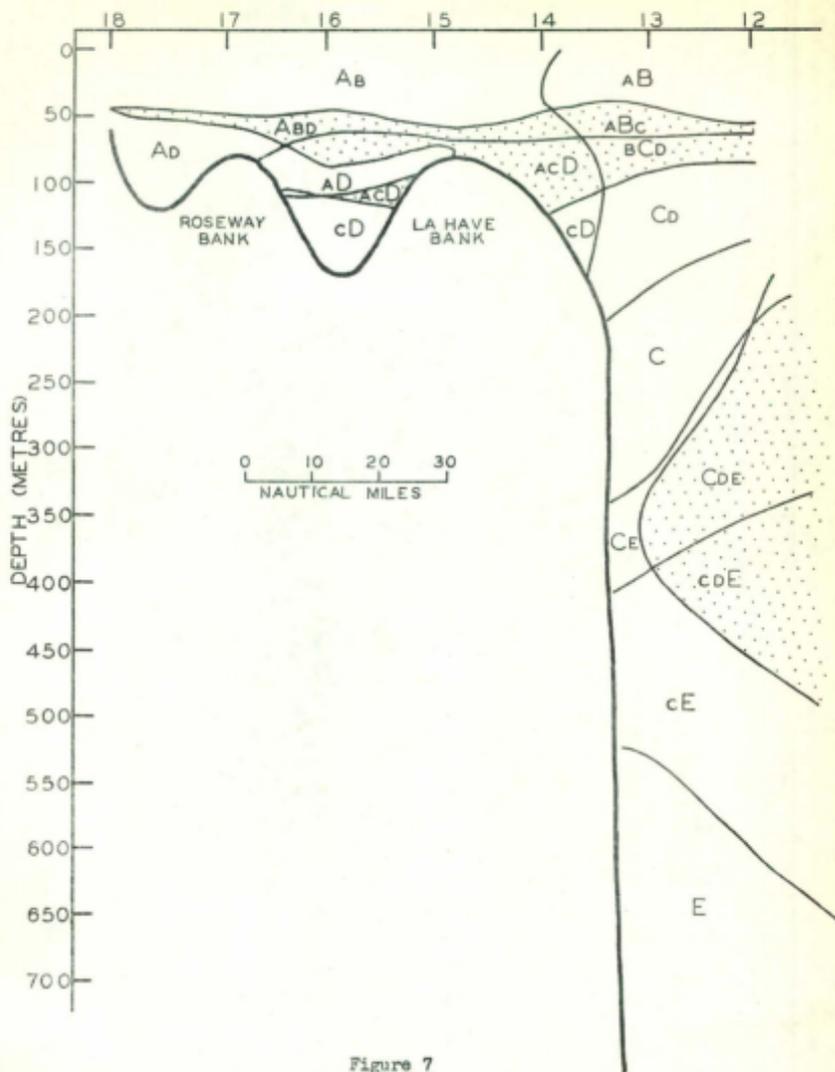Vertical distribution of water types in the Banquereau section.

Figure 6

Vertical distribution of water types in the Emerald Bank section.

Figure 7

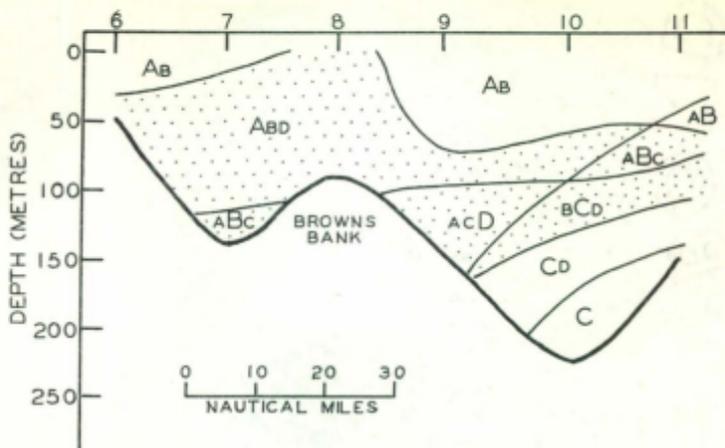Vertical distribution of water types in the Roseway, LeHave section.

Figure 8

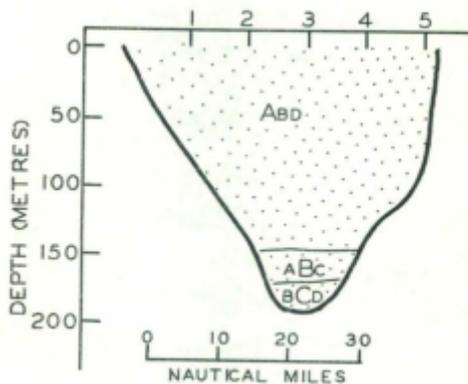Vertical distribution of water types in the Brown's Bank section.

Figure 9

Vertical distribution of water types in the Bay of Fundy section.