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SOME FEATURES OF THE OCEANOGRAPHY OF THE PASSAMAQUODDY REGION

by

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INTRODUCTION

General Geography

Passamaquoddy Bay, located just inside the entrance to the Bay of Fundy on the northwestern shore, is a large enclosed bay with an area of about 100 square miles. It is one of four large bays which are located more or less symetrically about the Bay of Fundy as shown in Figure 1. At the head of the Bay of Fundy are Chignecto Bay and Minas Basin, while St. Mary Bay is located directly opposite from Passamaquoddy Bay. In size, Passamaquoddy Bay is the smallest, but it differs radically from the others in that its mouth is almost completely blocked by a chain of islands.

The Passamaquoddy region may be defined as that area which includes all the water shoreward of a line between Deadman Head, N. B. and East Quoddy Head, Campobello Island, and north of a line between Welshpool and Buckman Head, Maine. Figure 2 shows a chart of the Passamaquoddy region indicating the general bottom configuration. This area has been called the Inner Quoddy region, while the Outer Quoddy region is between it and a line joining Grand Manan and Point Lepreau.

Geographically the Passamaquoddy region has three principal features which are: Passamaquoddy Bay, St. Croix Estuary, and the Western Isles Archipelago through which Western Passage and Letete Passage cut to form the main entrances to the Bay.

Passamaquoddy Bay which makes up the greatest portion of the area is relatively shallow with an average depth of 15-20 fathoms (27-36 m.). The St. Croix Estuary enters the Bay on its western side at the southern tip of St. Andrews Island. A relatively deep channel with depths between 10 and 17 fathoms (18-31 m.) reaches to the junction of the St. Croix and Waweig rivers. The Western Isles, of which Deer Island is by far the largest, almost completely fill the mouth of the Bay. Two channels form the principal entrances to the Bay. On the north, Letete Passage forms a short, tortous channel through the islands. Depths in this channel are extremely variable ranging between 10 and 40 fathoms (18-73 m.). A sill with depths of about 10 fathoms (18 m.) limits the flow of water through the channel. On the south, the long Western Passage and its extension, Head Harbour Passage, form the second principal channel between the two bays. This channel is deep and relatively free from obstruction as compared with Letete Passage. A sill near Wilson's Beach has limiting depths of about 22 fathoms (40 m.).

The land surrounding the Passamaquoddy region is relatively high, with many hills rising to heights greater than 300 feet. Two hills reach heights greater than 600 ft. The shoreline is for the most part steep and cliff-like, and the shores are rocky with outcroppings of ledges occurring frequently.

Geological Features

The principal features of the geology of the Passamaquoddy region have been described by Bailey (1917) from surveys made by the Canadian Geological Survey, the details of which are shown in Figure 3. Bailey concluded that the position and general outline of Passamaquoddy Bay were determined by disturbances and up-heavals antedating the opening of the Cambrian era. Ridges such as the Bocabec hills on the north, Deer Island and Campobello Island on the south, both converge eastwardly to and beyond St. George.

"Of the conditions characterizing the Cambrian era little is known. In the Silurian age, the basin was evidently in existance and occupied by shallow waters in which accumulated sand and mud beds, now more or less filled with marine fossils, over which spread the rhyolites, porphyries and ash beds which now constitute such eminences as Chamcook Mountain, Mt. Blair and Pendleton Island. In the Devonian age were produced the granite intrusions which now form the western side of the basin from Devil's Head to the lower part of Robbinston; somewhat later the course rocks of the Perry group, marking at this time considerable subsidences and the operation of powerful marine currents, as well as the intrusion of igneous masses. No rocks of later age are met with, but evidence of extensive glaciation during the Quaternary era abound. The estuarine portion of the St. Croix River and the channels at either end of Deer Island were probably fixed at this time." (Bailey, 1917).

Tides and Tidal Currents

The oceanography of the Passamaquoddy region is determined to a large extent by the action of the tides in forcing the water through the various entrances leading into Passamaquoddy Bay. The tides of the region are of the same type as those for the Bay of Fundy. The tide is of anomalistic type; that is, the variations in range with the change in the moon's distance from perigee to apogee is dominant and is distinctly greater than the variations from springs to neaps. (Atlantic Coast Tide and Current Tables, p.6).

Tides in the Passamaquoddy region have been related to those of Saint John, N. B. where the amplitudes of spring tides are greater than 28 feet and of neap tides greater than 14 feet. At Wilson's Beach, the ratio of tidal amplitude with that at Saint John is 0.88, while at St. Stephen the ratio is 1.01.

Very little is known about tidal currents in the region. They are reported to exceed 5 knots in the channels between the islands.

Rivers and River Water

Three rivers flow into Passamaquoddy Bay. These are the St. Croix, Digdeguash, and Magaguadavic Rivers. Of these the St. Croix is by far the most important. With a total average discharge of 4400 cu. ft. per sec. (Watson 1936), these rivers supply about eight percent of the total discharge of fresh water into the Bay of Fundy. Figure 4 shows the average discharge of the St. Croix and the Magaguadavic Rivers and their combined average discharges over the period 1916-1954. (Data supplied by the Department of Northern Affairs and National Resources, Water Resources Division).

In addition, the waters of the Saint John River which empty into the Bay of Fundy some distance from the Passamaquoddy region must be considered. This water, though somewhat changed in character, is carried along the coast and some of it reaches the entrances to Passamaquoddy Bay.

General Circulation

The details of the circulation of waters in Passamaquoddy Bay have been less thoroughly studied than those in the Bay of Fundy. Although a great many oceanographic observations have been made, there has been no systematic attempt at a quantitative description of the circulation. Hachey (Orig. MSS#430) carried out drift bottle experiments in 1927, the results of which indicate a cyclonic circulation in the Bay as indicated in Figure 5. Ketchum and Keen (1953) suggested that the effluent of the St. Croix, entering as it does on the western side of the Bay, would tend to establish and maintain a counter clockwise circulation.

Observations and calculations by Ketchum and Keen (1953), regarding the exchange of fresh and salt waters, indicate that on the average about eight days are required to exchange the water within the St. Croix estuary between St. Stephen and St. Andrews, and that an additional sixteen days are required for the exchange of waters in Passamaquoddy Bay.

Previous Investigations

Published records of oceanographic observations in the Passamaquoddy region date back to 1910. Copeland (1912) made observations of temperature and density at some eighty stations throughout the area to depths as great as 15 fathoms during July and August, 1910. His methods were somewhat crude by present day standards and only the most general conclusions may be drawn from the data. Craigie (1916) made a survey of temperatures and salinities at eighteen stations in the western part of the Bay and concluded from his data that warm water passes out through the Western Passage. He also suggested that a northeastward movement existed along the north shore of Deer Island. Vachon (1918) made extensive temperature and salinity observations in Passamaquoddy Bay between July and October, 1916. From the data collected he noted the seasonal changes in the waters, and the influence of the tides on the distributions of temperature and salinity in the St. Croix estuary. Hachey (Orig. MSS #430) undertook drift bottle experiments in 1927, the results of which are shown in Figure 5. Hachey and Huntsman (Orig. MSS #431) concluded from observations of temperature and salinity taken throughout the region in 1929, that the pecularities of water conditions in Passamaquoddy Bay were due principally to tidal action through the various passages. Watson (Orig. MSS #196) carried out oceanographic observations(part of which consisted of current measurements) in Bocabec Bay and Chamcook Harbour. The results of observations indicated differential movements of the waters. Hachey (1934) made current measurements in Digdeguash Harbour which indicated differential movements resulting from the mixing of stratified waters. Watson (1936) presented temperature data taken at the surface and at five metres at fifteen stations in the outer part of Passamaquoddy Bay. These data serve to show that the water inside the islands were warmer and moderately stratified while those outside were cooler and well mixed. Hachey and Bailey(1952) presented data taken at the mouth of Passamaquoddy Bay, but give no analysis of them. Surface temperatures of the waters at the Biological Station have been analysed by several authors, Hachey (1933, 1939), Hachey and McLellan(1948), and Lauzier (1952).

A very considerable quantity of work has been done in the Passamaquoddy region. Since 1916 over 2500 oceanographic stations have been occupied of which some 1500 were taken at station 6 in the St. Croix estuary. Temperature, weather and tidal data exist for all of these stations, however, a considerable quantity of the salinity data was lost in a fire in 1932. The loss was particularly great in that data taken in very extensive surveys between 1927 and 1931 were burned. The loss of these and a manuscript of the analyses of the data has left the region comparatively unknown.

A SURVEY OF SPRING CONDITIONS IN 1952

On April 21st. and 22nd. 1952, two complete surveys of the waters of the Passamaquoddy region were carried out from the C. N. A. V. "Sackville". The timing of the surveys was arranged so that oceanographic conditions at high water and at Low water could be observed synoptically. The locations of oceanographic stations occupied during this survey are shown in Figure 6.

Temperature observations and salinity samples were collected by means of rapid sampling techniques using a sea sampler (Spilhaus and Miller, 1948).

Vertical Distribution of Temperature and Salinity

The vertical distribution of temperature and salinity in two sections through Letite and Western Passage covering the eastern and western parts of Passamaquoddy Bay at High water and at Low water are shown in Figures 7-10. Temperatures ranged from 5.0°C. at the surface in the Bay to less than 3.4°C. outside at subsurface depths. The waters inside were warmer than those outside and varied with the state of the tide. Salinities ranged from 19.8‰ at the surface in the Bocabec Bay area to greater than 32.0‰ at 70 metres near The Wolves. For most of the region, salinities were between 30.0 and 32.0‰.

Several features of the circulation and dynamics of the region are illustrated by the vertical distribution of properties in the area. Vertical mixing was strong throughout most of the region and intense in the passages between the islands. Only near the sources of fresh water, that is at the mouth of the Magaguadavic and St. Croix rivers was there any degree of stratification. Further, the relative influences of the currents through the Passages are indicated by the relative amount of stratification between the two sides of the Bay as shown in Figures 7 and 9. In the section through Letite Passage, stratification extended to the entrance and was confined to the upper 10 metres. The waters below this level were similar to the waters found in the upper 10 metres outside of the Bay. In the section through Western Passage the more saline waters reached into the deeper portion, and the mixing extended almost to Station 4, about half way between the St. Andrews Peninsula and Western Passage. In this section the low salinity waters extended to a depth of 20 metres.

The flooding and ebbing of the tides causes a considerable change in the waters of a given area. Salinities are lowered during an ebbing tide, and increased during a flooding tide. Mixing is strong throughout the area and the changes in water conditions represent the influence, at this time of the year, of colder and salter waters from outside. This point is borne out by a comparison of the salinity distributions as illustrated in Figures 9 and 10. At High Water, the upper 10 metres were strongly stratified, while below this level the waters had a uniform salinity. At Low Water the stratification had broken down to some degree and the low salinity water extended to a depth of 35 metres at station 22.

A comparison of minimum temperatures in the Letite section indicates that they were about the same (3.4°C.) both inside and outside the Bay. However, salinities were about 1.0 parts per mille different. The temperature of the waters in the passage was considerably warmer than these minimum temperatures. This fact would seem to suggest that these cold waters entered the Bay at some earlier date, perhaps at the time of spring tides some ten days earlier. Vernal warming is strong at this time of the year and thus it is unlikely that the waters had been in the Bay for any extended length of time.

Jones (1929) has estimated the relative sizes of Letite and Western Passage as about 1 to 3. The relative influence of currents in these passages is more difficult to assess. From the vertical distribution of temperature and salinity, it would appear that all the water in the region west of a line between the St. Andrews Peninsula and Pendleton Island is directly influenced by the flow through Western Passage as indicated by the reduced stratification. In other areas, the cooler and more saline waters flow under the stratified surface waters. The influence of the flow through Letite Passage appears to extend only a short distance beyond its entrance.

Horizontal Distribution of Temperature and Salinity

Data were insufficient and too widely scattered for the production of reliable horizontal plots of temperature and salinity. The influence of the tidal currents in running over shoals and around islands caused the local condition to be so variable that charts as drawn had no particular significance. In addition, the data were so few that several widely different interpretations may be made. Thus, only the most general conclusions may be drawn from the data. These have been discussed in the previous section.

A SURVEY OF AUTUMN CONDITIONS IN 1952

On October 2 and 3, 1952, a survey of the inner part of

Passamaquoddy Bay was carried out from C. N. A. V. "Sackville". In this survey, the sections were run only to the mouths of the passages. The location of stations occupied during this survey are shown in Figure 6.

Temperature observations were taken with the bathythermograph, and water samples with Knudsen deep sea reversing water bottles with the thermometers and frames removed. This allowed observations to be taken nearer the bottom than could be done by using the sea sampler, and much quicker than by using reversing water bottles and thermometers alone.

Vertical Distribution of Temperature and Salinity.

The vertical distributions of temperature and salinity in the autumn of 1952, over the network of stations, are illustrated in Figures 12-15. The observations taken at High water in the western section shows the warmer and lighter water over-running the cooler and more saline waters from Western Passage. Mixing in the Passage was very strong, but not strong enough to thoroughly mix the waters from top to bottom.

In the area near station 2, surface waters were being forced under to a depth of about 15 metres. This phenomenon would appear to be due to the flooding tide passing over the shoal near Joe's Point. This phenomenon is visible from the surface and a well marked convergence zone may be seen where river water meets sea water.

Temperatures over the section ranged from 12.6 to 11.6°C., with the higher temperatures found in the estuary. Salinities varied from 31.67‰ at the surface at station 1 to 32.47‰ at 40 metres at station 7. Salinity conditions would be near the maximum and temperatures would for the most part be slightly below maximum summer temperatures. According to Bailey et al(1954), temperatures in this area attain their maxima between mid-September and mid-October, depending on depth and as indicated in Figure 18. Salinities attain their maxima at all depths about mid-October.

At Low water, the western sections (Fig. 11) showed an increase in temperature and a decrease in salinity at all depths from conditions at high water. As in the spring sections, the higher temperatures were observed at greater depths on the ebbing tide than on the flooding tide.

In the eastern part of Passamaquoddy Bay (Fig. 12) temperatures were slightly warmer (13.2°C.) than in the western part. The waters were stratified in the upper 20 metres with only small variations in temperature and salinity below this depth. The changes in temperature and salinity from one stage of the tide to another were confined for the most part to the upper 20 metres. This suggests that the sill depth in Letite Passage is limited to that depth. On a flooding tide the water pouring through Letite Passage had a temperature of about 12.1°C. and a salinity of 32.1‰, which made it heavier than most of the water in this section of the Bay and occupied a position near the bottom of the Bay at depths ranging from 20 to 60 metres.

It is evident that in Letite Passage there was an inflow of outside waters on the flood tide and an outflow of surface waters (upper 20 metres) on an ebb tide. In Western Passage the same is essentially true except that the deeper waters from the eastern part of the Bay must also be drawn out through this passage with the mixed waters.

However, since the two deeper parts of the Bay are separated by a sill with a maximum depth of 17 fathoms (31 metres), it is likely that the flow of heavier water from Letite Passage to Western Passage along the bottom is very restricted. The waters entering the Bay through Letite Passage mix with the fresher waters near the surface and thus make their way out of the Bay through either passage. The higher salinities were found in the vicinity of Western Passage and thus any salt transfer, if any, will be towards Letite Passage. This is to be expected since Western Passage is the deeper of the two and both Passagesreceive waters from the same source.

From the distributions of temperature and salinity, it may be expected that the general circulation in the upper 20 metres is cyclonic about the entire Bay while below 20 metres the circulation is cyclonic about the two basins near each of the passages.

NORMAL MEAN MONTHLY TEMPERATURES AND SALINITIES

Normal mean monthly temperatures and salinities(normals) for the surface, 10-, and 30-metre levels at station 2 are shown in Figure 16. These were calculated from observations taken monthly from 1916 to 1956. The temperature curves are sinusoidal in form, while the salinity curves are deformed by the excess of waters poured into the Bay at the time of the spring run-off.

