ESSA TR ERL 167-AOML 2

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PUBLICATION

ESSA Technical Report ERL 167-AOML 2

U.S. DEPARTMENT OF COMMERCE
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An Oceanographic Investigation Adjacent to Cay Sal Bank, Bahama Islands

ROBERT B. STARR

MIAMI, FLA.
JUNE 1970

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ESSA TECHNICAL REPORT ERL 167-AOML 2

An Oceanographic Investigation Adjacent to Cay Sal Bank, Bahama Islands

ROBERT B. STARR

ATLANTIC OCEANOGRAPHIC AND METEOROLOGICAL LABORATORIES
PHYSICAL OCEANOGRAPHY LABORATORY
MIAMI, FLORIDA
June 1970

For sale by the Superintendent of Documents, U. S. Government Printing Office, Washington, D. C. 20402
Price 55 cents.

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AN OCEANOGRAPHIC INVESTIGATION ADJACENT TO CAY SAL BANK, BAHAMA ISLANDS

Robert B. Starr

Forty-seven oceanographic stations were occupied in the Cay Sal Bank region of the Straits of Florida to investigate the water structure in the straits here and in the entrances to Nicholas and Santaren Channels. The water exchange through Nicholas Channel appears to be negligible; Santaren Channel contributes water to the northern Florida Straits below 350-m depth. Evidence of a possible south-flowing countercurrent in the Straits of Florida is also presented.

1. INTRODUCTION

An investigation of the physical and geological oceanography of the area of the Straits of Florida adjacent to Cay Sal Bank was conducted from June 20 through 26, 1962. This study consisted of 47 oceanographic stations and bathythermograph observations. There were 22 bottom sediment cores taken and a release of 10 drift bottles at each station. The locations of the stations are shown in figure 1* and were planned to investigate the water structure across Nicholas and Santaren channels, as well as the Straits of Florida to determine the effect of Cay Sal Bank on this structure and to learn the nature of the bottom in the area.

* The layout and numbering of sections (see figs. 7-11) are shown in figure 1.

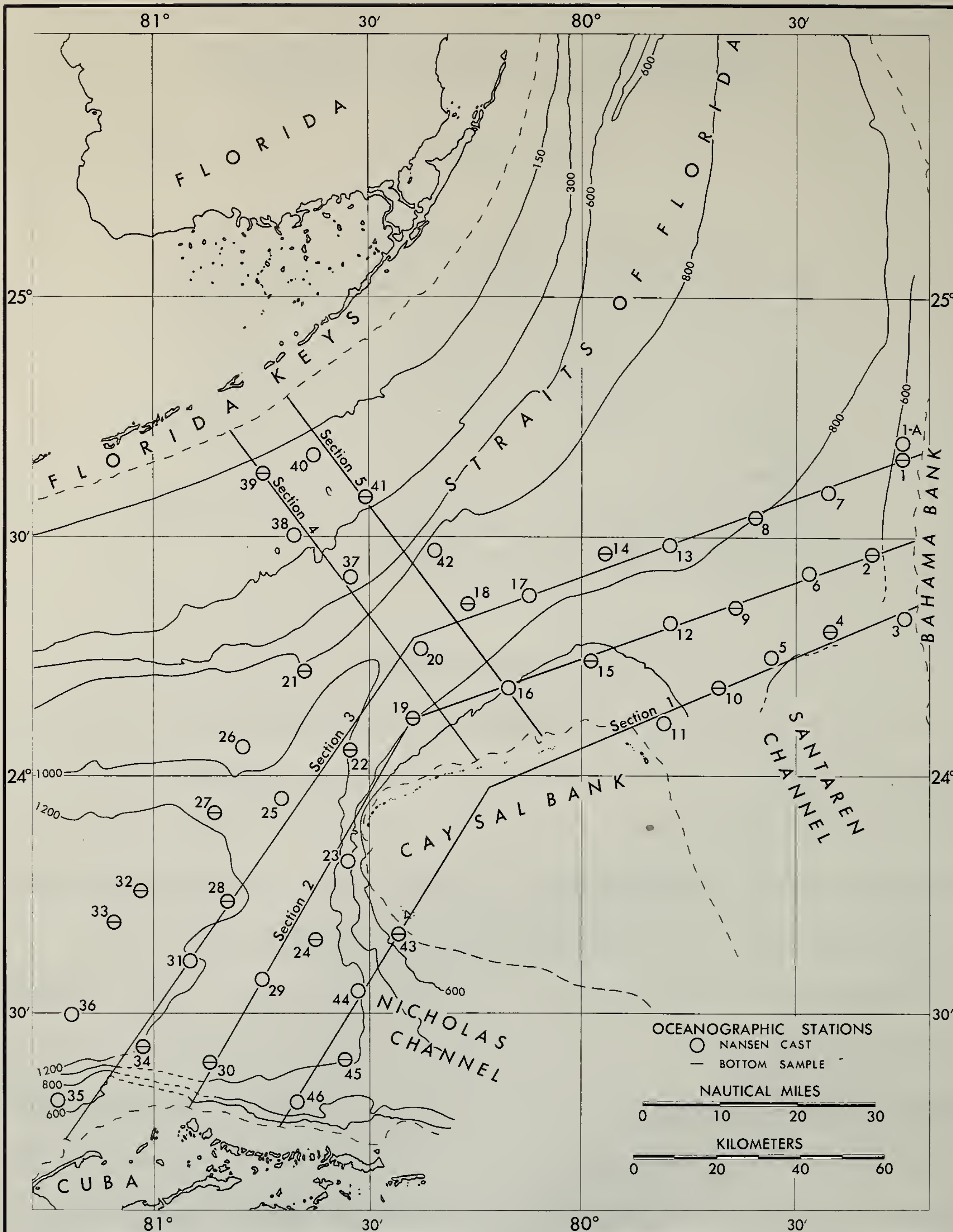

Figure 1. Chart of station locations, section locations, and general bathymetry (in meters).

The observations were made from the USC&GSS HYDROGRAPHER by the writer and Dr. Robert E. Burns, assisted by the officers and crew. The HYDROGRAPHER was commanded by Captain Raymond E. Stone.

Ship's navigation was by Loran A, radar, and visual fixes. The depths of 100 fathoms along the Florida Keys and 200 fathoms elsewhere were used as a secondary control when it was desired to position stations relative to the banks bounding the area. Fixes were taken every 15 min while the ship was on station so that when Loran reception was good or when the ship was close to land relative positions for determining the ship's drift were good to one-quarter mile. The plotted locations of the stations are accurate to 1 n mi, except when Loran reception was poor well away from land (see fig. 1). The oceanographic stations consisted normally of 2-8 bottle Nansen casts with modifications for shallow depths. These were taken starting from the surface to as near bottom as possible. A 180 lb steel ball was used as the Nansen cast weight to keep wire angles at a minimum. A bathythermograph observation to 900 ft or the bottom was taken at the time of each shallow cast.

All Nansen bottles were equipped with two deep-sea reversing thermometers, except one had three. Five unprotected thermometers were used on each cast for thermometric depth determinations. The thermometers had been recently calibrated at the Naval Oceanographic Instrumentation Center and were periodically exchanged among the bottles to reveal malfunctions or erratic operation.

The water samples for salinity analysis were bottled in aged citrate of magnesia bottles and shipped to Washington, D. C., where their salinities were determined by dual analyses on a South African conductive salinometer. Check analyses on a selected batch of samples were run on a HYTECH inductive salinometer.

2. PROCESSING AND DISPOSITION OF THE DATA

Processing of the serial oceanographic data included plotting station profiles of temperature and salinity against depth, the plotting of individual Temperature-Salinity (T-S) curves, and the comparison of these against a composite T-S curve. This composite curve is shown in figure 2. The verified station data were then transmitted to the National Oceanographic Data Center, where standard depth interpolations for the stations were made and the dependent parameters computed. A machine listing of the station data was then reviewed, density as sigma-t (σ_t) was plotted as a check, and hand interpolations of temperature and/or salinity were made where the machine ones were unacceptable. The final listings are available from NODC.

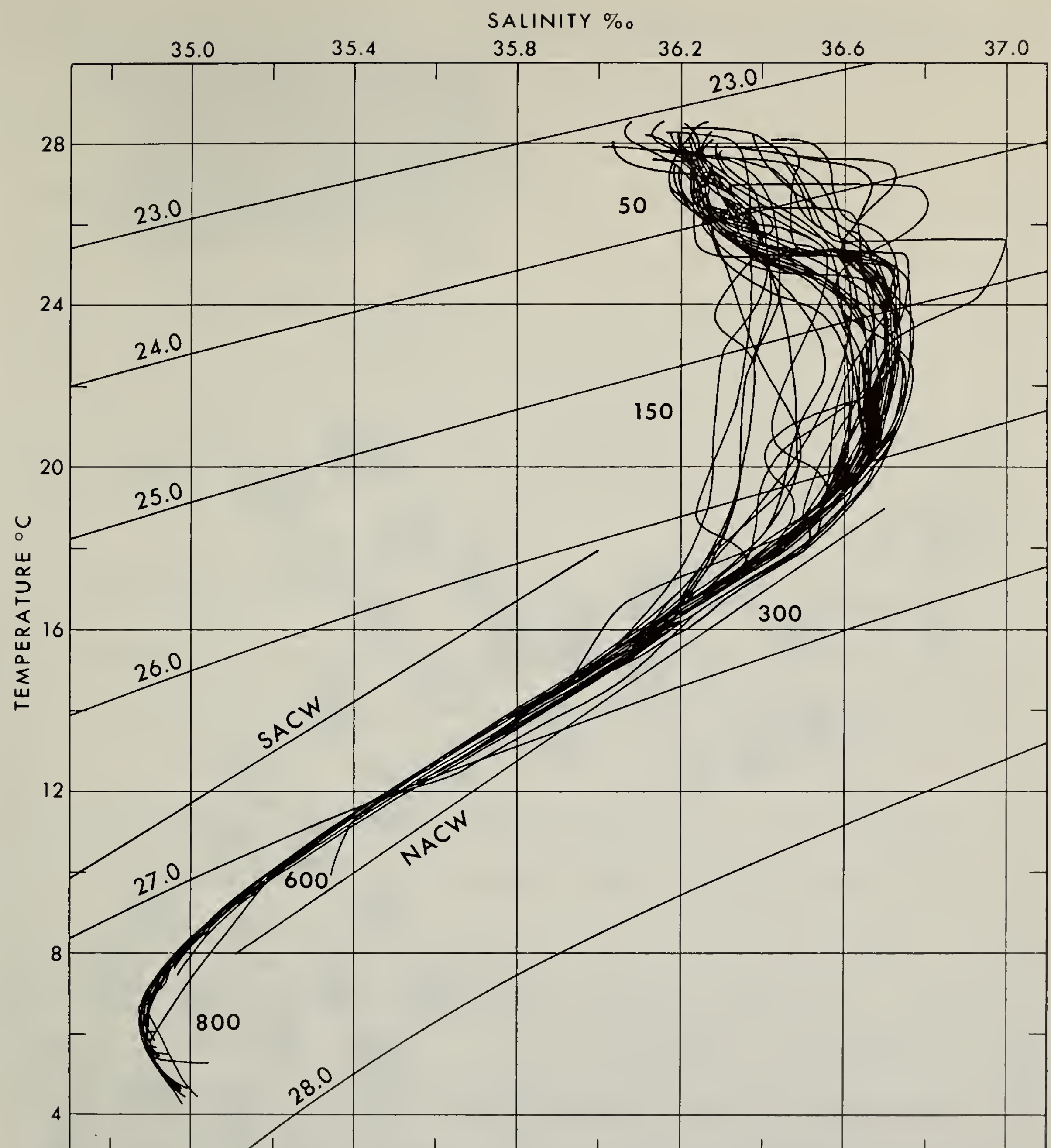

Figure 2. Composite Temperature-Salinity (T-S) Diagram. Depths are in meters. North Atlantic Central Water shown by line marked NACW, and South Atlantic Central Water shown by line marked SACW.

The NODC reference number is 31042. Except where questioned, the depths of the individual observations are considered to be accurate within 5 m, the temperatures to $\pm 0.02°C$, and the salinities to $\pm 0.01‰$ with relative accuracy to 0.003‰. Where two protected thermometers were paired, the average was used in most cases, but where the thermometers differed by more than 0.05°C, the more reasonable value was used. This sometimes happeded with observations in the steep thermocline, probably because of different thermal responses of the thermometers.

The bathythermograph observations taken on the oceanographic stations are available from NODC as cruise number 5296. The individual traces at the station locations are reproduced in figure 3.

The 28 returns from the 460 drift bottles released are listed in appendix A. These amount to a 6.1% recovery, all of which came from only 11 of the 46 locations where bottles were released. The nine bottles recovered from station 38 account for 32.1% of all returns.

