

A DETAILED OCEANOGRAPHIC ANALYSIS OF A GULF STREAM

MEANDERING AREA

by

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ABSTRACT

A detailed grid of thirty stations located inside a longitude and latitude square of 1.5° by 1.5° was occupied twice within fifteen days with a five-day waiting period between observations. The square fell along the southern edge or transitional side of the Gulf Stream as it was executing a steep meander. The existence of frictional eddies, the failure of the geostrophic equations to apply and give the correct picture of the flow pattern, and the variation of the T-S diagram across the Gulf Stream is shown. The method of isentropic analysis suggests eddies of different sizes and directions of rotation. The analysis also illustrates the discontinuity of the movements of the surface water with movements at depths. Finally, the plots of average temperature for the upper 200 m. are shown to destroy the detail of the turbulence and eddies created by the Stream passing through the area.

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The opinions or assertions in this manuscript are those of the author and should not be construed as being official or reflecting the views of the Department of the Navy or the Oceanographic Office.

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INTRODUCTION

Most oceanographic observations of the Gulf Stream consist of a single line of oceanographic stations traversing the Stream at a perpendicular or oblique angle from the Sargasso Sea side to the slope water side. Detailed temperature profiles to a depth of 300 m. have been taken over a relatively small area, but these measurements do not give the whole picture. They lack salinities to determine the dynamic topography, and the systematic concentration of observations to note the fine scale structure of the Gulf Stream. While the Gulf Stream '60 Survey fills this need to some extent, the detail for an area as small as the one studied here is not present. To fill this need and to answer some questions concerning the dynamics and structure of the current on a small scale, the present analysis has been made.

This thesis, therefore, is concerned with the analysis and interpretation of the physical ocean movements in an area where a high concentration of oceanographic stations were taken around the Sargasso Sea side of the Gulf Stream. Since the data points are so closely spaced, distance and timewise, the opportunity to acquire a new detailed look at the turbulent transition side of the Stream in a steep meander is possible.

BACKGROUND

The Gulf Stream has always been a source of interest to oceanographers, and in the last fifty years it has received intensive spasmodic study by oceanographers in the United States. At first these observations were set up in a routine pattern to try to discern the basic characteristics of the Stream (Iselin 1938 and 1940). They consisted of single lines of oceanographic stations across the Stream in either the Straits of Florida, or between Bermuda and some point on the American mainland. These measurements helped to reveal the general nature of the Stream, its speed, width, variation in mass transport, and temperature and salinity characteristics. As technology advanced, new theories as to the Stream's formation and new and rapid measuring instruments became available to the oceanographer to help pry loose the details of this phenomenon.

The introduction of rapid measuring techniques by the use of the bathythermograph (Spilhaus 1938) made feasible synoptic and quasi-synoptic studies of the surface of the Gulf Stream and their variations. While salinities are lacking in this case, techniques and methods have been devised to follow the movement of the Stream using only the temperature in the upper 300 m.

More recently, with the advent of infrared detectors and their ability to distinguish the sharp temperature gradient in the surface layers of the ocean (Stommel and Parsons 1953), the oceanographer is able to chart the general position of the Stream from a rapidly moving

aircraft, thus acquiring an almost instantaneous picture of its location or variation with time. Also, the rapid measurements of surface currents by the use of the geomagnetic electrokinetograph (GEM) (Von Arx 1950) has greatly enhanced the understanding of the complex velocity structure of the Gulf Stream. Finally, Loran C has given ships the ability to locate their position precisely in the area of interest, thus aiding charting and observation of the ships' set and drift, caused by the Stream, and therefore, the Stream's speed and direction.

These new instruments and techniques have shown that the Gulf Stream meanders, forms eddies, is composed of segments rather than being a long Stream (Von Arx et al, 1955), has maximum and minimum cores of velocity (Von Arx 1952, Worthington 1954), and varies its mass transport-- all of which were never realized thirty years ago. To complete the picture, the multiple current hypothesis proposed by Fuglister (1951 and 1955), the kinetic energy exchange (Webster 1961), the effect of the bottom topography on the path of the Gulf Stream (Warren 1963), and the Gulf Stream '60 Survey (Fuglister 1964) have further complicated the picture.

In the future, with the perfection of GEON (Gyro Erected Optical Navigation) accurate navigation data will be available. Also, perfection of new sensitive pressure measuring devices will provide long needed basic information as to the pressure fields and the role of the baroclinic and barotropic modes of flow.

Needless to say, as more is learned about the Gulf Stream more complicated details will be revealed and more sophisticated techniques,

theories, and equipment will be needed to answer the questions these details impose. While a vast store of knowledge about the Gulf Stream has been gathered, all possibilities of inquiry are not exhausted and the Stream will remain a major source of interest to oceanographers for years to come.

BASIC DATA

a. Accuracy and Validity of Data:

The measurements presented herein were obtained in mid-July 1963 by the USS San Pablo (AGS-30) in an area centered about $36^{\circ} 30''$ N., $66^{\circ} 30''$ W. Since the pattern of observations is unusual, in the sense of its concentration of stations, some word should be said as to the method of observation.

The area (Figure 1) consisted of thirty stations and was observed by Nansen cast twice (July 7 - 12 and July 17 - 21) with a five-day intermittent period between occupations. Of the sixty stations, five cast during the first occupation and six during the second were to the bottom at about 5,000 m. All shallow casts were to 500 m. or greater with the majority being between 800 m. and 1,000 m.

Salinities were determined at sea twice with a conductivity bridge and, in some cases, a third time to verify results. Temperatures were acquired by protected deep sea reversing thermometers, and depths of sample bottles were measured using paired protected and unprotected reversing thermometers.

To illustrate the validity of the data, Figure 2 shows a composite T-S curve for both occupations of the area. The width of the curve is a spread of .04 0/00 salinity. General accuracies can be summed up as shown in the following table:

Area Occupation	Number of Points Observed	Number of Points in Error	Percentage
1st	255	7	3%
2nd before sta. eliminated	295	65	22%
2nd after sta. eliminated	240	13	5%

The reason for the large number of points in error for the second occupation of the area is mainly due to the salinities. Trouble in the operation of the salinity bridge was detected after all the water for the salinity samples had been used for the stations in question, causing the values to read low by .04 0/00 or greater. Therefore, stations 12, 13, 22, 25, 26, 27, and 28 have been eliminated. Because of these salinity errors, 13 points out of 240, or 5% are in error after the elimination of the above-mentioned seven stations. One departure from this average T-S curve is the group of curves for the top of the area, stations 1 - 6 of the first occupation. These curves do not fit the average curve until a depth of about 500 m. is reached. However, their variations are caused by mixing and not by salinity errors, as discussed in a later section. It can finally be said that all salinities, except those of the seven stations listed above, and the small percentage in error, are considered accurate to $\pm .02$ 0/00 or better and all temperatures to $\pm .01^{\circ}$ C.

The navigation for the cruise was done with Loran C, and constant checks were made against these fixes with one of the two Loran A receivers aboard. While under way and on station, fixes were taken every thirty minutes and a plot made of the ship's set and drift. BT's, while

not available for this report, were taken at the beginning and end of every station and every thirty minutes while under way in the area.

While the observations are quasi-synoptic, the assumption through the rest of the report will be that of a synoptic set of data. Although this will lead naturally to a somewhat distorted picture, especially for such a small area, it is felt that this is the best way to treat the data at the moment. However, as will be shown, the picture presented may not be as distorted as it seems. Also, all stations are assumed to fall on a north-south or east-west line for the purpose of calculation of current velocities by the geostrophic method. No further explanation is given for this, other than that of convenience.

Finally, the problem of contouring is an old one in oceanography. As Fuglister has shown, for any one set of values several interpretations may prove valid. In this report the margin of error due to contouring has been considered and several methods have been tried to test the validity of the final pattern chosen. After much consideration, testing and elimination, the final pattern presented in this report was chosen by the author as that best representing the flow.

b. Description of Basic Data:

The basic data, i.e. temperature, salinity, and dynamic heights, calculated from these are given in Figures 3 - 22. Not all of the data is given, but only several graphs that best illustrate the general features. Representative profiles consisting of line two (a north-south line of stations 2, 11, 14, 23, and 26) and line five (stations 5, 8, 17, 20, and 29) are used for both temperature and salinity profiles and both times of occupation. Distribution of temperature is given at the surface, 200 m. and 500 m. depths, and salinity for the surface and 500 m. only. Finally, dynamic heights are contoured for the surface relative to the 800 m. level.

Figures 3, 4, 5, and 6 are the temperature and salinity profiles in the upper 1,000 m. of the area for the first series of observations. The slopes of the isotherms, Figures 3 and 4, are illustrative of the temperature structure of the transitional or right hand edge of the Gulf Stream. The slopes of the isotherms, in a north-south direction, increase from west to east and are the greatest at line five, from where they begin to decrease. Also illustrated is the wedge of Sargasso water (Worthington 1959) in the southern half of the area, and the warm core in the mid and northern parts of these profiles.

The salinity profiles, Figures 5 and 6, show the same general slope characteristics illustrated by the temperature profiles. Particularly obvious is the wedge of highly saline water (36.65 ‰) located about

150 - 200 m. in the main part of the Stream. This wedge is sometimes found in crossing the Stream, but is very seldom shown in the data and is thought to be discontinuous. However, in the first time through the area it was missing only in one profile, line four. It is believed that if more data were available further north of line four it would show here also.

Figures 7 - 10 demonstrate the temperature and salinity distribution in the second phase of the operation. As can be seen, the slope of the isotherms for line two is much less pronounced than before. Also a rise of the isotherms toward the surface in the middle of the profile indicates an eddy. Line five also shows an eddy, though not the same one as shown in line two, and a rise in the slope of the isotherms which indicates a nearness to the Gulf Stream. The salinity profiles, Figures 9 - 10, also indicate the same general trend. Here the displacement of the maximum salinity wedge is noticed. It consists of a small isolated pocket to the south of the eddy center in line two, and of one isolated pocket on each side of the eddy center in line five.

The temperature contours for the surface, 200 m. and 500 m., during the first survey are given in Figures 11 - 13. The isotherms at 500 m. indicate the existence of a strong current, but the contours for 200 m. and the surface show a strong current of a totally different nature. The salinities, Figures 14 - 15, are shown only for the surface and 500 m., and are in the same trend.

The second occupation, completed ten days after the finish of the first, shows a completely different picture as illustrated by the isotherms in Figures 16 - 18. Here it seems as though the Stream moved toward the west and two eddies then took over in the center of the area. The salinities, Figures 19 - 20, show a trend similar to the isotherms, but it is not as pronounced.

Finally, the dynamic heights for both occupations are given in Figures 21 and 22, and are drawn relative to the 800 decibar surface. Here data are plotted from actual observations to this depth, instead of interpolated values, since some of the station depths are variable.

ANALYSIS OF DATA

a. Presence of Gulf Stream

Because the extent of the data for the northernmost part of the survey is limited to a small area, it is very hard to determine if the slopes of the isotherms and isohalines are caused by the presence of the Gulf Stream or by an eddy that has been formed and detached itself from the Stream. Fuglister and Worthington (1951, Figure 4) have illustrated the varying positions of the inshore edge of the Gulf Stream, and the southernmost penetration illustrated is well in the present area under discussion. This observation was made by the RV Atlantis in June and July of 1947. Figure 23 is a map of the five-day mean temperature for the time of the first occupation, compiled by the United States Naval Oceanographic Office. The heavy black lines outline the area of observation and, as can be seen, the maximum temperature occurs inside the northern edge.

To postulate as to the depth of penetration into the Stream is very difficult. Using as a rough criterion that the 18° isotherm defines the left hand edge when it crosses the 200 m. level (Von Arx 1962), it is suggested that the northernmost stations, especially 4 and 5, were somewhere near the center of the Stream. The sharp slopes of the isotherms and isohalines and the concentration of the salinity maximum under the Stream also add to the argument.

Figures 24 and 25 are plots of the depth of the 10° isotherm. This type of plot is considered to be one of the best indicators of the

presence of the Stream and shows in Figure 24 how it sweeps through the area at depths. Of even more interest is the depth of the 10^0 isotherm for the second occupation, Figure 25. This figure illustrates the movement of the meander very well, as the isotherm has moved across the area from west to east. The total distance moved cannot be measured exactly, but by extrapolating the isotherm at 800 m. to where it should be on the line of northernmost stations, it is indicated that the Stream meandered at least seventy miles or more in the ten days between observations. This distance is somewhat close to the value proposed by Fuglister and Worthington of eleven nautical miles a day.

The temperature and salinity contours for the first occupation at the surface and 200 m. depth do not agree either with the dynamic heights relative to 300 m. or with the 500 m. temperature, although both of these agree fairly well with each other. However, when these plots are compared with the temperature and salinity contours for the second time through the area, it is very evident that the Stream has moved from the western part to the eastern edge of the area.

The velocity profiles for line two are given as an illustration of the type velocities in the area. The profile which contains the Gulf Stream, Figure 26, shows a maximum velocity of 60 cm./sec. This value is low because it was calculated relative to an 800 m. level and not to the bottom or usual 2,000 m. If the dynamic heights could be taken deeper, the velocities would increase to a more realistic value. Also, according to the dynamic height contours this line does not get into the maximum flow as line five does. A small counter-current is

illustrated, but if the dynamic heights were calculated from a different reference level this current would probably disappear.

The current profile for the second time through the area, Figure 27, shows a strong cyclonic eddy which will be discussed in detail later.

The average temperature for the upper 200 m. is plotted and contoured in Figures 28 - 29. These temperatures for the first leg, Figure 28, show the warm core of the Gulf Stream very well. Figure 29, for the second time through the area, is an excellent example of how averaging temperatures can destroy the detail caused by the Stream's movement.

b. Mixing:

As has been previously shown, the meander of the Stream into the southern area is probably the maximum distance at this longitude that it penetrates. With the advection of Gulf Stream water into an area of this size in the amount of time needed, it can be expected that there will be some mixing of the Gulf Stream and Sargasso water. However, the Stream will keep its general characteristics near its center, as illustrated in Figure 30.

The Gulf Stream is a distinct water mass from that of the Sargasso Sea and this difference is illustrated by the T-S curves for the top six stations when compared with the average T-S curve for the whole area. Going from west to east, the variation of the station T-S curves from the average is greater as the center of the Stream is approached. There is a systematic variation which begins at station one, reaches a maximum at station five, and decreases again at station six. The station curves begin above the core of maximum salinity and merge into the average T-S curve at about 500 m.

The relative maximum vertical stability is given by

$$S = \frac{\Delta \sigma_t}{\Delta Z} \quad (1)$$

where: $\Delta \sigma_t$ = change in specific volume anomalies

ΔZ = change in depth.

The depth, where S is a maximum in the area for the first survey, was variable, but generally was around the core of maximum salinity. Figure 31 demonstrates this for the first occupation.

Thus, it can be seen that the mixing for Figure 30 will probably be mostly vertical with some horizontal. Figure 31 shows very well that the layers above the core of maximum salinity are horizontally stratified and, therefore, vertically stable so that only horizontal mixing would be expected to occur in this region.

The problem of lateral mixing in the Gulf Stream has been discussed by Stommel in his book, The Gulf Stream. While Stommel points out the evidence for the lack of lateral transfer across the Stream, no mention is made of partial lateral mixing, especially for the right hand side.

c. Eddies and Turbulence:

One of the more fascinating aspects of the Gulf Stream is its constantly changing appearance in the form of meanders and eddies. Church (1932 and 1937) recognized that the Stream meandered and probably formed eddies; he even showed that the amplitude of the meanders increased as one goes westward. However, it was not until the multiple ship survey of 1950 that an eddy was mapped synoptically from its formation until its departure from the Gulf Stream. Since this time, questions such as the rate of formation, speed of movement and rate of decay are still unanswered.

Spilhaus (1940) first proposed that there were three sizes of eddies: (1) large scale--approximately 150 km. long, with distortion of isotherms down to a great depth, (2) intermediate--30 km. long, and (3) parasite--about 5 km. long. However, he made no stipulation as to how the eddies were formed.

Iselin and Fuglister (1948) proposed that friction drives a shear zone eddy of which two sizes are present: (1) 30 km. long, and (2) 7 km. long. Also, they suggested that these eddies rotate in the opposite direction of the larger eddies found on the right hand side, i.e. cold core eddies which rotate counterclockwise. However, none of these shear zone eddies have been found so far.

In the dynamic height diagrams for the first occupation, Figure 21, there seems to be a small eddy of the type that Iselin and Fuglister have described. It is shown to rotate in a clockwise direction and is

between the Gulf Stream and what appears to be a counter current. On the dynamic height diagram at 200 m. relative to 800 m. (which is not shown) the eddy has disappeared and it is, therefore, questionable if it actually existed. This disappearance will be discussed later on.

The second occupation gives a different picture as both the dynamic height contours and the temperature contours show the existence of two counterclockwise eddies. These eddies are approximately 60 km. wide and seem to be caused by the turbulence of the wake of the Gulf Stream. The temperature and salinity, Figures 7 and 9, illustrate these eddies.

Figure 32 is a plot of the salinity maximum between 20 and 200 meters (Wüst's Krunsheit method). This plot clearly shows a sinking region around stations 14 and 17 with a counterclockwise movement, and a clockwise eddy located between the two cyclonic eddies. In the discussion of isentropic analysis this will be shown to a better advantage.

Using the temperature profiles, one can see that the eddies extend to a depth of between 600 and 700 meters before the slopes of their isotherms and isohalines are eliminated. Some interesting features of the eddies are that while at the surface their axes are oriented mainly east-west, as depth is gained the eddies become diffused, their axes change generally to north-south, and then they disappear altogether.

Where these eddies came from or how they were formed cannot be answered by this analysis. The temperature and salinities of their

centers show them to be Sargasso water or, more remotely, slope water that has gained Sargasso Sea properties. Whether they were formed in the area or migrated into it from the outside may be answered by a look at the dynamic topography for both occupations of the area. When a line of constant dynamic height is picked at 1.5 m. and its movement followed, it is seen to go from an almost perfect east-west line to one which makes a 90° turn from north to east. This implies that the eddies were created by turbulent movements of water to fill the void caused by the passage of the Gulf Stream out of the area of observation.

d. Flow Patterns:

As has been previously mentioned, the temperature, salinity and dynamic height contours at the surface and 200 m., first occupation, do not agree. Also, the salinity and dynamic heights at the surface, and the temperature, salinity and dynamic heights at 200 m., second occupation, do not agree.

In both occupations of the area the temperature, salinity and dynamic heights agree at the 500 m. level, but the temperature and dynamic heights agree at the surface for the second occupation only. In several of the plots it will be noted that the lower half of the diagrams for both temperature and salinity agree with the dynamic heights.

From the discrepancies of the surface temperature and 200 m. level temperature and salinity when compared with the corresponding dynamic topography at these levels, it is evident that the dynamic topography may not represent the actual field of motion. Therefore, the question is raised as to the wide disagreement between the quantities plotted.

The first cause for the discrepancy is that the geostrophic equation is not satisfied. The equation for geostrophic flow is:

$$C_g f = \frac{1}{\rho} \frac{\partial p}{\partial m} \quad (2)$$

where:

f = Coriolis parameter

ρ = density

$\frac{\partial p}{\partial m}$ = pressure gradient along a line segment .

C_g = geostrophic velocity

From this simplified form of the equations of motion, the relative velocities are calculated using dynamic sections. Both formula (2) and the method of dynamic sections make the assumption that: (1) the flow is unaccelerated, (2) the flow is frictionless, (3) the pressure field is in hydrostatic equilibrium, and (4) the station observations are simultaneous.

It is immediately obvious that some or all of these conditions do not hold. The handicap of quasi-synoptic instead of synoptic data has already been discussed. In the contours at the different levels for both occupations, the need for the centrifugal and frictional terms is apparent. When the differences in the pattern of the contours are compared for both occupations of the sector, it is clearly indicated that the meander and eddies make it necessary to consider the local derivatives ($\frac{\partial u}{\partial t}$ and $\frac{\partial v}{\partial t}$) of the total derivatives ($\frac{du}{dt}$ and $\frac{dv}{dt}$), i.e. the fluid is no longer in a steady state.

While the ocean as a whole may be considered in a steady state equilibrium, the assumption is questionable for a small area and the fast moving processes which are present here. The turbulent motion indicated by the eddies during the second occupation confirms the existence of the non-steady state conditions on the transitional side of the Gulf Stream in this survey.

Therefore, one of the reasons that the temperature, salinity and dynamic heights agree at the 500 m. level is that here the velocity

has decreased, causing: (1) the frictional force to balance the centrifugal force, and (2) the pressure gradient and f term to define the pattern of flow. This is seen in Figures 13, 15, and 21.

The disagreement between the contours in the upper 200 m. is due to the simplifying assumptions of the equations of motion and, possibly, mixing. However, several other factors are influential also. One of these is the major disadvantage of the choice of the reference level in this study. Because of the limiting depth of the stations, 800 m. was used as a reference level rather than 2,000 m. or the bottom. Finally, wind stress has been completely ignored as to how it may effect the surface layers, especially the mixing and movement in the upper 200 m. Thus, from the factors not considered, the use of the dynamic topography to trace the water movements in the particular cases of the first and second occupations is questionable.

One method used to study the movements that does not depend on the dynamic topography is isentropic analysis by means of identifying properties. This method has been worked out and described by Parr (1936a, 1936b, 1938a, and 1938b) and used by Montgomery (1938), Soule (1938) and others. The advantages of this method over the dynamic topography method is: (1) no reference level is needed, (2) flow is parallel to the isolines, and (3) the method is not limited to a two-dimensional ocean.

The results of this method are given in Figures 33 - 36 for the first occupation, and Figures 37 - 40 for the second. Because salinities are used as the identifying properties in these illustrations,

some stations are omitted in Figures 37 - 40 either for reasons already described or they are used only to give an indication of the direction of the flow pattern. The isohalines represent lines of flow along a constant σ_t surface and are plotted for $\sigma_t = 25.5, 26.0, 26.5$, and lines of constant σ_t represent flow for the surface layer.

The use of the isentropic analysis in this study brings out a totally different picture in the surface layers than does the dynamic heights or salinity.

The σ_t contours, Figure 33, form the same general pattern as the isotherms for the surface. However, these isolines do not represent the actual flow pattern. Figures 34 and 35 (σ_t surfaces of 25.5 and 26.0) illustrate the gradual change of the flow pattern at the surface to that which the dynamic heights, temperature, and salinity indicate at 500 m. Figure 36 shows the 26.5 σ_t surface and its correspondence to the dynamic topography at 500 m. Here, there is no indication of an anticyclonic eddy along the Stream's edge for the $\sigma_t = 25.5$ surface, as was illustrated in the dynamic heights. However, the $\sigma_t = 24.5$ (not shown) and 26.5 show the formation of pockets of salinity at depths which indicate movements in a counterclockwise and clockwise direction.

In the second set of diagrams, the second occupation, again the temperature and σ_t seem to agree, but here they also agree with the dynamic heights. However, as the depth is increased there seems to be no good agreement between the dynamic heights and the isentropic analysis. The isentropic analysis shows a pocket of cyclonic and anticyclonic eddies that seem to indicate a turbulent region with sinking and rising

motion. All the diagrams ($\sigma_t = 25.5, 26.0, \text{ and } 26.5$) agree with the maximum salinity contours, Figure 32. If the representative temperature and salinity profiles are observed, it will be seen that the slopes of the isotherms and isohalines indicate these eddies. Thus, the isentropic analysis gives a representative picture of the possible water movements which the dynamic heights did not show.

While it is questionable that there exists as much detail in the area as the isentropic analysis shows, it is interesting to study the different patterns and speculate as to the actual flow direction in three dimensions.

