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PRECISION SOUND VELOCITY PROFILES IN THE OCEAN

VOLUME V

SOUND SPEEDS AND TEMPERATURES OF BERMUDA
WATERS IN AUTUMN AND WINTER
(October 1964 - March 1966)

by

Ants T. Piip

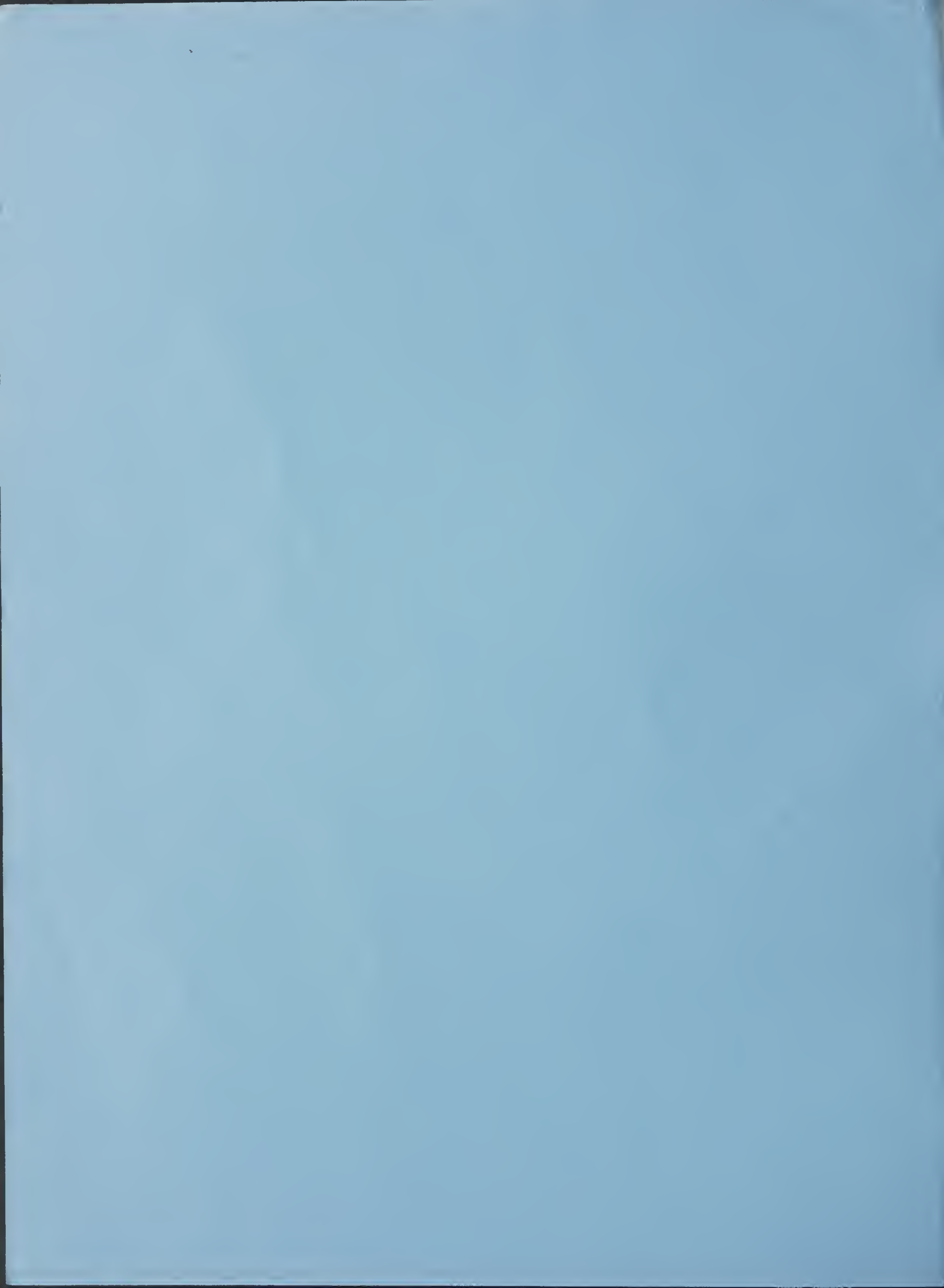
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ABSTRACT

A collection of high-resolution, precision simultaneous sound speed and temperature profiles to 2200m depth, and their envelopes for each station is presented for 25 stations in Bermudian waters in the months of October, December and March. The period October to March covers the full range of large seasonal changes in the near-surface waters from summer to winter; while the deep waters remain relatively stable and do not show any definite seasonal changes. For two long constant depth stations, in and below the main thermocline, time series and their power density spectra are shown for sound speeds and temperatures. A table of sound channel parameters at all stations concludes the report. The report emphasizes the variability and short-lived phenomena in oceanic waters around Bermuda.



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LIST OF STATIONS AND FIGURES

STATION NUMBER	POSITION		DATE	# OF PROFILES	FIGURE NUMBER		
	North	West			PROFILES	TEMPERATURE	ENVELOPES
40	31°35'	64°35'	1 Oct. 64	4	SOUND SPEED 2	3	56
41	30°37'	64°37'	2-5 Oct. 64	22	4	5	57
	Constant Depth Recordings: depth 1170m (41CD1):				6; Spectrum:	8	
	930m (41CD2):				7; Spectrum:	9	
42	30°37'	64°35'	10/11 Oct. 64	8	10	11	58
43	32°23'	64°28'	2 Dec. 64	2	32	33	63
45	32°18'	64°25'	6 Dec. 64	4	34	35	64
46	31°42'	64°41'	13 Dec. 64	2	36	37	65
47	31°54'	64°12'	13 Dec. 64	2	38	39	66
48	32°13'	64°28'	17 Dec. 64	2	40	41	67
86	32°52'	63°55'	13/14 Dec. 65	4	42	43	68
87	32°22'	63°40'	14 Dec. 65	2	44	45	69
88	31°58'	64°00'	16/17 Dec. 65	4	46	47	70
89	31°45'	64°44'	17 Dec. 65	4	48	49	71
90	31°42'	64°37'	22 Mar. 66	4	50	51	72
91	32°02'	64°37'	23 Mar. 66	2	52	53	73
92	32°02'	64°37'	25 Mar. 66	2	54	55	74
109	32°13'	64°30'	13 Oct. 66	2	12	13	59
110	32°14'	64°25'	18 Oct. 66	2	14	15	60,61
111	31°34'	65°21'	19 Oct. 66	4	16	17	"
112	32°17'	65°53'	20 Oct. 66	4	18	19	"
113	33°01'	65°16'	21 Oct. 66	4	20	21	"
114	32°58'	64°25'	22 Oct. 66	6	22	23	"
115	32°58'	63°26'	22 Oct. 66	4	24	25	"
116	32°17'	63°56'	22 Oct. 66	5	26	27	"
117	31°34'	64°26'	23 Oct. 66	4	28	29	"
119	32°14'	64°34'	10 Nov. 66	2	30	31	62

"Circle around Bermuda"



INTRODUCTION

This volume presents a collection of high-resolution, precision simultaneous sound speed and temperature versus depth profiles from 25 stations taken in Bermudian waters during the months of October, December and March of several years. The time between October and March encompasses nearly the full range of seasonal changes in the ocean around Bermuda.

In October the surface waters around Bermuda still retain their summer character, with a very warm and shallow surface layer. By March they have reached their full winter structure where the topmost several hundred meters are nearly isothermal. December is intermediate in character, the thin warm water layer has disappeared from the surface, the isothermal region only reaches to about a hundred meters. At greater depths, the bottom of the 18° Sargasso Sea (i.e., the main thermocline) shows some seasonal changes, but these are not very drastic.

In addition to showing profiles, we have included two sound speed and temperature time series at constant depths, one just below, the other inside the main thermocline, and their power density spectra. This data was obtained during a long anchor station in over 2000 fathoms depth, about 100 miles south of the island.

INSTRUMENTATION, DATA PROCESSING

All stations in this report were taken from our R/V SIR HORACE LAMB, using several generations of our sound velocimeter instrument package and associated shipboard recording gear. Although the instrumentation at different times might have differed in detail, the principles and methods have remained unchanged over the years.

The underwater sensor package contained two NBS-type velocimeters (Modified TR-2) for channels 2 and 3; a FM-output precision pressure gauge for channel 1; and a FM-output platinum resistance thermometer (Hytech 4002) in channel 4. Each instrument was fed by an individual voltage regulator. The instrument outputs, after suitable frequency divisions to prevent overlapping, and filtering, were combined in a summing cable driver amplifier and sent up via a single-conductor cable. The underwater package was powered from a topside constant-current DC supply through the same cable.

On shipboard the composite signal was separated into its component channels. The frequencies were multiplied by a chain



of push-push doublers to four times the basic instrument frequencies in order to improve resolution. The 4 channels were scanned and counted in a 1-2-1-3-1-4 sequence, a second for each channel, and the frequencies printed on paper tape.

In profiling, cable speed was controlled to give a depth change rate of about 1 m/s. Thus, sound speed readings were obtained about every 3.5m, temperature every 9m, and depth every 3m, on the average.

Our methods of data processing ashore, and quality control, have been described in previous volumes of this series. Suffice to mention that data reduction was done on the LDGO computer, yielding machine-drawn original profiles as well as numerical output data; and that the sound speed as given in the graphs is the validated average of the two velocimeter readings.

ACCURACY, CORRECTIONS TO THE PLOTS

The sound speeds in the graphs pertain to a velocimeter standardized for + 10°C. For other ambient temperatures, the readings in the plots have to be corrected for sound path expansion effects:

$$\text{True sound speed} = V_i + \text{Correction}$$

$$\text{Correction} = 1.46 \cdot 10^{-5} (T - 10) V_i$$

where T: ambient temperature, °C

and V_i : indicated sound speed

<u>T, °C</u>	<u>Correction, m/s</u>
25	+ 0.33
20	+ 0.22
15	+ 0.11
10	0.00
5	- 0.11
0	- 0.22

Depths in this report are true, corrected values.

Conservative estimates of the quality of our data are as follows:

	Total uncertainty, absolute	Reproducibility, resolution
Sound speed	± 0.15 m/s	± 0.10 m/s
Temperature	± 0.05 °C	± 0.03 °C
Depth	± 5m ± ½% ≤ ± 10m	± 2.5m ± ¼% ≤ ± 5m



The sound speed uncertainties are relative to the standard used in laboratory calibration of our velocimeters (Greenspan & Tschiegg, 1957). These tables were used as published, although it is generally believed they are too high by about 0.3 m/s (C.E. Tschiegg, NBS, 1966, personal communication).

ORGANIZATION OF PLOTS

Figure 1 is a chart of our stations. Since the character of the oceanic water structure really depends only on the time of the year, the seasonal changes being repeated with minor variations from year to year, we have grouped our stations according to months: October '64 and '66, December '64 and '65, and March '66.

There are three figures for each station: 1) the individual, consecutive sound speed profiles, 2) the individual, consecutive temperature profiles, and 3) sound speed and temperature profile envelopes, showing the total spread of either quantity over the duration of the station.

The individual profiles have been spaced by 5 m/s, or 2 °C to improve legibility (except in very long stations, where the spacing is smaller). Each profile carries marks at round sound speed or temperature values, e.g. 1495, 1500, 1505 m/s, etc.; or 5, 10, 15 °C, etc. The small horizontal ticks on the sound speed profiles are 10-minute time marks: the times and depths for each tick are listed in the Appendix "Timing of Profiles".

Temperature and sound speed profile envelopes are given in the same figure: temperature at left, sound speed at right. An exception is Stations 111 - 117 which constitute a near-synoptic survey of the waters around the island, on a circle about 60 miles radius: for these stations all temperature envelopes have been combined in one figure, sound speeds in another — in order to present a better "snapshot" of the hydrography around the island.

All profiles have been reproduced on a uniform scale: 100m depth = 0.2 inches; 1 m/s = 0.1 inches; 1 °C = 0.2 inches. An easy way to read the profiles is to prepare a transparent overlay of 10 x 10 to the inch graph paper.

RESULTS

I. STATIONS 40-42, 109-119: OCTOBER

The shallower portions of the two October series are quite different. The 1964 stations, taken early in the month, are typical summer profiles: uniformly increasing temperature near the surface, from about 100m upwards, with occasional near-isothermal patches. The upper knee of the main thermocline (more precisely, the knee in the sound speed profiles: a combined effect of the thermocline knee and the mild salinity maximum above it) is at roughly 400m depth.



The 1966 stations, taken towards the end of the month, already show an autumnal water structure: a well-defined, 50m thick isothermal surface layer, and the upper knee of the thermocline has sunk to 500m depth.

This summer-autumn transition occurs around Bermuda during September or October — sometimes earlier, sometimes later, depending largely on the local weather.

At depths beyond 500m, no real differences can be observed between the two years.

In 1964 we were mainly concerned with the stability of the sound channel, thus most of the profiles in these three stations (40,41,42) do not reach into the surface waters. Instead, there are long series of consecutive profilings in and below the thermocline. Stations 41 and 42 were anchor stations. (Our technique of anchoring at depths over 2000 fathoms has been described in Volume III of this series.)

