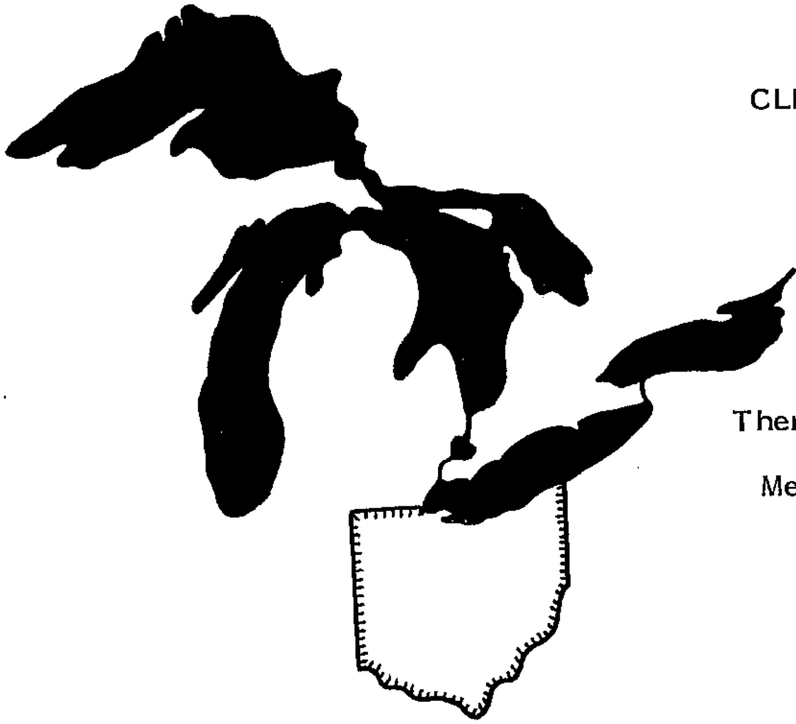

CLEAR TECHNICAL REPORT NO. 289

Thermal Stratification in the Western Basin of Lake Erie: Its Characteristics, Mechanisms of Formation, and Chemical and Biological Consequences

Prepared by

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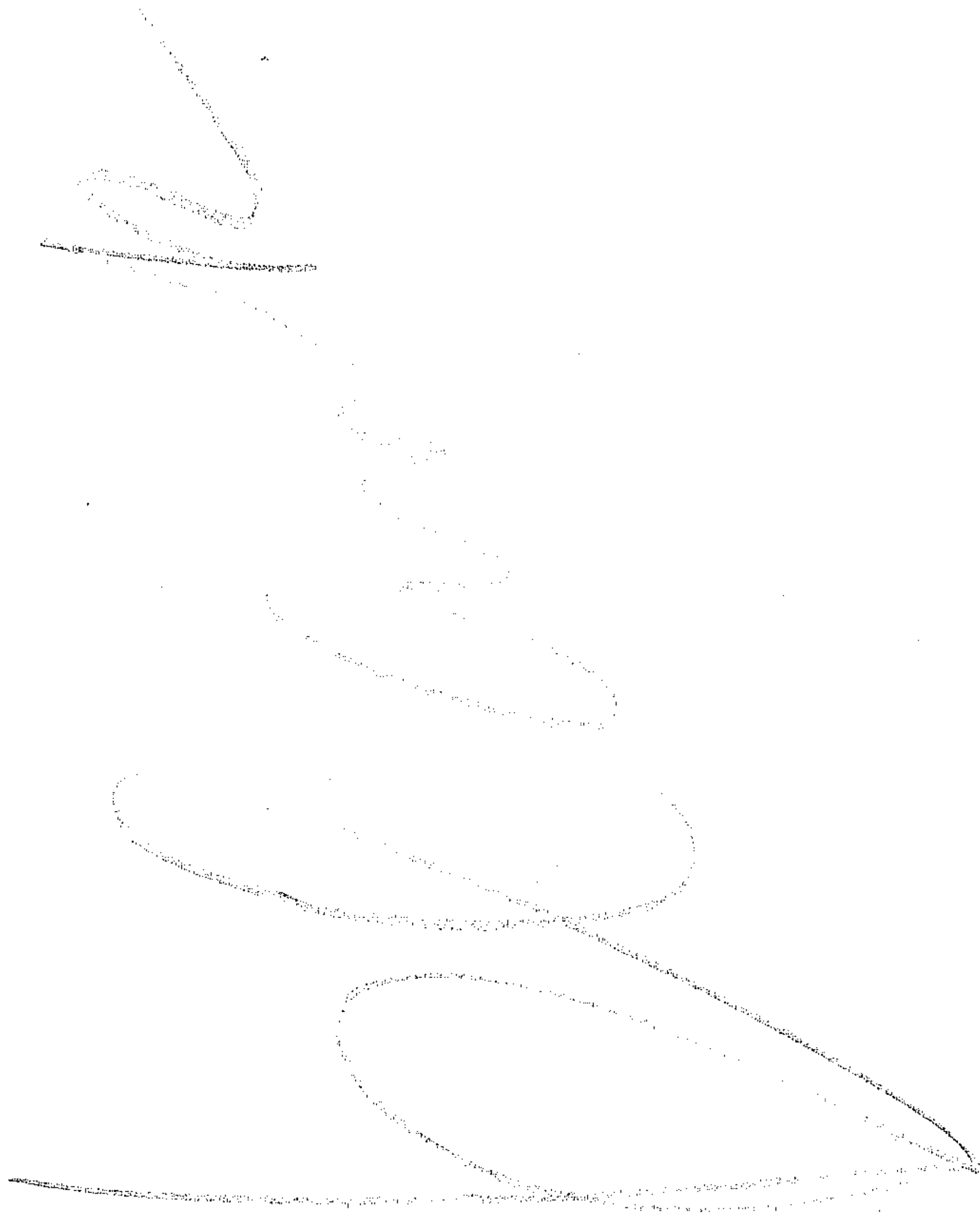
COLUMBUS, OHIO

1984

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES



INTRODUCTION

The present scientific knowledge of the western basin of Lake Erie is in somewhat of a paradoxical state. Although one of the most highly studied bodies of water in the world, several very basic limnological aspects of the basin are still not understood. One reason for this lack of clarity results from the morphological features of the basin. Because of the basin's small volume (25.6 cu.km.) in relation to its large area (3,411 sq.km.), limnological conditions are very responsive to meteorological changes. Relatively minor, daily fluctuations in air temperature, wind speed and direction, precipitation, and barometric pressure are often sufficient to cause significant changes in the characteristics of the water column. Even slight to moderate winds can completely mix the water column and resuspend the surficial sediments, resulting in wide daily variations in dissolved nutrients and turbidity. In addition, overall precipitation and Detroit River flow affects the sediment and nutrient loading to the basin and the distribution of the water masses. Therefore, due to the significant impact that daily variations in meteorological factors have on the western basin, possibly the most accurate description of the basin is that it is highly variable: from year to year, season to season, and even day to day.

Just as the morphometry of the western basin influences the water quality, it also affects the thermal properties of the water column. The shallow mean depth (7.6m), high flow-rate (2.4 month retention time, Burns, 1976a), and the relatively long wind fetch (approximately 60 km) from all directions results in vertically well-mixed, or isothermal, conditions throughout the basin. Therefore, stratification is generally inhibited. Occasionally, a thermocline may develop with resultant stratification lasting up to several days. The establishment of a thermocline in the western basin has been attributed to meteorological forces; i.e., calm variable winds accompanied by high air temperatures. However, Wright (1955), Carr et al. (1965), and Britt (pers. comm.) have suggested that stratification may have been caused by cooler central basin water flowing into the western basin. This cool central basin water, being more dense, would displace the warmer western basin water, and a thermocline could form between the two masses. Although it has been shown that central basin water does occasionally move into the western basin (Hartley et al., 1966 and Herdendorf, 1969), such an intrusion has usually been observed to mix completely with western basin water, and therefore not exist as a distinct water mass. The possibility that a discrete central basin water mass is responsible for the stratified conditions in the western basin has not, until now, been seriously considered.

The purpose of this study was to investigate the occurrences of thermal stratification in the western basin of Lake Erie. More specifically, objectives were:

1) to characterize the nature of thermally stratified conditions in the western basin, such as period of occurrence, frequency, stability, the horizontal and vertical location, accompanying changes in water quality, and possible biological effects; and,

2) to determine if central basin hypolimnetic water flowed into the western basin, resulting in stratified conditions.

Regardless of the mechanism by which the western basin stratifies, these events have been documented and observed on numerous occasions since 1929 (Wright, 1955). Wright's (1955) observances of stratification were mostly east of the islands, in the western end of the central basin. Thermal stratification in the central basin is continuous throughout the summer, and Wright (1955) was observing the western margin of its hypolimnion. Following Wright's (1955) 1929 study, several investigators have recorded stratification at various points throughout the western basin (Chandler, 1940, 1944; Chandler and Weeks, 1945; Britt, 1955a and b; Carr et al., 1965; Hartley, 1966; Britt et al., 1968, 1973; Herdendorf, 1967; Zapotosky and Herdendorf, 1980; and Gladish and Munawar, 1980). In contrast, some major studies undertaken in Lake Erie have reported the western basin to be devoid of thermal stratification (Weiler and Chawla, 1968; Burns, 1976; Fay and Herdendorf, 1981;). These reports, as it will be shown later, are due to the ephemeral and intermittant nature of stratification in the basin, and should not be construed to mean that stratification in the basin does not occur. Although documented observations of thermal stratification in the western basin are numerous, these accounts provide no generalization of the thermal characteristics.

Due to its ephemeral nature, stratification has generally been considered unimportant. Yet, severe oxygen depletion often accompanies stratified episodes, and the disappearance of the mayfly (Hexagenia) has been attributed to such an event (Britt, 1955a). Concurrent with oxygen depletion is the release of nutrients (i.e., phosphorus, silica, and ammonia) and toxics from the sediments to the overlying waters. The frequency of occurrence of stratification, and the accompanying regeneration of various chemical species, has an effect on determining nutrient budgets and general chemical models. The degree of internal nutrient loading resulting from anoxia has not been documented in the western basin.

Boyce et al. (1980) measured the movement of hypolimnetic water from the eastern to the central basin of Lake Erie. If a similar process occurs between the central and western basins, the resultant effects on the water chemistry, the sediments, and the benthos could be deleterious, depending on the conditions of the central basin hypolimnetic water. Although it was difficult in this study to ascertain the effects of inflow, the possibility and mechanism of it were investigated.

METHODS

Data were collected during 1980-1981 along a north-south transect across the western basin of Lake Erie (Figure 1). Twelve stations were evenly spaced (approximately 5.3km apart) along this transect, extending from Locust Point, Ohio, to Leamington, Ontario (Figure 2). The transect was designed to investigate the general chemical, physical, and biological limnology of the western basin.

Sampling was conducted from March 1980 through December 1981. Frequency of sampling was roughly twice a month during the period May through September, and once a month from October through April (Table 1). This enabled an investigation into the short-term variability of conditions during the summer season. Thirteen cruises were conducted in 1980, 18 in 1981.

Sampling cruises were conducted aboard the Research Vessel Hydra, operated by the Center for Lake Erie Area Research, Ohio State University. This 20m vessel is equipped with an analytical laboratory for immediate physical and nutrient analysis. In 1981, two transect cruises were performed by small boat and the two winter cruises were carried out aboard United States Coast Guard icebreakers. The first winter cruise (Jan 29) was conducted aboard the USCGC Bristol Bay, the following cruise (Mar 2) with the USCG Neah Bay.

As part of the open lake surveillance/monitoring for Lake Erie, the Center for Lake Erie Area Research also sampled several stations throughout the western and central basins during 1980 and 1981 (Figure 3). These whole lake cruises were

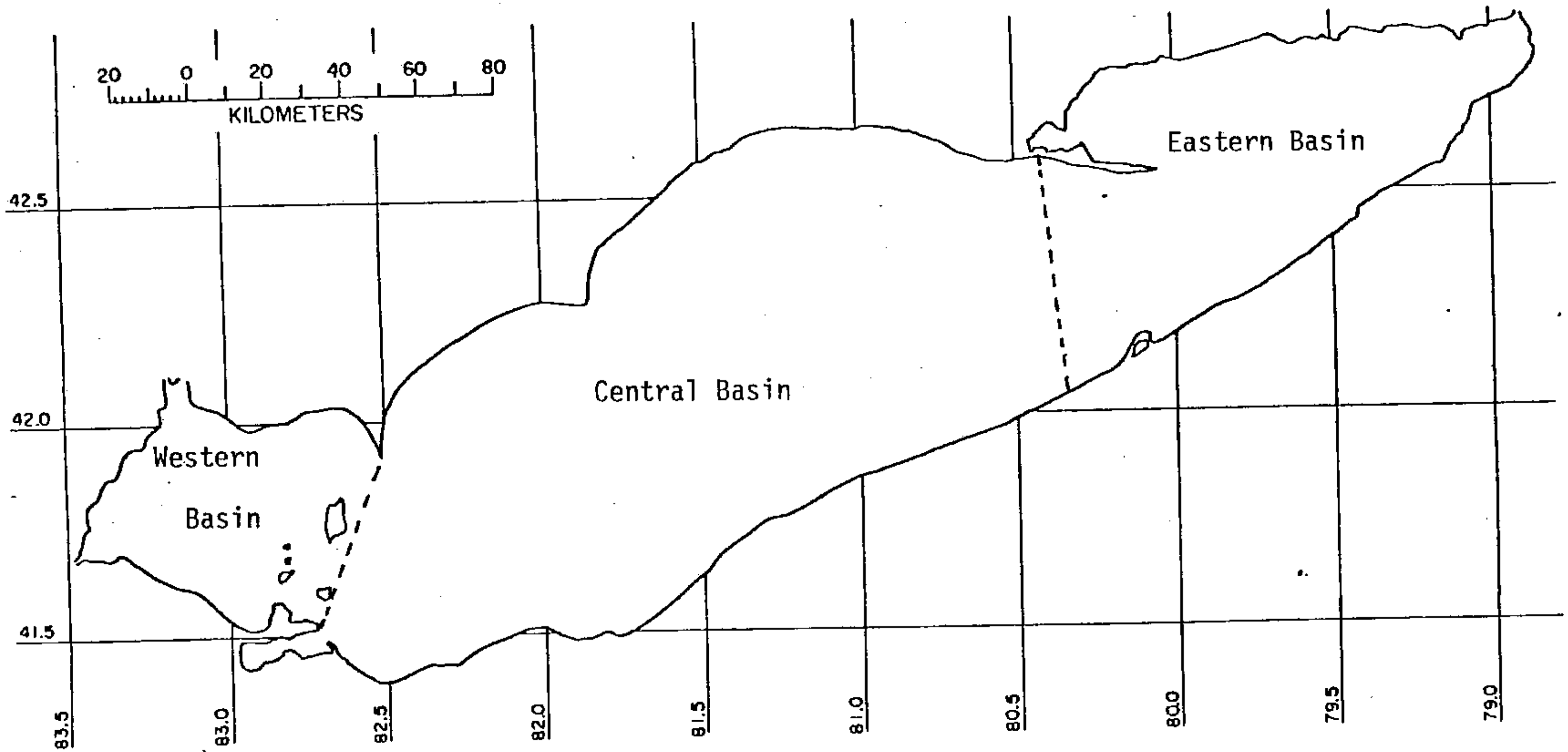


Figure 1. Lake Erie, showing approximate boundaries of the western, central, and eastern basins.

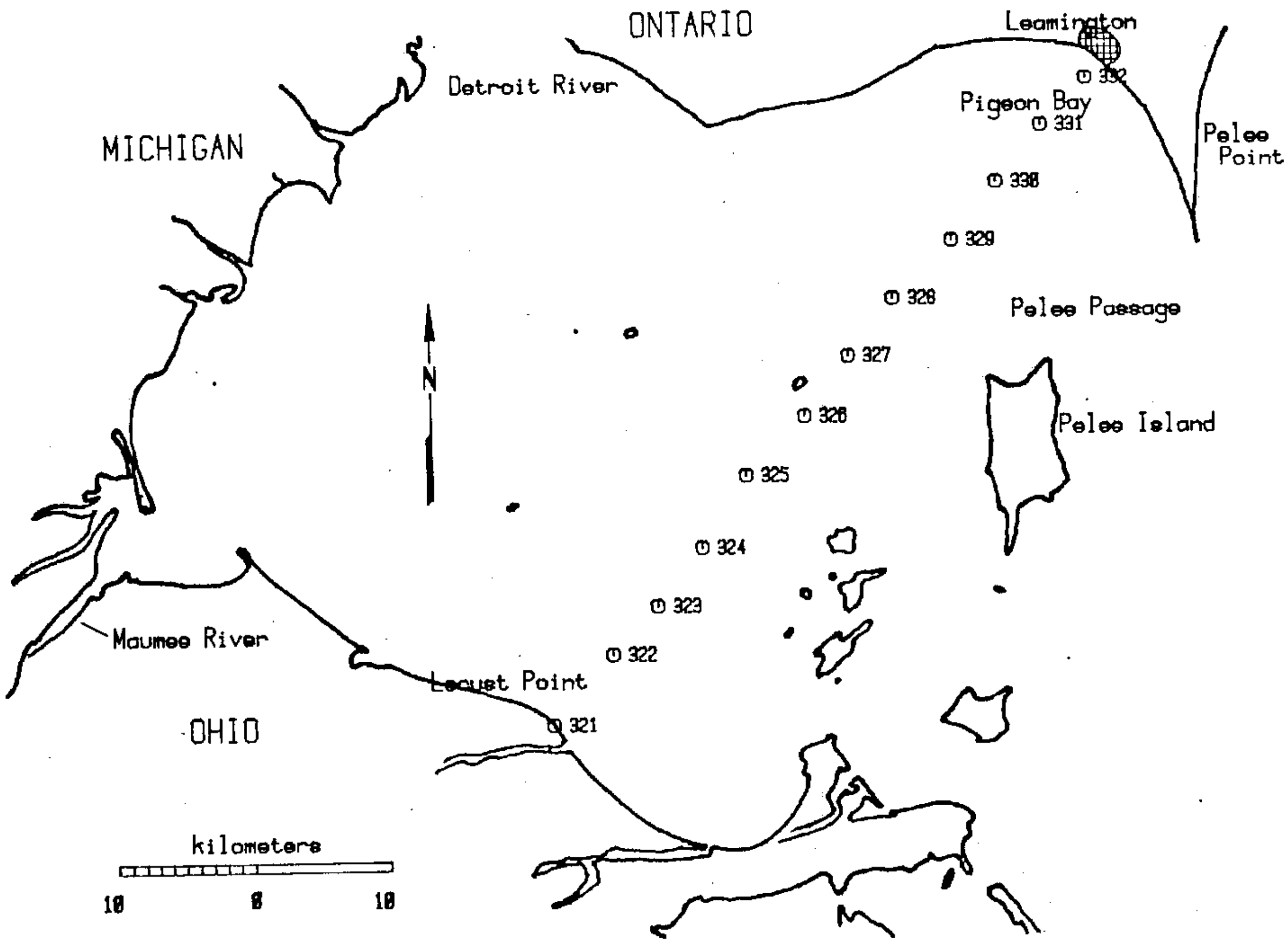


Figure 2. Western basin of Lake Erie with transect station locations.

TABLE 1

Sampling dates, western basin transect and Lake Erie open lake surveillance program

YEAR	CRUISE	SAMPLING DATES	
		WESTERN BASIN TRANSECT	WHOLE LAKE
1980	1	2 Apr	1-4 Apr
	2	30 Apr	28 Apr-2 May
	3	29 May	27 May -2 Jun
	4	19 Jun	
	5	30 Jun	29 Jun-6 Jul
	6	23 Jul	
	7	1 Aug	28 Jul-8 Aug
	8	14 Aug	18-23 Aug
	9	30 Aug	28 Aug-6 Sep
	10	15 Sep	
	11	28 Nov	27 Sep-1 Oct
	12	9 Nov	27 Oct-5 Nov
	13	23 Nov	23 Nov-4 Dec
1981	1	29 Jan	
	2	2 Mar	
	3	26 Mar	24-29 Mar
	4	5 May	2-6 May
	5	15 May	
	6	3 Jun	2-7 Jun
	7	12 Jun	
	8	24 Jun	24 Jun-3 Jul
	9	12 Jul	
	10	21 Jul	
	11	12 Aug	
	12	11 Sep	1-11 Sep
	13	23 Sep	12-24 Sep
	14	29 Sep	
	15	23 Oct	23-30 Oct
	16	31 Oct	
	17	14 Nov	12-19 Nov
	18	5 Dec	3-6 Dec

conducted nines times each year, and coincided with the transect sampling effort (Table 1). Several of these stations, particularly western basin stations and those in the western end of the central basin, provided useful comparitive information concerning basin-wide processes, and their data were included when pertinent.

Sampling depths for western and central basin are summarized in Figure 4. During unstratified periods, all stations in the central basin were sampled at three horizons: surface, mid-depth, and bottom. During stratified periods, samples were also obtained one meter above the thermocline (Lower Epilimnion) and one meter below the thermocline (Upper Hypolimnion), with no mid-depth sample. Stratification in the central basin was defined as a thermal gradient of at least 2° C/m. All stations in the western basin were sampled at surface and bottom, regardless of the presence of stratification. Due to the shallowness and well-mixed nature of the western basin, surface and bottom samples are generally of similar characteristics, making a mid-depth sample unnecessary. Temperature profiles at each station were determined with an InterOcean in situ CSTD oceanographic probe, lowered from the vessel from 1m below the surface until it rested in the sediments. Continuously recorded temperatures and depths were displayed on a Hewlett-Packard X-Y recorder. Sampling depths were then determined from the profile.

Several physical and chemical parameters were measured. In situ determinations were made of temperature, conductivity, pH, and transparency. Water samples were obtained with a submersible pump, and shipboard laboratory measurements were made of dissolved oxygen (DO), pH, conductivity, turbidity, soluble reactive phosphorus (SRP), ammonia (NH_3), nitrate plus nitrite (NO_3+NO_2), and soluble reactive silica (SRS). In addition, water was collected and/or filtered

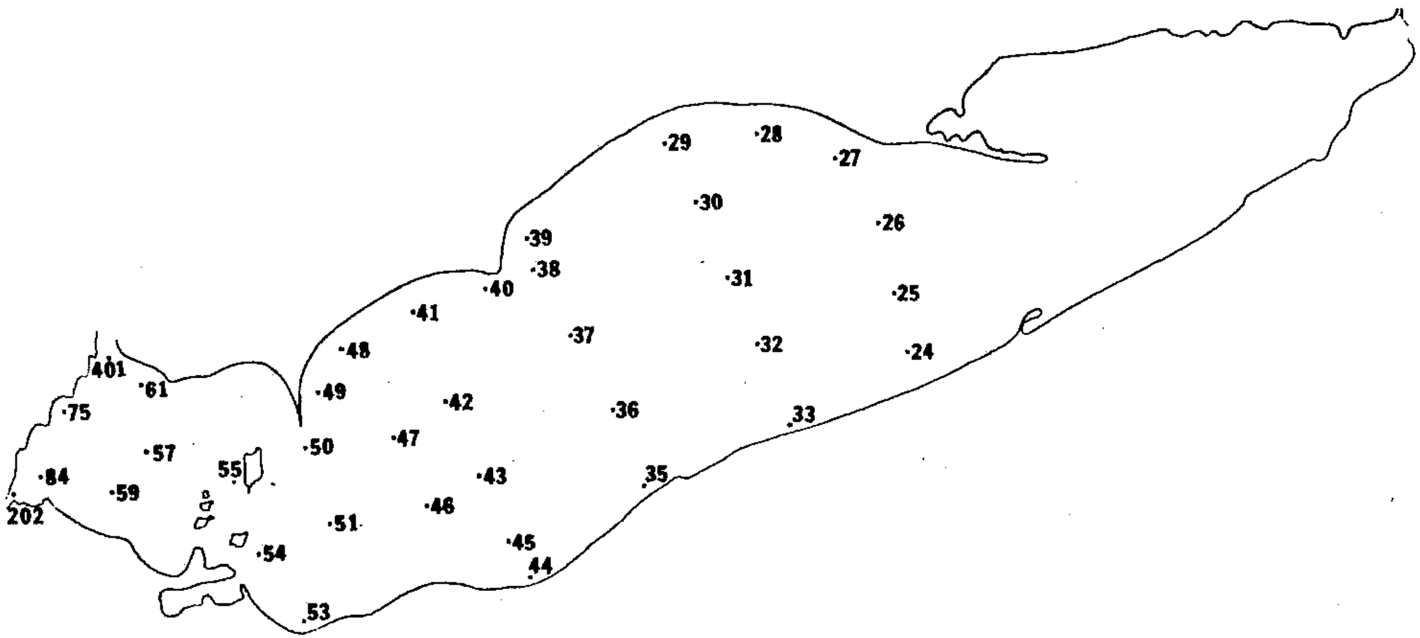


Figure 3. Station locations, Lake Erie monitoring/surveillance program.

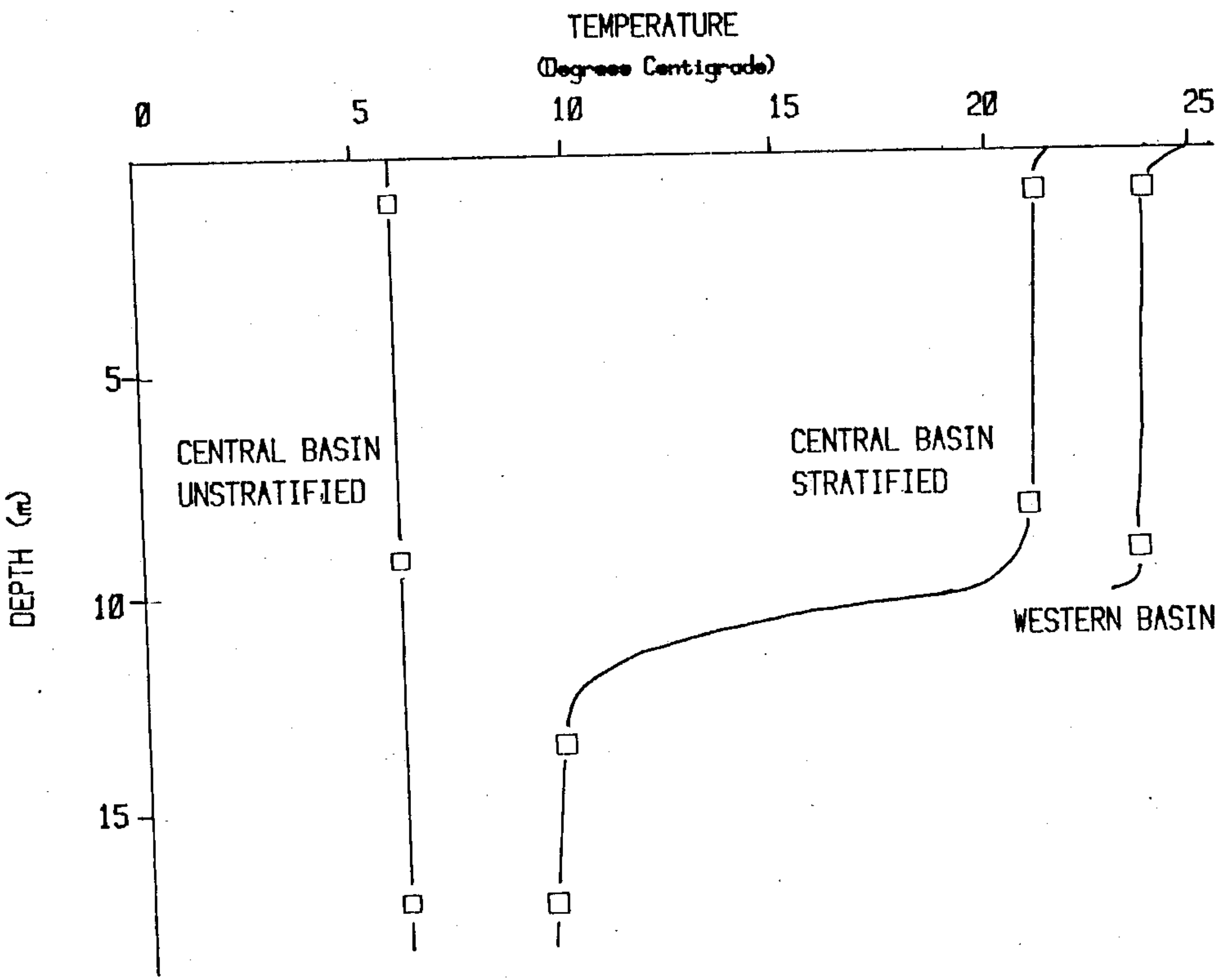


Figure 4. Sampling depths utilized during stratified and non-stratified periods.

for later analysis of chlorophyll a, suspended solids (TSS), total phosphorus (TP), particulate phosphorus (PP), non-apatite inorganic phosphorus (NAIP), particulate organic carbon (POC) and particulate organic nitrogen (PON). Several meteorological parameters and wave conditions were also recorded at each station. A list of parameters, their methods of measurement, detection limits , and ranges are given in Table 2. Further detail is given in Letterhos, 1982.

Data were compiled and entered into a Digital PDP-11 computer, and are available through the CLEAR Data System and STORET. Descriptive statistics were performed on the data using SAS and BMDP programming packages. The thermal profiles obtained were used to produce a two dimensional plot of the temperature distribution along the transect, providing a cross-sectional view of the western basin. Surface and bottom plots of concentrations for various parameters were produced with a Hewlett-Packard Graphic Plotter.

TABLE 2

Methods, Ranges, and Detection Limits of Parameters Measured During the Western Basin Transect Study, 1980 and 1981

Parameter	Method	Range	Detection Limit
Conductivity	In situ probe(InterOcean) Electrode (Beckman)	0-1000 umhos/cm	5 umhos ± 1%
Tempreature	In situ probe(InterOcean)	0-35° C	.2° C
Transparency	Secchi Disk (30 cm Whipple)	NA	.01m
Dissolved Oxygen	Electrode(InterOcean) Titrimetric(Winkler Azide Modification)	0-20 mg O_2 /1	.05mg O_2 /1
pH	Electrode (Orion)	0-14	.1 SU
Turbidity	Hach Turbidimeters	0-1000 NTU	.02 NTU
Chlorophyll	Acetone Extinction Spectrophotometer	0-50 ug/1	.02ug/1
Suspended Solids	Gravimetric Whatman GF/C glass fiber filters	0-10,000 ug/1	.01 ug/1
Carbon and Nitrogen Particulate,Organic	Elemental Analyzer (Perkin Elmer model 240)	0-1000 ug/1	.01 ug/1

TABLE 2 CONTINUED

Parameter	Method	Range	Detection Limit
NUTRIENTS	Automated Technicon Autoanalyzer II		
Ammonia	Phenate Method	0-100 ug N/1	.5 ug N/1
Nitrate + Nitrite	Cadmium Reduction	0-1.0 mg N/1	.005 mg N/1
Phosphorus			
Soluble Reactive	Stannous Chloride	0-50 ug P/1	.5 ug P/1
Total	Persulfate Digestion	0-100 ugP/1	1.0 ug P/1
Particulate	Persulfate Digestion	0-100 ug P/1	1.0 ug P/1
Nonapatite	NaOH Extraction	0-400 ug P/1	4.0 ug P/1
	CDB Extraction	0-100 ug P/1	1.0 ug P/1
Apatite	H_2SO_4 Extraction	0-400 ug P/1	4.0 ug P/1
Soluble Reactive Silica	Molibdosilicate-ascorbic acid and oxalic acid	0-5.0 mg SiO_2/1	.03 mg SiO_2/1

RESULTS

Cross-sections of the thermal structure along the western basin transect during several summer sampling cruises are shown in Figures 5a through 5l. Cross-sections for all cruises are shown in Appendix A. Temperature distribution during each sampling period was essentially uniform across the transect, both vertically and horizontally. The small horizontal variation found was largely restricted to the shoreline areas (Figures 5a and 5b), indicating a more rapid response of nearshore waters to seasonal changes in air temperature. Differences between surface temperatures (on any particular cruise) never exceeded 4°C (30 April 1980, Figure 5b), with no sharp gradients encountered. Significant vertical variation occurred only during the late spring and summer, yet even during these months, conditions were often vertically isothermal (Figure 5c). Distinct vertical gradients were observed three times in 1980; 23 July, 1 and 30 August; and five times in 1981; 5 May, 3, 12, and 24 June, and 12 July (Figures 5d, e, g, h, i, j, k, l). These gradients were sporadic, occurring and disappearing thoughout the summer. Generally, temperature gradients were located very near to the bottom, often within 1 m of the sediments. The temperature differences between the surface and the bottom were usually slight (approximately 2°C) and the maximum change was 6.0°C (Station 331; 1 August 1980 and 12 July 1981). Temperature/depth profiles for stations 331 and 325 are shown in Figures 6 and 7. These profiles indicate the temperature difference was slight, but often the gradient was substantial, as much as 5.5°C /m. Also, the region of steep temperature decline often extended to the bottom, thus no distinct, well-mixed bottom layer was present (Station 331, 30 August 1980).

Figures 5a through 5l. Thermal structure of the western basin transect during 1980-1981.