A summary of the movements of the water through the area for the first and second occupations is given in Figures 41 and 42 respectively. The width of the movement, as indicated by the black lines separating the different colors, does not mean that there is an abrupt change in velocity across the dividing line, but represents the approximate position of the smallest definable flow. The arrows indicate the proposed direction of flow, but not the magnitude of the velocity. The two sections between the surface and 500 m. levels represent thicknesses or slabs of water.

As can be seen from the diagrams, the water movement on the Sargasso side of the meander varies in direction and velocity with respect to depth. Figure 41 in particular shows this and also suggests the possibility of the axis slanting as the Stream flows along its meander. As the surface is approached from depth the water movements

become more diffused, larger in magnitude and erratic in their direction so that the correlation of the water movements at the surface with those at depth is extremely difficult.

Figure 42 illustrates the change of the eddies with depth. As the 500 m. level is approached from the surface the eddies decrease in intensity, spread out and disappear. Also, at the 500 m. level the edge of influence of the Gulf Stream can just be seen, as it has moved off to the east.

It should be pointed out that the diagrams made no suggestion as to the happenings at depths below 500 m. Also, it should be stressed that the diagrams are an interpretation based on actual data and should be considered susceptible to the errors of an interpretative analysis.

CONCLUSIONS

In summary, it can be said that the Gulf Stream was penetrated in the first occupation of the area and the core was approached. In the second series of observations the Stream had moved to the right so that only a small trace of it was visible. While it is admitted that the phenomenon may be that of a large eddy, it is necessary to point out that the characteristics observed will be common to a Gulf Stream or recently detached eddy.

For the transitional side of a meandering Gulf Stream that has a cyclonic movement, the flow is varied and complex. As the surface is approached from depth the water movements become larger in magnitude and in area of influence. The movement and magnitude of the Stream vary and become erratic so that correlation of the movement of the surface water with the movements at depths becomes highly improbable.

In a very steep meander the assumption of geostrophic flow is not justified. Steady state conditions do not apply because of the movements of the eddies and Stream, and frictional and centrifugal forces which play an important role in the top layers of the fast moving water. Therefore, the assumption of geostrophic flow for tracing water movements gives an untrue picture of the flow pattern.

Evident in the area during the second occupation were two cyclonic eddies which were formed by the turbulence of the transitional side of the Gulf Stream after its movement across the top of the area between observations. These eddies were not caused by an entrapment of slope water during the sharp meander, but rather by the turbulence previously

stated. Their size was roughly 60 km. across, and depth of influence between 600 and 700 meters. The eddies observed here have the tendency to orient their axis east-west at the surface and to change them to north-south at depths. This may be due to the way the Stream is moving the water which fills its place after it traverses the area.

Definite proof of a small, shallow eddy which turns in a clockwise direction on the transitional side of the Stream is not present in the analysis of the data for the first occupation. However, in the second occupation of the area it is clearly shown by the isentropic analysis that the development of an anticyclonic eddy is possible. This eddy looks very much like a frictional effect caused by the cyclonic eddies on either side of it. Both types of eddies seem to have the characteristic of spreading out with an increase in depth.

From the analysis of the meander in this set of observations compared with that of the Gulf Stream '60 Survey, it can be concluded that the function of the sea mounts in the above-mentioned Survey report seems to be that of "tying down" the meander, thus restricting its movement.

The average temperature for the upper 200 m. destroys the small scale structures and even some of the large scale ones. Still it gives a very good picture of the warm core of the Stream.

As area detail increases, the data indicate more complex movements and a finer structure than has been seen before. In future surveys, to observe this detail over a large area in a short time will require several ships or a complex series of buoy stations.

APPENDIX

Figures:

All temperatures are given in degrees Centigrade, salinities in parts per thousand, dynamic heights in dynamic meters, and velocities in cm/sec., unless otherwise specified.