IA. Station 41: CONSTANT DEPTH RECORDINGS IN AND BELOW THE THERMOCLINE: INTERNAL WAVES AND THEIR SPECTRA *

In station 41 we tried to take a close look at the internal waves around the main Sargasso Sea thermocline. We anchored the ship in over 2000 fathoms of water about 100 miles south of Bermuda and started our station by taking half a dozen profiles to a little over 2000m depth. (Figs. 4, 5.) These showed that the waters were normal, no large cells or thick layers were to be seen anywhere, except a medium-sized one around 1000m, and the currents were no stronger than usual.

We stopped our instruments on the sound channel axis, below the lower knee of the main thermocline, and kept them there for the next 30 hours at a depth of 1167 ± 2 meters (41CD1). This was followed by 12 profiles of the usual kind, after which we had another constant-depth session, inside the thermocline but still close to the lower knee at 923 ± 2 meters (41CD2). After 18 hours at this depth, the weather worsened and we had to terminate our station.

During the constant depth periods we slowed down our sampling rate to 80 seconds for a complete depth-temperature-sound speed reading sequence — a compromise between amount of digital data gathered and high-frequency resolution.

Total recording time on station was 77 hours.

* Condensed from "Internal Waves In and Below the Sargasso Sea Thermocline", presented as paper O-43 at the 50th Annual Meeting of the American Geophysical Union, Washington, D. C., April 1969.



Figures 6 and 7 show the results of our constant depth sessions, depth, temperature and sound speed versus time: Fig.6 below the thermocline, Fig. 7 inside the thermocline. (NB: Vertical scales of the two figures are not the same.)

The actual constant-depth parts of the two sessions have been extended in time by taking readings at the proper depths from our profiles before and after the constant depth parts. These very low resolution "wings" help to extend our observation times for very long period waves.

The two time series show immediately the near-perfect correlation between the temperature and sound speed traces. The amplitudes of these two traces are an order of magnitude larger than could be caused by depth variations alone — we are seeing internal waves, an up-and-down fluctuation of the water mass. These oscillations are a combination of a true up-and-down oscillation of the waters, plus some current effects. The latter are probably small compared to the first.

The maximum temperature and sound speed variations observed over the duration of our station are $0.25\text{ }^{\circ}\text{C}$ (1.1 m/s) below the thermocline (Fig. 6). Inside the thermocline (Fig.7), the variations are nearly twice as much: $0.44\text{ }^{\circ}\text{C}$ (1.86 m/s). Comparing these figures to the mean gradients at the depths of measurement ($1.25 \cdot 10^{-2}\text{ }^{\circ}\text{C/m}$ at 920m; $0.6 \cdot 10^{-2}\text{ }^{\circ}\text{C/m}$ at 1170m), we can infer wave amplitudes of at least 32 meters inside the thermocline, 40 meters just below it. Nothing definite can be said about the periods of these large slow waves, although there are indications they might be close to tidal. Our samples really are not long enough to let us decide, but the very washed-out peaks in the time series tracings are separated by intervals which look roughly diurnal and semidiurnal. The major peaks do not coincide with surface tide extremes, they fall about half-way between.

In addition to the slow large waves both time series show complex, random more rapid oscillations of varying amplitude and periodicity. No persistent or dominant frequencies can be seen in either recording. Occasionally quite distinct single-frequency wavetrains can be discerned — they are of very short duration, of a few periods each. These short single-frequency wavetrains are more common inside the thermocline than below it.

The two constant-depth time series have been spectrally analyzed for power density, using the standard technique of taking the autocorrelation function of the time series and Fourier transforming this into the frequency domain. (Blackman & Tukey, 1959; Hassell, 1965; Onyx, 1966; Richards, 1967) The first, fairly obvious result of the analysis is that the time series at both depths are not yet stationary for our observation times, 18 and 30 hours. Considering the very long periods of the large waves involved, series of at least a week or more might tend to become stationary. Even then we would probably have to eliminate seasonal changes from the analysis.



Because of the shortness and non-stationarity of our time series, we cannot claim any general validity of our power density spectra — they should only be considered illustrative, typical of relatively short periods of observation.

Two different windows were tried in our analysis: a narrow v. Hann window (weighting coefficients $0.25 + 0.50 + 0.25$), and an approximately 8 minutes wide modification ($0.05 + 0.1 + 0.2 + 0.3 + 0.1 + 0.05$) of the same for a wider passband. The results of the two windows are similar, but at the time of this writing we cannot give an explanation why the two windows produce different slopes in the low-frequency part of the spectra.

The power density spectra of our two depths (Figs. 8, 9) are superficially similar, but differ significantly in detail. In both cases power decreases with increasing frequency, both can be divided into three regions: a steep drop at low frequencies, an intermediate region, and a flat high-frequency tail.

The "intermediate region" is more or less centered around the local Väisälä frequency — the high frequency limit of propagating internal waves. This limit is directly proportional to the square root of the mean local density gradient.

Waves do occur at frequencies higher than this limit, but they do not travel very far, they suffer considerable attenuation and are soon lost. These high-frequency waves have either leaked from an adjoining region of high density gradient, or they can originate locally at thin interlayer boundaries. In the latter case their energy and amplitudes would be quite small.

Our power spectrum from below the thermocline (Fig. 8) shows these regions and relationships in a very clear fashion. At the low frequency end there is a rapid dropoff in energy until we reach the deep water Väisälä frequency at about 0.6 periods per hour. These are the slow, high amplitude waves which involve very large and thick water masses, and can propagate unhindered anywhere in the ocean. The frequency-power relationship of the wide window spectrum in this region is close to the $5/3$ power law.

The "intermediate" region in this deep spectrum fits perfectly between the Väisälä frequencies for deep water and the mean thermocline. The local Väisälä frequency is 1.3 periods per hour, halfway between the deep waters and the thermocline. This is not very surprising — we are still very close to the thermocline, close enough for a large amount of the high-frequency waves, which are permissible in the thermocline, to leak down.

The spectral power in this region decreases approximately with frequency to the power of $-4/3$.

Above the high-frequency break in this spectrum there is a very weak, practically flat tail.



Figure 9 seems to indicate that the relationships inside the thermocline, a little above its lower knee, are not as clearcut as 250m deeper. We probably can blame our much shorter recording time for some of this.

Again, there is a sharply dropping low-frequency section which more-or-less follows the $5/3$ law. At a frequency close to 1 per hour this levels off to a nearly level, "white" intermediate region reaching to 5 or 6 periods per hour, a little above the high-frequency limit of the thermocline as a whole. The local Väisälä frequency, 3 per hour, is again near the center of this region. At periods shorter than 12 minutes there are several minor peaks in the spectrum, at non-harmonically related frequencies. We suspect these are caused by small local oscillations of high-gradient interfaces between layers of slightly different waters — the individual temperature and sound speed profiles are quite wiggly at this depth. Inside the thermocline, temperature gradients of the order of $1/4$ °C/m can be found at thin interlayer boundaries — the Väisälä period for such a high gradient is of the order of 5 minutes. It is hard to believe the oscillations in the spectrum are caused by aliasing or noise, since recording quality and conditions for this constant depth session were identical to the first one.

IB. STATIONS 111-117: CIRCLE AROUND BERMUDA .

In October 1966 we made a 5-day series of stations around Bermuda, equally spaced at about 60 miles distance from the islands. The sound speed and temperature profile sequences are shown in Figs. 14-29; the combined envelopes for the whole series in Figs. 60 and 61.

Each of the stations consisted of 4 consecutive profiles, except Station 114: there we took 6 profiles since the quick-look shipboard XY recorder showed a large water mass rapidly moving in between profiles 2 and 3 (Figs. 22, 23), in the middle of the main thermocline. One does not often meet large, over 100m thick water cells in the thermocline proper, and even more unusual is the cold character of this cell. In approximately one hour this cell had attained its full concentration. It lifted the 12 °C isotherm by about 50m, or reduced the temperature at 700-800m depth by a full degree C. A quick look at the depth-sound speed-temperature relations, by reversing Wilson's sound speed formula, shows this cell (profile 3) to have a nearly 0.3% salinity deficiency compared to our profile 2. Between our profiles 3 and 6 the cell was gradually sinking deeper and growing less and less distinct. By the end of the station it was barely noticeable.

We do not have any accurate data on the ship's motions, even relative to the water, during the station, but any reasonable assumption about currents and drifts yields a lateral size of the cell of the order of a very few miles, say 3-5 at most. There are no signs of the cell in the neighbor stations (113, 115, 116).



Concurrently with the cold mass at 600-800m there were two warm water masses appearing in the same station, at both knees of the thermocline: at 300-400m and 1100-1300m depth. These were not by far as prominent as the central cold cell.

The two southernmost stations (111,117) of our circle differ from the others by having a much lower minimum sound speed at the sound channel, and a main thermocline about 50m shallower than the rest between 5 °C and 15 °C. If we postulate a deep current coming from the North, we could explain this deformation as a rolling-up of the thermocline by the wake of the island pedestal. (Station 110, too close to the island and in its shadow, shows a normal thermocline).

With the exception of the three stations discussed in detail, there is not much that can be said about the other stations: their differences are negligible. The only significant difference is the high surface and mixing layer temperature in the southeastern stations (111,112), and close to the island (110).

IC. 15° ISOTHERMAL WATER, STATION 119.

Station 119, two weeks after "the circle", has been included because of its unusual temperature structure between 350 and 800m depth. The well-defined isothermal 14.8 °C water between 550-800m is seen occasionally in summer and autumn just below the 18° water, and seems to be sharply defined cell of short apparent lifetime, indicating small lateral dimensions of the cell and rapid transport by currents at this depth.

The two sharply defined, thin cold layers at 400m we have only seen in this particular station. We have no idea of their source, lifetime or lateral dimensions.

II. STATIONS 43-48, 86-89: DECEMBER.

All these December stations show a typically autumnal surface water structure: a nearly isothermal, about 100m thick surface layer. The bottom part of this layer is quite variable and probably patchy: in some of the stations the knee of the sound speed profiles is very sharp, in some quite round and gradual.

The surface waters in 1965 were appreciably more variable than in '64, in spite of the shorter time span covered. Station 88 is interesting: over the duration of the station there is a progressive cooling of the surface proper, and a radical shape change of the uppermost 100m between profiles 1 and 2. Our interpretation is that we were observing the edge of a patch of "abnormal" surface waters in profile 1.



Deeper down, the differences between the two years are very small. The main difference is that the deep waters, under the main thermocline, were a trifle colder in 1965 than in 1964. As a consequence, the sound channel was slightly shallower in 1965 than in 1964, and its minimum sound speed was slightly lower.

III. STATIONS 90-92: MARCH.

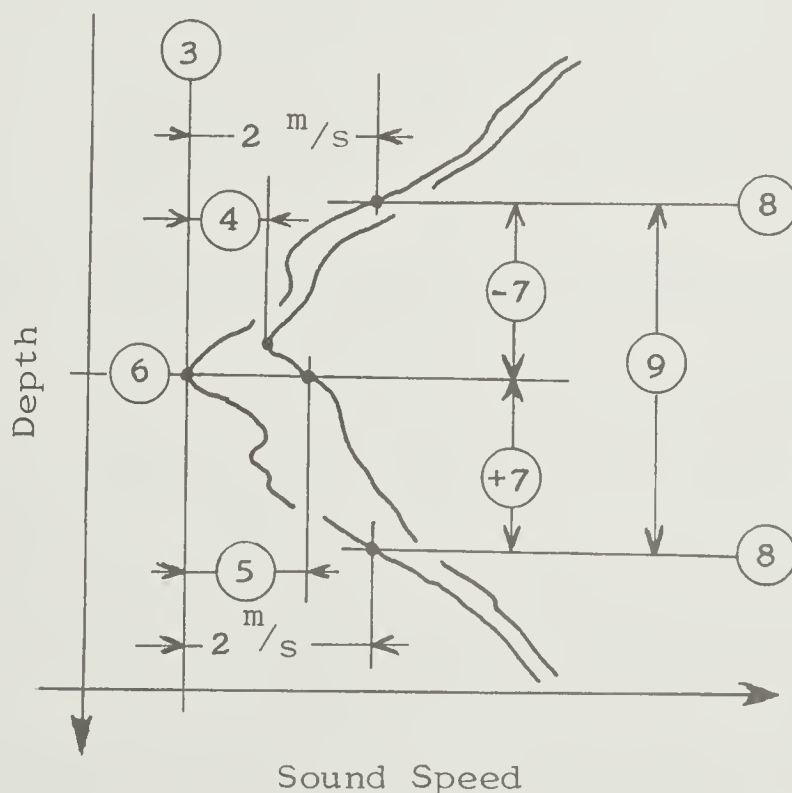
These three stations show typically winter surface waters: the warm mixed layer has disappeared, the top-most 200m are nearly isothermal (18.5-18.8°C), rather variable and probably patchy. In all cases, however, there is a very pronounced acoustic duct at the surface.

The only interesting feature worth mentioning in the deep waters is the rapid rise of temperatures between profiles 2 and 3 of station 90, at depths between 800 and 1300m.

TABLE 1: SOUND CHANNEL PARAMETERS.