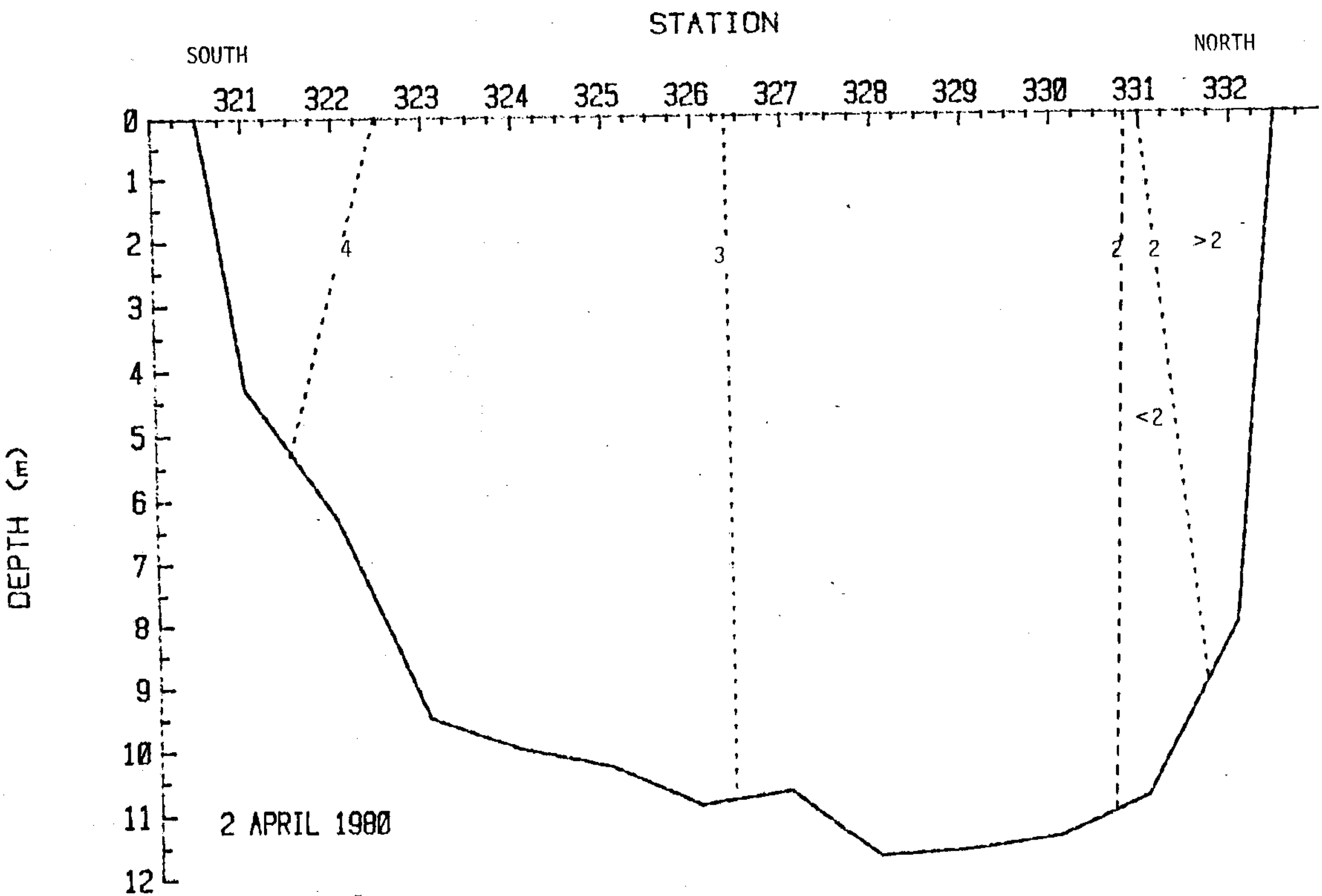

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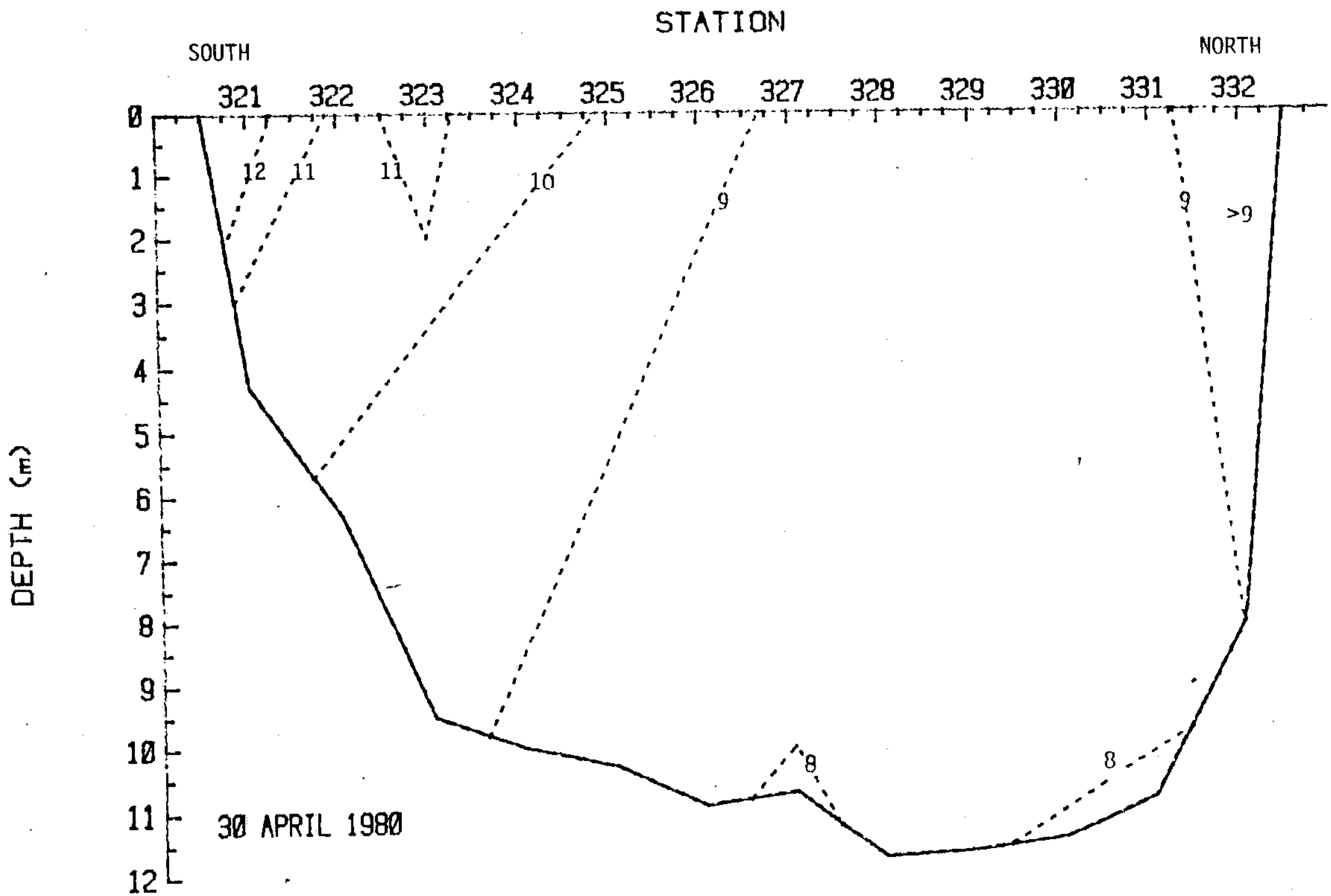
Figure 5a.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30 APRIL 1980

Figure 5b.

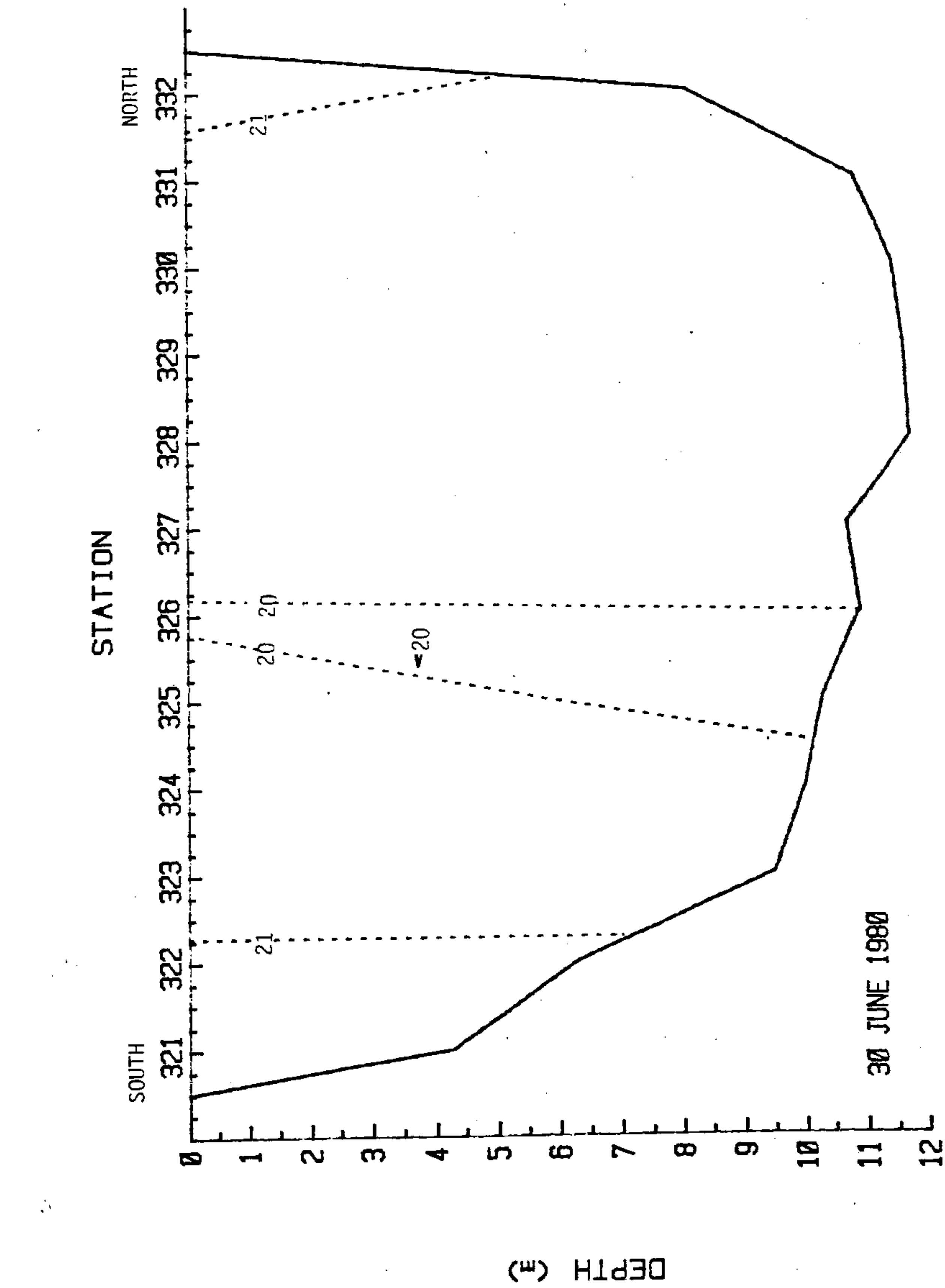
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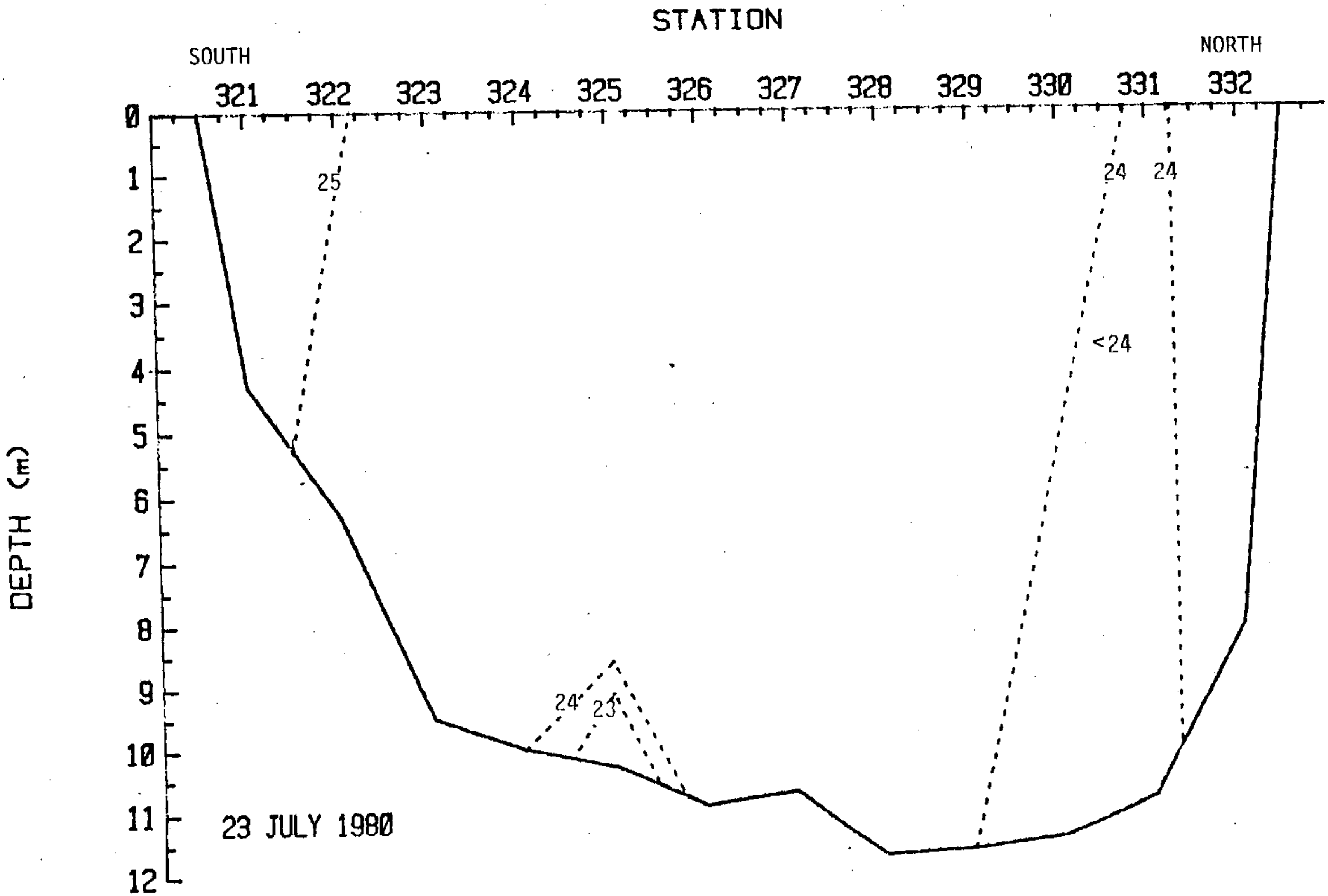
Figure 5c.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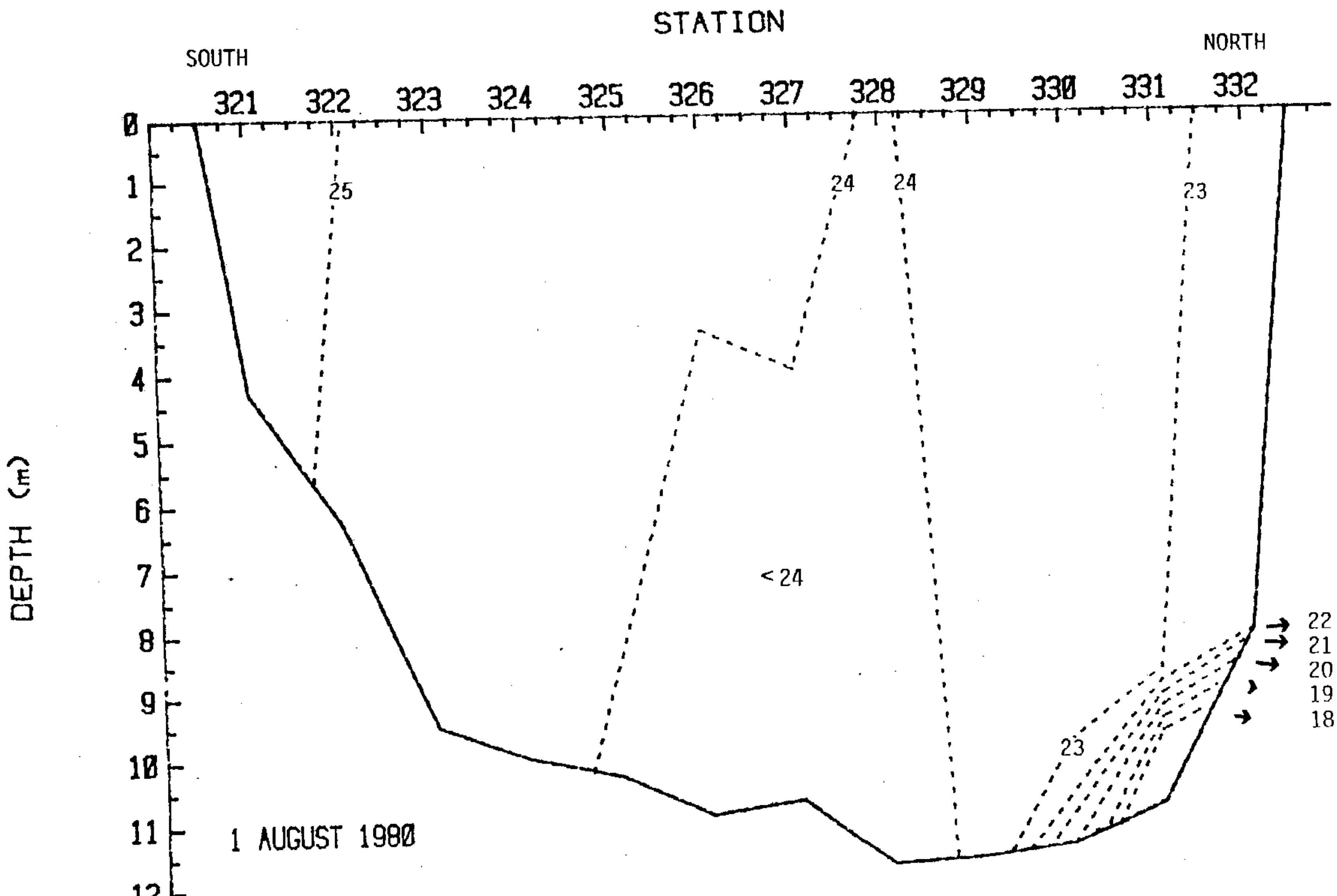
23 JULY 1980

Figure 5d.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1 AUGUST 1980

Figure 5e.

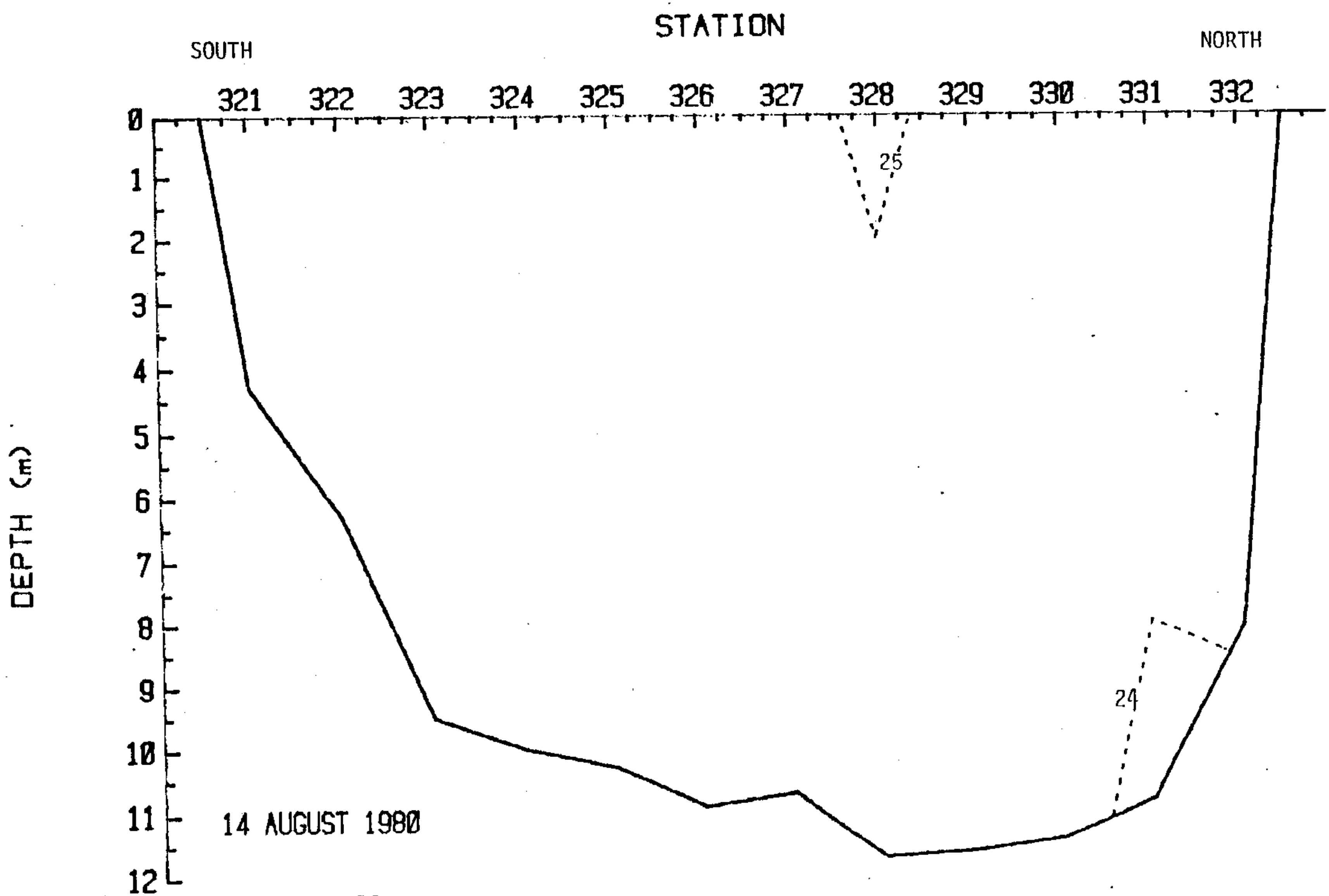
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Figure 5f.

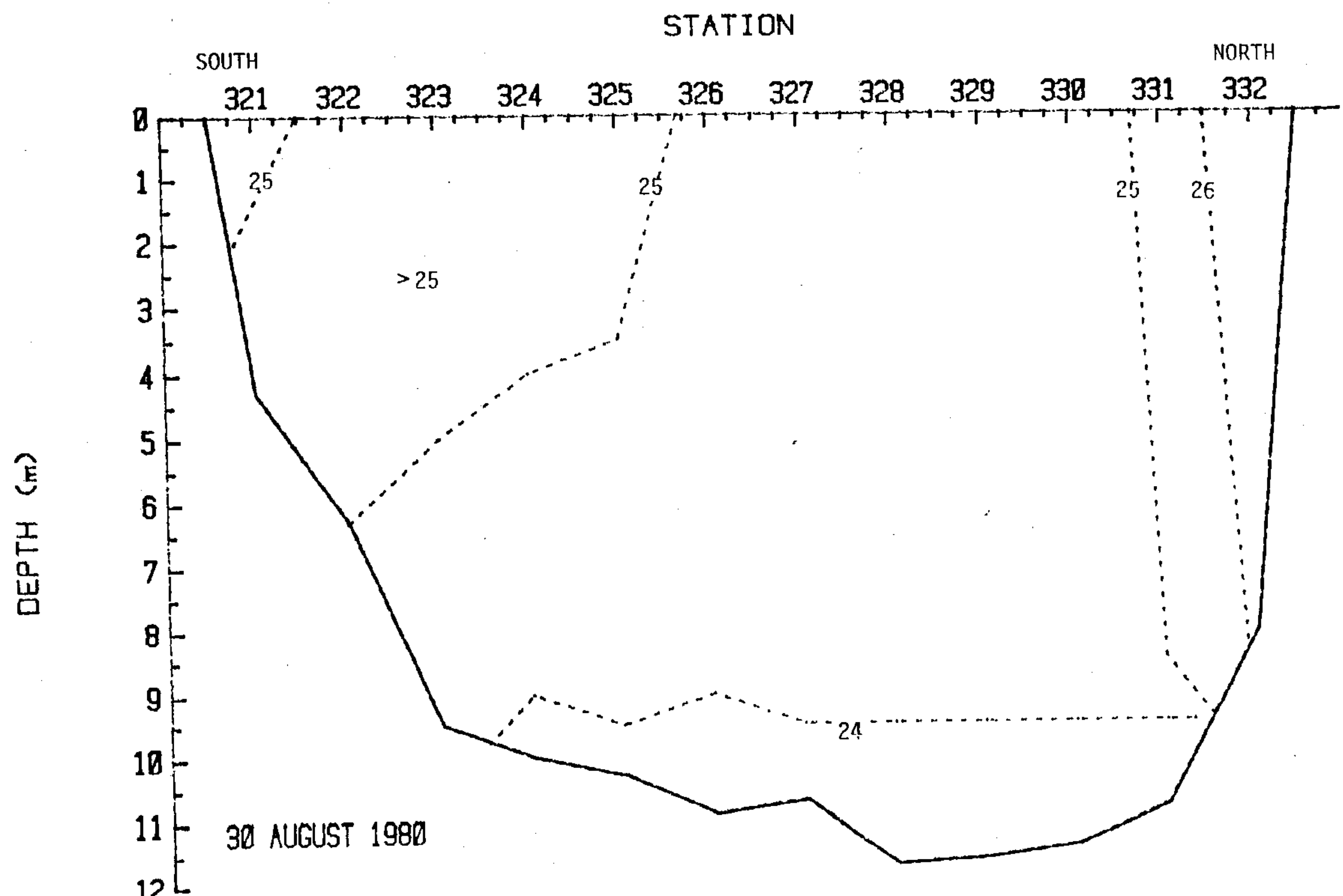
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Figure 5g.

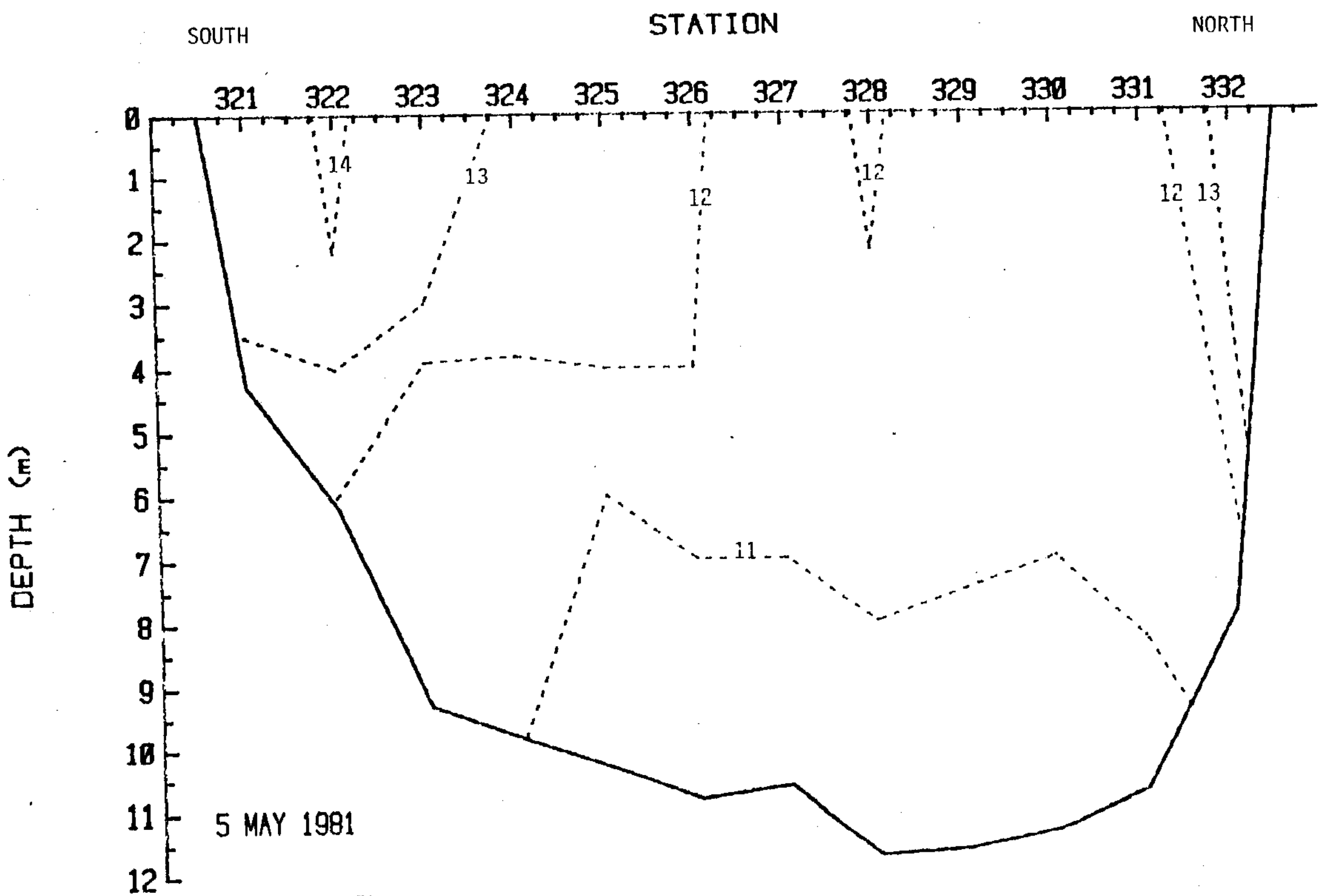
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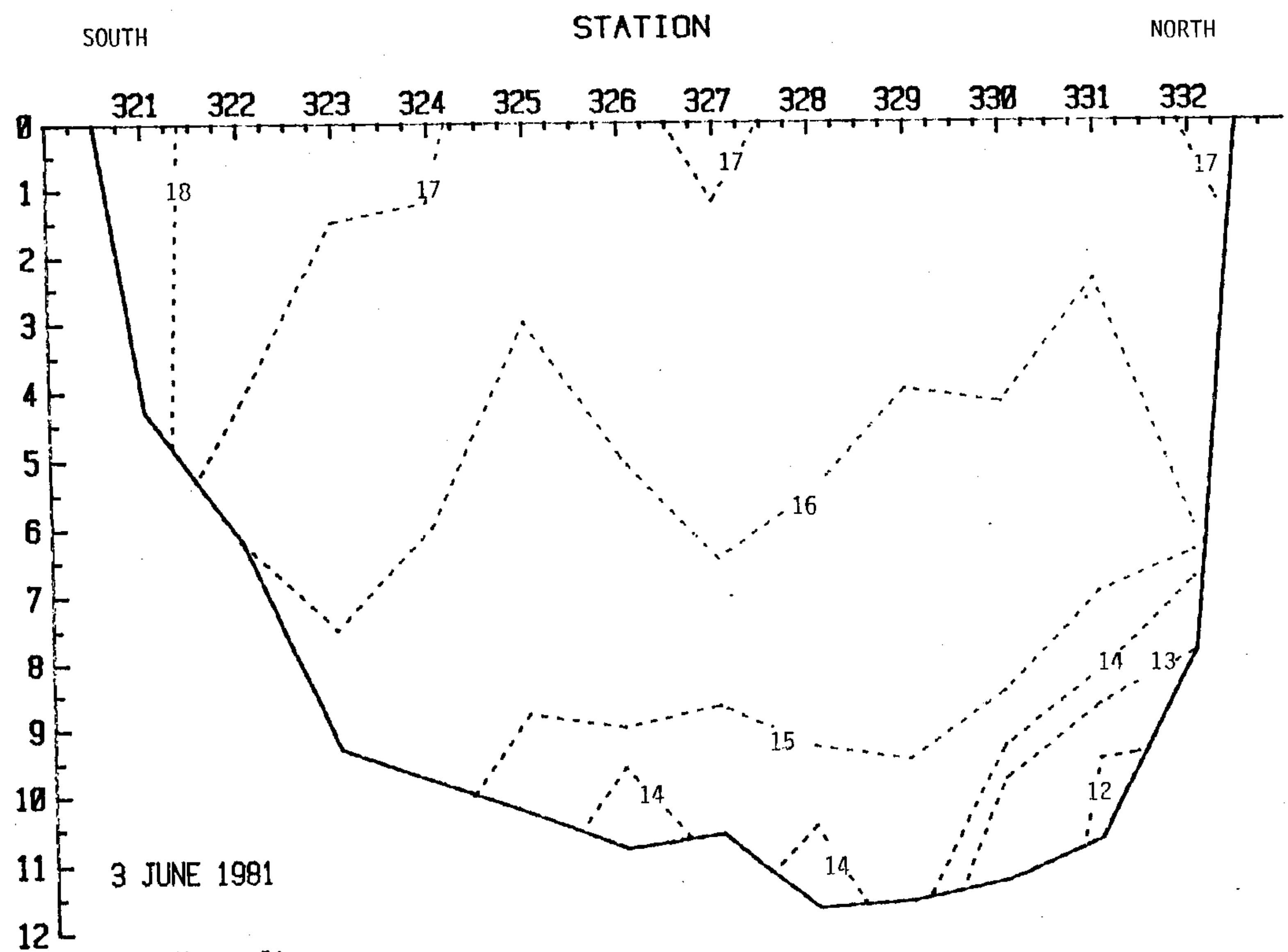
Figure 5h.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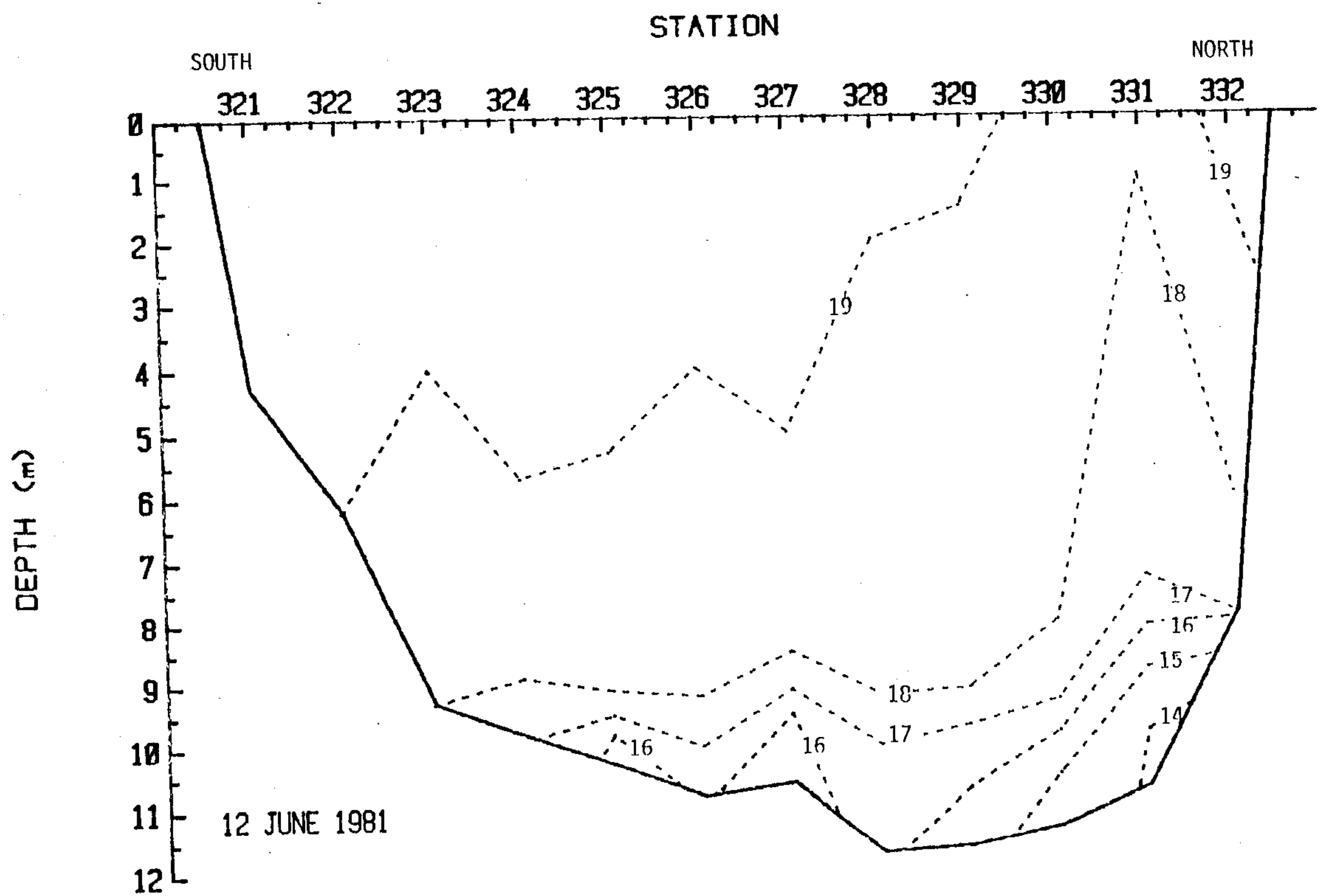
3 JUNE 1981