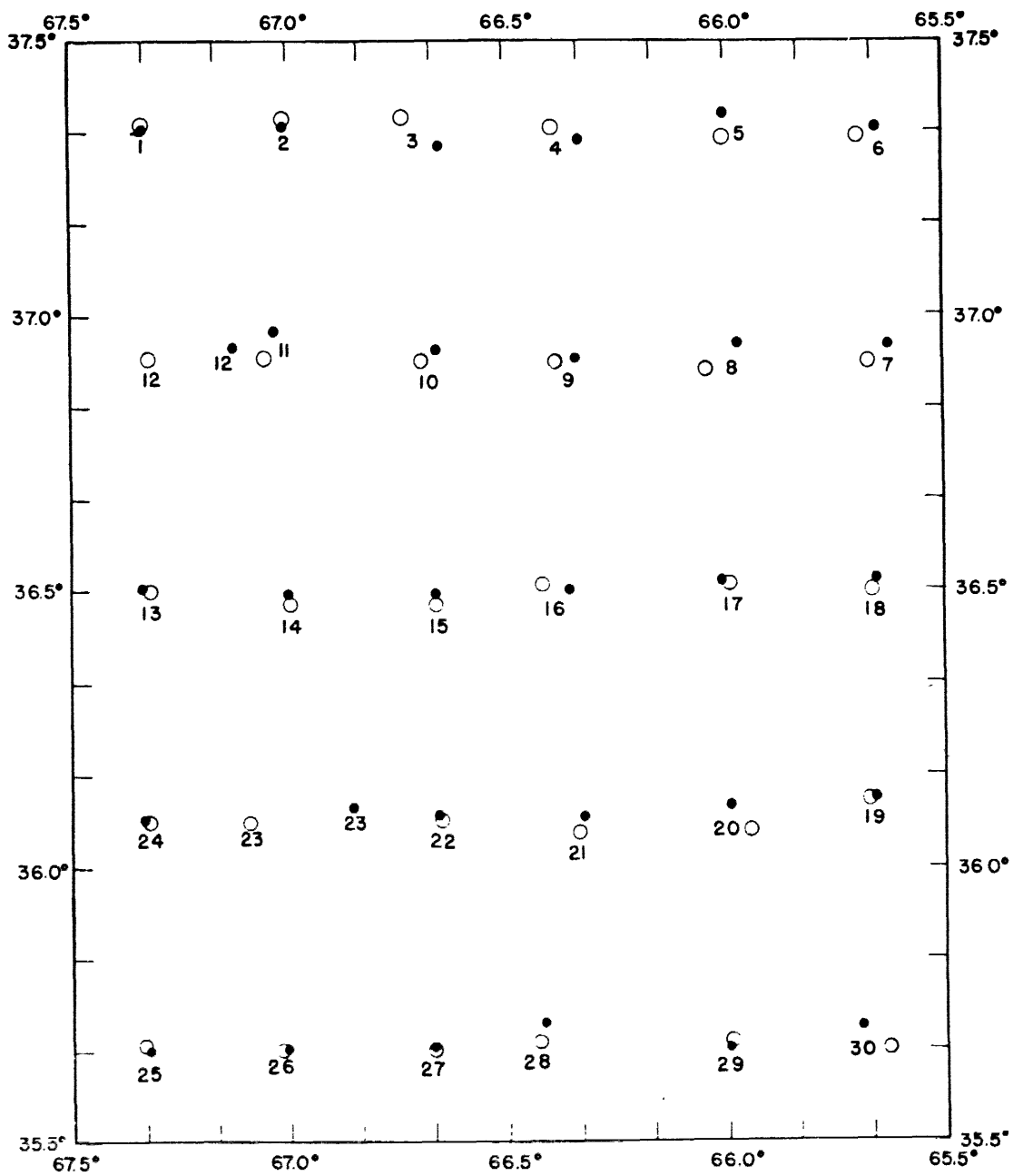


FIGURE I
Area of Observation

● First Occupation
○ Second Occupation

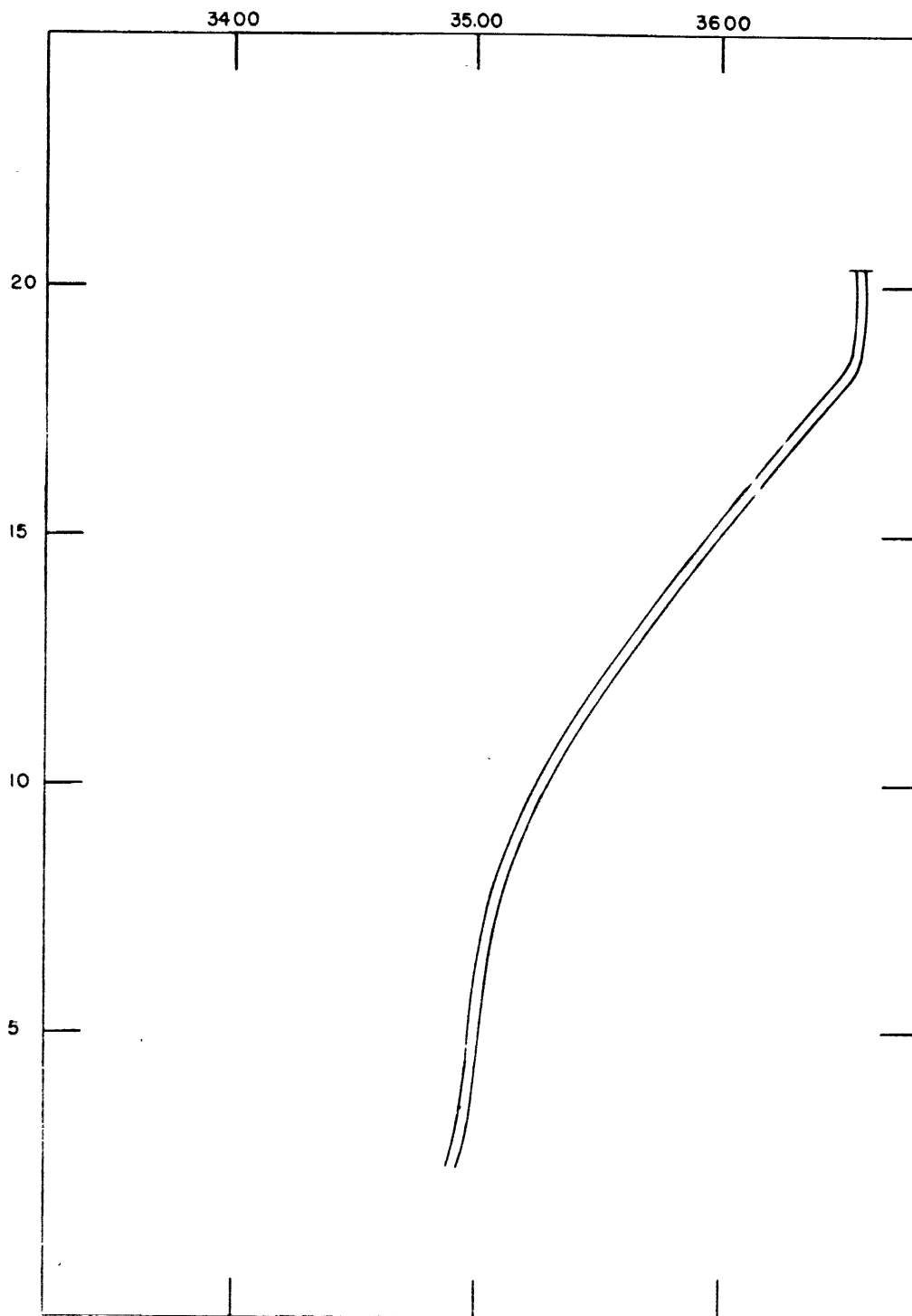


FIGURE 2
Composite T-S Curve

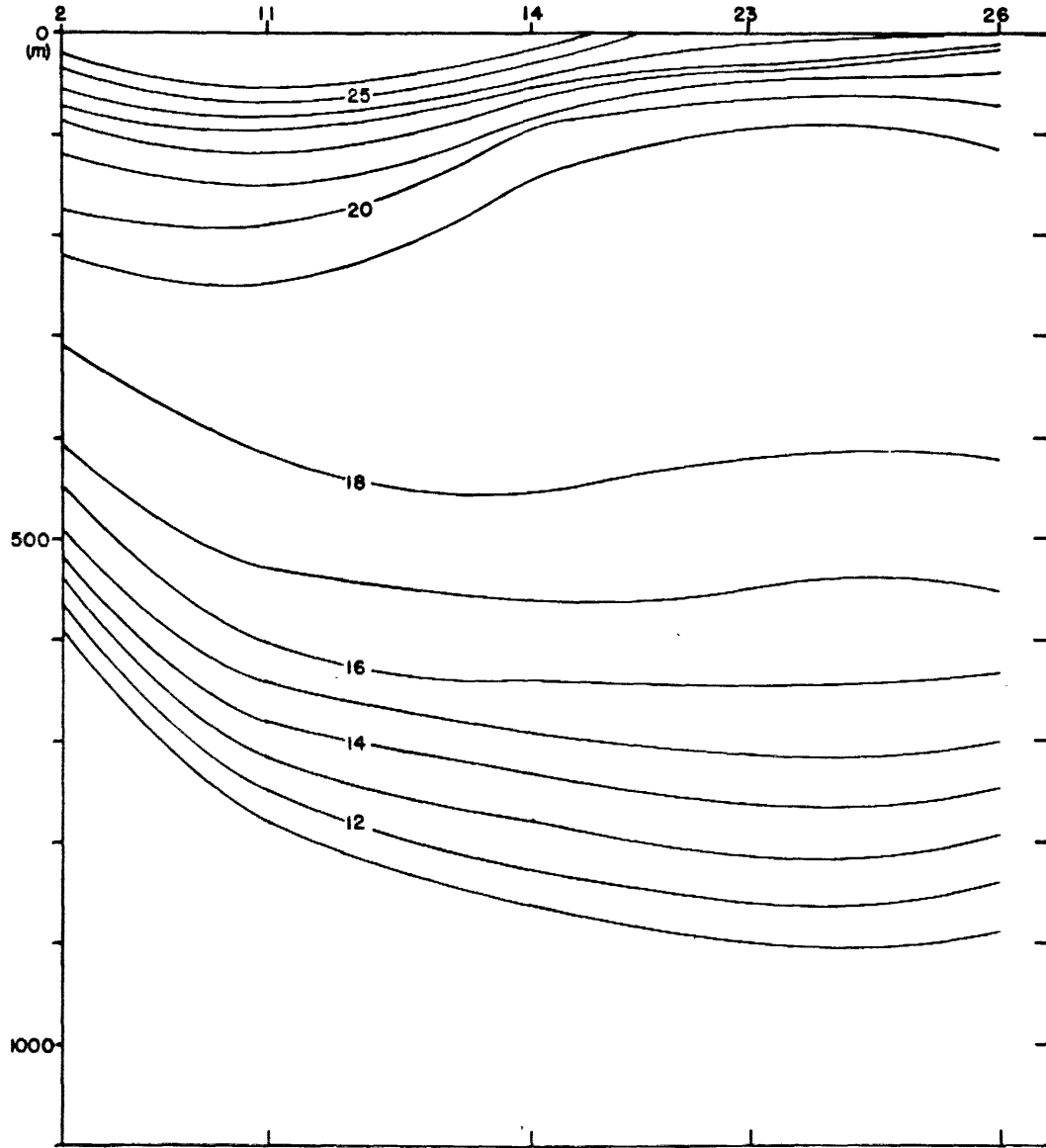


FIGURE 3
Temperature Profile Line Two, First Occupation

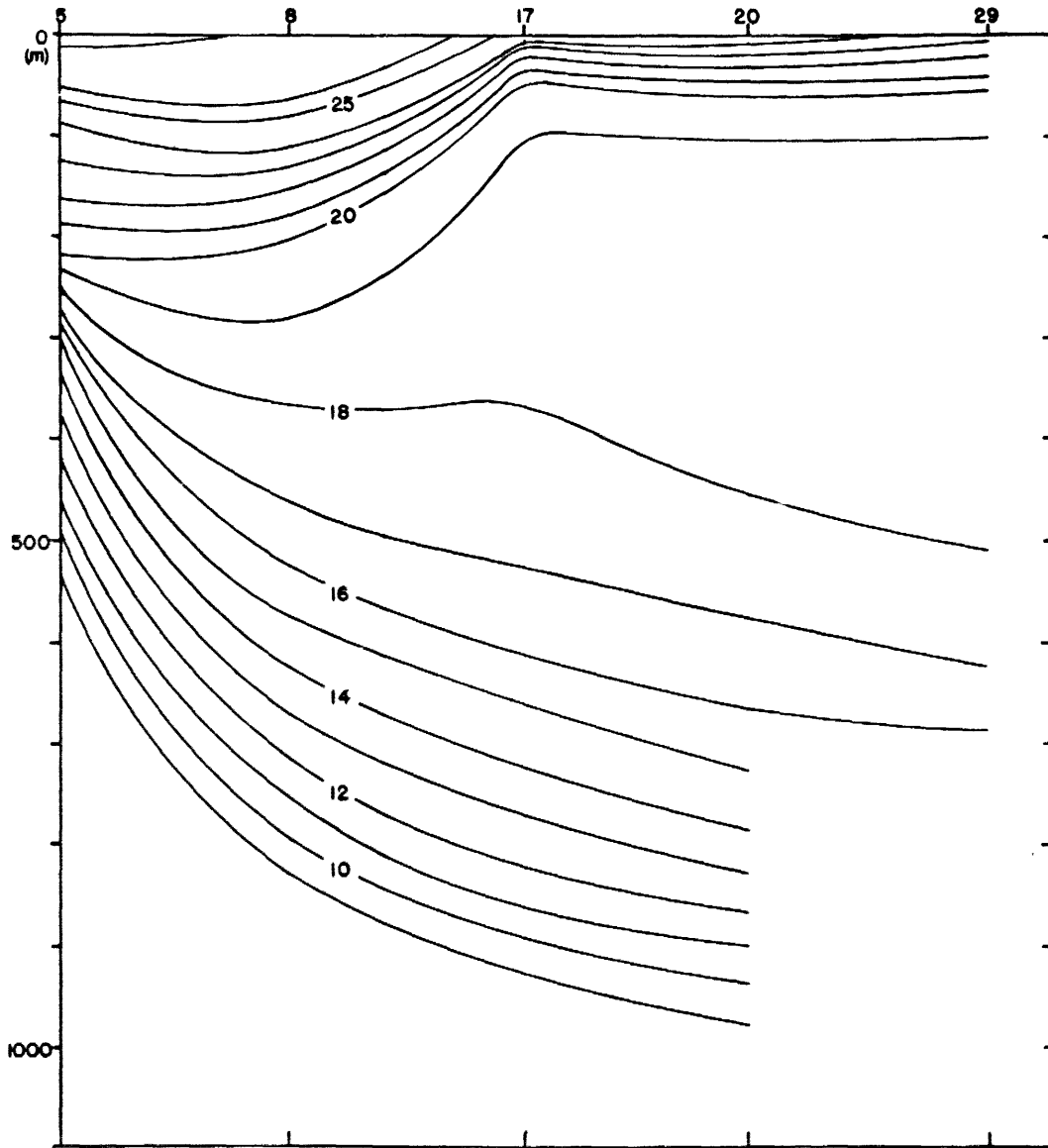


FIGURE 4
Temperature Profile Line Five, First Occupation

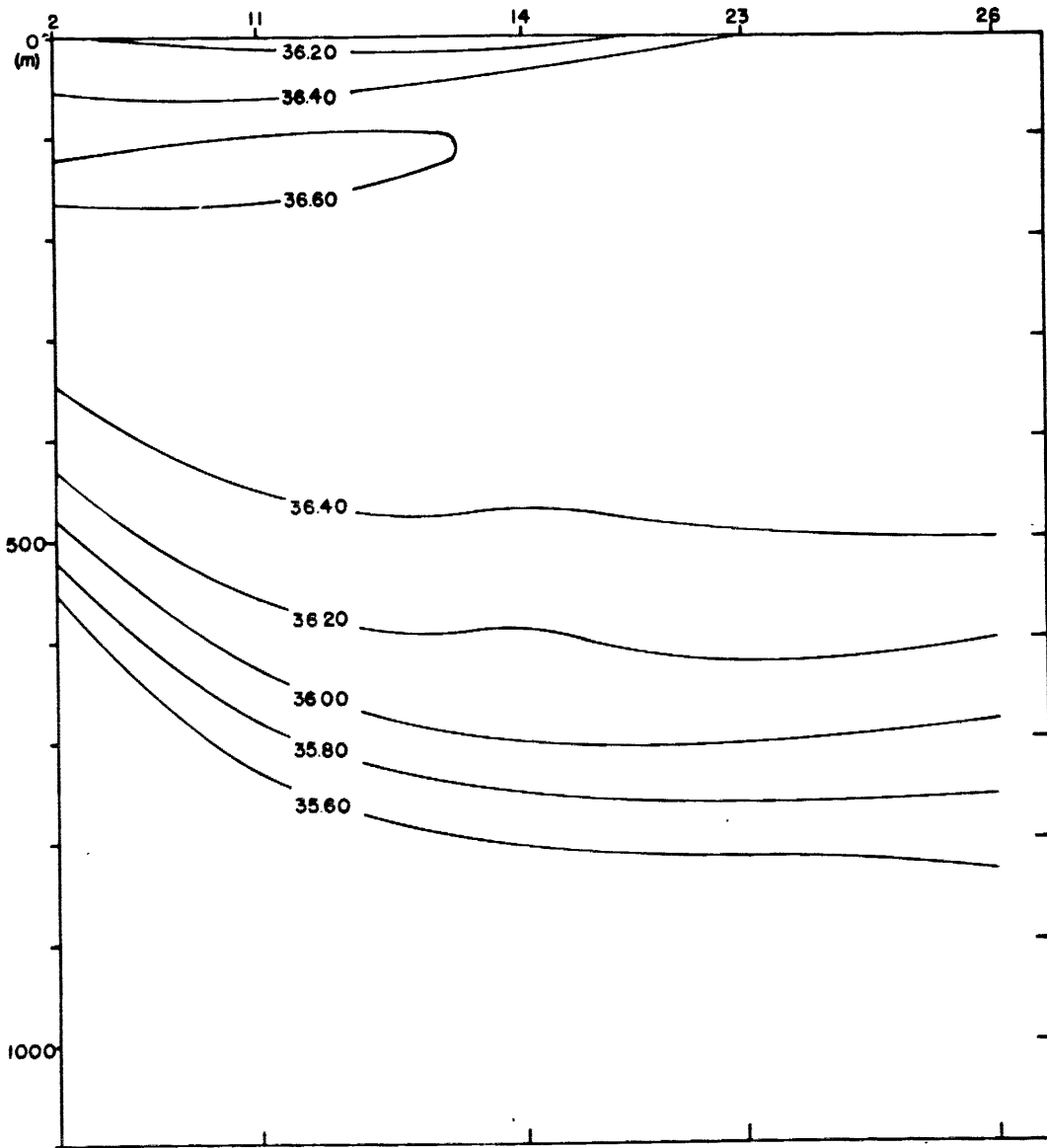


FIGURE 5
Salinity Profile Line Two, First Occupation

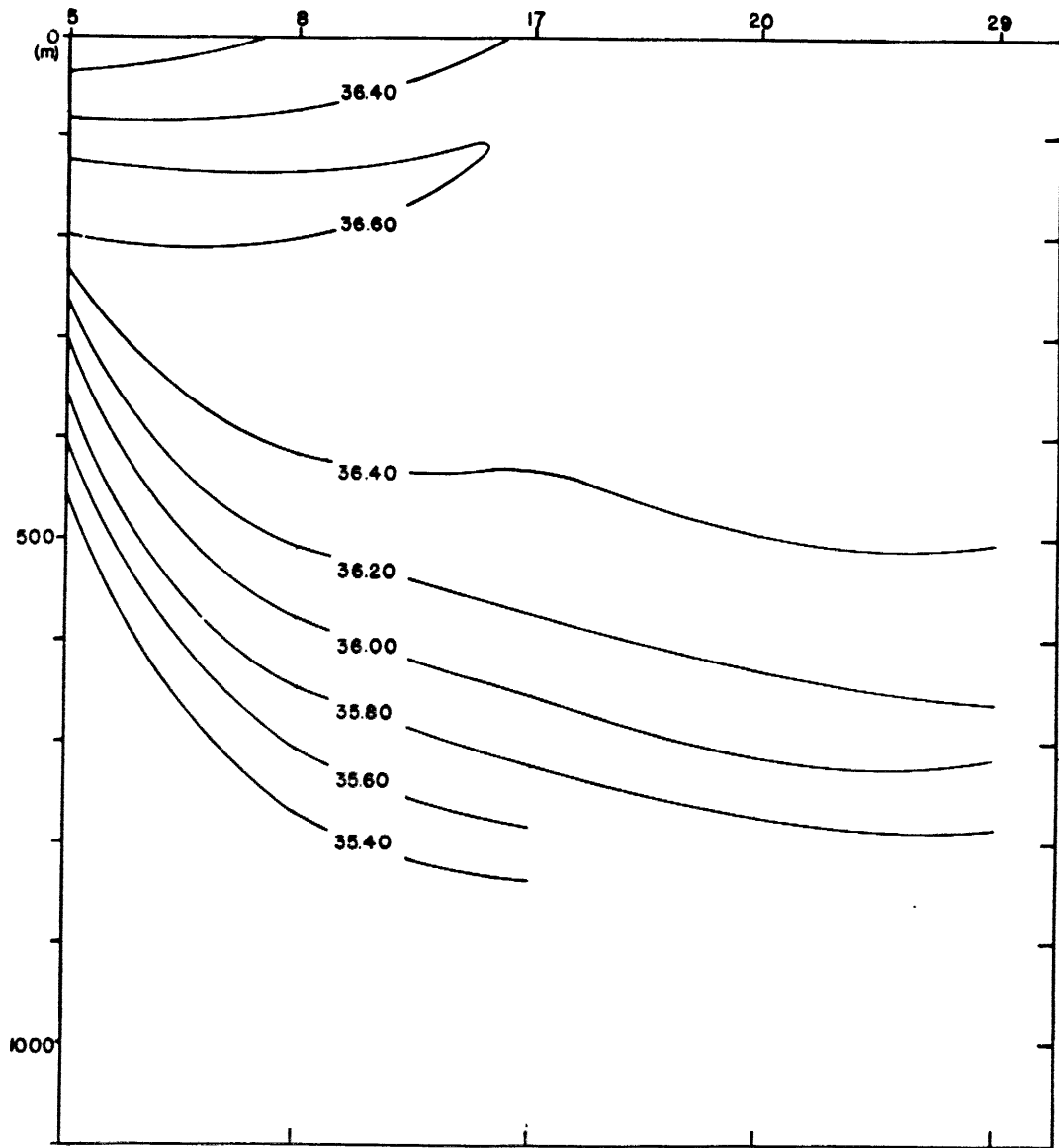


FIGURE 6
Salinity Profile Line Five First, Occupation

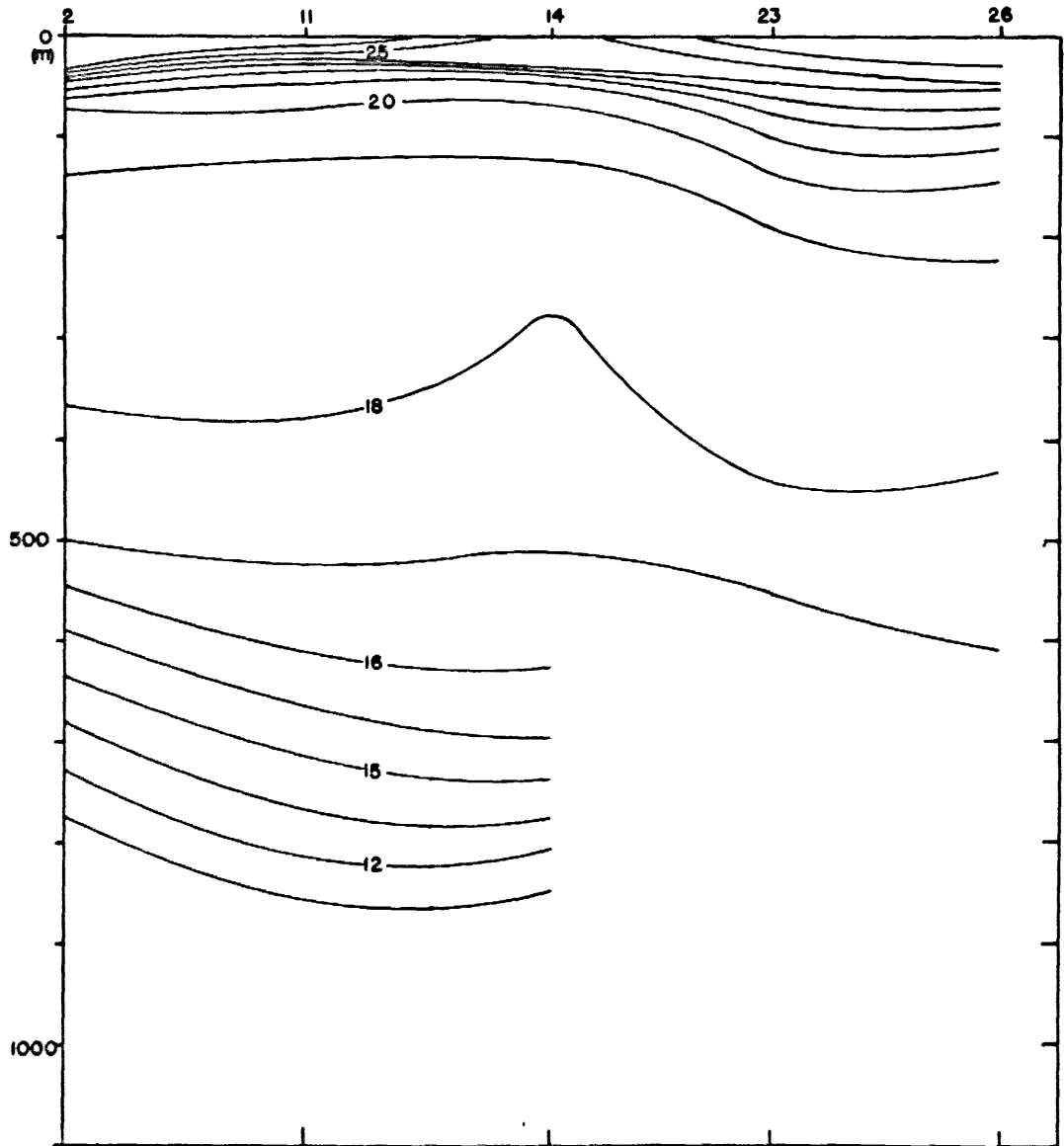


FIGURE 7
Temperature Profile Line Two, Second Occupation

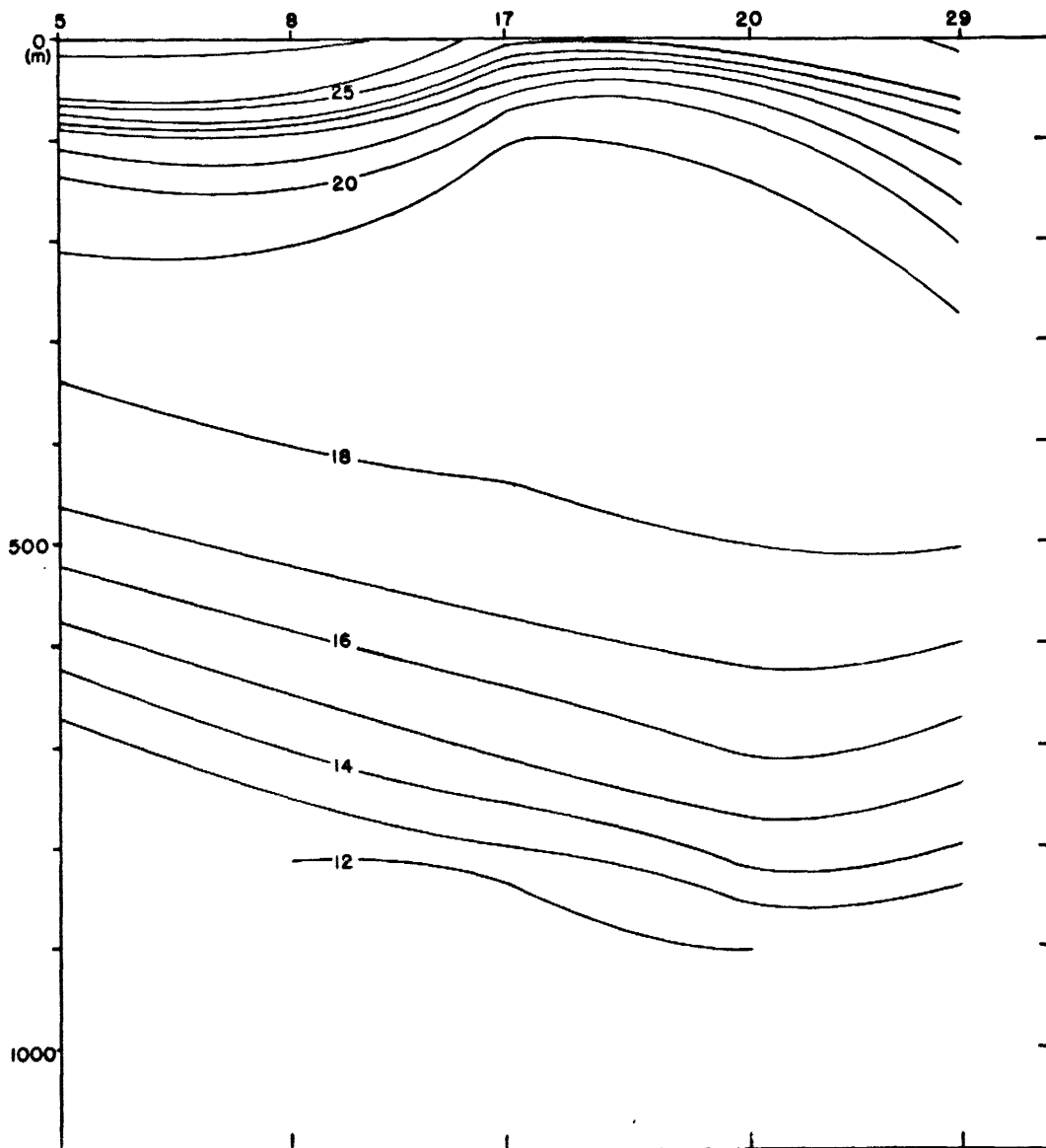