The temperature curves although having the same form have noteworthy differences. The surface curve has its maximum and minimum a month earlier than the other two. The three curves show how the normal temperatures vary in relation to one another, with the water column becoming uniform in temperature in March and October. For seven months of the year negative temperature gradients exist, while positive gradients are prevalent for the remainder of the year. It is evident from the normal curves that the surface layer is very thin, since the curve for the 10-metre level closely resembles that for 30 metres. The salient features of each normal temperature curve are presented in Table I.

Table I. Important features of the normal mean monthly temperature curves at three levels at station 6.

	Max.	Date	Min.	Date	Annual Mean
Surface	13.15°C.	Aug.15	0.44°C.	Feb.15	6.43°C.
10 metres	12.01	Sept.15	0.86	Feb.15	6.35
30 metres	11.59	Sept.15	1.12	Feb.15	6.23

The normal salinity curves indicate that the very thin surface layer is considerably influenced by river discharges, particularly during the spring freshets and to a lesser degree during the autumn freshet. The waters at 10 metres are only slightly less saline than those at 30 metres. The relationship between the salinity at 10 and at 30 metres remain about the same throughout the year. These and other features of the normal salinity curves are presented in Table II.

Table II. Important features of the normal mean monthly salinity curves at three depths at Station 6.

	Max.	Date	Min.	Date	Annual Mean
Surface	30.84‰	Sept.15	24.99‰	May 15	29.16‰
10 metres	31.69	Oct. 15	29.93	May 15	30.96
30 metres	32.04	Oct. 15	30.56	May 15	31.48

T-S Relationships

The normal T-S relationships for each depth at station 6 are produced in Figure 17, by plotting the normal temperature and salinities and joining the points relative to each layer. The T-S cycle for each depth is thus illustrated. Lines of σ_t are plotted in the diagram so that densities of the water column may be readily determined.

The entire cycle of the oceanographic conditions at station 6 is clearly defined by the T-S diagram. The normal values of temperature and salinity are illustrated as well as the normal conditions that are described. However, large deviations from the normal may occur in any particular year.

Bailey et al (1954) described a similar T-S diagram (Fig. 18) for conditions in three layers at station 5. Although the two diagrams are basically the same, several important details are radically different At station 5, the waters became thoroughly mixed for a short period in February. At station 6 this phenomenon does not occur, the water column is always stable. The effect of the spring run-off is not as great at station 5 as at station 6 and the effect is proportional in all layers. At station 6 the effect is very large at the surface but only moderate at 10 and 30 metres.

In February all layers reach their minimum temperatures with the warmest waters at the bottom. In March, the waters begin to warm and as river discharges increase with the advent of warmer air temperatures and increased insolation, the salinities decrease. This salinity condition reaches a minimum in May at the height of the spring freshet. The large volume of fresh water added to the estuary is confined to the surface. Mixing serves to decrease the salinity at 10 and 30 metres by only relatively small amounts. The effect of freshet conditions decreases rapidly between May and June. Salinities continue to decrease throughout the summer until mid-September when temperatures are at their peak. Thereafter both temperature and salinity decrease. The temperatures attaining their minima in February. The salinities, however, reach a second minimum in December which may be associated with increased river discharges at this time.

Equations of Curves for Normal Mean Monthly Temperatures.

On the basis that the normal curves of temperatures are sinusoidal, the equations would be of the form:

$$y = A - B \sin \frac{2\pi}{T} (x + \varepsilon)$$

where y is the normal monthly mean temperature in degrees Centigrade,

A is the annual mean temperature

B is one-half of the annual amplitude

T is the period of 12 months

x is the time in months

ε is the phase or lag in months.

The curves for the normal theoretical temperatures are shown in Figure 19 with the normal temperatures indicated.

Using the general equation to determine the particular equations for temperatures at station 6, we obtain the following:

Station 6 Normal Monthly Mean Temperatures

(a) Surface: $y = 6.9 - 6.4 \sin \frac{\pi}{6}(x + 1.9)$

(b) 10 metres: $y = 6.4 - 5.6 \sin \frac{\pi}{6}(x + 1.4)$

(c) 30 metres: $y = 6.2 - 5.2 \sin \frac{\pi}{6}(x + 1.3)$

It is readily seen from the plotted results that the equations represents the water temperatures extremely well.

<u>Comparisons with other Curves of Normal Temperatures.</u>

Air and water temperatures which vary sinusoidally may also be described in the above manner. These include the air temperatures for St. Andrews and Saint John, N. B., surface water temperatures taken at the Biological Station wharf, and water temperatures in three layers at station 5.

Hachey (1939) presented normal curves and their equations for surface water temperatures at a number of localities scattered throughout the Canadian Atlantic region from data collected between 1920 and 1935. These may serve to indicate how temperatures at station 6 are related to other areas on the Atlantic coast.

In the Passamaquoddy region, Bailey *et al* (1954) presented the equation for normal curves at station 5. It is of interest to note the equations for the surface water temperature at the Biological Station wharf, and for the air temperature at Saint John and St. Andrews. The normal curves for these are as follows:

(a) Surface water temperatures at the Biological Station wharf, St. Andrews, N.B.:

$$y = 6.8 - 6.4 \sin \frac{\pi}{6}(x + 1.9)$$

(b) Air temperatures at Biological Station, St. Andrews, N.B.:

$$y = 6.2 - 12.8 \sin \frac{\pi}{6} (x + 2.7)$$

(c) Air temperatures at Saint John, N.B.:

$$y = 5.2 - 11.7 \sin \frac{\pi}{6}(x + 2.7)$$

It should be noted that the equations for the normal curves for the surface waters at station 6 and at the Biological Station wharf are identical. This is not surprising since the two locations are about one-half mile apart.

Long Term Trends.

Since the relationship between data taken at Station 6 and from the wharf at the Biological Station, St. Andrews is known, we may use the latter set of data to indicate what changes have occurred in the past. Analyses of these data have been undertaken by Hachey and McLellan (1948) and Lauzier (1952).

Figure 20 shows the variations of the annual mean temperatures for St. Andrews.

It can be seen from the Figure that there has been a general increase in temperatures since 1921, although fluctuations have been quite considerable. The most apparent increase have been in the period 1940 to 1953. Recent data indicate that temperatures are on the decline and predictions are that waters will cool over the next few years (Lauzier, personal communication).

The annual variations in temperature are controlled at the surface by a large number of factors, chief of which are: radiation, the character of the currents, and the prevailing winds. In the surface layers, the temperature variations, as pointed out by Sverdrup, Johnson and Fleming (1942), are due to the variations in the amount of heat that is absorbed at different depths, to the effect of heat conduction, to variations in the currents related to lateral displacement of water masses, and to the effect of vertical motion. "

TIME SERIES OF TEMPERATURE AND SALINITY

During the period 1932-34 two oceanographic stations (6 and 848) in Passamaquoddy Bay were occupied weekly and two stations (5 and 880) outside the Bay were occupied monthly. For the most part, the observations at the four stations were taken within a day of one another. Since stations 5 and 6 have been occupied for many years, these data provide an opportunity to see what relationships other parts of the region have to them.

Temperature-time and salinity-time curves for various levels at station 5, 6, 848 and 880 for 1933 are given in Figures 21 and 22.

A comparison of the temperature-time curves for stations 5 and 880 shows that the waters were the same at these two stations and that data taken on a monthly basis were almost interchangeable. Differences in temperature do exist between stations 880 and 848. Waters at station 848 located between 10 and 40 metres had temperatures very similar to those at the surface at station 880. Surface temperatures were lower by about 0.5°C. inside the Bay. These comparisons indicate that waters below 10 meters inside the Bay are similar to the surface waters in the vicinity of station 880. Temperatures at station 848 and 6 correspond extremely well, even minor fluctuations in temperature were reflected at both stations.

A very noticeable feature of the surface temperature traces at stations 6 and 848 is the wide fluctuations. A comparison of these traces with the daily range from tide at Saint John, N.B. (Fig. 23) indicates that the main fluctuations are associated with changes in the tidal amplitudes from springs to neaps.

Salinity observations at stations 5 and 880 are very nearly identical, and were only slightly influenced by freshet conditions in 1933. At stations 6 and 848, salinity-time curves show a considerable number of fluctuations, particularly in the surface layer. A comparison with the discharge plot for the St. Croix River at Baileyville, Me. (Fig. 24) indicates that major fluctuations in salinity were for the most part due to changes in the daily river discharges. Other fluctuations are associated with changing tidal amplitudes. A comparison of salinities at stations 6 and 848 indicate that changes in salinities at station 6 are reflected about 7 days later at station 848. This figure agrees well with a mean flushing time of 8 days for the St. Croix estuary(Ketchum and Keen, 1953).

CHEMICAL PROPERTIES

In addition to the salinity, determinations of the phosphate and silica contents have been made.

Phosphate

Hachey and Morton (Orig. MSS #223) presented results of phosphate determinations made monthly at four stations between 1929 and 1931. The determinations were made for the surface and bottom waters and the results for 1930 are shown in Figure 25.

At stations 5 and 880, the phosphate content varied between 18 and 85 mg/cubic metre. The minimum occurred in the summer with the content remaining high during most of the year.

"Stations 6 and 848 are in the region which receives the most benefit from the tidal mixing at the entrance to Passamaquoddy Bay. Consequently, there is a continued supply of phosphate always available, and the content does not diminish to any considerable degree. On the other hand, stations 880 and 5 are farther removed from the direct influence of this tidal mixing. Consequently, the average noticeable consumption is higher and the diminuation in the curve of 880 is most marked. The phosphate content at a depth of 90 metres is always fairly high. This is no doubt due to its great depth as well as to the position which it has with respect to the mixing mechanism. As a result of experience, the plankton tows at station 848 are the richest of the four stations."

"Various rivers empty into Passamaquoddy Bay and the phosphate content of these rivers would directly effect the determinations at stations 6 and 848. From a few determinations the phosphate content of these river waters is found to be very low. Consequently, we would be led to believe that these waters freshen and lower the phosphate content of the waters in the region of stations 6 and 848. Due to the enormous tides of the region, the effect would be noticeable only during the time of freshets. Station 880, on the other hand, is in the direct path of the surface water proceeding from the Saint John river which drains a very large area. The phosphate content of the waters of this river have not been determined to date.

The amount of sunshine which is a necessary factor in the process of photosynthesis, may vary considerably in this region. The month of June is usually a month of fog. Records show that in June, 1930, fog prevailed for 19 days, while only ½ day of the month was accompanied by a clear sky. This lack of sunshine at this time of the year was probably responsible for the slowing up of the process of photosynthesis and resulting increase to the phosphate at this time." (Hachey and Morton, Orig. MSS #223).

Morton (Orig. MSS #404) has indicated that the phosphate content does not vary with tidal amplitude, but that offshore winds caused an increase in the surface phosphate values.

Redfield, Smith and Ketchum (1937) investigated the distribution of phosphorous present as inorganic phosphate, as dissolved organic compounds, and as particulate matter (detritus and microorganisms) at all depths throughout the year of 1935-36 at a station (42°22'N, 69°33'W) in the western part of the Gulf of Maine.

"In late winter over 90 percent of the phosphorous is in inorganic form and three-quarters of the remainder is present as soluble organic compounds. In the spring - February to May, inorganic phosphorous is converted to organic form by photosynthesis in the upper layer of water. Most of this fraction sinks to considerable depths before undergoing decomposition."

"During the summer - May to November, large quantities of dissolved organic phosphorous appear at all depths, indicating a very considerable transport of inorganic phosphate from deep water to the surface, and the sinking of an equivalent amount of phosphorous in particulate form to the depths in which organic compounds are liberated by decomposition. Decomposition appears to take place throughout the water column."

"During the winter - November to February, the organic phosphorous compounds are converted to inorganic phosphate. This and vertical mixing of preformed phosphate are about equally important in bringing about the equalization of phosphate concentration throughout the depth of water." (Redfield, Smith and Ketchum, 1937).

Silicates

A limited investigation into the silica (SiO_2) content of the waters in the Passamaquoddy Bay region was carried out during July and August, 1931. The results have been presented by King (1931).

The results of silica determinations at four stations are given in Table I (after King, 1931). Fairly large variations in the silica content occurred from one observation to the next. This is particularly evident in the upper 10 metres. At times there were considerable variations in content with depth. These variations are probably due to influences from the tides and rivers. It is noteworthy that the silica content at stations 6 and 848 are much less than those outside the Bay.

Table III Silica content of sea water in Passamaquoddy Region - July and August, 1931 - milligram SiO_2 per litre.

Station	Depth	July 30	Aug.6	Aug.13	Aug.20	Aug.25
848	0 m.	.17	.49	.21	.17	.21
	2	.22	.40	.17	.19	.23
	3	.33	.47	-	-	-
	5	-	.30	.22	.24	.27
	7	.46	.35	-	-	-
	10	.45	.39	.28	.39	.30
	20	.41	.46	.33	.39	.24
	30	.38	.57	-	.55	.33
	40	.35	.50	.39	.43	.41

water from bottom ooze 2.22

		July 23	Aug.5	Aug.12	Aug.19
6	0 m.	.39	.45	.34	.41
	2	.36	.52	.34	.47
	5	.37	.45	.32	.35
	10	.44	.49	.32	.35
	20	.33	.38	.35	.33
	33	.32	.47	.34	.41

Station	Depth	Aug. 15
880	0 m.	.42
	2	.65
	5	.48
	10	.71
	20	.64
	30	.75
	47	.89
5	0 m.	.86
	2	.80
	5	.82
	7	.81
	10	.90
	20	.86
	50	.74
	90	.85

CONCLUSIONS

From the foregoing discussion, it is evident that tidal influence is the greatest single factor in determining the circulation in Passamaquoddy Bay. The bottom configuration, and the distributions of temperature and salinity as they effect the density of the water, are also contributing factors. The influence of the wind on the surface layer is considerable, but observations are not sufficient to give any concrete results in the region.

Results of drift bottle experiments and observations of temperature and salinity in Passamaquoddy Bay and near its mouth, indicate a cyclonic circulation within the Bay and a cyclonic circulation in the region off the mouth of Passamaquoddy Bay. This circulation is maintained by the influence of the flood and ebb of the tides, the effects of the earth's rotation and the bottom configuration.

Figure 26 shows the general circulation of the Quoddy region as derived from the results of drift bottle experiments and from observations of temperature and salinity as presented by Hachey and Bailey (1952).

Summary

1. The vertical distribution of temperature and salinity in the spring in Passamaquoddy Bay showed the salinity ranged from 19.8‰ near the shore to 32.0‰ at 70 metres in the outer part of the area. Corresponding temperatures ranged from 5.0 to 3.4°C.
2. Vertical mixing is strong throughout the whole region and intense in the Passages.
3. The waters below 10 metres in Passamaquoddy Bay have similar temperature and salinity characteristics as waters above 10 metres outside the Bay.
4. A flooding tide introduces waters to the subsurface layers in the Bay while an ebbing tide removes surface waters from the Bay.
5. The vertical distributions of temperature and salinity inside Passamaquoddy Bay in the autumn showed salinities ranging from 31.7‰ at the surface to 32.5‰ at 40 metres. Corresponding temperatures ranged from 12.6 to 11.6°C.
6. The distributions of temperature and salinity indicate a general

cyclonic circulation about the entire Bay in the upper 20 metres. Below 20 metres the circulation is probably cyclonic about the two basins near each passage.

7. Calculations of normal mean monthly temperatures and salinities for the surface, 10-metre and 30-metre levels at station 6 indicate:
   (a) A thin surface layer, less than 10 m. thick.
   (b) A well mixed subsurface layer extending from a depth of less than 10 metres to the bottom, and
   (c) A surface layer that is greatly influenced by fluctuations in river discharges.
8. Equations of curves for Normal Mean Monthly Temperatures at station 6 were calculated at three levels as:
   (a) surface $y = 6.9 - 6.4 \sin \frac{\pi}{6}(x + 1.9)$
   (b) 10 metres $y = 6.4 - 5.6 \sin \frac{\pi}{6}(x + 1.4)$
   (c) 30 metres $y = 6.2 - 5.2 \sin \frac{\pi}{6}(x + 1.3)$
9. Weekly observations of temperature and salinity at serial depths at four locations during the period 1932-34, showed that the waters were noticeably influenced by spring and neap tides and by fluctuations in river discharges.
10. Changes in river discharge rates were almost immediately reflected by the salinities at station 6 and about seven days later at station 848.
11. Results of early drift bottle experiments and density distributions indicate a cyclonic circulation at the Mouth of Passamaquoddy Bay.