Figure 5i.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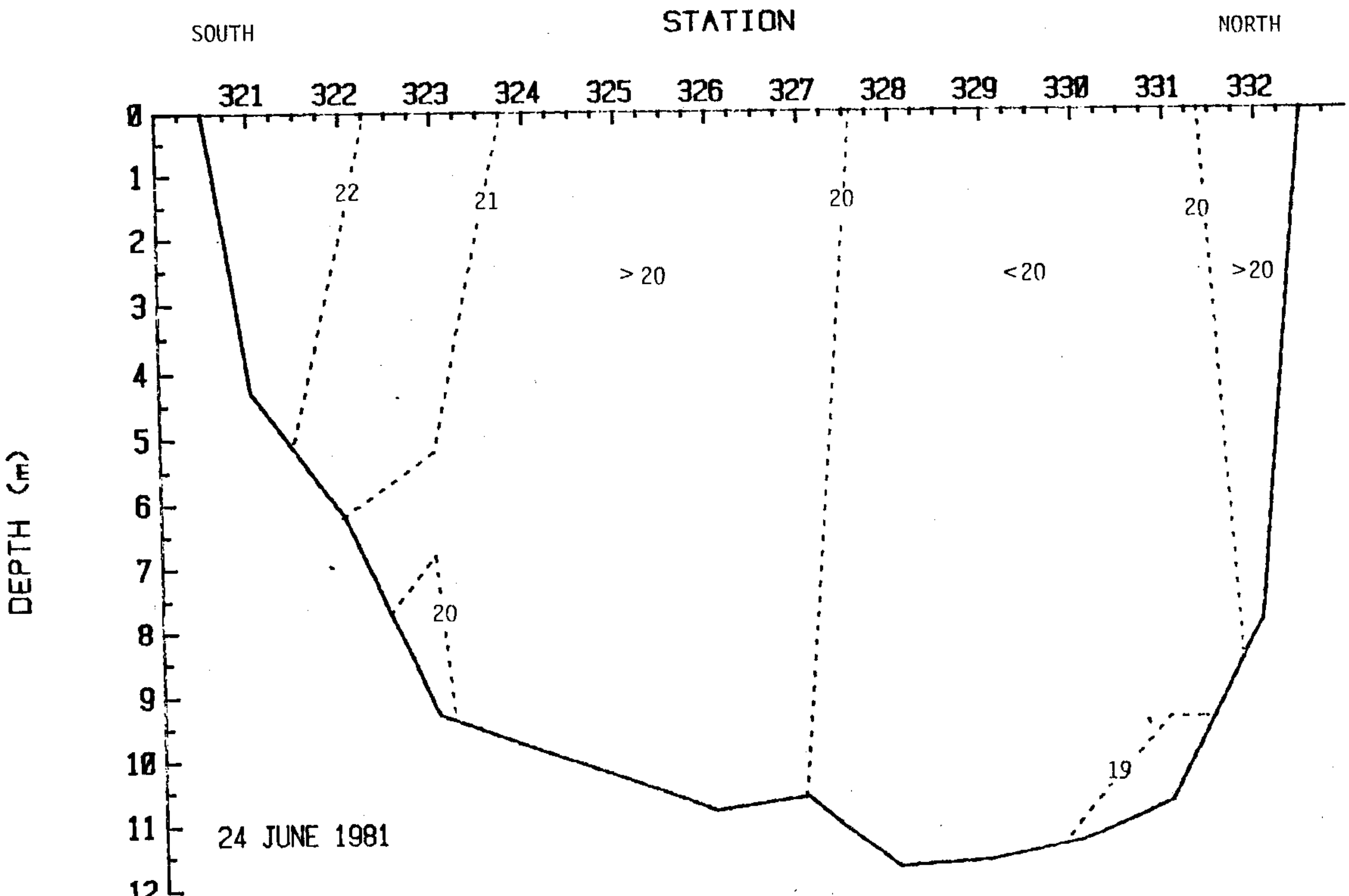
12 JUNE 1981

Figure 5j.



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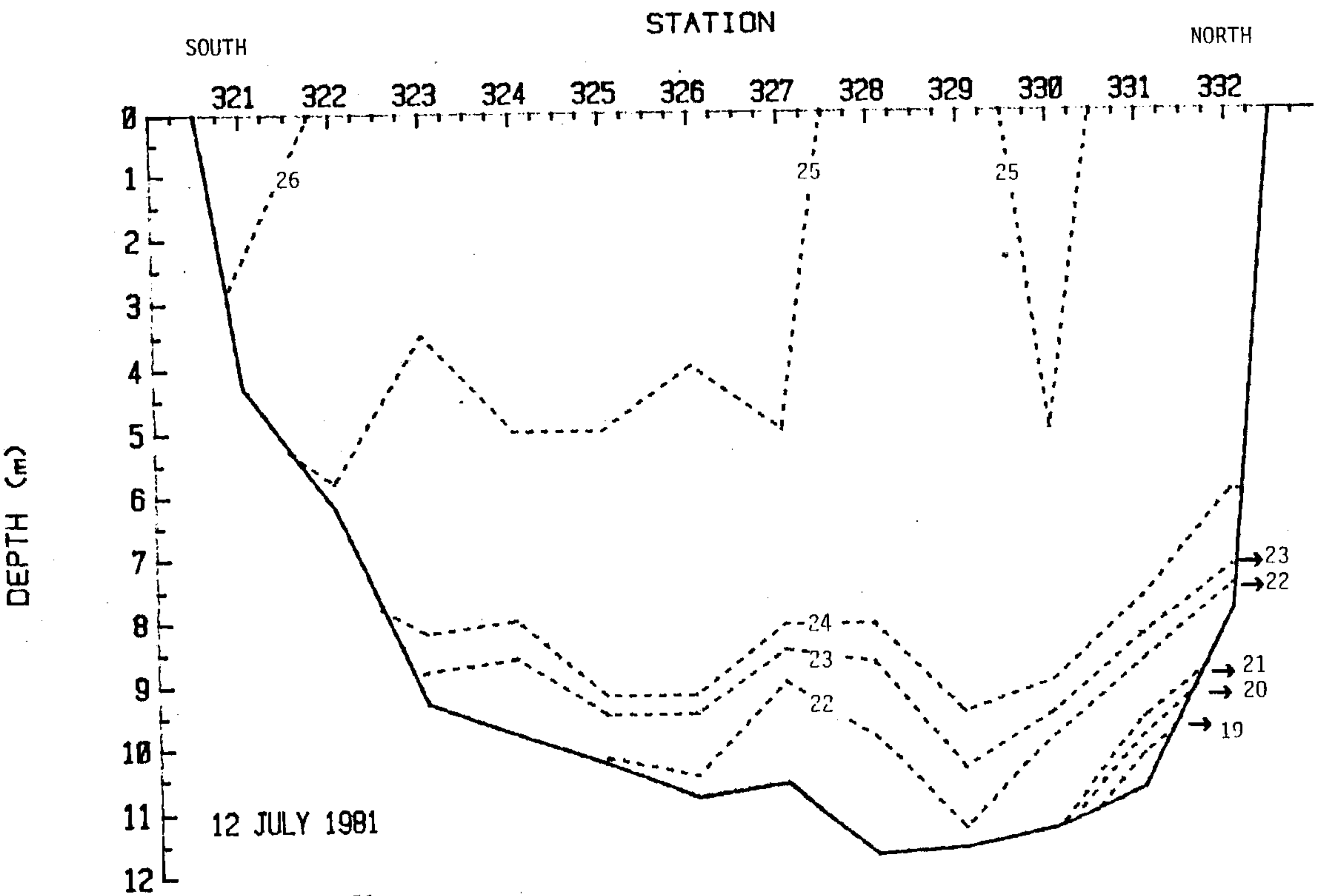
24 JUNE 1981

Figure 5k.


STATION
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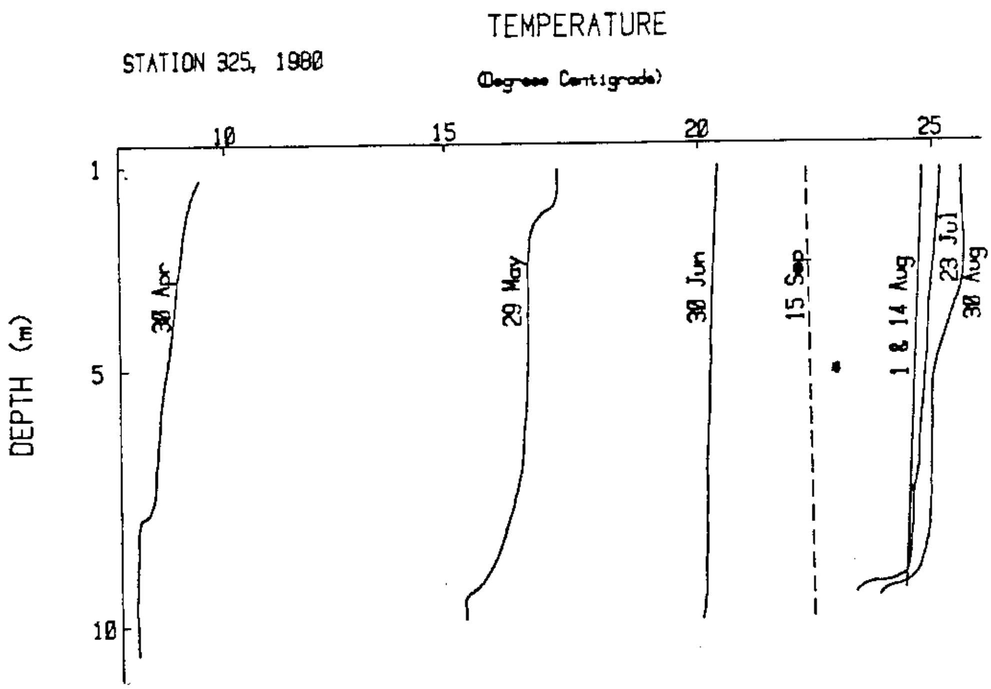
12 JULY 1981

Figure 51.

Occurrences of thermal gradients were, on four occasions, (23 July, 1 August 1980, 5 May and 24 June 1981), spatially isolated; in that a small region exhibited a thermal gradient while the remainder of the transect was isothermal. Isolated, or localized, gradients were most commonly found in the Pigeon Bay region (Stations 331 and 330). Although not the deepest portion of the transect, this region is characterized by the coolest water temperatures in the spring and summer, and warmest in the fall. Local gradients were also observed to the northwest of the Bass Islands, usually at Station 325. Thermal gradients were observed throughout the transect on the remaining four occasions (30 August 1980, 3 and 12 June, and 12 July 1981), with the occasional exceptions of the shallower shoreline regions (Stations 321, 322, and 332).

The thermal profiles for station 331, in 1980 and 1981 (Figure 7), illustrate the general heating pattern that typifies western basin thermal characteristics. Occurrences of thermal gradients were often punctuated by isothermal conditions. Both surface and bottom temperatures increased with each subsequent occurrence of a gradient, except during the two instances of stratification in 1980. On these two events, bottom temperatures were lower than during the previous sampling period.

Although it was difficult, with a sampling frequency of 2-3 weeks, to accurately assess the duration of these thermal gradients, they were undoubtedly short-lived and probably did not exist for much more than a week. From the yearly profiles of station 331 (Figure 7), it was evident that the occurence of thermal gradients was not a permanent, season-long phenomenon.



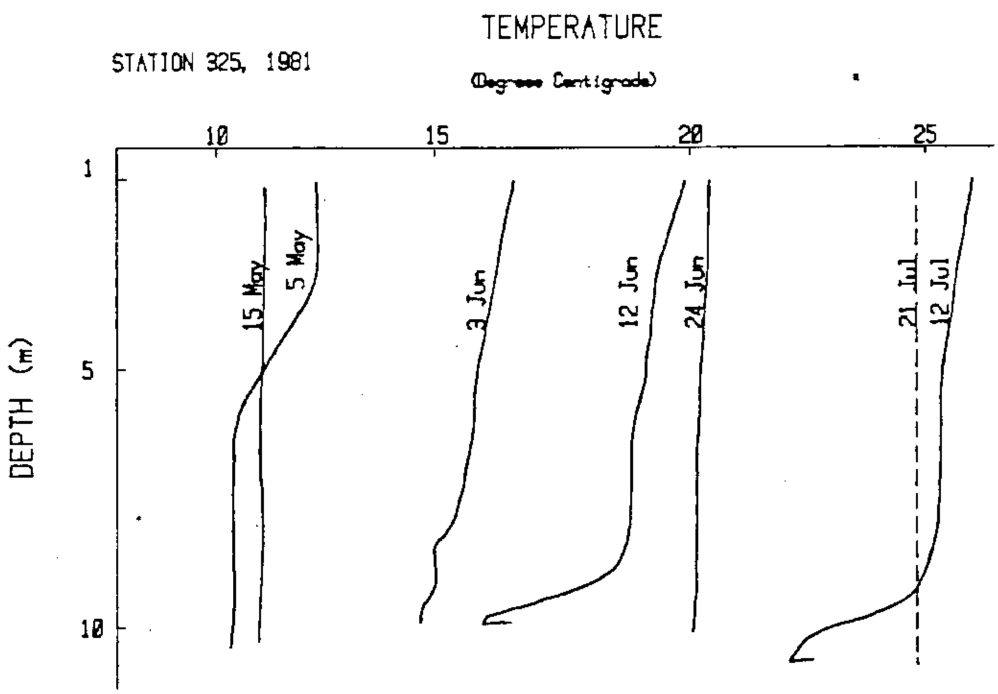


Figure 6. Thermal profiles during warming period, station 325, 1980-1981.

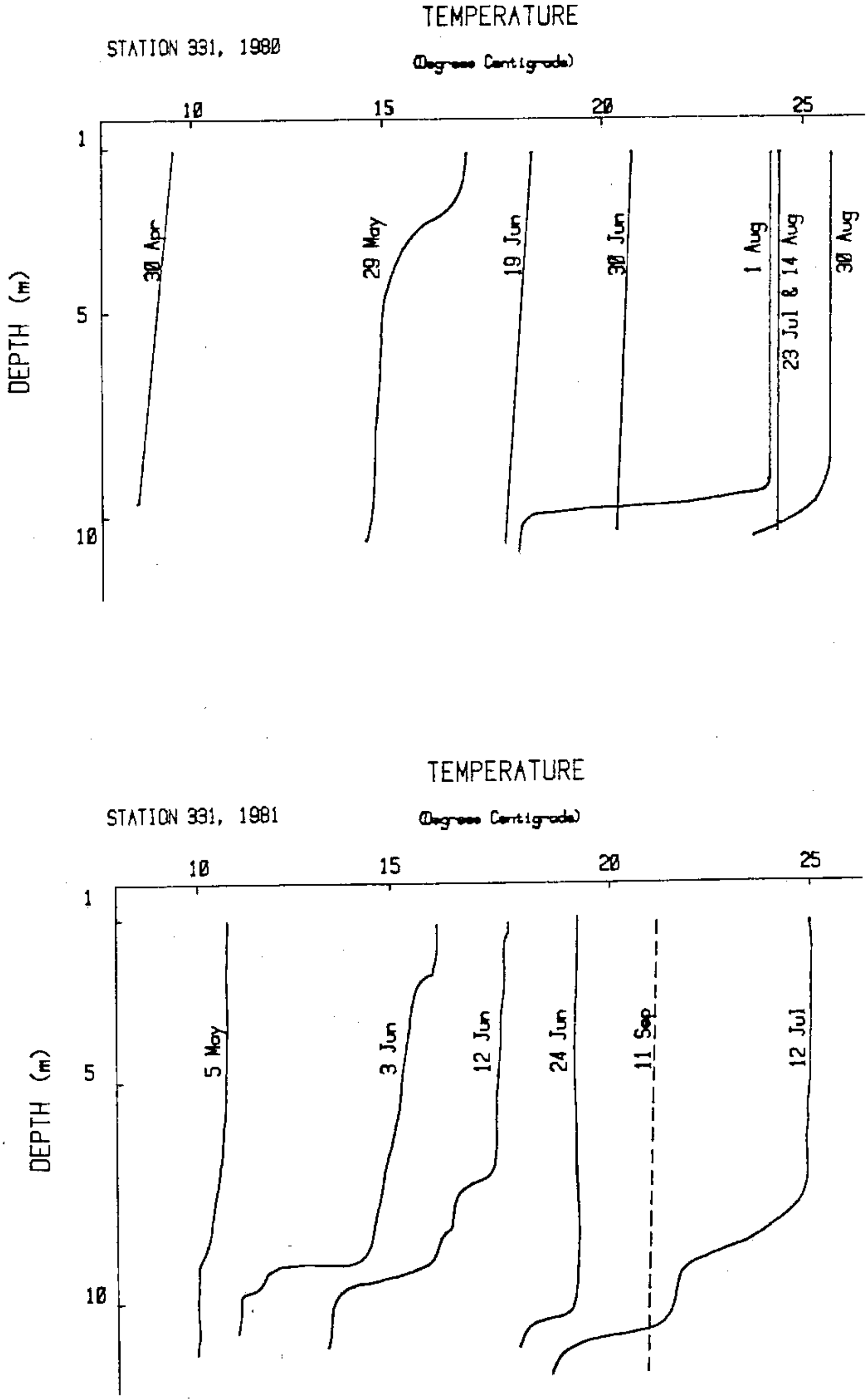


Figure 7. Thermal profiles during warming period, station 331, 1980-1981.

Due to the extremely thin lens of water below the thermal gradient, it was often difficult to confidently obtain a water sample from this lower water mass. On occasions when this mass could be confidently sampled (when the gradient was more than 1m above the sediments), water chemistry indicated the lower water mass had characterisitics distinctly different from those of the surface waters. Dissolved oxygen, pH, conductivity, silica, and ammonia were different from those of the surface. When no thermal gradient existed, there was virtually no difference between surface and bottom water chemical values (Figures 8-14).

At all stations, surficial sediment temperatures were measured by lowering the bathythermometer into the sediments. Evidence of sediment temperatures warmer than the overlying water mass was occasionally found (Figure 6; 12 June and 12 July). This phenomena was observed only during the presence of a thermal gradient, and never were sediment temperatures observed to be lower than the overlying water mass. Observations of higher sediment temperatures were made at stations 321, 324-327, and 332.

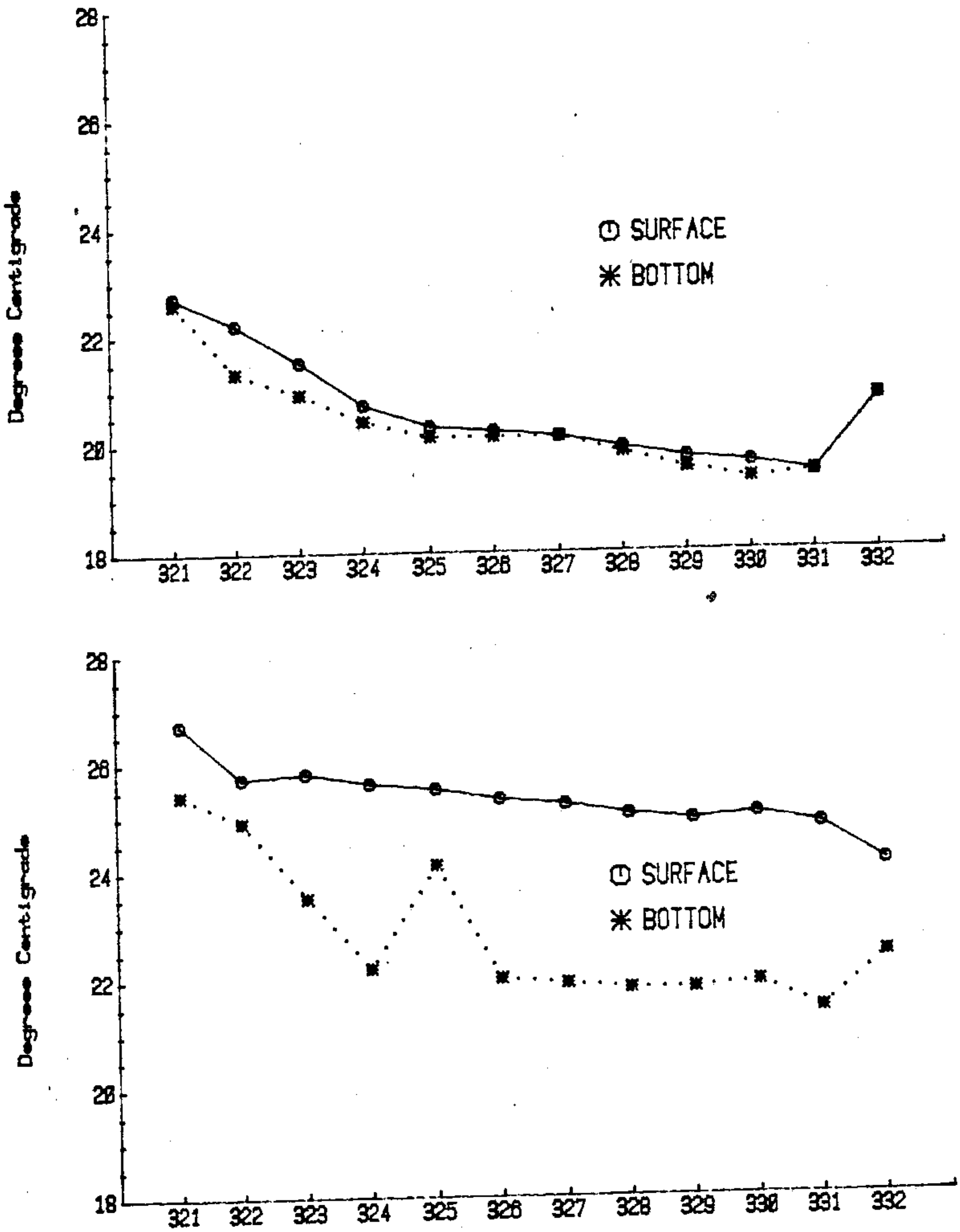
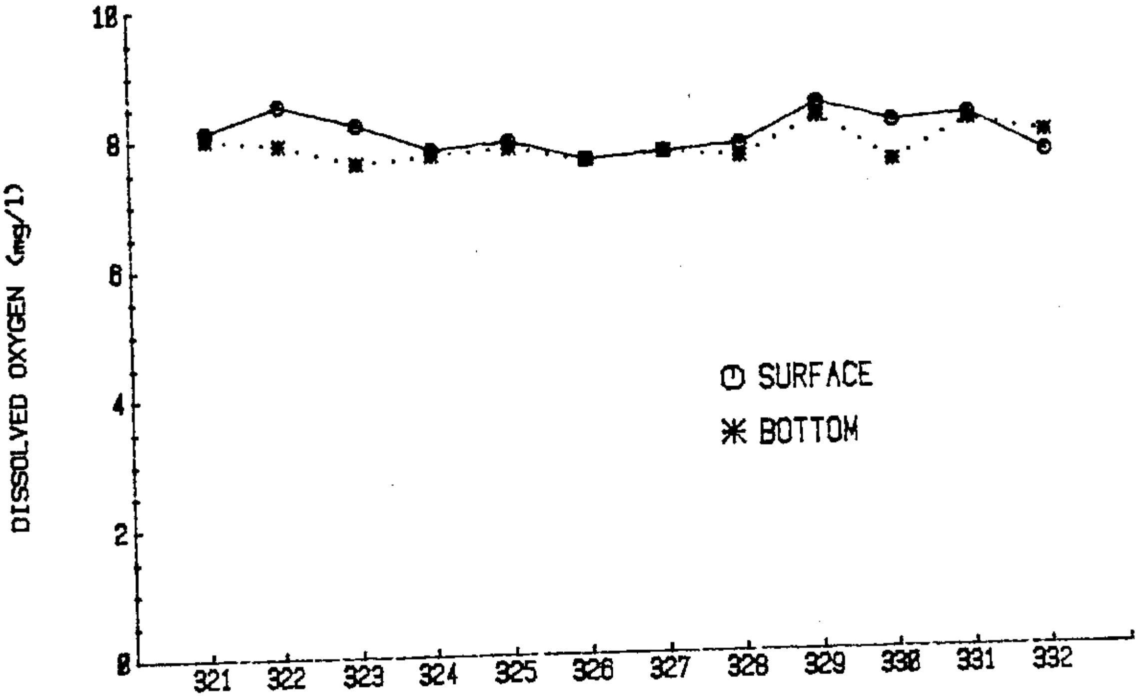


FIGURE 8. SURFACE AND BOTTOM TEMPERATURES ALONG THE WESTERN BASIN TRANSECT, 24 JUNE (TOP) AND 12 JULY 1981 (BOTTOM).



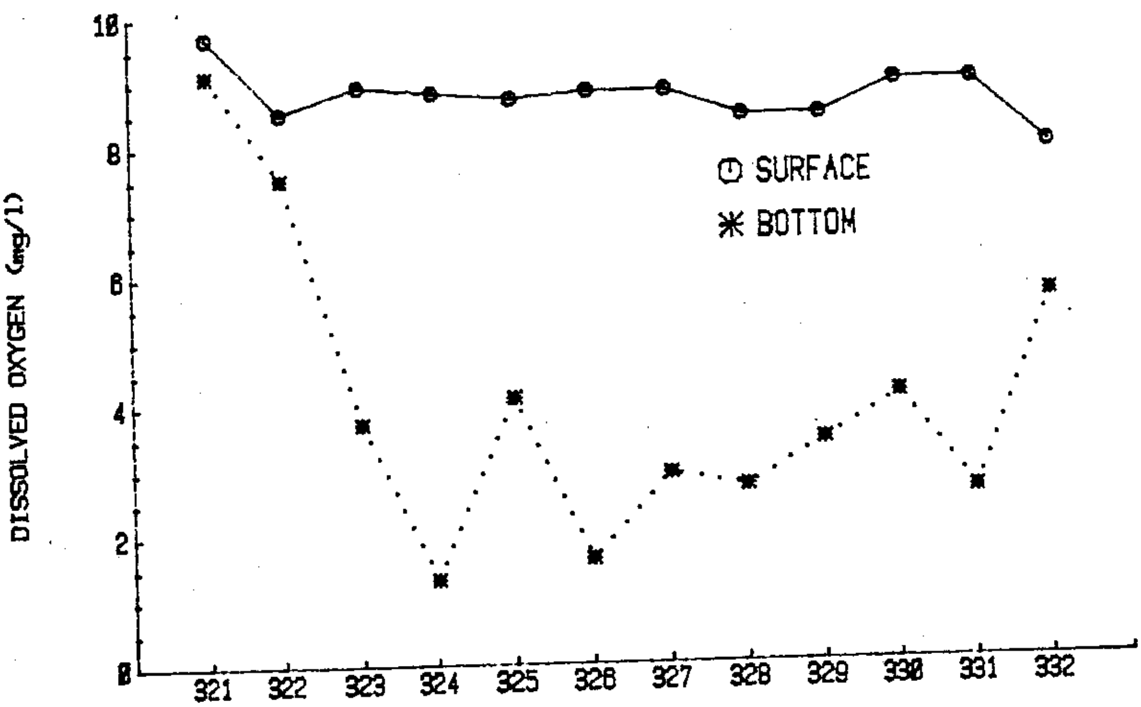


FIGURE 9. SURFACE AND BOTTOM DISSOLVED OXYGEN VALUES ALONG THE WESTERN BASIN TRANSECT, 24 JUNE (TOP) AND 12 JULY 1981 (BOTTOM).

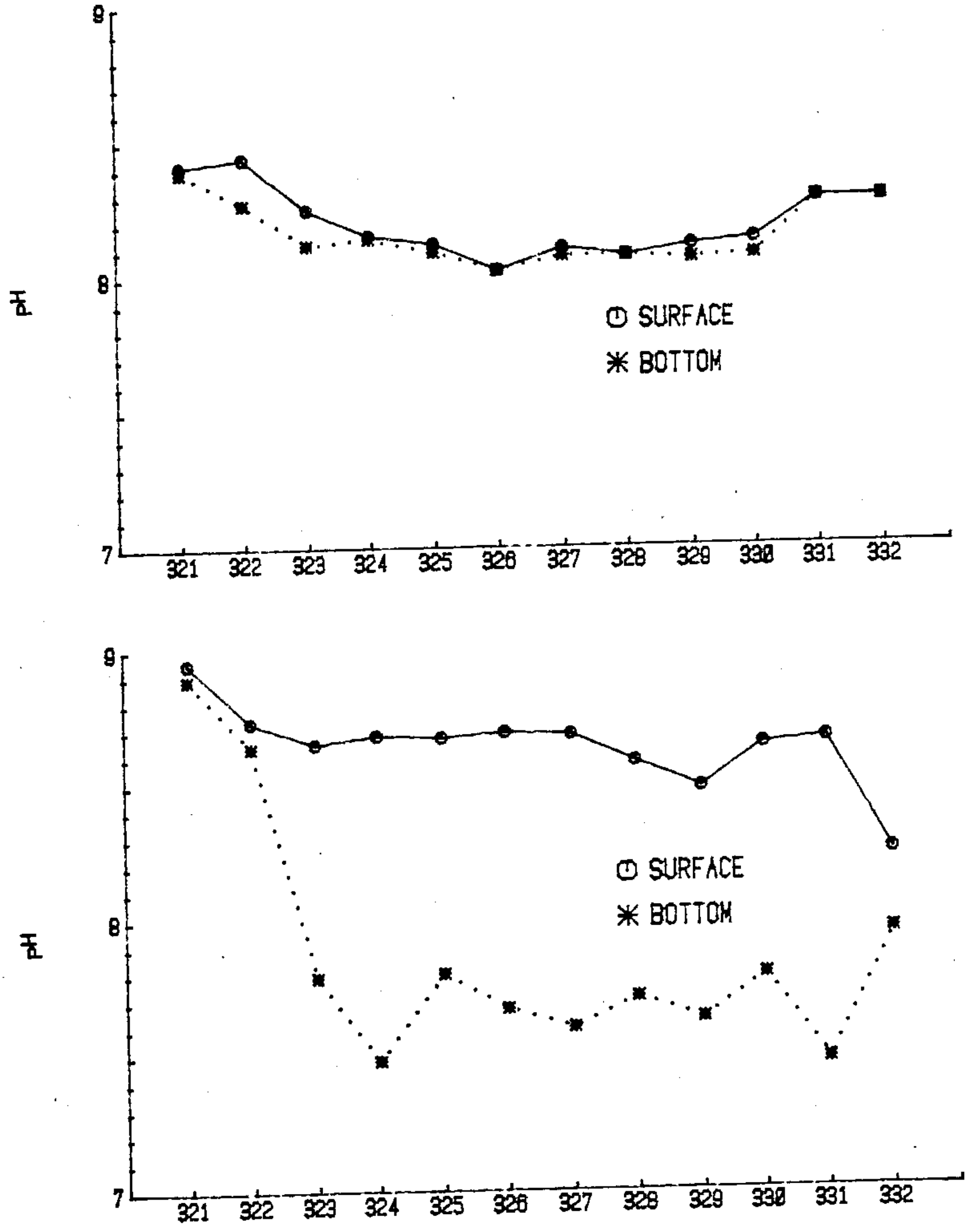


FIGURE 10. SURFACE AND BOTTOM pH VALUES ALONG THE WESTERN BASIN TRANSECT, 24 JUNE (TOP) AND 12 JULY 1981 (BOTTOM).