Twenty-two bottom sediment cores were taken with 60- and 80-pound Phleger Corers with 3-foot barrels. Immediately after recovery, the cores were preserved with 5 ml of alcohol and sealed. Their visual physical characteristics were logged, and they were stored in the ship's refrigerator. These cores were transferred to Florida State University and used by

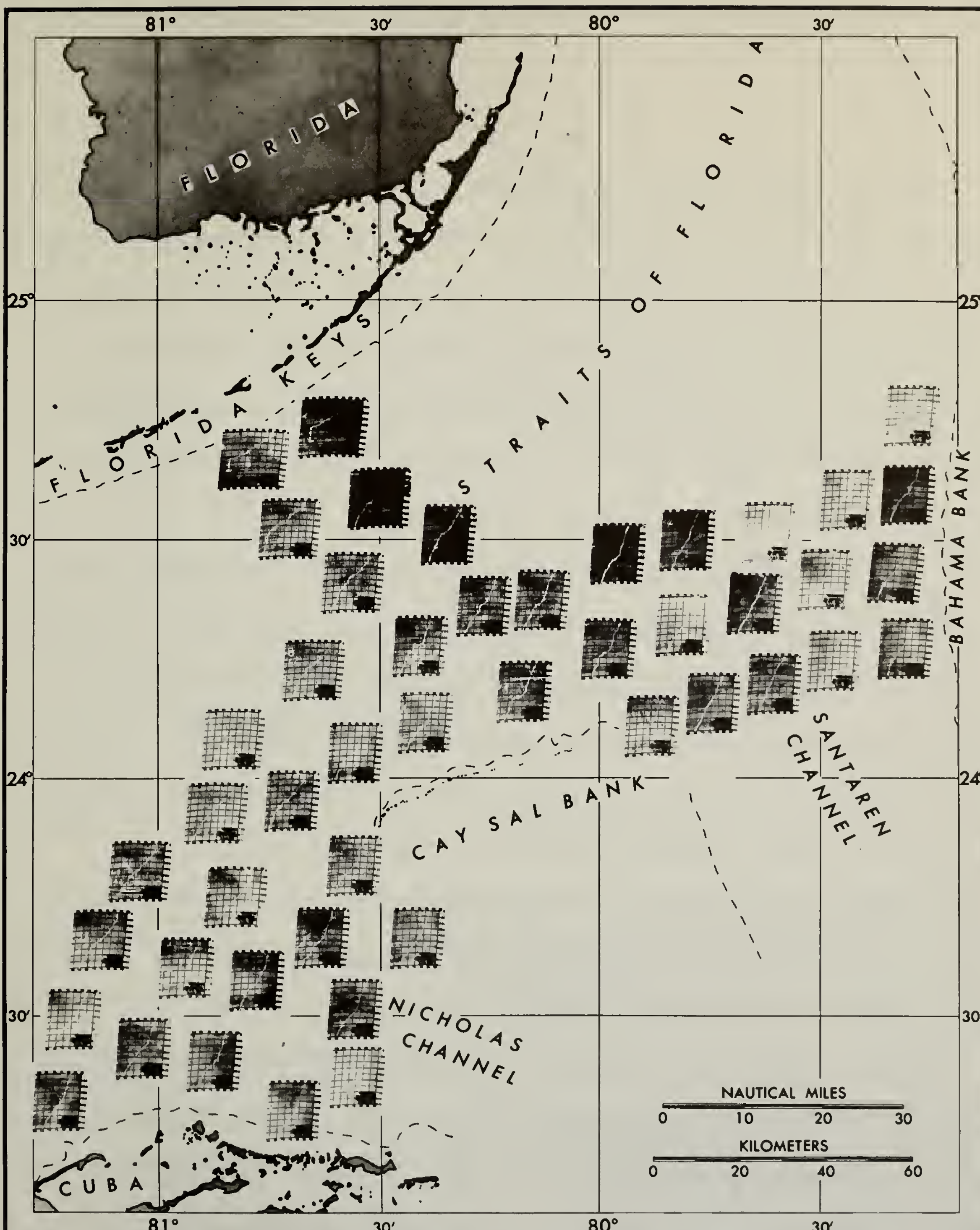

Figure 3. Bathythermograms taken at the oceanographic stations.

Donald Milligan as part of a Master's thesis (Milligan, 1962).

3. SETTING

Cay Sal Bank may be considered an outlier of the Florida-Bahama Province. This province is not a continuous platform now but consists of extensive shallow water areas of generally less than 20 m depth transected by narrow, relatively deep channels of which the Straits of Florida and Santaren and Nicholas channels are examples. These are shown in figure 1 with their general bathymetry.

The Cay Sal Bank area is located where the trend of the Straits of Florida changes from generally east-west to north-south. This change in conjunction with the bank and its associated Santaren and Nicholas channels significantly influneces the Florida Current. Since the current probably reaches to the bottom in this part of the straits, a knowledge of the general bathymetry (fig. 1) and the controlling sill depths is necessary for understanding the structure of the current in this area.

Recent Coast and Geodetic Survey soundings in the northren Straits of Florida have established that depths increase gradually from a sill of 730 m at Latitude 27°20°N., Longitude 79°34'W. This southward gradient increases appreciably west of Cay Sal Bank. The straits are also considerably wider from this point to the west (fig. 1). The sill of the

Yucatan Channel between Cuba and Mexico at 2,100 m (C&GS Chart 1007) is so deep that it does not restrict the water properties of the straits.

The relatively wide and shallow Santaren Channel joins the Straits of Florida northeast of Cay Sal Bank, while the deeper but narrower Nicholas Channel connects with the straits southwest of the bank (fig. 1). At the southeast end of Cay Sal Bank, Santaren and Nicholas channels merge into the Old Bahama Channel that separates the Great Bahama Bank from Cuba. The sparse sounding data from these channels indicate that their controlling sill depth occurs in the Old Bahama Channel and is roughly 410 m. This channel also is considerably narrower than either Santaren or Nicholas Channel (C&GS Chart 1002).

4. OCEANOGRAPHIC BACKGROUND

The water masses occurring in the Cay Sal Bank area are defined best by referring to the composite Temperature-Salinity (T-S) curve of the oceanographic stations (fig. 2). This reveals the admixture of several water masses of diverse origin. The scatter in the plot to about 75-m depth reflects the influence of locally generated modifications, particularly a secondary salinity maximum at 50 m, which is apparently caused by the sinking of relatively dense bank water introduced into the Bahamian and Florida Keys margins by tidal currents.

Below this surface layer the main salinity maximum of 36.60 to 36.77‰ at an average sampled depth of 150 m comprises a relatively thin stratum of water that Wust (1964) calls the Subtropical Underwater. This is water that has passed through the Yucatan Channel from the Caribbean Sea. It appears likely that the maximum salinity of this stratum lies closer to 125-m depth, but this level was not sampled frequently enough for this to be established. The 100-m salinity of 36.99‰ in this layer at station 10 appears anomalously high, but it has been retained because there appeared to be no evaporation from the sample bottle and because there was a 0.07°C. temperature inversion at this depth established with paired reversing thermometers and the BT observation. Furthermore, the density determined from these data did not imply instability. The lower salinities evident at 150 m occurred in the stations taken in the center and left-hand side of the Florida Current. These correspond to the Continental Edge Water of Wennekens (1959), which he interprets as being derived from the surface waters of the northern and eastern Gulf of Mexico and having sunk to their equilibrium level after winter cooling.

Below 300 m, local and seasonal effects disappear from the composite T-S plot so that from 300 to about 700 m the curve reflects, for the most part, the result of a mixture of North Atlantic Central Water with some South Atlantic Central Water. The influence of the South Atlantic Central Water appears to be most prominent at about 550 m (27.0 σ_t level) where it comprises up to 30% of the water type (fig. 2), but most of the water in this range is of North Atlantic origin. In particular, stations 2, 9, and 42 (see fig. 1) appear to have relatively high percentages of North Atlantic Water at some levels.

The minimum salinity evident in the T-S curve at roughly 800 m indicates the influence of Antarctic Intermediate Water. This water, which is also known as Subantarctic Intermediate Water, is considered to be formed at the Antarctic Convergence by mixing and sinking of Antarctic and Subantarctic surface waters. As the resulting water mass moves north it gradually mixes with adjacent waters so that by the time it reaches the North Atlantic at about 27° N. Latitude, the salinity minimum used to trace this water is gone. Its presence in the Straits of Florida with a value of 34.87 ‰ indicates an appreciable quantity of water of South Atlantic origin at about 800 m.

The observations below the salinity minimum show a positive gradient in the salinity to the greatest depths sampled. This reflects the presence of Upper North Atlantic Deep Water with possibly the traces of an admixture of Mediterranean Water. These depths were attained at only the stations west of Cay Sal Bank, and were well below the sills to the north and east. While for any level above the minimum, salinity increases to the right in the Florida Current, below the minimum it increases to the left. Temperature apparently always decreases to the left.

5. TIDES AND TIDAL CURRENTS

Because the channels of the Cay Sal Bank area are relatively restricted, there is an appreciable bathymetric influence on the currents. Since tides and tidal currents become amplified in restricted waters, their effect probably influences the oceanographic station observations significantly; consequently, some of the irregularities evident in the charts and sections of properties may reflect tidal modification of the water column depending on the time of the individual station relative to the tidal cycle.

The predicted and observed tides at Key West, the nearest reference station, were compared for the period of the oceanographic stations and were in good agreement. These, in turn, were compared with the tide predictions nearest the oceanographic stations at Elbow Cay on Cay Sal Bank and Tennessee Reef on the Florida Keys side of the straits. While Key West has a mixed tide, the tide at Elbow Cay and Tennessee Reef is predominantly semidiurnal. According to Dietrich (1963) the tide wave progresses upstream against

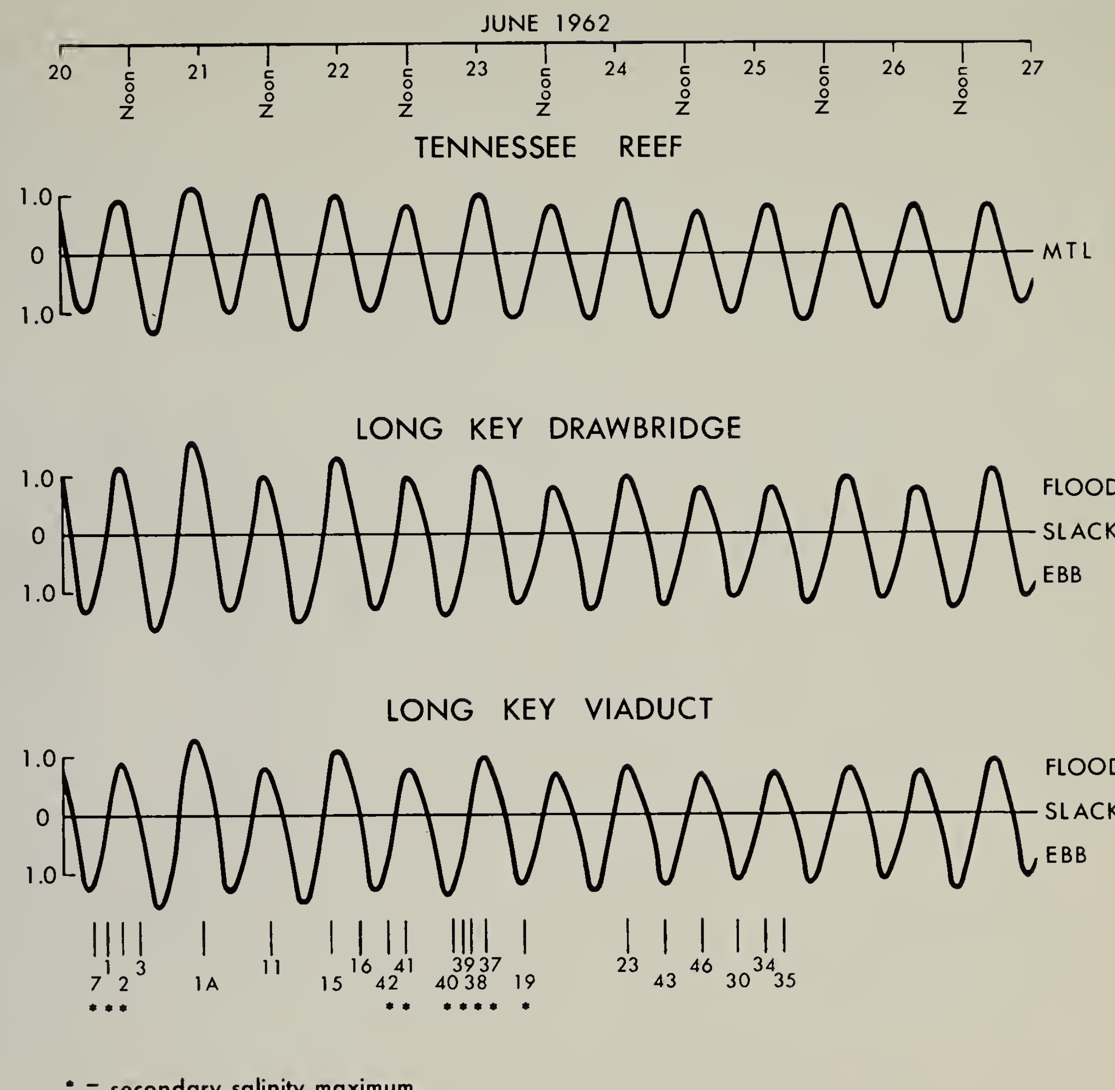

Figure 4. Predicted tide curves in the Cay Sal Bank area. Station numbers listed are explained in the text.

the flow of the Florida Current.