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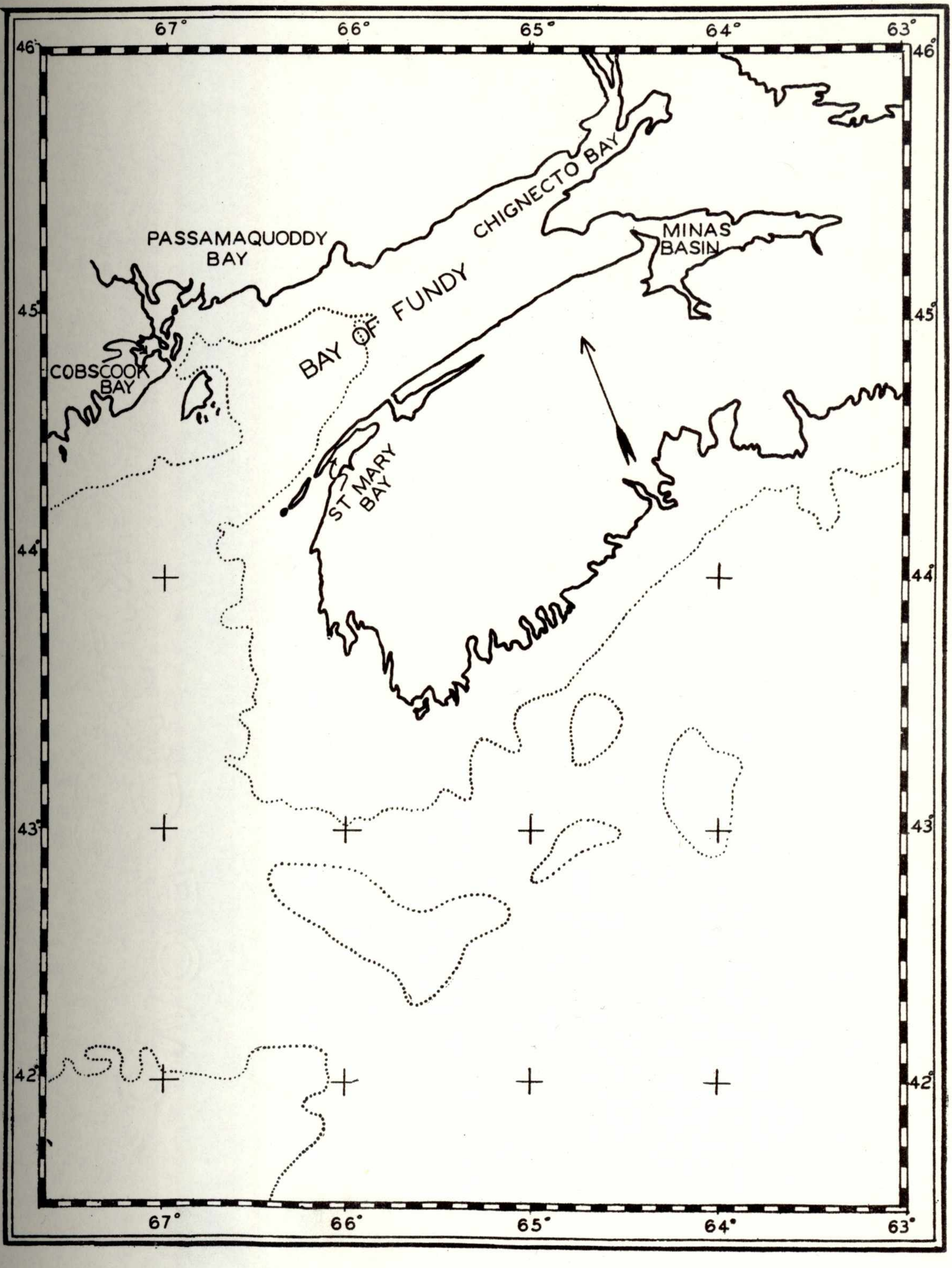

Fig. 1 General map of Bay of Fundy region.

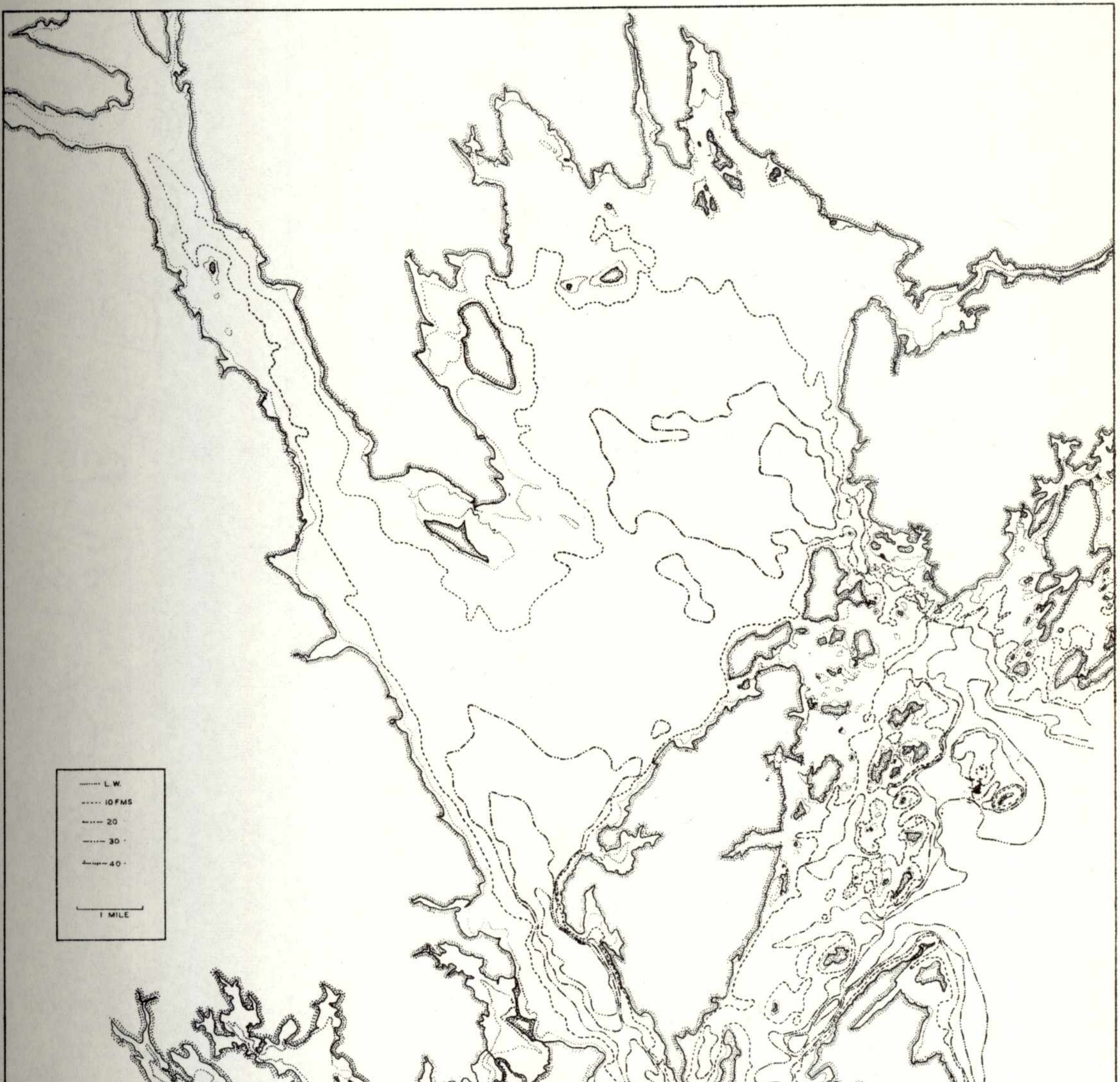

Fig. 2 Bathymetric chart of Passamaquoddy region.

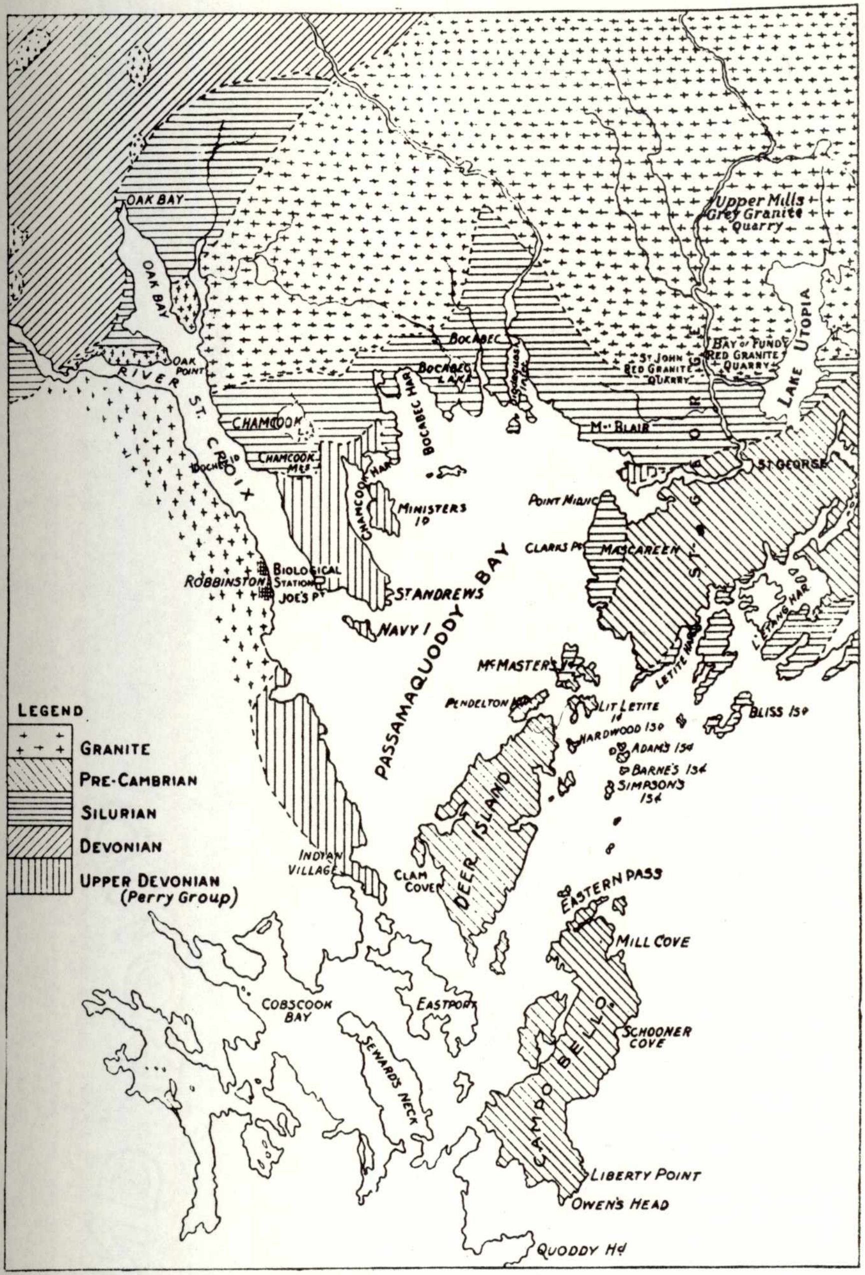

Fig. 3 Geological map of Passamaquoddy Bay (after Bailey 1917)

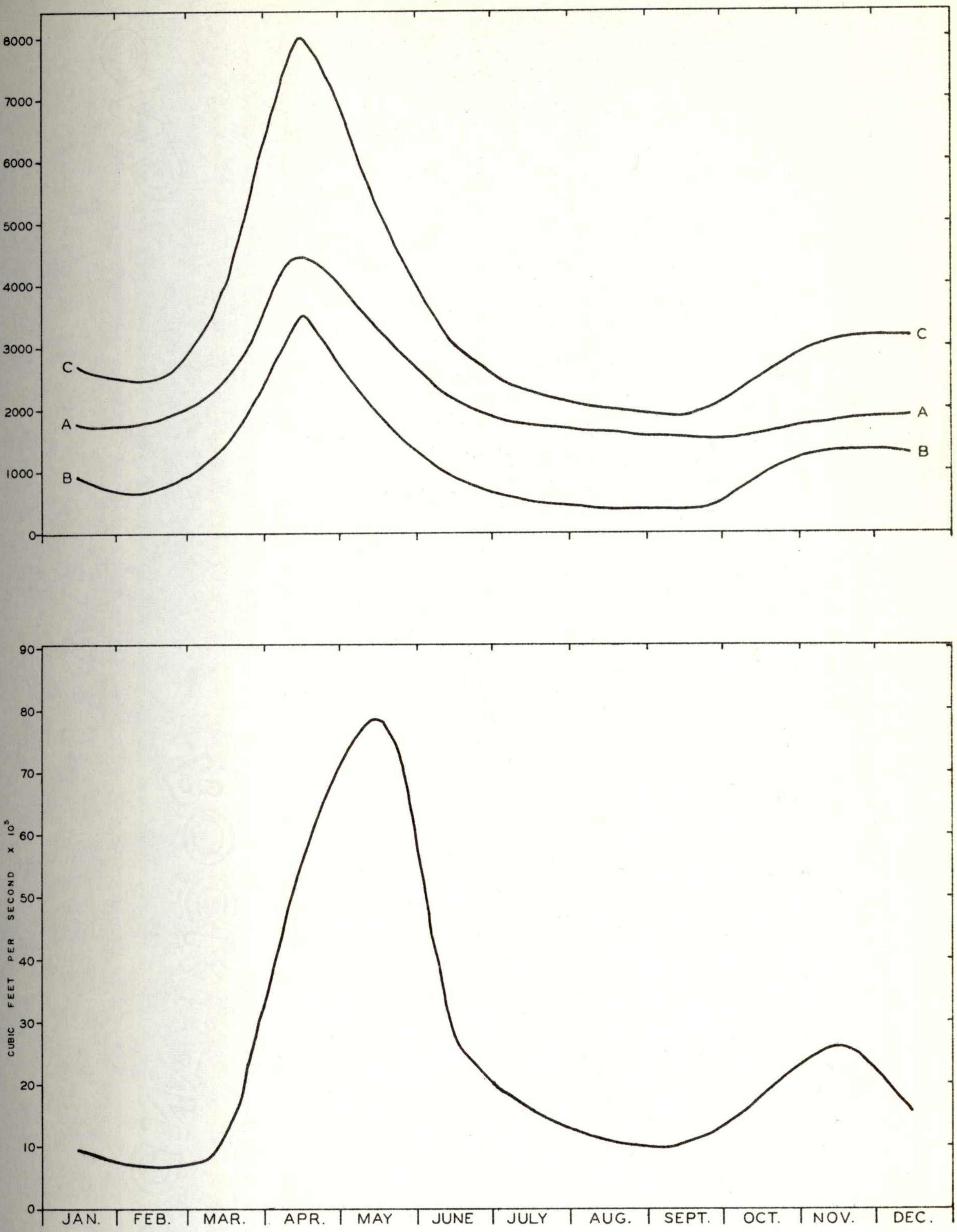

Fig. 4 Average discharges of rivers influencing oceanographic conditions in Passamaquoddy Bay. Upper diagram:(A) St. Croix River (b) Magaguadavid River (c) Combined discharges Lower diagram: Saint John River.