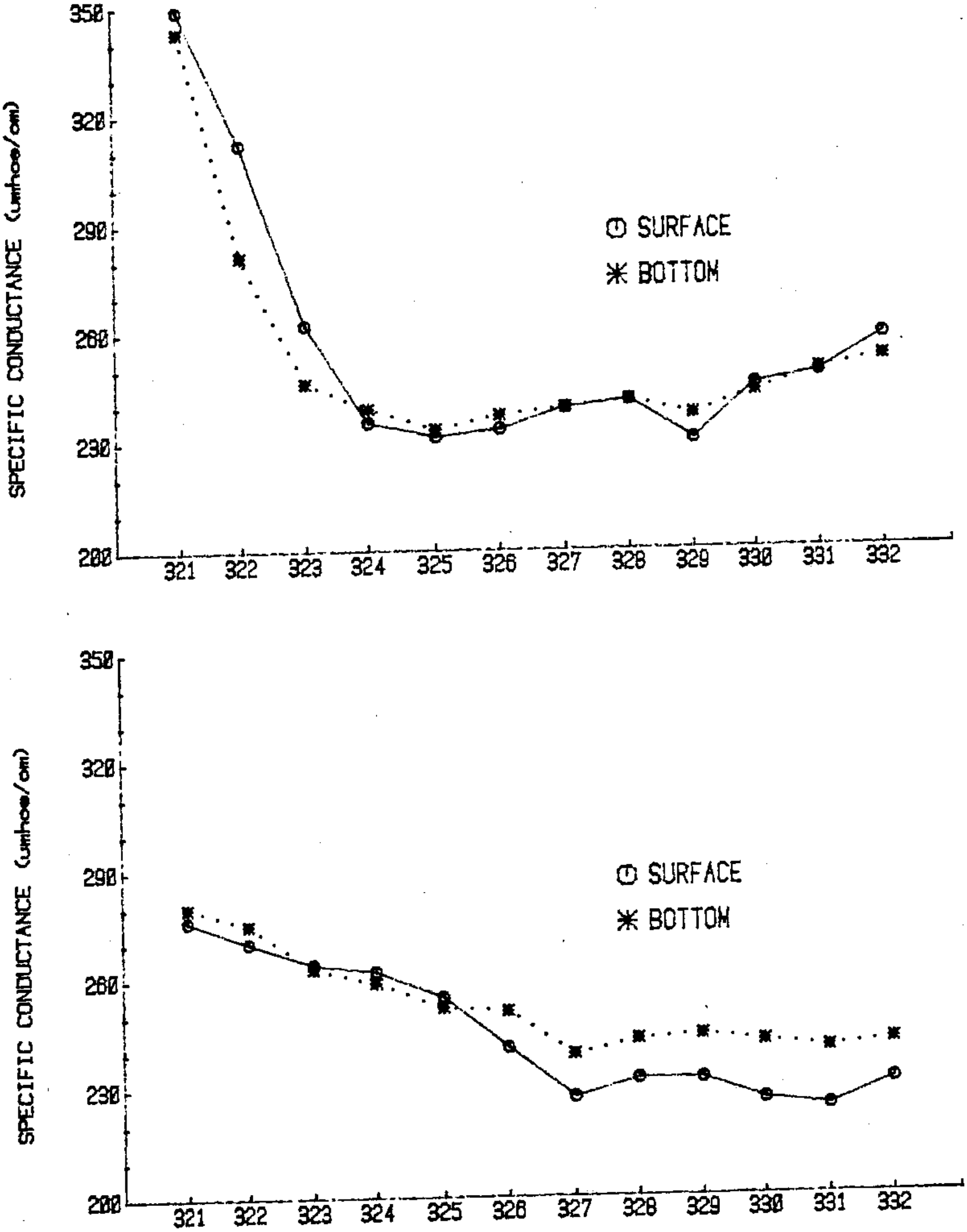
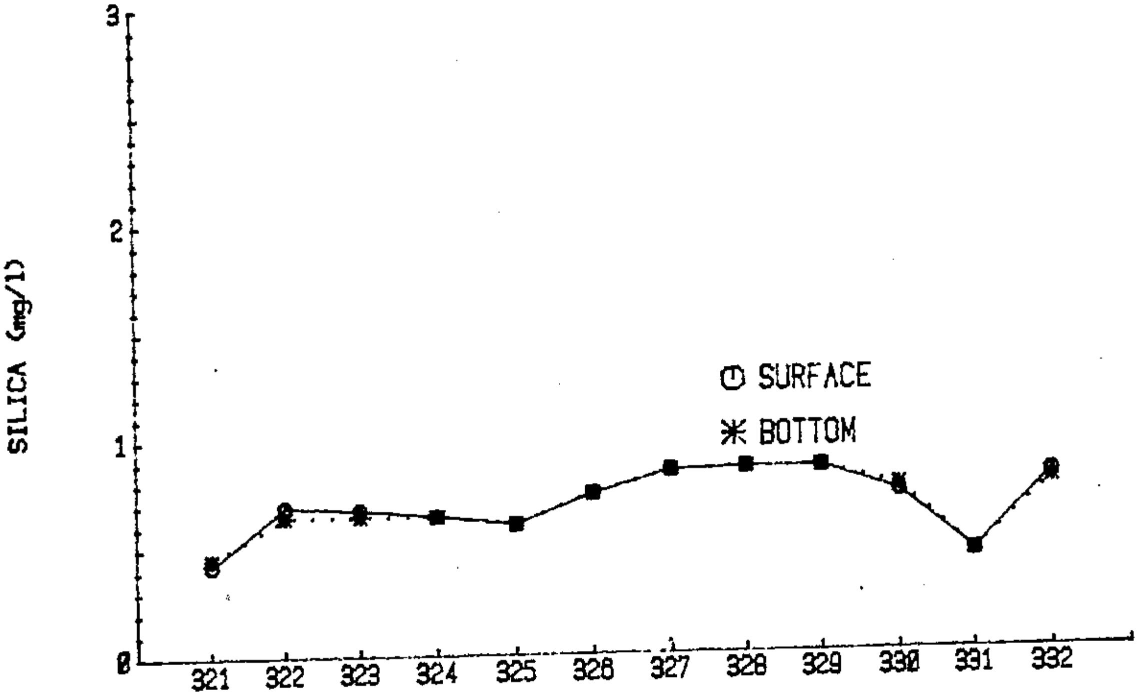


FIGURE 11. SURFACE AND BOTTOM CONDUCTIVITY VALUES ALONG THE WESTERN BASIN TRANSECT, 24 JUNE (TOP) AND 12 JULY 1981 (BOTTOM).



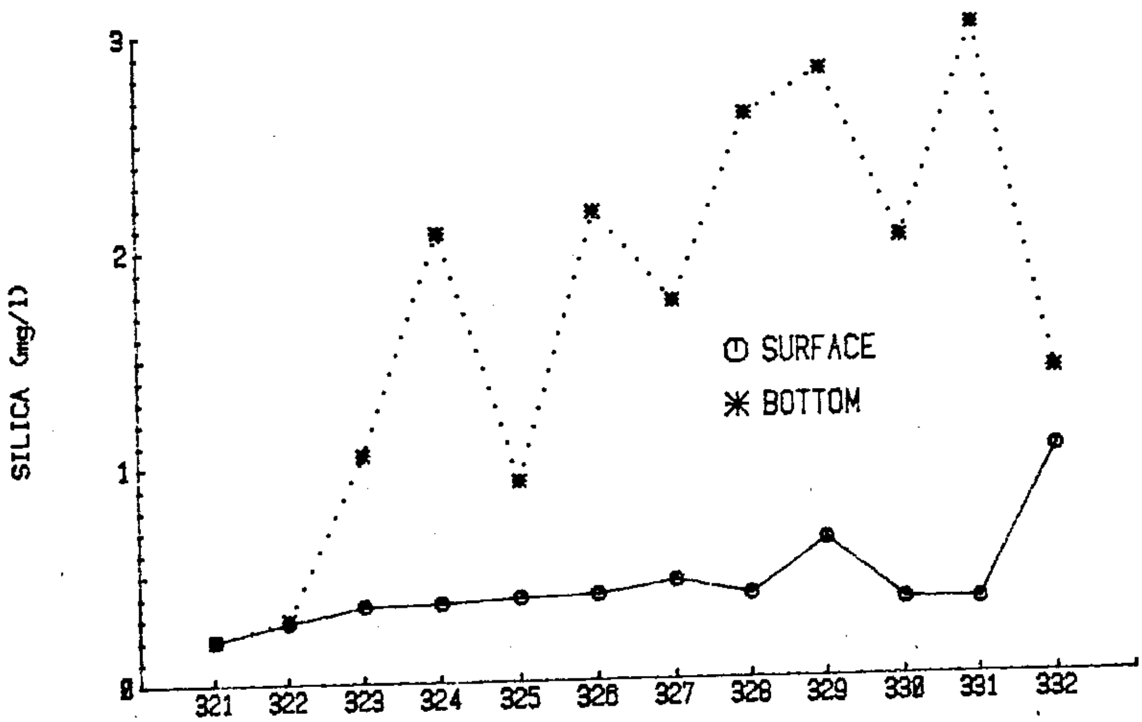


FIGURE 12. SURFACE AND BOTTOM SILICA VALUES ALONG THE WESTERN BASIN TRANSECT, 24 JUNE (TOP) 12 JULY 1981 (BOTTOM).

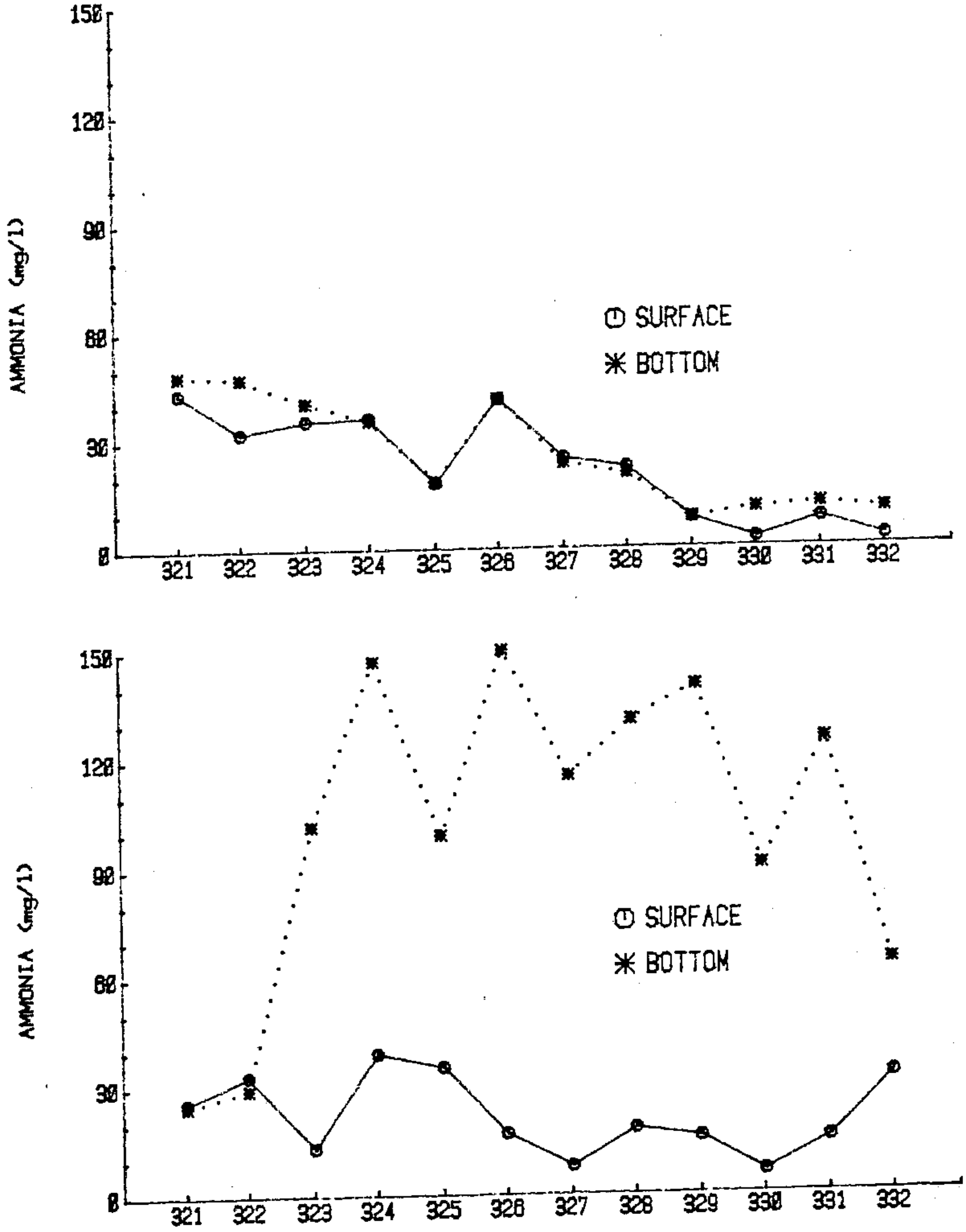


FIGURE 13. SURFACE AND BOTTOM AMMONIA VALUES ALONG THE WESTERN BASIN TRANSECT, 24 JUNE (TOP) AND 12 JULY 1981 (BOTTOM).

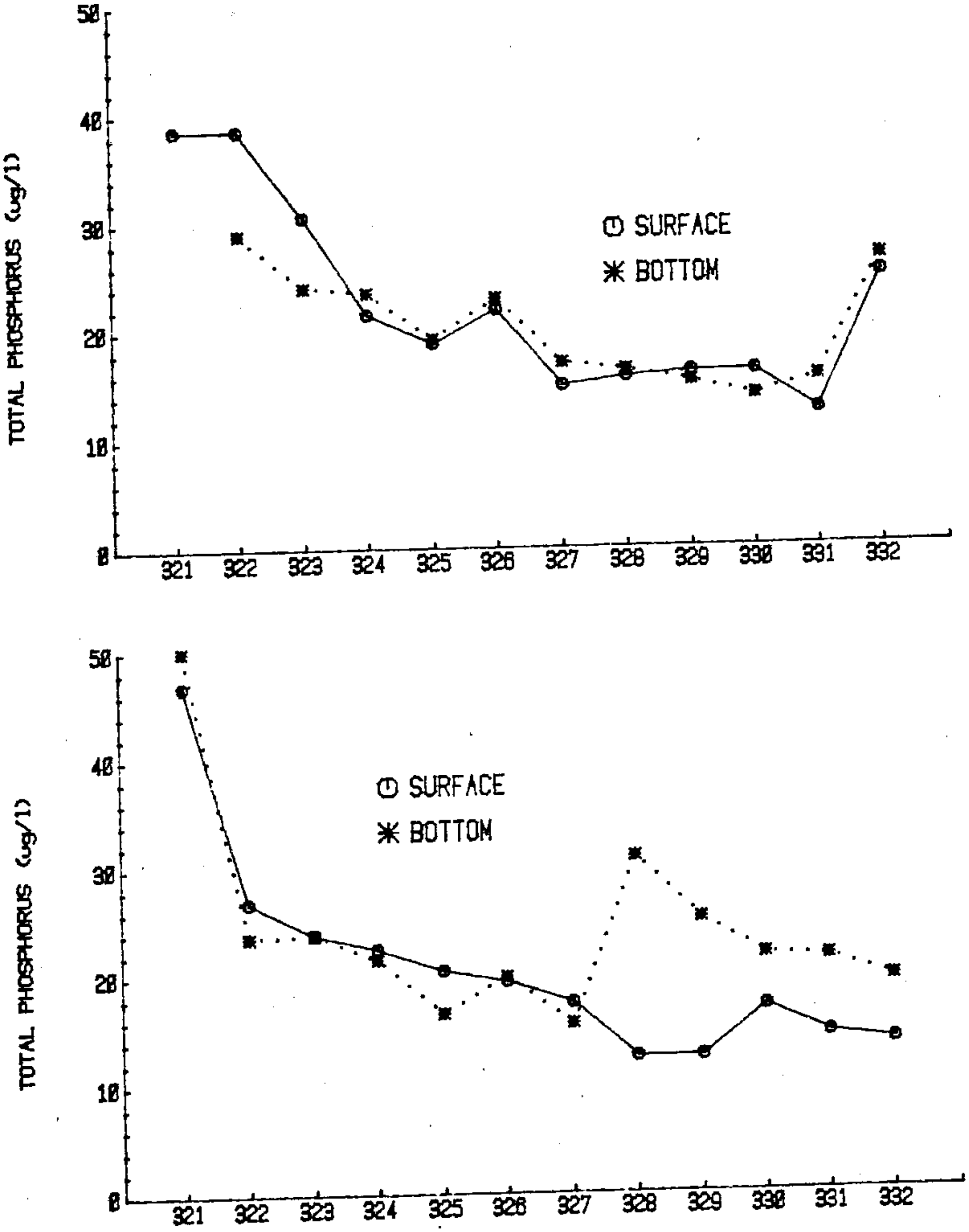


FIGURE 14. SURFACE AND BOTTOM TOTAL PHOSPHORUS VALUES ALONG THE WESTERN BASIN TRANSECT, 24 JUNE (TOP) AND 12 JULY 1981 (BOTTOM).

DISCUSSION

Before commencing a characterization of the thermal patterns in the western basin of Lake Erie, it is necessary to review the general process of thermal stratification. In a "typical" temperate zone lake, ice-cover disappears in the early spring, the lake's waters are well-mixed, and temperatures are vertically isothermal. Atmospheric warming and the sun's radiation heat the surface waters and winds effectively distribute this heat throughout, thus warming the entire water column. As water temperatures increase, so does the work needed to mix the water. The surface waters continue to warm, while the bottom waters remain cool. The resulting temperature gradient between the upper and lower water masses becomes an effective, physical barrier to wind-induced mixing. This temperature gradient is termed the "thermocline," and the upper and lower water masses are the "epilimnion" and "hypolimnion," respectively. Also, the region of rapid temperature change (in which the thermocline is located) is termed the "mesolimnion." Throughout the summer, surface waters continue to warm and the temperature difference between the epi- and hypolimnion increases. As the temperature gradient sharpens and increases, the stability of the system also increases. When atmospheric temperatures decrease in the late summer and early fall, surface waters lose heat, and the temperature difference between the epilimnion and hypolimnion lessens. The stability of the water column decreases, eventually, the thermocline is disrupted, epi- and hypolimnion become mixed, and isothermal conditions result (Wetzel, 1975).

Thus atmospheric warming and wind force have contrasting effects on the thermal structure of a lake, and determine the position of a thermocline. The wind mixes the waters, and inhibits the establishment of a thermal gradient. Atmospheric warming heats the surface waters, and in the absence of wind, a thermocline would form near the surface. Together, these two forces produce a thermocline at a depth greater than would be affected by atmospheric heating alone (Birge, 1916).

In the western basin of Lake Erie, thermocline formation is greatly affected by water depth. Because of the relatively shallow depth of the basin (7.6m), western basin wind fields are usually capable of mixing the upper warmed waters throughout the entire water column, thus preventing stratification. Therefore, the western basin is considered, and rightly so, to be a system in which isothermal conditions prevail, with most studies regarding the western basin as vertically isothermal and chemically homogenous.

Occasionally, distinct thermal gradients are observed in the western basin which prevent mixing between the upper and lower water masses. Examples of this have been noted on several occasions (Wright, 1955; Chandler, 1940, 1944; Chandler and Weeks, 1945; Carr et al., 1965; Britt, 1955a), and can be seen in Figure 5. As referred to in the Results, occurrences of stratification in the western basin are characterized by a thermocline extremely close to the bottom (0-3m), a slight temperature difference between the epi- and hypolimnion (1-5°C), and a short duration of the gradient (1-10 days). Because of these differences between stratification in the western basin and that in a "typical" lake, some question arises as to whether or not, by definition, thermal gradients in the western basin can correctly be termed "stratification," and if the accompanying terminology can also be applied. Specifically, can the term "thermocline" be used to describe the density/temperature gradients that occasionally occur in the western basin?

Birge (1897) defined a thermocline as a layer in which the temperature change with depth is at least $1^{\circ}C$/meter. This criterion is most often used today to determine if the water column is "stratified;" however, this definition deserves closer attention. Although thermal stratification is simply a layering of different temperature waters, it is actually the density difference that is responsible for the separation of the two water masses. Density decreases as temperature increases (above $4^{\circ}C$), but this decrease is non-linear (Figure 15). At higher temperatures, the change in density per degree change in temperature is much greater than at lower temperatures. In two hypothetical lakes, each with a thermocline (by Birge's (1897) definition), one has a temperature change from 4 to $5^{\circ}C$ across a 1m thick thermocline, the other 24 to $25^{\circ}C$. Although both lakes exhibit thermoclines, the warmer lake has a stability (or a density difference) that is more than 30 times greater than the cold lake. In order for the cool lake (with a $4^{\circ}C$ hypolimnion) to have equal stability as the warm lake, the epilimnion must be $10^{\circ}C$. Although the use of Birge's (1897) criteria is common, it is arbitrary in assessing a lake's thermal stability, or the potential of the thermal gradient to inhibit mixing (Hutchinson, 1957).

In this paper, Birge's (1897) definition of a thermocline will be used. In the western basin, thermoclines were present on eight occasions during 1980 and 1981 (Fig. 5) and have been noted many times during the period of record. The terms epi-, meso-, and hypolimnion will be used to denote the upper, middle, and lower water masses delineated by the thermocline, and the water column will be

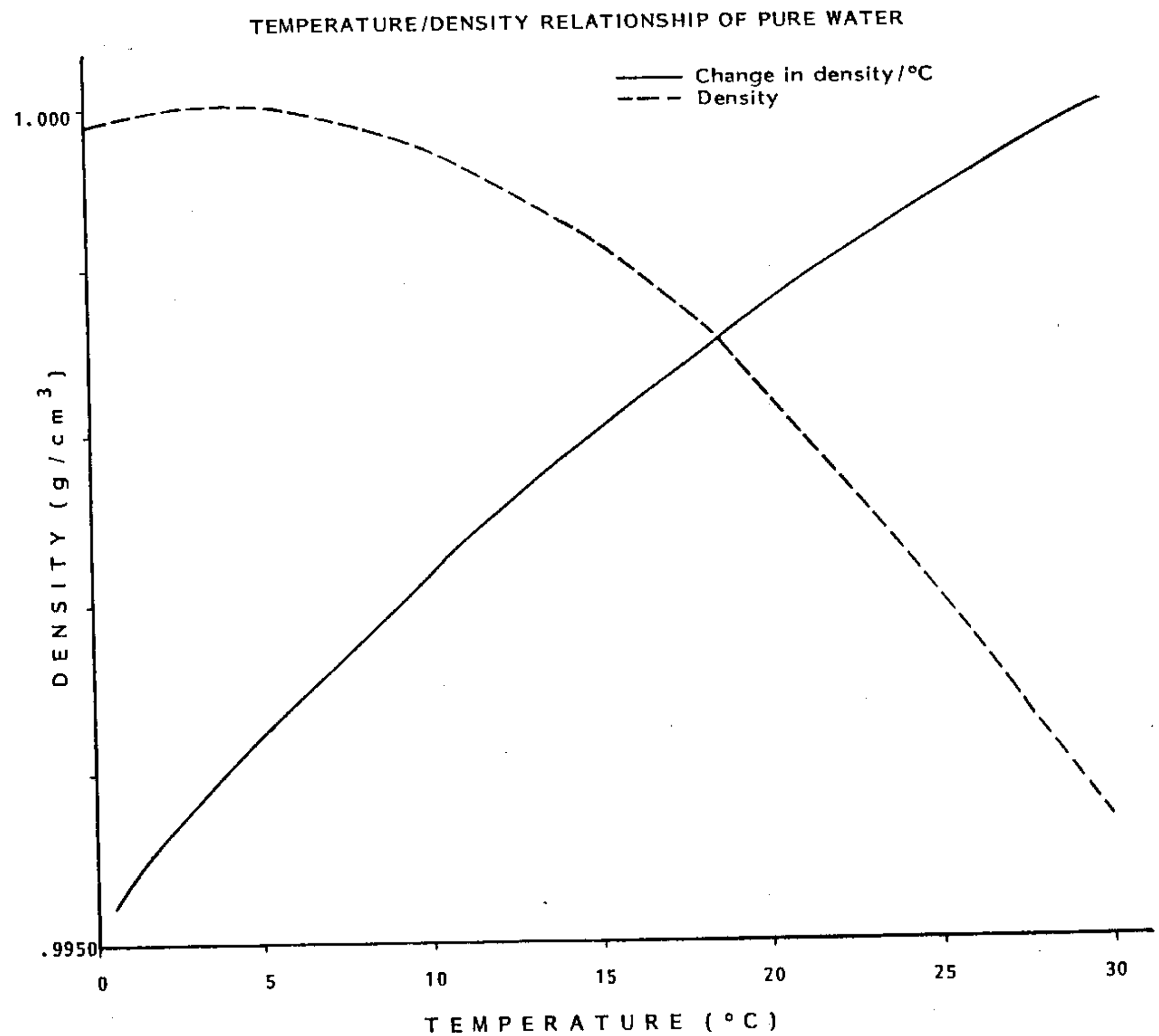


Figure 15. Temperature/density relationship of pure water.

considered to be "stratified." It is important to keep in mind the ephemeral nature of stratification in the western basin. When the term "stratified" is used to describe conditions in the western basin, it denotes the presence of a thermocline at a point in time, and does not suggest the stable, summer-long system described for a "typical" lake. Thermal stratification in the western basin, therefore, refers only to short periods when slight thermal gradients (thermoclines) are present.

CHARACTERISTICS OF WESTERN BASIN THERMAL STRATIFICATION

Heating Cycle

The western basin is typically isothermal at 0-1°C from late December until early March, and often completely ice-covered (FWPCA, 1968). Ice cover disappears in March, and warming begins. In April and May, wind action is sufficient to keep the water well-mixed. Occasionally in May, a thermocline may develop, but these early occurrences are usually shallow and have a small temperature difference across the thermocline. As atmospheric temperatures increase in June and stabilize in July and August, stratified conditions become more prevalent. This is due to the temperature/density relationship. At higher temperatures, slight changes in temperature result in a significant change in density; and light winds (0-5m/s) are incapable of countering the buoyancy exerted by the cooler, more dense, bottom water mass. However, moderate to high winds creating heavy seas or seiche activity will destroy stratification. When the disruptive wind or seiche activities cease, the water column begins to restratify, until the next episode again destroys the thermocline. By late summer, atmospheric temperatures decrease, after which no new formation of a thermocline occurs. Water temperatures will then continue to decrease, and isothermal conditions prevail.

Typical summer western basin thermal profiles would exhibit alternating periods of stratification and mixing. Following destratification, the bottom water would be warmed to the temperature of the epilimnion, and the next thermocline would form with bottom waters at the same or higher temperatures. Thus each successive period of stratification would occur with bottom waters warmer than the previous period (Hartley, 1966). However, bottom water temperatures have been observed to decrease while surface temperatures increase (Wright, 1955; Carr et al., 1965). This phenomenon will be discussed later.

As noted in the Results, stratification existed as early as May 5 (1981) and as late as August 30 (1980). Historically, most observations of thermoclines were during June and August, the earliest being 23 May (Chandler, 1940), and the latest 5 September (Britt, 1955a). The period of thermocline occurrence in the western basin (Mid-May through early September) compares favorably with the stratified period of the central basin. Stratification persists longer in the central basin because of its greater hypolimnion volume; epilimnetic waters cool slower; the temperature difference between the epi-and hypolimnion are greater; and the thermocline is deeper and less affected by winds.

Frequency of Stratification

In the western basin, the frequency of stratification is variable, from year to year, and from one location to the next. At station 331 (Figure 7), there were two occurrences in 1980, and four occurrences in 1981, while at station 325 (Figure 6), 2 in 1980 and 2 in 1981. Stratification was observed along the transect during eight of the fifteen sampling cruises conducted from May through August. In 1930, Wright (1955) noted stratification on three occasions, and Carr et al. (1965) estimated that stratification occurred an average of 3 times per year from 1953 to 1963. This estimate was based on the occurrences of calm, warm weather of sufficient duration to allow for thermal development. It is unlikely that stratification does not occur during a specific summer. However, due to the extremely short duration and localized occurrences of stratification (discussed below), the actual number of occurrences would be difficult to substantiate. Stratification may occur, but may not be observed due to sampling frequency or location. An extensive array of stations throughout the basin, sampled frequently, would be needed to make this assessment.

Duration of Stratified Conditions

The duration of stratification was as difficult to determine as was frequency. The thermocline observed on 1 August 1980, assuming it was established immediately after the previous 23 July cruise and existed until the 14 August cruise, would have lasted 22 days (conditions on both 23 July and 14 August were isothermal). By similar calculation, the occurrence observed on 30 August 1980 could have lasted 30 days. These estimated maximum stratified periods are not probable, and most studies have reported stratification to last not more than 4-7 days. (Chandler, 1940, 1944; and Britt et al., 1968, 1973). In 1981, between 3 and 12 June, the hypolimnion warmed at a rate of .2°C/day, or 2°C over the 9-day period. In contrast, the central basin hypolimnion warms at a rate of 1.5°C/month

(Burns, 1972), but warming in the western basin hypolimnion would be expected to be more rapid, due to its small volume. Stratification may have been continuous from 3-12 June, however, the hypolimnion was too thin to sample on 12 June. By 24 June, however, a thermocline was absent at all but station 331. Stratification on 12 June, 24 June, and 12 July are assumed to be separate instances, with periods of mixing occurring between each.

In 1953, an extended period of high air temperatures and low wind velocities persisted through August and into September (Carr et al., 1965). Whether stratified conditions were actually present during the entire period is not discernable, but the resultant depletion of dissolved oxygen from the hypolimnion and the extensive die-off of the benthic aquatic mayfly (Hexagenia) nymphs indicated that stratification was extensive. As with determining the recurrence of stratification, frequent sampling is also required to ascertain the exact duration. Although stratified periods are certainly short-lived, the effects are critical to the water quality of the basin and the benthic biota (discussed later).

Location

Thermoclines have been observed throughout most of the areas of the western basin. All stations along the transect have shown some degree of stratification, as have stations 50, 54, 57, 59, and 61 (Figure 16). Previously, most reports of thermal stratification were in the vicinity of the Islands region (Figure 17). The frequent observance of stratification in this region is an artifact of sampling; investigations were concentrated in the island region due to the location of a biological field station on South Bass Island. Many of Wright's (1955) 1929-

Figure 16. Areas exhibiting thermal stratification, 1980-1981.

AREAS OF THERMAL STRATIFICATION, WESTERN BASIN, LAKE ERIE

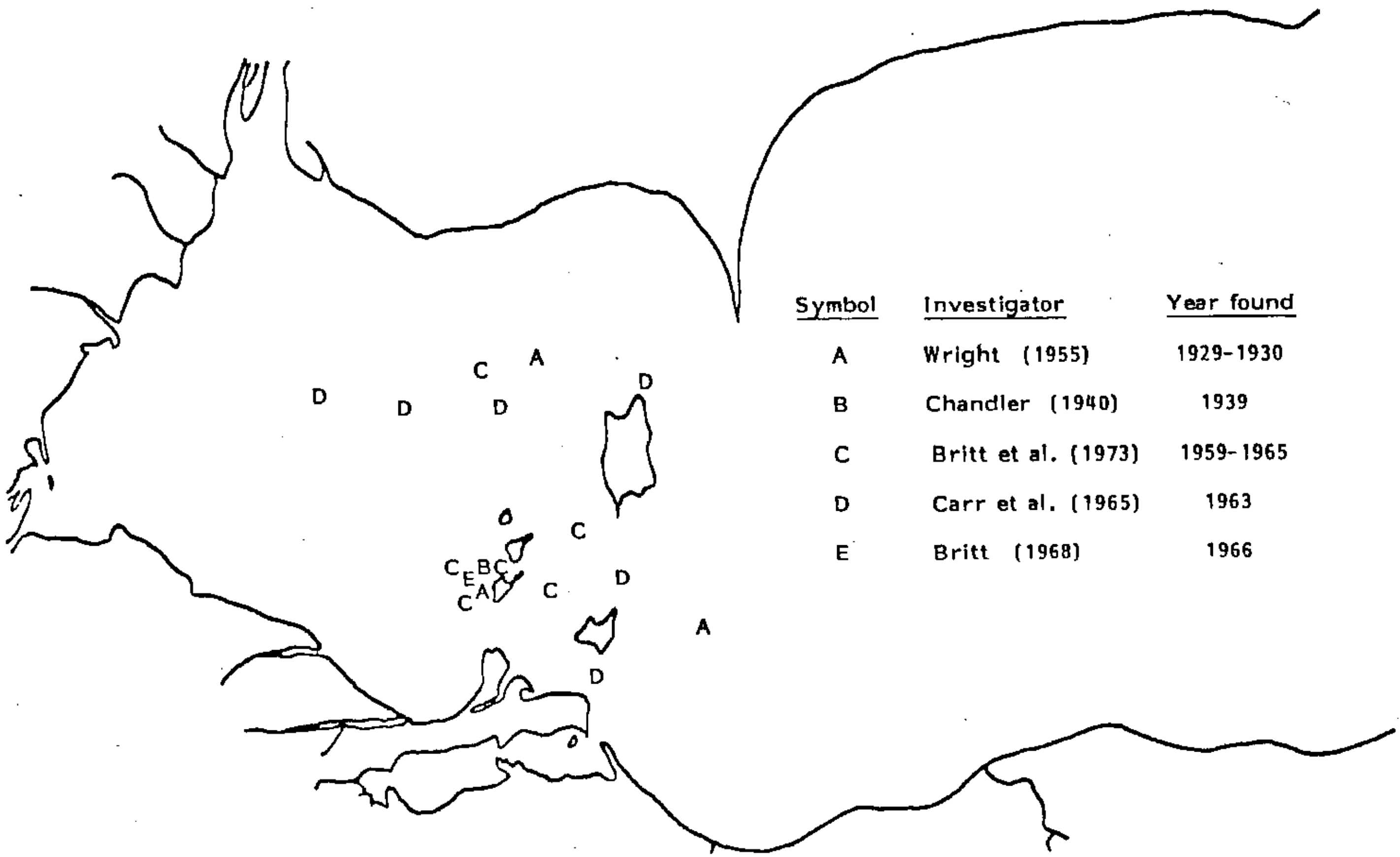


Figure 17. Previous observances of thermal stratification.