Tidal current data in the area are available as predictions only, and these are restricted to the Florida Keys side of the straits. In figure 4, the predicted tide at Tennessee Reef is presented with the closest tidal current predictions at a point east of Long Key Drawbridge and at Long Key Viaduct. The direction of flood current at these sites is north and of the ebb current, south. Also included in this figure are the messenger times of the shallow casts of the oceanographic stations taken adjacent to the margins of the channels and of those that show the shallow, secondary salinity maximum.

This secondary maximum has its greatest areal development along the Florida Keys but is more saline by approximately 0.3 ‰ along the Bahama Banks. Along the Florida Keys the salinity gradient indicates a source from the west, but the gradient along the Bahama Banks indicates a warm saline tongue with a probable northern source. This is corroborated by the ship's drift at station 7 (fig. 5). Station 3 along the Bahama Banks that would be expected to show the shallow maximum but did not was outside of this tongue. This salinity distribution is evident on the 50-m depth chart (fig. 6). None of the southern stations along Cay Sal Bank and the Cuban coast show the secondary maximum. This is due possibly to the phase and speed of the tidal currents during

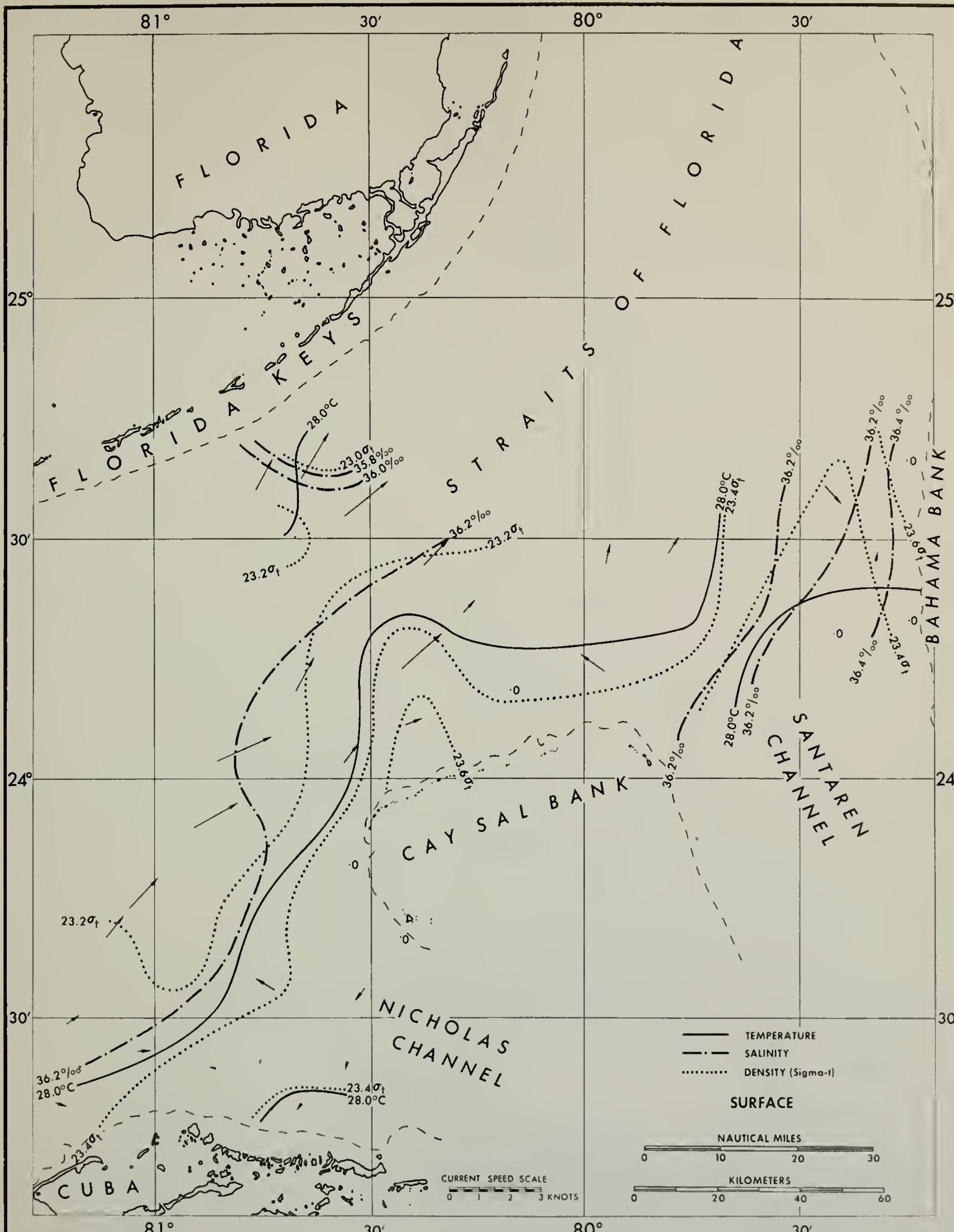

Figure 5. Distribution of temperature, salinity, and density at the sea surface. Arrows are vectors of ship's drift. Zero indicates no discernible drift.

Figure 6. Distribution of temperature, salinity, and density at 50 m. Arrows are vectors of ship's drift. Zero indicates no discernible drift.

the time these stations were occupied (fig. 4), but it is more likely due to the lack of a shallow area of adequate size for evaporation to produce high salinities. The higher average velocity and longer duration of flow of the ebb current compared to the flood current at Long Key indicate that the net transport of water is from the Gulf of Mexico side of the Keys into the Straits of Florida. The water introduced into the western side of the straits by this net transport is probably the source of the secondary salinity maximum found here.

6. OCEANOGRAPHY

The results of the HYDROGRAPHER oceanographic stations are presented in the accompanying charts and sections of the distribution of temperature, salinity, and derived sigma-t (σ_t)*. Isopleths of sigma-t are a convenient expression for the density of water at surface pressure for a given temperature and salinity. They approximate the distribution of potential density very closely and may be considered as defining quasi-isentropic surfaces. Since these isopleths indicate the variation of density at any given level, they are useful for determining the approximate

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* The layout and numbering of sections (see figs. 7-11) are shown in figure 1.

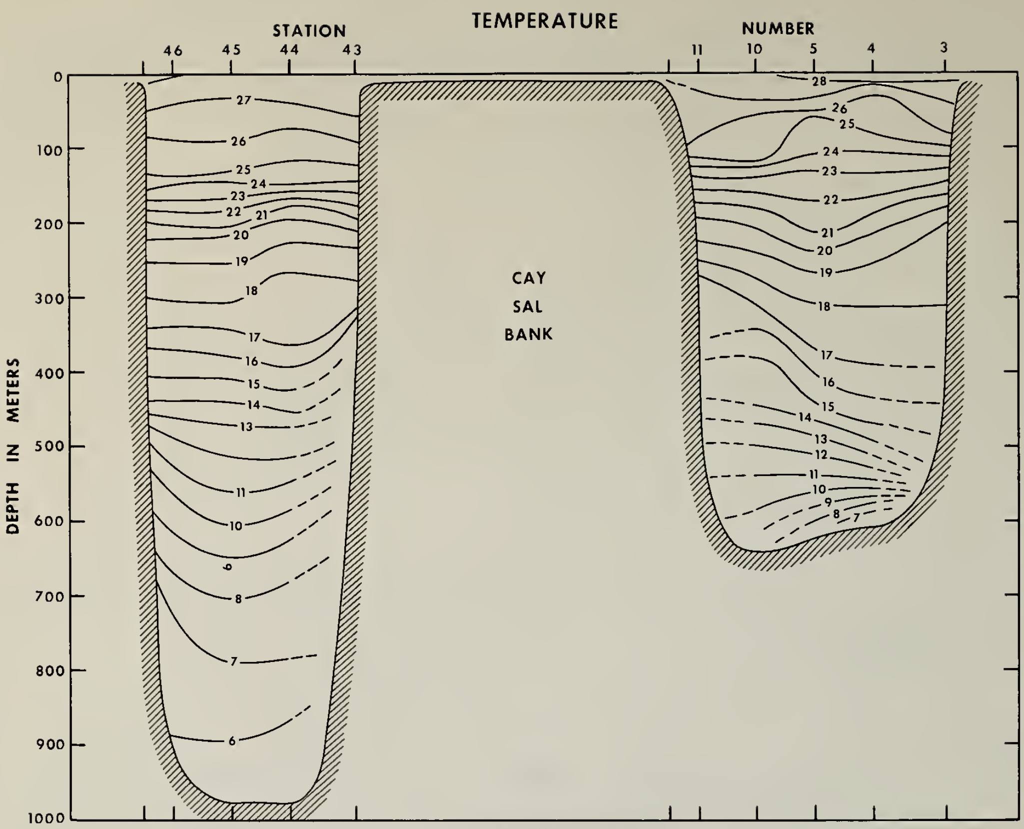

Figure 7a. Distribution of temperature (in degrees Celsius) along section 1.

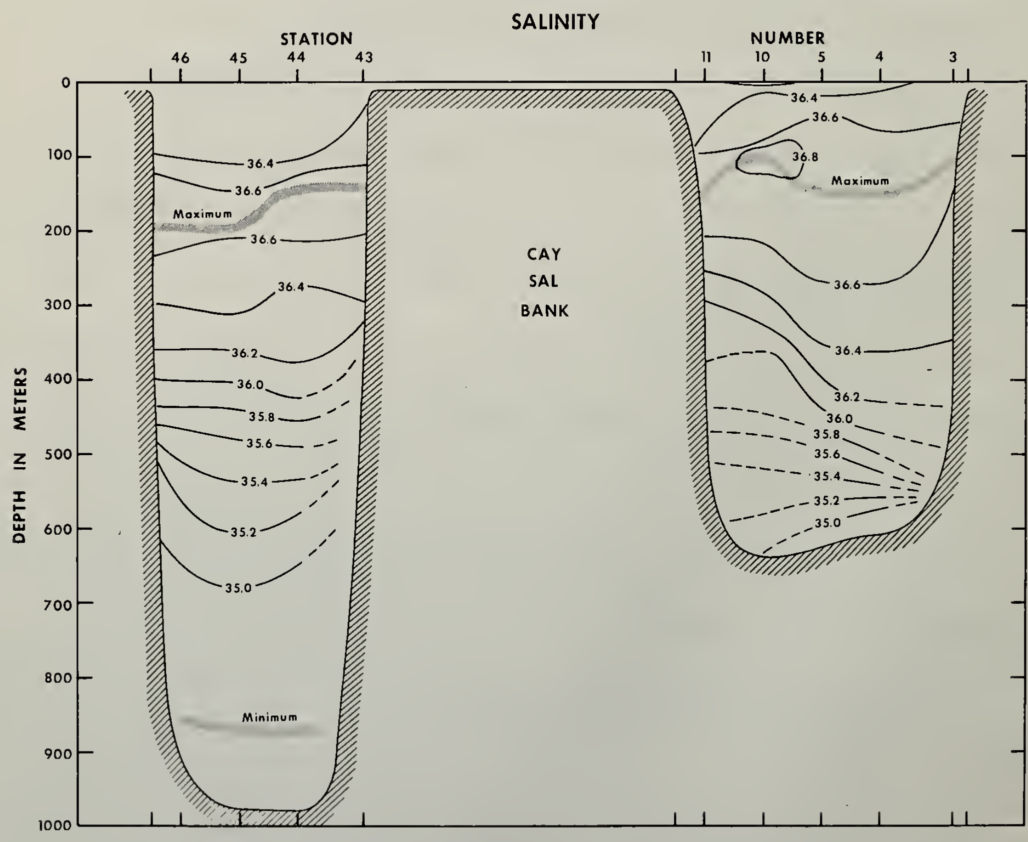

Figure 7b. Distribution of salinity (in parts per thousand) along section 1.