FIGURE 8
Temperature Profile Line Five, Second Occupation

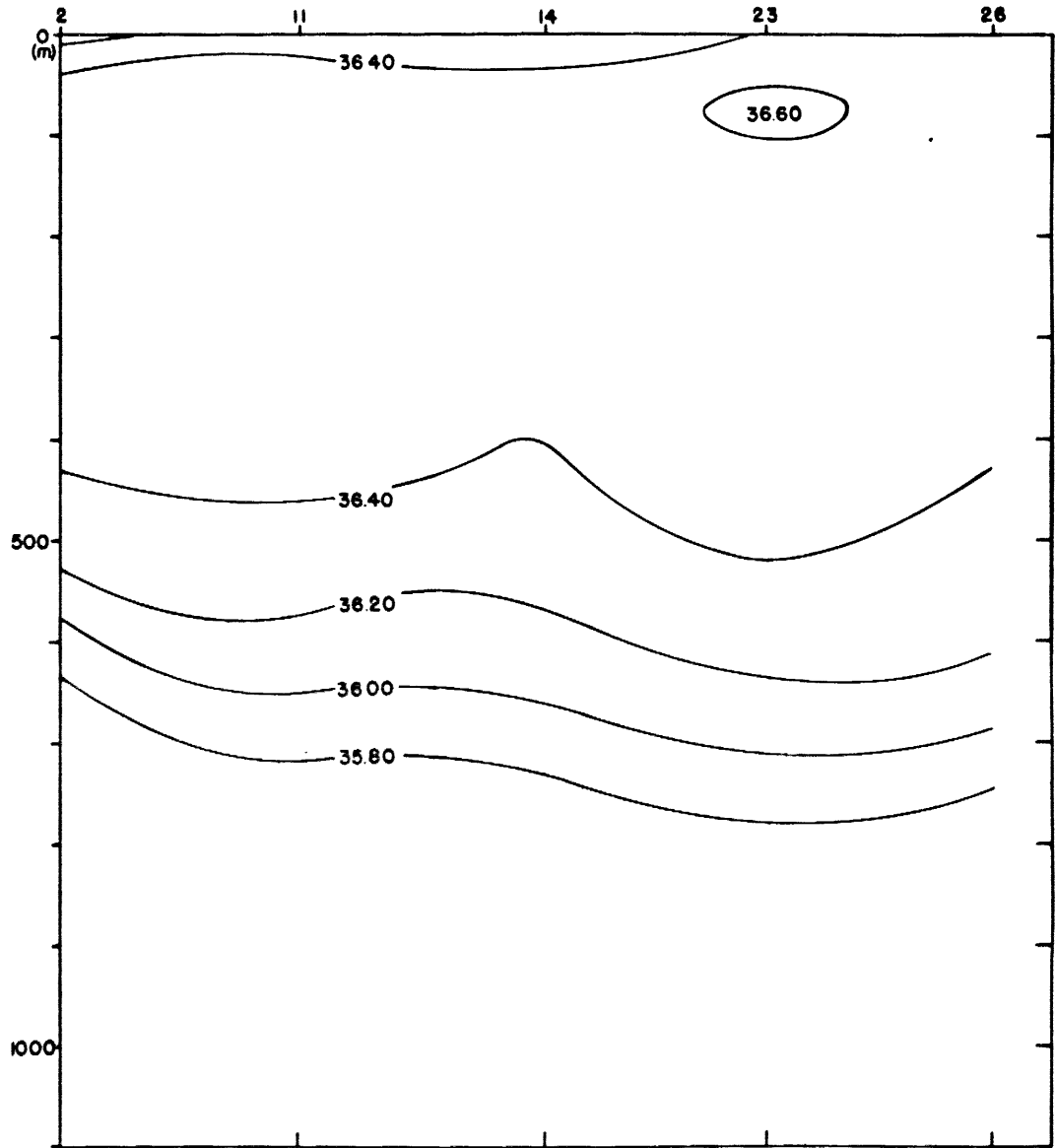


FIGURE 9
Salinity Profile Line Two, Second Occupation

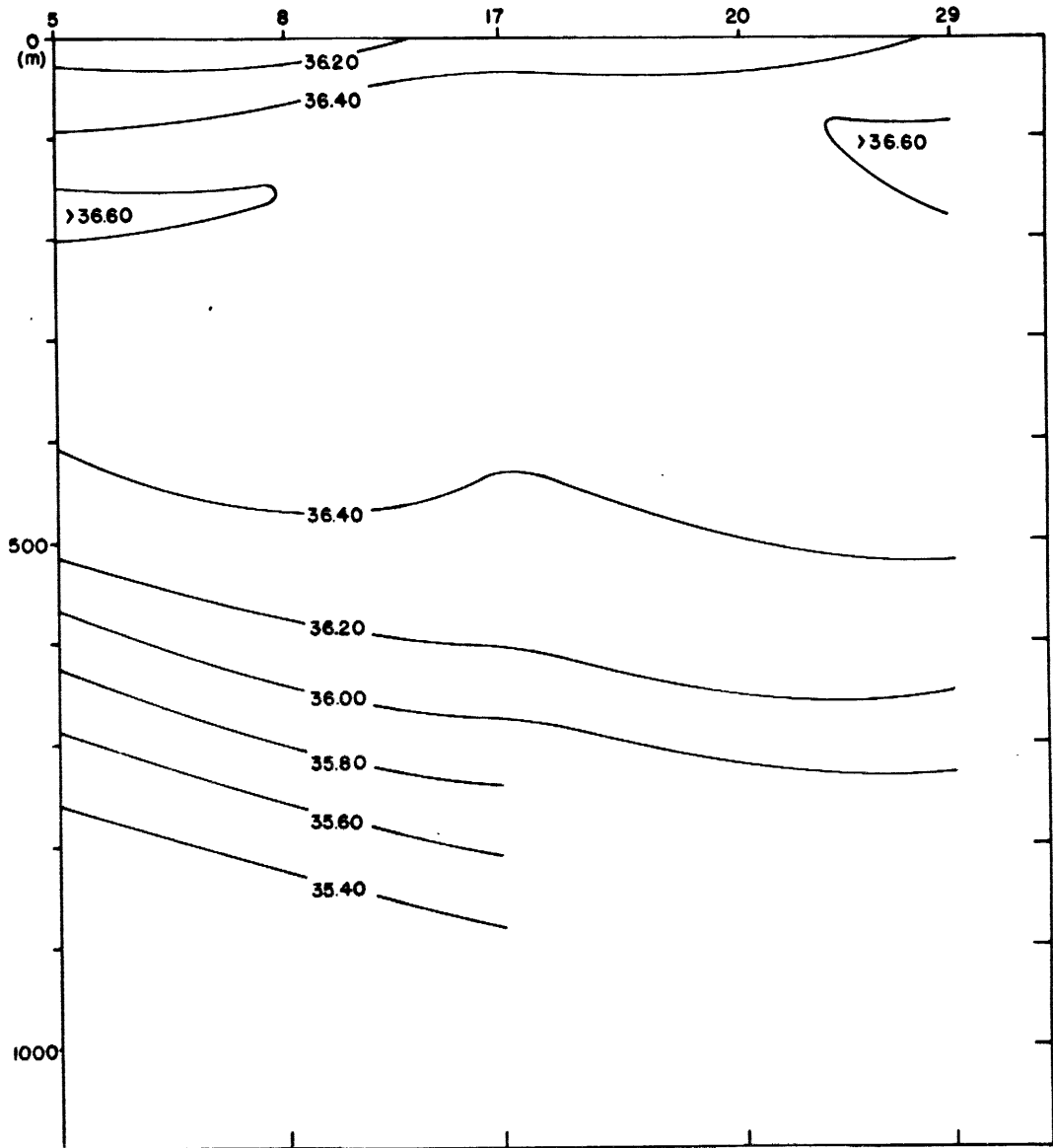


FIGURE 10

Salinity Profile Line Five, Second Occupation

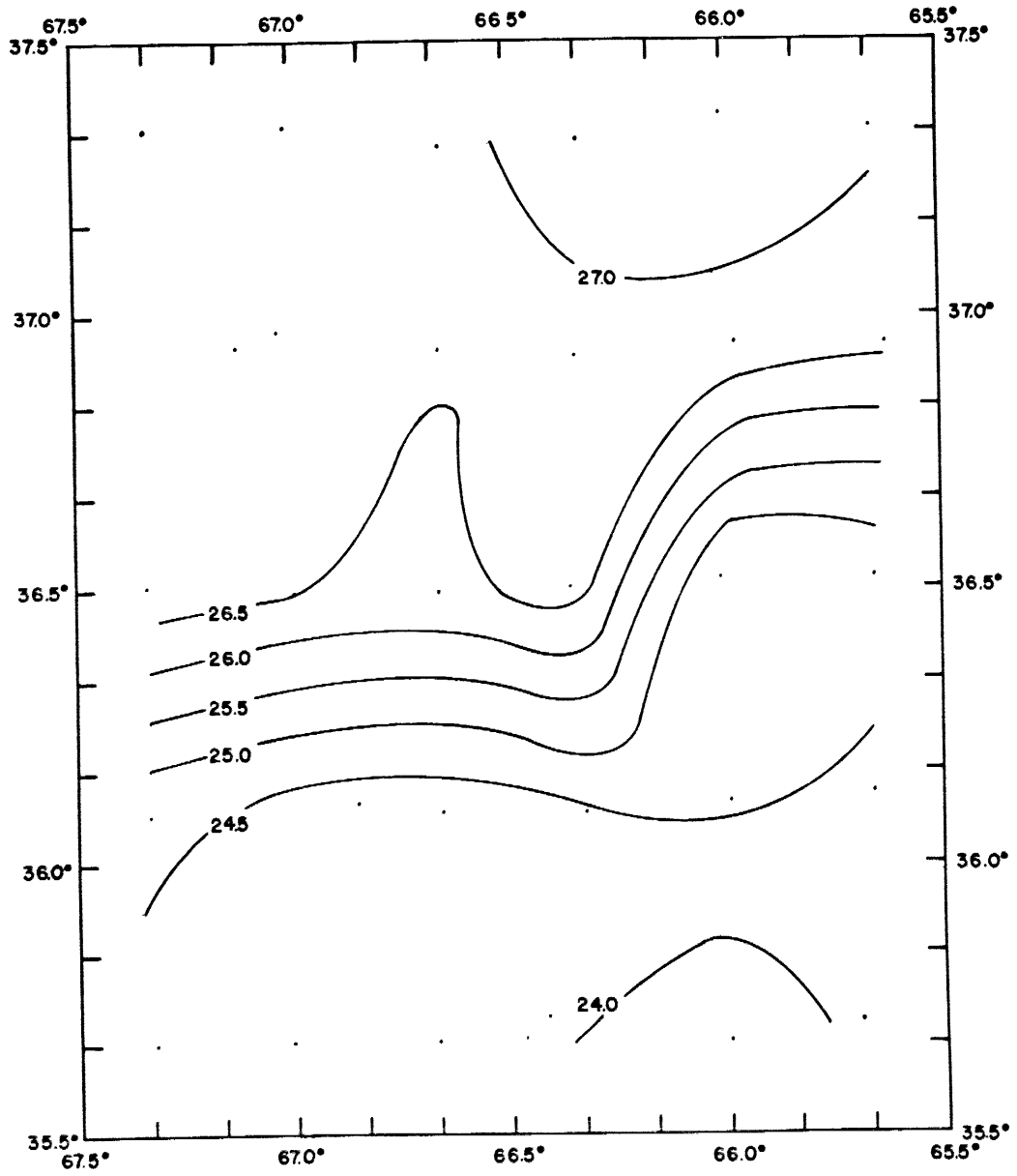


FIGURE II
Surface Temperature Contours, First Occupation

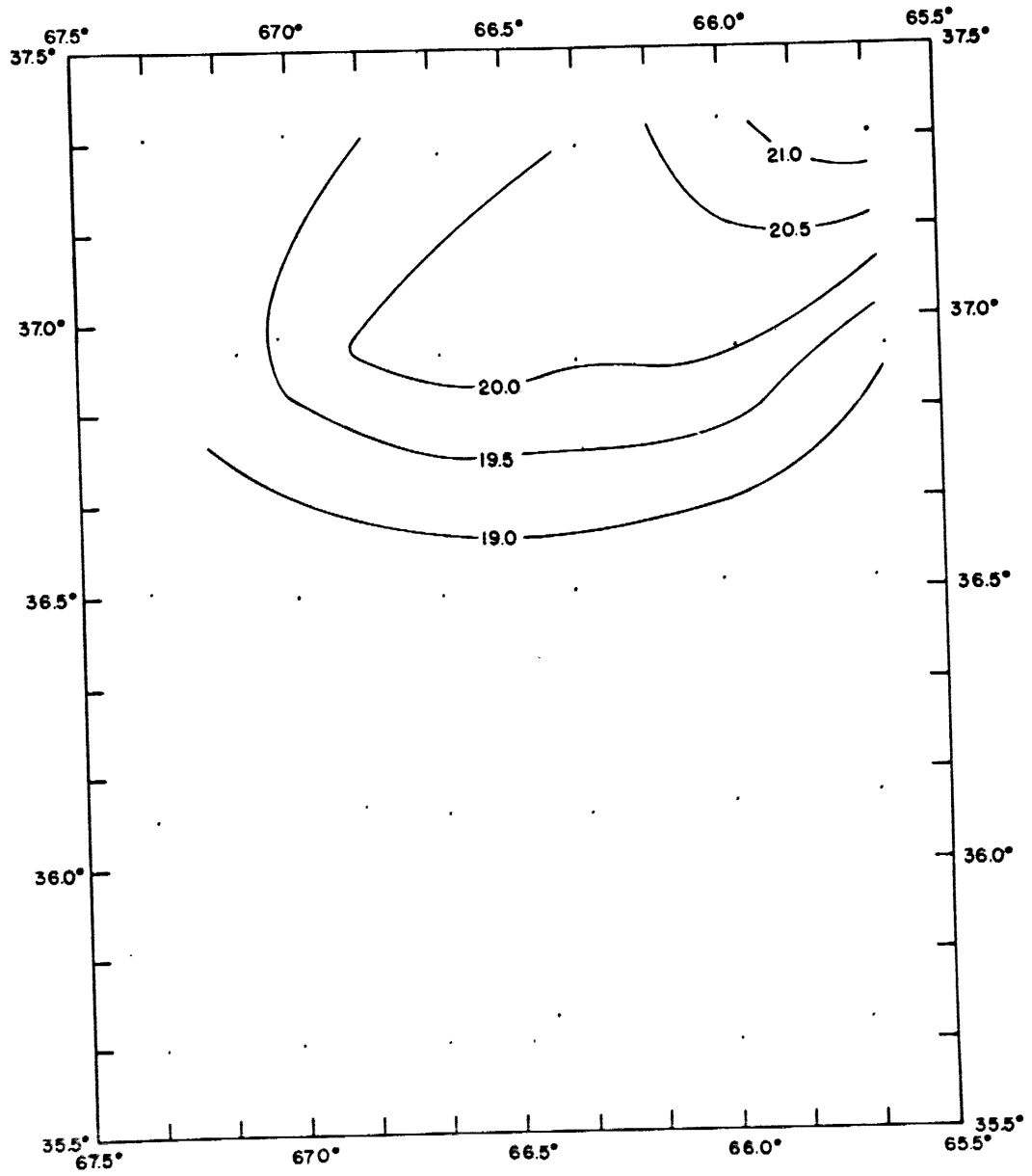


FIGURE 12
200 m Temperature Contours, First Occupation

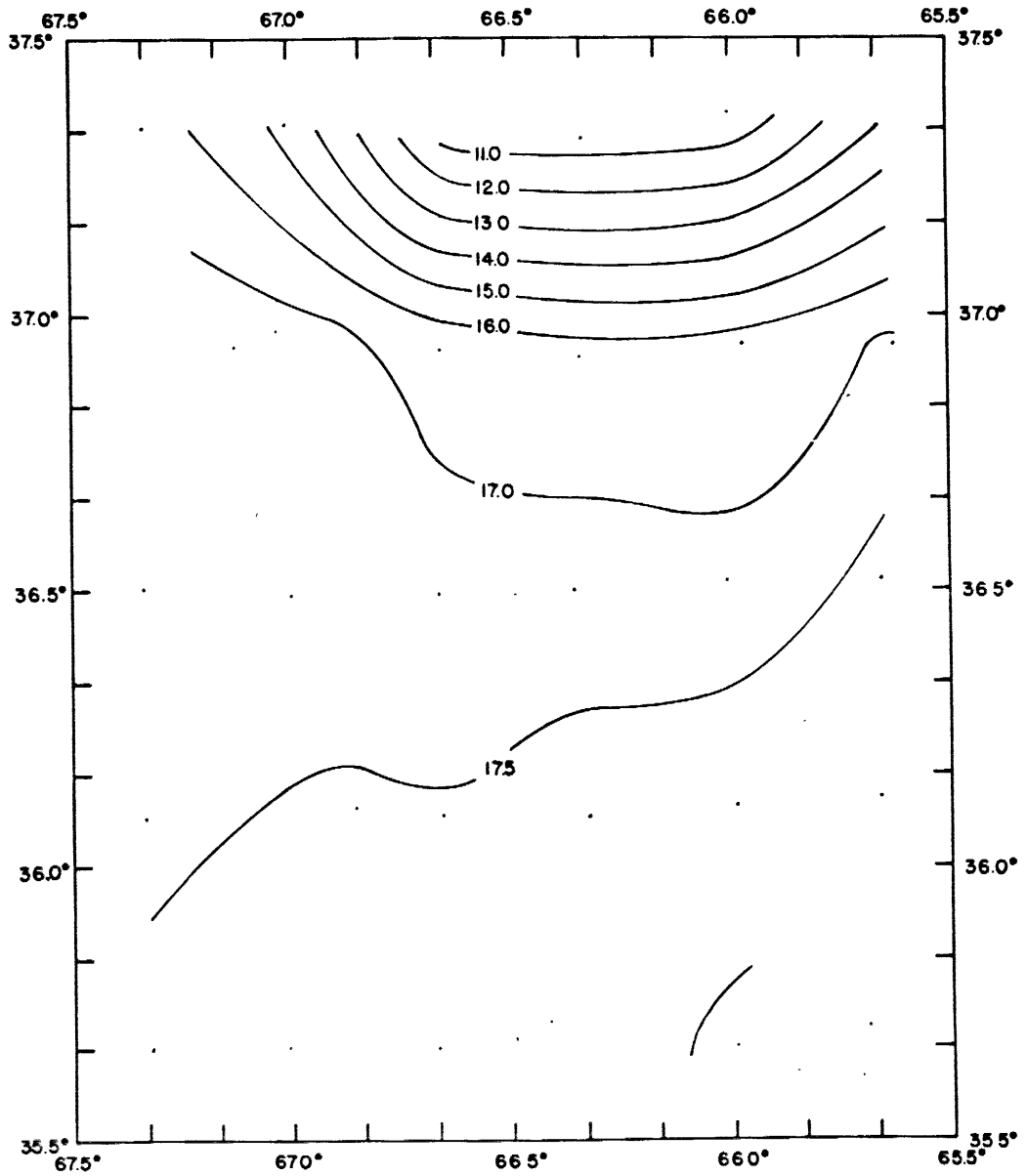


FIGURE 13
500 m Temperature Contours, First Occupation

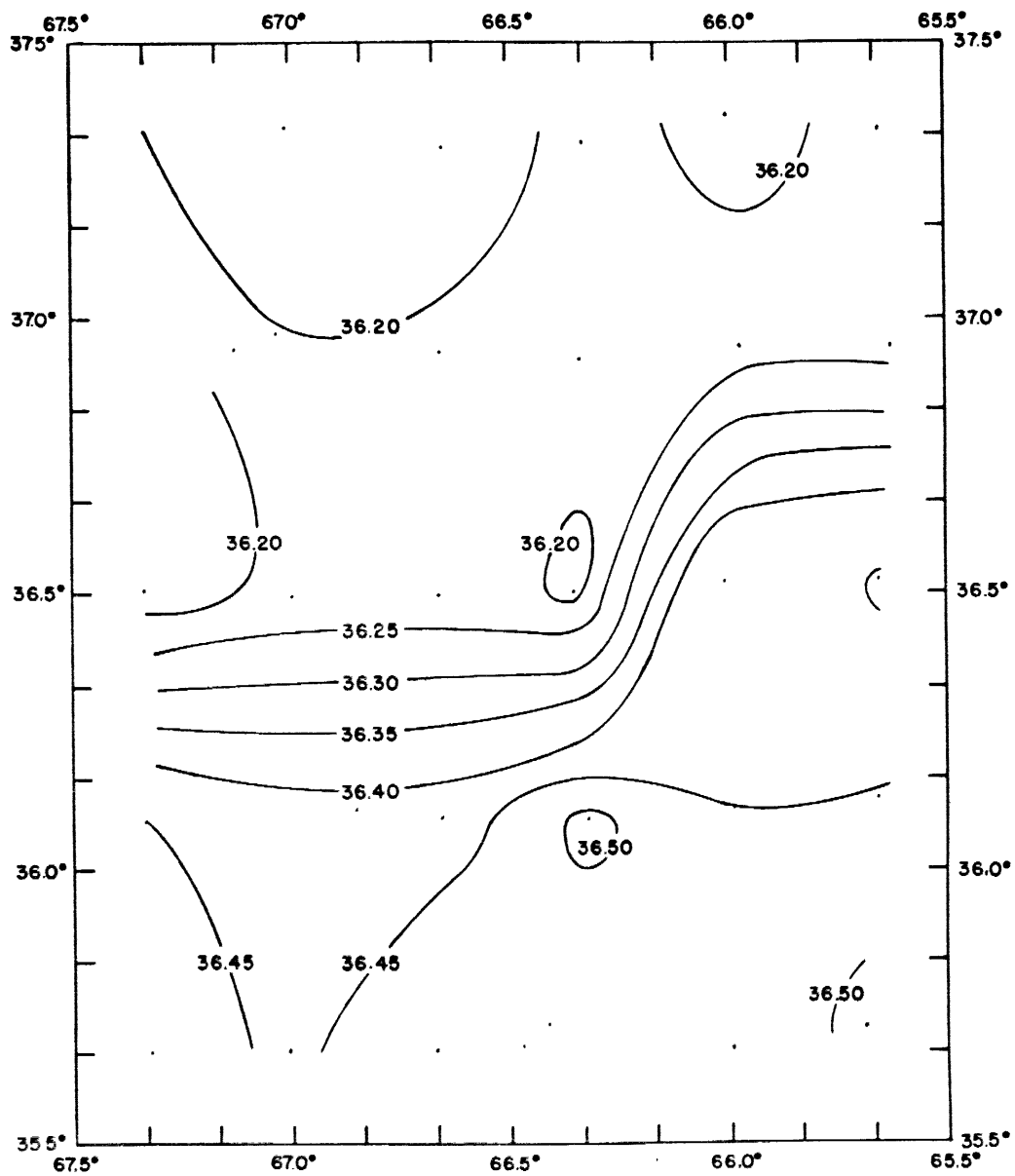


FIGURE 14

Surface Salinity Contours, First Occupation

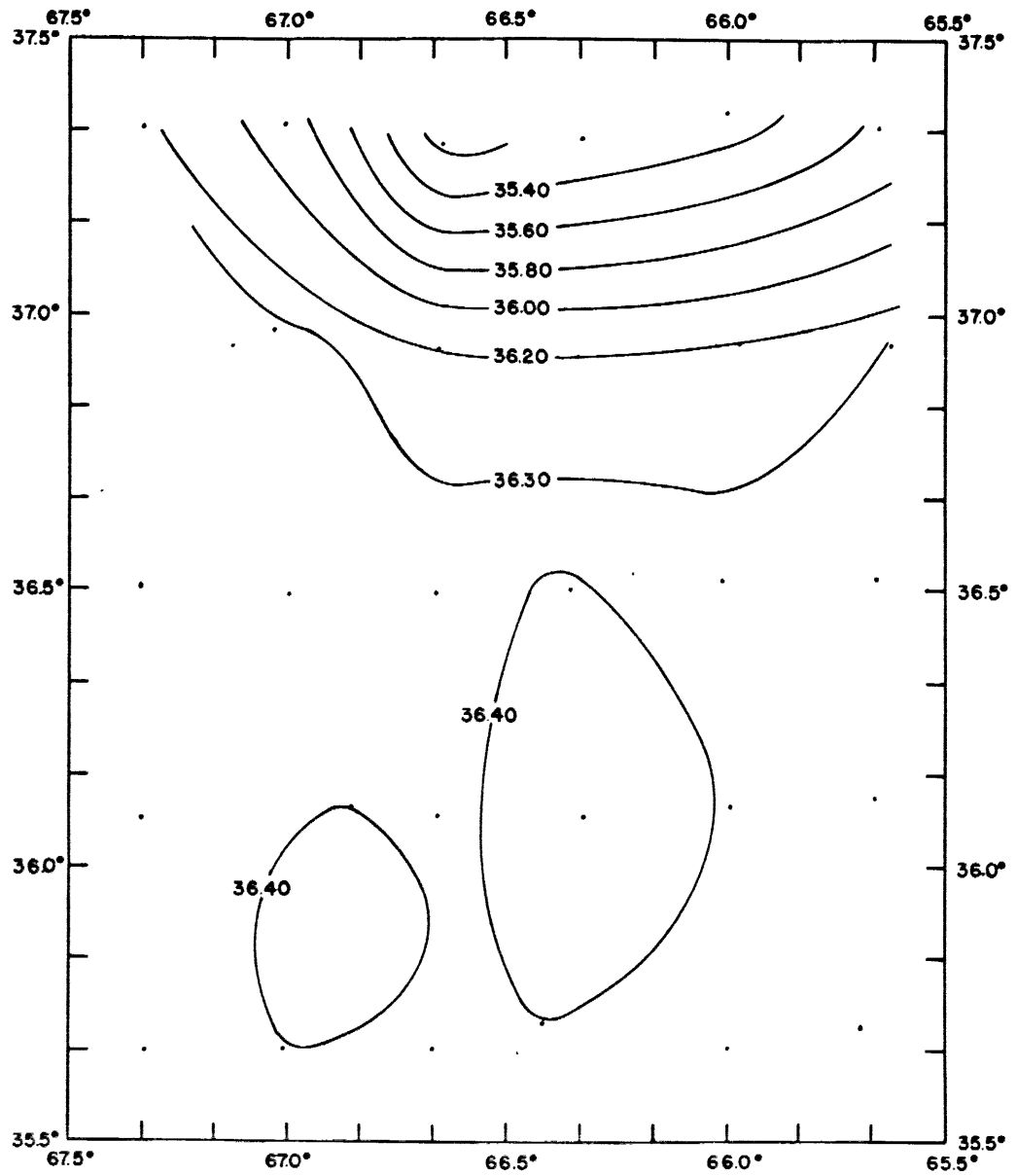


FIGURE 15