1930 reports of stratification were east of the islands, nearing the western margin of the central basin. His observations of stratification in this region were probably of central basin hypolimnion (Britt et al., 1973). Wright (1955) also reported stratification in the central part of the western basin, west of Middle Sister Island, as did Carr et al. (1965).

During 1980-1981, stratification was observed most often (six times) in the Pigeon Bay region (Stations 332, 331, 330) (Figure 2). The Pigeon Bay region consistently exhibited the lowest water temperatures of all the transect stations, and contained water that was of "best" quality (i.e., highest transparency, lowest nutrient concentration, lowest turbidity). In this respect, water in Pigeon Bay closely resembles waters of the Detroit River or central basin. Hartley et al. (1966) and Herdendorf (1970) have suggested, from temperature, conductivity, and turbidity measurements, that central basin water moves through Pelee Passage and into the Pigeon Bay/North Channel region. Also, Pigeon Bay is influenced by Detroit River water (Olson, 1950; Verber, 1953). Both explanations may account for the good quality water in Pigeon Bay. Surprisingly, stratification does not occur more frequently at stations 328 and 329, representing the deepest area of the western basin (approximately 12m) (Figure 18). These two stations lie in the heavily used shipping channel between Point Pelee and the Detroit River light. Large vessels drawing 8m or more are restricted to the northern channel, and their passage through the region of stations 328 and 329 would certainly cause disruption of the entire water column. On several occasions, muddy trails were observed in the wake of a freighter, due to resuspension of bottom sediments (pers. obs.).

Figure 18. Western basin bathymetry.

At station 325, located in the center of the transect (Figure 2), stratification was observed on five occasions. In the central region of the basin there is less turbulence and mixing, and a greater tendency for stratification (Cooper et al., 1977; Hartley, 1968).

Areas in the western basin that would be expected to show thermal stratification would be the deeper water, away from the turbulent tributary inflow or high flow rate areas (such as channel areas between the islands). This has not necessarily held true, as stratification has been observed in tributary mouths, in water as shallow as 4m along the south and west shores, and in the channel areas in the Island region.

Thermal Structure

When thermal stratification occurred in the western basin, it was usually characterized by a thin hypolimnion with a small temperature difference between the hypolimnion and the epilimnion. Wright (1955) and Britt (1955a) observed thermoclines between 8-10 m of water. As noted in the Results, the thermocline was normally within 2m of the bottom, except on 12 July 1981, when the thermocline was 3.5m from the sediments. Carr et al. (1965) recorded numerous thermoclines in the midwater depths, at 5-7 meters, with hypolimnion thicknesses as great as 5m. The thermal profiles resembled those of the central basin as a thermocline forms: a distinct, sharp lower inflection point, and a very weak, gradual upper inflection point.

The steep gradients observed in this study (as much as 5.5°C/m) are unlike those previously reported. Although many past studies contain temperature data at discrete intervals, therefore making it difficult to analyze the slope of the thermoclines, some investigators did use bathythermographic equipment to record continuous vertical thermal profiles. Both Carr et al. (1965) and Britt (1955a) noticed rather steep temperature gradients, but generally these gradients had more gentle, curving gradients compared to the sharp, rapid changes observed in this study.

In any stratified system, forces such as wind-induced mixing and surface waves may depress the thermocline and cause oscillations of several meters in its depth (Mortimer, 1974). In a system with a 10m thick hypolimnion, oscillations in the thermocline depth would not disrupt the thermal stability. However, because the hypolimnion in the western basin is thin (1-2m), an internal wave with an amplitude exceeding the thickness of the hypolimnion would push the thermocline to the bottom, and destroy the thermal structure. Therefore, the stability of the thermal structure in the westerm basin was aided by the large density differences, but hindered by the thin hypolimnion.

Hypolimnetic Water Quality

The chemical changes that took place in the western basin hypolimnion corresponded to those that occurred in a typical hypolimnion (Mortimer, 1941; 1942; Burns and Ross, 1972). For example, during the 12 July 1981 cruise (Figures 8-14), a distinct difference in chemical content of the epilimnion and hypolimnion indicated a sufficient inhibition of water transfer across the thermocline.

Hypolimnetic dissolved oxygen and pH values were much lower than epilimnetic values; conductivity, soluble reactive silica, and ammonia were higher. There was no appreciable difference in total phosphorus (Figure 14). The chemical changes (except phosphorus) in the western basin hypolimnion were consistant with expected hypolimnetic changes (Mortimer, 1941) and with the central basin (Burns and Ross, 1972). Total phosphorus did not increase distinctly, due to two possible reasons: 1) phosphorus forms are not released by the sediments to the overlying waters until the dissolved oxygen is less than 1.0mg/l (Frevert, 1980). Silica and ammonia are released at a higher dissolved oxygen concentration; or 2) removal of phosphorus (precipitation and biological uptake) is rapid, and may have already occurred.

Britt (1955a), first noticed significant chemical changes associated with thermal stratification. Although Wright (1955), Chandler (1940; 1944), and Chandler and Weeks (1945) witnessed earlier occurrences of stratification, they observed little, if any, dissolved oxygen depletion in the hypolimnion. Carr et al. (1965) observed low hypolimnion dissolved oxygen values in the western basin. Using meteorological records, Carr et al. (1965) estimated the beginning of stratification, then assumed an initial dissolved oxygen concentration. From the results, they concluded that the sediment oxygen demand rate of the sediments had increased significantly since stratification had first been observed in 1929 (Wright, 1955). Presently, a stratified event will result in a change in the bottom water chemistry, with anoxia often developing.

Depletion rates of dissolved oxygen in the western basin were directly measured by Davis (1981) and determined to be 1.65g oxygen/sq.m./day. Using this calculation, it has been determined that anoxia would result after 3-4 days of stratification, assuming a hypolimnion height of 2m and an initial dissolved oxygen concentration of 5.0mg/l (Rathke, 1984).

Effects on Biota

The best documented account of the biotic effects of western basin stratification is Britt's (1955a and b) study on the disappearance of the mayfly (Hexagenia sp.). Following an extensive calm weather period in August and September, 1953, Britt observed thermal stratification and severe oxygen depletion in the hypolimnion. As a result, a massive die-off of the benthic larval mayfly population occurred. Areas which had supported hundreds of larvae per square meter, now had from 0 to 40. The mayfly continued to survive for several years afterward (Beeton, 1963), but continued episodes of stratification and accompanying anoxia has eliminated them from all but the shallowest, most aerated portions of the basin (Keeler, 1981; Britt, unpublished data; and personal observation). Since mayflies are intolerant of low oxygen levels, their disappearance suggests that the stratified episode of 1953 was the first extensive instance of anoxia in the basin. Species which presently inhabit the benthos of the basin are "pollution resistant" organisms (i.e., oligochaetes and chironomids) that can survive the numerous occurrences of extended anoxia now taking place. No periodic biological sampling was conducted in this study, but on several occasions, bottom dredges were taken per requests by other researchers, or for personal curiosity. No mayflies were ever found.

It is difficult to assess the true effect the eradication of the mayfly had on the ecology of Lake Erie. Mayfly nymphs burrowed into the sediments, circulated oxygenated water through their burrows, keeping the top 1-2cm of sediments well-aerated. The oxic sediments had a more cohesive property (Britt, pers. comm.), unlike the unconsolidated sediments present today, probably due a different bacteria population inhabiting the sediments. As a result, resuspension of sediments, due to wind-induced agitation, was certainly not as significant as it is today. The silver chub (Hybopsis storeriana) declined drastically from Lake Erie shortly after 1953, as its main food source was mayflies. Possibly other fish species (northern pike, walleye) fed upon the silver chub (Britt, pers. comm.) and were thus similarly affected.

INFLOW OF CENTRAL BASIN WATER

Several investigators suggested that stratification in the western basin may occur by mechanisms other than conventional stratifying forces. One proposed mechanism was inflow of cooler central basin water, underflowing the western basin water mass, resulting in a stratified condition. This theory was based on observations and water quality measurements, not on direct measurement (i.e., current measurements documenting movement of the water mass from the central into the western basin). In 1980, two thermal stratification events were observed; one event identified to have been caused by conventional heating; the other by inflow of central basin water.

If the western basin stratifies by two processes, inflow of central basin water and conventional-heating, differences in the characteristics occurring in each instance would be expected. The characteristics of the water column include: the temporal progression of bottom water temperatures; hypolimnetic specific conductance; the temperature of the surficial sediments; and the horizontal expanse of the thermocline. Meteorological conditions prior to the observance of the stratified event may also indicate the process of stratification. Before discussing the results of two stratified events in 1980, the above five conditions were evaluated to distinguish between conventional stratification and central basin inflow.

Differences Between Conventional and Inflow Stratification

Bottom water temperatures. As discussed previously, western basin bottom temperatures progressively increase during the conventional warming cycle, although not at a steady rate, due to the alternating periods of stability and mixing. In contrast, a hypolimnion resulting from central basin inflow would be colder than the water mass in place in the western basin; thus, a decrease in bottom water temperature would result. The decrease in bottom temperatures is the most significant difference between stratification resulting from conventional meteorological effects and that resulting from inflow of cooler central basin water. Wright (1955) and Carr et al. (1965) observed a decrease in western basin bottom water temperatures and suggested inflow of central basin water as one possible explanation. Other explanations offered were: 1) air temperature changes, in which the entire water column cooled during a period of low air temperatures, and subsequently restratified by conventional-heating processes; 2) inflow of a cooler water mass from Detroit River; and 3) heat loss from the bottom water layers to the sediments. These three processes, however, would account for only slight changes in temperature. In the first process, it is extremely unlikely that the air temperature would decrease sufficiently (during the warming season) to result in water temperature changes of more than 1-2°C. Second, Detroit River temperatures generally mimic the warming pattern of the atmosphere, and effects due to inflow of cooler Detroit River water would tend to be found isolated near the mouth and main flow area of the river. Third, although little is known concerning the rate of heat loss from the water to the sediments, it is assumed to be negligible. Hypolimnia of other systems generally gain heat through the summer, and on no occasion during this study were surficial sediment temperatures found to be lower than the overlying water.

Wright (1955) attributed an observed occurrence of stratification, in which bottom temperatures declined, to heat loss. He chose this explanation by the process of elimination; atmospheric cooling did not occur between the sampling periods, and winds were too light to "cause sufficient westward displacement of central basin water (1955:49)." Since inflow, or "westward displacement of central basin water," is not directly dependent on wind forcing (discussed later), inflow was most probably the cause of stratification. Carr et al. (1965) attributed a similar event to either central basin inflow or heat loss to the sediments.

Although a reduction in bottom temperatures will accompany every central basin inflow stratification event, it is important to realize that, due to sampling frequency, reduced temperatures may not always be observed. Three hypothetical thermal profiles (Figure 19) display the importance of sampling frequency to the observations of reduced bottom temperatures. On Days 10 and 17, profiles indicated isothermal conditions at temperatures of 17 and 19.5°C, respectively. The water was stratified on Day 25; surface temperature was 23.5°C, bottom was 18°C. A reduction of bottom temperatures is evident. However, if a profile had

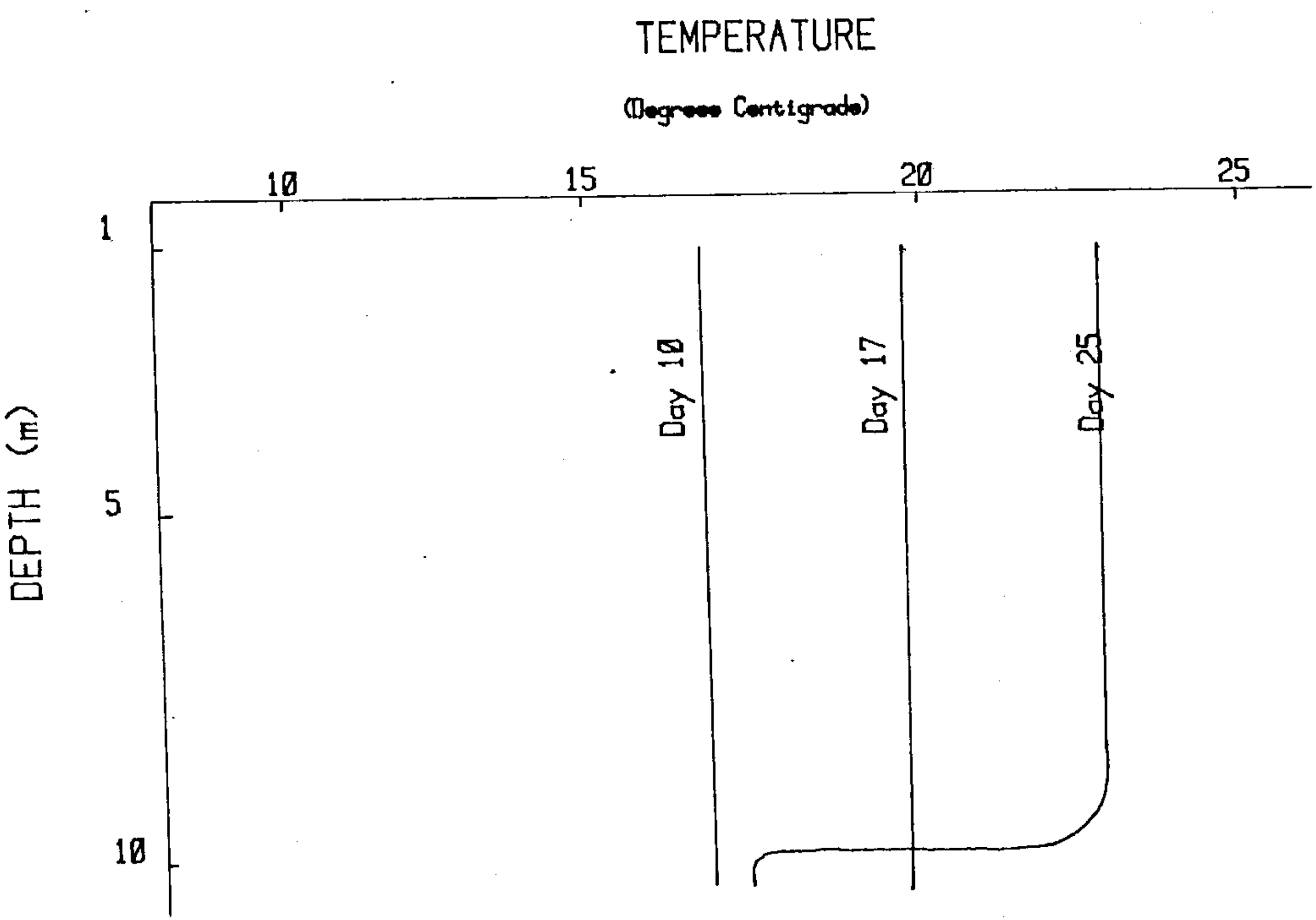


Figure 19. Hypothetical thermal profiles, showing the importance of sampling frequency to the observance of a reduction in bottom temperatures.

not been obtained on Day 17, no reduction would have been observed. Therefore, the absence of a decrease in bottom temperatures during a stratified event does not necessarily indicate conventional stratification.

Specific conductance. Specific conductance is a measure of the ability of a substance to conduct an electrical current. Conductivity is, in turn, governed by the amount of dissolved salts (ions) present in the water. Due to evaporation removing water and concentrating the dissolved material, and to increased loading, a body of water will tend to show increasing conductivity from its source to its mouth. In the Great Lakes, conductivity increases steadily from Lake Superior to the Gulf of St. Lawrence. Conductivity is a reliable indicator of water masses (Hartley et al., 1966). In a hypolimnion, the release of chemical species from the sediments to the water increases ionic content of the water, resulting in increased conductivity. Therefore, just as the western and central basins differed in conductivity, so did the epilimnion and hypolimnion of each, due to regeneration and decomposition in the hypolimnion. If stratification were to occur by conventional formation of a thermocline, specific conductance values of the hypolimnion would be somewhat higher than epilimnetic values. If inflow caused stratification, conductivity would be markedly different between the epilimnion and hypolimnion, and would resemble the central basin mass.

Sediment temperatures. The surficial sediments of a lake will be cooler than the overlying water during the warming period (May-September) and warmer during the cooling period (September-December), much the same as the water in relation to air temperatures. Due to the high latent heat of the sediments in relation to water, sediment temperatures tend to vary much less over the year, lagging behind water temperatures (Mortimer, 1941). When inflow of a cooler water mass occurs, sediment temperatures would take time to equilibrate with this cooler water, and for a short time, sediments would be warmer than the water. During conventional stratification there is no sudden change in bottom temperatures, thus, there would exist little difference in temperature between bottom water and sediments. As in the observance of decreased bottom water temperatures, higher sediment temperatures occurring with central basin inflow would not always be observed, depending on sampling frequency. Following central basin inflow, sediment temperatures would equilibrate with the bottom water temperatures.

Sediments warmer than the overlying waters (Figure 6, 1981) were observed at several western and central basin stations. In the central basin, it occurred in areas which are peripheral to the central basin hypolimnion (pers. obs.). Along the north and south shores and in the western end of the central basin, warmer sediments indicated the movement of the hypolimnion, in and out of the region (sloshing). In the eastern end of the basin, warmer sediments resulted from the intrusion of cooler, eastern basin hypolimnetic water into the central basin (Boyce et al., 1980).

Areal extent of stratification. Conventional stratification would be expected to be found throughout the open waters of the western basin. Meteorological conditions are generally uniform across the basin, therefore, stratifying forces would be exerted to all regions. Areas that might not show stratification would be shallow shoreline areas and areas encountering turbulence, i.e., tributary mouths and island passages. Inflow of central basin water would more likely result in isolated, small pockets of stratification, and tend to occur most frequently nearer to the western basin-central basin boundary.

Meteorological conditions. Stratification by conventional heating processes in the western basin requires a period of warm temperatures and calm winds, allowing establishment of thermal gradients and subsequently, a thermocline. Carr et al. (1965) estimated the conditions necessary for a thermocline to form; a five-day period of average daily wind speed not exceeding 6kts, maximum speed not exceeding 13kts, and an average daily air temperature of 18.5^{o}C. The air temperature criteria is inadequate: water temperatures are in excess of 18.5^{o}C from mid-June through the end of September (encompassing most of the period in which stratification occurs), consequently air temperatures of 18.5^{o}C would not affect stratification.

Kramer et al. (1970) stated that complete mixing occurs to all depths in the western basin when "the wind mixing factor (time since last calm in hours x wind velocity) is between 200 and 350 miles. This is comparable to a 10-knot wind for 24 hours (1970:13)". If density gradients were present, the force necessary to mix the water column completely would increase. Thermal/density gradients increase the relative thermal resistance of the water column to mixing (Birge, 1910), and the amplitude of the temperature gradient determines the extent of the resistance. It is not known if Kramer et al. (1970) took this into consideration when establishing their wind-mixing factor.

Central basin inflow events are only indirectly related to air temperatures and wind speed. Bottom water currents and seiche activity are more likely to govern inflow, and are determined primarily by wind direction and barometric pressure.

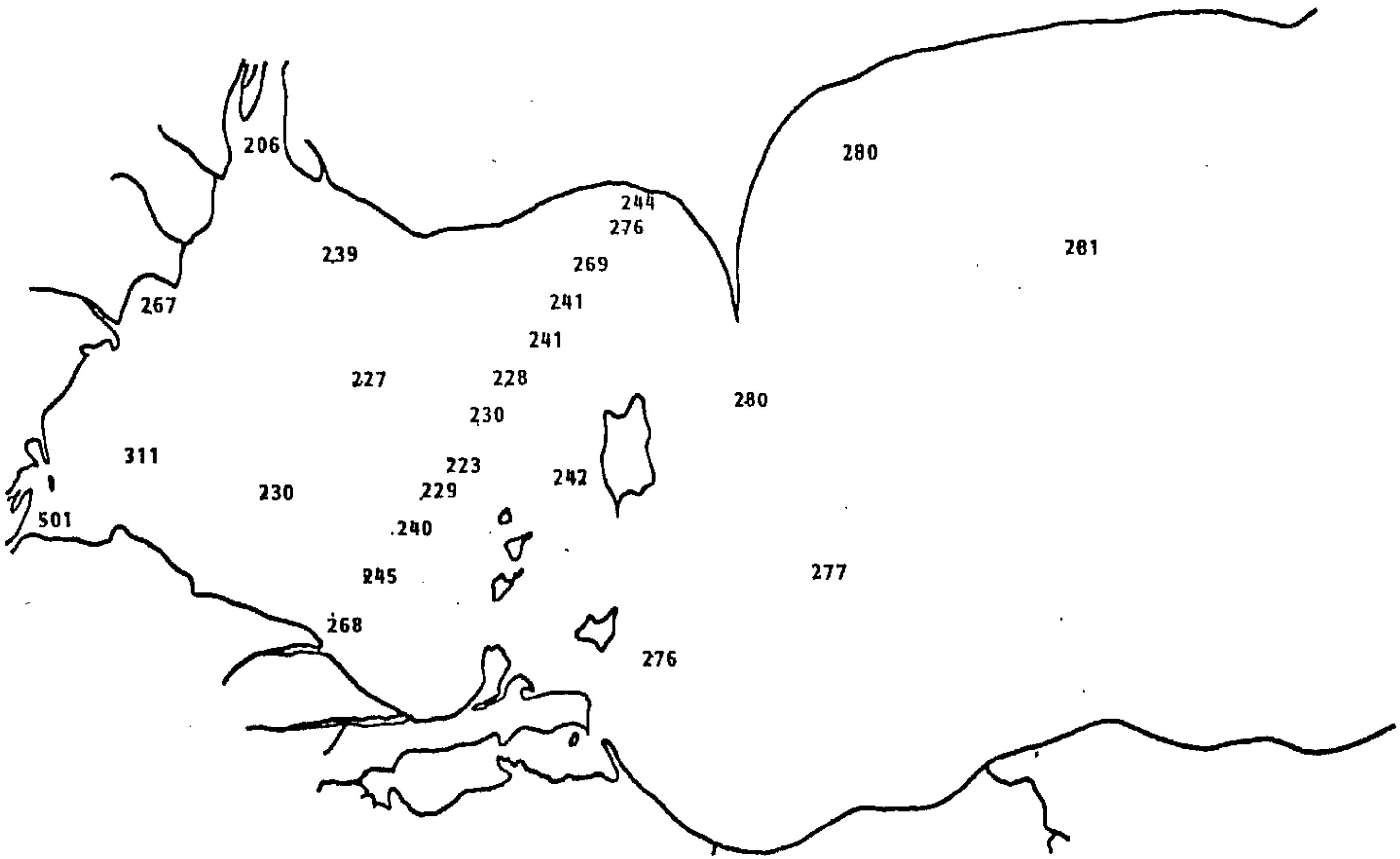
The Events of 1 and 30 August 1980

1 August 1980

Inflow of central basin meso- or hypolimnetic water resulted in the stratified event observed on 1 August 1980, at stations 330 and 331. Temperature profiles (Figure 7) and thermal structure (Figure 5e) showed an isolated area of stratified water in Pigeon Bay. All other transect stations were isothermal. Temperature profiles for station 331 indicate the bottom temperatures (18°C) were well below those found at station 331 for the two previous cruises, and only slightly higher than the temperature found 40 days earlier (17.6°C), on 19 June. Air temperatures were consistantly higher than 18°C, thus the decrease in water temperature was not due to atmospheric effects. Detroit River temperatures also were well above the temperature of the bottom waters at station 331 (18°C). If heat loss of the bottom waters to the sediments was responsible for the decrease in temperature, the sediments would have to have cooled the water by 6°C in 9 days. If heat loss occurred at a rate of .7°C/day, one would expect to find evidence of cooling more frequently and throughout the basin.

Bottom conductivity values in the western half of the lake are shown in Figure 20. Values throughout the western basin range from 220-240 umhos/cm. with two exceptions: the bottom conductivities in Pigeon Bay and in the western

BOTTOM CONDUCTIVITIES*, WESTERN LAKE ERIE, 01 AUG 1980



* Specific conductance (umhos/cm) corrected to 25° C.

Figure 20. Bottom conductivity values in the western end of Lake Erie, 1 August 1980.

half of the basin. The latter commonly exhibit high values, because of tributary loading from the Maumee River. The bottom conductivity values at stations 330 and 331 are significantly different from surface (Figure 21) and very similar to those found in the central basin hypolimnion (Figure 20).

Although indications of sediments warmer than the overlying water were not observed at either station 330 or 331, it is not a necessary condition in inflow stratification, and suggests the inflow event occurred several days prior to sampling.

30 August 1980

Conventional, atmospheric heating resulted in the stratification observed on 30 August, 1980. Thermal structure (Figure 5g) and profiles (Figure 7) indicated a very slight temperature gradient within 1m of the bottom. At some stations, this gradient was insufficient to be considered a thermocline ($1^{\circ}C/m$). However, the density gradient separated an upper and lower water mass of distinctly different chemical characteristics (Table 3). Immediately apparent was the basin-wide extent of stratification, with the exception of the shallower shoreline stations (323, 322, 321). A decrease in bottom temperatures from the previous cruise (14 August) was evident. In this case the temperature decrease did not result from central basin inflow, but from atmospheric changes that occurred between 14 and 30 August. Following 14 August, two periods of cool atmospheric temperatures (Figure 22) reduced the temperature of the entire water column. Subsequently (26 August), air temperatures warmed considerably; winds became calm and variable; and the upper strata of water again increased in temperature.

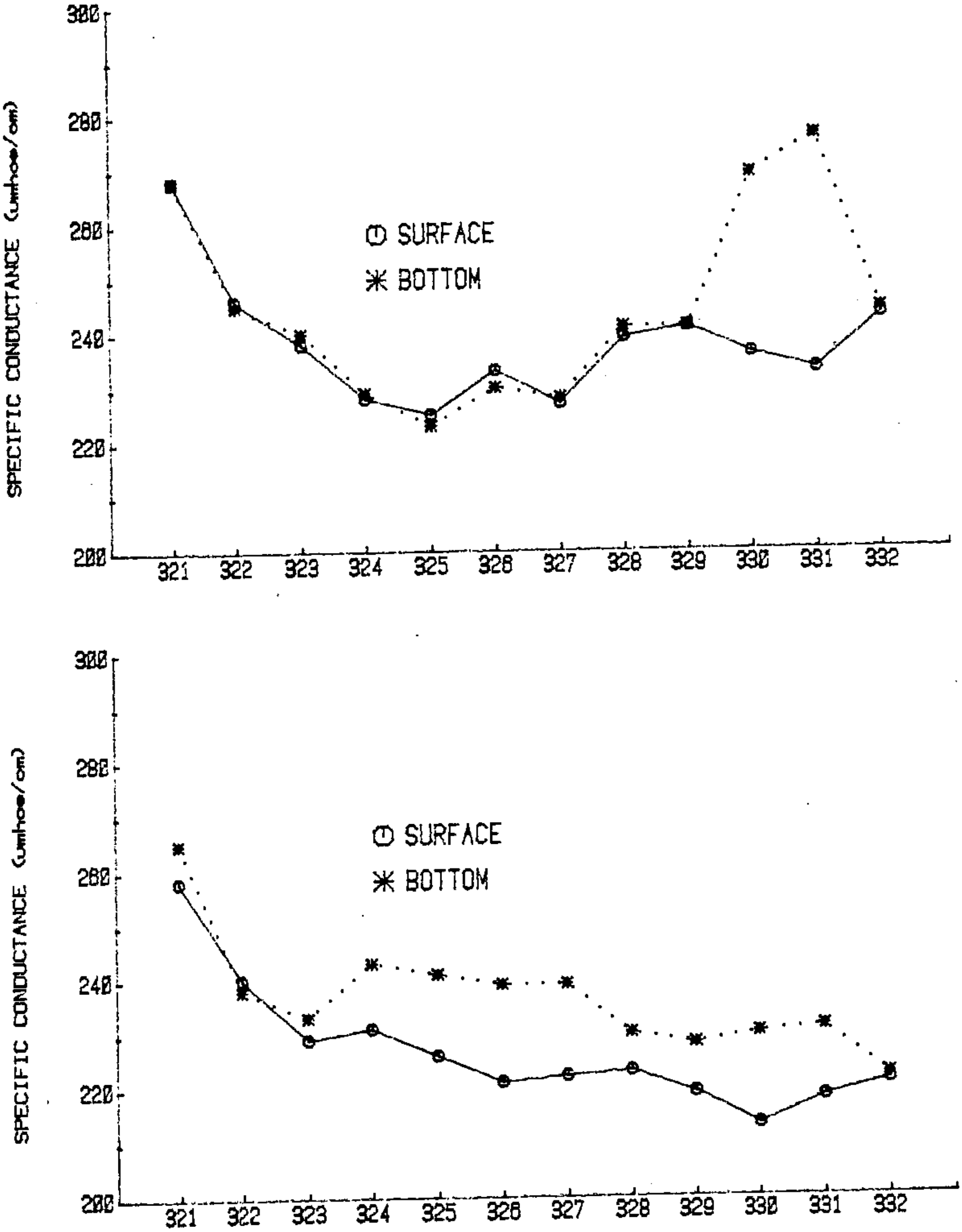


FIGURE 21. SURFACE AND BOTTOM CONDUCTIVITY VALUES ALONG THE WESTERN BASIN TRANSECT, 1 AUGUST (TOP) AND 30 AUGUST 1980 (BOTTOM).

Table 3.

Surface and bottom physical and nutrient data along the western basin transect, 30 August 1980.

Sta.	Temp °C		DO mg/1		pH		Cond umhos/cm		Silica mg/1		Ammonia ug/1		TP ug/1	
321	25.6	24.8	7.3	7.2	8.65	8.57	258	265	.40	.40	8.2	8.0	47.9	48.2
322	25.5	24.9	9.9	8.1			240	238	.30	.32	7.3	7.6	38.2	27.1
323	25.4	24.5	10.2	8.2	9.06	8.72	229	233	.38	.46	4.8	19.8	36.5	22.2
324	25.2	23.7	10.2	2.0			231	243	.30	2.25	6.1	225.0	40.0	33.1
325	25.1	23.5	9.9	1.4	9.04	8.42	226	241	.42	2.00	4.6	152.5	33.6	44.0
326	25.0	23.4	9.5	1.2			221	239	.58	2.50	6.8	122.5	29.3	52.4
327	25.0	23.3	9.4	1.9			222	239	.67	2.54	6.6	94.5	27.1	41.5
328	24.7	23.1	8.9	2.7	8.82	7.70	223	230	.91	2.94	10.0	86.8	22.2	28.8
329	24.8	23.1	9.4	3.2	8.81	7.85	219	228	.76	2.65	3.3	45.5	21.6	25.5
330	24.7	23.0	9.1	2.1	8.84	7.89	213	230	.80	3.25	7.0	4.0	20.1	24.1
331	25.2	23.3	9.2	2.9	8.94	7.88	218	231	.88		5.0	2.9	20.1	23.9
332	26.3	26.2	8.4	8.1	8.75	8.58	221	222	.98	1.05	5.5	26.2	27.2	32.4

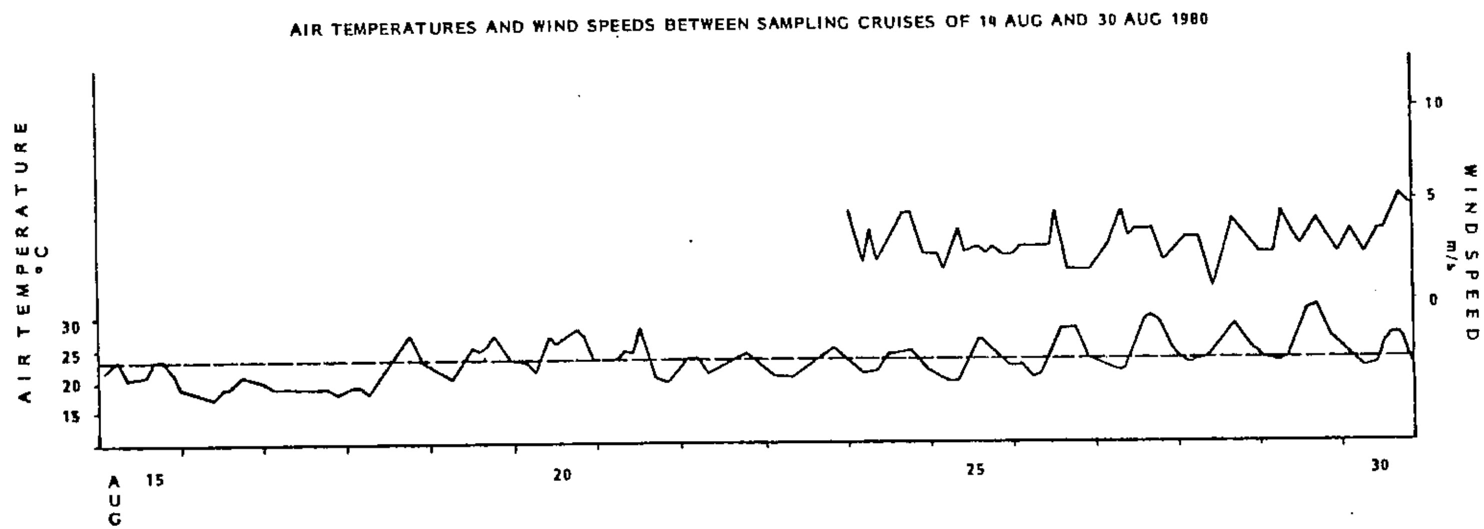


Figure 22. Air temperatures and wind speed from 14 to 30 August 1980. The dashed horizontal line is the lowest bottom temperature measured along the transect on 30 August.