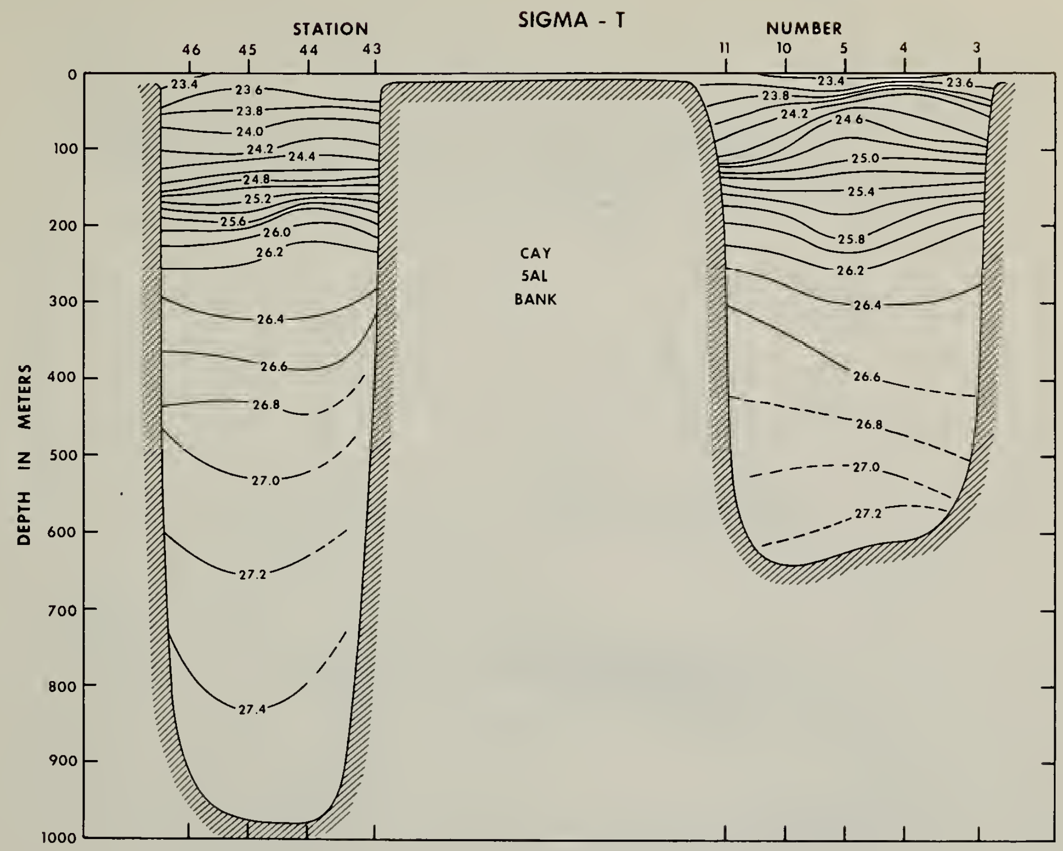

Figure 7c. Distribution of density (as Sigma-T) along section 1.

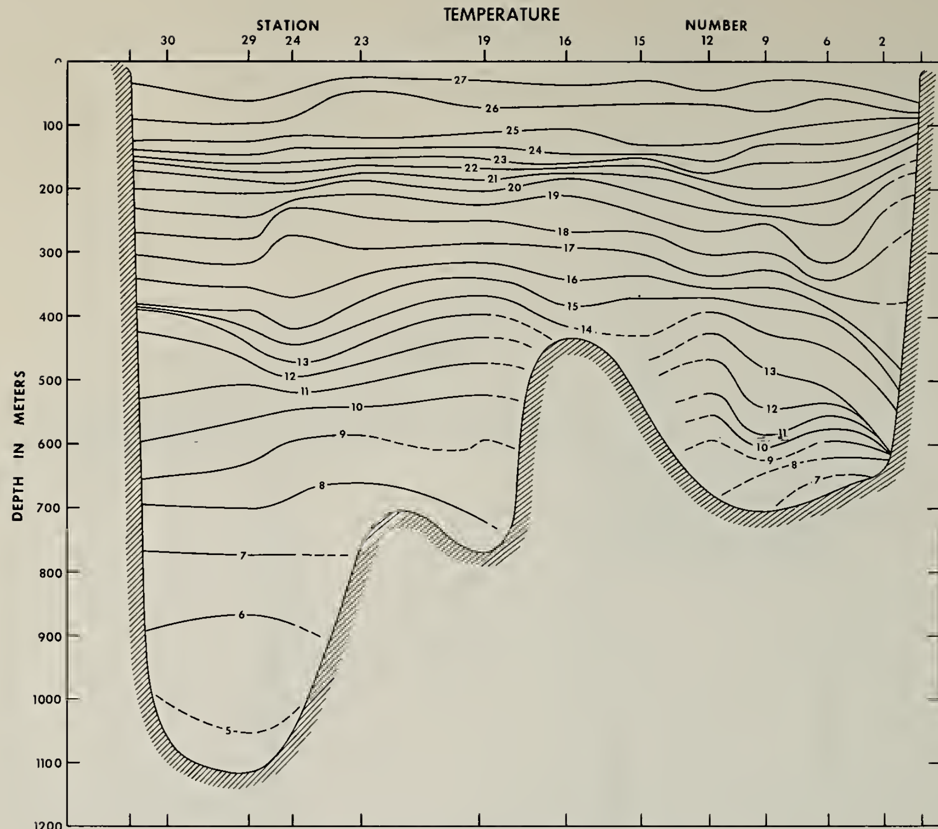

Figure 8a. Distribution of temperature (in degrees Celsius) along section 2.

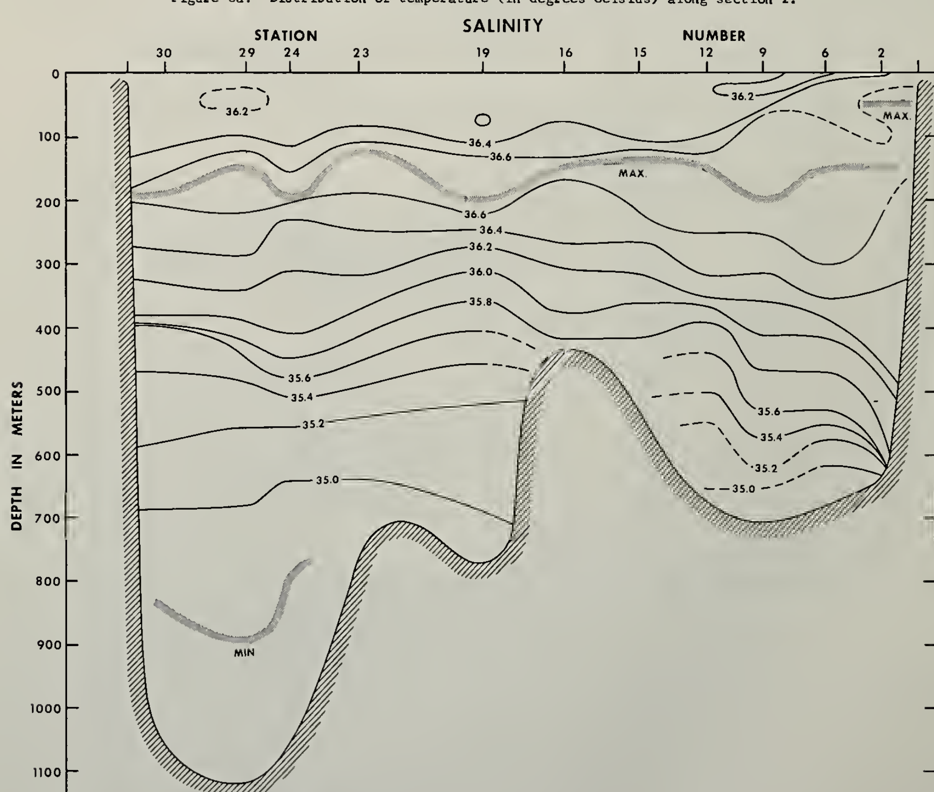

Figure 8b. Distribution of salinity (in parts per thousand) along section 2.

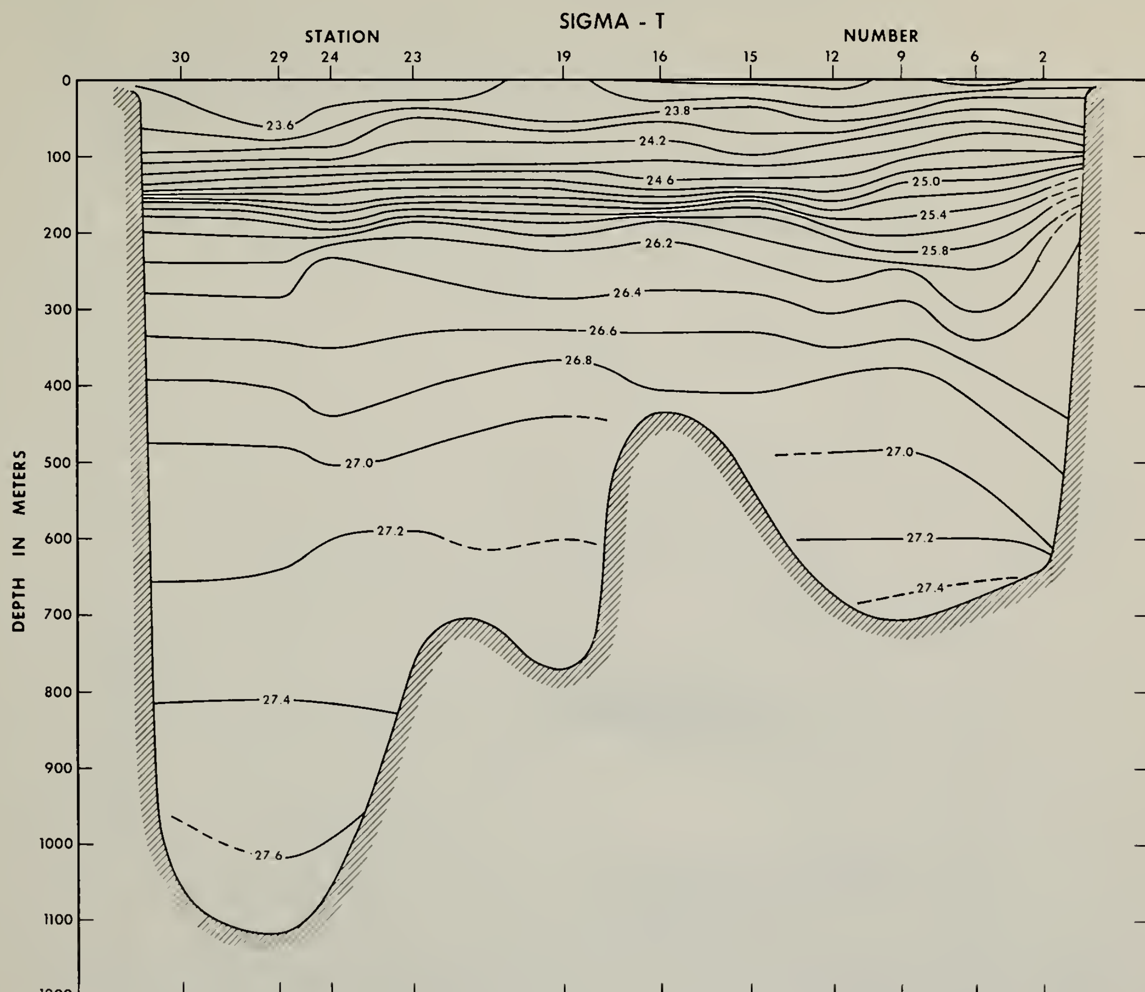

Figure 8c. Distribution of density (as Sigma-T) along section 2.

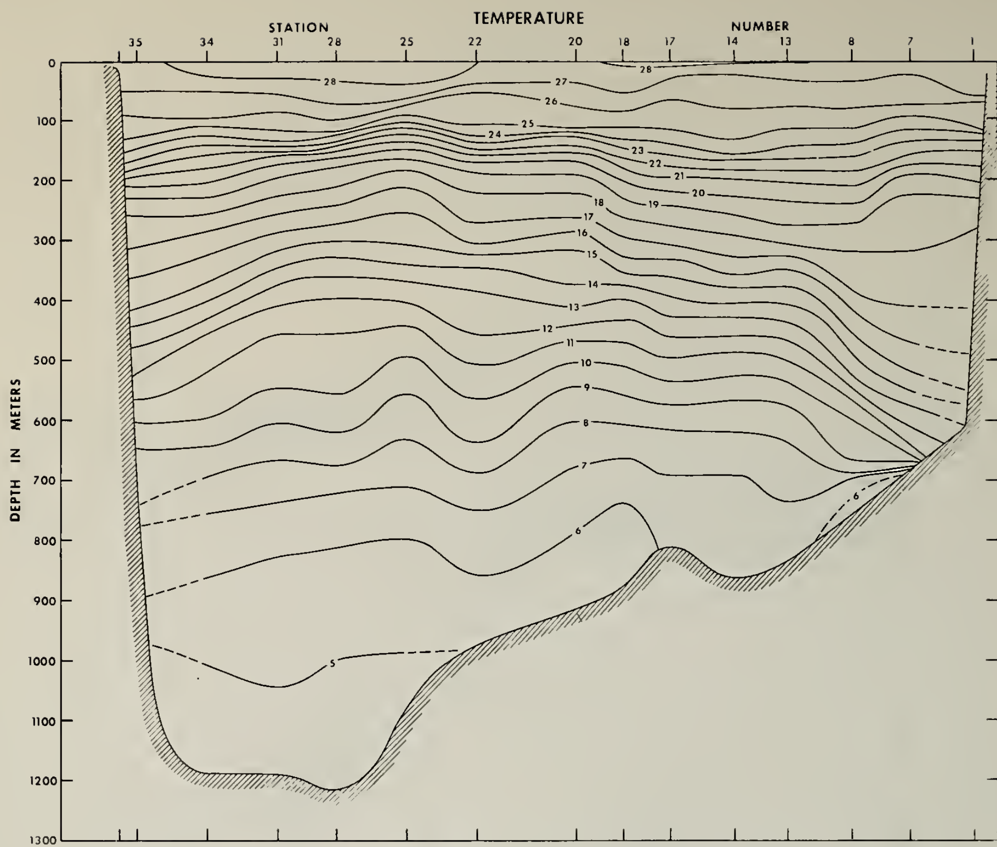

Figure 9a. Distribution of temperature (in degrees Celsius) along section 3.