500 m Salinity Contours, First Occupation

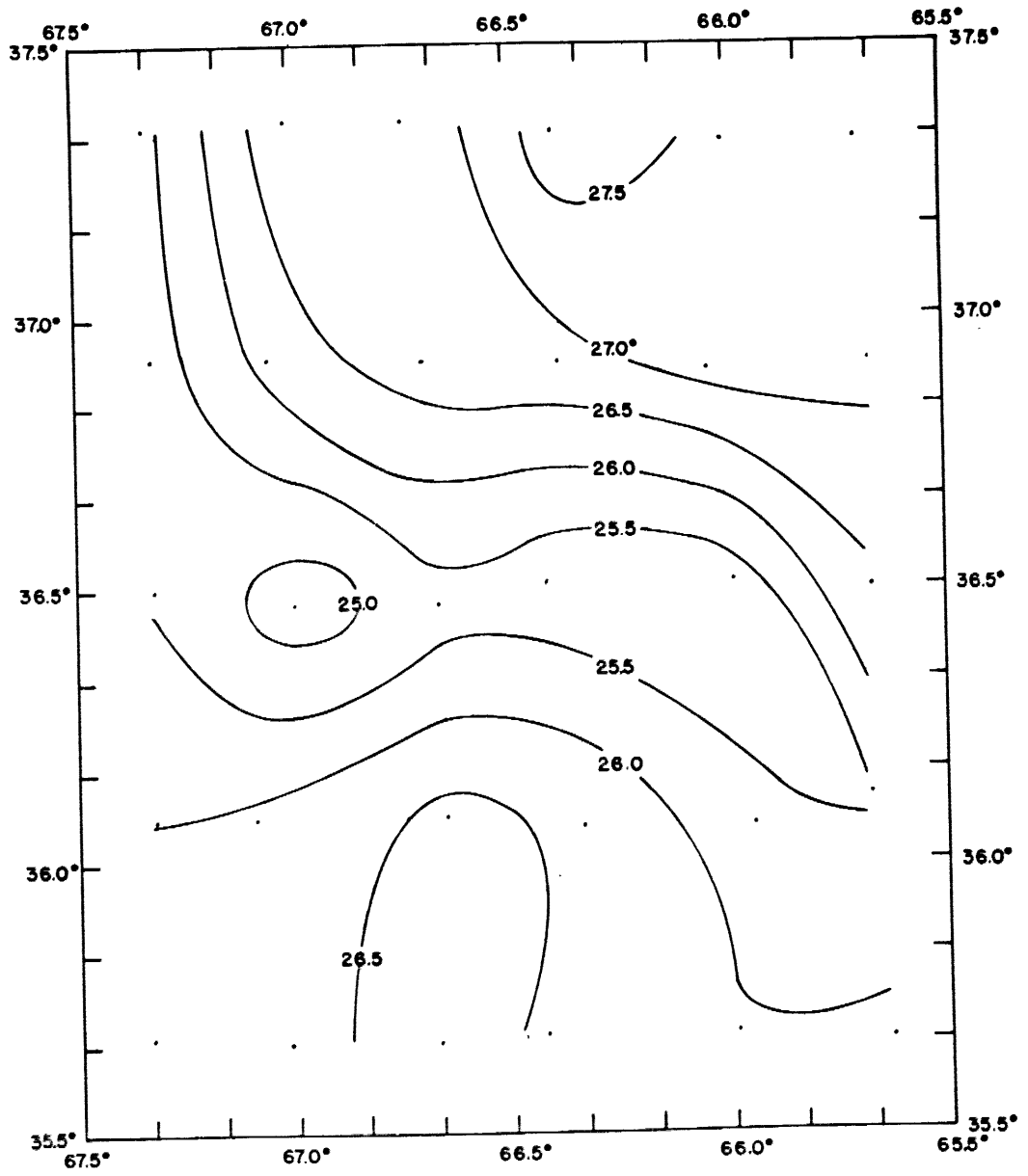


FIGURE 16

Surface Temperature Contours, Second Occupation

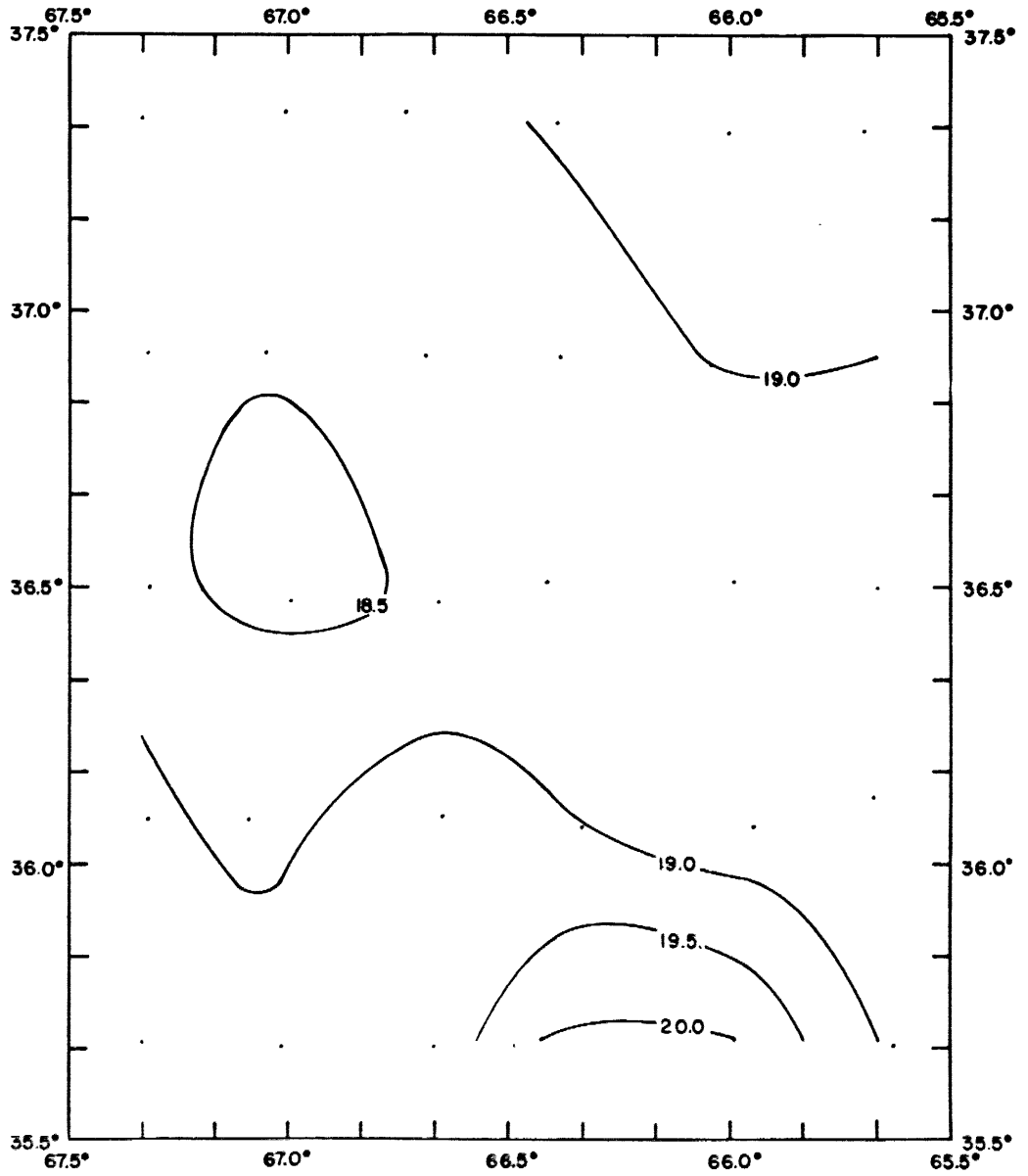


FIGURE 17

200 m. Temperature Contours, Second Occupation

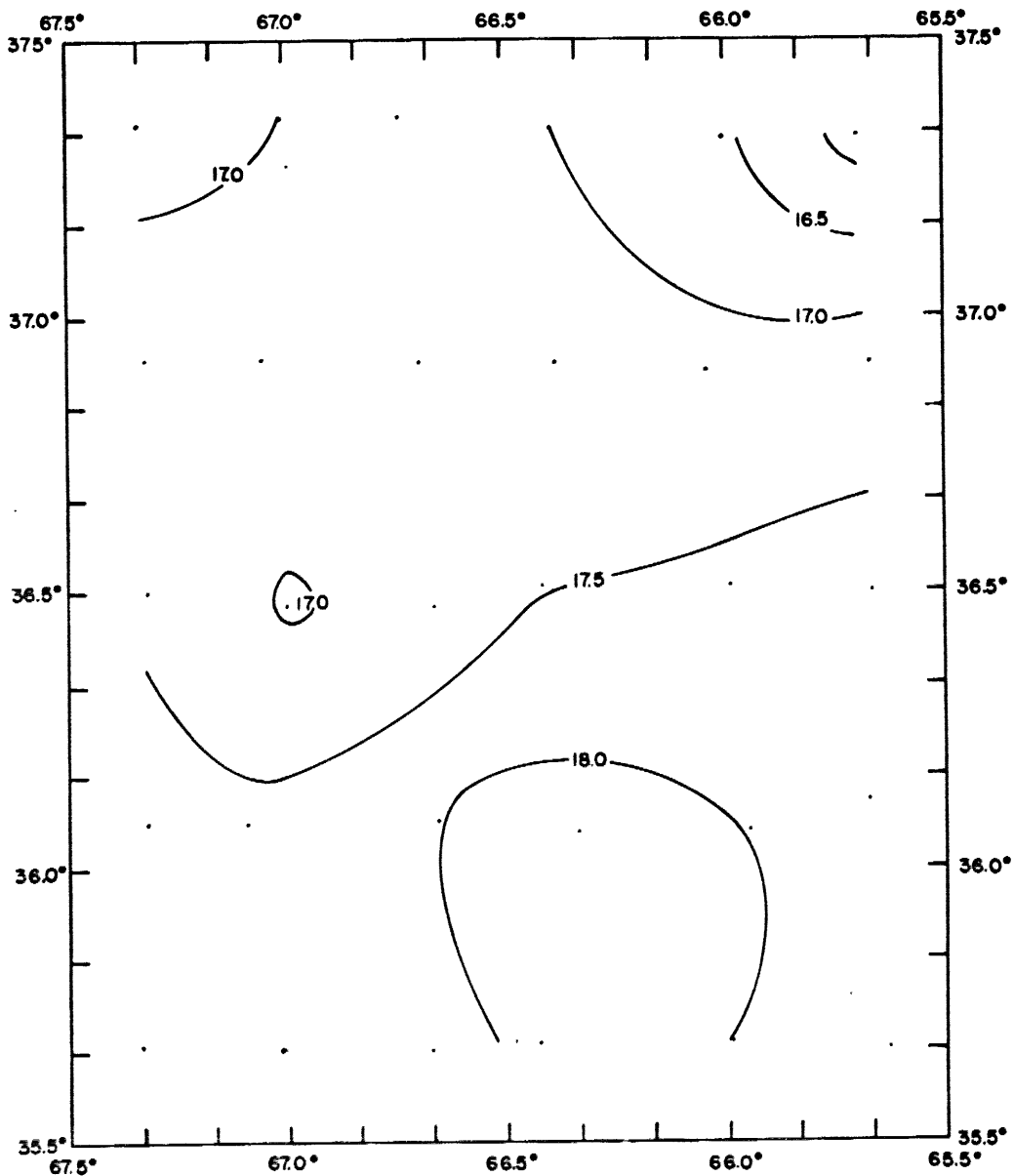


FIGURE 18

500 m. Temperature Contours, Second Occupation

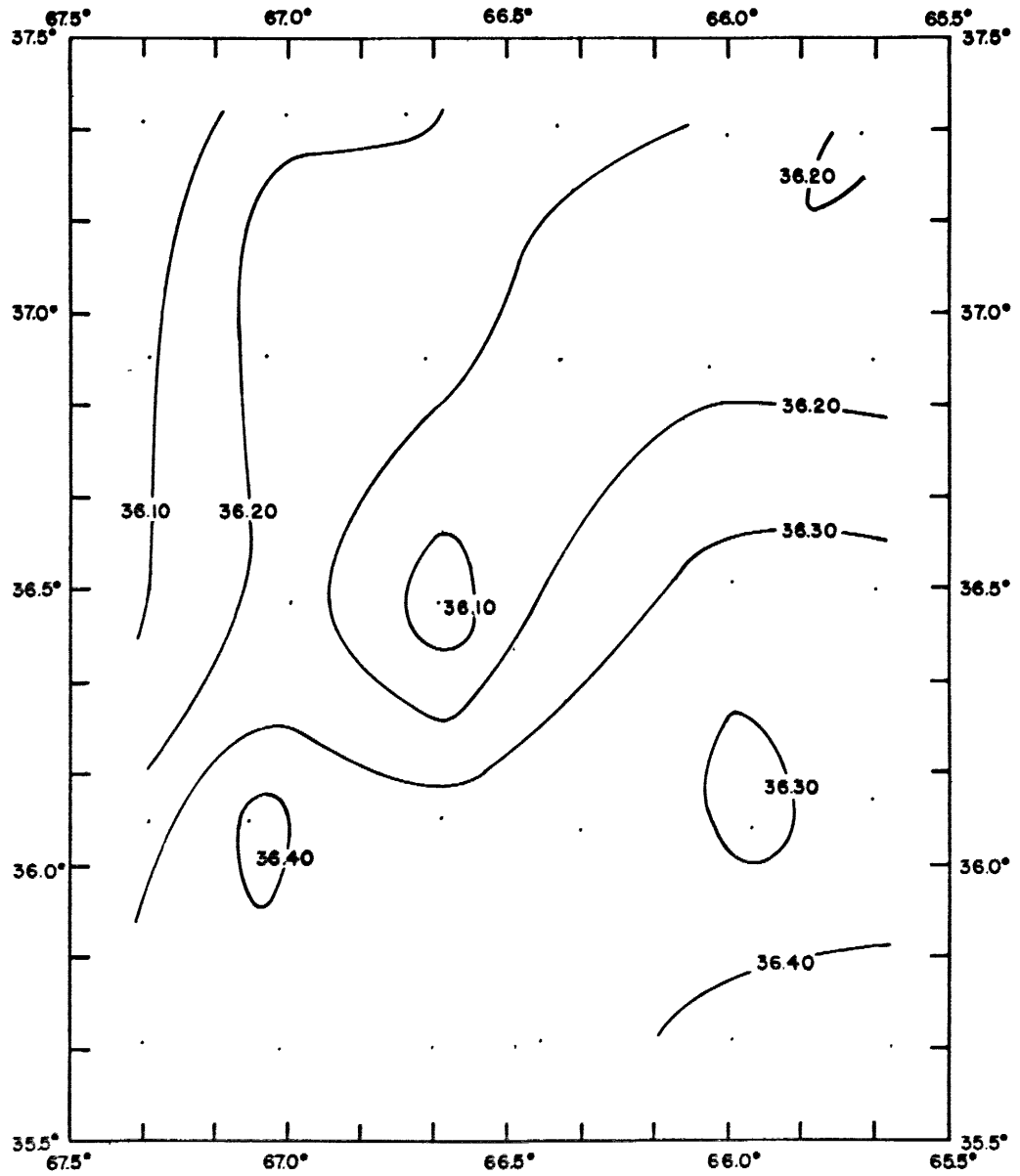


FIGURE 19
Surface Salinity Contours. Second Occupation

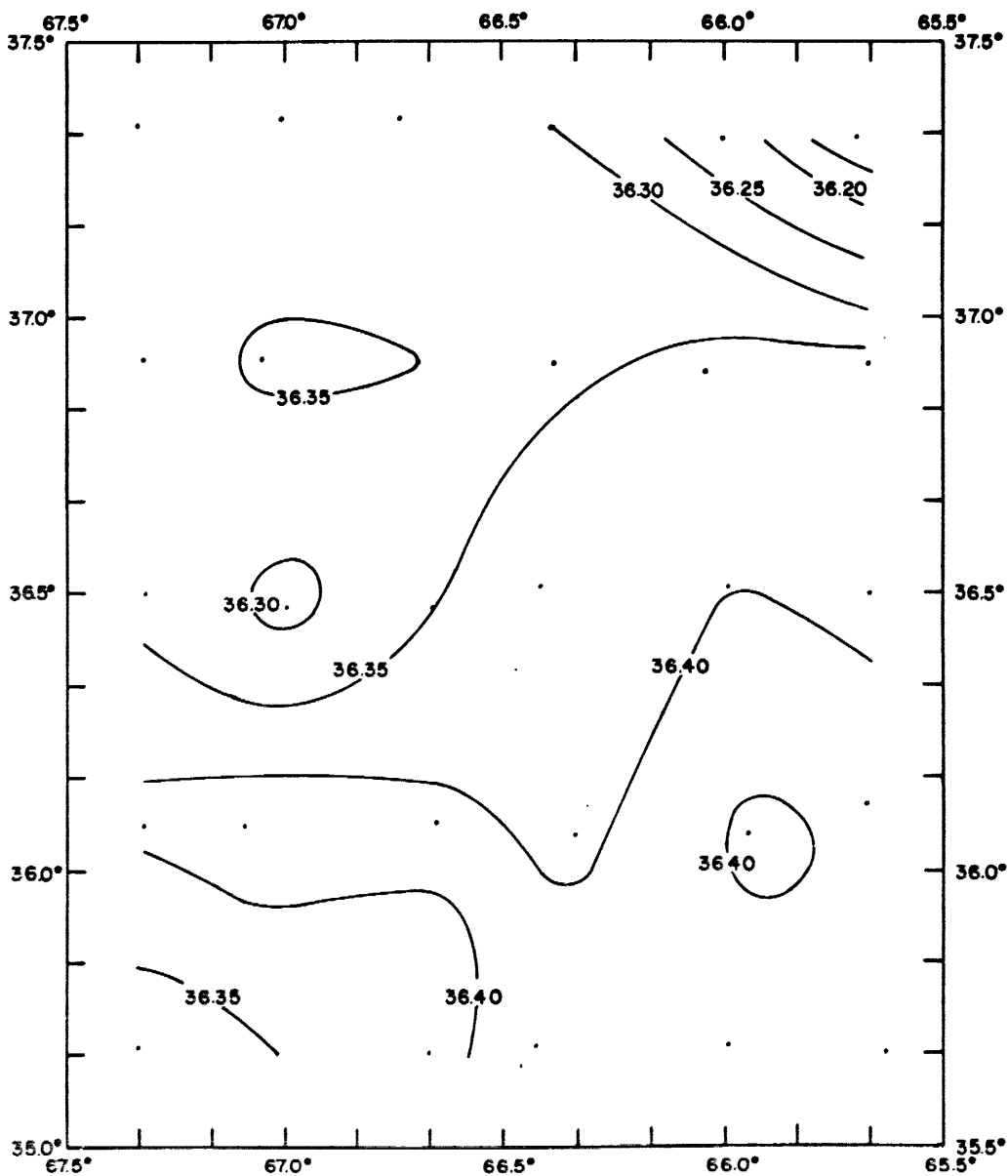


FIGURE 20

500 m. Salinity Contours, Second Occupation

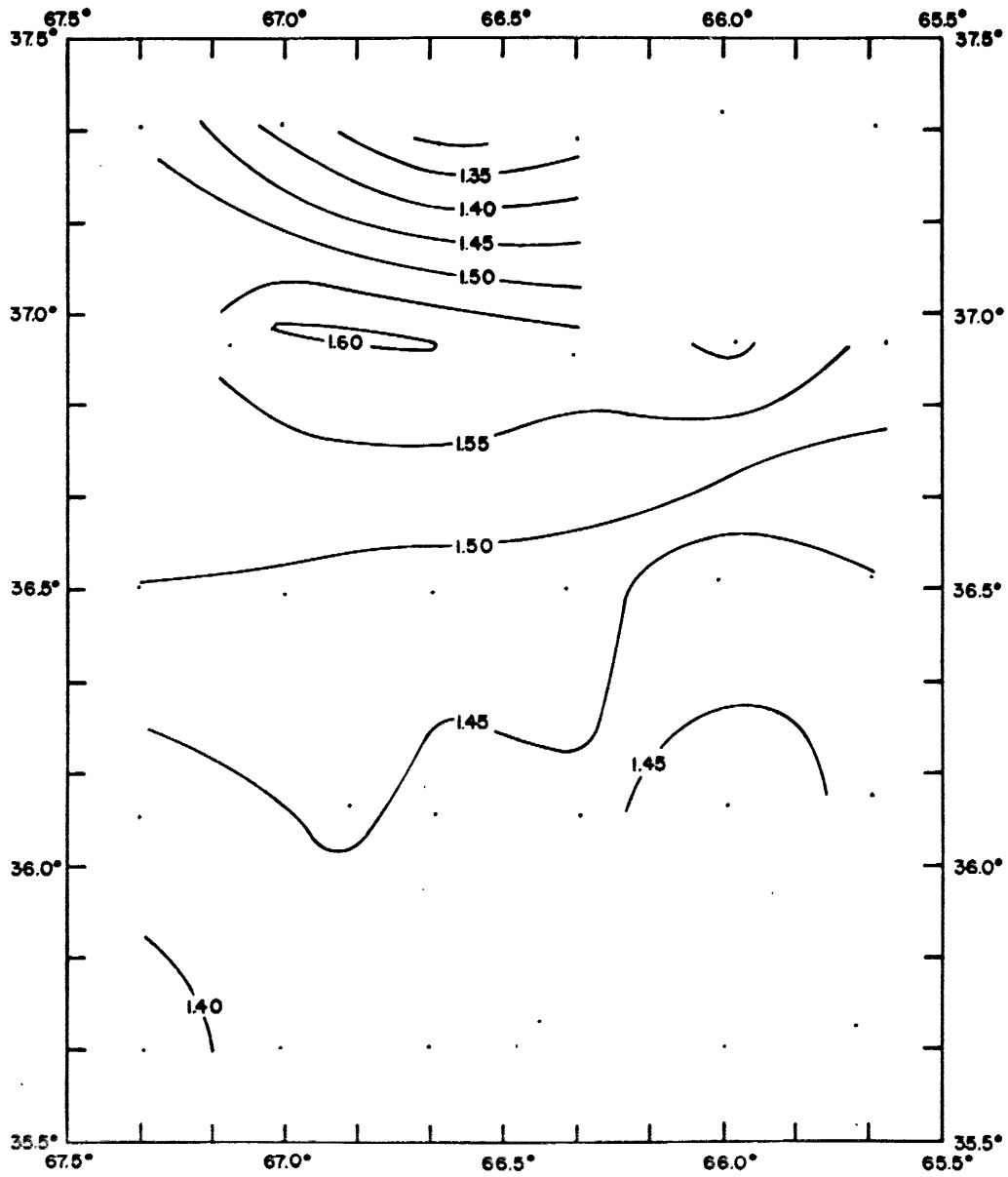


FIGURE 21

Dynamic Heights Relative to 800m, First Occupation

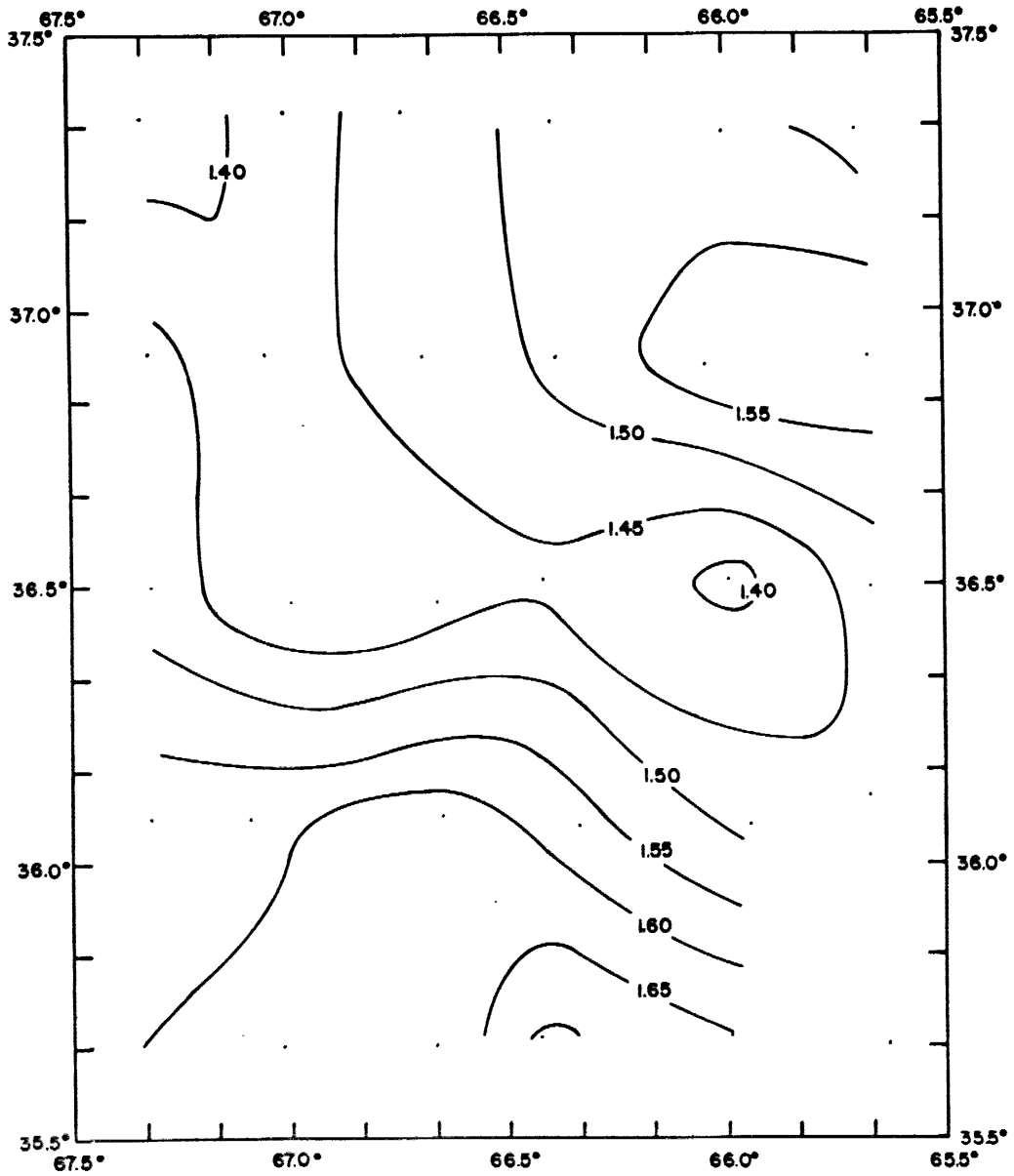


FIGURE 22