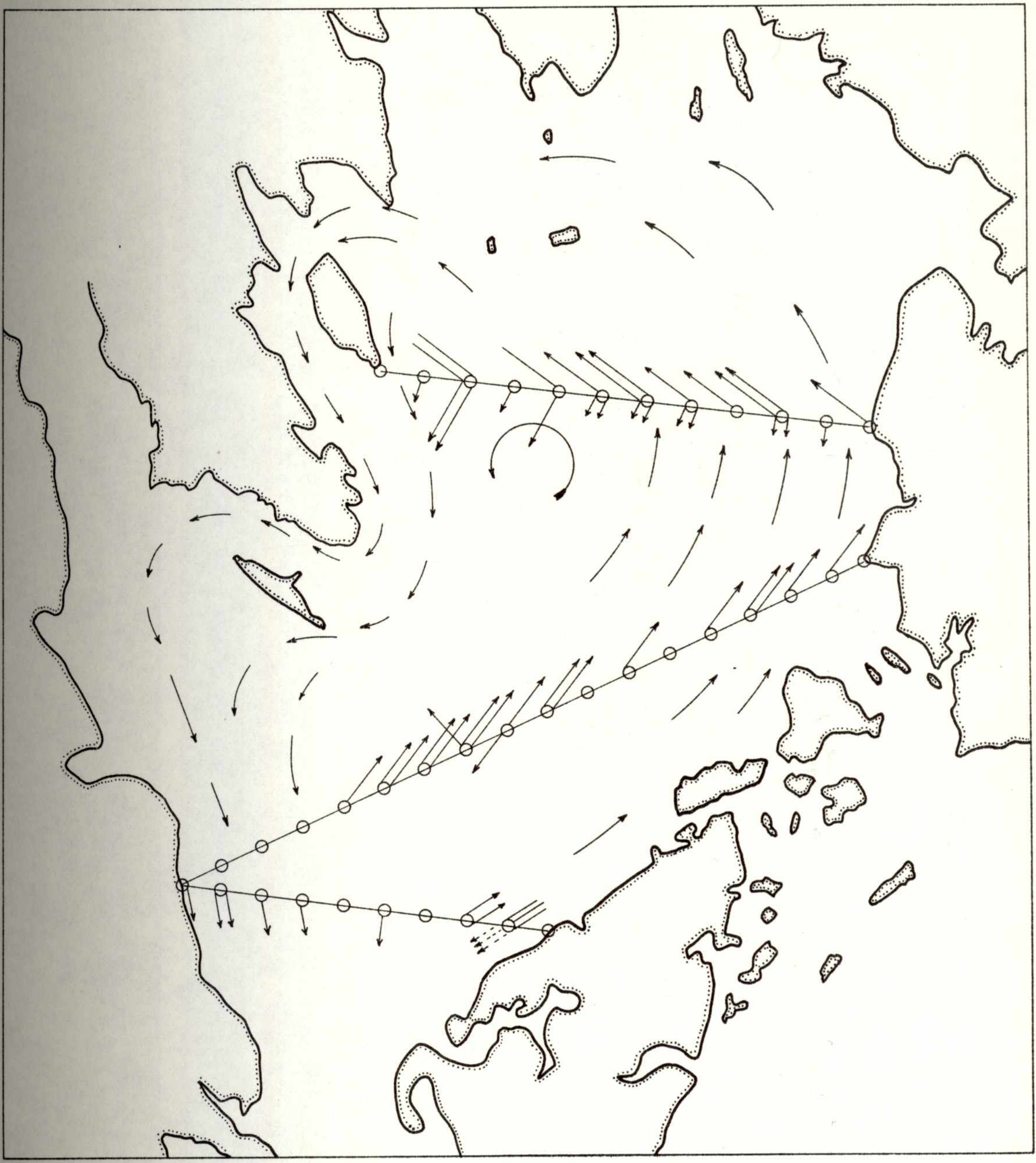

Fig. 5 Results of drift bottle experiments carried out in Passamaquoddy Bay in 1927 (after Hachey)

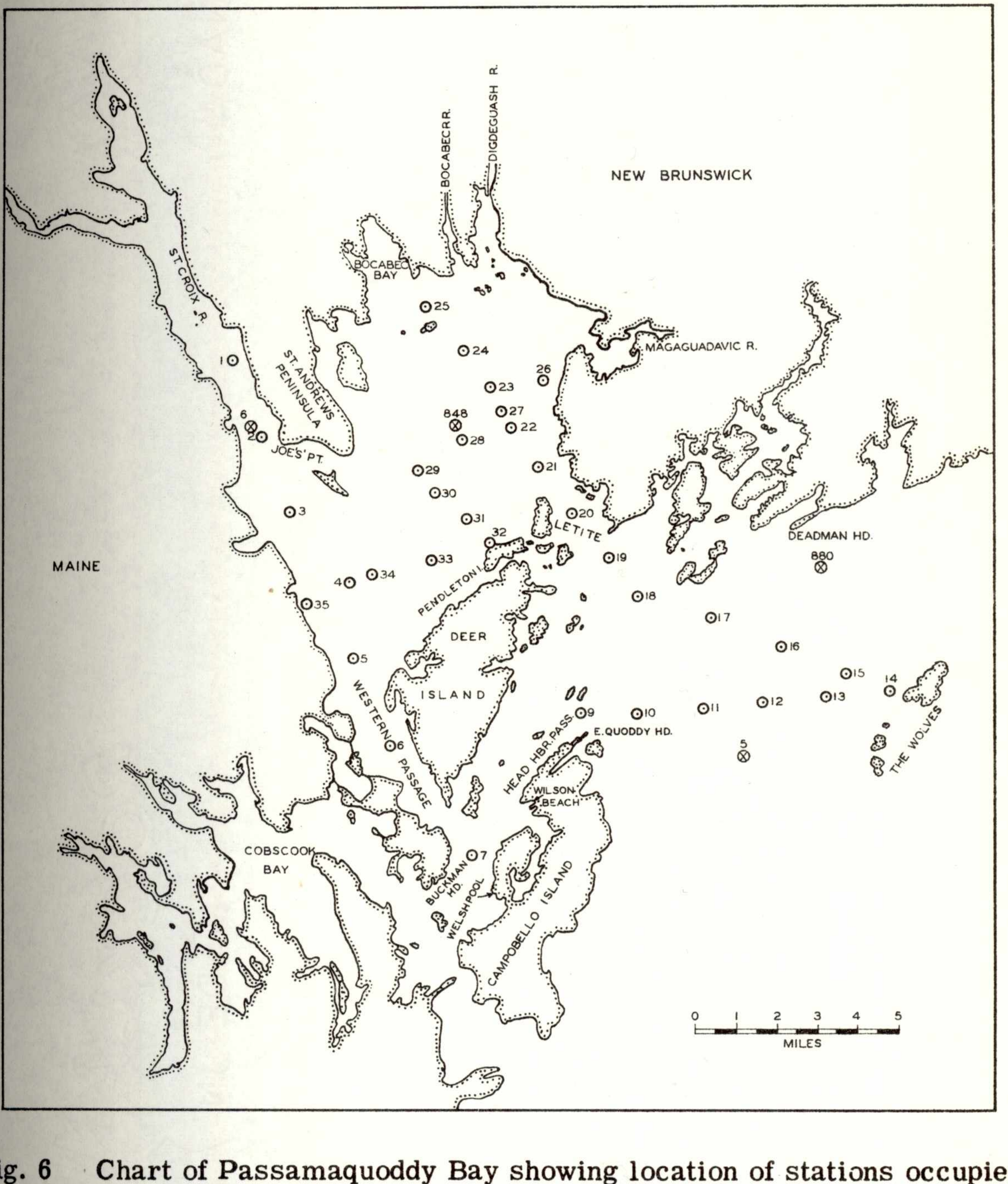

Fig. 6 Chart of Passamaquoddy Bay showing location of stations occupied in 1952 (⊙), and in 1933 (⊗) or earlier.

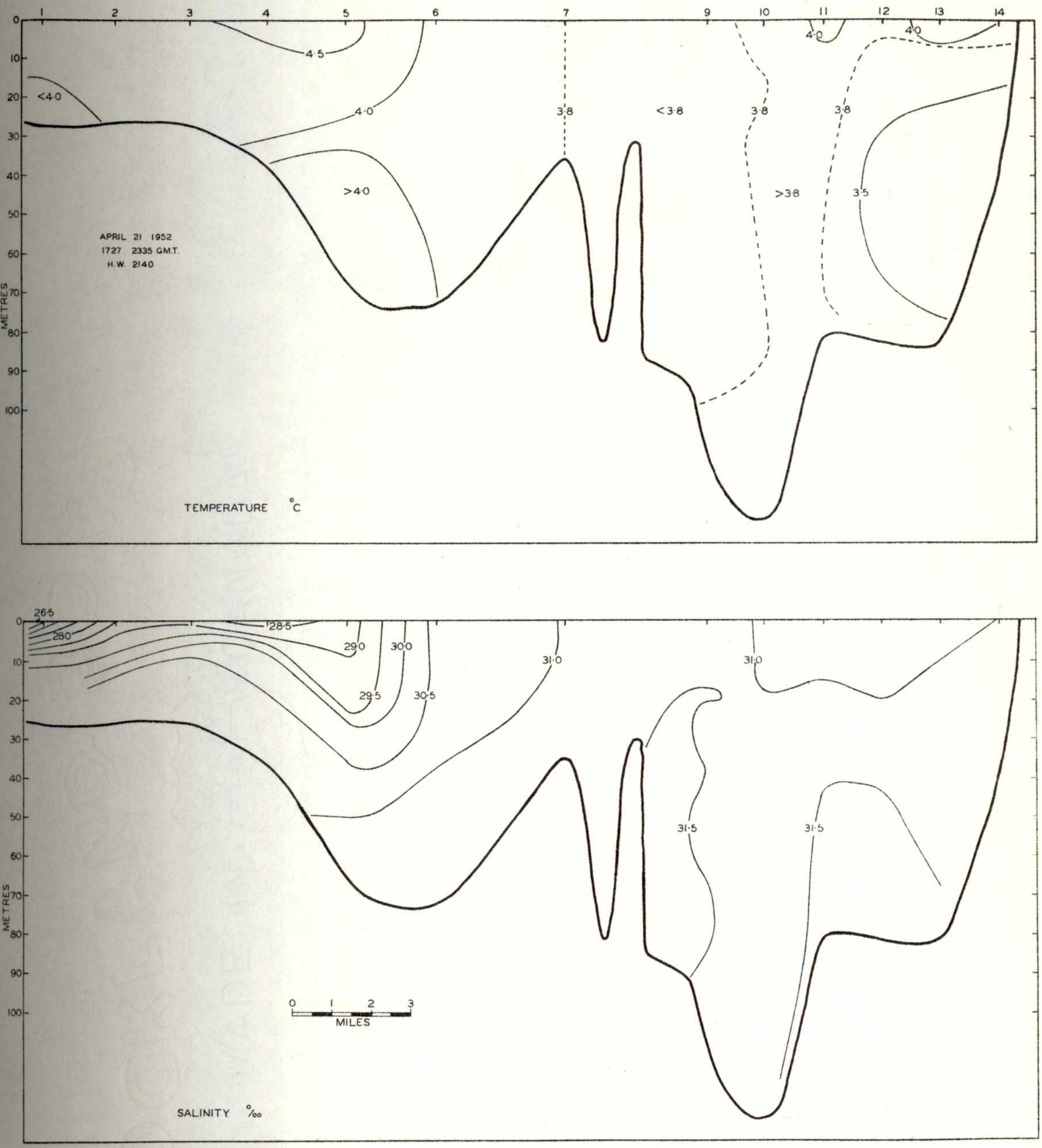

Fig. 7 Distribution of temperature and salinity at stations 1 - 14 near high water on April 21, 1952.

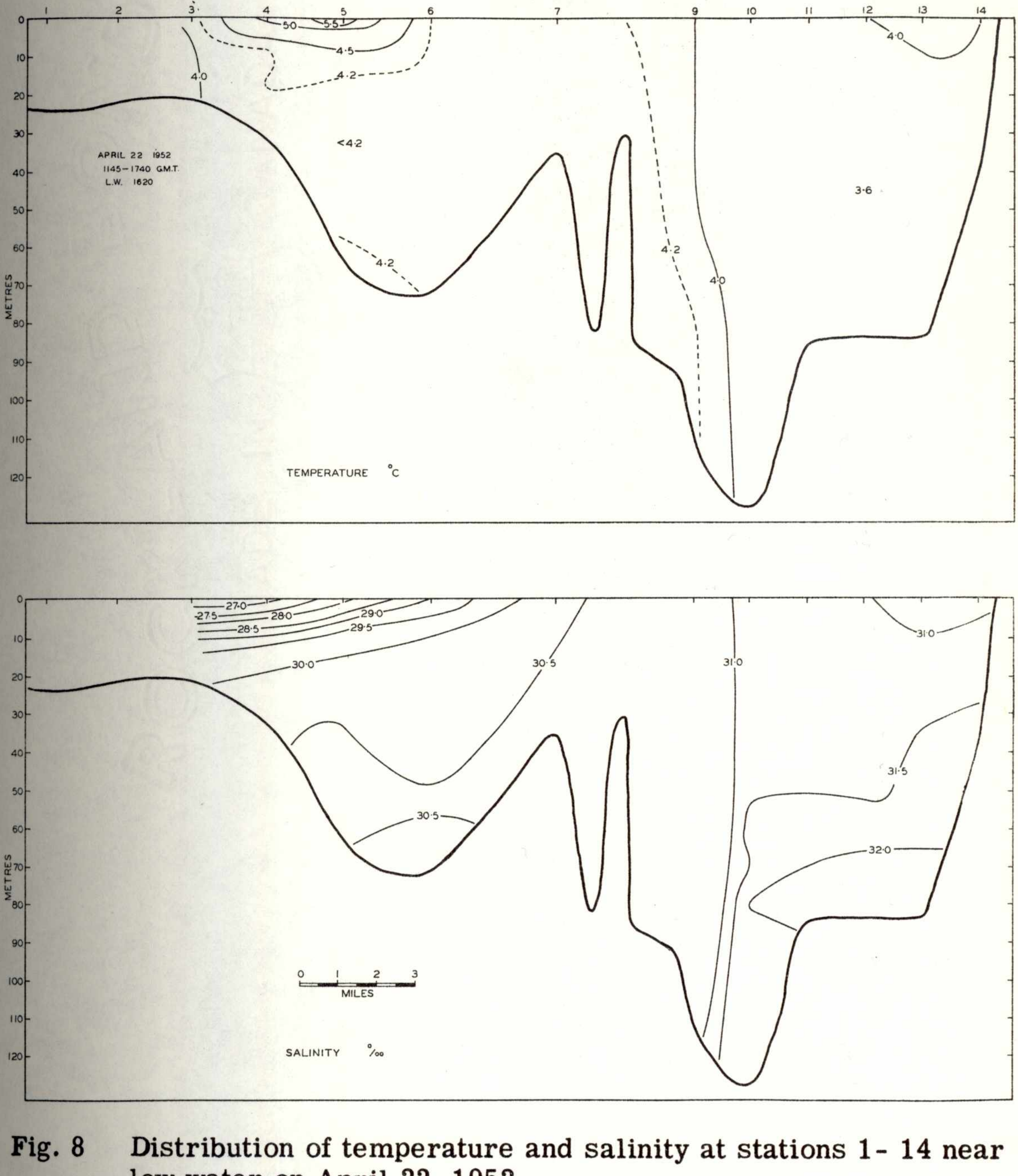

Fig. 8 Distribution of temperature and salinity at stations 1- 14 near low water on April 22, 1952.