Table 1 attempts to give a numerical description of the sound channel region and its variability for all stations. This table is based on readings from the composite sound speed profile envelopes at each station.

The columns in the table are defined as follows (circled numbers in sketch correspond to column headings):





- Column 1: Station number.
- Column 2: Mean sound speed at 1500m depth.
- Column 2A: Mean sound speed at 2000m depth.
- Column 3: The axis or minimum minimum sound speed is the lowest speed in the composite profile envelope.
- Column 4: The sound channel width is defined as the difference of the minima of the high speed (right-hand) and low speed (left-hand) contours of the composite envelope. These minima do not necessarily occur at the same depth, they can be separated by several hundred meters.
- Column 5: Variability at the sound channel axis. Defined as the width of the composite envelope at the depth of the minimum minimum sound speed.
- Column 6: Axis depth: The depth at which the minimum minimum sound speed occurs.

For columns 7, 8, 9, we have arbitrarily defined the sound channel as the region between points on the low speed (left-hand) side of the composite envelopes, having a sound speed 2 m/s higher than the minimum minimum speed.

- Column 7: Vertical spread of the upper and lower boundaries of the sound channel, up and down from the minimum minimum speed (axis) depth.
- Column 8: Depths of the upper and lower boundaries of the sound channel.
- Column 9: Total vertical extent of the sound channel.
- Column 10: Duration of station, hours.

ACKNOWLEDGEMENTS

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TABLE I
SOUND CHANNEL PARAMETERS

1	2	2A	3	4	5	6	7	8	9	10
Station number	Mean sound speed at 150m depth	Mean sound speed at 200m depth	Axis (min. min.) sound speed	Sound channel width (min. max. - min. min.)	Variability at axis depth	Axis (min. min. s.s.) depth	S. channel spread, up and down from axis	Sound channel depth limits	Vertical extent of sound channel	Station duration
#	m/s	m/s	m/s	m/s	m/s	m	m	m	m	h
40	1493.4	1499.3	1491.5	1.0	2.1	1250	-220 +210	1030 1460	430	7
41	1494.6	-----	1492.9	1.8	3.0	1110	-140 +360	960 1470	510	77
42	1494.5	-----	1492.9	0.7	1.1	1200	-225 +340	975 1540	565	28
109	1493.3	1499.6	1492.2	0.1	0.1	1320	-260 +250	1060 1570	510	4
110	1493.2	1499.6	1492.3	0.2	0.5	1240	-175 +360	1065 1600	535	2
111	1493.0	1499.2	1491.0	0.2	0.4	1240	-210 +270	1030 1510	480	3
112	1493.3	1499.6	1492.9	0.5	0.6	1310	-240 +290	1070 1600	530	5
113	1494.0	1500.2	1493.1	0.7	1.2	1310	-330 +310	1080 1590	540	5
114	1493.8	1499.6	1492.2	0.3	0.6	1240	-160 +320	1080 1560	480	7
115	1493.5	1499.8	1492.9	0.2	0.7	1280	-220 +290	1060 1570	510	4
116	1493.4	1499.4	1492.4	0.5	0.6	1240	-150 +350	1090 1590	500	8
117	1493.0	1499.2	1490.6	1.0	1.0	1180	-180 +310	1000 1490	490	5
119	-----	-----	1492.4	0.2	0.2	1280	-180 -----	1100 -----	---	2
43	1493.1	-----	1492.0	0.1	0.1	1260	-235 +340	1025 1600	575	2
45	1493.2	1499.0	1491.8	0.6	0.7	1240	-155 +280	1085 1520	435	3
46	1492.8	-----	1491.3	0.1	0.1	1285	-165 +275	1120 1560	440	1
47	1493.2	-----	1492.2	0.3	0.5	1285	-265 +315	1020 1600	580	1
48	1493.0	-----	1492.8	0.4	0.6	1270	-270 +315	1000 1585	585	2
86	1493.0	1499.5	1491.4	1.1	2.4	1180	-150 +315	1030 1495	465	6
87	1494.8	1499.4	1490.6	0.1	0.1	1190	-220 +310	970 1600	530	3
88	1492.6	1499.2	1491.6	0.7	1.1	1255	-220 +290	1035 1545	510	7
89	1492.8	1499.2	1492.0	1.5	2.0	1190	-130 +290	1060 1480	420	6
90	1492.4	1499.4	1491.3	1.3	1.4	1250	-290 +380	1020 1630	610	6
91	1495.2	1499.6	1493.6	0.3	0.4	1130	-260 +480	970 1710	740	3
92	1495.5	1499.4	1493.8	0.3	0.4	1100	-210 +470	990 1670	680	3

OCTOBER '64

OCTOBER '66

DECEMBER '64

DECEMBER '65

MARCH '66

APPENDIX
Timing of Profiles

<u>Profile</u>	<u>D(m)</u>	<u>GMT</u>	<u>Profile</u>	<u>D(m)</u>	<u>GMT</u>	<u>Profile</u>	<u>D(m)</u>	<u>GMT</u>	<u>Profile</u>	<u>D(m)</u>	<u>GMT</u>
40/1	595	2020	41/1	1	1625	41/5	844	2300	41/10	1165	1040
	759	2030		65	1630		981	2310		885	1050
	1000	2040		241	1640		1168	2320		702	1100
	1289	2050		383	1700		1397	2330		647	1103
	1502	2100		564	1710		1502	2340	41/11	646	1103
	1740	2110		794	1720		1574	2350		720	1110
	1767	2111		1046	1730		1675	2400		960	1120
40/2	1769	2113		1277	1740		1792	0010		1202	1130
	1738	2120		1432	1750		1892	0019		1420	1140
	1668	2130		1613	1800	41/6	1894	0022		1619	1150
	1574	2140		1862	1810		1793	0030		1804	1200
	1471	2150		1893	1813		1644	0040		1890	1206
	1354	2200	41/2	1894	1819		1474	0050	41/12	1894	1220
	1213	2210		1889	1820		1286	0100		1774	1230
	1060	2220		1701	1830		1082	0110		1618	1240
	898	2230		1464	1840		840	0120		1459	1250
	713	2240		1228	1850		638	0127		1304	1300
	508	2250		1038	1900	41/7	636	0129		1150	1310
	372	2256		871	1910		640	0130		996	1320
40/3	373	2259		695	1920		803	0140		831	1330
	381	2300		648	1923		968	0150		651	1340
	593	2310	41/3	645	1925		1111	0200	41/13	642	1357
	850	2320		696	1930		1147	0203		658	1400
	1068	2330		833	1940	41CD1	1168	30hr.		779	1410
	1325	2340		964	1950	(Constant Depth)				896	1420
	1568	2350		1064	2000	41/8	1162	0815		1015	1430
	1867	2400		1167	2010		1100	0820		1109	1440
	2064	0010		1313	2020		927	0830		1214	1450
	2169	0015		1370	2030		731	0840		1319	1500
40/4	2169	0030		1533	2040		636	0844		1460	1510
	2109	0040		1753	2050	41/9	637	0845		1606	1520
	2035	0050		1895	2055		690	0850		1790	1530
	1950	0100	41/4	1895	2113		892	0900		1895	1536
	1822	0110		1830	2120		1085	0910	41/14	1894	1552
	1636	0120		1736	2130		1195	0920		1815	1600
	1432	0130		1586	2140		1335	0930		1643	1610
	1213	0140		1406	2150		1480	0940		1458	1620
	997	0150		1243	2200		1668	0950		1256	1630
	830	0200		1096	2210		1870	1000		1060	1640
	655	0210		945	2220		1893	1002		867	1650
	455	0220		785	2230	41/10	1891	1004		654	1700
	229	0230		641	2238		1763	1010		640	1701
	1	0240	41/5	642	2242		1592	1020			
				712	2250		1394	1030			

APPENDIX (Cont.)
Timing of Profiles

<u>Profile</u>	<u>D(m)</u>	<u>GMT</u>	<u>Profile</u>	<u>D(m)</u>	<u>GMT</u>	<u>Profile</u>	<u>D(m)</u>	<u>GMT</u>	<u>Profile</u>	<u>D(m)</u>	<u>GMT</u>
41/15	636	1706	41/19	731	2320	42/2	1278	1848	42/5	1315	0140
	673	1710		874	2330		1265	1850		1438	0150
	814	1720		1012	2340		1180	1900		1569	0200
	917	1730		1133	2350		1111	1910		1723	0210
	1018	1740		1262	2400		1003	1920		1753	0214
	1106	1750		1427	0010		868	1930	42/6	1752	0217
	1200	1800		1610	0020		767	1940		1733	0220
	1288	1810		1786	0030		628	1950		1644	0230
	1401	1820		1894	0038		401	2000		1534	0240
	1543	1830	41/20	1894	0043		335	2010		1414	0250
	1670	1840		1831	0050		149	2020		1307	0300
	1789	1850		1724	0100		1	2029		1191	0310
	1894	1858		1588	0110	42/3	1	2040		1067	0320
41/16	1898	1903		1435	0120		125	2050		931	0330
	1813	1910		1267	0130		265	2100		785	0339
	1646	1920		1084	0140		374	2110	42CD1	775	12hr.
	1472	1930		972	0150		415	2120	(Constant Depth)		
	1281	1940		839	0200		592	2130	42/6A	777	1600
	1074	1950		694	0210		776	2140		694	1610
	837	2000		533	0220		898	2150		589	1620
	626	2008		329	0230		1076	2200		484	1630
41/17	629	2014		296	0231		1194	2210		378	1640
	738	2020	41/21	296	0241		1316	2220	42/7	372	1644
	965	2030		464	0250		1450	2230		430	1650
	1164	2040		687	0300		1673	2240		550	1700
	1356	2050		868	0310		1905	2250		651	1710
	1533	2100		908	0314	42/4	1901	2250		744	1720
	1701	2110	41CD2	924	17hr.		1788	2300		850	1730
	1863	2120	(Constant Depth)				1586	2310		979	1740
	1895	2122	41/22	922	2057		1347	2320		1086	1750
41/18	1895	2124		538	2100		1253	2330		1183	1800
	1841	2130		1	2110		1125	2340		1269	1810
	1656	2140					1024	2350		1339	1820
	1448	2150	42/1	1	1715		868	2400		1444	1830
	1220	2200		67	1720		765	0010		1528	1840
	1042	2210		230	1730		587	0020		1642	1850
	906	2220		375	1740		362	0030		1758	1858
	757	2230		381	1750	42/5	363	0034	42/8	1759	1902
	591	2240		629	1800		419	0040		1702	1910
	396	2250		803	1810		536	0050		1615	1920
	295	2258		1045	1820		669	0100		1518	1930
41/19	297	2258		1194	1830		839	0110		1419	1940
	334	2300		1285	1835		1005	0120		1309	1950
	579	2310					1204	0130		1190	2000



APPENDIX (Cont.)
Timing of Profiles

Profile	D(m)	GMT	Profile	D(m)	GMT	Profile	D(m)	GMT	Profile	D(m)	GMT
42/8	1040	2010	46/1	4	0427	86/1	1	0010	87/1	1171	1310
	860	2020		98	0430		197	0020		1455	1320
	631	2030		488	0440		474	0030		1768	1330
	343	2040		1006	0450		745	0040		2069	1340
	309	2050		1399	0500		1004	0050	87/2	2037	1345
	165	2100		1901	0508		1231	0100		1920	1350
	1	2108	46/2	1899	0510		1437	0110		1663	1400
				1423	0520		1657	0120		1360	1410
43/1	10	1340		830	0530		1803	0130		1021	1420
	470	1350		287	0540		2038	0140		641	1430
	967	1400		1	0546		2185	0149		257	1440
	1529	1410				86/2	2190	0150		17	1450
	1764	1419	47/1	1	0919		1952	0200			
43/2	1754	1422		17	0920		1670	0210	88/1	1	2136
	1358	1430		369	0930		1297	0220		66	2140
	1082	1440		766	0940		954	0230		412	2150
	629	1450		1327	0950		724	0240		453	2151
	159	1500		1889	0958		456	0250	88/2	2	2310
	1	1505	47/2	1895	1001		178	0300		192	2320
				1543	1010		1	0309		549	2330
45/1	1	1628		948	1020	86/3	1	0319		883	2340
	31	1630		321	1030		36	0320		1302	2350
	479	1640		1	1036		167	0330		1660	2400
	1008	1650					304	0340		1877	0010
	1388	1700	48/1	3	1629		387	0350		2110	0020
	1919	1710		13	1630		754	0400		2134	0021
	2025	1711		285	1640		952	0410	88/3	2137	0023
45/2	2001	1720		598	1650		1204	0420		1888	0030
	1543	1730		851	1700		1493	0430		1570	0040
	1103	1740		1212	1710		1816	0440		1283	0050
	677	1750		1485	1720		2081	0449		1081	0100
	234	1800		1767	1730	86/4	2069	0454		862	0110
	1	1808		1935	1737		1920	0500		614	0120
45/3	1	1809	48/2	1936	1739		1605	0510		369	0130
	37	1810		1931	1740		1271	0520		183	0140
	500	1820		1740	1750		1020	0530		1	0150
	759	1830		1392	1800		752	0540	88/4	1	0150
	1121	1840		1041	1810		487	0550		134	0200
	1415	1850		770	1820		132	0600		389	0210
	1688	1900		519	1830		9	0610		729	0220
	1965	1903		226	1840					1021	0230
45/4	1905	1917		12	1850	87/1	1	1225		1185	0240
	1781	1920		1	1851		64	1230		1370	0250
	1513	1930					272	1240		1596	0300
	1324	1938					538	1250		1855	0310
							836	1300		2131	0319