Dynamic Heights Relative to 800 m., Second Occupation

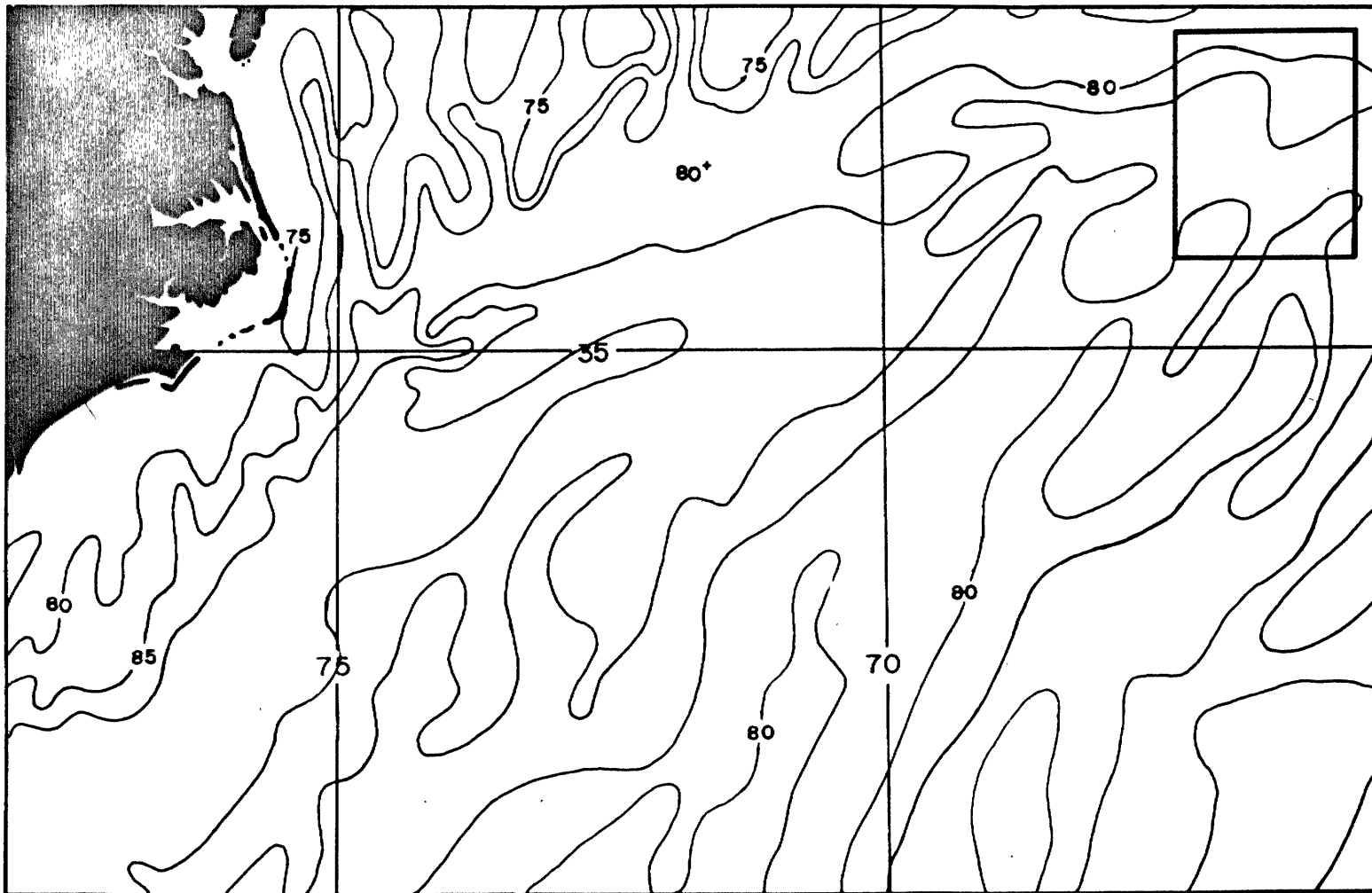


FIGURE 23
Average Sea Surface Temperature Over 5 Day Period (July 7-12) F°

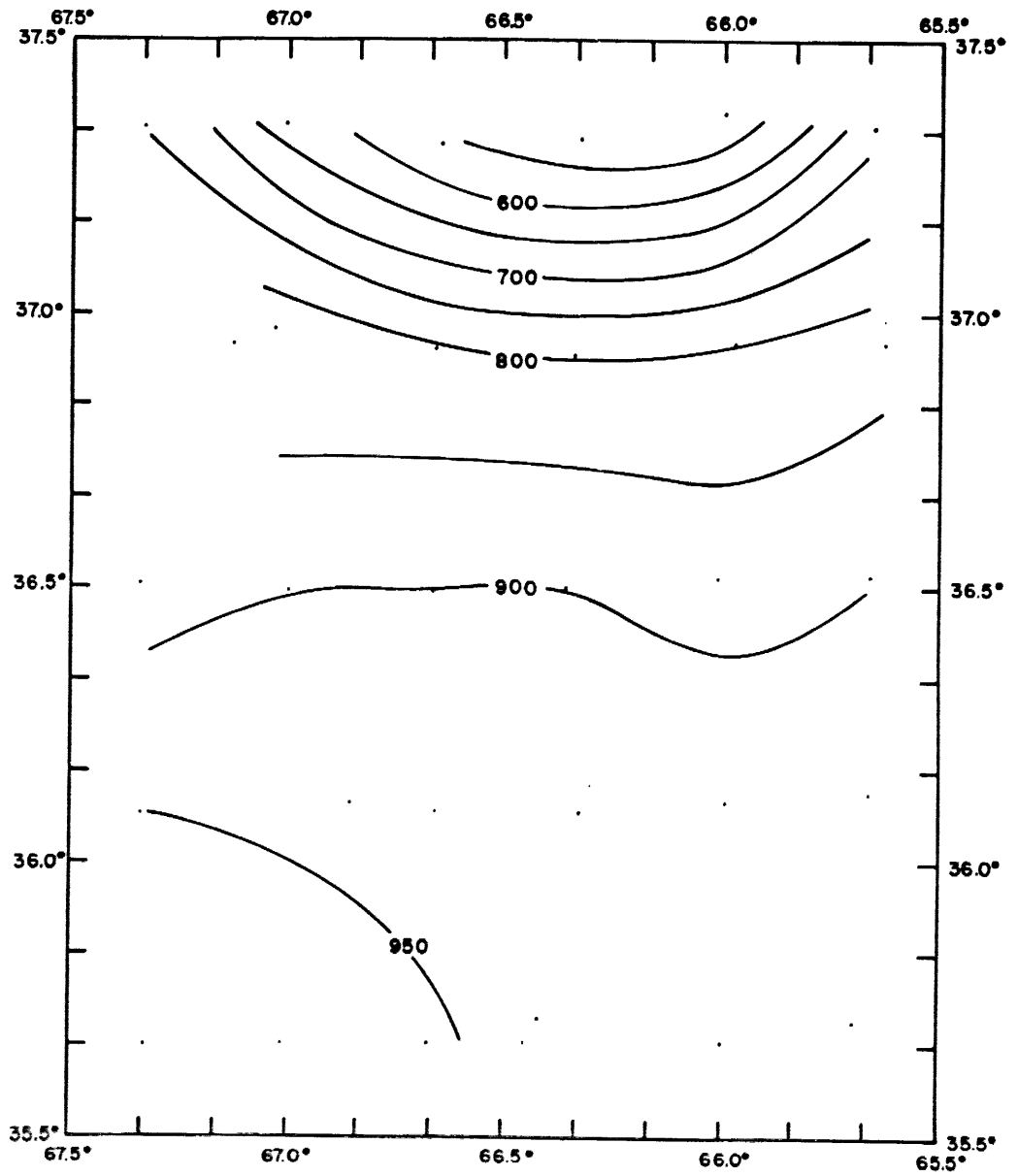


FIGURE 24

Depth of 10° Isotherm, First Occupation

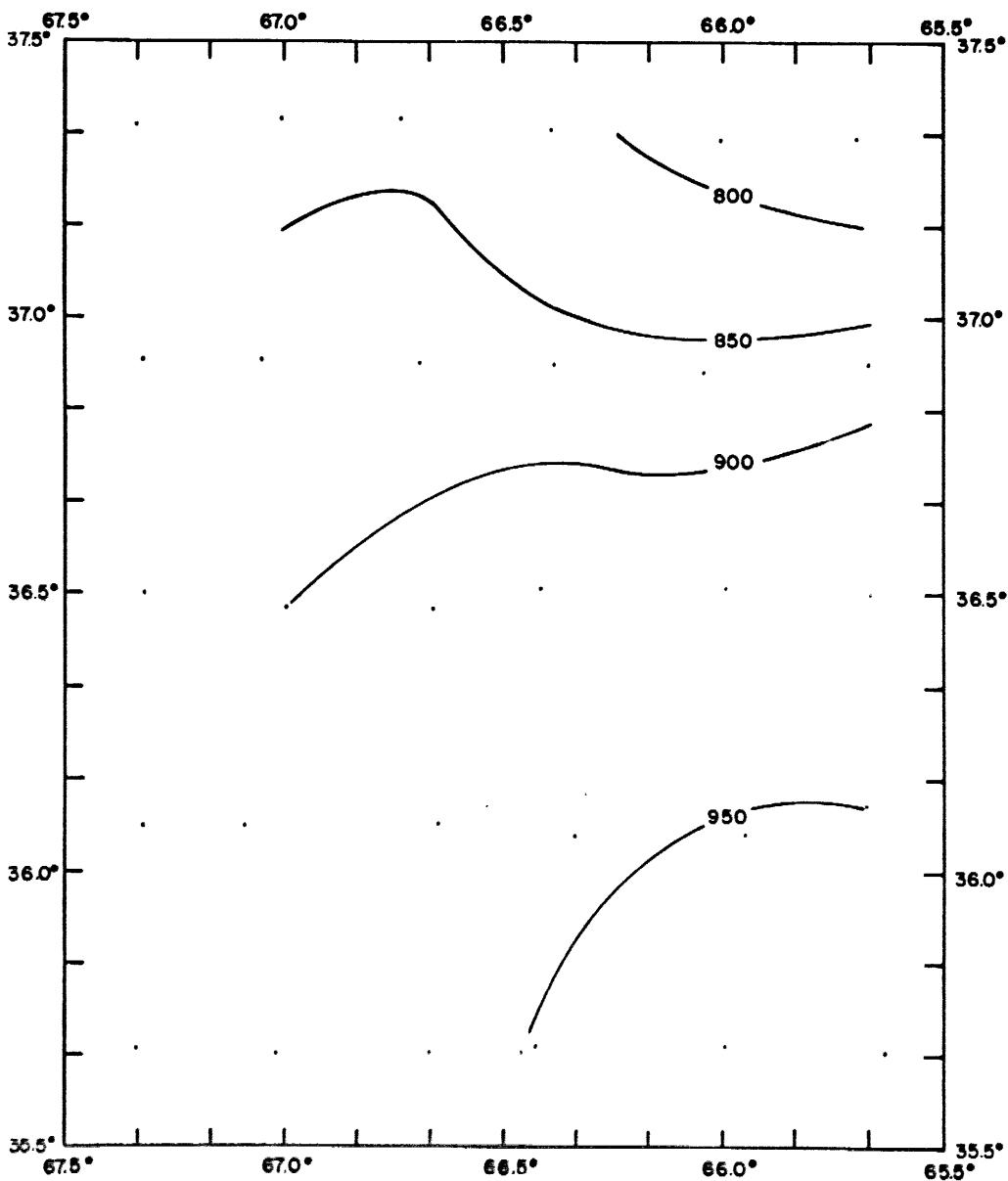


FIGURE 25

Depth of 10° Isotherm, Second Occupation

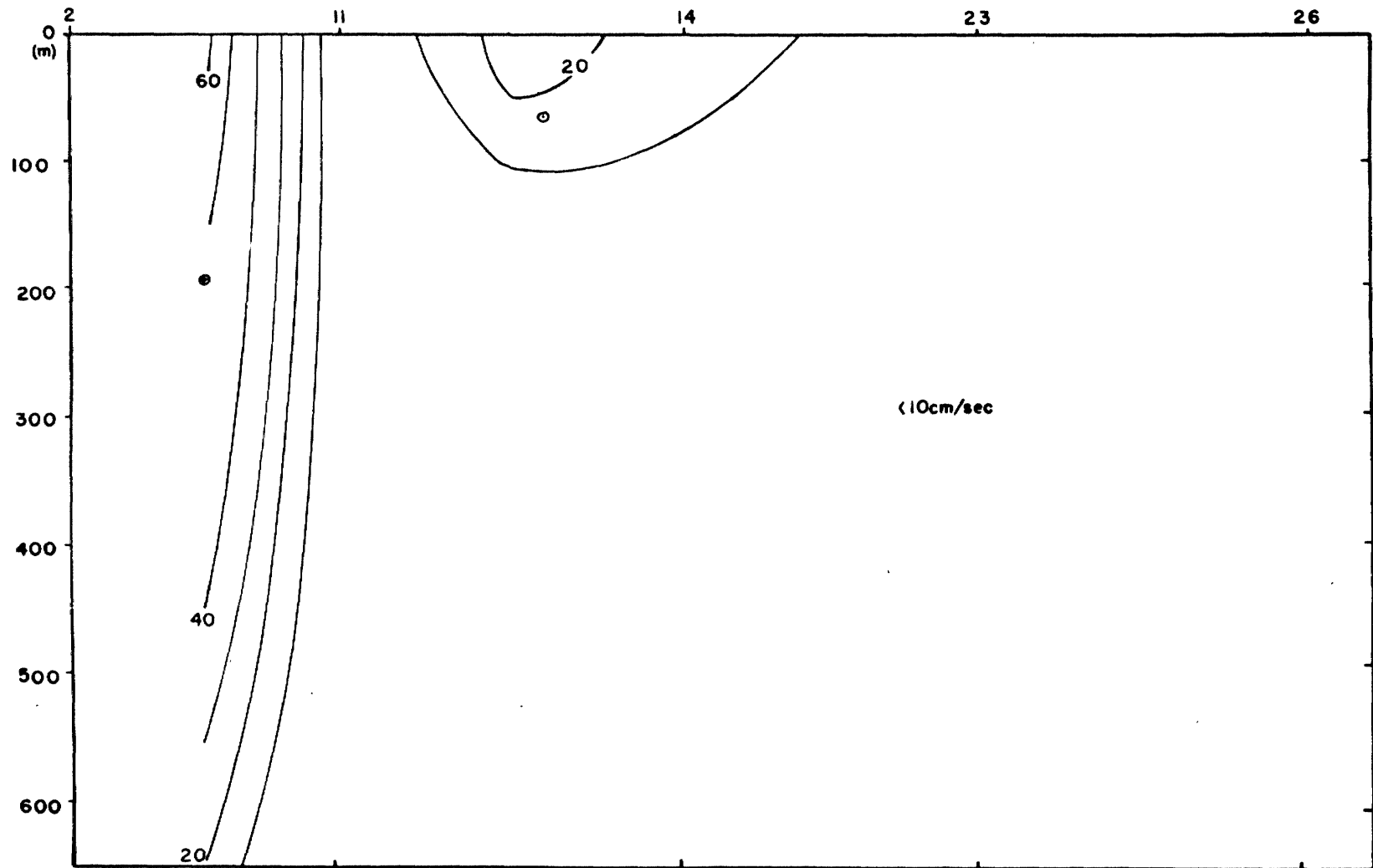


FIGURE 26
 Velocity Profile Line Two, First Occupation

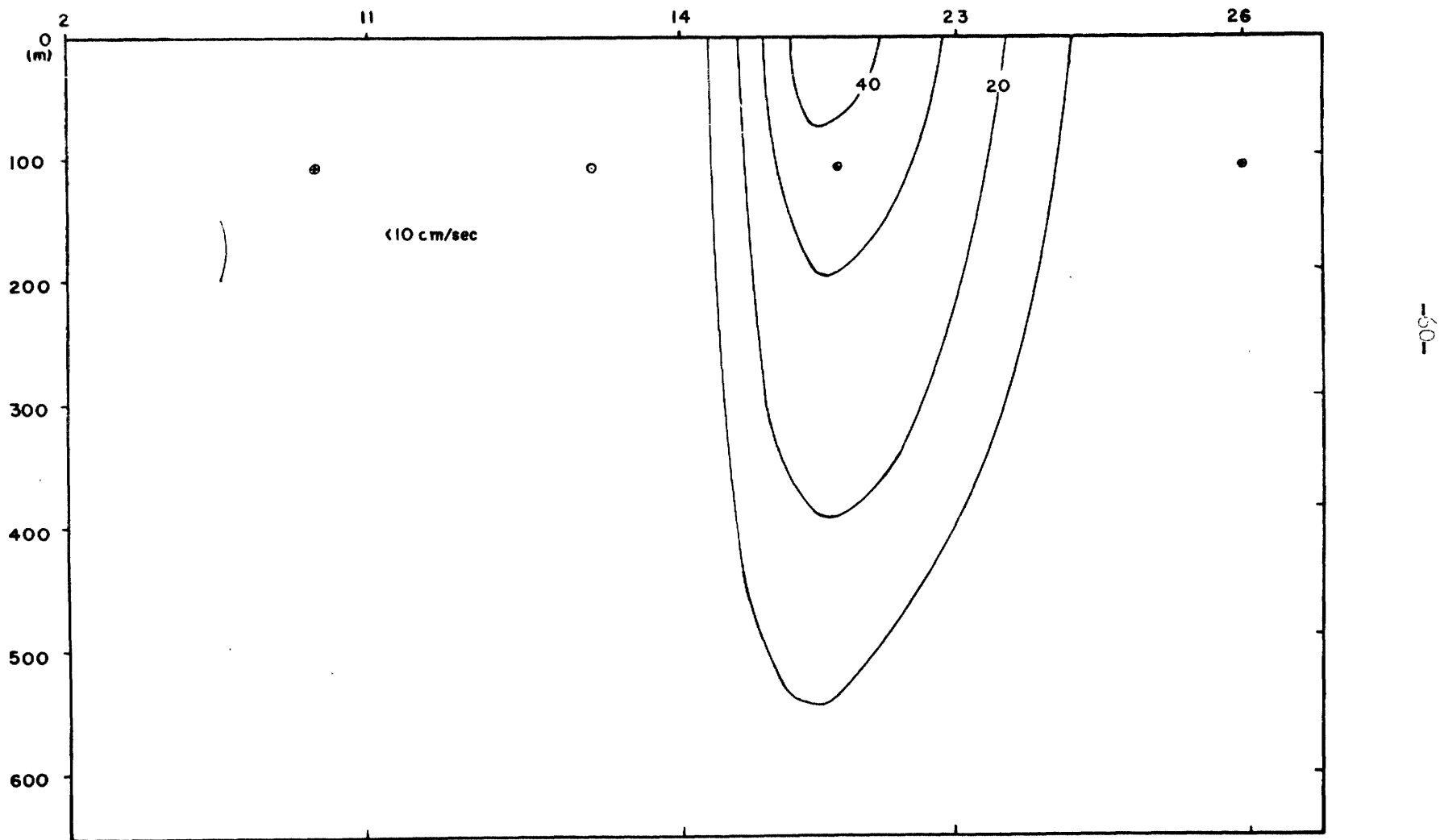


FIGURE 27

Velocity Profile Line Two, Second Occupation

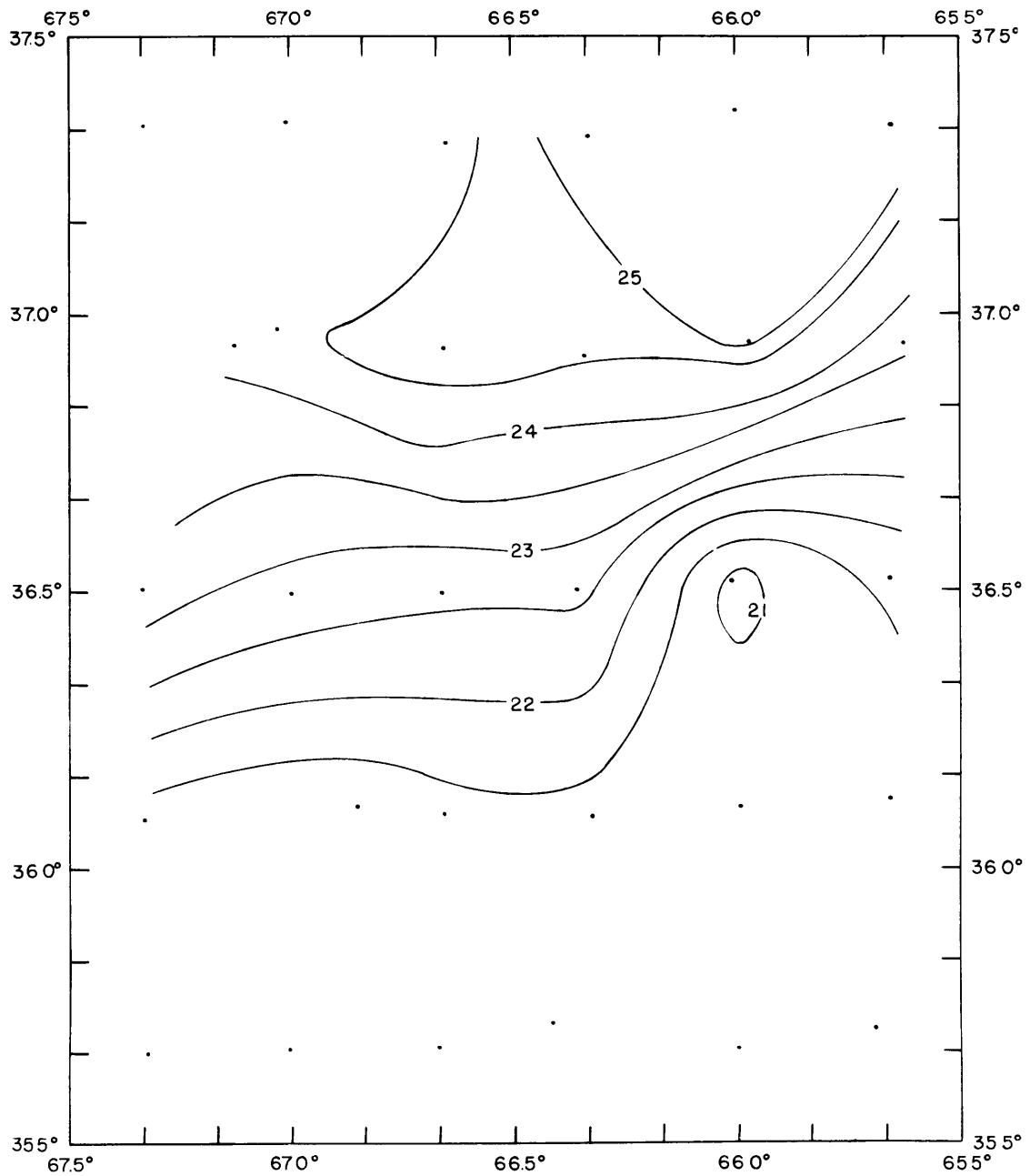


FIGURE 28

Average Temperature Upper 200 m., First Occupation

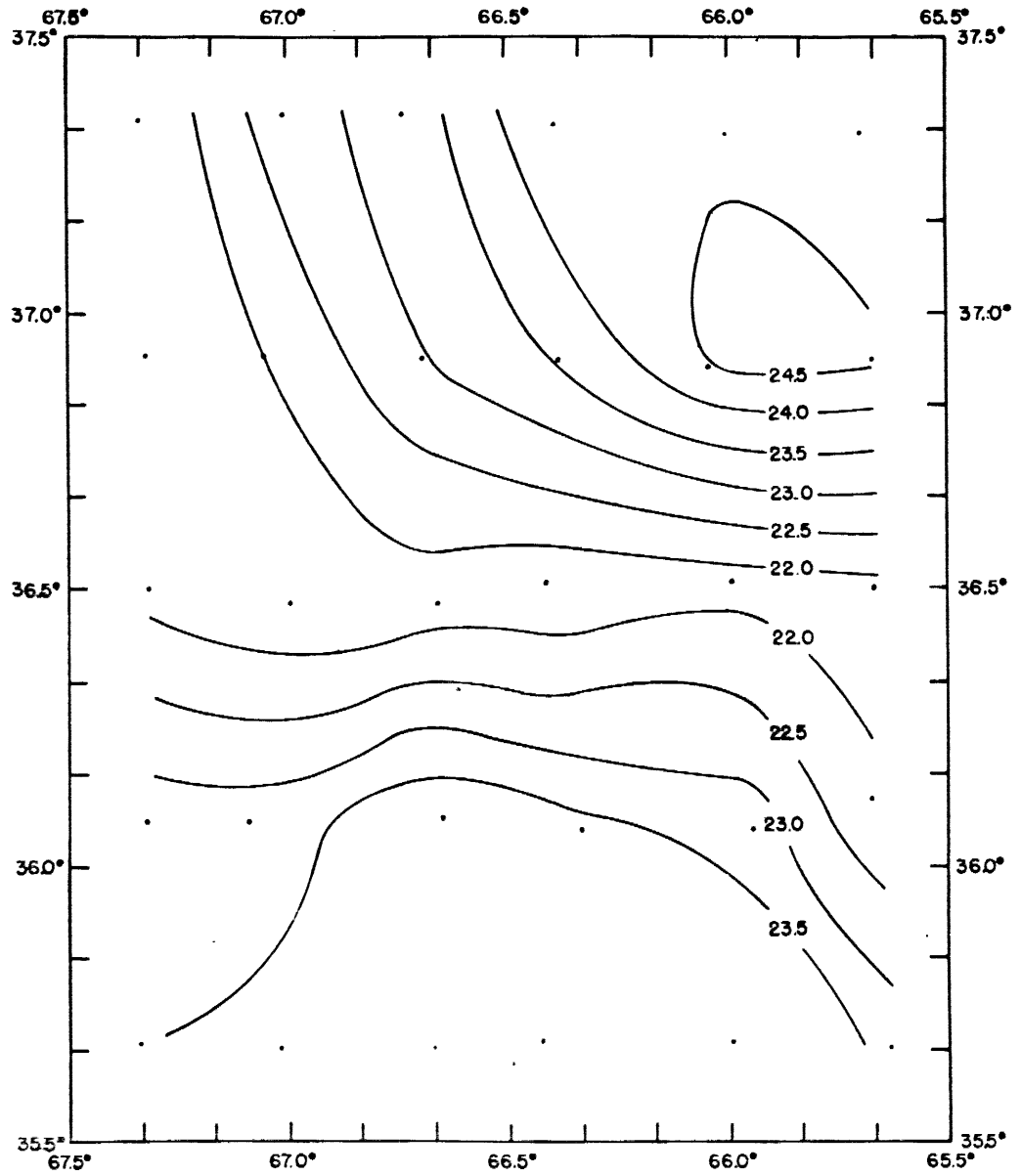


FIGURE 29
Average Temperature Upper 200m Second Occupation