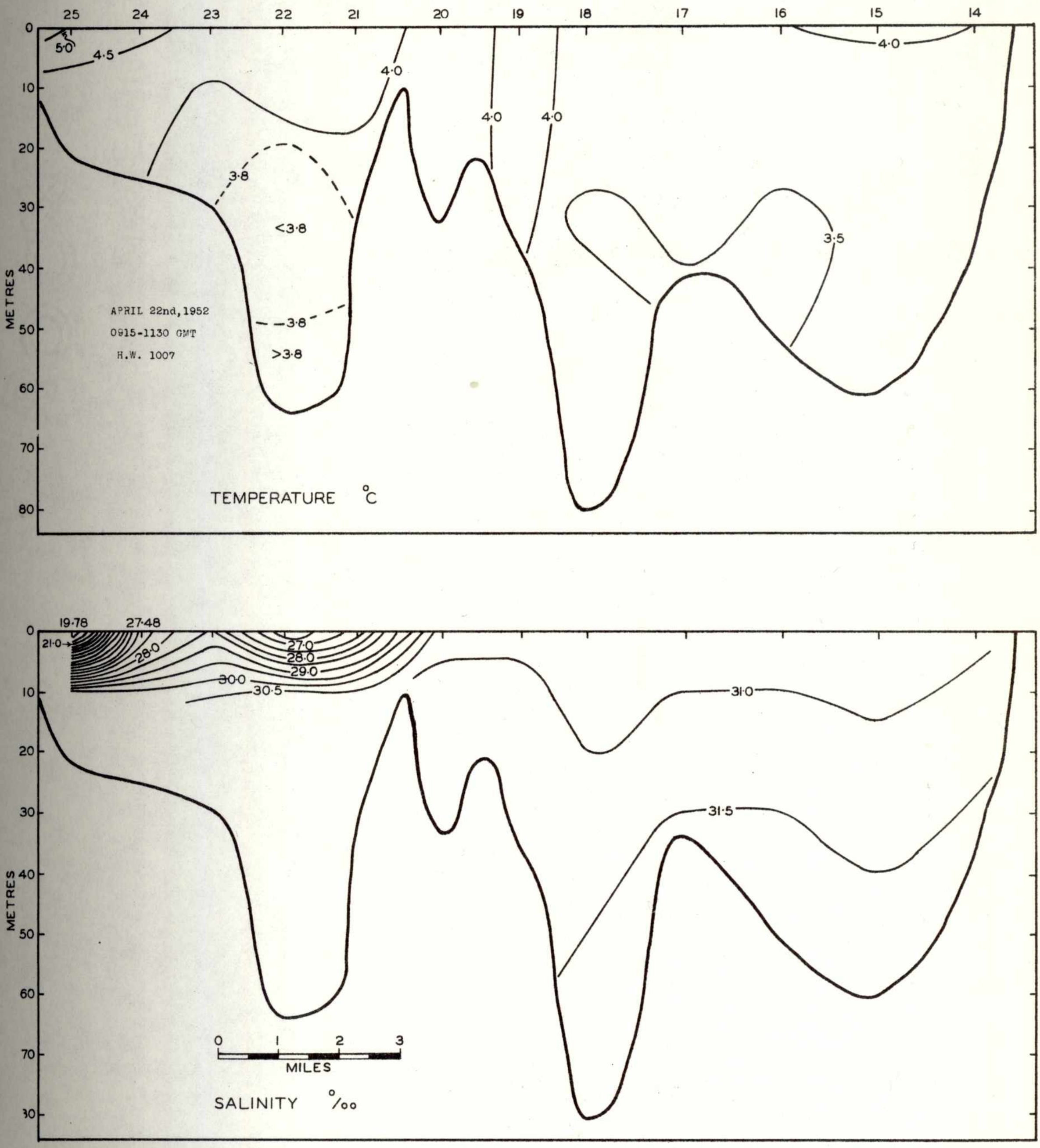

Fig. 9 Distribution of temperature and salinity at stations 14-25 near high water on April 22, 1952.

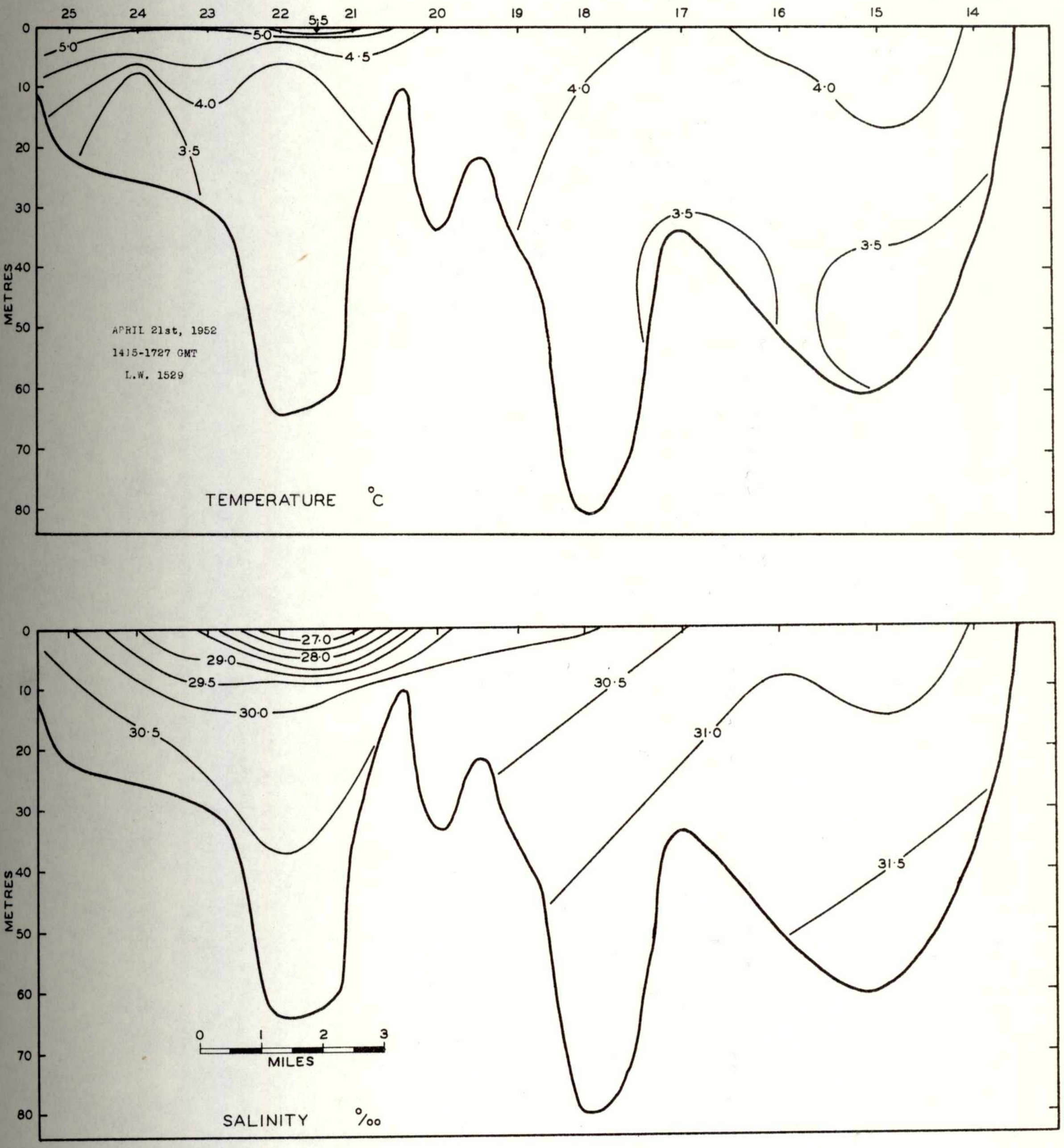

Fig. 10 Distribution of temperature and salinity at stations 14-25 near low water on April 21, 1952.

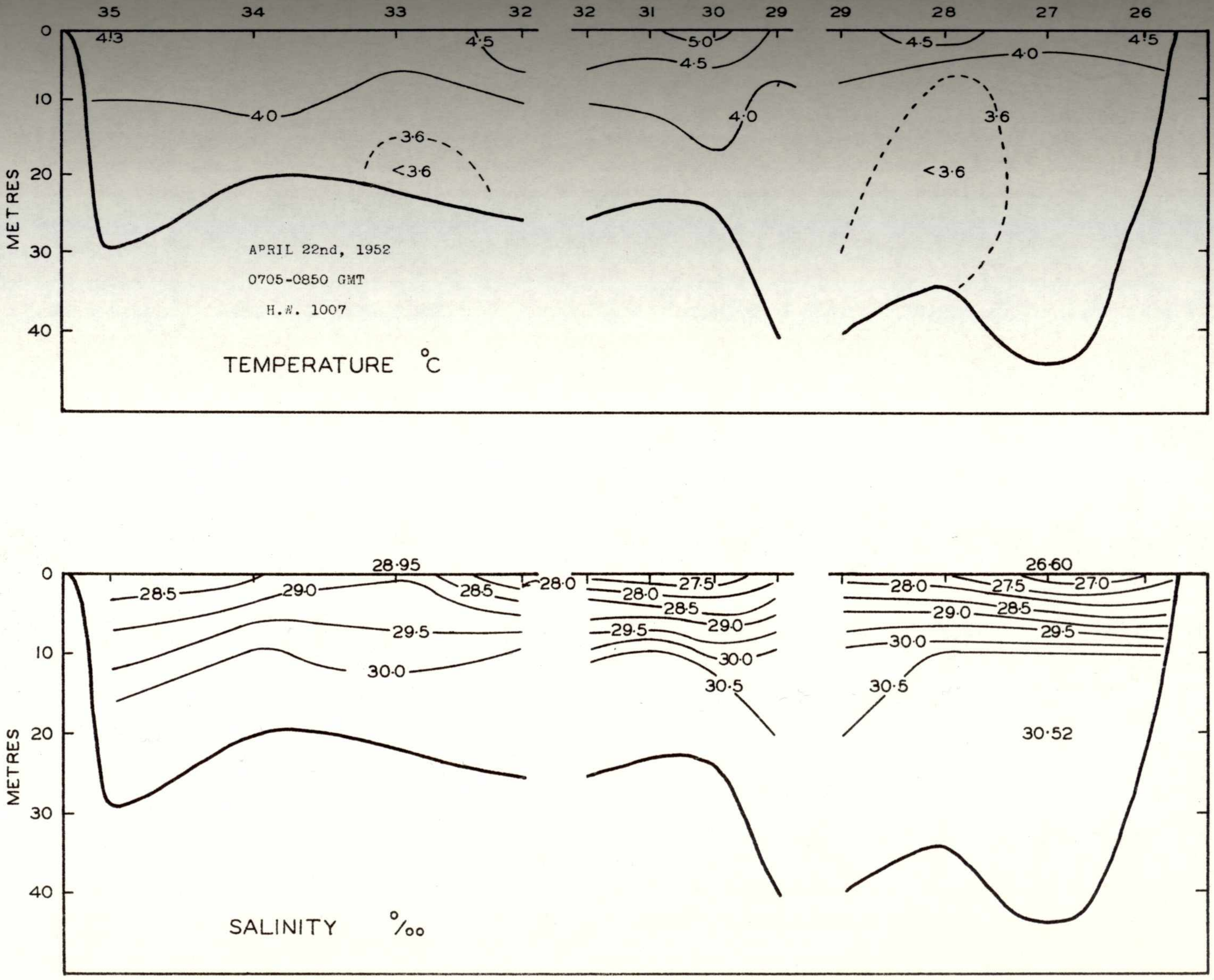

Fig. 11 Distribution of temperature and salinity at stations 26-35 on April 22, 1952.

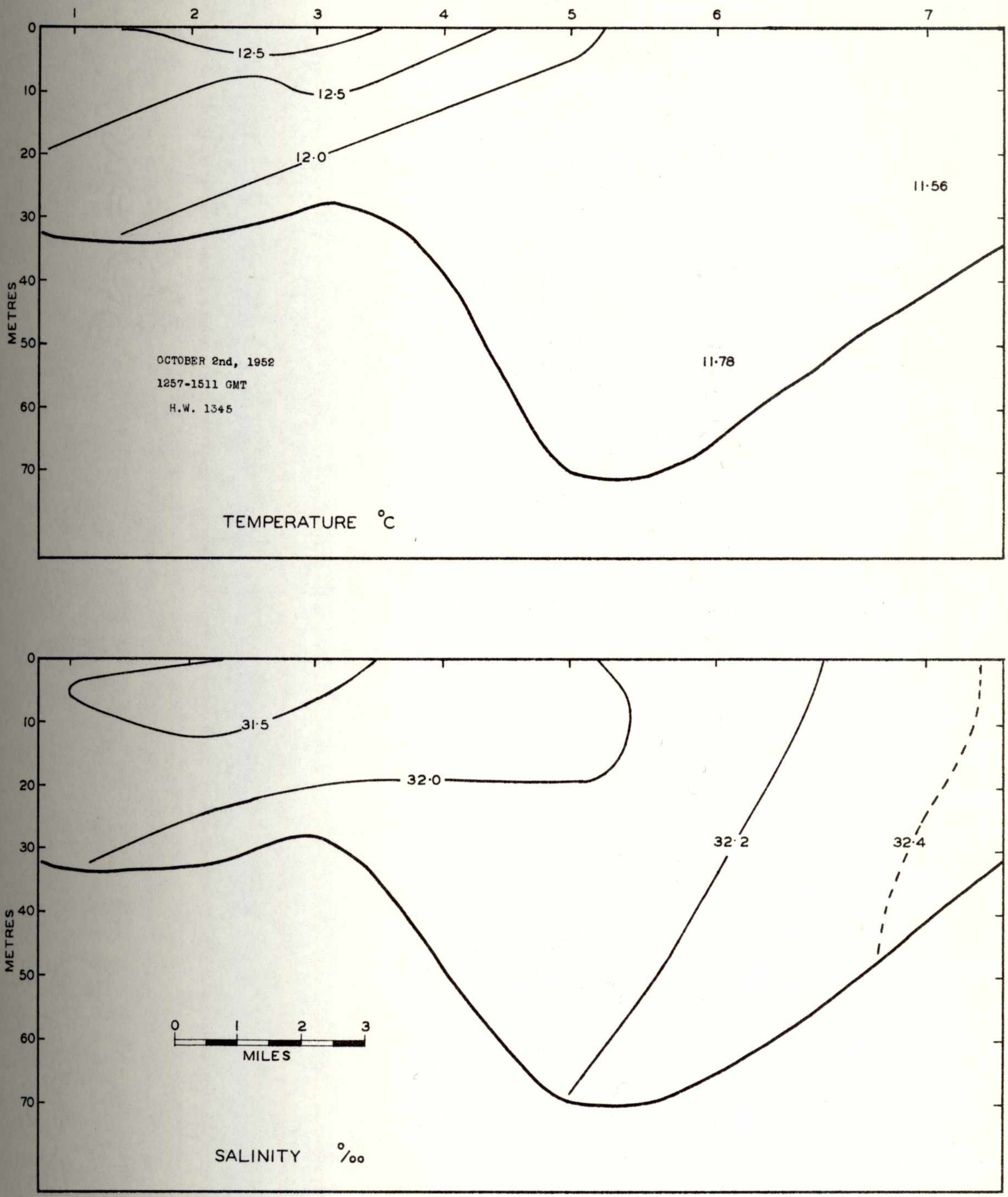

Fig. 12 Distribution of temperature and salinity at stations 1-7 near high water on October 2, 1952.