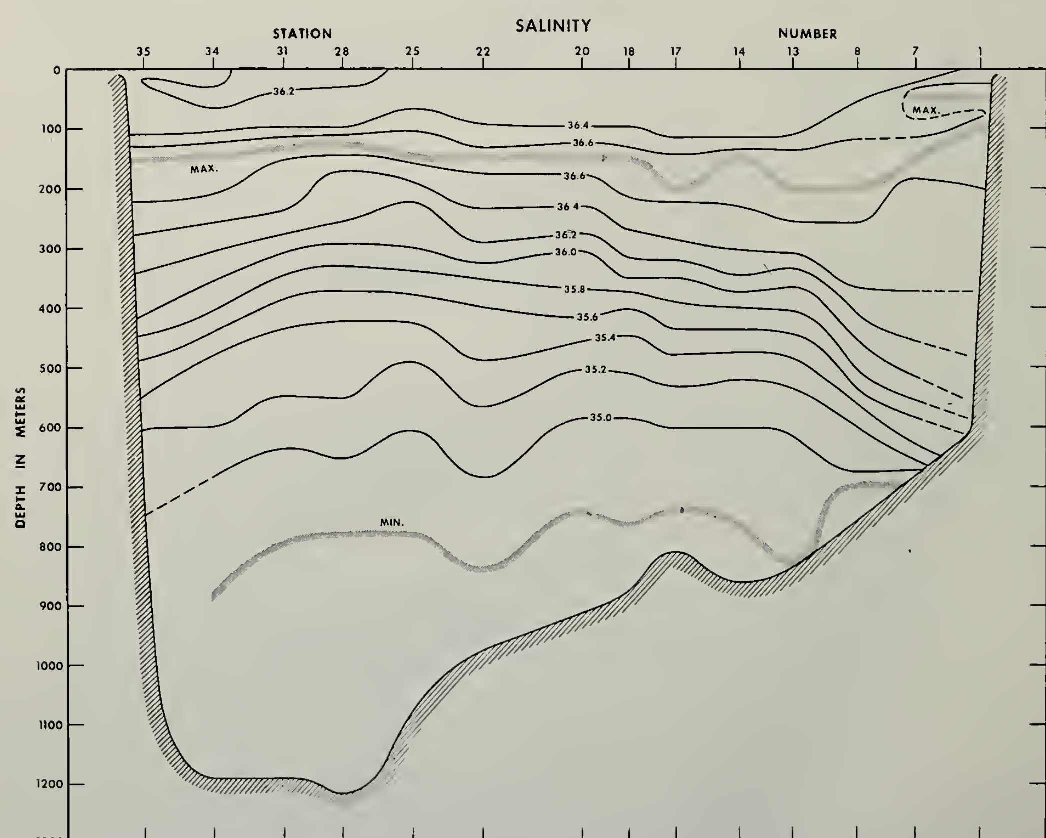

Figure 9b. Distribution of salinity (in parts per thousand) along section 3.

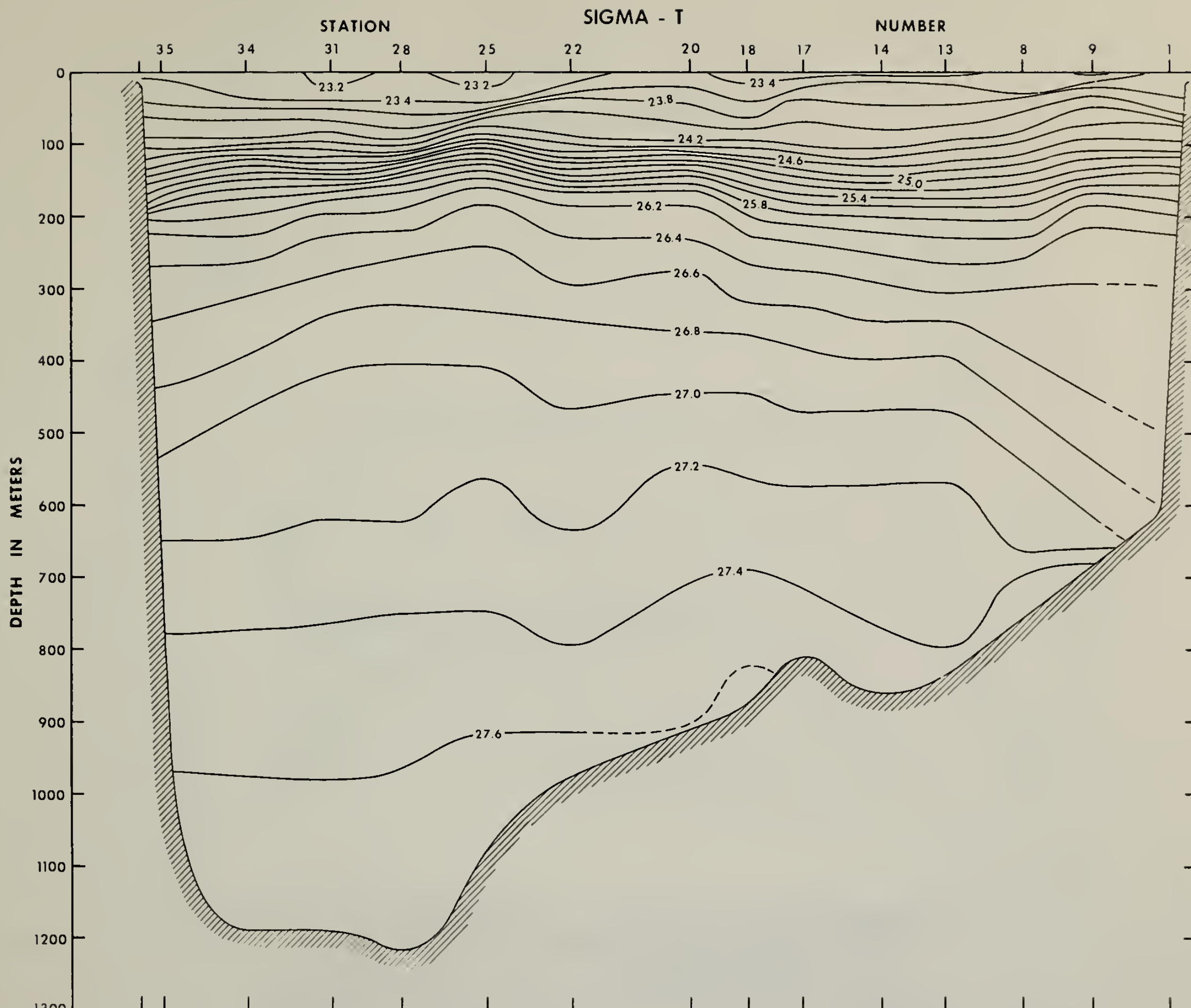

Figure 9c. Distribution of density (as Sigma-T) along section 3.

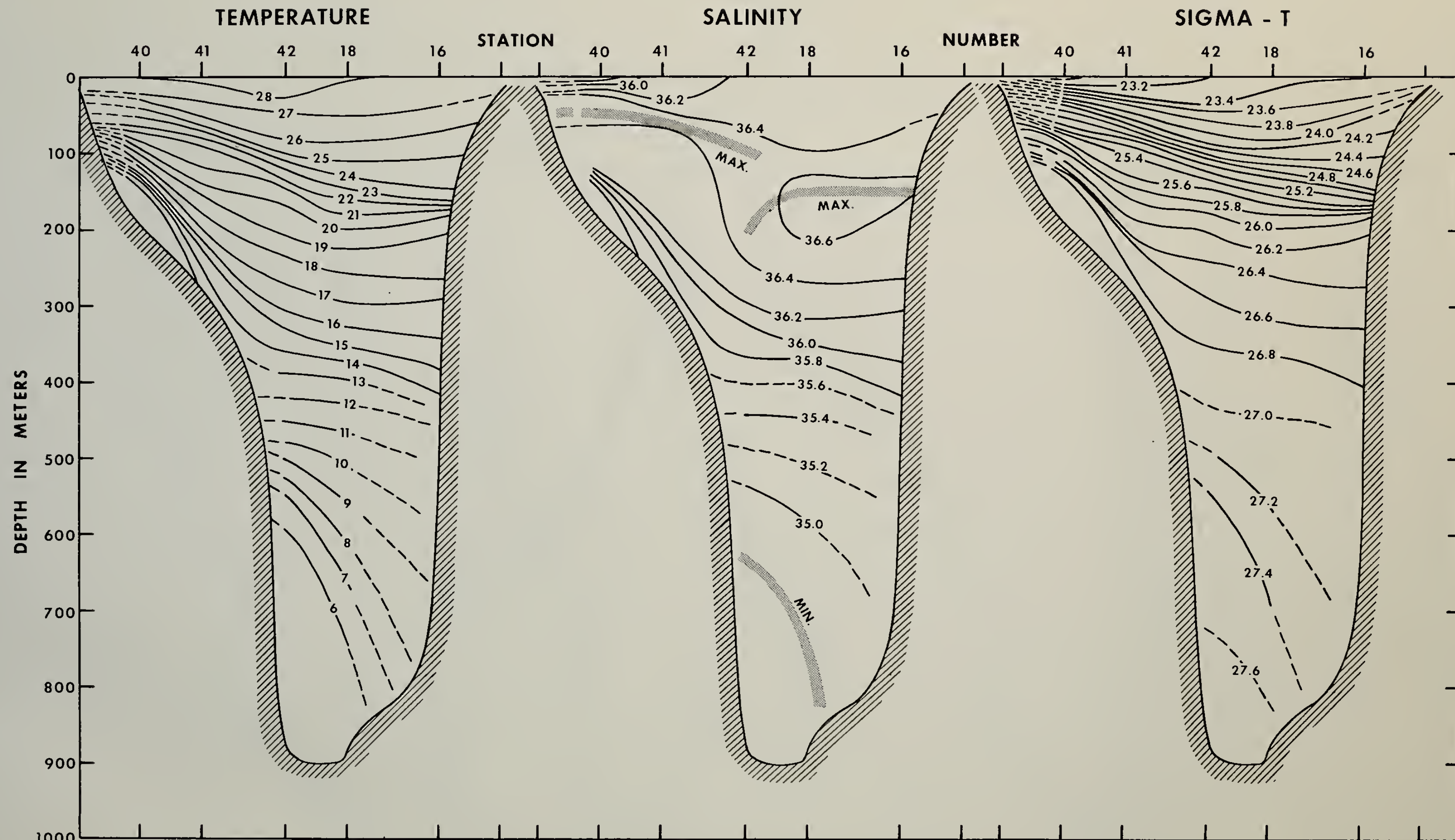

Figure 10. Distribution of temperature (in degrees Celsius), salinity (in parts per thousand), and density (as Sigma-T) along section 4.