APPENDIX (Cont.)
Timing of Profiles

Profile	D(m)	GMT	Profile	D(m)	GMT	Profile	D(m)	GMT	Profile	D(m)	GMT
88/5	2132	0321	89/1	1651	1340	90/4	277	2240	109/1	1089	1250
	1843	0330		1375	1350		100	2250		1346	1300
	1595	0340		1087	1400		1	2255		1933	1310
	1280	0350		871	1410					1983	1312
	1041	0400		612	1420	91/1	1	0320	109/2	2054	1327
	817	0410		399	1430		216	0330		2021	1330
	584	0420		264	1440		565	0340		2021	1340
	416	0430		110	1450		890	0350		1984	1350
	146	0440		1	1500		1259	0400		1592	1400
	23	0450					1556	0410		1159	1410
	1	0451					2022	0420		720	1420
			90/1	1	1730		2007	0450		291	1430
				200	1740	91/2	1775	0500		1	1438
89/1	1	0915		602	1750		1685	0510			
	208	0920		957	1800		1150	0520	110/1	2	1201
	550	0930		1320	1810		1008	0530		419	1210
	984	0940		1683	1820		576	0540		971	1220
	1333	0950		2023	1830		34	0550		1703	1230
	1657	1000		2052	1831		1	0552		2048	1235
	2129	1010	90/2	2044	1837				110/2	2052	1238
89/2	2117	1015		1970	1840					2004	1240
	2011	1020		1688	1850	92/1	1	1100		1737	1250
	1834	1030		1348	1900		197	1110		1336	1300
	1586	1040		1073	1910		406	1120		863	1310
	1258	1050		804	1920		668	1130		306	1320
	938	1100		765	1930		910	1140		1	1326
	665	1110		558	1940		1157	1150			
	382	1120		342	1950		1380	1200			
	198	1130		8	2000		1605	1210	111/1	5	2329
	1	1136	90/3	6	2010		2072	1220		27	2330
89/3	4	1140		274	2020	92/2	2061	1226		376	2340
	428	1150		621	2030		1976	1230		708	2350
	762	1200		886	2040		1676	1240		1029	2400
	1006	1210		1098	2050		1347	1250		1452	0010
	1231	1220		1404	2100		1025	1300		1944	0020
	1434	1230		1800	2110		714	1310		2071	0022
	1597	1240		2080	2120		516	1320	111/2	2068	0026
	1735	1250	90/4	2089	2136		173	1330		1971	0030
	1871	1300		1993	2140		1	1338		1644	0040
	1992	1310		1752	2150					1317	0050
	2096	1320		1543	2200					971	0100
	2164	1326		1298	2210	109/1	1	1223		619	0110
89/4	2149	1326		1000	2220		175	1230		238	0120
	2014	1330		633	2230		595	1240		1	0128

APPENDIX (Cont.)
Timing of Profiles

Profile	D(m)	GMT	Profile	D(m)	GMT	Profile	D(m)	GMT	Profile	D(m)	GMT
111/3	3	0130	112/4	797	1310	114/1	778	0120	114/6	1	0721
	424	0140		483	1320		1114	0130			
	778	0150		195	1330		1471	0140			
	1102	0200		1	1337		1816	0150	115/1	6	1218
	1436	0210					2041	0200		73	1220
	1773	0220					2070	0201		407	1230
	2068	0228	113/1	4	1522	114/2	2071	0205		748	1240
111/4	2064	0232		317	1530		1967	0210		1074	1250
	1781	0240		724	1540		1686	0220		1392	1300
	1376	0250		1048	1550		1388	0230		1771	1310
	988	0300		1397	1600		1095	0240		2071	1315
	645	0310		1781	1610		817	0250	115/2	2059	1323
	326	0320		2068	1617		509	0300		1850	1330
	34	0330	113/2	2057	1621		243	0310		1492	1340
	1	0332		1761	1630		1	0320		1148	1350
				1339	1640	114/3	4	0323		764	1400
				1127	1650		171	0330		373	1410
112/1	2	0851		934	1700		434	0340		1	1420
	246	0900		718	1710		678	0350	115/3	3	1424
	588	0910		461	1720		958	0400		171	1430
	896	0920		258	1730		1279	0410		499	1440
	1190	0930		15	1740		1625	0420		842	1450
	1437	0940		1	1741		2008	0430		1182	1500
	1659	0950	113/3	1	1746		2074	0431		1508	1510
	1900	1000		87	1750	114/4	2078	0434		1883	1520
	2068	1007		408	1800		1908	0440		2071	1524
112/2	2034	1011		639	1810		1634	0450	115/4	2069	1528
	1735	1020		783	1820		1316	0500		2000	1530
	1474	1030		963	1830		948	0510		1615	1540
	1243	1040		1163	1840		565	0520		1509	1550
	1017	1050		1545	1850		292	0530		1102	1600
	724	1100		1939	1900		1	0534		760	1610
	415	1110		2069	1903	114/5	2	0541		430	1620
	79	1120	113/4	2066	1905		247	0550		86	1630
	1	1122		1946	1910		506	0600		1	1633
112/3	4	1130		1538	1920		747	0610			
	395	1140		1114	1930		1054	0620	116/1	3	2044
	819	1150		876	1940		1488	0630		183	2050
	1228	1200		615	1950		1554	0631		589	2100
	1594	1210		322	2000	114/6	1563	0634		250	2110
	1901	1220		1	2009		1416	0640		1	2115
	2068	1226					1008	0650	116/2	1	0028
112/4	2050	1231					567	0700		43	0030
	1769	1240	114/1	4	0054		270	0710		392	0040
	1450	1250		200	0100		18	0720			
	1123	1300		498	0110						

APPENDIX (Cont.)
Timing of Profiles

<u>Profile</u>	<u>D(m)</u>	<u>GMT</u>	<u>Profile</u>	<u>D(m)</u>	<u>GMT</u>
116/2	746	0050	117/2	2014	1056
	1104	0100		1935	1100
	1426	0110		1710	1110
	1723	0120		1438	1120
	1996	0130		1144	1130
	2069	0133		839	1140
116/3	2053	0136		474	1150
	1924	0140		73	1200
	1554	0150		1	1202
	1202	0200	117/3	2	1209
	866	0210		19	1210
	480	0220		369	1220
	76	0230		764	1230
	1	0232		1124	1240
116/4	4	0237		1456	1250
	80	0240		1752	1300
	449	0250		2044	1310
	849	0300		2071	1311
	1237	0310	117/4	2074	1313
	1583	0320		1844	1320
	1894	0330		1515	1330
	2070	0336		1129	1340
116/5	2060	0338		738	1350
	2008	0340		378	1400
	1679	0350		18	1410
	1366	0400		1	1411
	1062	0410			
	689	0420	119/1	5	1352
	378	0430		427	1400
	60	0440		947	1410
	1	0447		1470	1420
			119/2	1471	1430
117/1	3	0926		1156	1440
	143	0930		742	1450
	488	0940		416	1500
	758	0950		21	1510
	910	1000		1	1512
	1156	1010			
	1419	1020			
	1650	1030			
	1874	1040			
	2038	1046			