Bottom conductivity values for the western half of Lake Erie are shown in Figure 23. Along stratified stations in the western basin, bottom values were only slightly higher than surface values (Figure 21), and not similar to central basin conductivities. No occurrences of sediment warming were observed.

Physical Mechanisms of Inflow

The upper knee of the central basin thermocline is generally at a depth of 14-18m. However, this depth is not uniform throughout the basin. Due to the predominant south-west winds and to Coriolis effect, epilimnetic waters are driven to the southern shore. The surface waters accumulate, resulting in a depressed thermocline along the south shore. Hypolimnetic waters are then pushed out of the area, and flow north-westward toward the Canadian shore, where upwelling of the hypolimnion occurs and the thermocline is shallow (Blanton and Winklhofer, 1972). Consequently, there is a semi-permanent tilt to the thermocline; deepest in the east and along the southern shore; shallowest to the west and along the northern shore (Blanton and Winklhofer, 1971; Zapotosky, 1980).

A longitudinal cross-section of the western half of Lake Erie is presented in Figure 24, depicting a normal August central basin thermocline depth. This depth is below the western basin bottom depth, thus the only mechanism for bottom waters to pass into the western basin would be to flow "uphill." Upwelling of hypolimnetic water is most prevalent east of Point Pelee and near Point aux Pins (Blanton and Winklhofer, 1971). If the hypolimnion upwelled to a depth of approximately 10m, bottom waters could penetrate into the western basin.

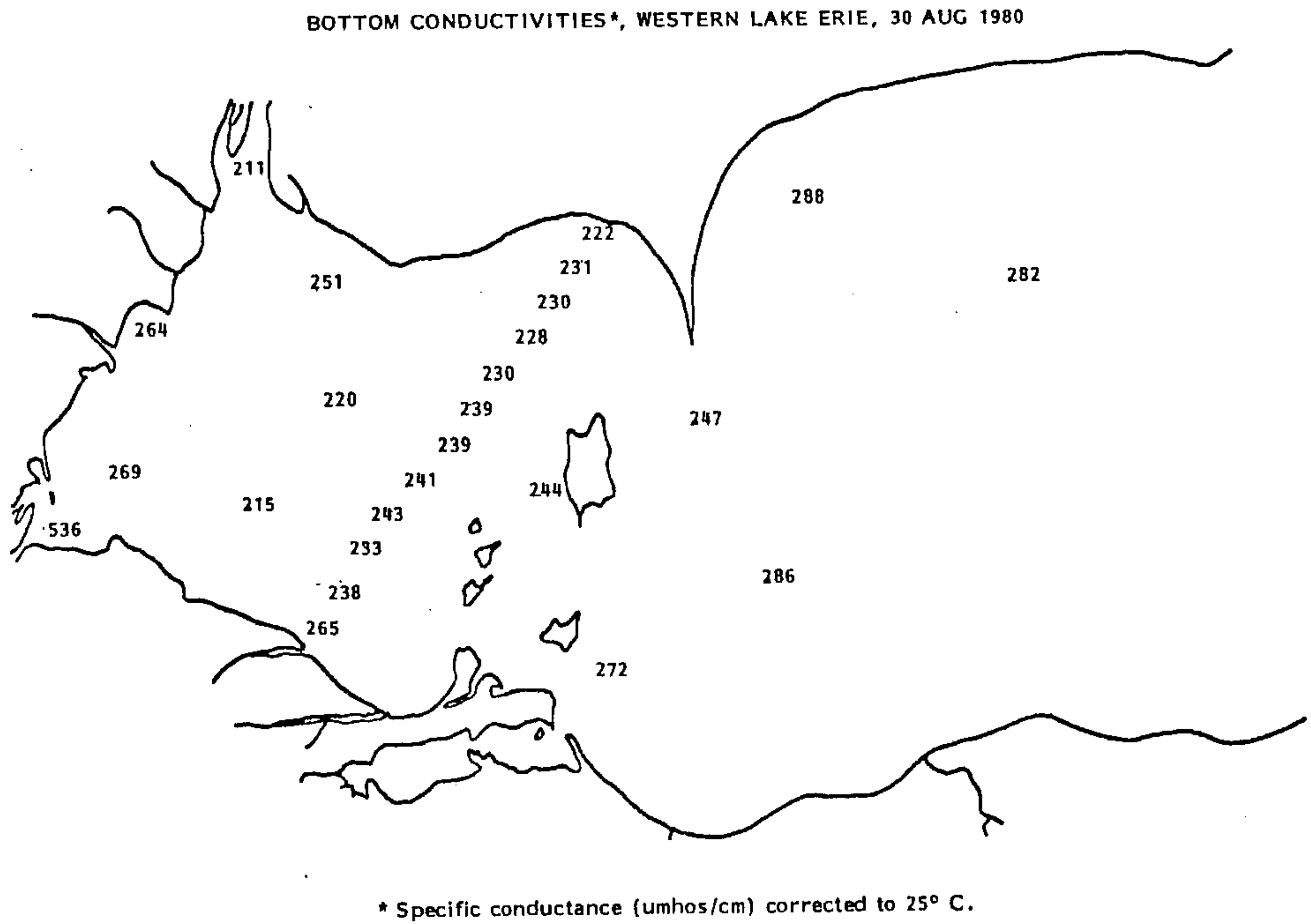


Figure 23. Bottom conductivity values in the western end of Lake Erie, 30 August 1980.

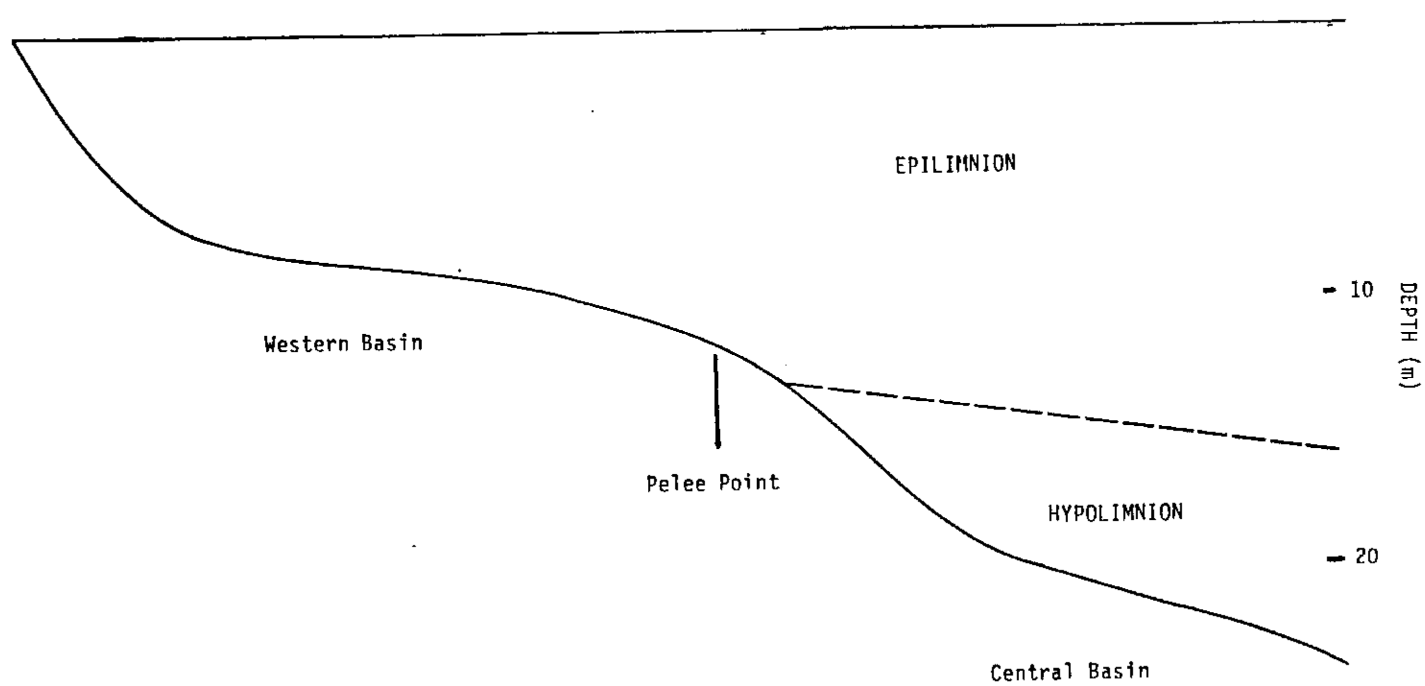


Figure 24. Longitudinal cross-section of western Lake Erie, showing normal thermocline level during August.

Resulting stratification in the western basin would be an extension of the western boundary of the central basin hypolimnion. Hypolimnetic upwelling/internal seiche is the mechanism by which inflow occurs. Strong south-westerly winds may push surface waters east through the Pelee Passage, establishing a counter-current along the bottom and moving central basin water westward through the passage. However, currents alone could not transport water from the hypolimnion if the thermocline was below approximately 10m. Therefore, whenever inflow occurred, the thermocline in the western central basin would be expected to be very shallow (approximately 10m).

Recorded thermocline depths along a mid-lake transect, sampled from 27 July to 3 August (Figure 25), show a relatively deep, flat thermocline in the middle of the central basin, and then extreme upwelling of water in the western end of the basin, at station 47. This upwelling elevated the thermocline to 9m, permitting meso- and hypolimnetic water to spread into the western basin.

An occurrence of central basin inflow is similar to the stratified density wedges found near tributary mouths, especially in estuarine areas, where stratification is caused more by the difference in salinity than in temperature. However, stratification caused by inflow is also commonly noted in reservoirs and has been shown to occur in the Hamilton Harbor channel (Dick and Marsalek, 1972). All are instances of stratification resulting from a denser water intrusion which does not mix with the receiving body of water.

Conventional stratification was independent of the central basin thermocline depth. However, when a thermocline has been formed in the western basin by the

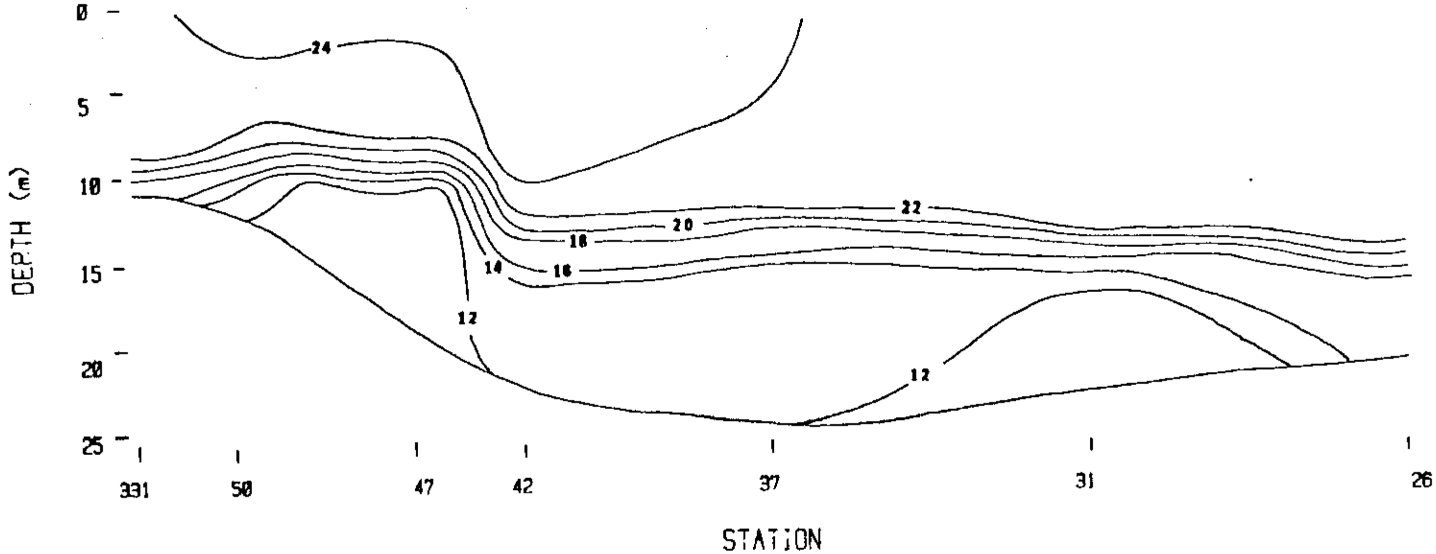


Figure 25. Actual central basin thermocline depth during 27 July to 3 August 1980.

conventional/heating process, a secondary, intermittant thermocline may simultaneously form in the central basin (Hartley, 1966).

Movement of central basin water into the western basin on 1 August 1980, occurred through one of two pathways: the Pelee Passage/North Channel region between Pelee Point and Pelee Island; or the Islands/South Channel region, which stretches from the Catawba/Marblehead Peninsulas to Pelee Island. It has been shown that most of the tributary water entering the western basin exits through the Pelee Passage (Harrington, 1895; Olson, 1950; Verber, 1955; and Hartley, 1968), and that the flow capacity of the passage is only slightly less than that of the Detroit River (Saylor and Miller, 1983). In the southern channels, flow is variably east or west (Olson, 1950; Hartley et al., 1966; Herdendorf, 1969), fluctuating in response to seiche activity (Verber, 1955; Saylor and Miller, 1983). In addition, the dominant flow pattern in the western basin (Figure 26) facilitates central basin flow through the southern passages. First, the northward flow of water west of the Bass Islands creates a "pull" on water in the Island region. Second, there is a clockwise gyre rotation of water around Pelee Island (Harrington, 1895; Olson, 1950). This rotation, as it sweeps southward along the east side of the island, may entrain central basin water and carry it into the southern islands area. Intrusions of central basin water masses through the Southern passages have been observed on numerous occasions (Hartley et al., 1966; Herdendorf, 1969). However, it is unlikely that a thermocline in Pigeon Bay would result from an intrusion of central basin water moving through the southern islands region, across the North Channel and into the Pigeon Bay.

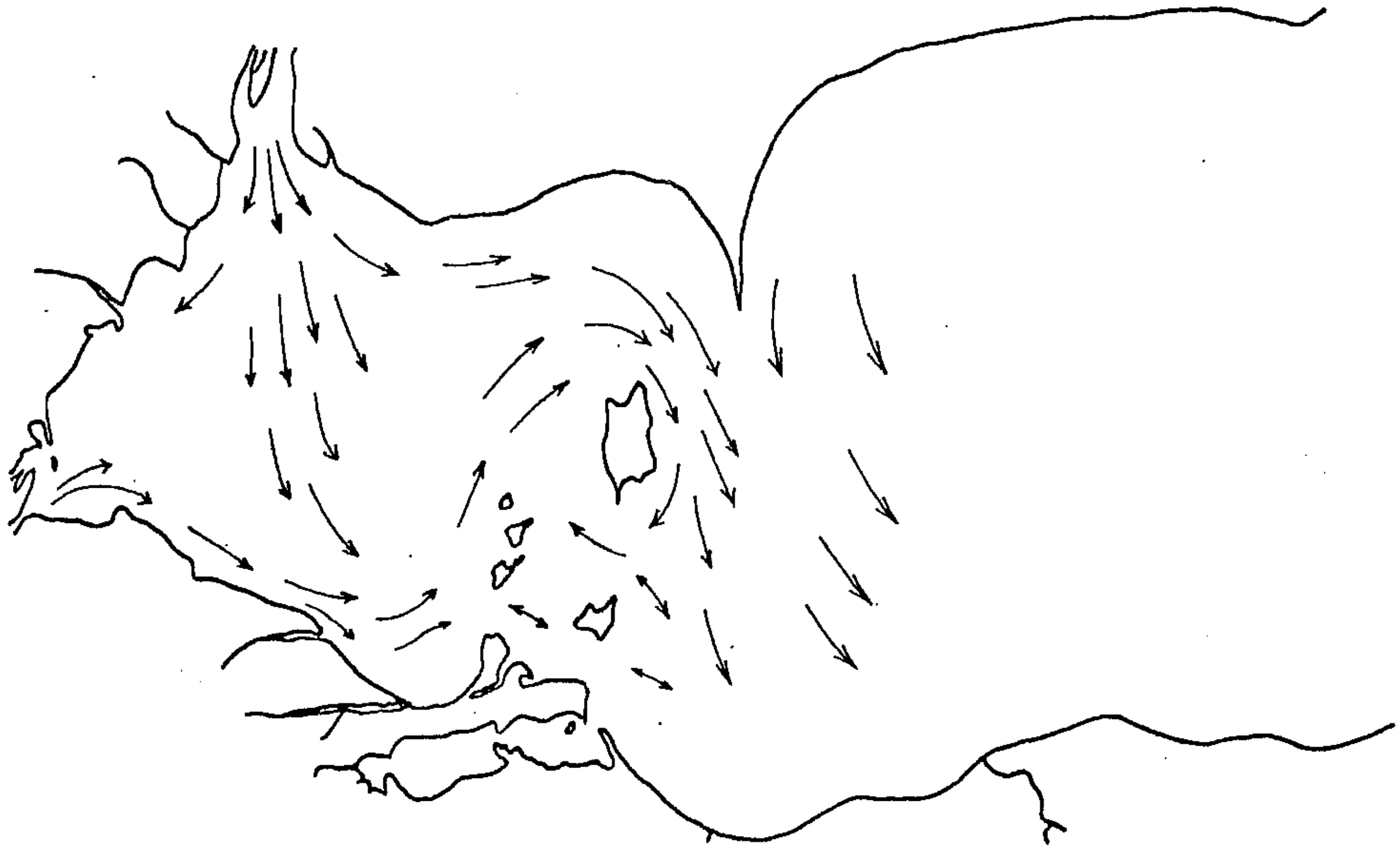


Figure 26. Dominant surface flow patterns, western basin Lake Erie.

Transport into the western basin via the Pelee Passage is feasible. Pelee Passage is deeper than the southern passages (Figure 18), and although there exists a dominant high eastward flow, both surface and subsurface counter-currents (westward movement) have been shown to occur (Hartley et al., 1966). The intrusion of central basin water accounts for the good quality of water in Pigeon Bay.

Hypolimnetic flow in the central basin tends to be directed toward the northwest, due to the surface pressure gradient produced by the dominant southwest winds and Coriolis effect (Blanton and Winklhofer, 1972; Saylor and Miller, 1983). In addition to causing an upwelling of the thermocline in the western end of the central basin, the northwest flow would drive water closer to the north shore. Water which is in the south-west portion of the central basin may have split from the main body as it encountered the Pelee Point peninsula. The water mass travelled along the western shore of Pelee Point into Pigeon Bay. The mass may have separated from the main body, and exist as an isolated mass, or continued to be connected to the central basin hypolimnion. Stratification at station 50 during the event of 1 August 1980 indicated the water mass in Pigeon Bay was an extension of the central basin hypolimnion (Figure 27).

Assuming the water mass in Pigeon Bay on 1 August was connected to the central basin hypolimnion, a calculation of the maximum areal and volumetric extent of the stratification was attempted. The thermocline was extended to stations 329 and 332, which were isothermal and bounded the areas of stratification. The observed mesolimnion thickness (.8m) was held constant in the calculated extension of the thermocline (Figure 28). It was then assumed that the

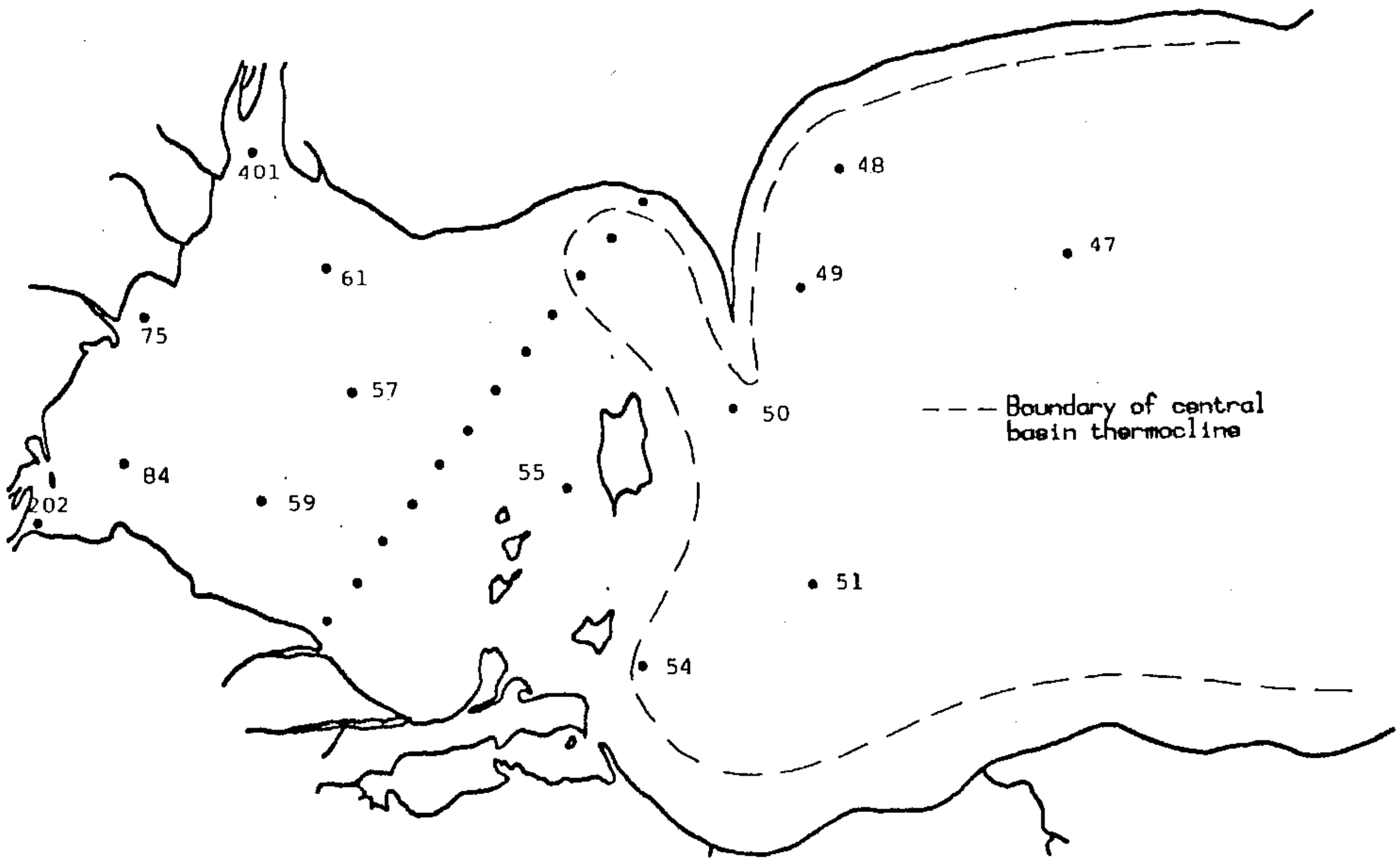
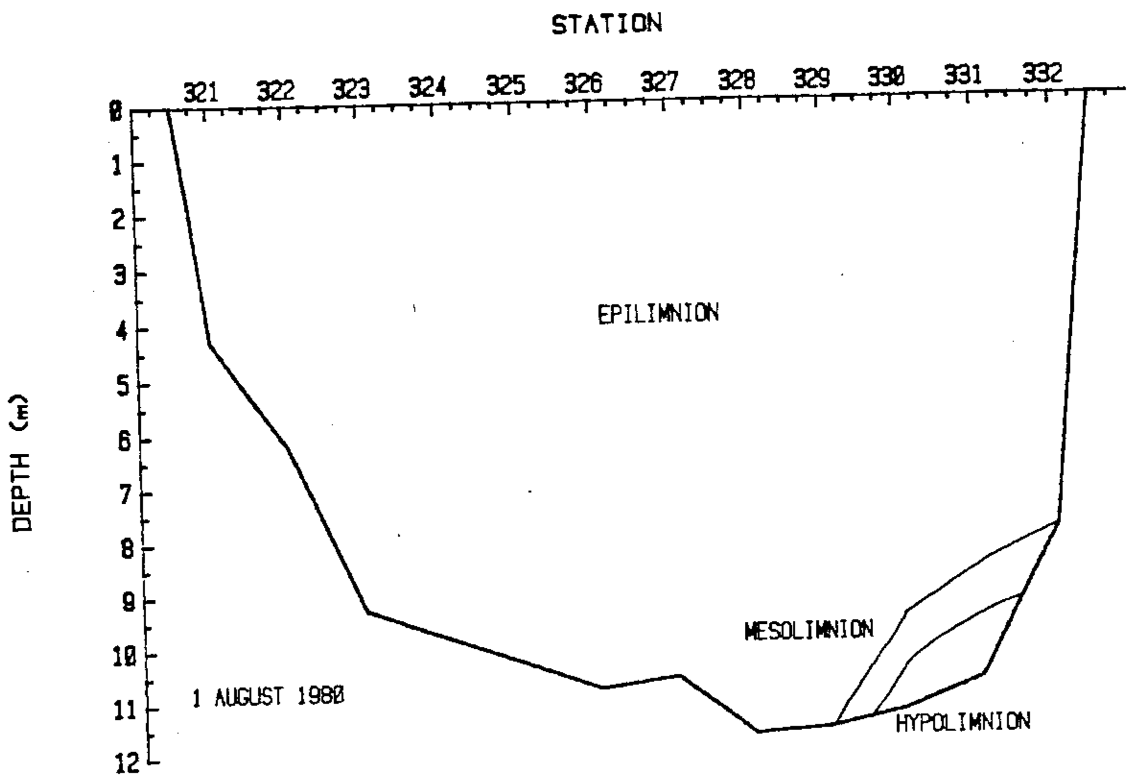


Figure 27. Western extent of the central basin thermocline, 1 August 1980.



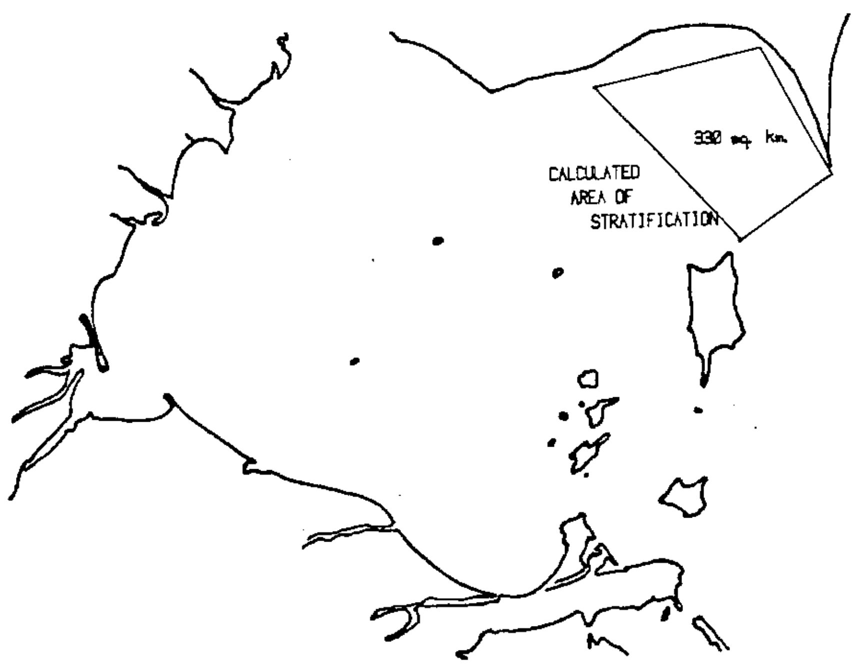


Figure 28. Calculated depth (top) and areal (bottom) extent of stratification during 1 August 1980.

water column maintained this configuration northwestward to the 7m contour, and southeastward through Pelee Passage. Drawing the boundary of the western basin as the line from Point Pelee to Pelee Island, the calculated stratified area would have been 330 sq.km. With a continuous hypolimnion/mesolimnion configuration as shown in Figure 28, the volume of the of the combined hypolimnion/mesolimnion was 0.29 cu.km. Even though this value is an over-estimation of the maximum volume possibly affected on the occasion of stratification (1 August), it represents an insignificant fraction of water in the western basin (approximately 1%) and an even smaller percentage (.004%) of the central basin hypolimnion (72.9 cu.km.) during this period. Presumably little force was required to transport such a small quantity of central basin water into the western basin through this mechanism, indicating inflow may account for several occurrences of stratification each year.

CONCLUSIONS/RECOMMENDATIONS

Although thermal stratification in the western basin is not a stable, season-long phenomenon; it is common, not rare, as has generally been believed. Stratified conditions were observed 3 times in 1980 and 5 times in 1981, or on more than half of the sampling cruises conducted during the warming period (May through August).

Because of the characteristics of western basin stratification, incidences of stratification are often undetected. The ephemeral, sporadic occurrences and localized horizontal extent requires frequent and extensive sampling. In addition, the extremely low-lying hypolimnion often escapes detection.

In spite of the characteristics listed above, and contrary to general belief, the effects of stratified occurrences are far from insignificant. Due to the small hypolimnion volume and the high temperatures at which the basin stratifies, anoxia would result after only 2-9 days of stratification.

Central basin hypo- or mesolimnetic water flowed into the western basin and resulted in stratification. This movement involved an insignificant amount of central basin water, and its presence in the Pigeon Bay was simply an extension of the central basin hypolimnion. This sloshing of central basin hypolimnion probably occurs frequently, and is similar to the processes occurring in the southwestern end of the central basin, near Huron, Ohio.

The western basin stratified by two processes; one meteorological, the other hydromechanical. Hydromechanical process of stratification certainly occurs in other systems, such as Green Bay/Lake Michigan, Saginaw Bay/Lake Huron, and also estuarine environments, i.e., Chesapeake Bay, coastal inlets, and harbors.

The understanding of stratification in the western basin would benefit from more direct measurements. A series of thermistors and current meters situated on the bottom in the Pelee Passage would conclusively track the movement of hypolimnetic water from the central basin. Also, an efficient, high volume, horizontal water sampler is needed to confidently obtain water samples from the thin hypolimnion. These samples would aid in determining water source, rates of dissolved oxygen depletion and accompanying chemical changes of the hypolimnion.