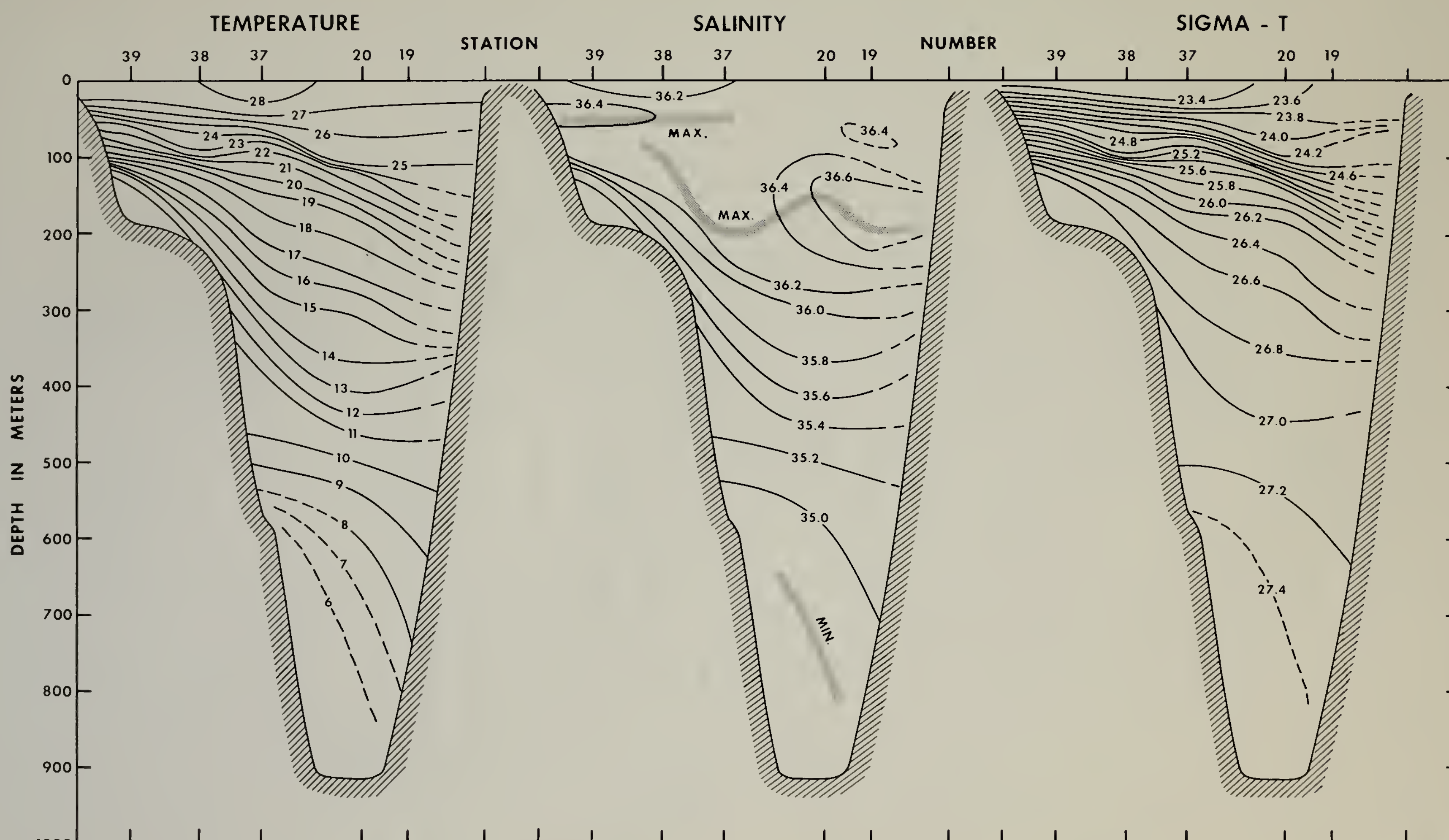

Figure 11. Distribution of temperature (in degrees Celsius), salinity (in parts per thousand), and density (as Sigma-T) along section 5.

relative velocity of currents that are related to the distribution of mass by applying the rule that, except for near-surface anomalies, in the northern hemisphere the lighter water lies on the right side of a current. The relationship of the water properties and the deduced currents in the vicinity of Cay Sal Bank to those near the adjacent banks is seen best on the charts (see figs. 5, 6, 12, 13 & 14), while the sections (see figs. 7-11) illustrate the distribution of properties and the characteristics of the water masses in the Florida Straits and adjoining channels. The layout and numbering of the sections are indicated in fig. 1. These are drawn at a vertical exaggeration of approximately 120 to 1.

The charts present the distribution of properties and sigma-t at the surface, 50, 150, 300, and 600 m. Levels below 600 m are not shown, because greater depths exclude over 40% of the stations including all of those in Santaren Channel. The surface and 50-m depth charts include current velocities derived from the ship's drift on station when the positioning was considered reliable and wind speeds, for the most part, were 12 knots or less. These wind speeds were read from the ship's anemometer. Wind velocities up to 20 knots were accepted on stations where the ship drifted into the wind or where the ship was in the high velocity core of the Florida Current. The current and wind velocity data for

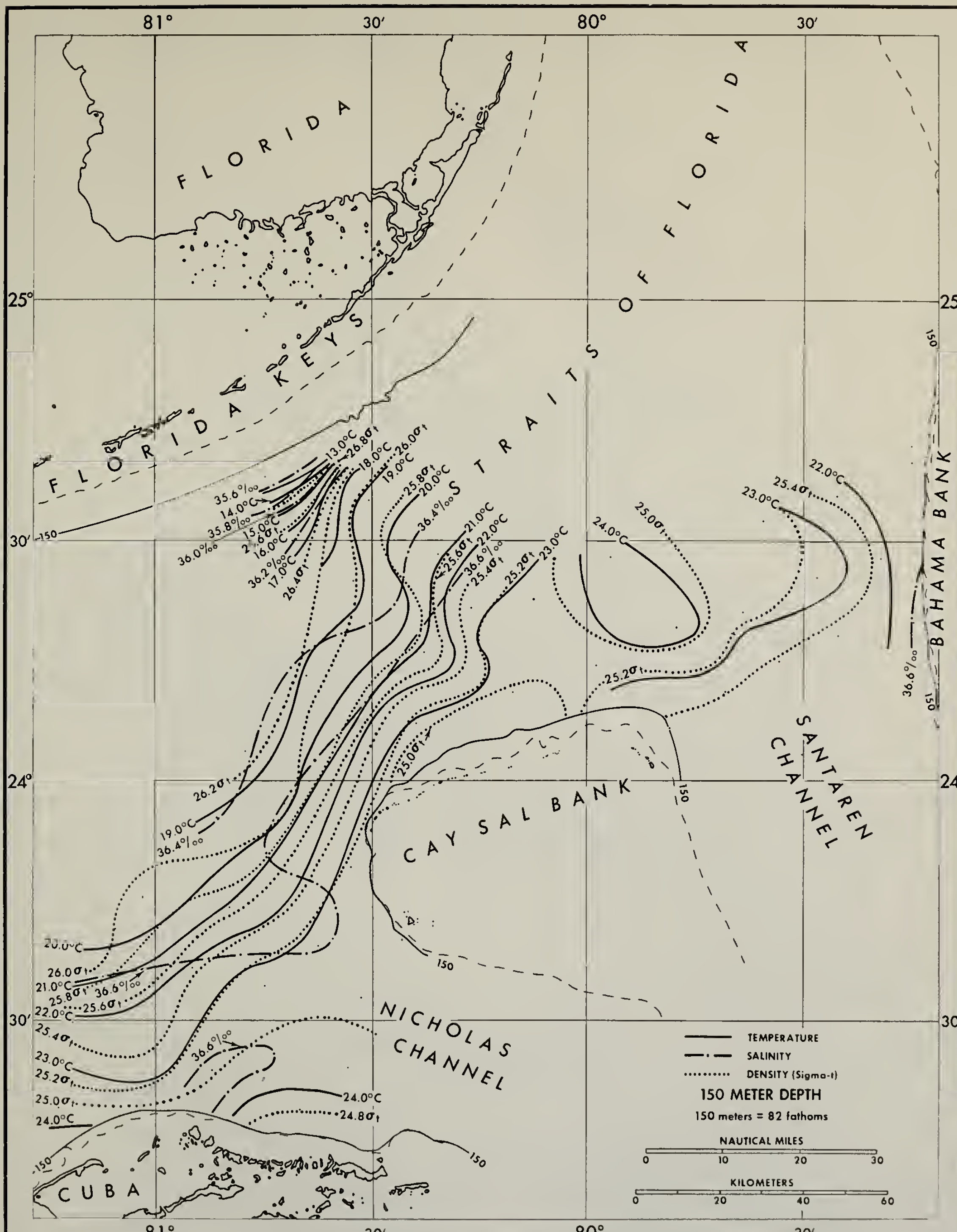

Figure 12. Distribution of temperature, salinity, and density at 150 m.

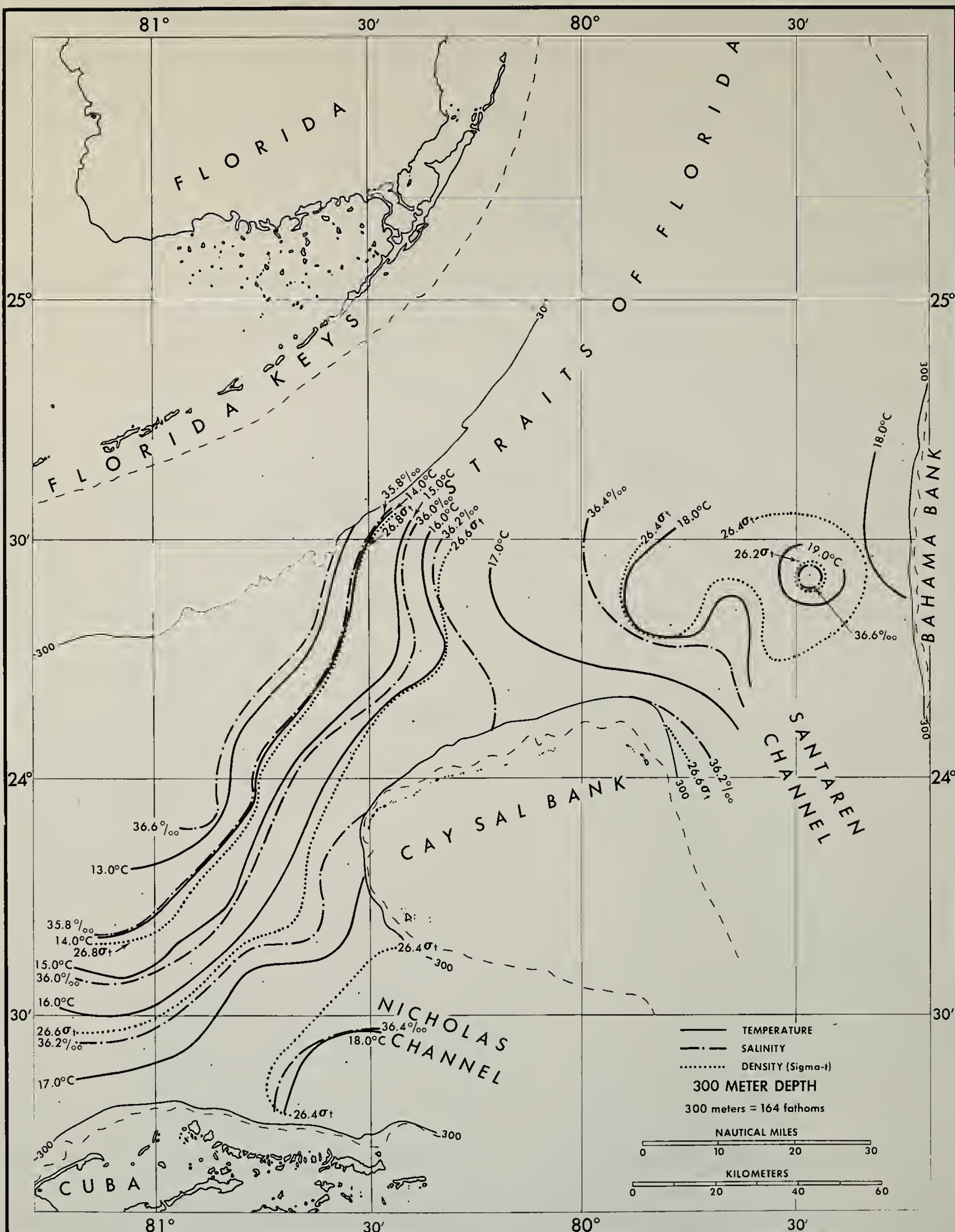

Figure 13. Distribution of temperature, salinity, and density at 300 m.