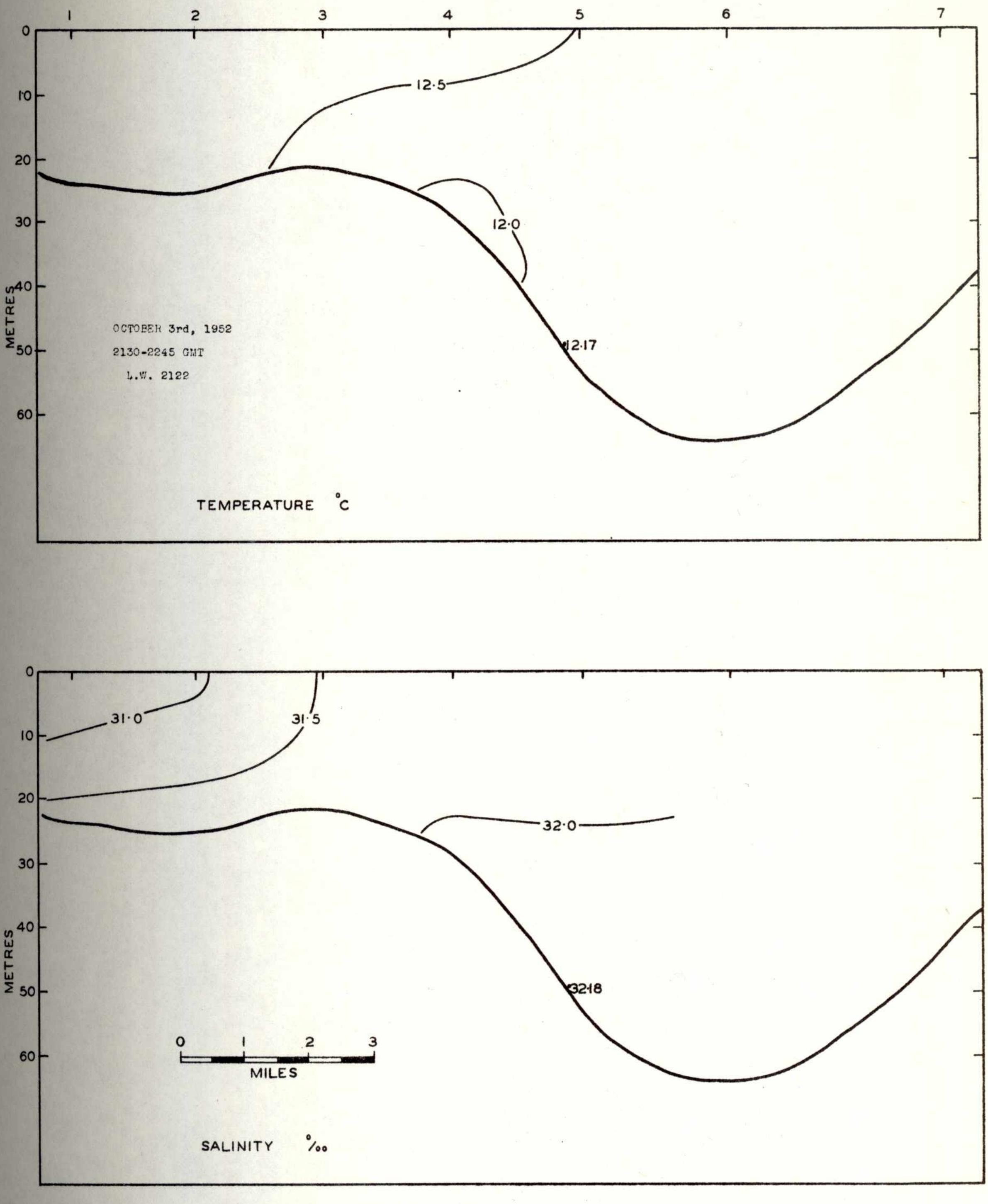

Fig. 13 Distribution of temperature and salinity at stations 1-7 near low water on October 3, 1952.

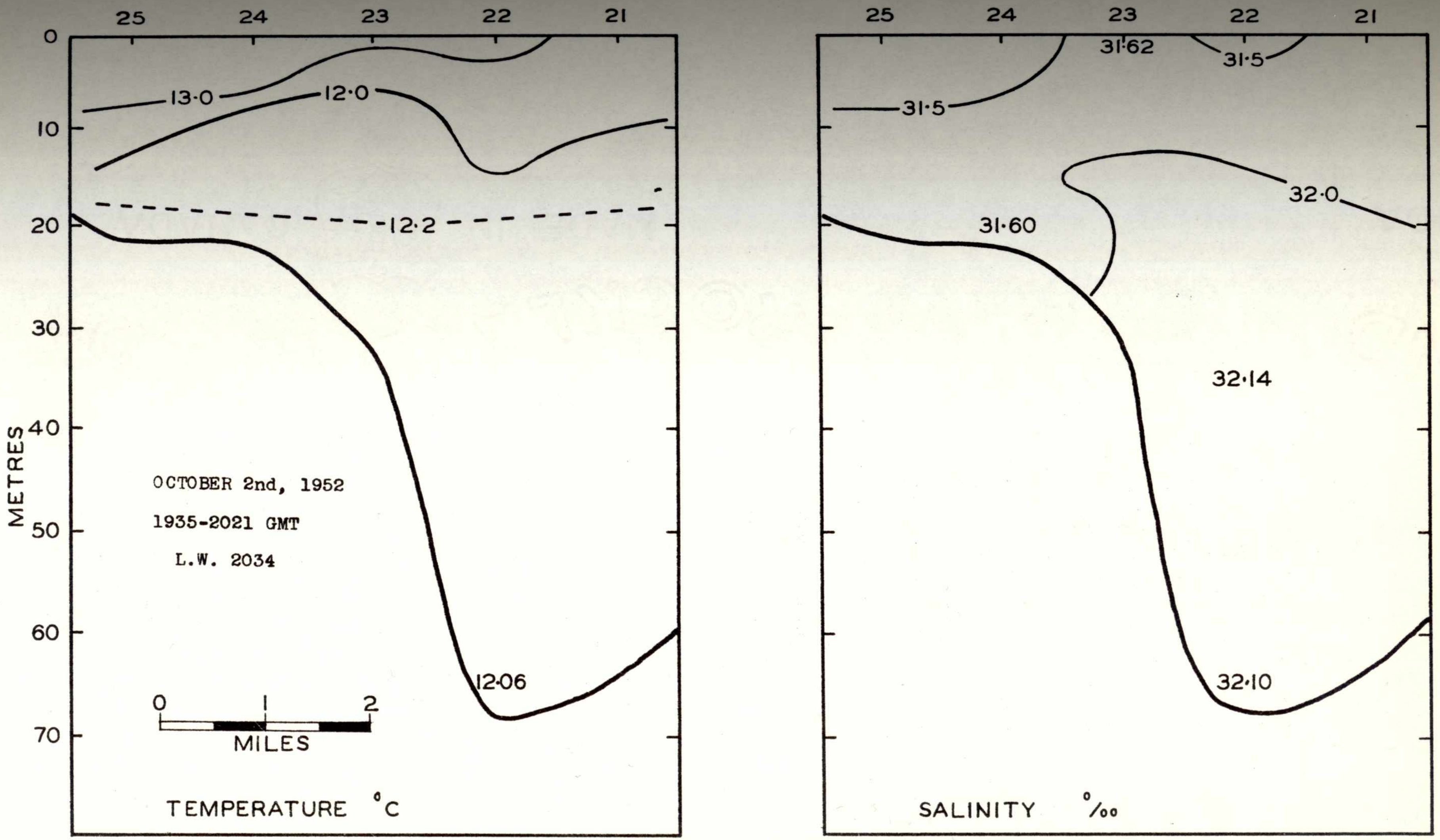

Fig. 14 Distribution of temperature and salinity at stations 21-25 near low water on October 2, 1952.

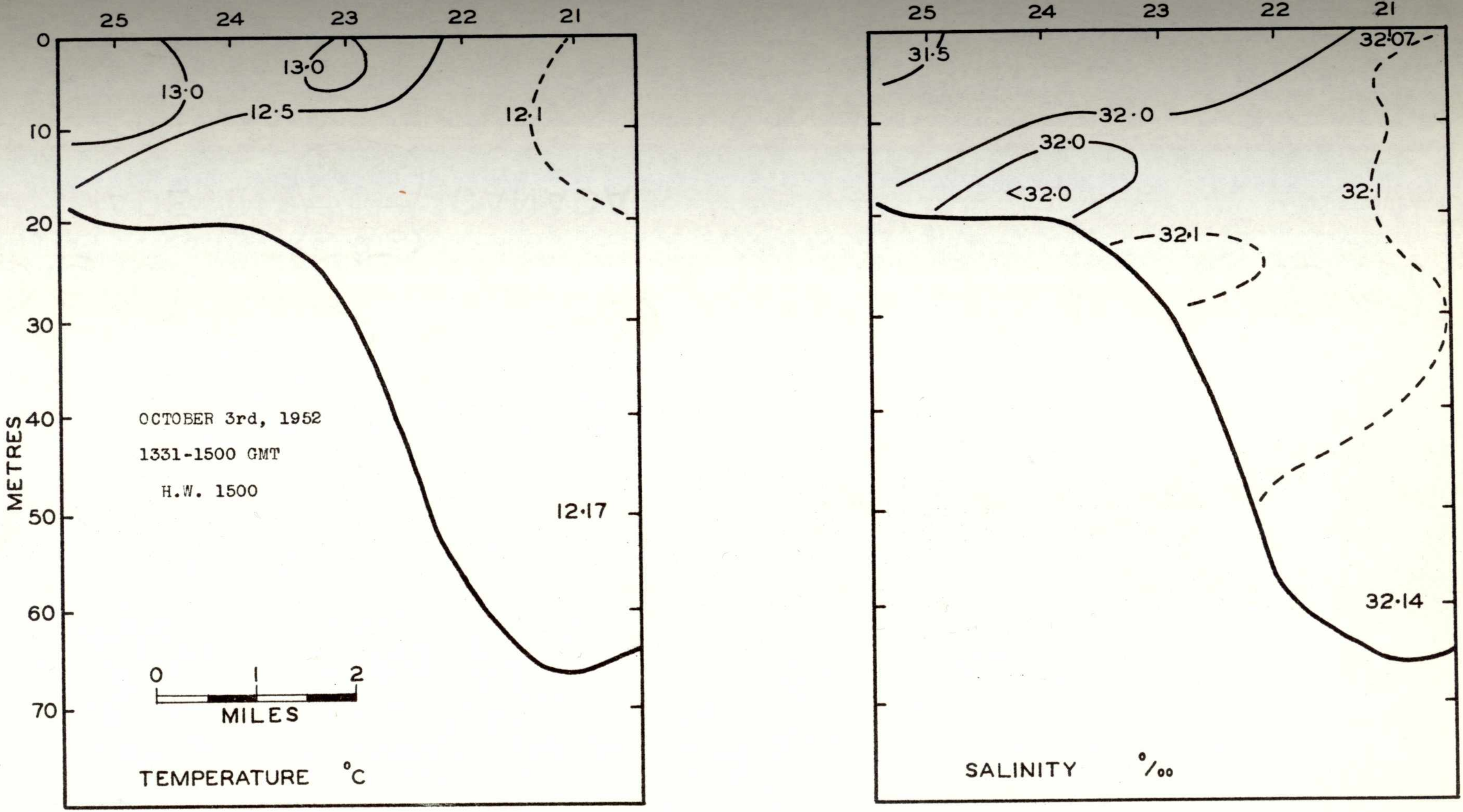

Fig. 15 Distribution of temperature and salinity at stations 21-25 near high water on October 3, 1952.

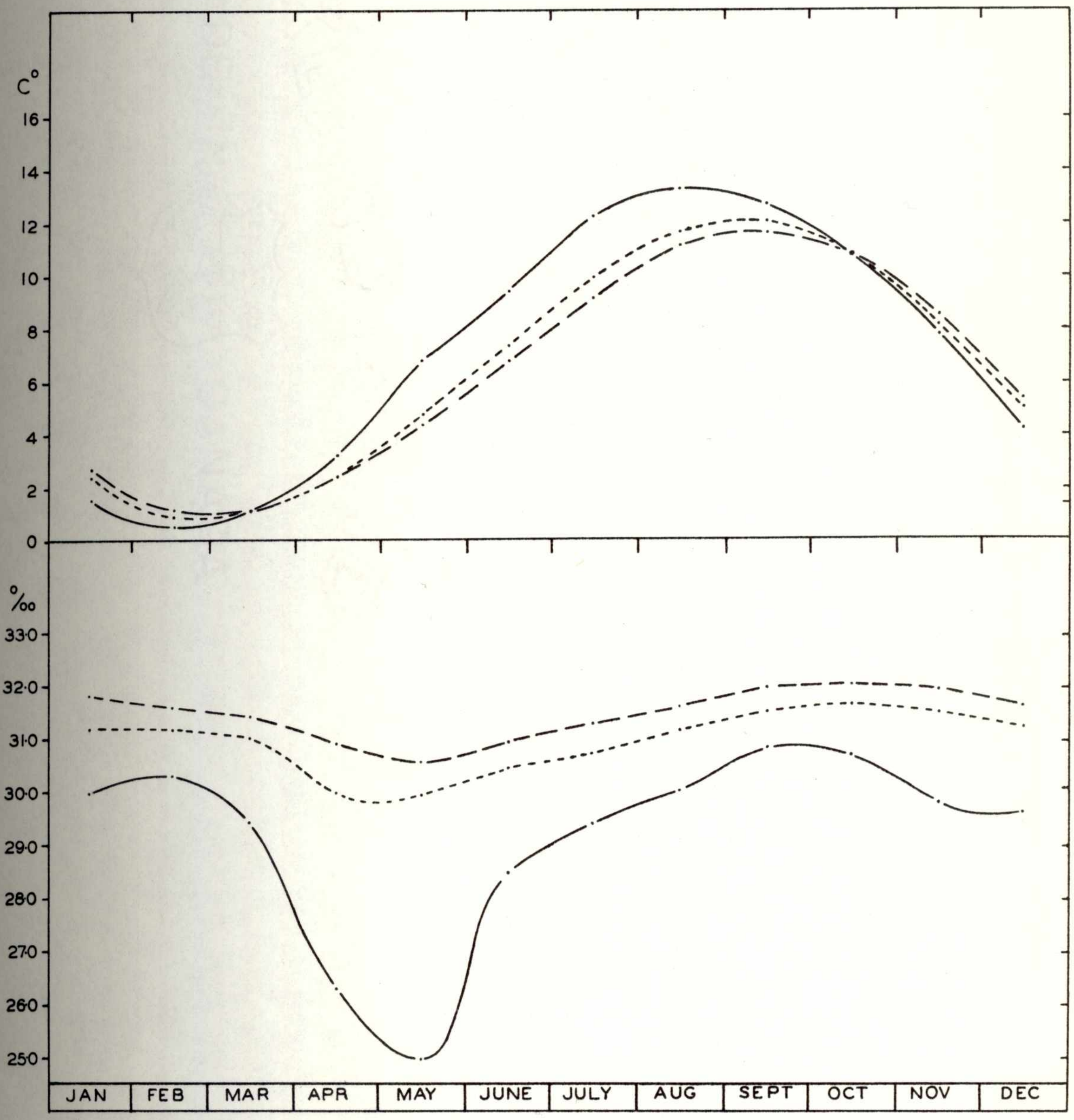

Fig. 16 Normal curves of temperature and salinity at surface (—), 10 metres (---) and 30 metres (– –) at station 6.