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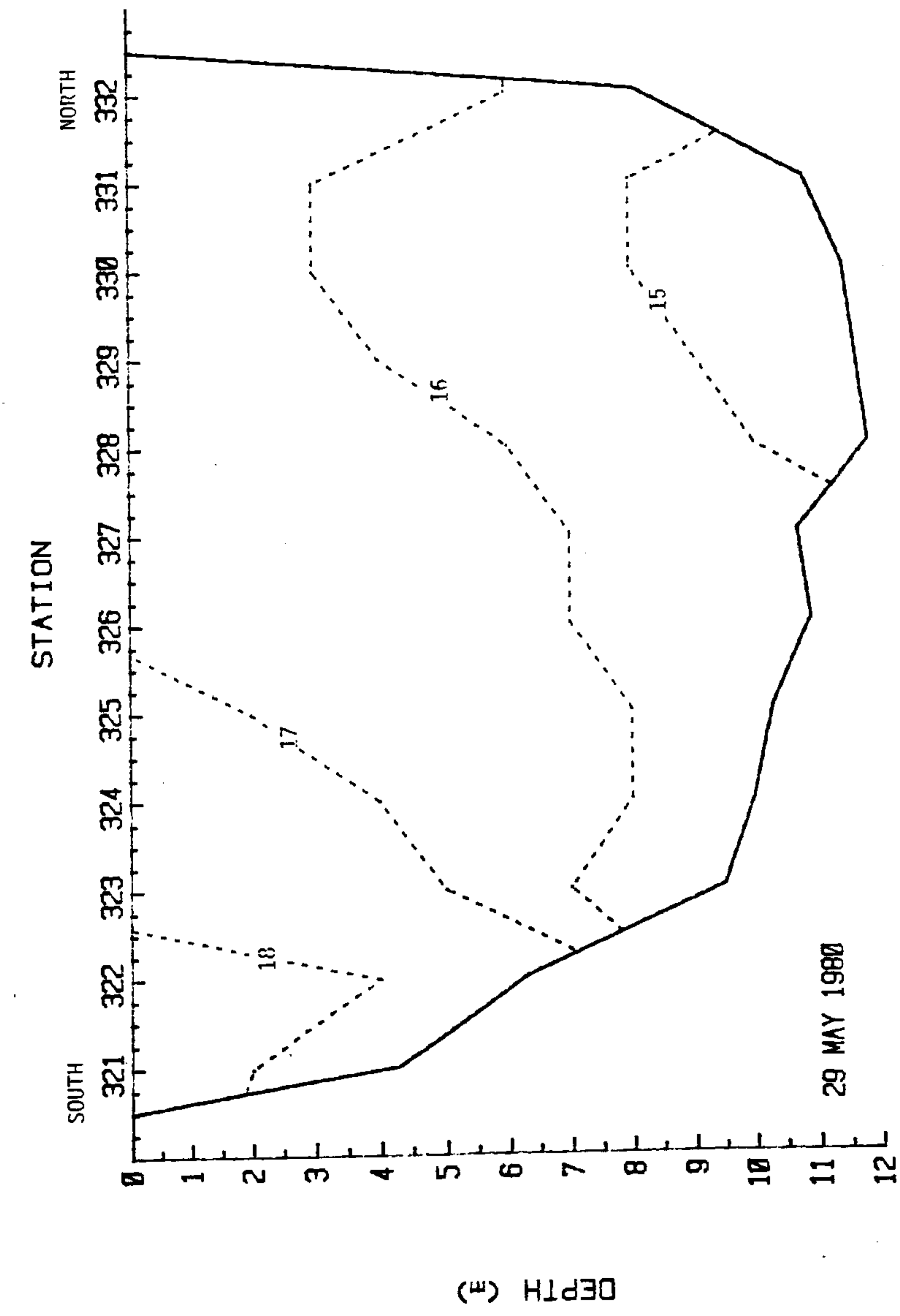
APPENDIX

Thermal Structure of the Western Basin Transect During All Cruises,

1980 - 1981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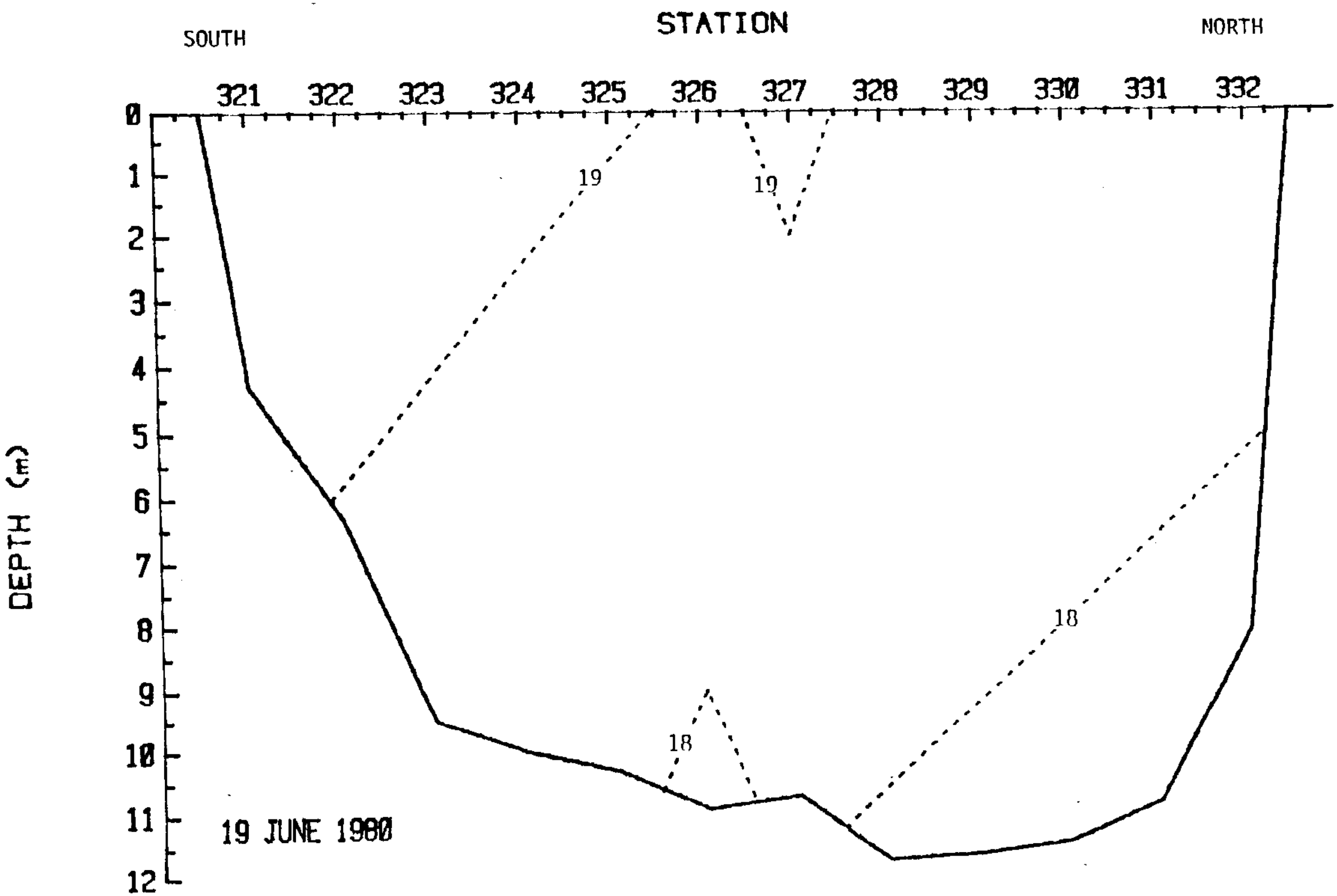
DEPTH (m)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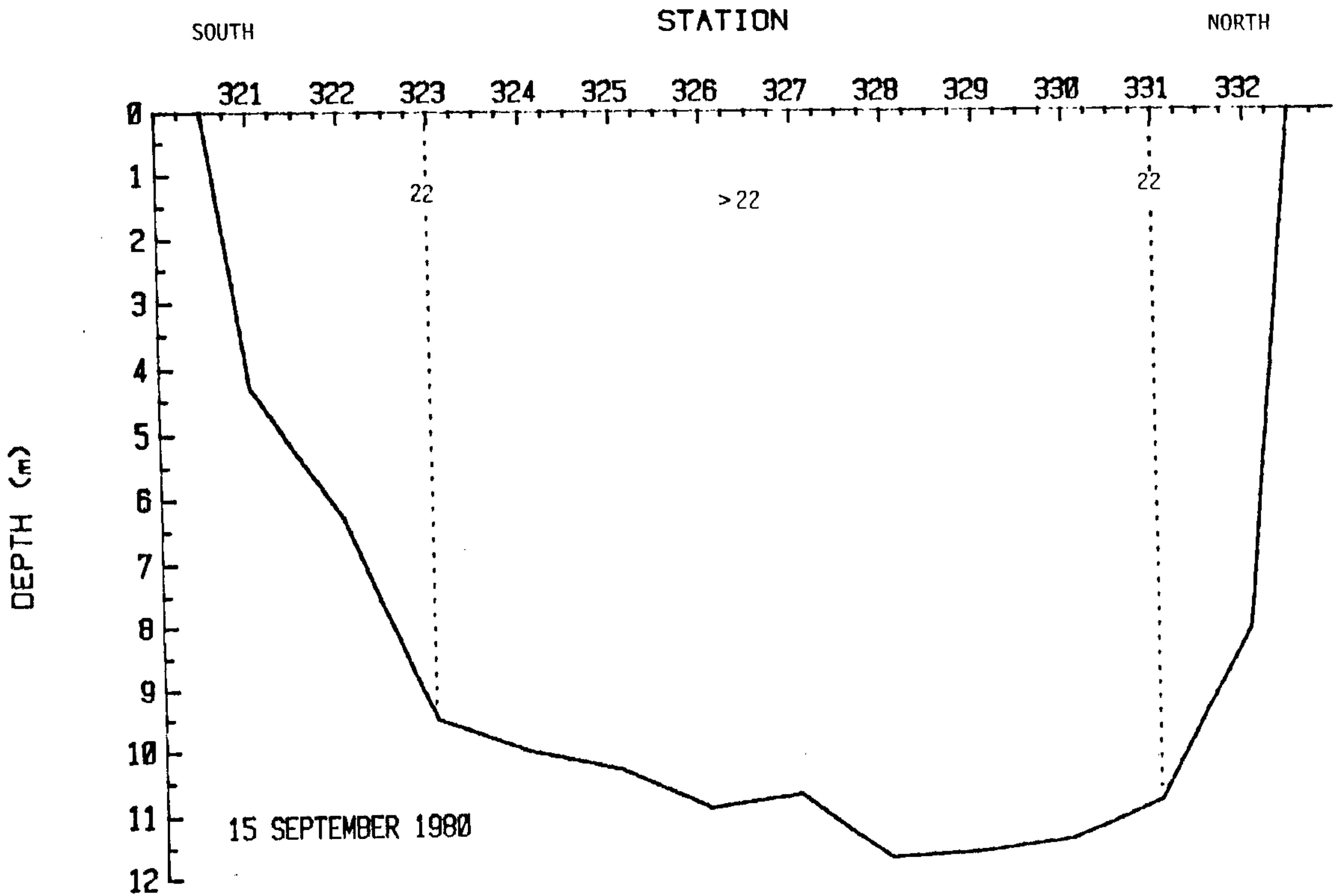
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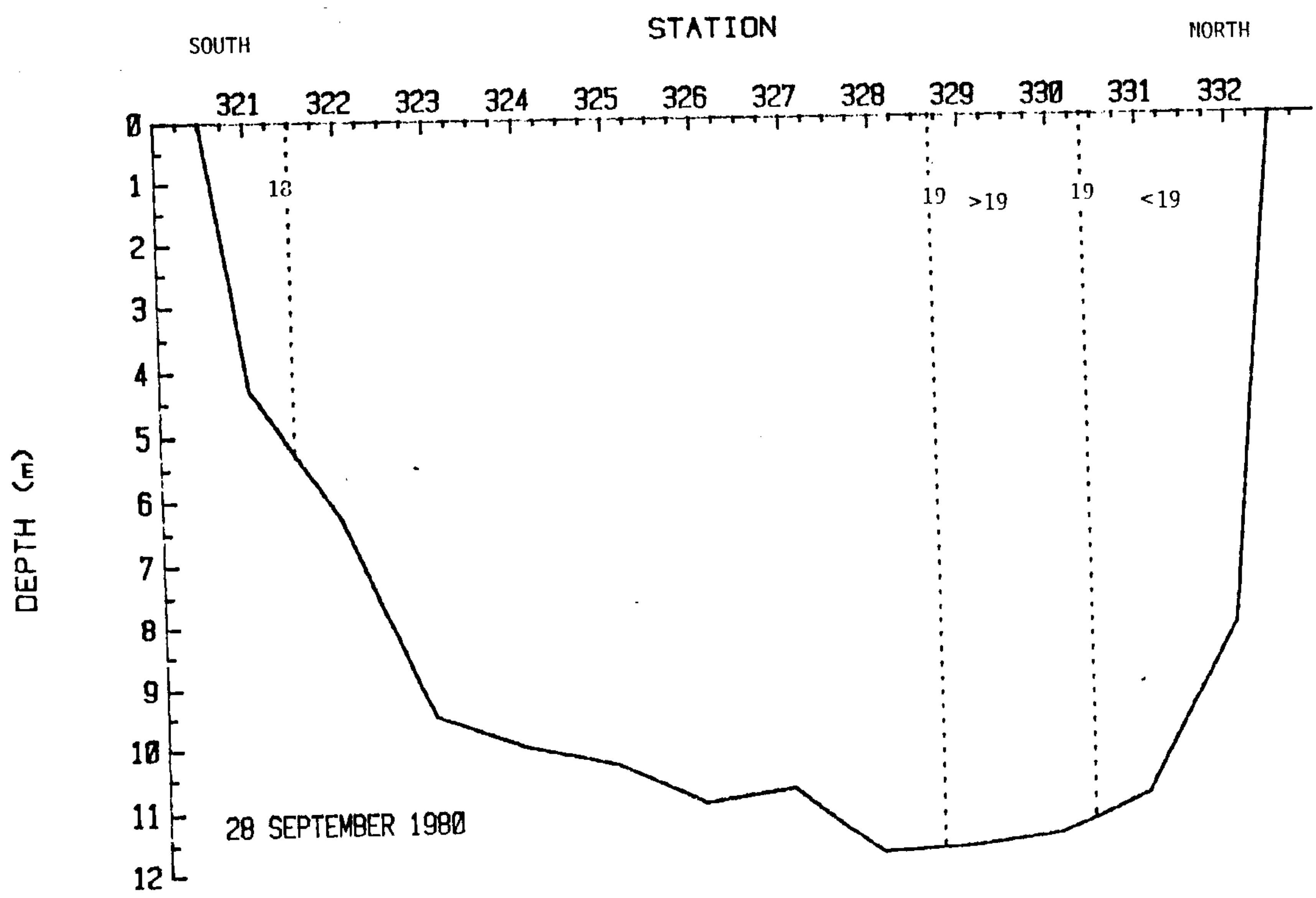
22
15 SEPTEMBER 1980


STATION
SOUTH
NORTH
321
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327
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329
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332
0
1
2
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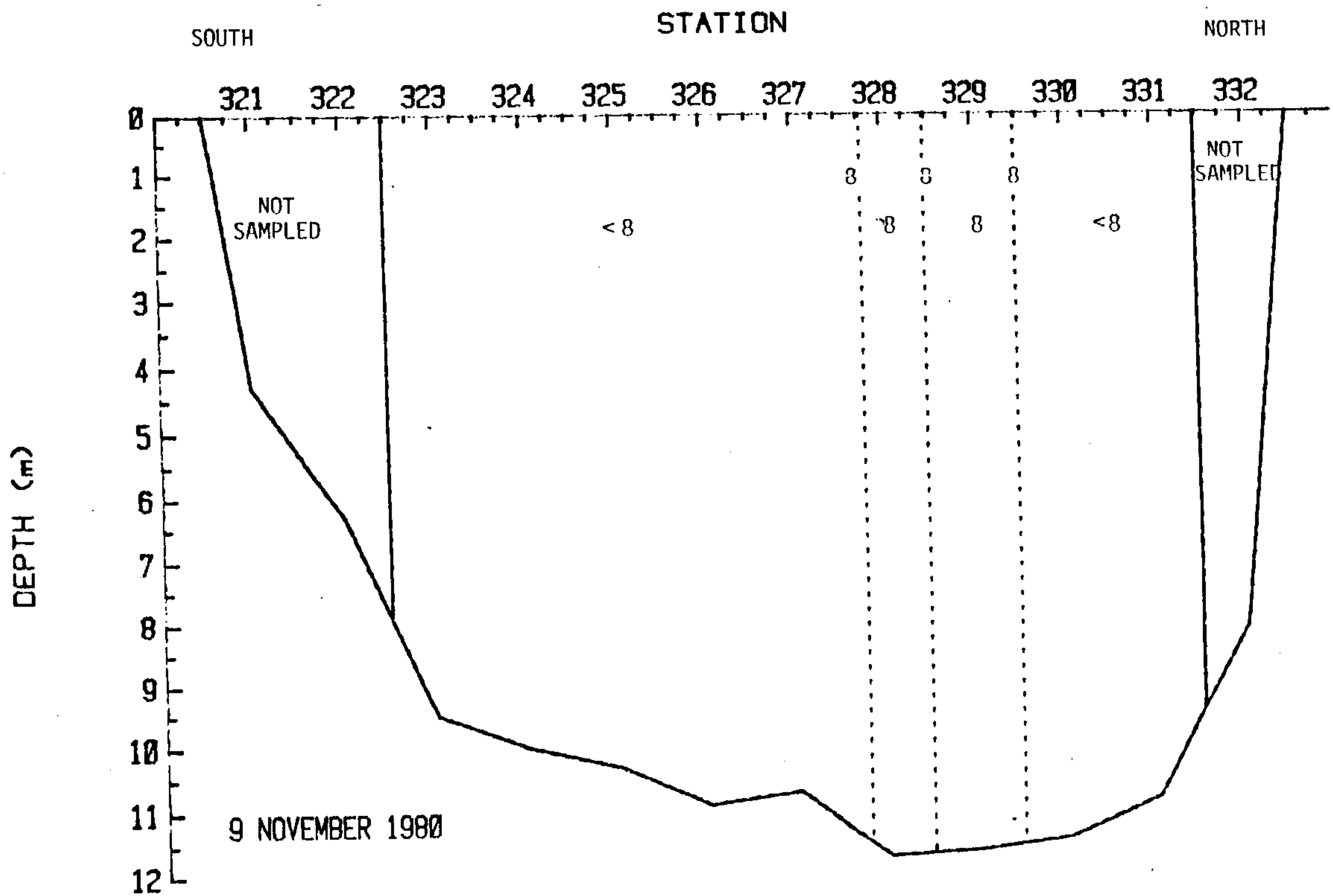
12
DEPTH (m)
18
19
>19
19
<19
28 SEPTEMBER 1980


STATION
SOUTH
NORTH
321
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325
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327
328
329
330
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332
DEPTH (m)
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2
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NOT SAMPLED
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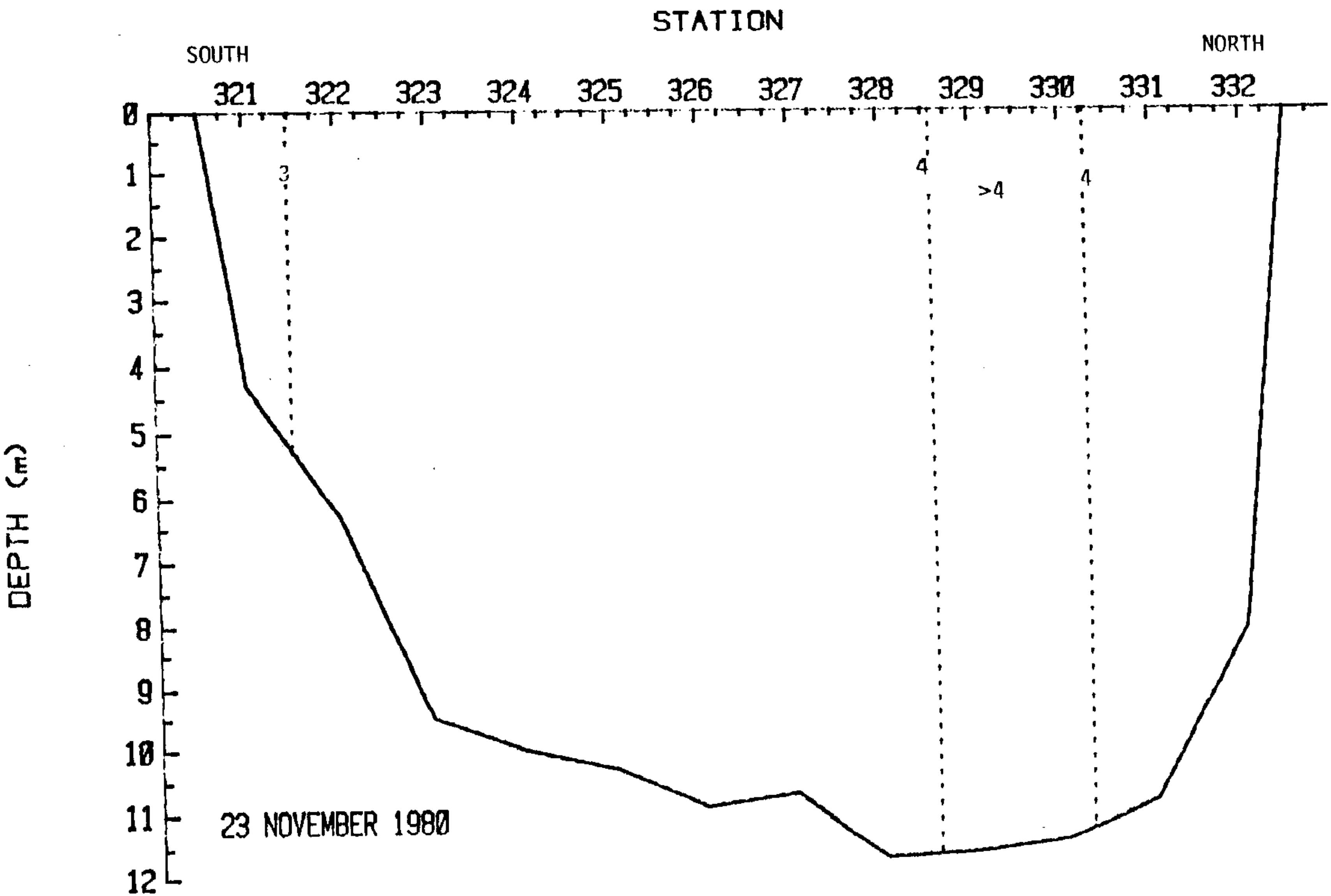
STATION
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325
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332
DEPTH (m)
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12
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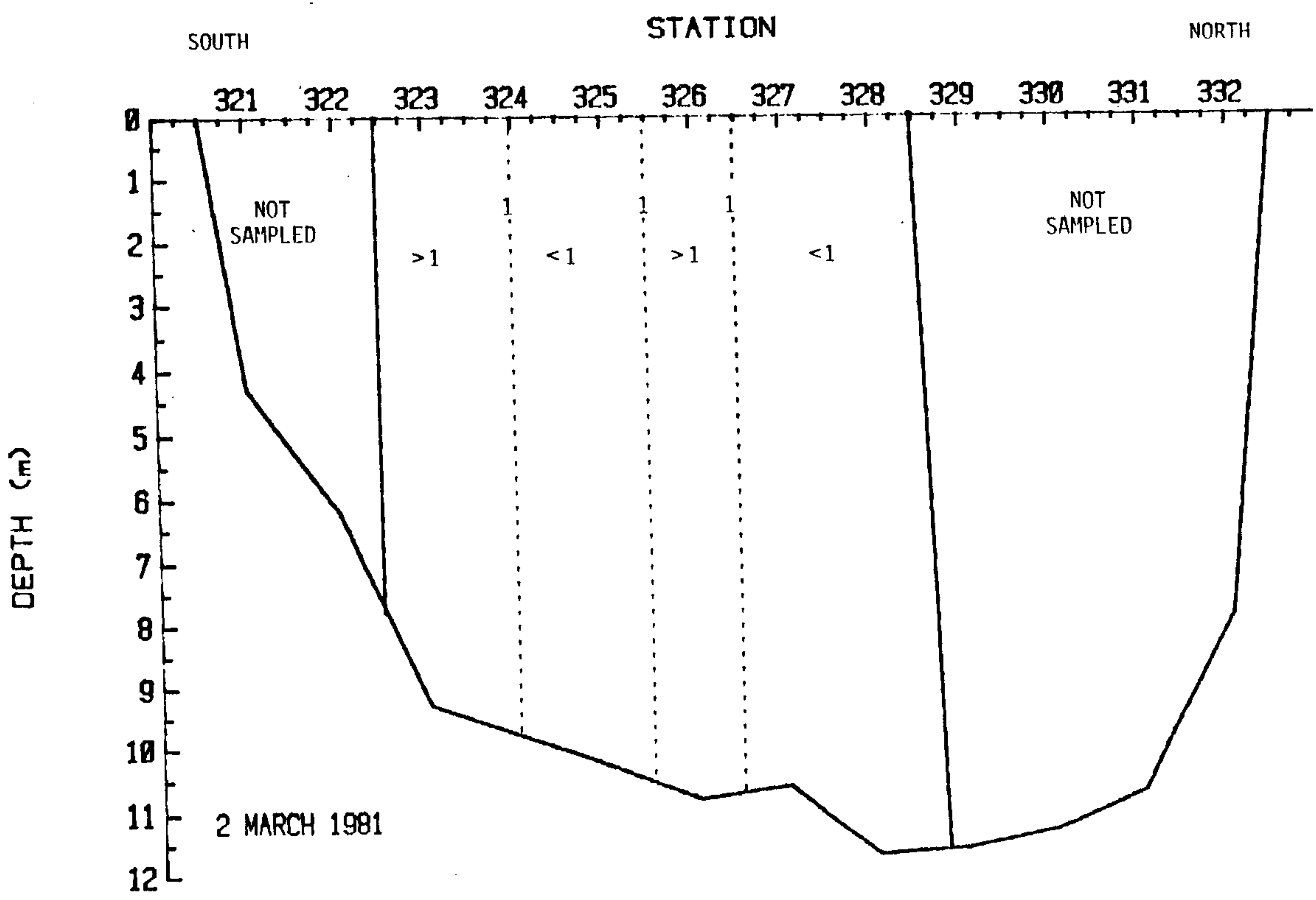
STATION
SOUTH
NORTH
321
322
323
324
325
326
327
328
329
330
331
332
NOT SAMPLED
NOT SAMPLED
>1
<1
>1
<1
1
1
1
DEPTH (m)
0
1
2
3
4
5
6
7
8
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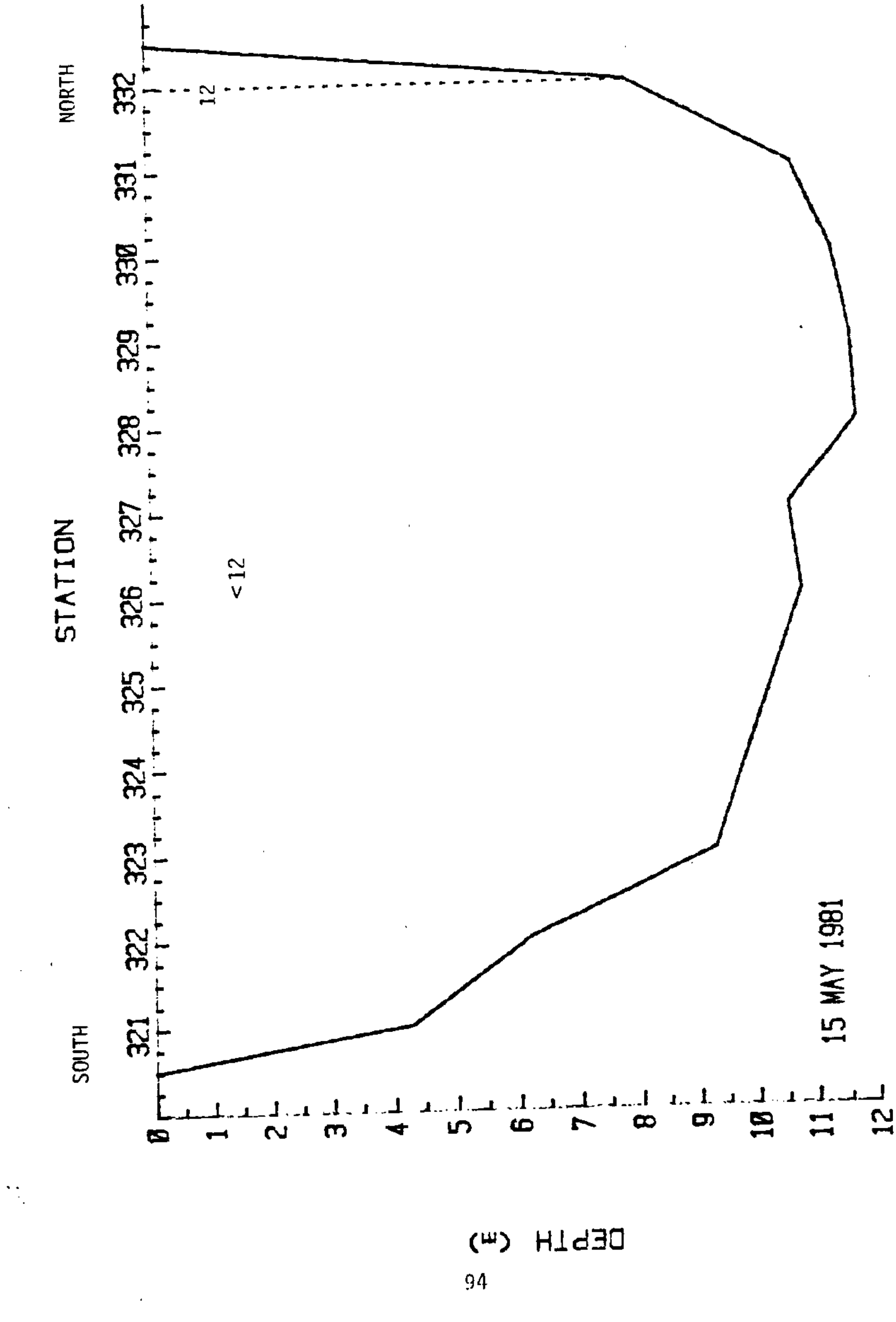
10
11
12
2 MARCH 1981


STATION
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NORTH
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323
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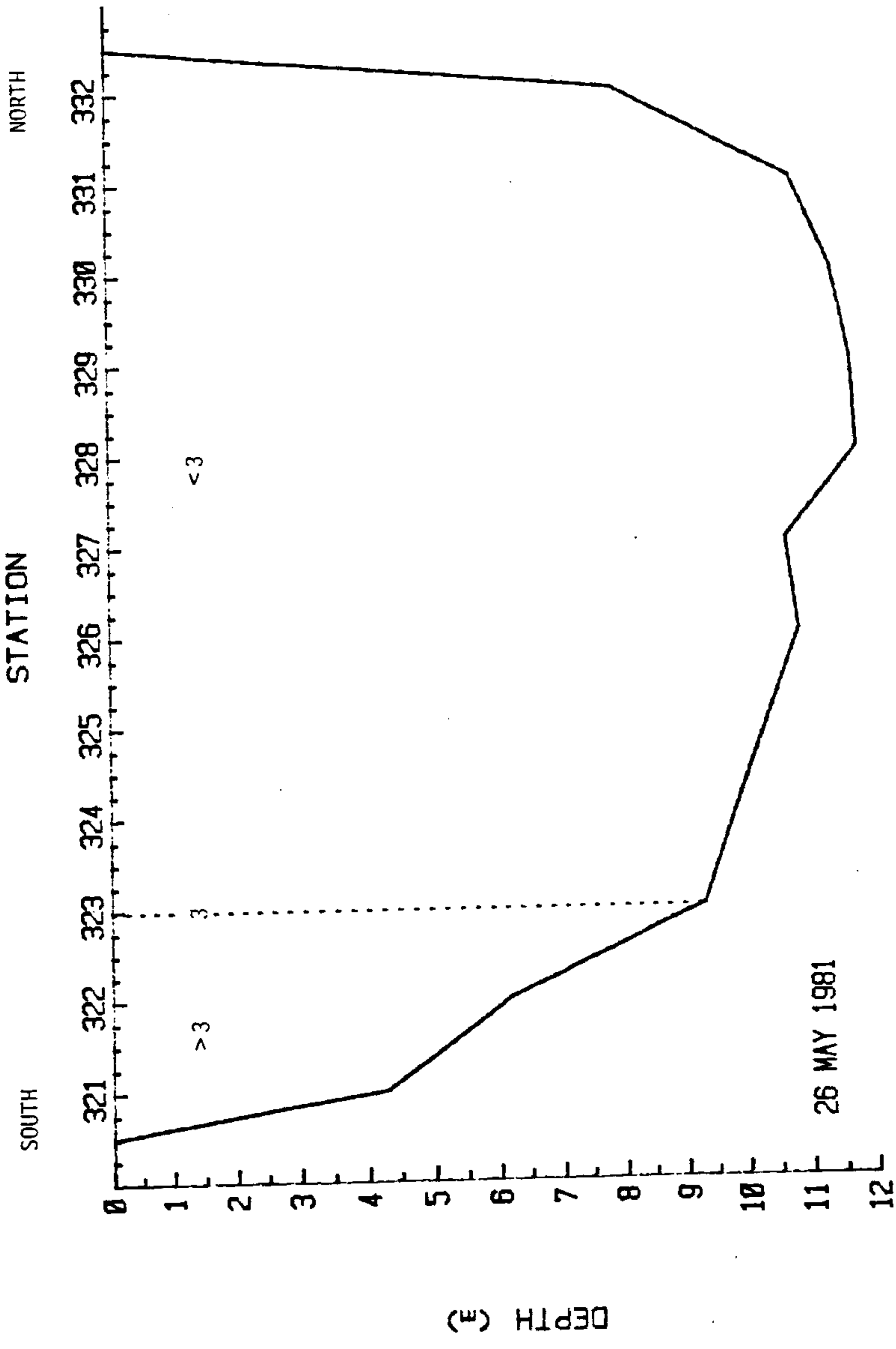
329
330
331
332
12
<12
15 MAY 1981
0 1 2 3 4 5 6 7 8 9 10 11 12
DEPTH (m)