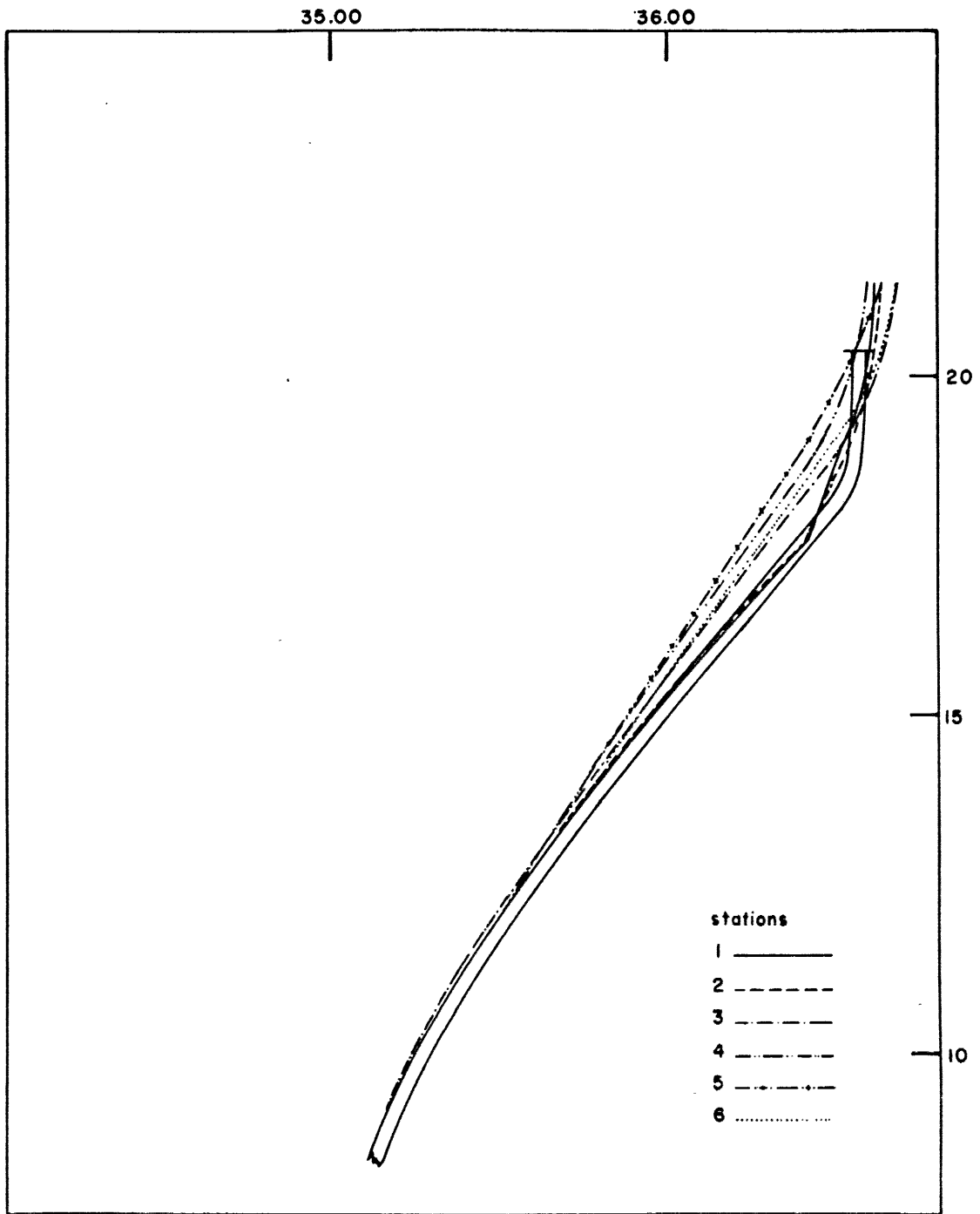


FIGURE 30

Gulf Stream T-S Curves Compared to Average T-S Curve

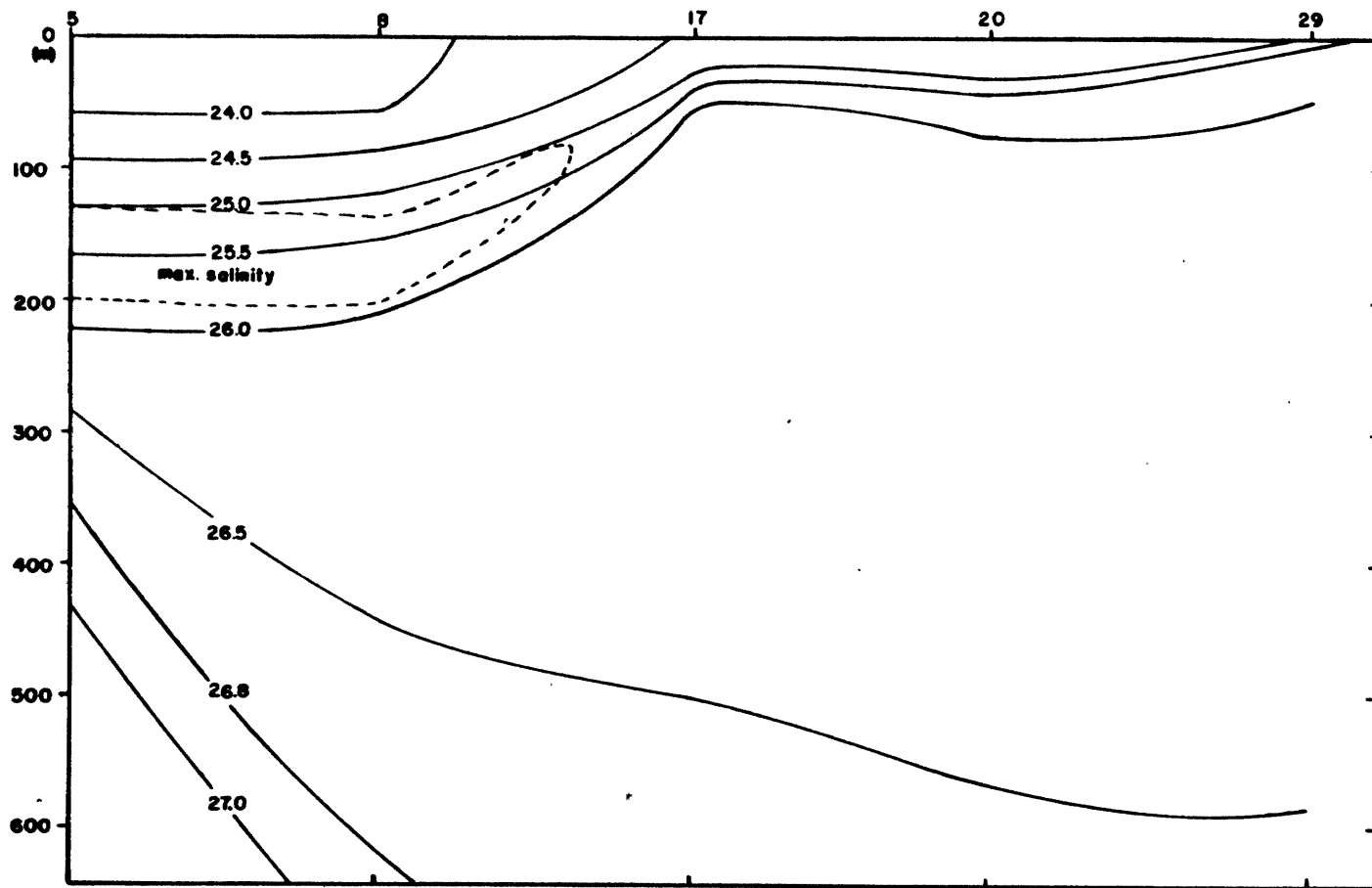


FIGURE 31
 Q₁ Profile Line Five, First Occupation

49

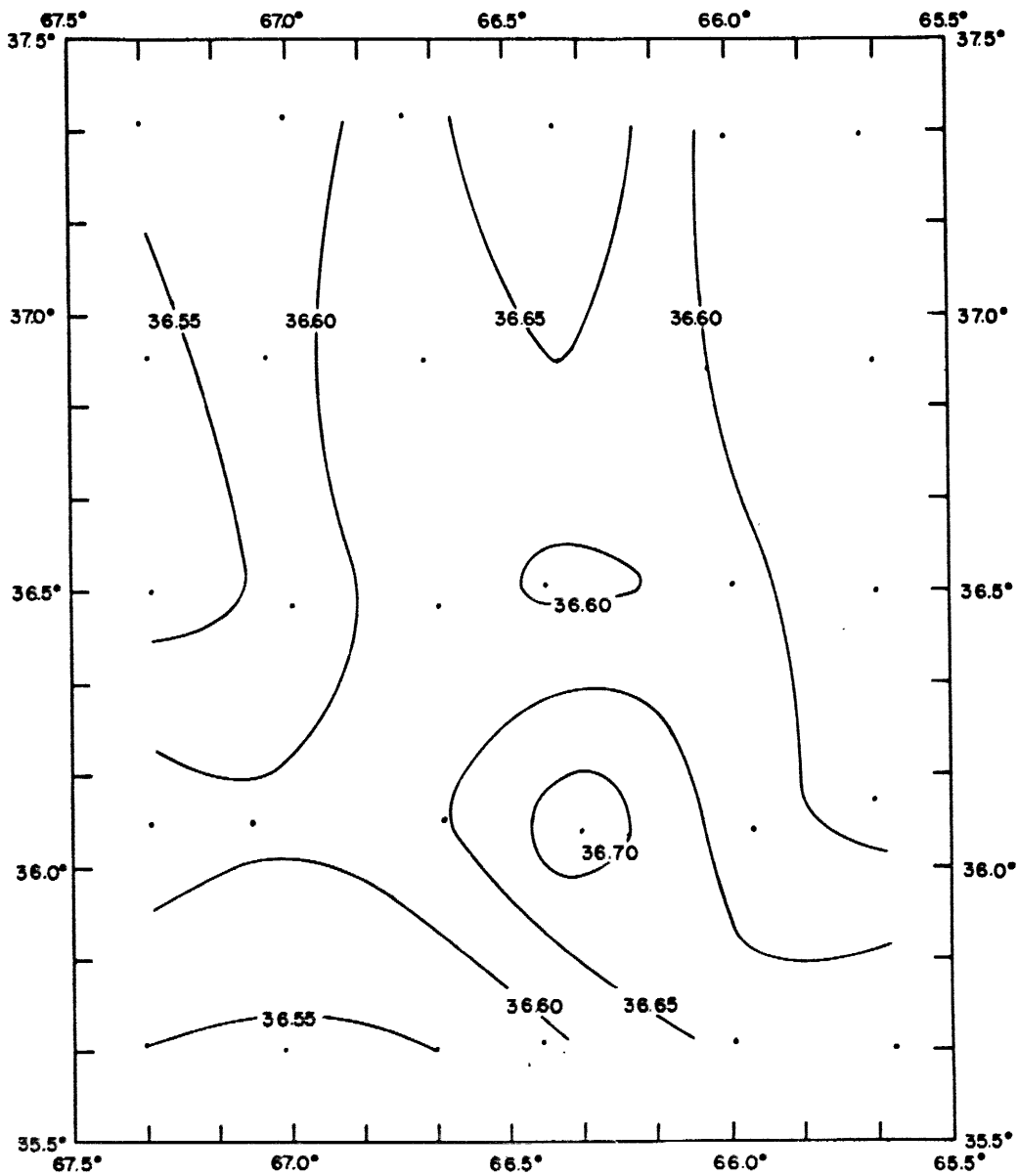


FIGURE 32

Salinity Maximum 20-200 m, Second Occupation

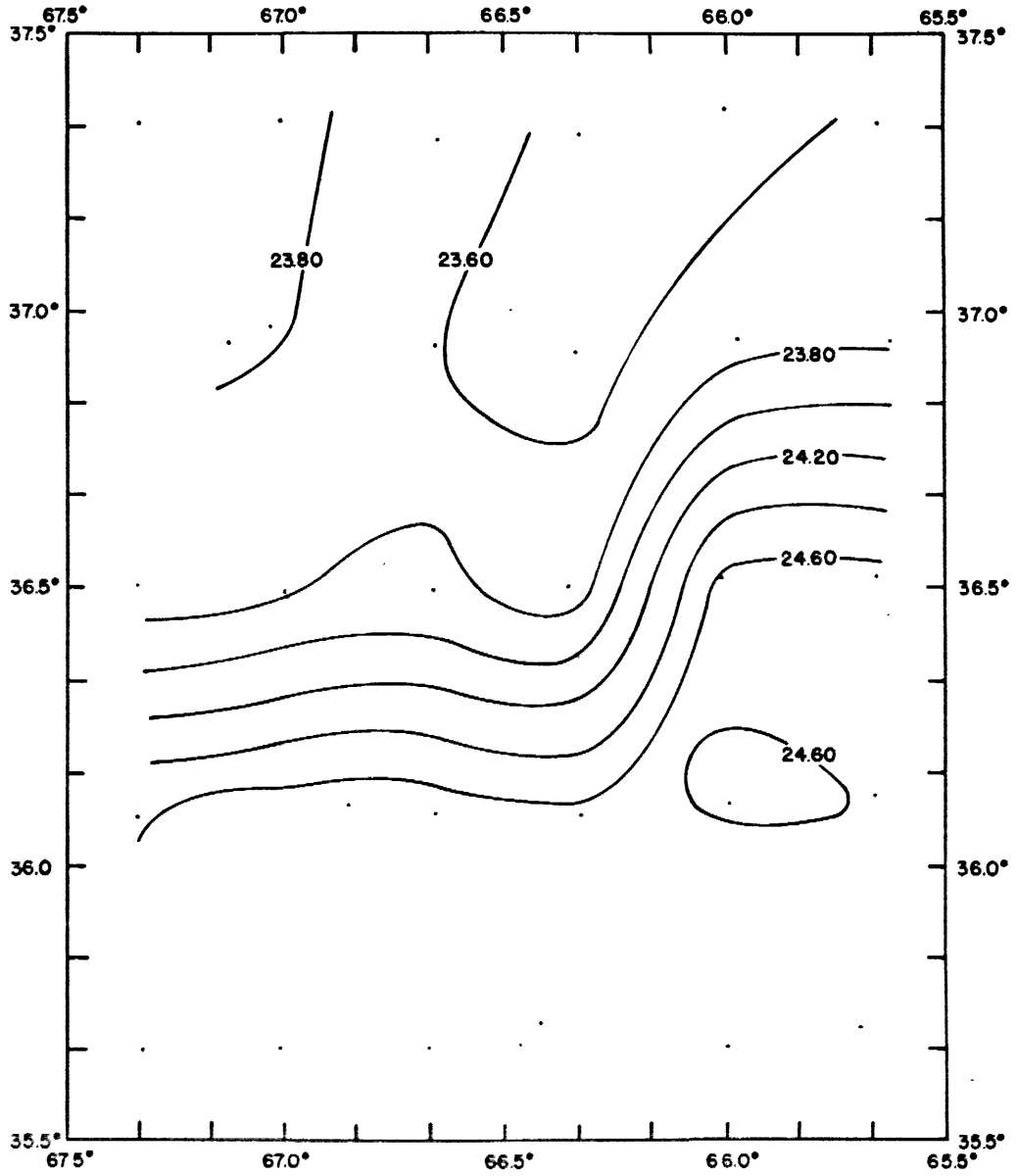


FIGURE 33
Surface Q_1 Contours, First Occupation

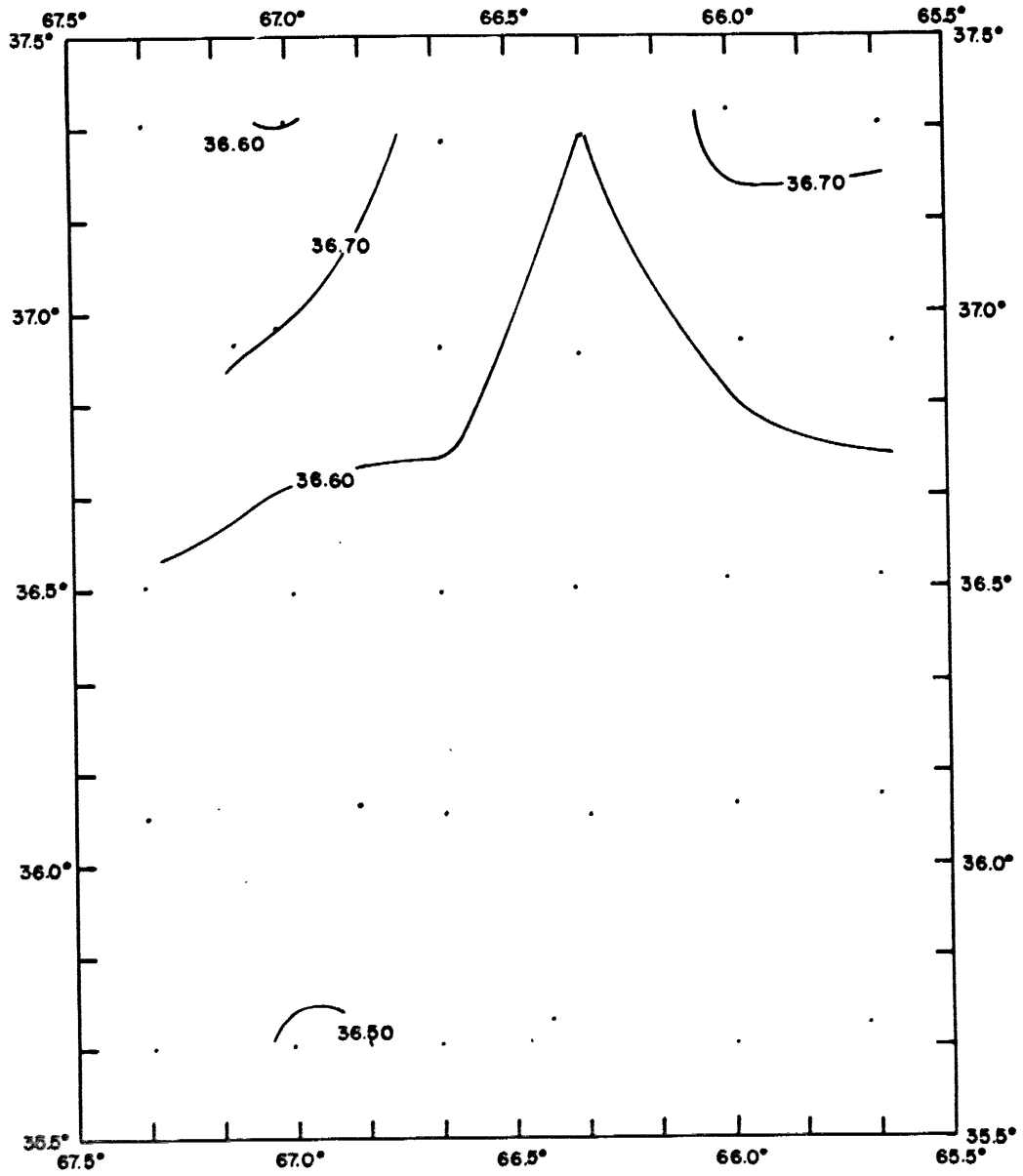


FIGURE 34

Salinity Contours, σ_t , Surface 25.5, First Occupation

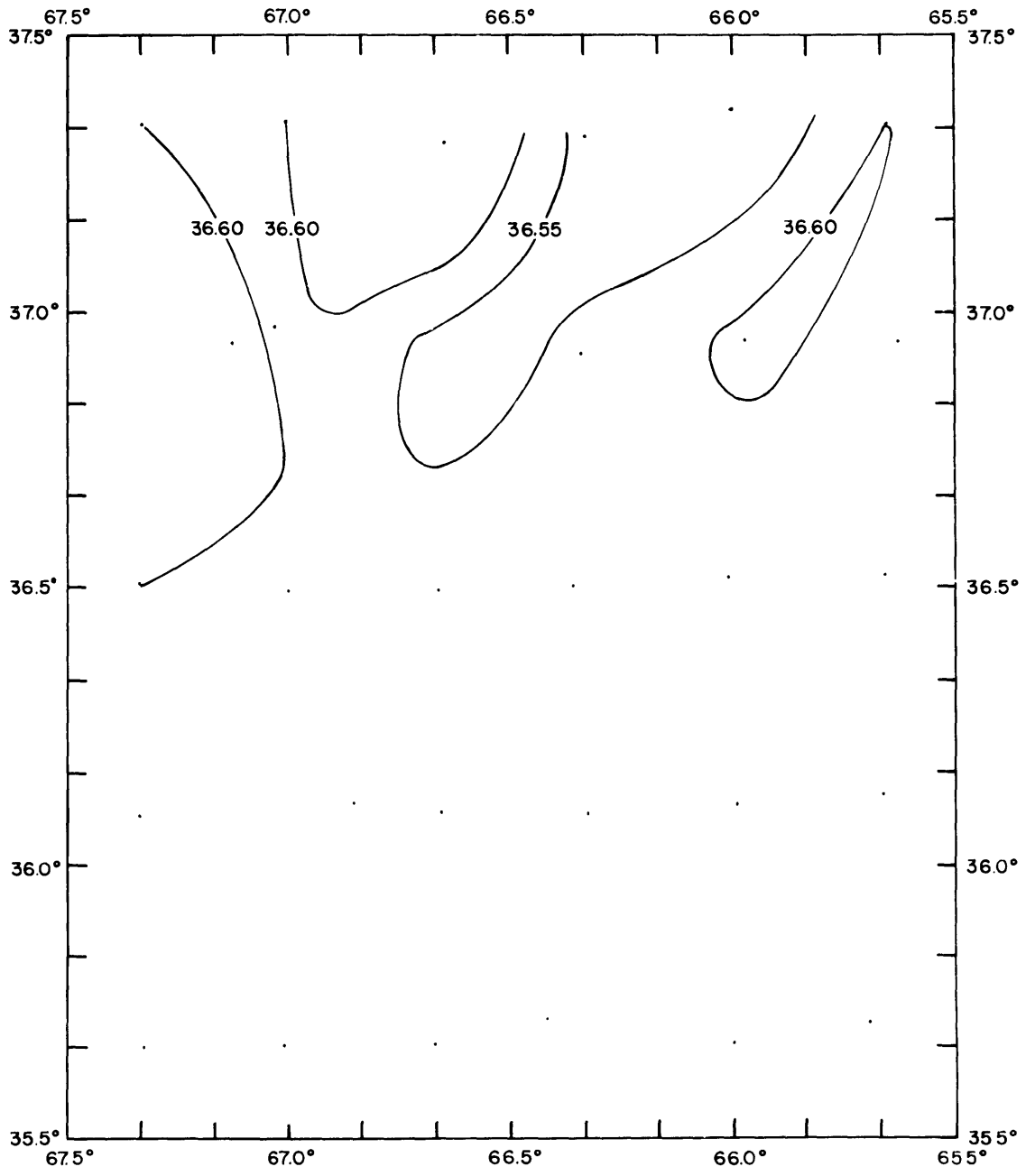


FIGURE 35
Salinity Contours, σ_t Surface 26.0, First Occupation

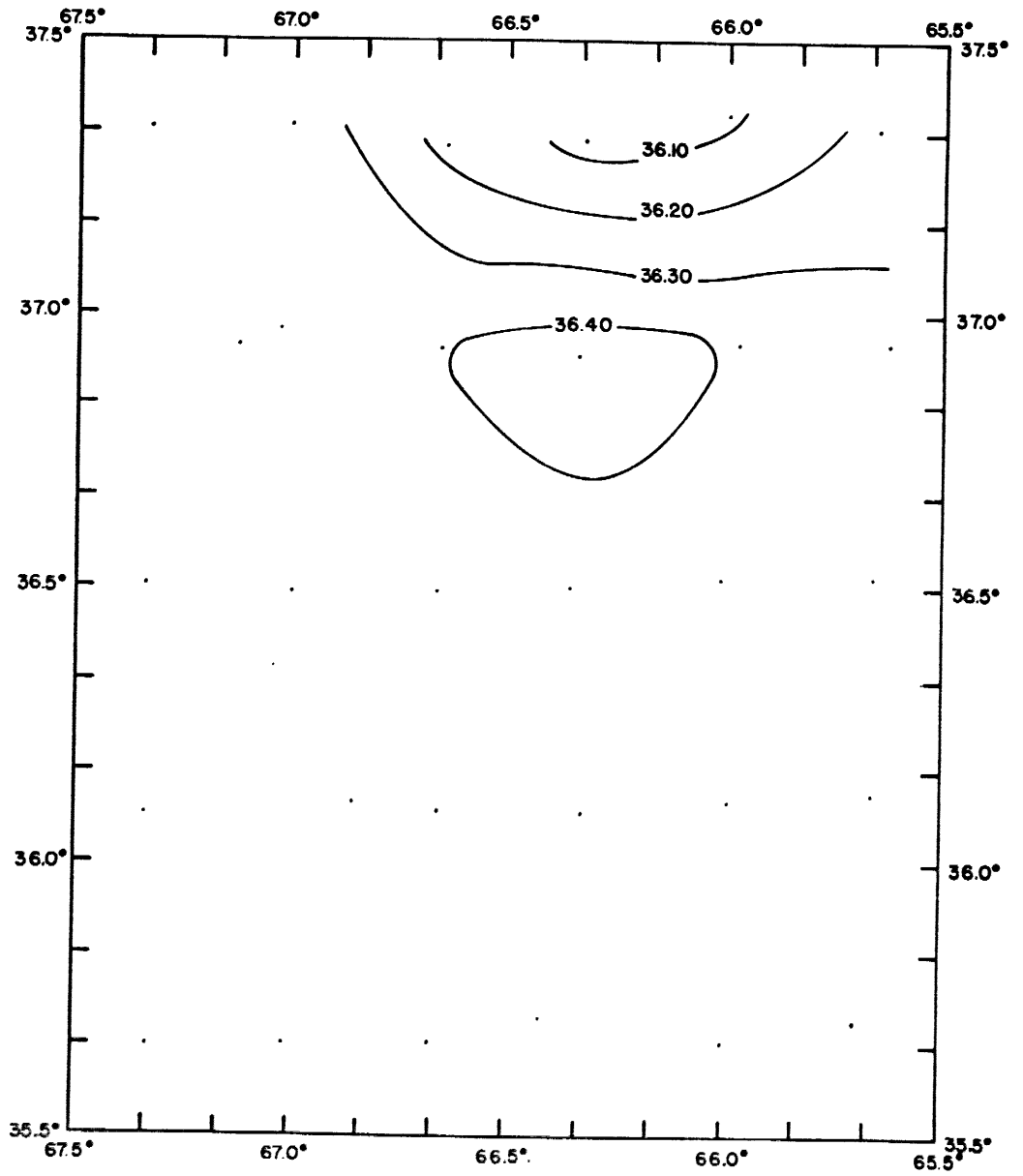


FIGURE 36

Salinity Contours, σ_t Surface 26.5, First Occupation