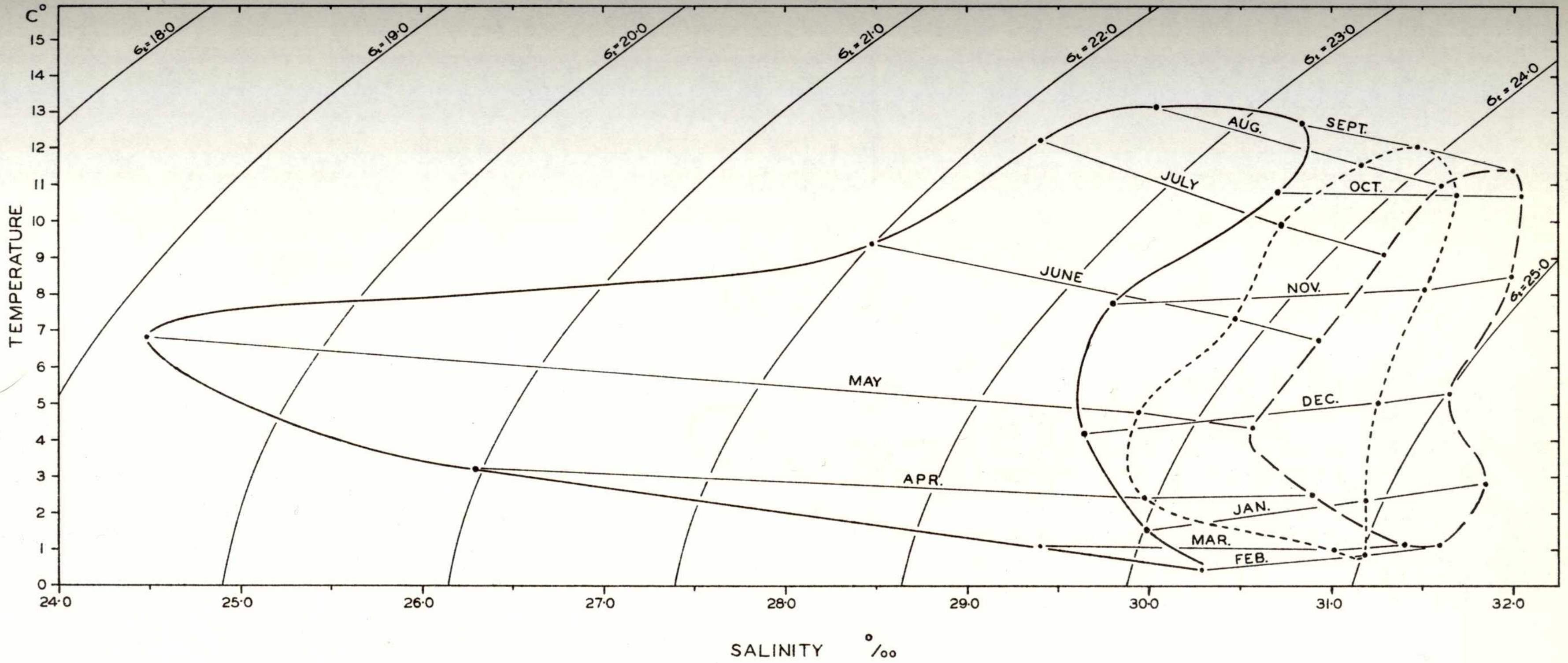

Fig. 17 Normal T-S curves for each for each month and the normal annual T-S cycle for the surface (–), 10 metric (---) and 30 metres (– –) levels at station 6.

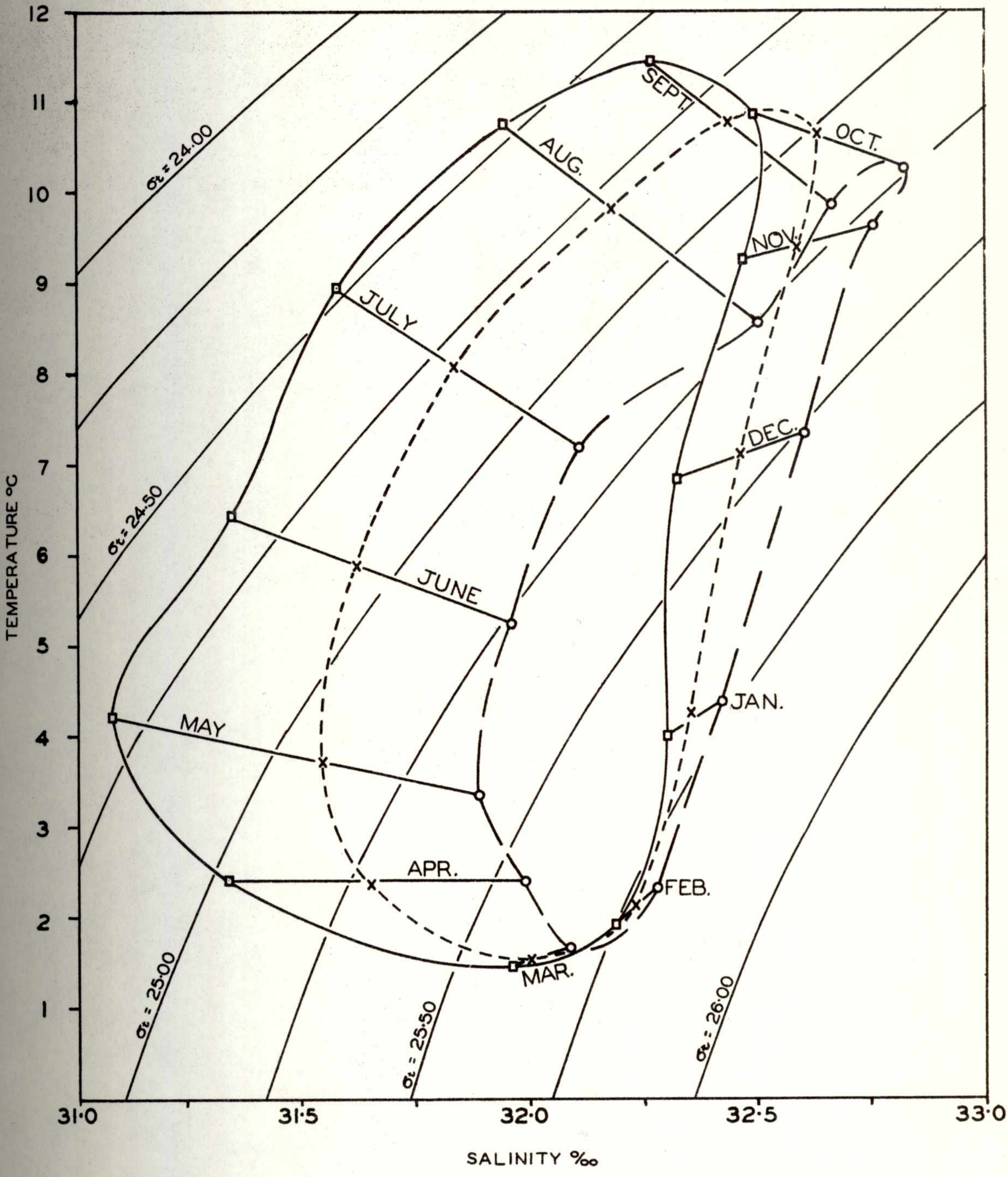

Fig. 18. Normal T-S curves for each month, and the normal annual T-S cycle for the surface (——), intermediate (----), and bottom (—— ——) layers.

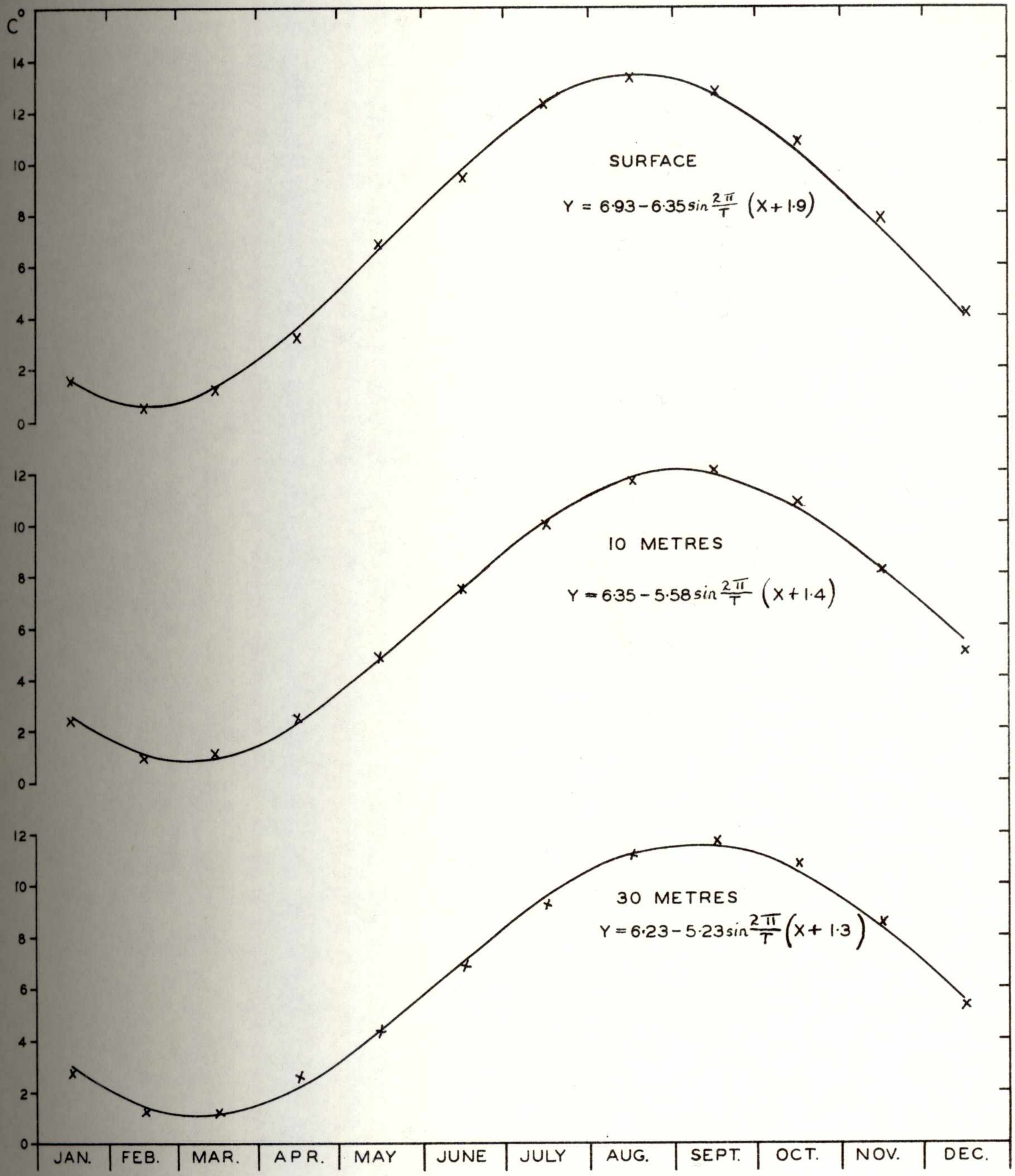

Fig. 19 Normal theoritical temperature-time curves for the surface, 10 metre and 30 metre levels at station 6.

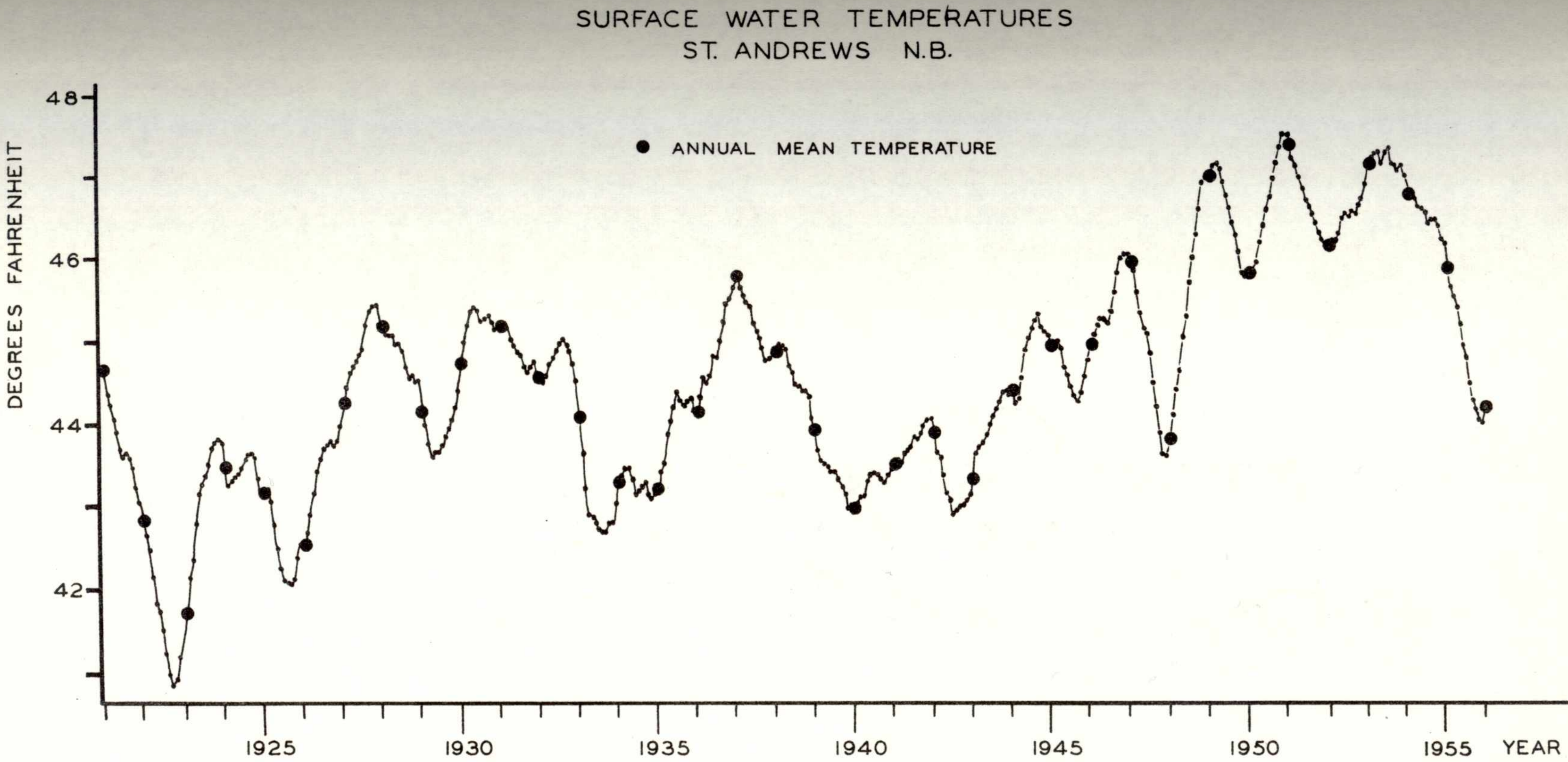

Fig. 20 Surface water temperatures at St. Andrews, N. B.

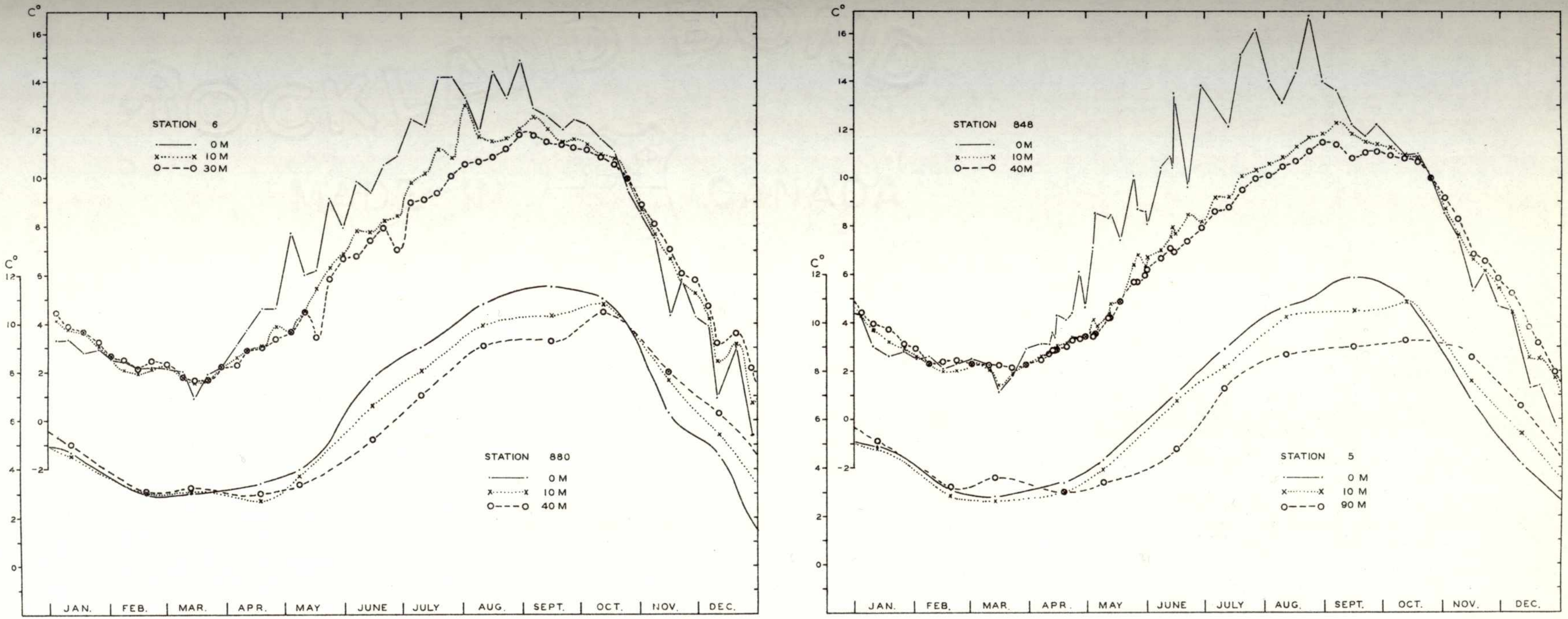

Fig. 21 Temperature-time curves for stations 6, 880, 848, and 6 for the year 1933.