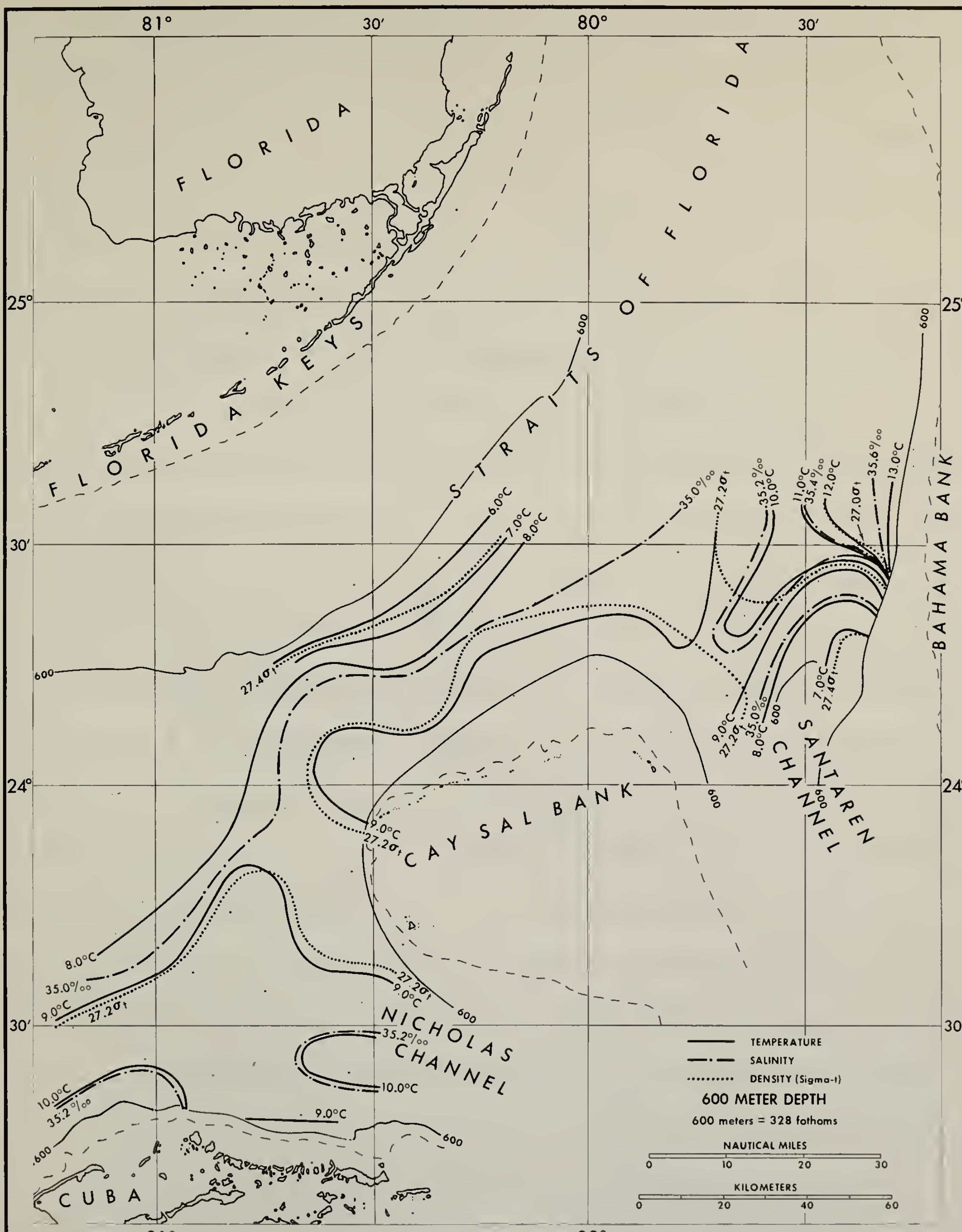

Figure 14. Distribution of temperature, salinity, and density at 600 m.

the acceptable stations are summarized in table form in appendix B with the wire angles and directions of the oceanographic casts.

7. THE SURFACE CIRCULATION

In the central portion of the Straits of Florida the high drift velocities found correspond to water temperatures above 28.0° C., except for station 20 (see fig. 1) which appears to be influenced by upwelling (fig. 5). The distribution of surface salinity does not correlate as well with the deduced current, except perhaps for a low salinity tongue associated with a southeastward drift in the entrance of Santaren Channel. Here low salinities at stations 6, 7 and 10 (see fig. 1 and 5) are possibly analogous to those associated with the high velocity core of the stream, but at these stations they seem to coincide with a zone of transition between Straits of Florida waters and those found in Santaren Channel. This zone of transition is defined by the 36.2‰ salinity band on the surface chart (fig. 5) and is apparent in the near-surface layering evident in the BT traces at these stations (fig. 3).

In Santaren Channel a thin film of slightly warmer surface water is apparent at the southern stations along the Bahama Banks side, and there is an appreciable salinity increase toward the banks as well (see fig. 7 and fig. 5). A much more varied temperature and salinity distribution is evident here than in Nicholas Channel. Along the western side of the Florida Straits, the cause of a relatively low salinity at station 40 (fig. 5) is unknown but it is not from rain or contamination from ship overboard discharge.

A decrease in velocity near Cay Sal Bank in the Straits of Florida is apparent in the reduced drift at stations 19 and 22 and by the absence of a detectable current at station 16, while a northwesterly drift was found at station 15 (see fig. 1 and 5). These stations were all within visual bearing and radar range of the cays on Cay Sal Bank. The high surface density at station 19 and configuration of the adjacent isopycnics suggest upwelling, which appears on section 4 (see fig. 10) to be from a depth of about only 40 meters. This probably reflects a damming effect on the subsurface high velocity core of the Florida Current by Cay Sal Bank.

The ship's drift, surface temperature and salinity, and density structure evident in the western entrance to Nicholas Channel agree, in that, except for a possible southward drift at the three eastern stations north of Cuba (fig. 5), little appreciable surface current appears to exist here. This southward drift may be the eastern side of a weak anti-cyclonic gyre. Santaren Channel, however, as noted previously, does not seem to be quite so passive. Here the velocity decrease indicated by the reversal of slope of the near surface isopycnics along the Bahama Banks extends to a depth of only about 20 m, as is evident in sections 1, 2, and 3 (see figs. 7, 8, and 9). The associated surface salinity gradient is the result of high salinities generated on the bank in the lee west of Andros Island (Cloud, 1962). The low salinity tongue with corresponding relatively low temperatures and resulting 23.4 isopycnic extending northeast from Cay Sal Bank (fig. 5) not only separates the northerly flow of Santaren Channel from the Florida Straits water but appears to represent a zone of mixing and a path of southerly flow toward Cay Sal Bank. Unfortunately most of the ship's drift observations in this area were unacceptable, but those at stations 1, 2, and 3 (see figs. 1 and 5) support the interpretation of a slow northerly flow decreasing in velocity toward the banks, while observations at stations 7, 15, 14, and 13 indicate that this zone may be the eastern side of a gyre between the Florida Current and the Santaren Channel outflow (fig. 5). This inference is also upheld by the sigma-t structure in sections 1, 2, and 3 (see figs. 7, 8, and 9) which indicates that this circulation is more than 100 m deep.

8. THE SUBSURFACE CIRCULATION

The 50-m depth was chosen as one of the levels to show the distribution of properties because its proximity to the surface permits correlation with the drift measurements and it reflects the oceanographic conditions associated with the highest current velocities, but it is deep enough to be out of the influence of short term meteorological factors. In addition, this is the level of most of the secondary salinity maxima and is near the top of the high gradient of the pycnocline. It can be seen on the composite T-S plot (fig.2) that his level posseses considerable variability in the T-S relationships.

The Straits of Florida at the 50-m level exhibit a pattern considerably different from the surface chart in detail but similar in general features. The core of the current at this depth appears to be delineated by a sigma-t of 23.8, which hugs the Cay Sal Bank side of the channel in the vicinity of Nicholas Channel but trends toward the western side of the straits north of Cay Sal Bank (see fig. 6). The distribution of the temperature, salinity, and sigma-t isopleths along the Florida Keys side of the straits reflects the effect of the influx of water from the Gulf of Mexico with its associated secondary salinity maximum.

The sources and characteristics of these maxima have already been discussed. The absence of this feature at station 3 along the Bahama Banks reflects the dominance of the northward-moving Santaren Channel flow at this point over the Florida Straits counterflow, which carries the high salinities generated on the Bahama Banks in the lee of Andros Island, as previously indicated. This Santaren Channel water, which is colder at 50 m than the water to the north, appears to have its core at station 5 (see fig. 6). As it travels north it mixes with the warmer, more saline southward-flowing Bahama Banks water and becomes part of the anticyclonic eddy suggested in the discussion of the surface circulation. This pattern is defined by the 25° C. and 24.6 sigma-t isopleths in sections 1, 2, and 3 (see figs. 7, 8, and 9). The high salinity found at the 100-m level of station 10 may be a remnant of the secondary salinity maximum caused by tidal currents, a salinity maximum that has descended as it moved southwestward in the eastern arm of the gyre.

In the western entrance to Nicholas Channel at the 50-m level a slight penetration of the Florida Current appears as the anticyclonic eddy mentioned previously. This extends to about 100 m depth (see fig. 8). It is well defined by the 27.0° C. temperature and 23.8 sigma-t isopleths and shows up also as a core of minimum salinity (fig. 6). The available reliable drift determinations at stations 44, 45, 46 and 30, shown in figures 1 and 6, are in agreement with this. As far as the water budget in the area is concerned, this gyre does not appear to be particularly significant, and apparently very little net water transport is occurring in

Nicholas Channel above 100 m.

The average depth of the main salinity maximum, and therefore the core of the Subtropical Underwater, is close to 150 m. For this reason and because 150 m is in the lower part of the high gradient of the main pycnocline, this level was chosen to display the distribution of properties. Although this is the depth of the salinity maximum, there is still a considerable spread evident in the composite T-S curve (fig. 2). The lower salinities at 150 m evident in this plot result from an admixture of Gulf of Mexico water described previously.

In the Straits of Florida the 150 m level is the first to show a sinuous pattern in temperature, salinity, and sigma-t (see fig. 12) that continues to deeper levels. The vertical displacement of the 20° isotherm equivalent to the meander evident on this level is approximately 45 m, and that of sigma-t, 30 m, neither of which are excessive amplitudes for internal waves or tides. However, the fact that the disturbance is uniform across the channel suggests that it is not caused by short-period fluctuations. This pattern does seem to be associated with a marked change in trend of the depth contours along Pourtales Terrace, as shown by Jordan et al. (1964) and as evidenced by the 600- and 800-m isobaths of figure 1. Sections 4 and 5 (see figs. 1, 10, and 11) cross the straits immediately downstream from where it changes in direction from east-west to northeast-southwest. These sections also follow the maximum constriction in width of the straits, at the surface by Cay Sal Bank to roughly 65%, and at 600 m by Pourtales Terrace and Cay Sal Bank to approximately 30% of what it was west of the bank. It is evident from the trend of the plotted variables at 150 m and other depths that the Florida Current is already flowing toward the northeast before it reaches sections 4 and 5 (see fig. 12). This is probably due to the hydraulic block caused by Cay Sal Bank and the relatively inert water of Nicholas Channel. Because these changes in the configuration of the straits are upstream from the two lines of stations, the undulation evident in the properties is most probably an expression of the accommodation of the Florida Current to the change in direction and to the widening of the channel downstream from the constriction.

The extreme gradient evident in the properties at 150 and 300 m along the Florida Keys (see fig. 12 and 13) is not apparent in the 50-m or 600-m charts. The depth interval between 150 and 300 m includes most of the area of Pourtales Terrace (see figs. 1, and 11). The gradient in the water properties may be due in part to their accommodating themselves to the transverse component of the sinuous wave as it interacts with the shoaling surface of Pourtales Terrace, but there appears to be another factor operating as well:

Below 150 m, the water at oceanographic stations 39 and 40 was isothermal, isohaline, and of indifferent stability. The bathythermograms obtained at these stations (fig. 3) illustrate the isothermal structure very well. The depth range of 150 to 300 m is the depth at which the principal artesian aquifer (Floridan) of Florida is expected to outcrop in this area (Stringfield and LeGrand, 1966; Kohout, 1967). It is therefore suggested that the strong gradients evident in the charts and the absence of isopleths near the bottom at stations 39 and 40 in sections 4 and 5 (fig. 10 and 11) respectively reflect the introduction of artesian water into the Straits of Florida.

This possibility has been suggested by Stringfield and LeGrand (1966). From Kohout's (1967) interpretation of the hydrology and thermology involved, it is impossible to judge whether relatively fresh artesian water is expected to be relatively warm or cold. Jordan et al.(1964) present bathythermograph sections obtained by the HYDROGRAPHER in the area in 1953. These give a more detailed thermal picture of this phenomenon. The unusual layer at station 39 is colder, fresher, and less stable than that at station 40. This suggests that the source of the anomalous water is closer to station 39 and is being absorbed as it moves northeast with the Florida Current. The bathythermogram obtained at station 38 on Pourtales Terrace also shows this structure from 530 feet (160 m) to the bottom. Unfortunately the Nansen cast observations at depth differ from the BT temperatures because biological fouling of the oceanographic wire required the bottom bottles to be relowered; meanwhile the ship drifted out of the immediate area of the BT cast. It should be noted that this is the only BT observation (see fig. 3) that shows appreciable hysteresis in the thermocline between the times of lowering and raising the bathythermograph. The particular area of Pourtales Terrace over which station 38 was begun is one of Karst topography (Jordan et al. 1964), so that the anomalous water found there could possibly have originated from a sink hole.