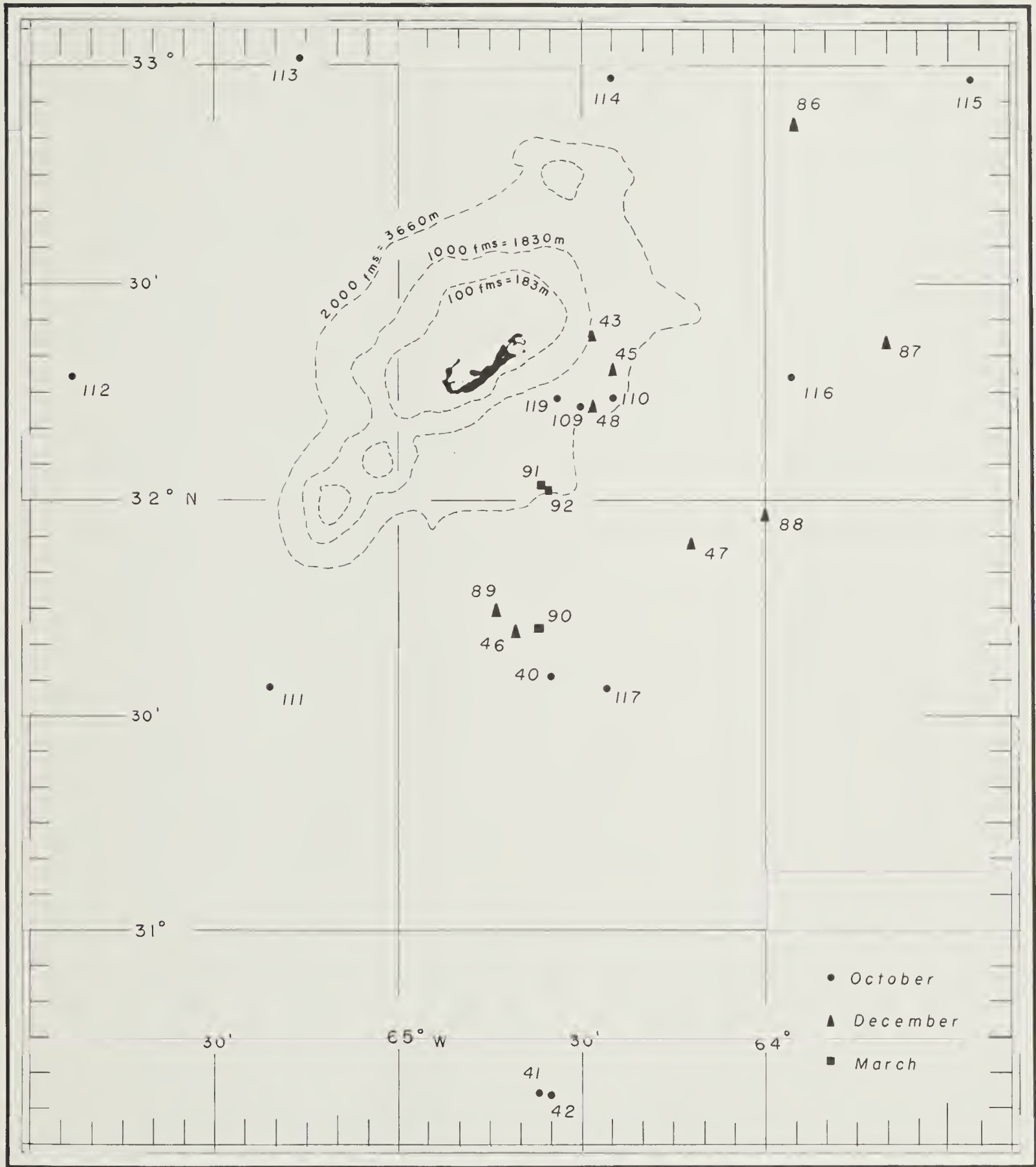


Fig. 1 Chart of Stations



Fig. 2 Sound Speeds -- Station 40

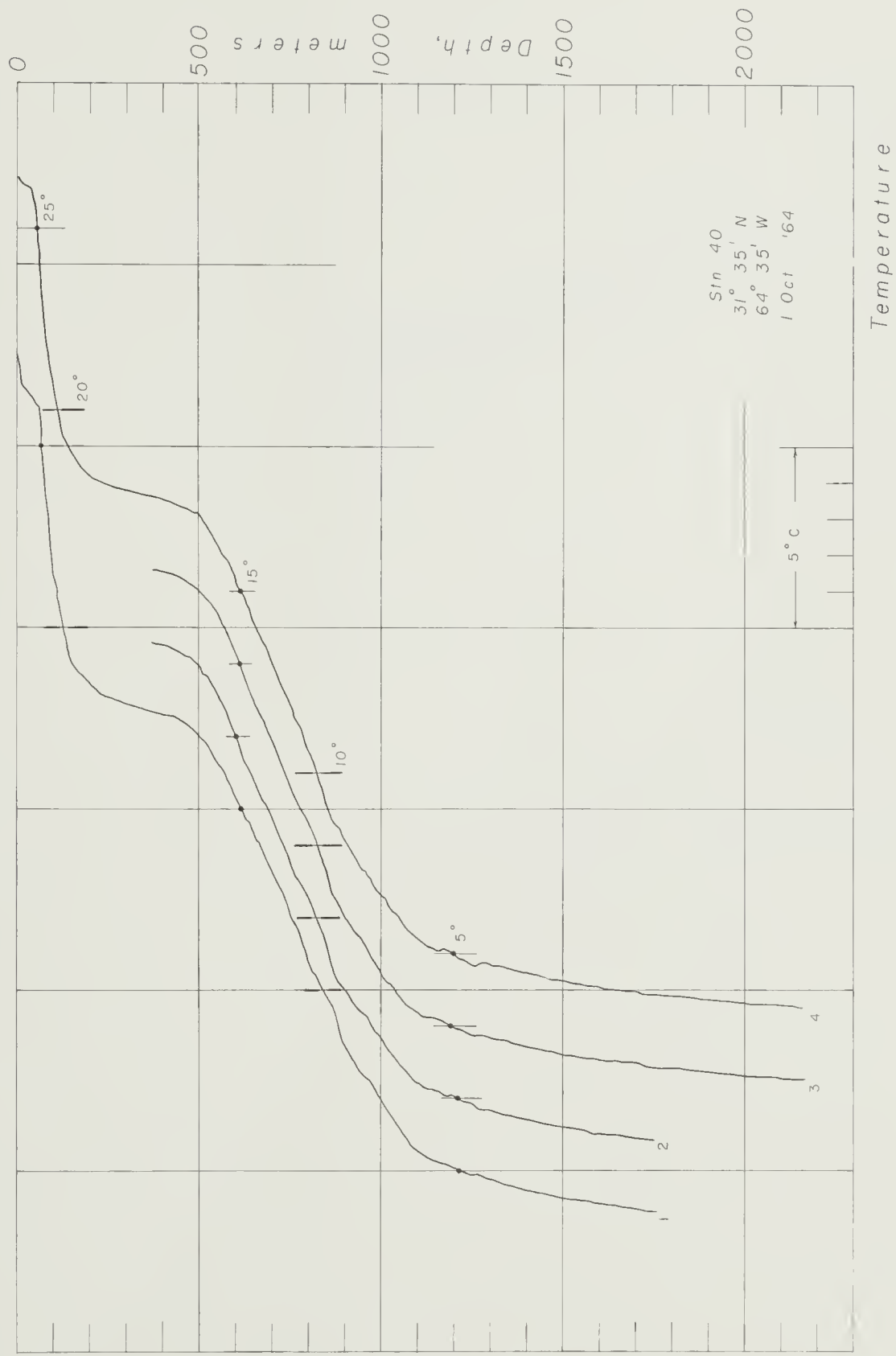


Fig. 3 Temperatures — Station 40

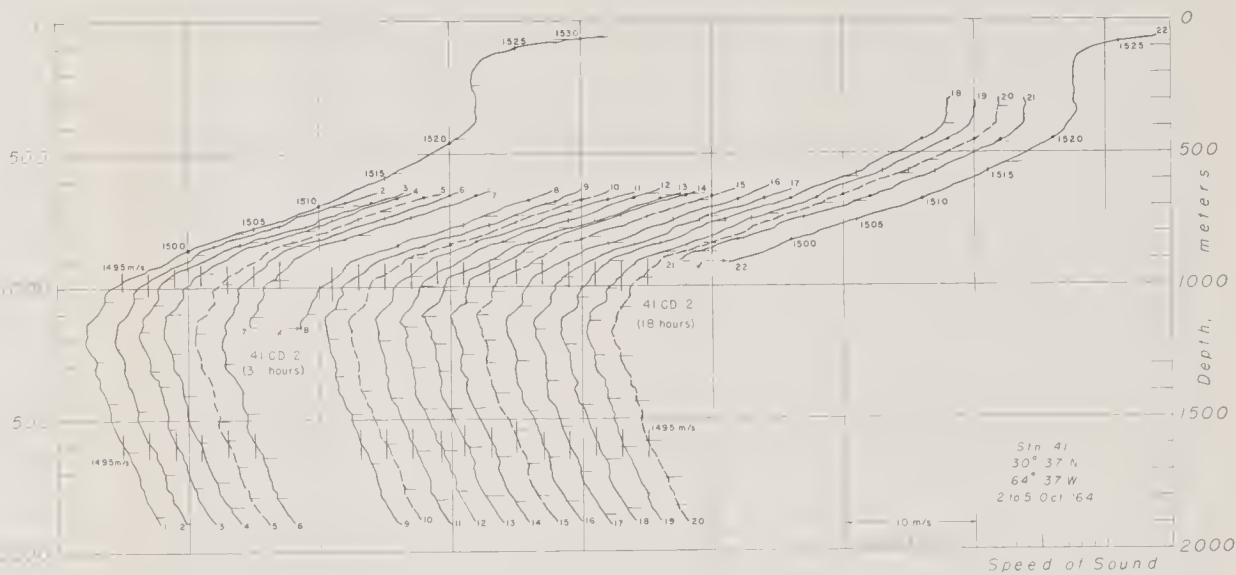


Fig. 4 Sound Speeds — Station 41



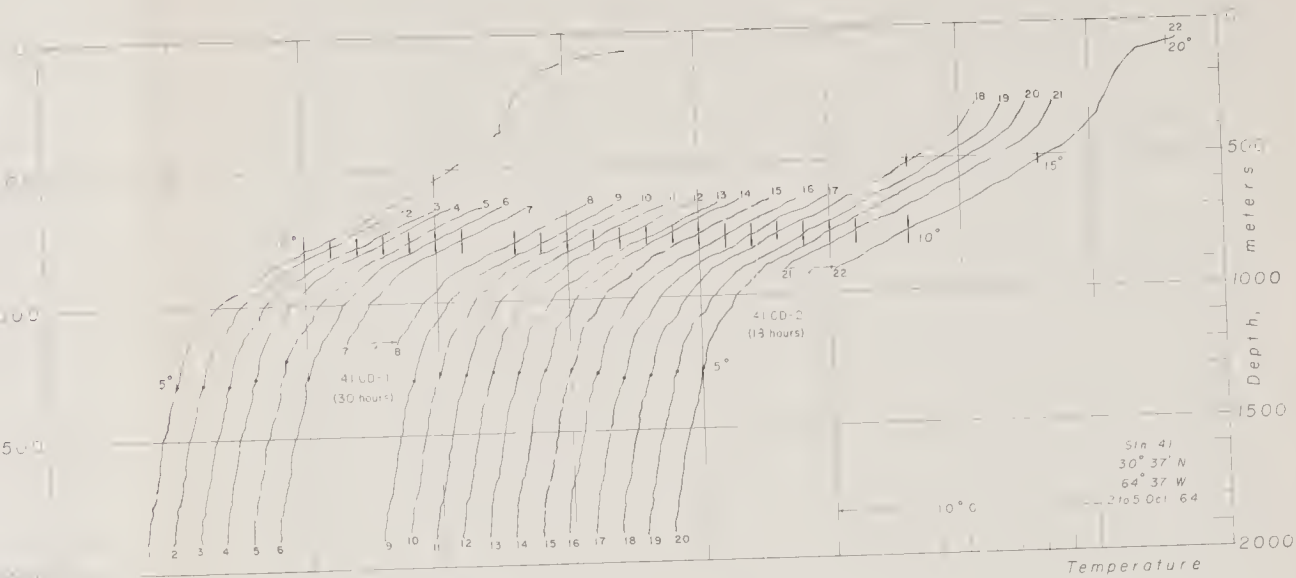


Fig. 5 Temperatures — Station 41

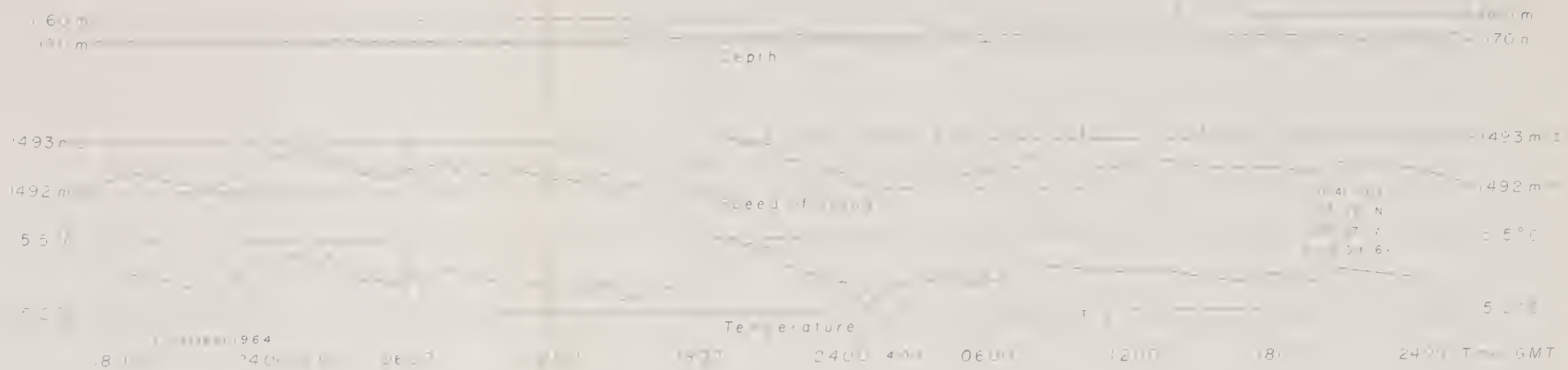


Fig. 6 *Constant Depth Time Series, 41 CD 1.*
Sound Speed and Temperature at 1170 m, below the Main Thermocline

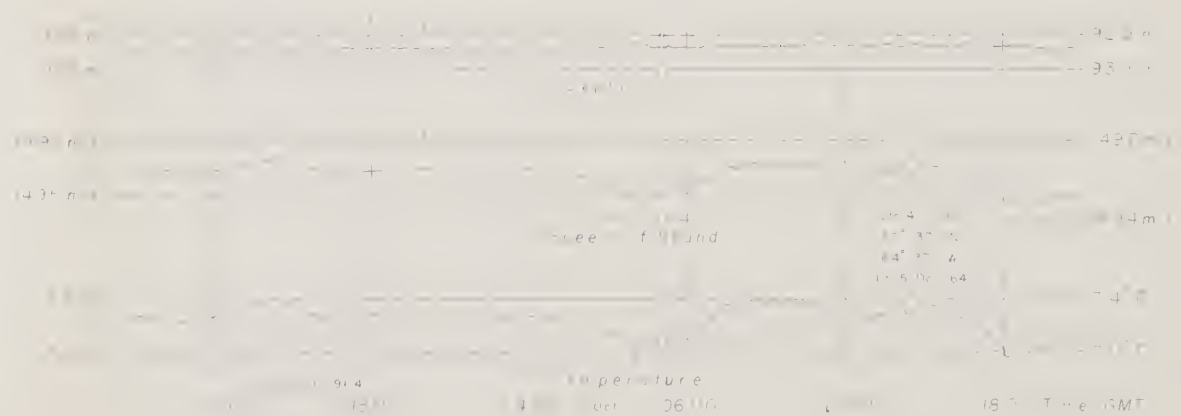


Fig. 7 *Constant Depth Time Series, 41 CD 2.*
Sound Speed and Temperature at 920 m, in the Main Thermocline



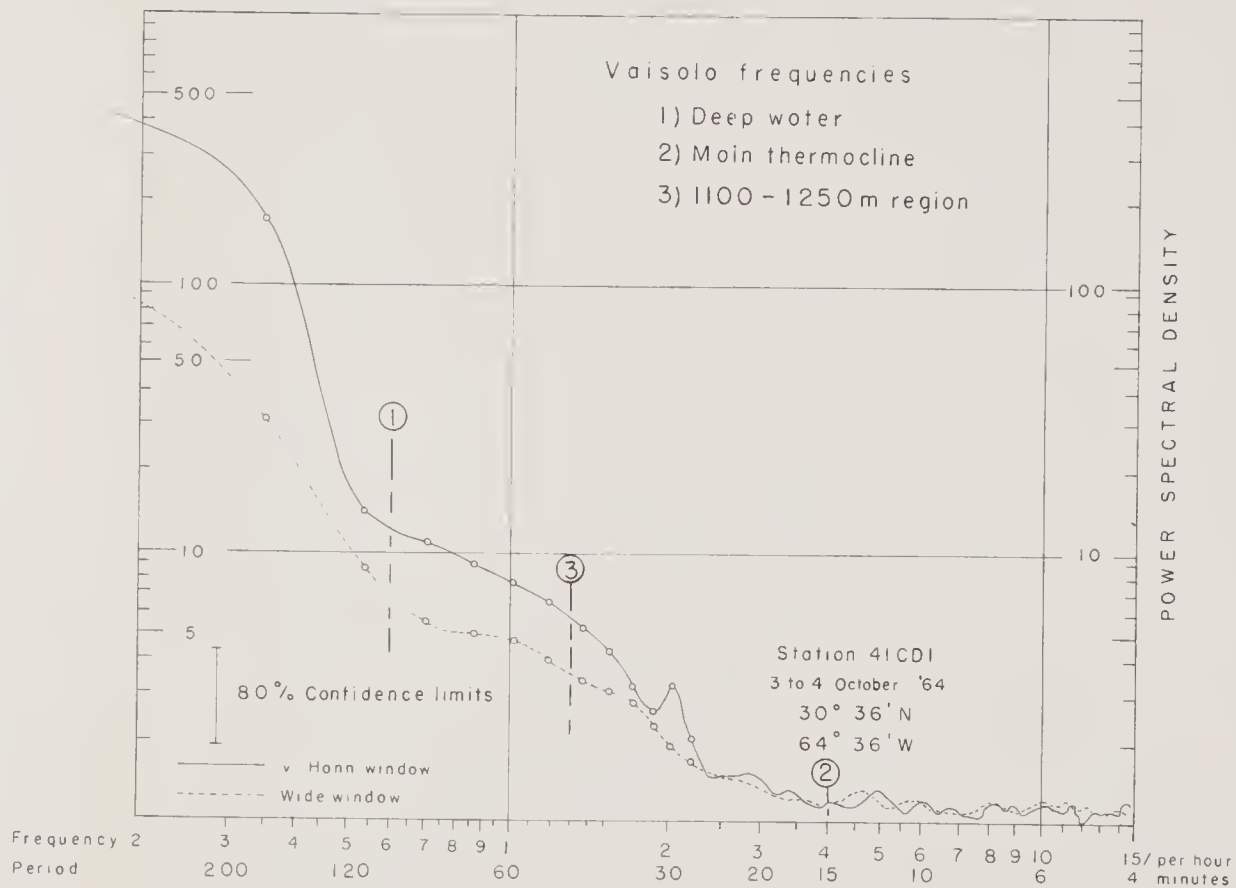


Fig. 8 POWER DENSITY SPECTRUM of 30 hour constant depth recording at 1170 meters
(Below main Thermocline)