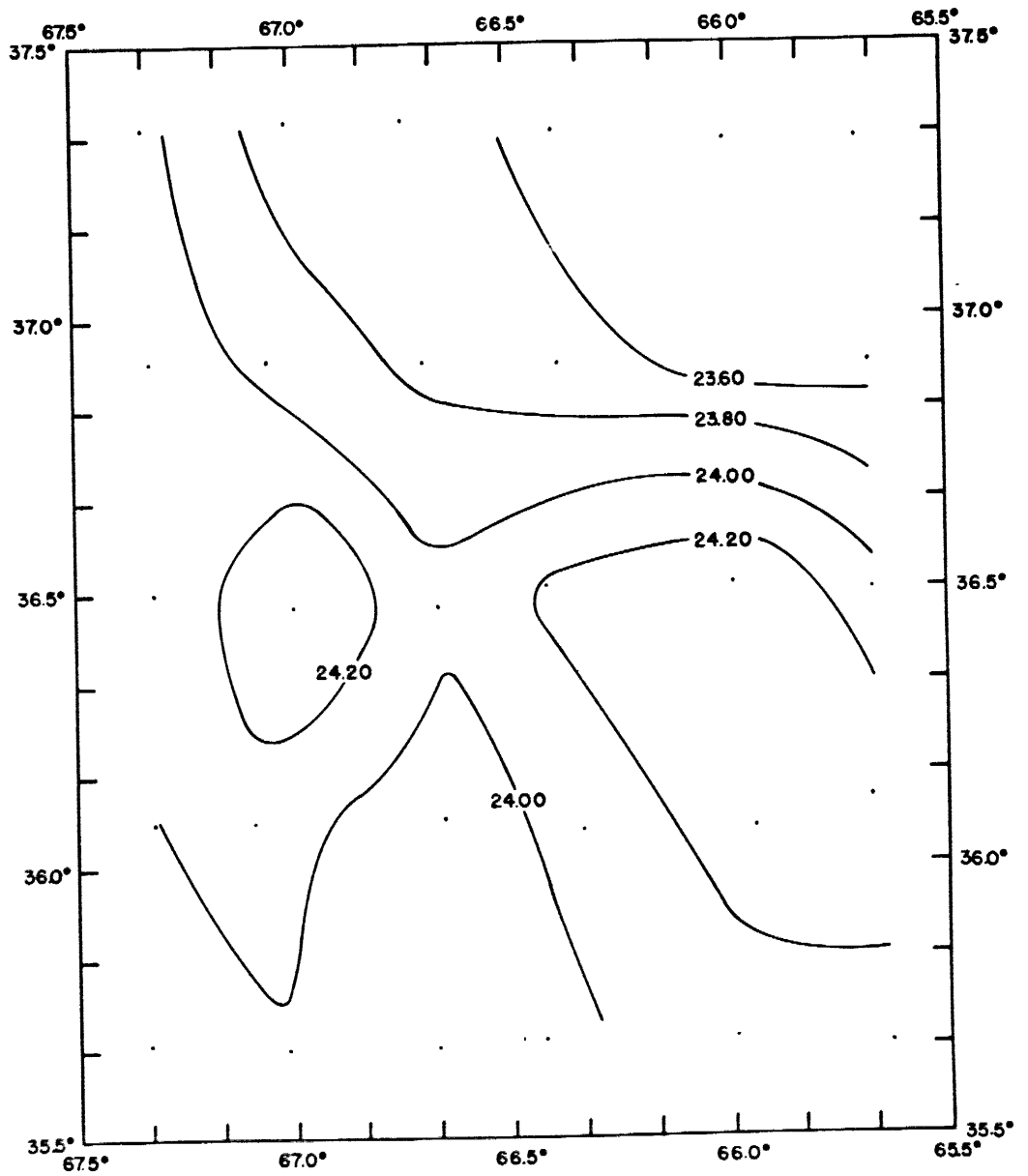


FIGURE 37

Surface Q₁ Contours, Second Occupation

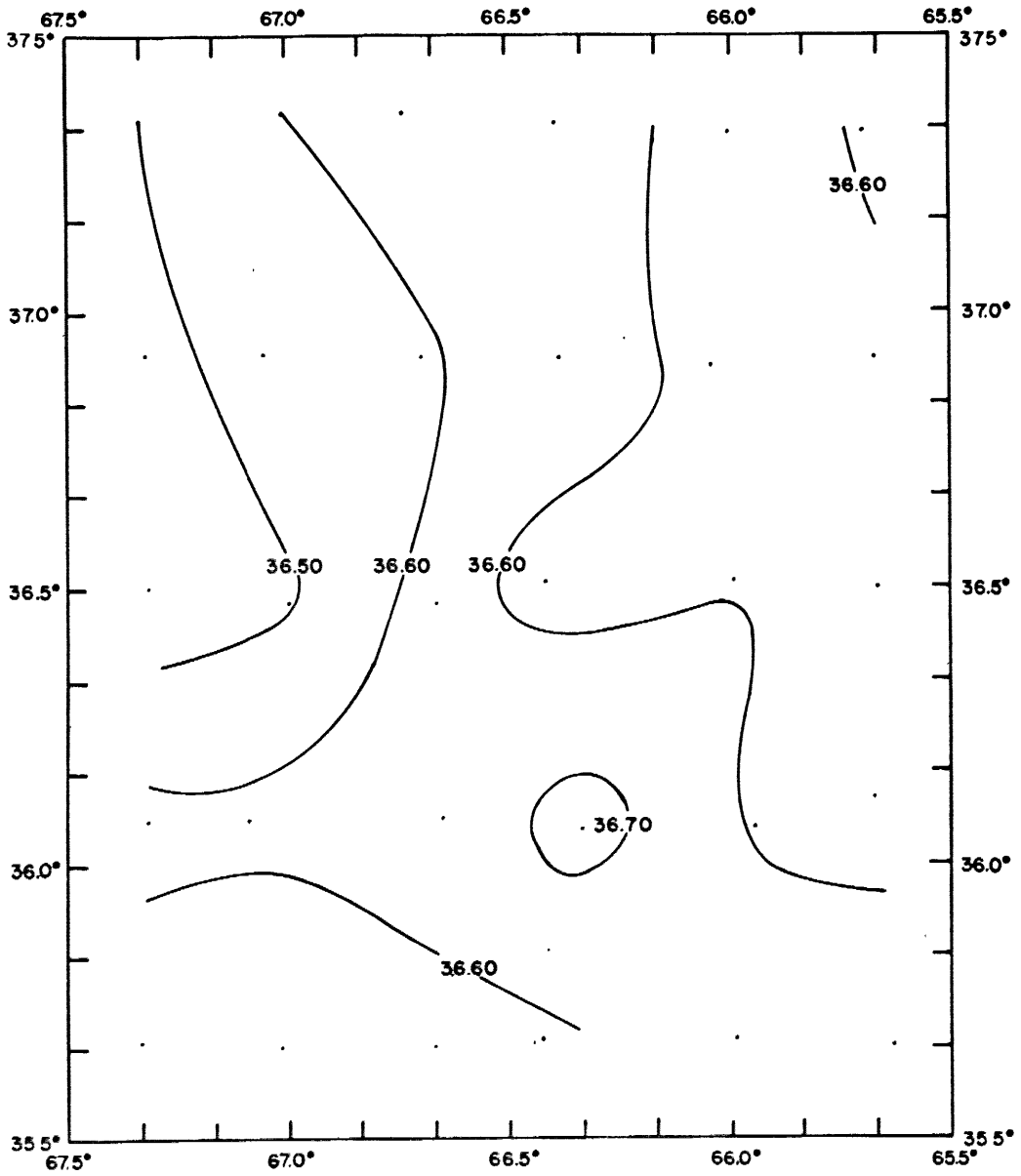


FIGURE 38

Salinity Contours, σ_t , Surface 25.5, Second Occupation

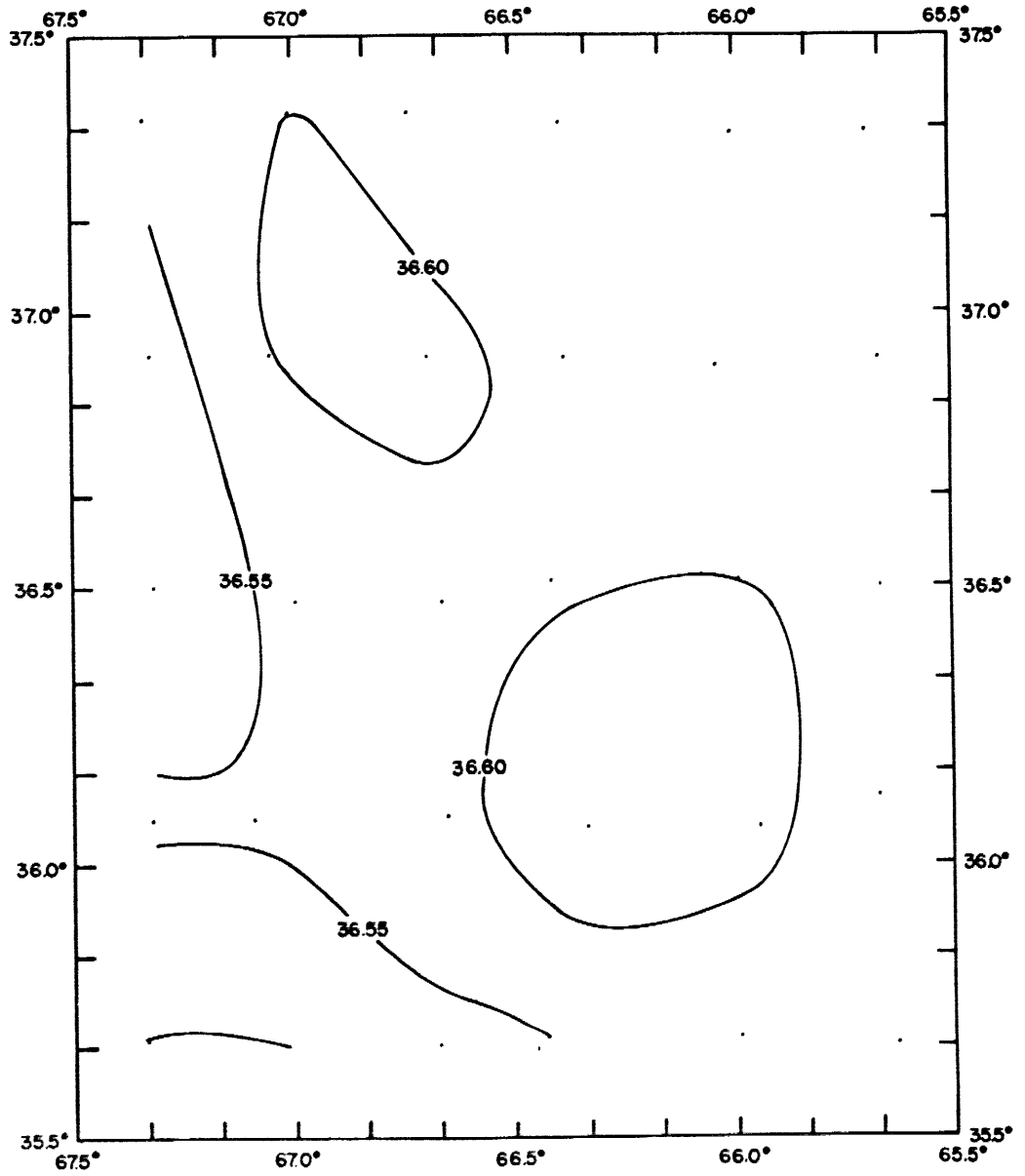


FIGURE 39

Salinity Contours, σ_t Surface 26.0. Second Occupation

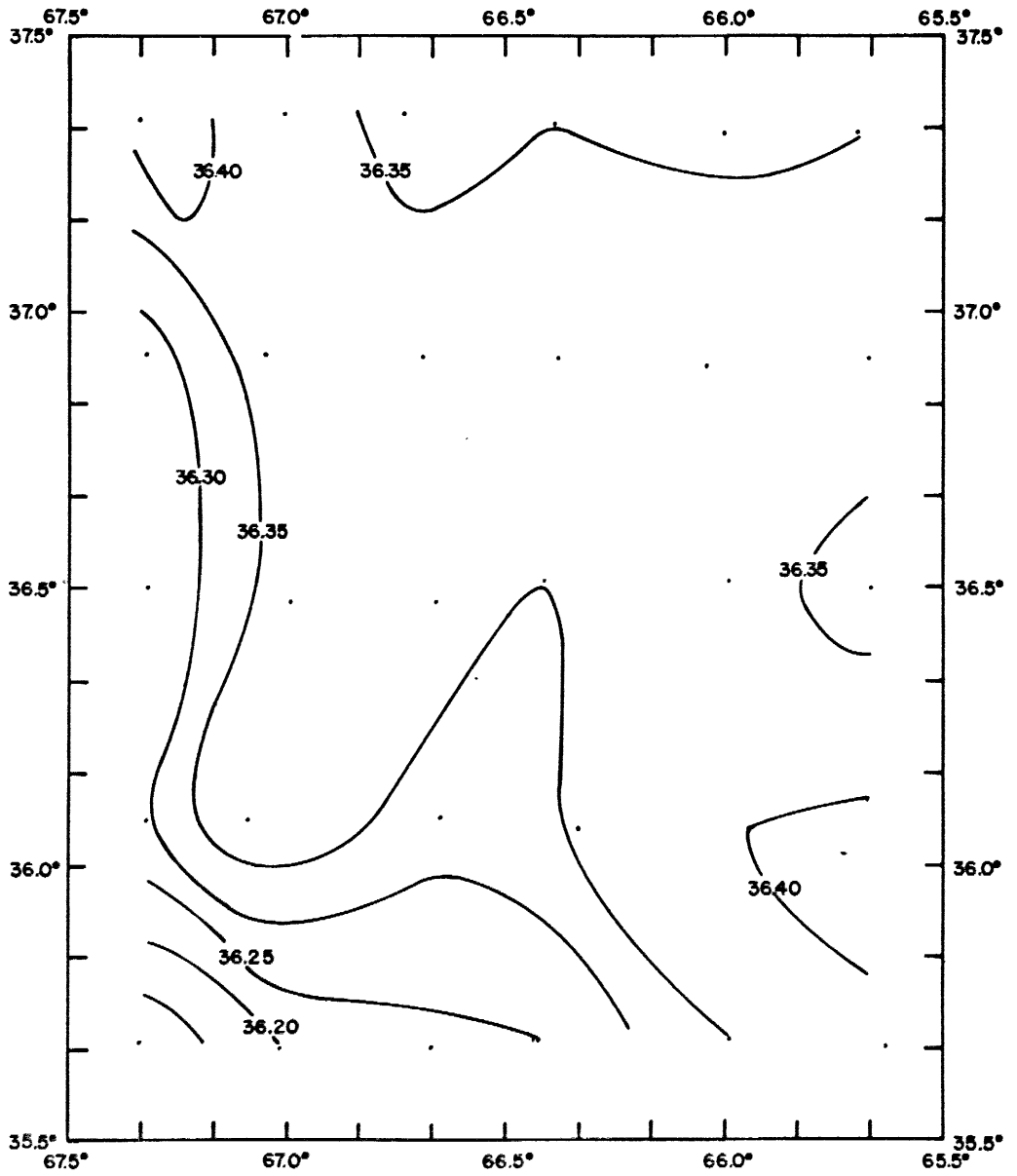


FIGURE 40

Salinity Contours, σ_t Surface 26.5, Second Occupation

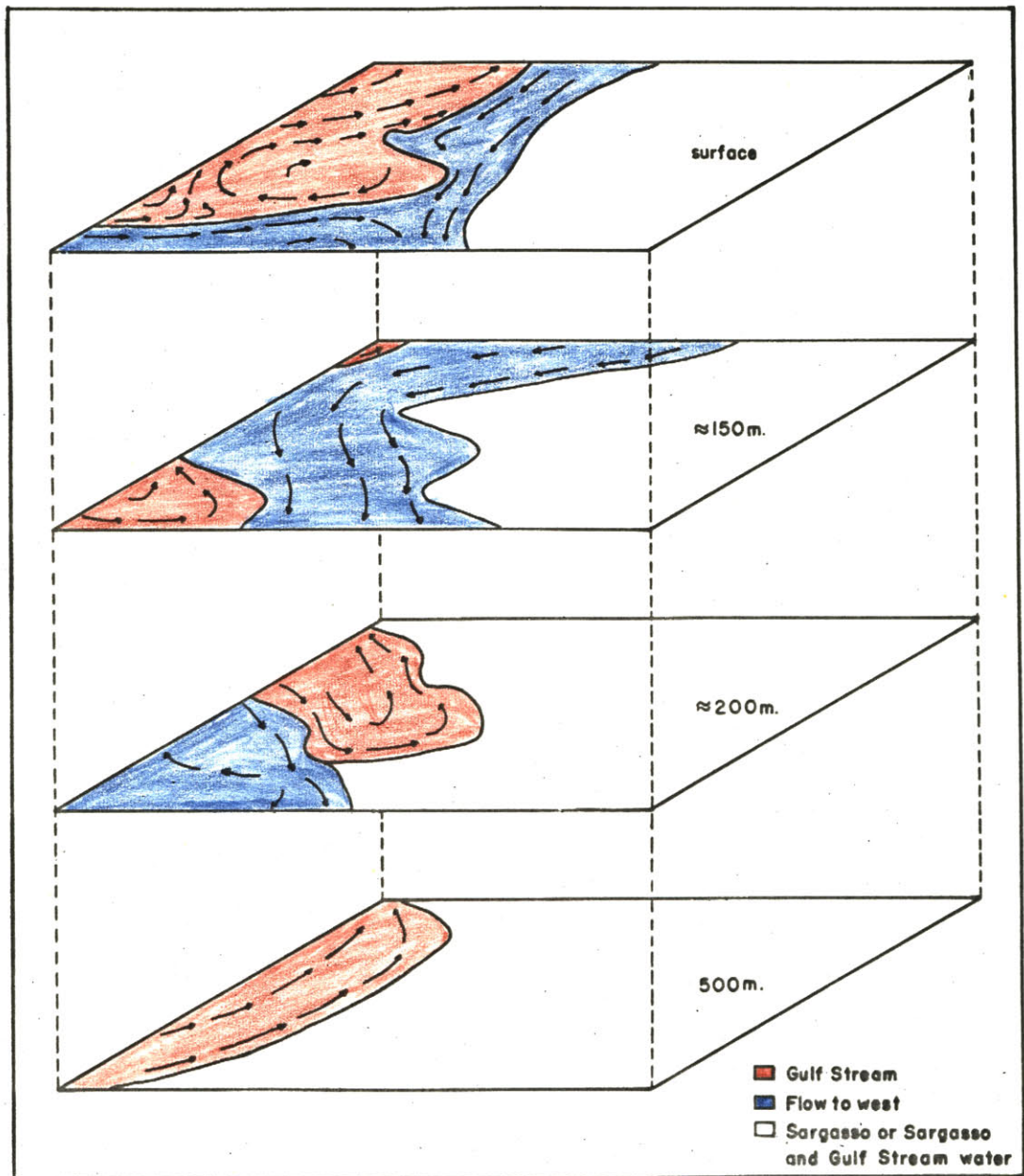


FIGURE 41

Summary of Water Movements in Area, First Occupation

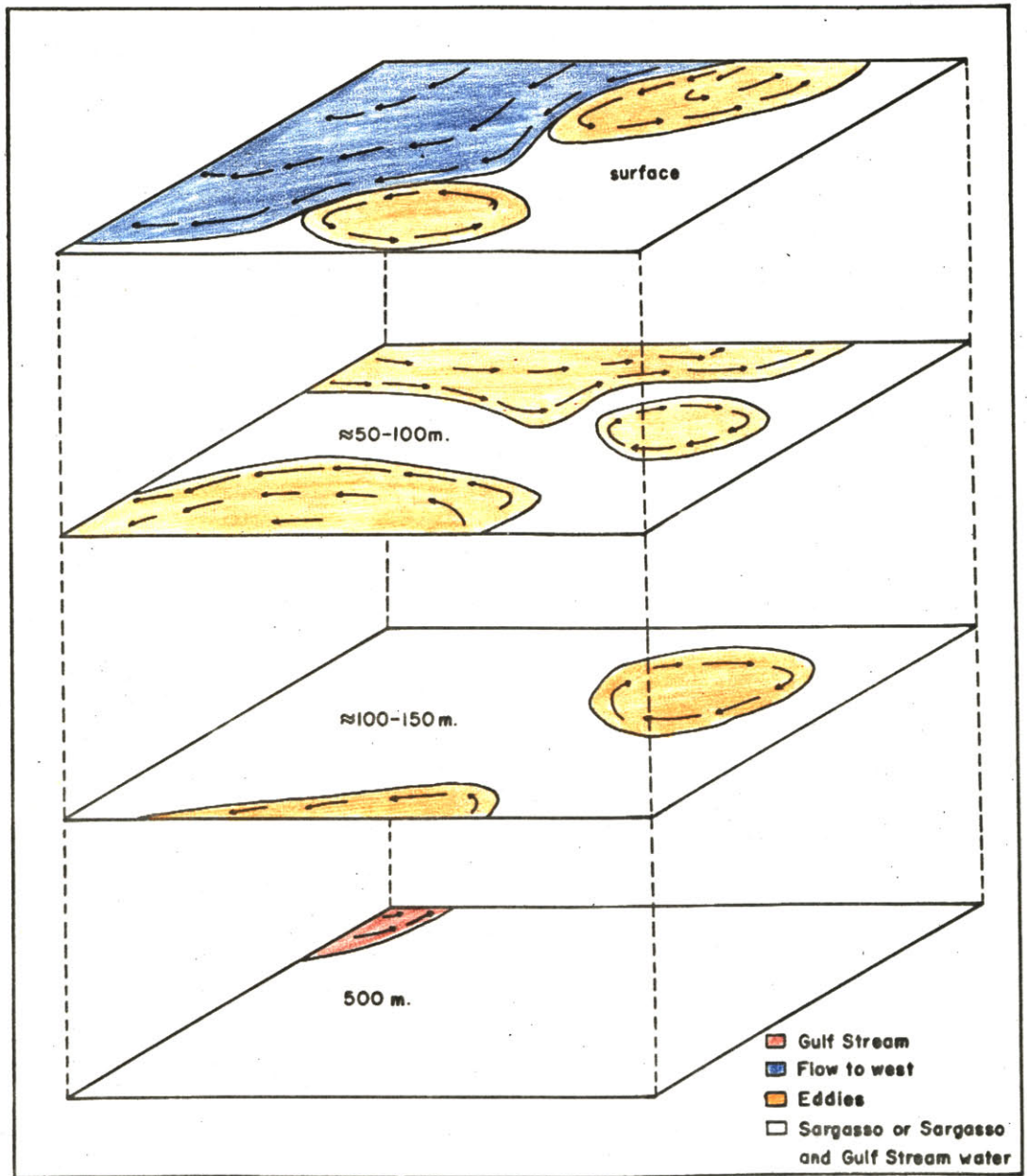


FIGURE 42

Summary of Water Movements in Area, Second Occupation

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