NORTH
SOUTH
STATION
321
322
323
324
325
326
327
328
329
330
331
332
<3
3
>3
26 MAY 1981
DEPTH (m)
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1
2
3
4
5
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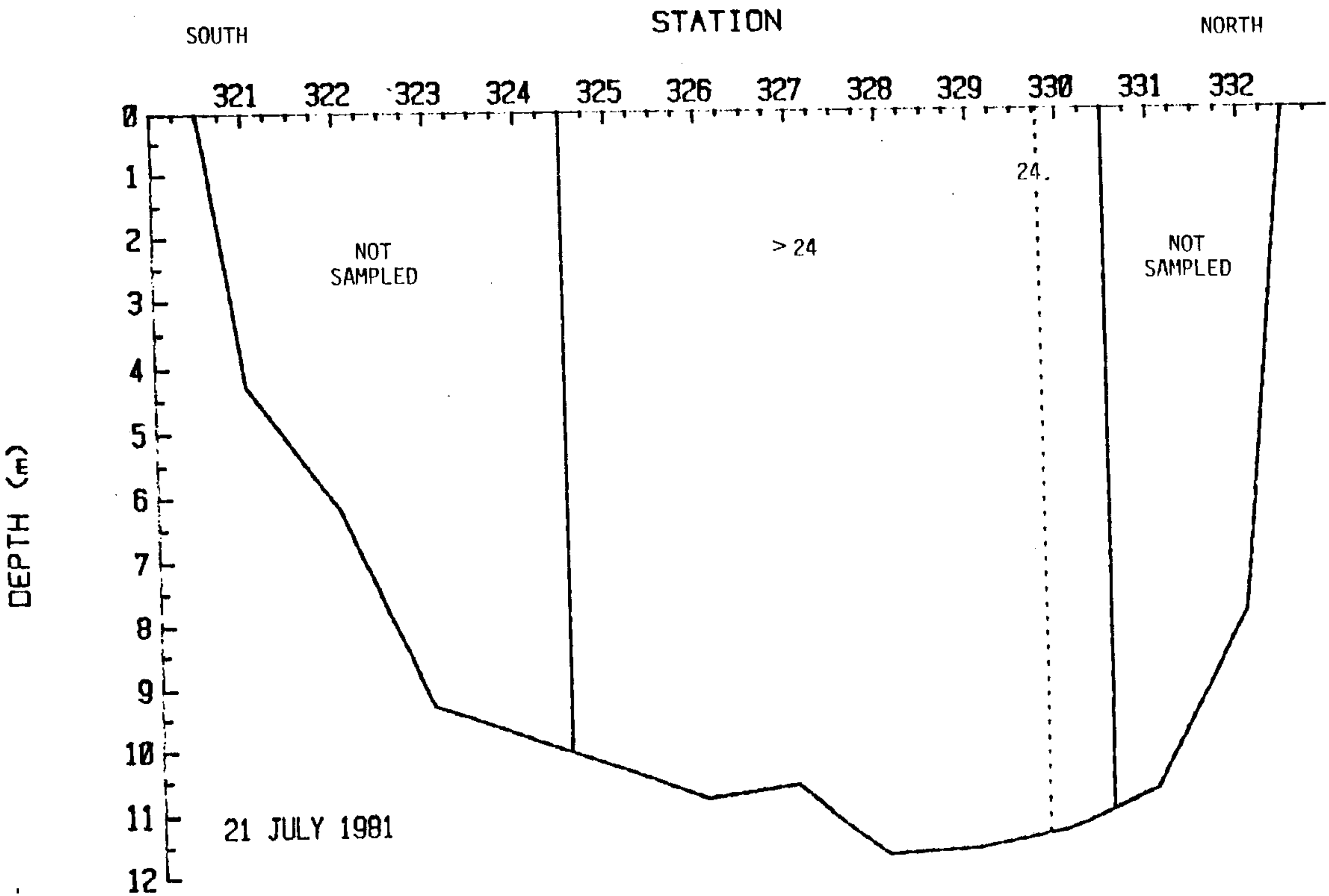
11
12


STATION
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NORTH
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323
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325
326
327
328
329
330
331
332
DEPTH (m)
0
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9
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11
12
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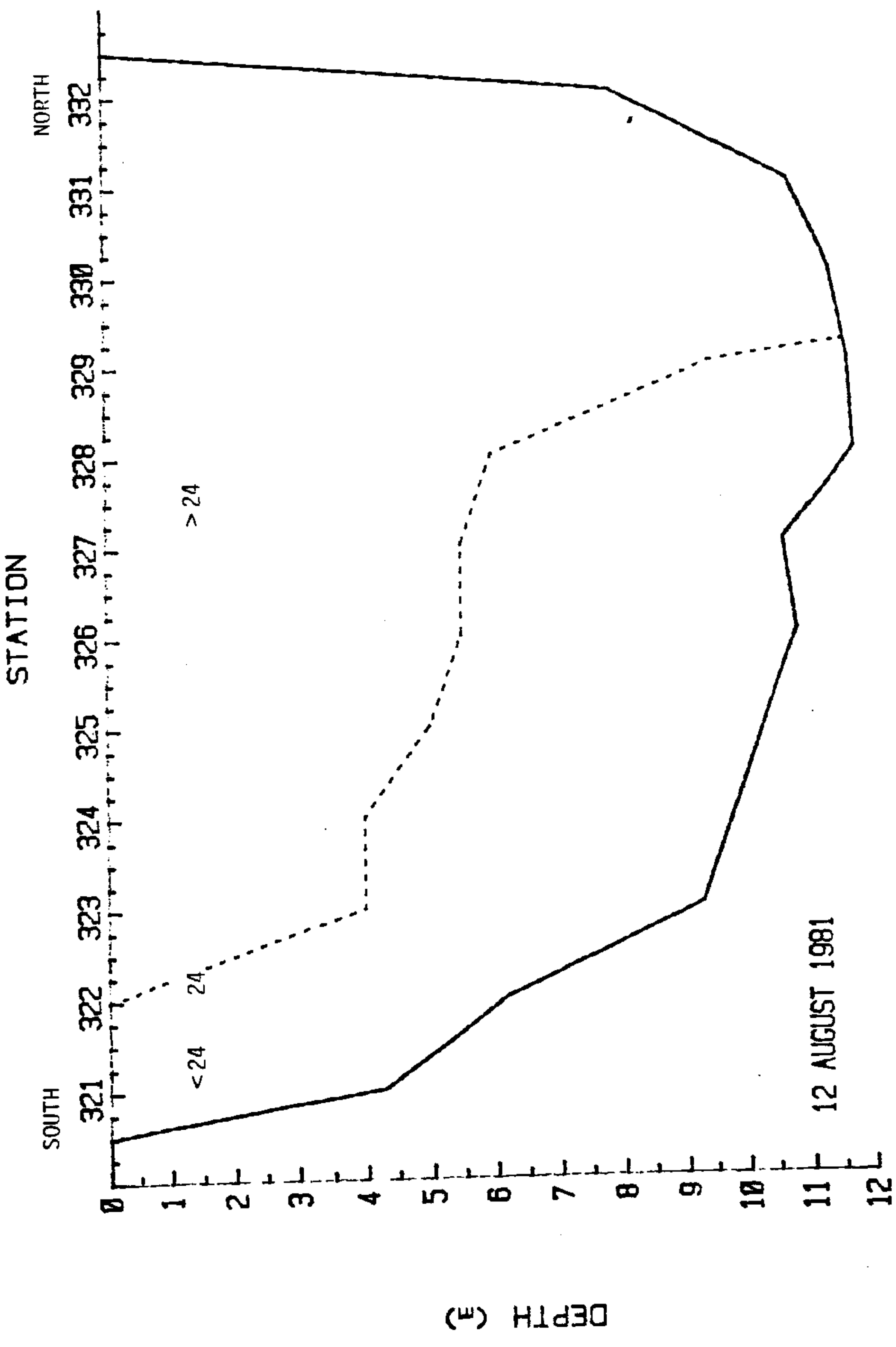
> 24
24.
NOT SAMPLED
21 JULY 1981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329
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332
<24
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>24
12 AUGUST 1981
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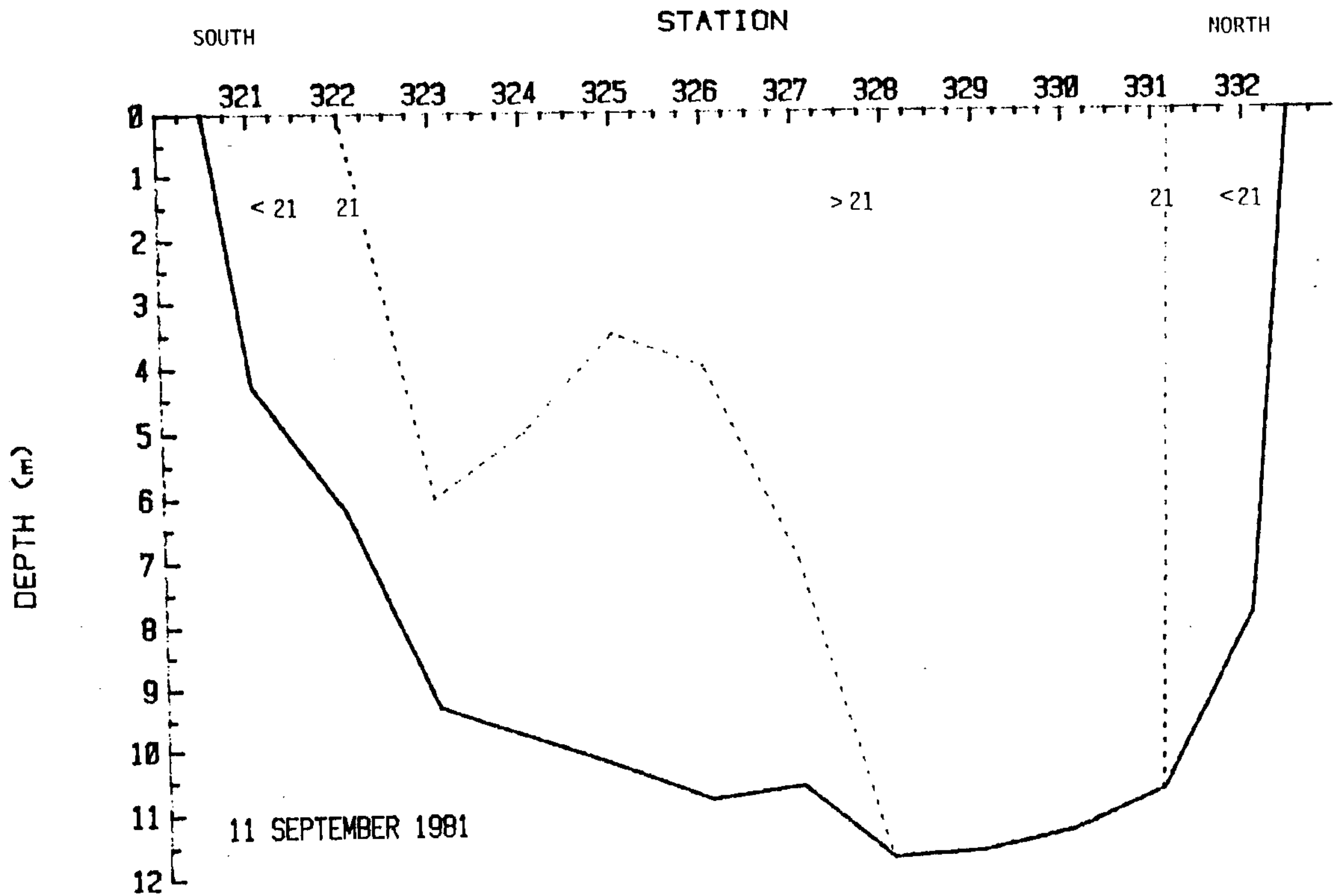
12
DEPTH (m)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SOUTH
NORTH
321
322
323
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325
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327
328
329
330
331
332
DEPTH (m)
0
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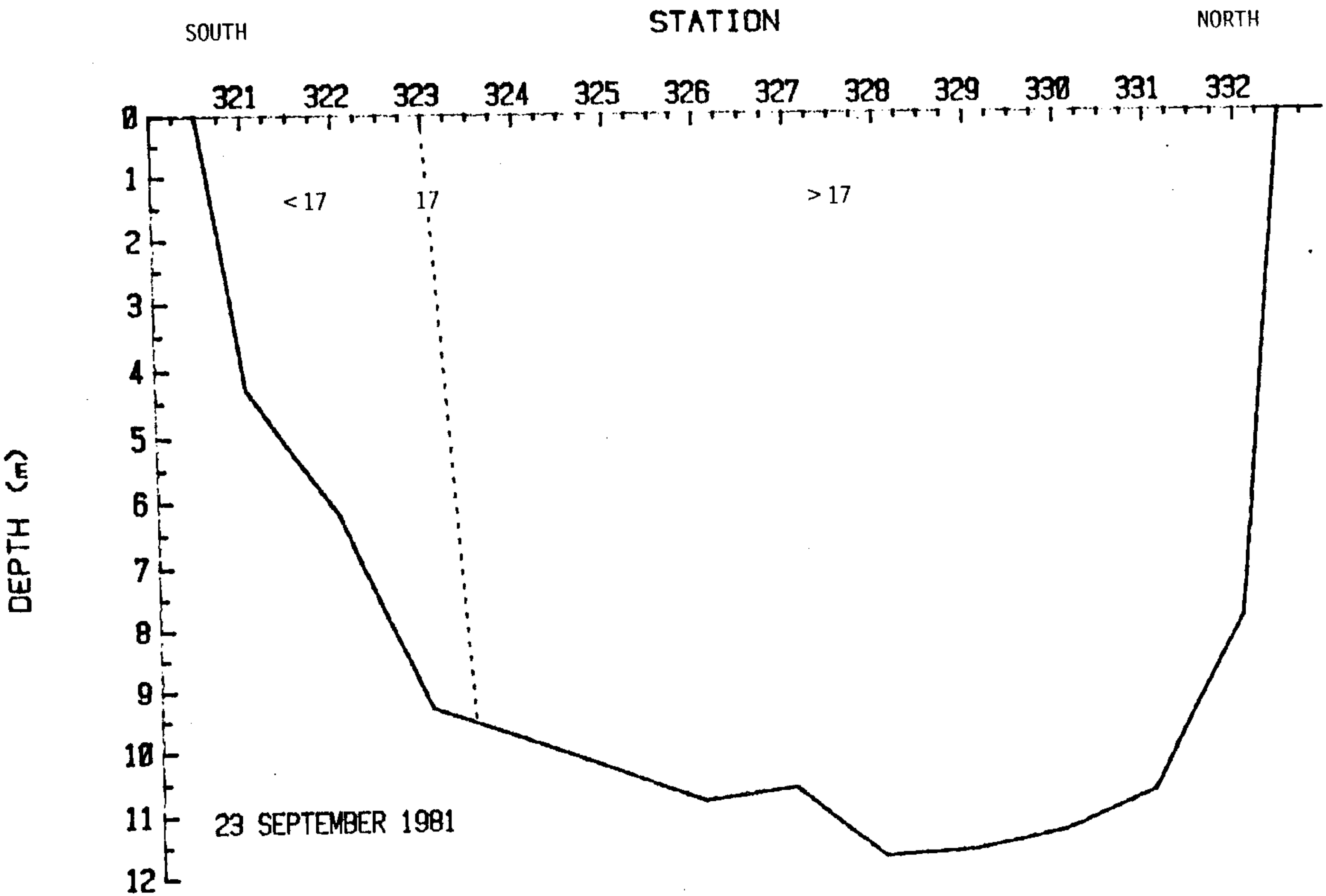
12
< 21
21
> 21
21
<21
11 SEPTEMBER 1981


STATION
SOUTH
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325
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327
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331
332
DEPTH (m)
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12
< 17
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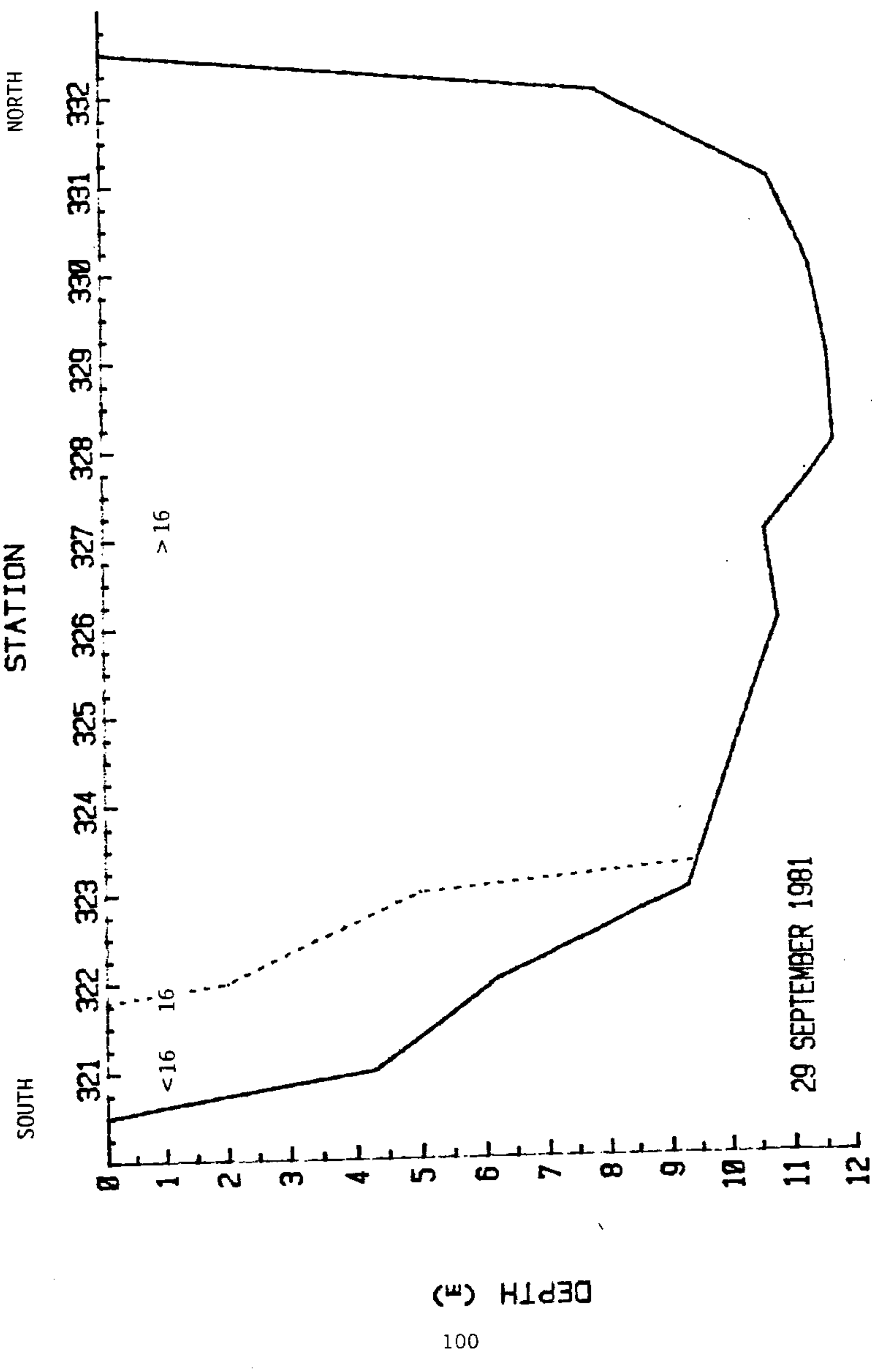
> 17
23 SEPTEMBER 1981


STATION
SOUTH
NORTH
321
322
323
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325
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327
328
329
330
331
332
<16
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>16
29 SEPTEMBER 1981
DEPTH (m)
0
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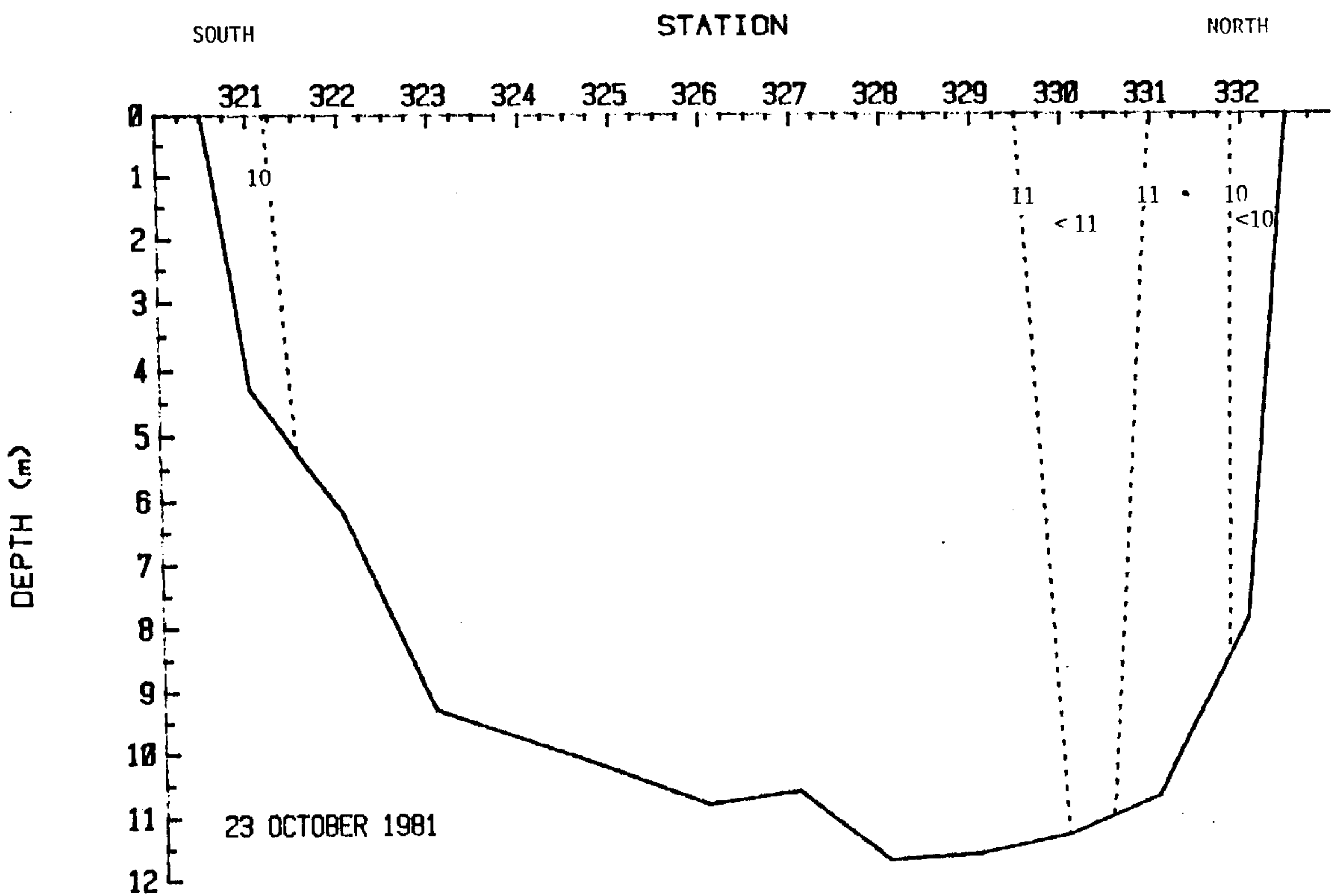
STATION
SOUTH
NORTH
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332
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DEPTH (m)
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11
< 11
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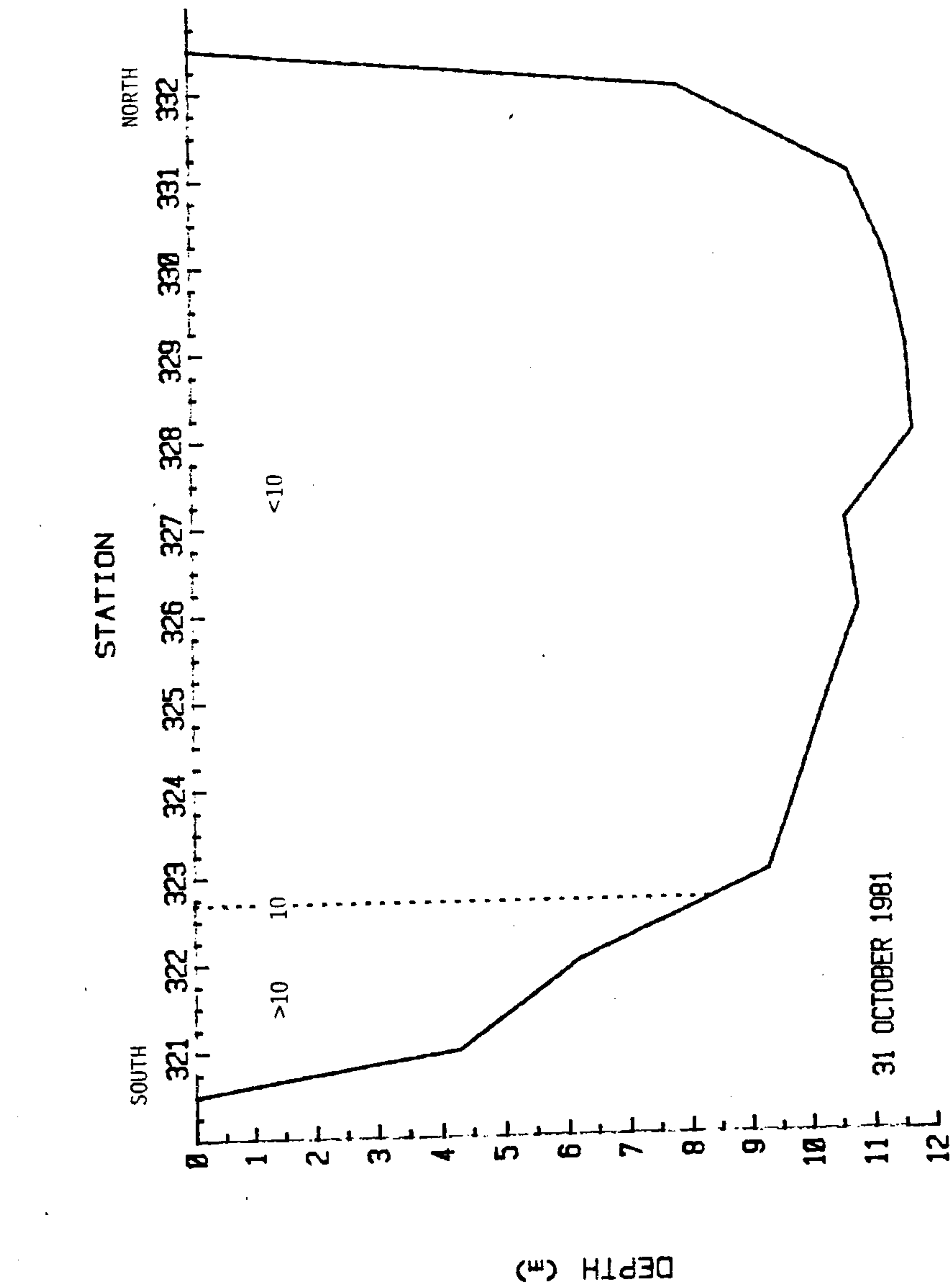
10
<10
23 OCTOBER 1981


STATION
SOUTH
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332
<10
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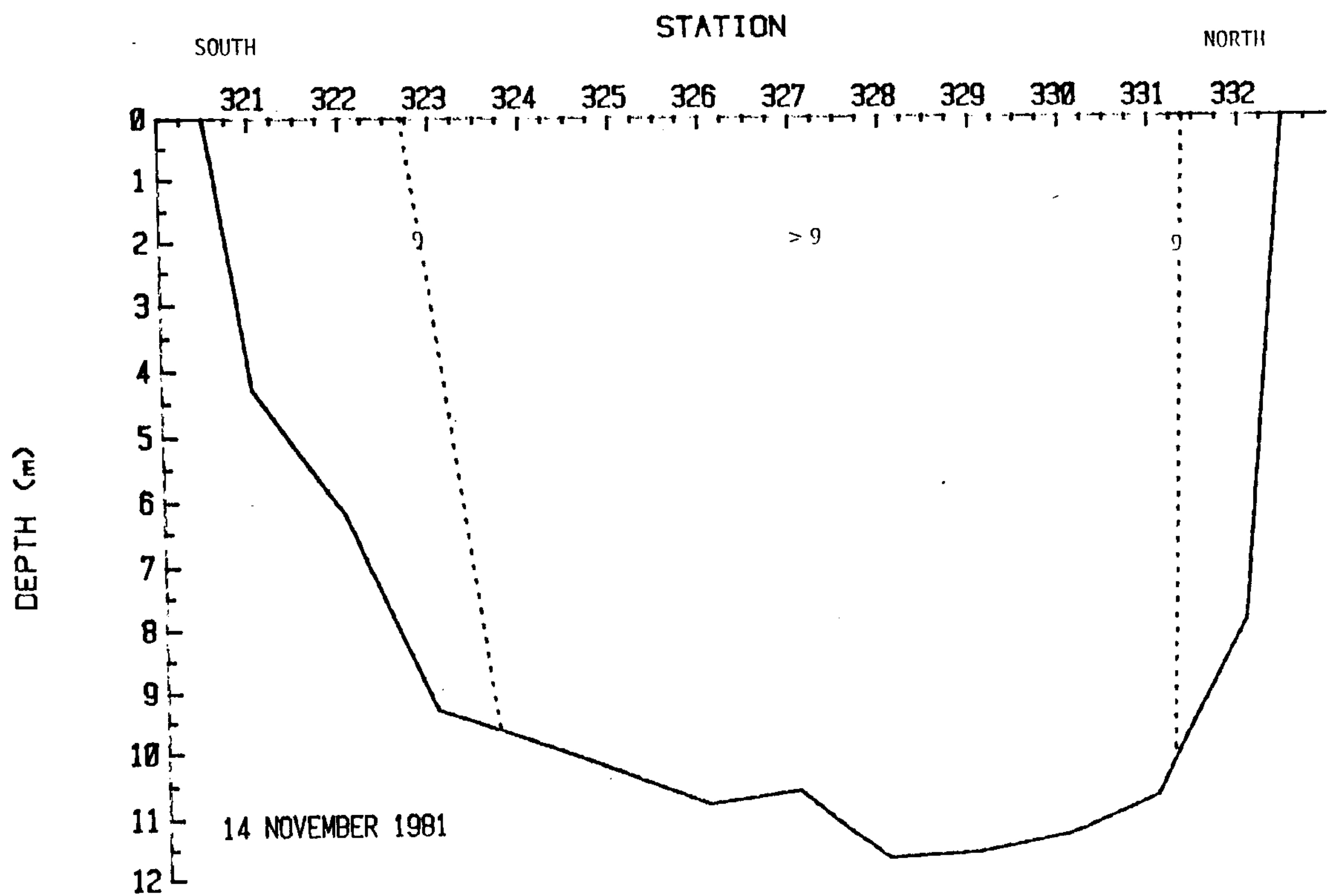
DEPTH (m)


STATION
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331
332
DEPTH (m)
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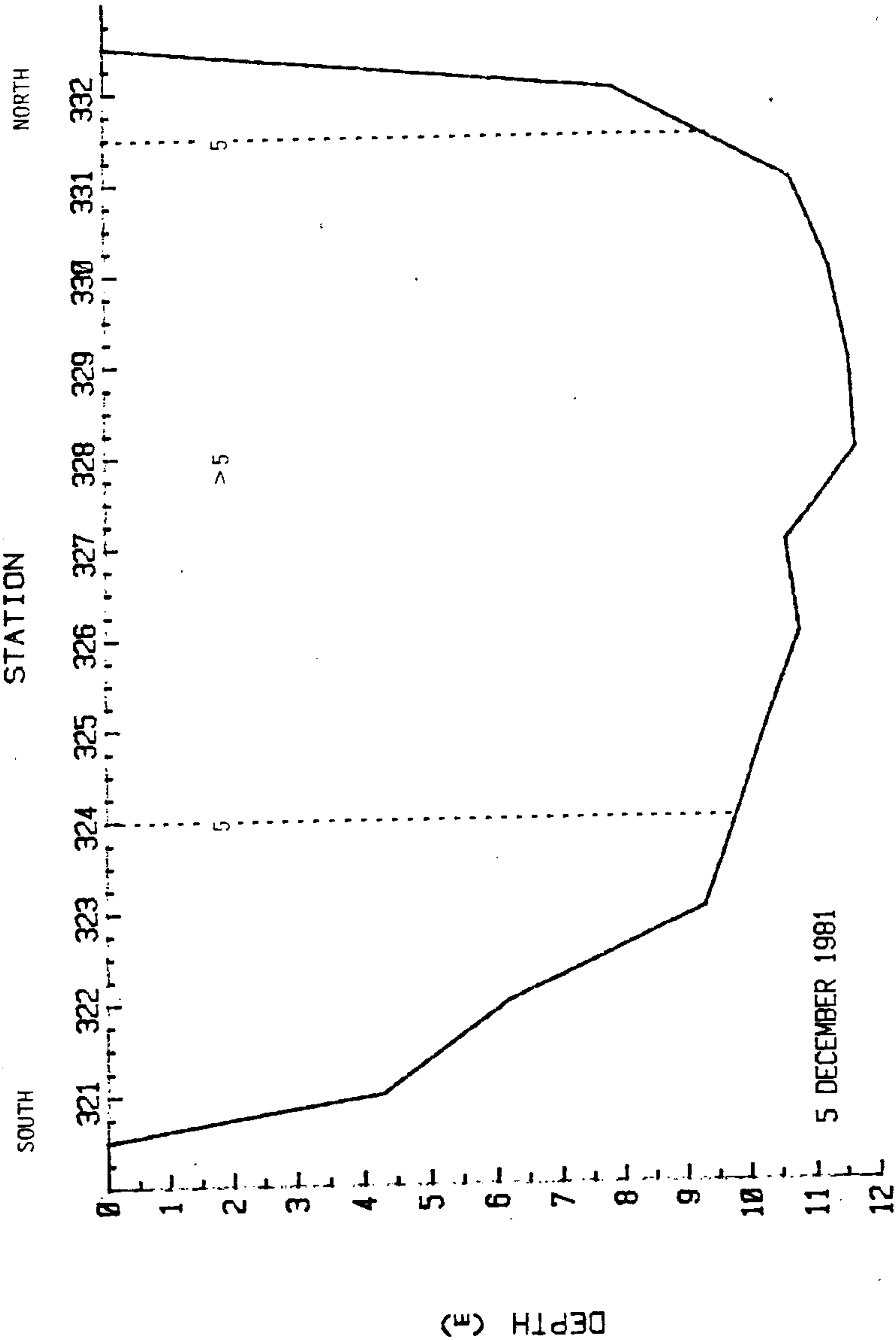
> 9
9
14 NOVEMBER 1981


STATION
SOUTH
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>5
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5 DECEMBER 1981
DEPTH (m)
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