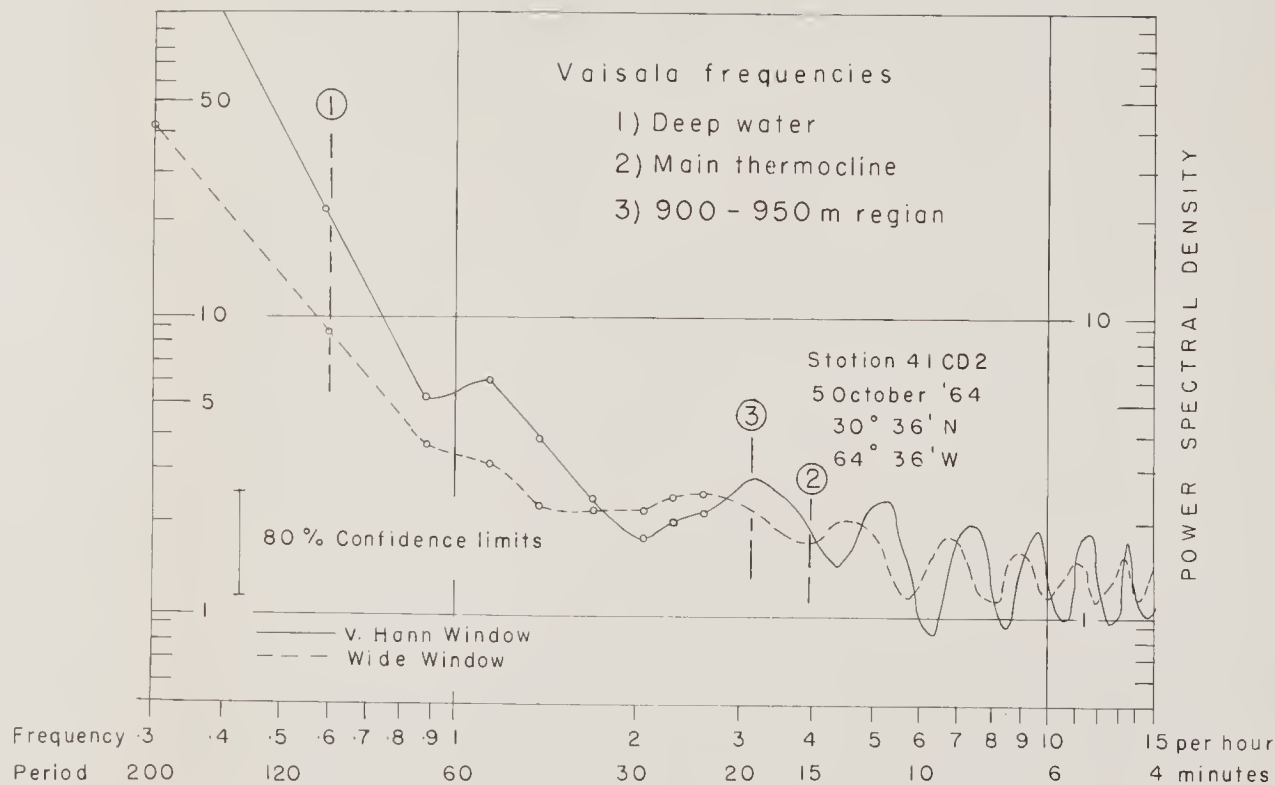


Fig. 9 POWER DENSITY SPECTRUM of 18 hour constant depth recording at 920 meters
(In main Thermocline)