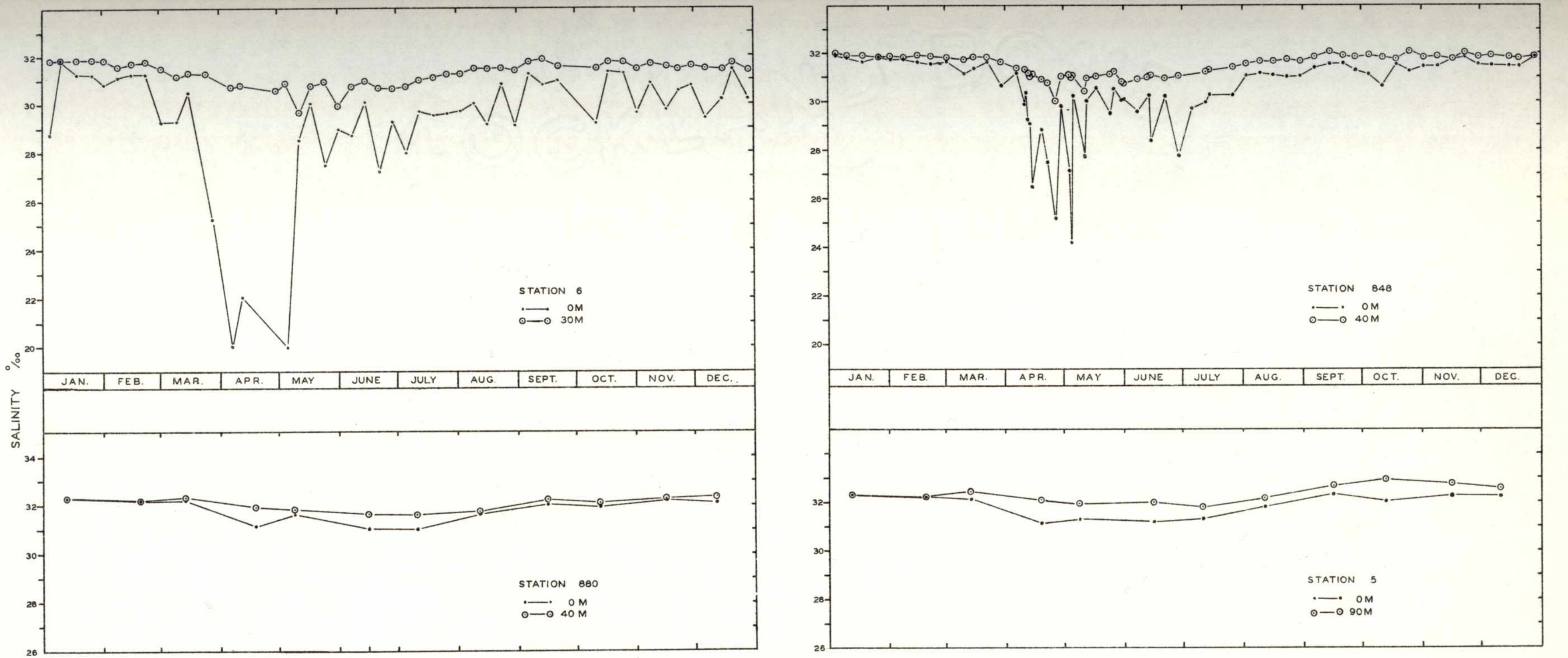

Fig. 22 Salinity-time curves for stations 6, 880, 848 and 5 for the year 1933.

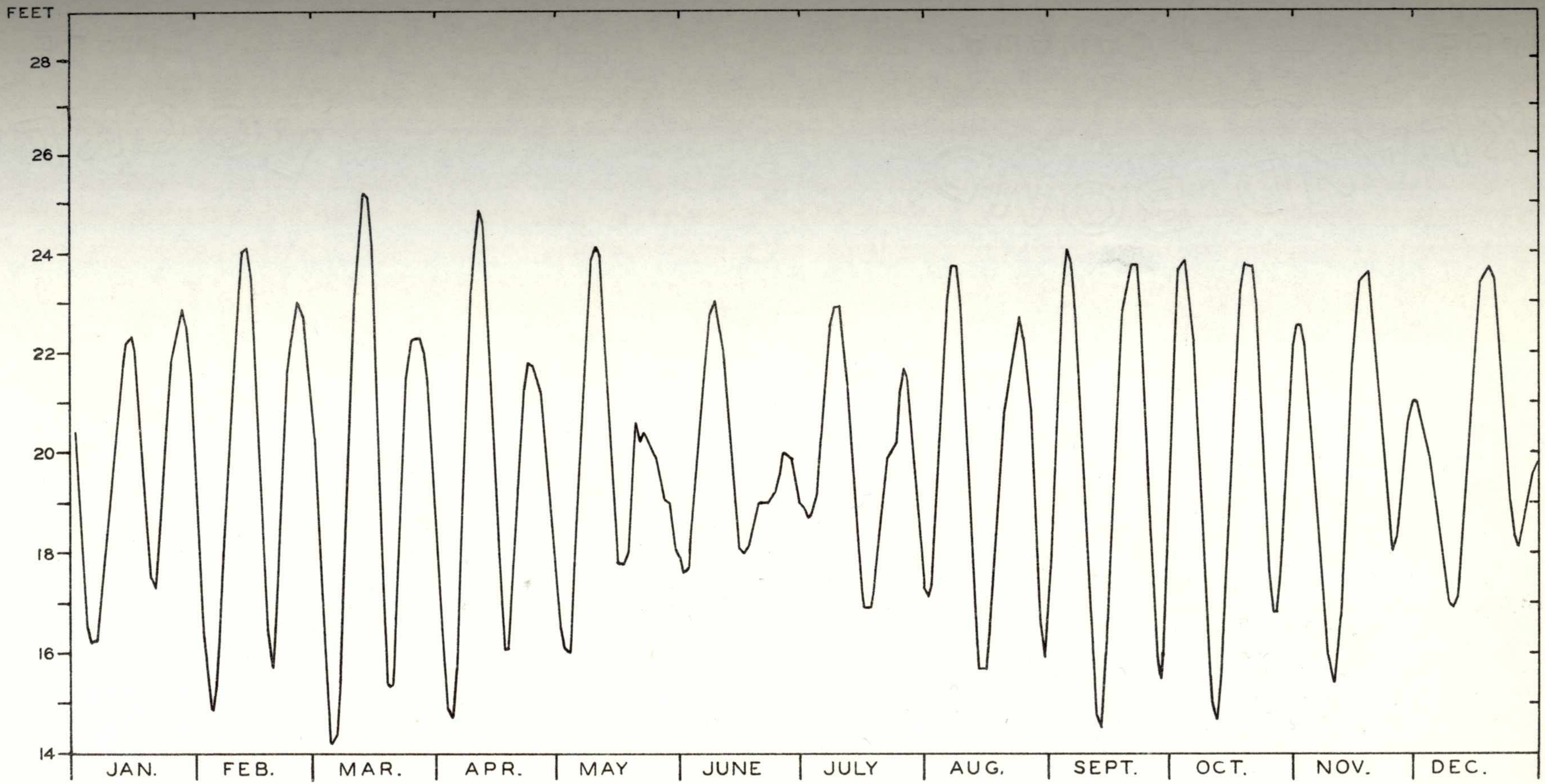

Fig 23 Daily predicted range of the tides at St. John, N.B. for the year 1933.

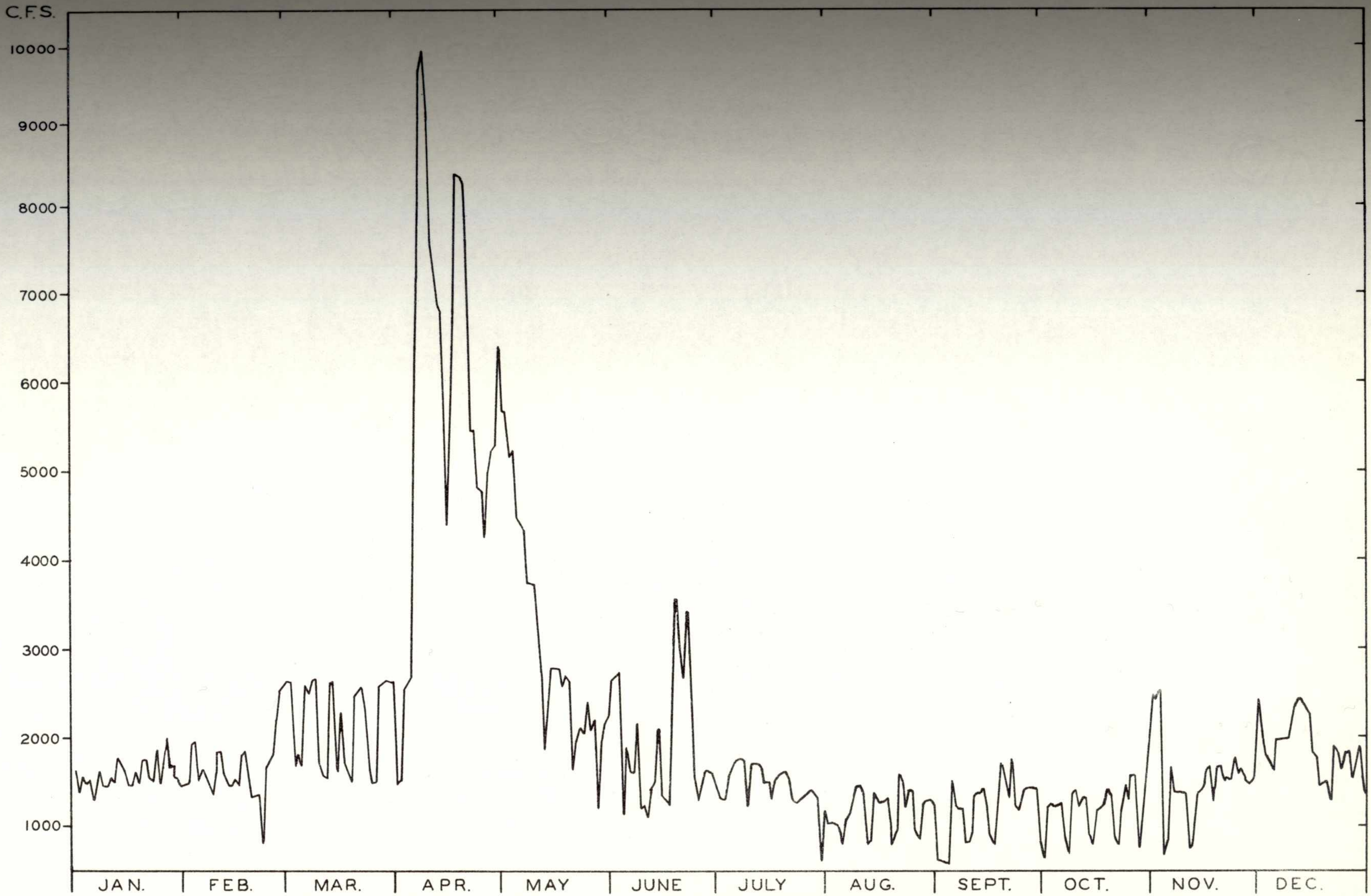

Fig. 24 Daily discharges of the St. Croix River at Bailyville, Maine for the year 1933.

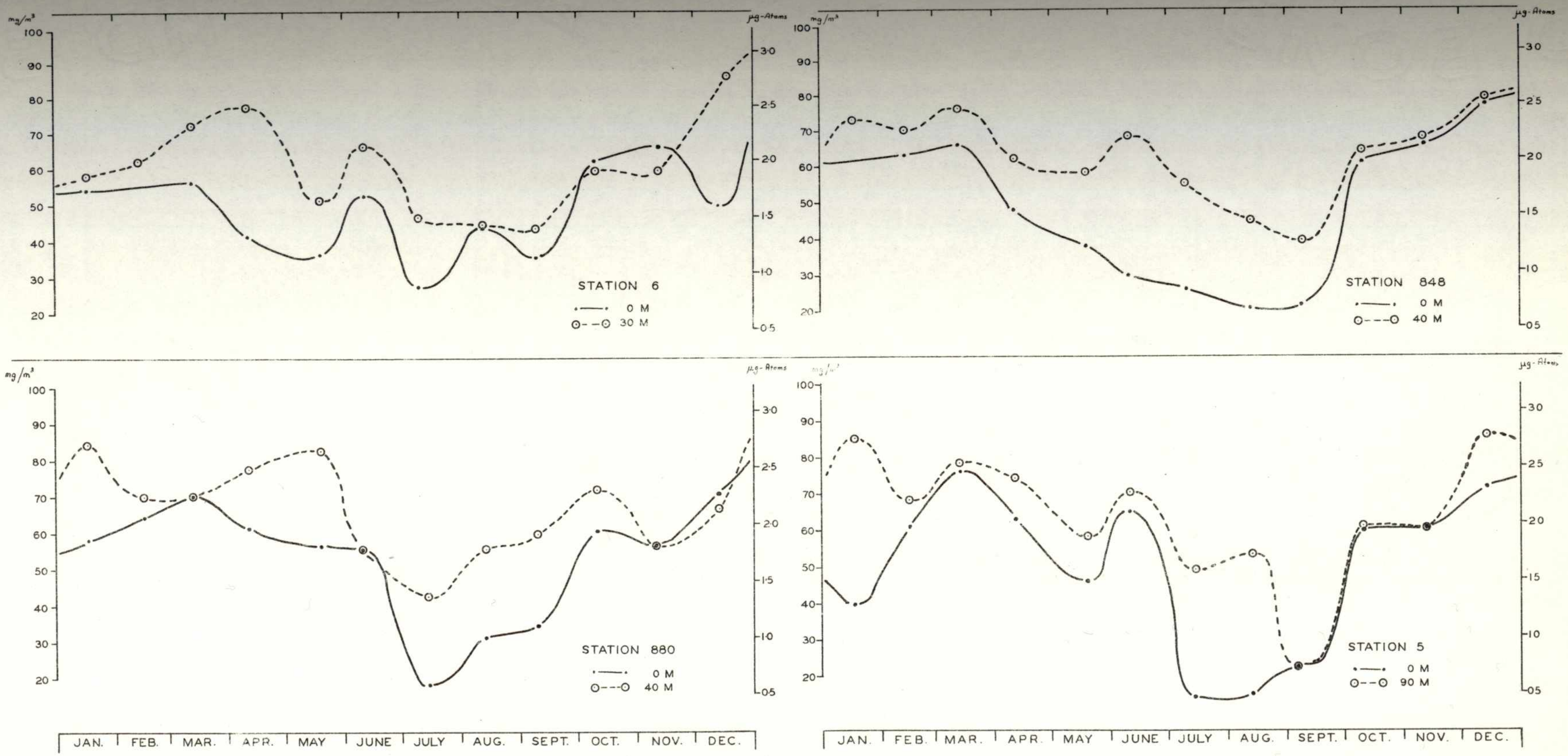

Fig. 25 Phosphate concentrations at stations 6, 898, 880 and 5 in 1930.

Fig. 26 An interpretation of the general surface circulation in the Passamaquoddy region from results of drift bottle experiments and density distributions.