At 150 m both Nicholas and Santaren channels appear to lack any appreciable circulation (fig. 12). In Nicholas Channel the isopleths of the physical properties and sigma-t suggest a possible slight inflow along the Cuban coast. At 150 m in Santaren Channel the anticyclonic eddy described previously apparently dominates the entire entrance to the channel and probably blocks any effective circulation between the channel and the Straits of Florida at this level.

The next depth chosen to show the distribution of properties is at 300 m. This is below the steep gradient of the pycnocline and is approximately the level at which the curves of the composite T-S plot (see fig. 2) converge, indicating that external influences are minimal and that the water masses here and below have uniform properties except for several special cases. The 300-m chart (see fig. 13) is the first to show an appreciable reduction in the width of the Straits of Florida other than that caused by Cay Sal Bank itself. This contraction is due principally to the presence of Pourtales Terrace along the Florida Keys.

At 300-m, the structure of the physical properties of the Straits of Florida is very similar to that at 150 m. The isopleths of properties are still quite closely packed and continue to trend northeast-southwest, while the sinuous pattern they display persists in the same region and at about the same magnitude that it did at 150 m. Cay Sal Bank station 19 shows an anomalously low salinity at this level on the composite T-S plot,(fig. 2). This low salinity possibly results from upwelling caused by blockage of the Florida Current by the northern flank of Cay Sal Bank.

Nicholas Channel, at 300 m, exhibits slight evidence in section 1 (see fig. 7) of a possible weak anticyclonic eddy that appears to exist from this depth to the bottom. Since the sill depth at the eastern end of Nicholas Channel is approximately 410 m, this gyre probably has no connection there but is driven by a segment of the Florida Current that is deflected into Nicholas Channel by the steep western end of Cay Sal Bank. There is an indication of this deflection in the trend of the isopleths of temperature and salinity in the northern half of the entrance to Nicholas Channel on the 300-m chart.

In Santaren Channel, the 300-m depth appears as part of a transition between the distribution of properties above and below. According to these (fig. 13) the core of the anti-cyclonic eddy that has dominated the upper layers of the entrance to the channel seems to be located at station 6. The last trace of this gyre apparently dies out at about 350 m at this station (sec. 2, fig. 8) and at approximately this same depth in sections 1 and 3 (fig. 7 and 9). At 300 m the isopleths of properties and sigma-t indicate a probable northwesterly flow into the Straits of Florida between the eddy and the northeastern end of Cay Sal Bank.

Between 350 and 550 m, the northwesterly flow appears to become more northerly and to occupy the entire width of Santaren Channel. This is evident in sections 1, 2, and 3 where the reversal in gradient along the eastern half of the channel and steepening of the isopleths, particularly that of sigma-t, indicate a zone of high shear that suggests a probable considerable outflow reaching close to the bottom. Apparently the major contribution of water from Santaren Channel to the Florida Current occurs in this interval. This outflow of water is defined best by its range of properties rather than an average depth range. These are temperatures between 17.5 and 10.5° C., salinity between 35.3 and 36.4‰, and sigma-t between 26.5 and 27.1. A comparison of these values with those found in the Straits of Florida between the average levels of 350 to 550 m is shown in table 1.

Table 1. Comparison of Physical Properties of Florida Straits and Santaren Channel Waters

	Temperature (° C.)	Salinity (‰)	Sigma-t
Santaren Channel	17.5 - 10.5	36.4 - 35.3	26.5 - 27.1
Straits of Florida	14.5 - 09.0	35.8 - 35.1	26.7 - 27.2

It is clear that at these depths the water in Santaren Channel is about 2.0° C. warmer, 0.3‰ more saline, and 0.2 sigma-t units less dense than in the Straits of Florida. This flow extends beyond section 3 (fig. 1) and obviously contributes to the flow along the eastern side of the Florida Current along the Bahama Banks. The markedly increasing temperatures and salinities to the north and east at any given level apparently result from the Santaren Channel water accommodating itself to the increasing depth as it moves northward into the Straits of Florida.

In the core of this flow, station 9 deviates from the composite T-S curve (see fig. 2) in most of the observations below 400 m because of a consistently high salinity anomaly of about 0.1‰ or low temperature anomaly of about 0.5° C. At this station, the values at 4 of the 5 depths sampled from 400 m to the bottom of the cast produced this deviation so that there can be little question as to the validity of the observations. The resulting T-S curve is very close to that of North Atlantic Central Water (Sverdrup et al., 1942), except for the observation at 558 m that agrees with the composite T-S curve.

The deepest level chosen to be charted is that at 600 m. Below this, at 700 m, the bottom excludes almost 50% of the stations, including all of those in the entrance to Santaren Channel. The reduction in area of the straits between Cay Sal Bank and the Florida Keys relative to the upper levels, and to the straits to the west and north is very evident on the 600-m chart (fig. 14). This level is well down in the intermediate gradient of the pycnocline and is about 200 m above the salinity minimum.

In the Straits of Florida, the northeast trend paralleling the isobaths and the curvature of the isopleths is as evident here as at the upper levels (fig. 14). In sections 4 and 5 (see fig. 10 and 11) it can be seen that the cross-stream gradients of the properties and sigma-t from about 500 m to close to the bottom intensify markedly. The increased shear that this intensified gradient implies suggests an increasing velocity to compensate for the narrowing and shoaling of the straits.

It has been reported that there is a south flowing counter-current along the bottom of the Straits of Florida (Hurley and Fink, 1963). Because of the extreme difficulty of sampling the water immediately adjacent to the bottom in the high velocity core of the Florida Current, it is difficult to assess the oceanographic regime in this very critical part of the water column. However, in section 5 (see fig. 11) where the sampling was deepest, the 27.6 sigma-t isopleth does indicate a decrease in cross-stream gradient. Possibly of more significance, however, is that from 600 m to the bottom of the cast, the water at station 42 (fig. 1 and 14) is significantly colder at a given level than at any other station and that at 500 m, which is just above the maximum depth sampled by station 37, the cold water at station 42 relative to station 37 reverses the sigma-t gradient. On the T-S plot (fig. 2) station 42 is the line to the right of the main group of curves between 600 and 800 m and is very similar to North Atlantic Central Water. Whether this cold water and reversed gradient are indicative of a southerly flow along the continental slope here is conjectural, but a southerly flow along the slope to the north has been reported (Stewart, 1962). In addition, from 700 m to the bottom of the casts, the salinity, which above this normally decreases to the left of the Florida

Current at any given level, consistently increases from the middle of the channel to the Florida Keys side of the straits. There is not, however, a cross stream reversal of the density gradient, as described for stations 37 and 42.

In the entrance to Nicholas Channel, the pattern of the isopleths on the 600-m chart (fig. 14) clearly suggests an anticyclonic gyre. This appears to extend from the 300-m level to the bottom, which, at the entrance to the channel is slightly over 100 m.

In Santaren Channel, the 600-m level is very close to the bottom. Consequently the isopleths of the properties and sigma-t reflect the influence of the bathymetry, particularly a midchannel ridge. A relatively warm, saline tongue of water appears to be moving north and sinking along the Bahama Banks side of the channel, as it does at shoaler depths (fig. 14). Most of it enters the Straits of Florida, but some appears to recurve southward to the west side of the ridge. The final destination of this south flowing water is unknown, but it has properties intermediate between the north flowing tongue and the Straits of Florida water with which it is mixed.

9. SUMMARY AND CONCLUSIONS

Forty-seven oceanographic stations taken in the vicinity of Cay Sal Bank across the Straits of Florida, Nicholas, and

Santaren channels provide an insight into the effects of these features and the change in direction of the straits on the Florida Current. The deep, relatively narrow Nicholas Channel appears to have very little net circulation. An anticyclonic eddy, driven by the Florida Current, occupied its entrance. The Florida Current changes from east flowing to northeast flowing before it reaches Nicholas Channel.

The structure of the Florida Current indicates that along the Cay Sal Bank side between 200 and 500 m, the velocities probably are much less than above and below. Along the Florida Keys side, overlying the Pourtales Terrace, the structure of the water column near the bottom indicates the possibility of artesian water seeping into the straits from sink holes in the terrace. East of the terrace there is some indication of a possible south-flowing undercurrent along the bottom on the Florida Keys side of the straits.

Santaren Channel, from the surface to 300 m, appears to be blocked by an anticyclonic eddy driven by the Florida Current. There appears to be a considerable net transport into the straits below this to the bottom.

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APPENDIX A

DRIFT BOTTLE RECOVERY RECORD

Release				Recovery			
Sta. No.	Latitude	Longitude	Date	Latitude	Longitude	Date	Days Before Found
						June 1962	
39	24°38'N	80°45'W	23	25°00'N	80°31'W	25	2
38	24°30'N	80°40'W	23	26°14'N	80°05'W	26	3
27	23°55'N	80°52'W	25	26°52'N	80°03'W	28	3
27	23°55'N	80°52'W	25	26°49'N	80°02'W	29	4
27	23°55'N	80°52'W	25	26°52'N	80°03'W	29	4
38	24°30'N	80°40'W	23	26°21'N	80°04'W	27	4
38	24°30'N	80°40'W	23	26°03'N	80°07'W	27	4
38	24°30'N	80°40'W	23	26°14'N	80°05'W	27	4
38	24°30'N	80°40'W	23	26°09'N	80°06'W	29	6
38	24°30'N	80°40'W	23	26°20'N	80°04'W	30	7
						July	
39	24°38'N	80°45'W	23	25°00'N	80°31'W	1	8
38	24°30'N	80°40'W	23	26°44'N	80°02'W	2	9
39	24°38'N	80°45'W	23	24°56'N	80°37'W	9	16
38	24°30'N	80°40'W	23	27°15'N	80°13'W	11	18
38	24°30'N	80°40'W	23	27°09'N	80°09'W	12	19
39	24°38'N	80°45'W	23	25°00'N	80°31'W	23	30
						Oct.	
45	23°24'N	80°34'W	24	29°55'N	81°17'W	12	110
9	24°21'N	79°38'W	21	24°43'N	77°47'W	28	129

APPENDIX A (cont.)

Release				Recovery			
Sta. No.	Latitude	Longitude	Date	Latitude	Longitude	Date	Days Before Found
45	23°24'N	80°34'W	24	22°15'N	77°49'W	Nov. 6 1963	135
6	24°25'N	79°28'W	21	23°04'N	74°54'W	Jan. 1	194
40	24°40'N	80°38'W	22	25°25'N	80°19'W	Mar. 20	271
28	23°44'N	80°50'W	26	32°20'N	64°41'W	Apr. 2	280
13	24°29'N	79°48'W	21	25°14'N	78°08'W	Sept. 8	443
33	23°41'N	81°05'W	25	39°05'N	28°03'W	Oct. 4	466
40	24°40'N	80°38'W	22	25°16'N	80°18'W	Dec. 1 1964	556
2	24°28'N	79°19'W	20	59°20'N	6°00'E	Oct. 19	851
40	24°40'N	80°38'W	22	25°29'N	80°20'W	Nov. 29	918
40	24°40'N	80°38'W	22	25°29'N	80°20'W	Dec. 6	925

APPENDIX B

SUMMARY OF SHIP'S DRIFT, WIND DATA, AND

WIRE ANGLES ON OCEANOGRAPHIC STATIONS

Sta. No.	Current Speed (knots)	Current Direction (deg. T)	Wind Speed (knots)	Wind Direction (deg. T)	Wire Angle (degrees)	Wire Direction (deg. T)
1	0	---	10	180	3	220
2	0.7	007	2	200	10	---
3	0	---	7	200	5	---
4	0	---	7	205	3, 17	---
7	1.5	134	12	180	12	---
13	1.2	033	7	160	8	180
14	1.3	009	5	135	15	155
15	1.9	302	5	150	23	---
16	0	---	6	140	0	---
18	1.0	041	7	135	14	185
19	1.2	070	10	120	9	---
20	3.5	049	12	100	10	125
21	2.5	028	14	090	18	110
22	1.5	039	12	090	9	---
23	0	---	12	085	6	070
26	3.8	066	20	090	9	080
27	3.2	060	12	090	23	205
29	1.4	303	12	090	14	100
30	0.5	286	12	090	30	095

Sta. No.	Current Speed (knots)	Current Direction (deg. T)	Wind Speed (knots)	Wind Direction (deg. T)	Wire Angle (degrees)	Wire Direction (deg. T)
32	2.7	044	16	110	26	---
33	1.8	038	18	110	36	---
34	0.8	093	16	077	6	040
35	0.7	101	12	050	12	045
36	1.0	057	12	090	31	---
37	2.6	048	14	090	0.25	---
39	2.2	028	7	120	3	---
40	3.4	032	8	115	19	230
41	3.5	051	10	135	32	185
42	2.3	042	7	120	29	180
43	0	---	9	120	17	110
44	1.0	215	7	120	15	110
45	0.6	197	9	090	15	030
46	0.5	210	9	075	22	060

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