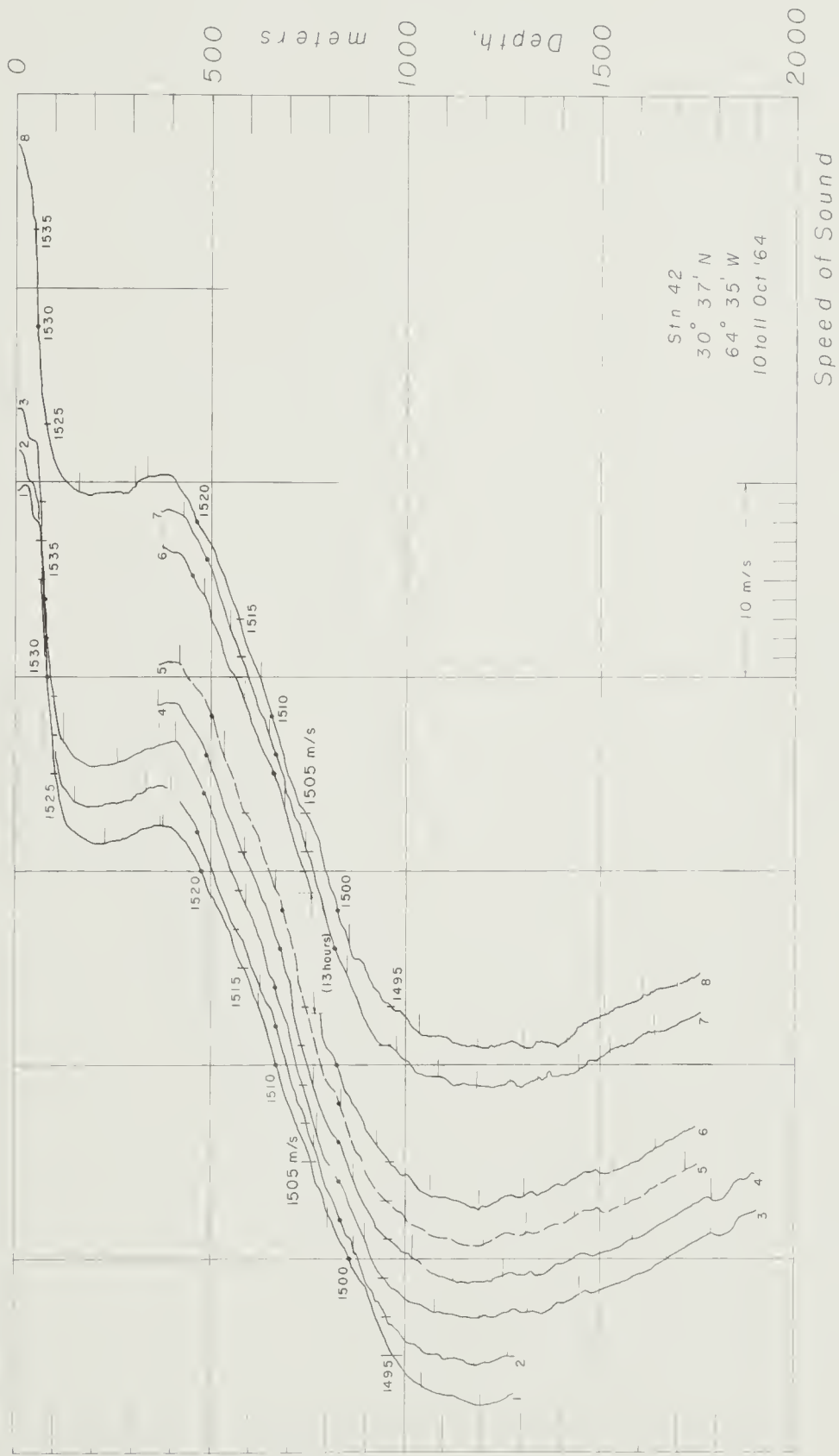


Fig. 10 Sound Speeds - Station 42

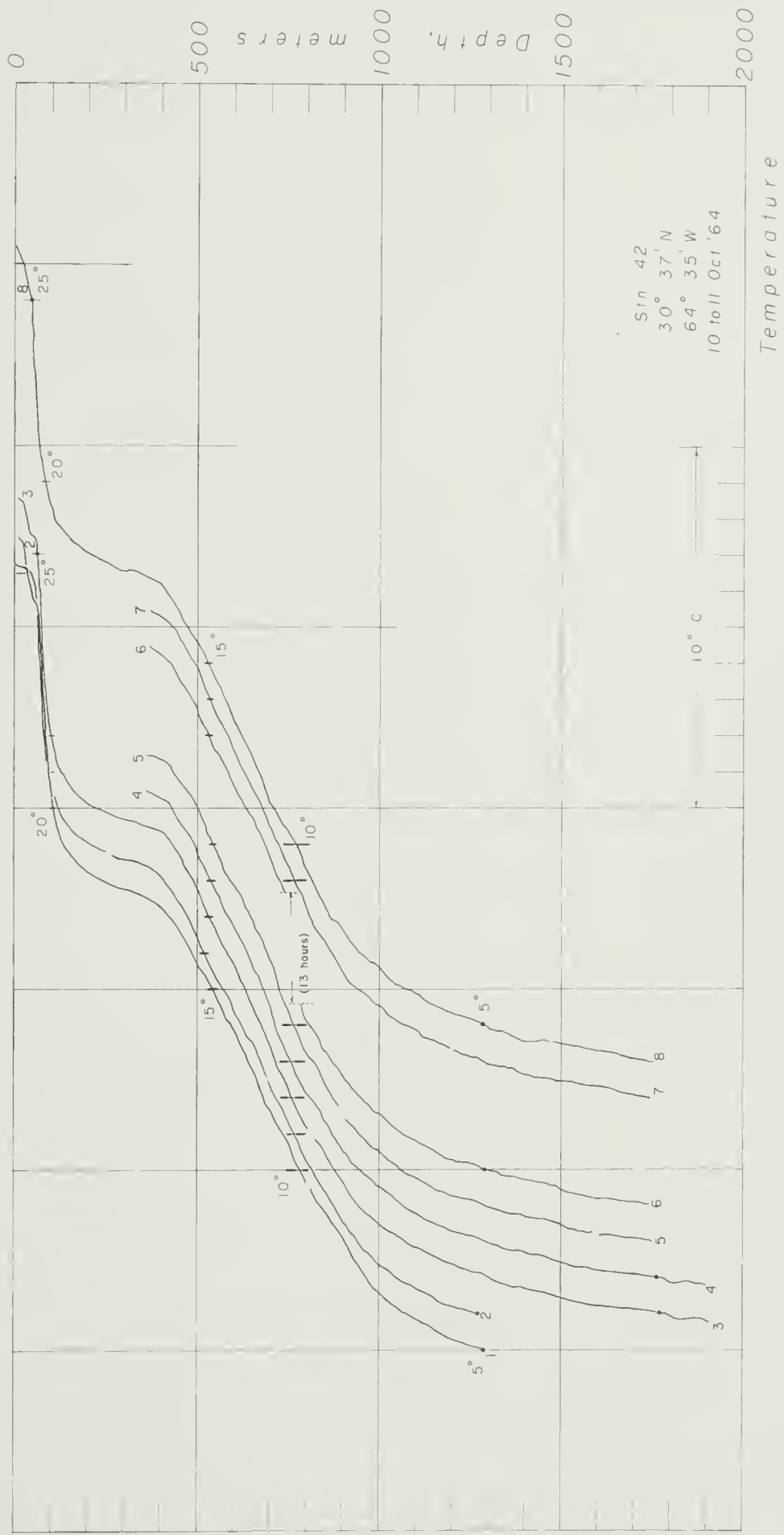


Fig. II Temperatures - Station 42

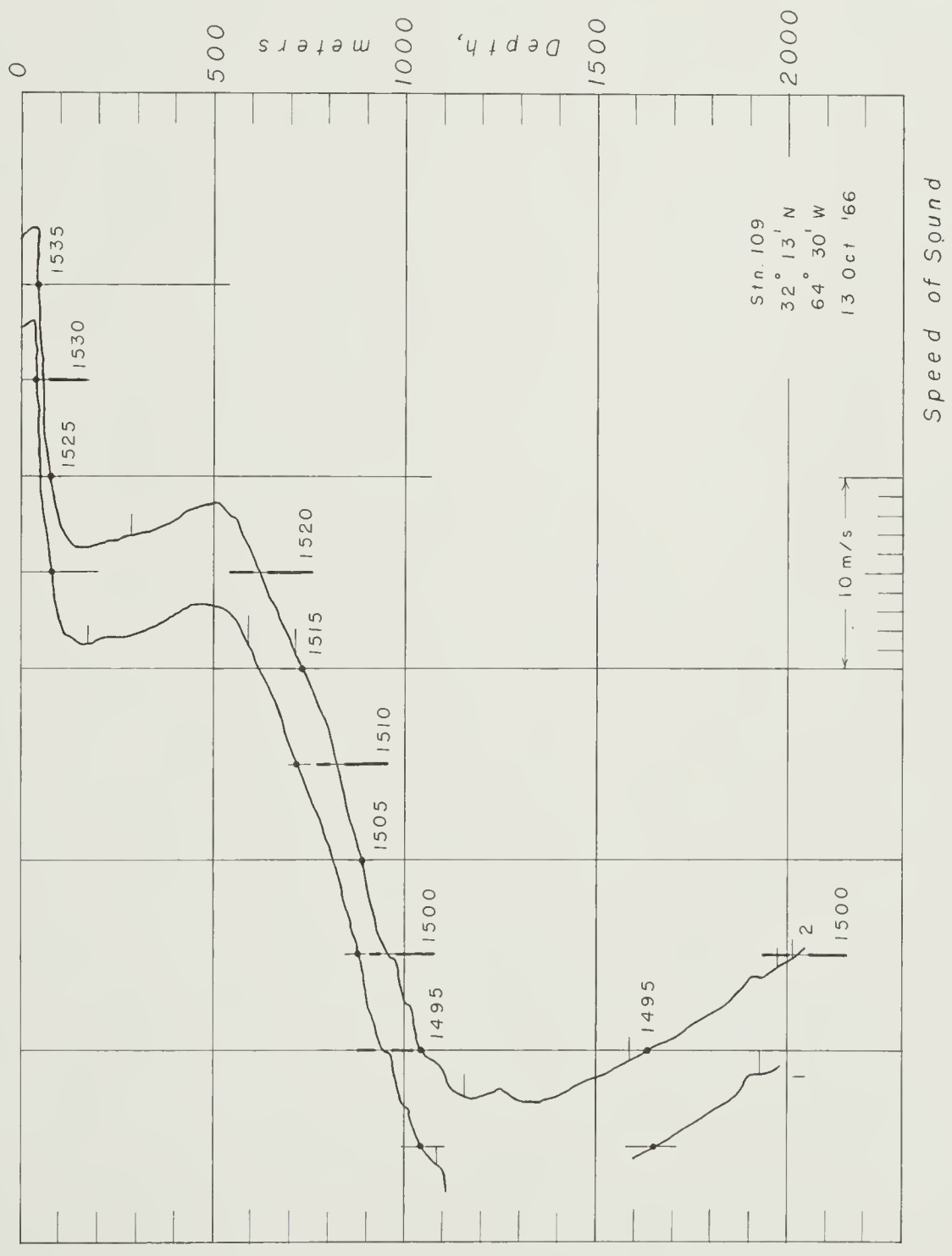


Fig. 12 Sound Speeds – Station 109

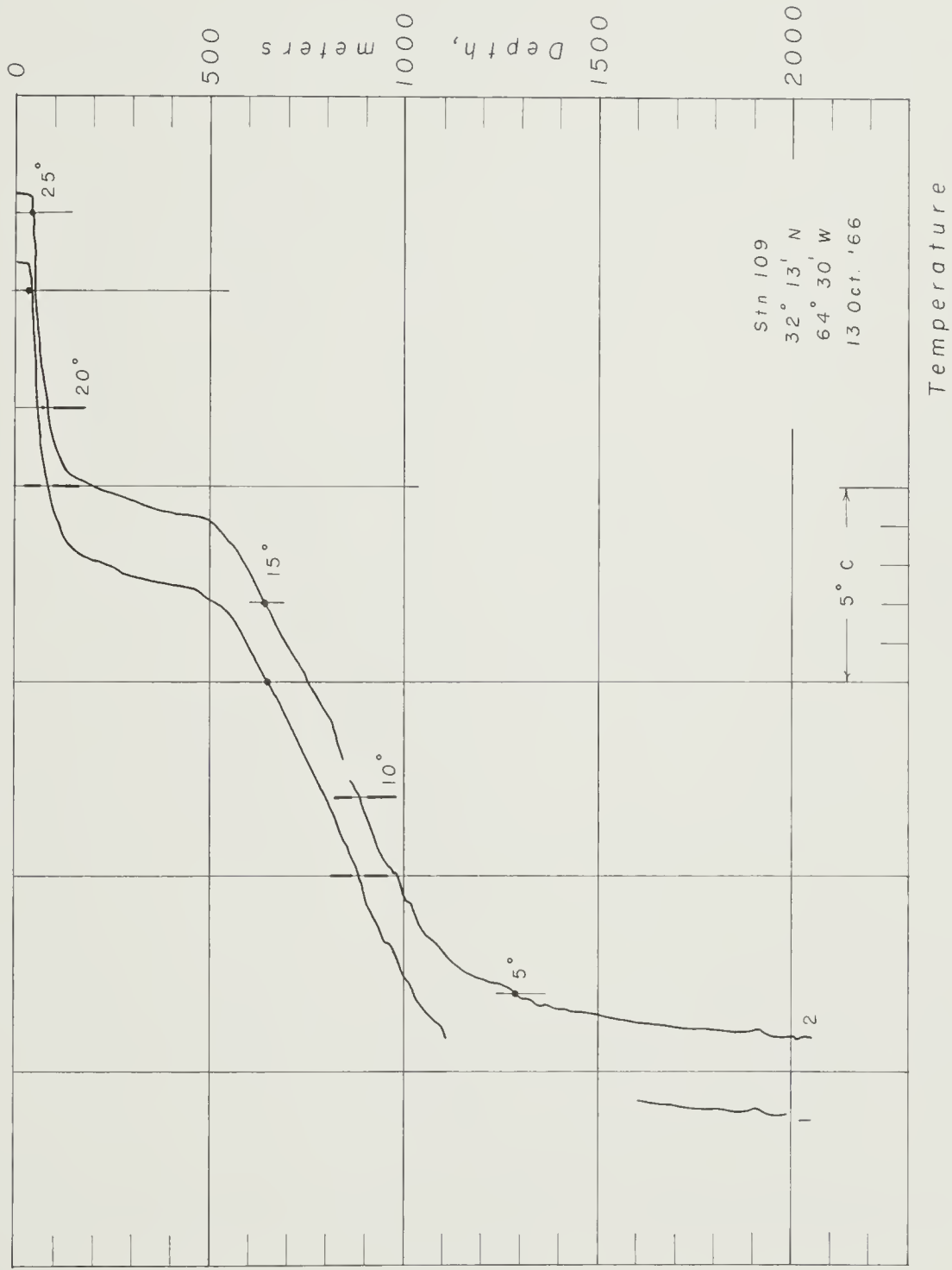


Fig. 13 Temperatures - Station 109

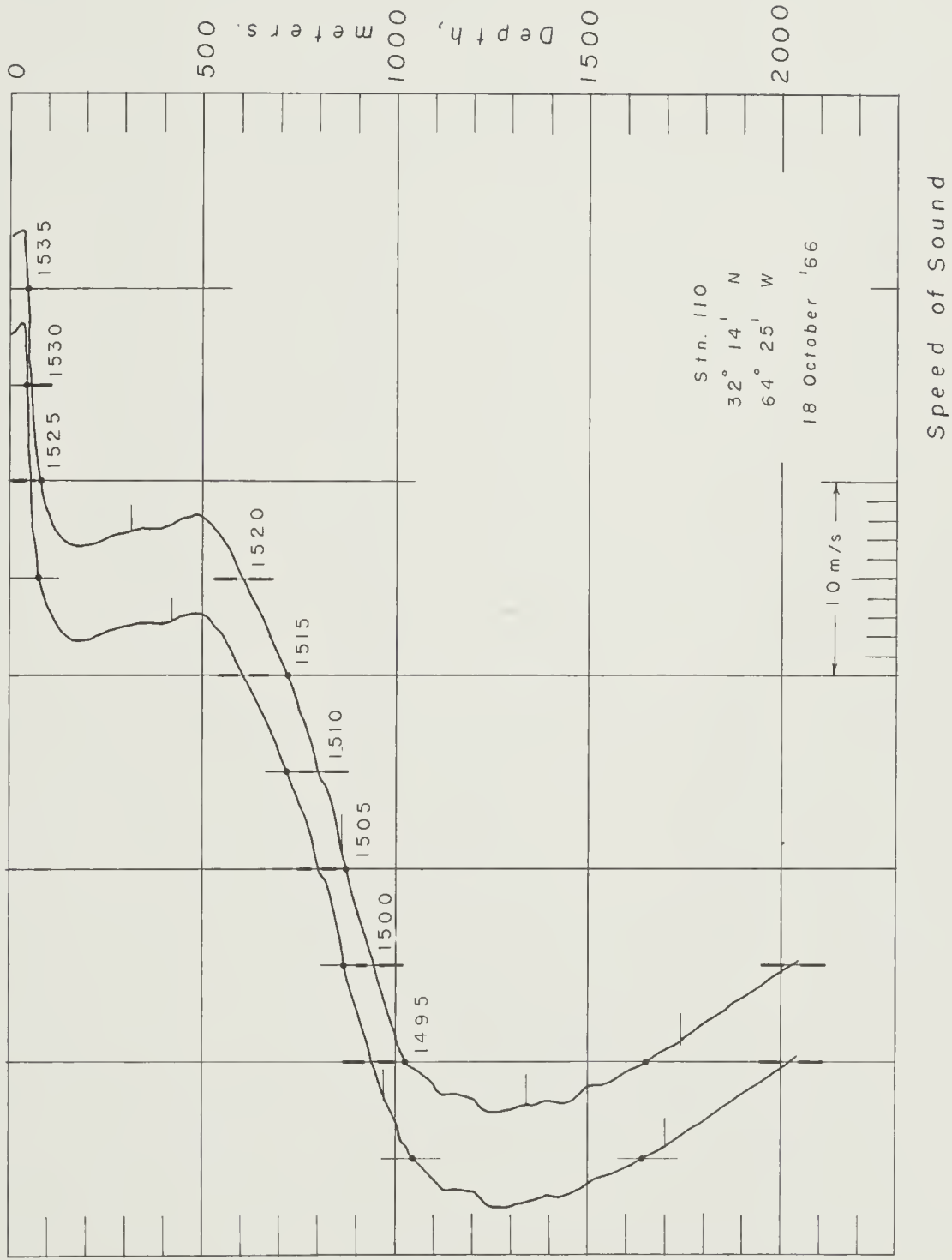


Fig. 14 Sound Speeds - Station 110

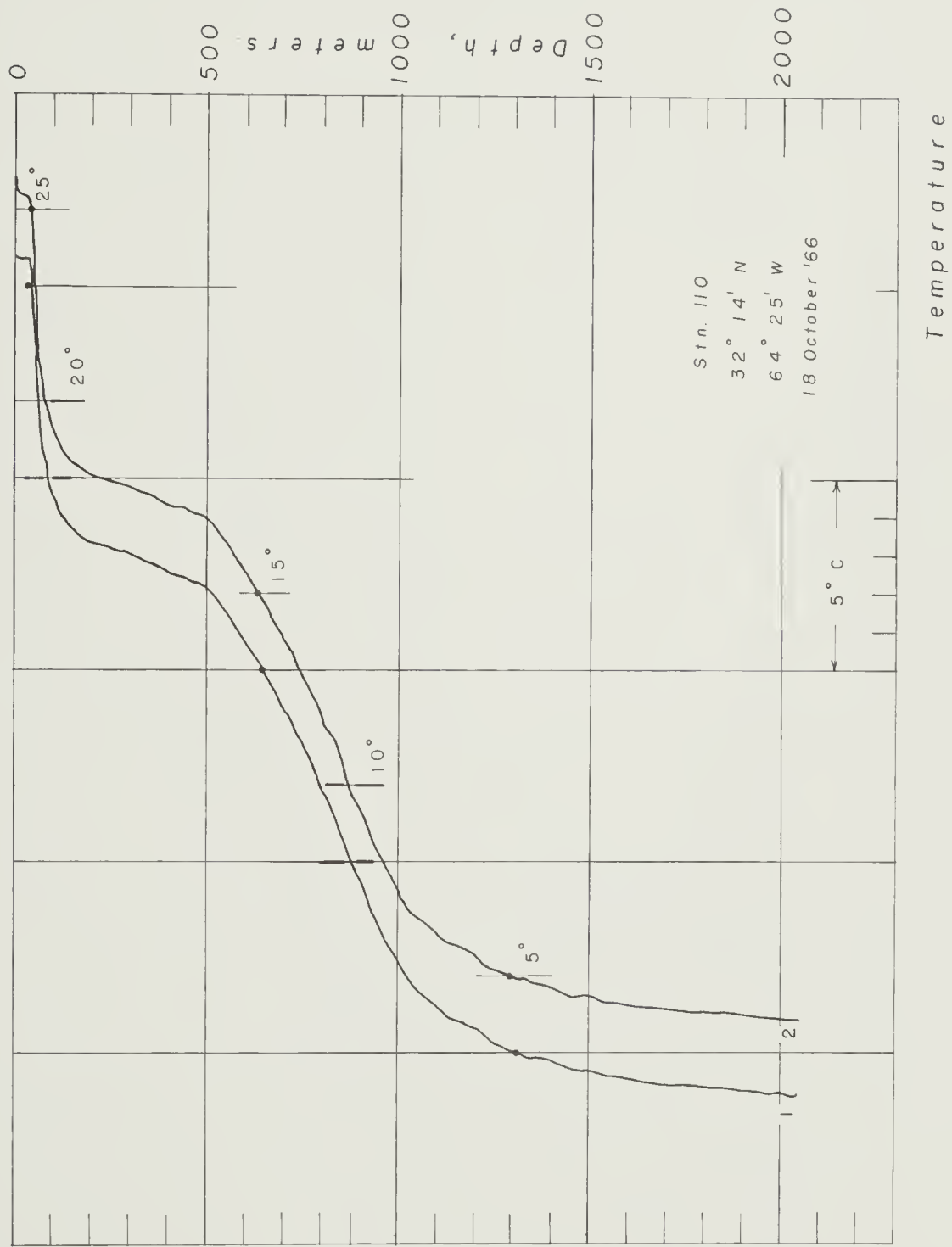


Fig. 15 Temperatures - Station 110

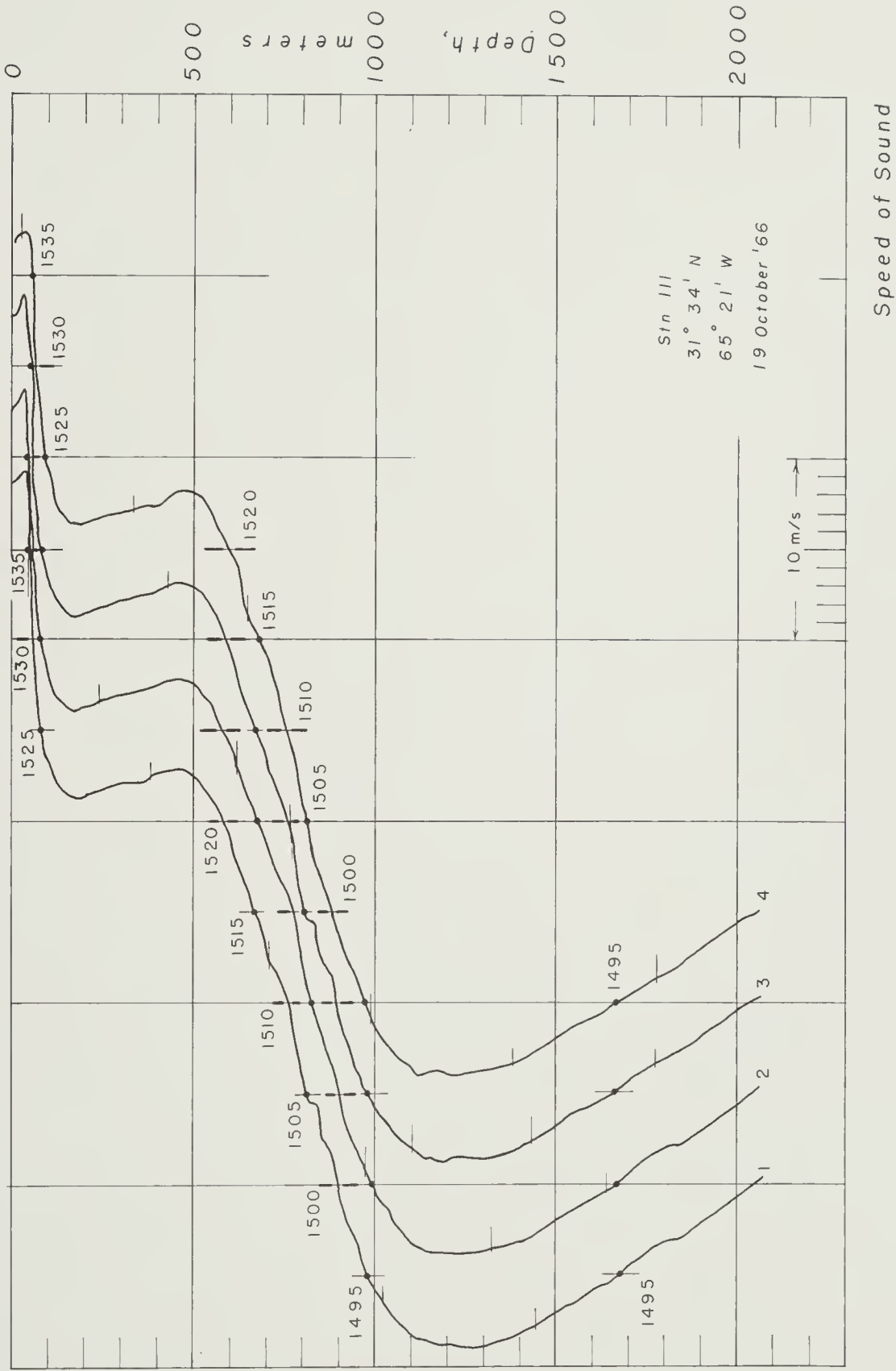


Fig. 16 Sound Speeds - Station III

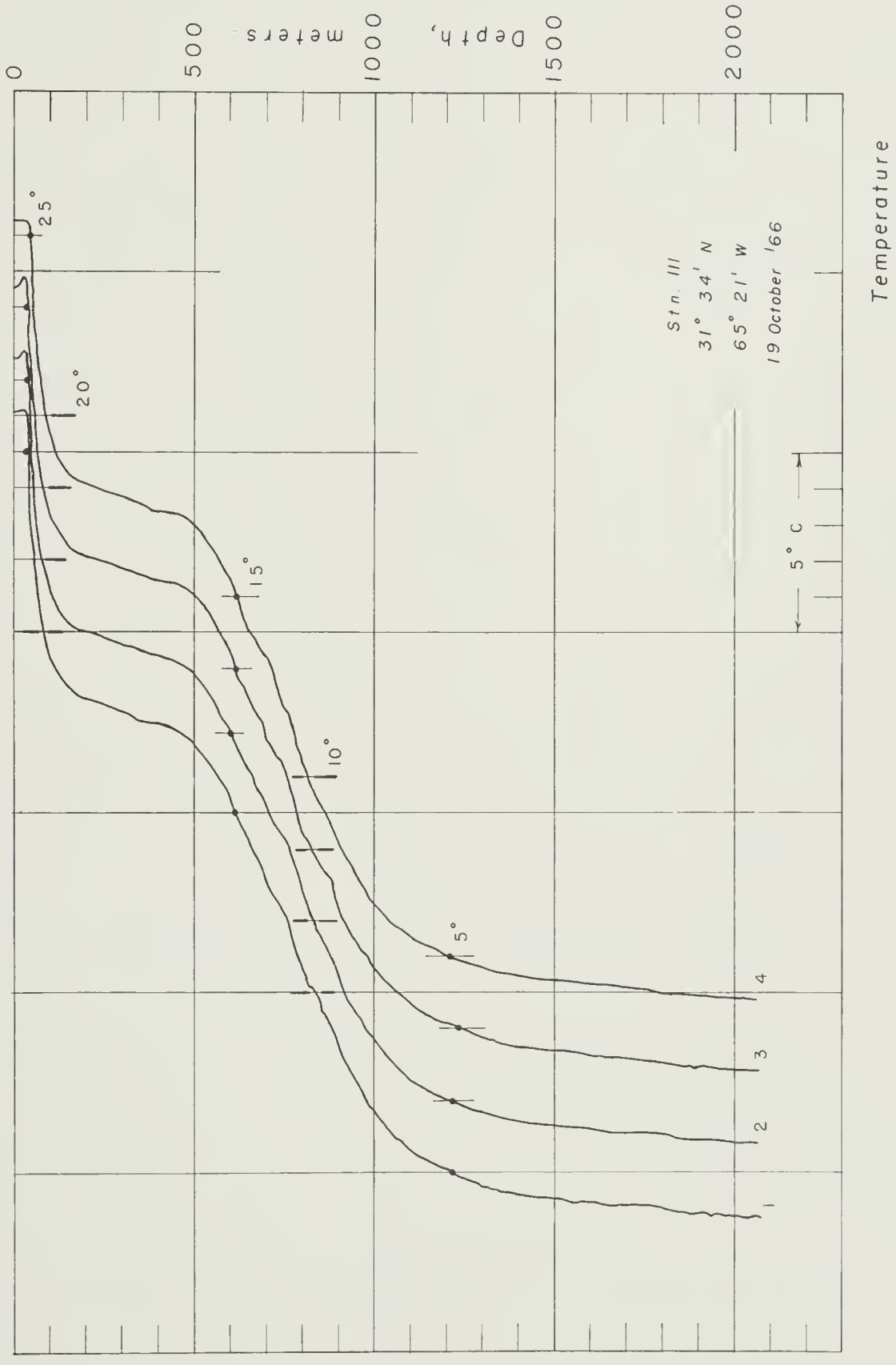


Fig. 17 Temperatures - Station III

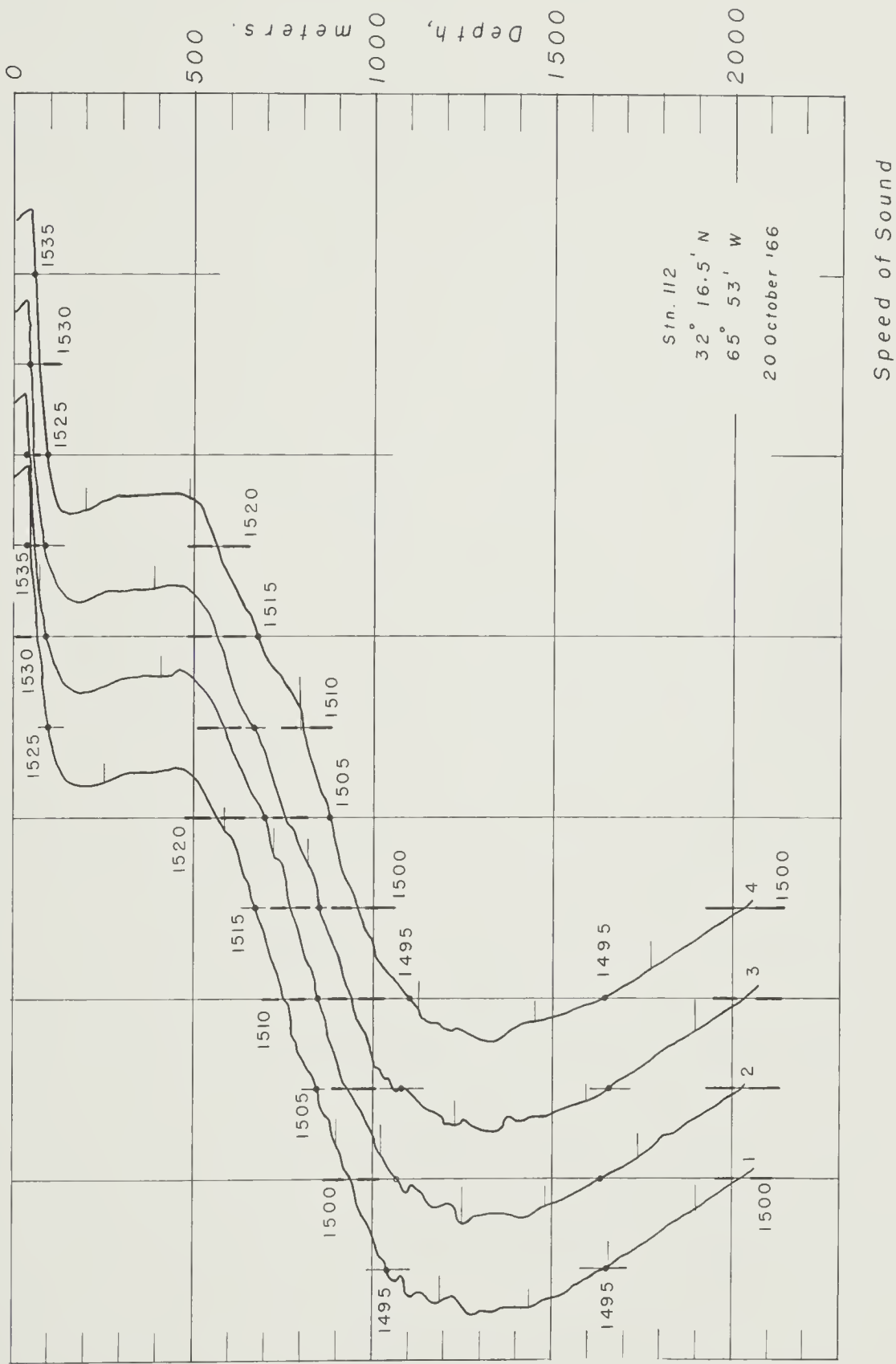


Fig. 18 Sound Speeds - Station 112

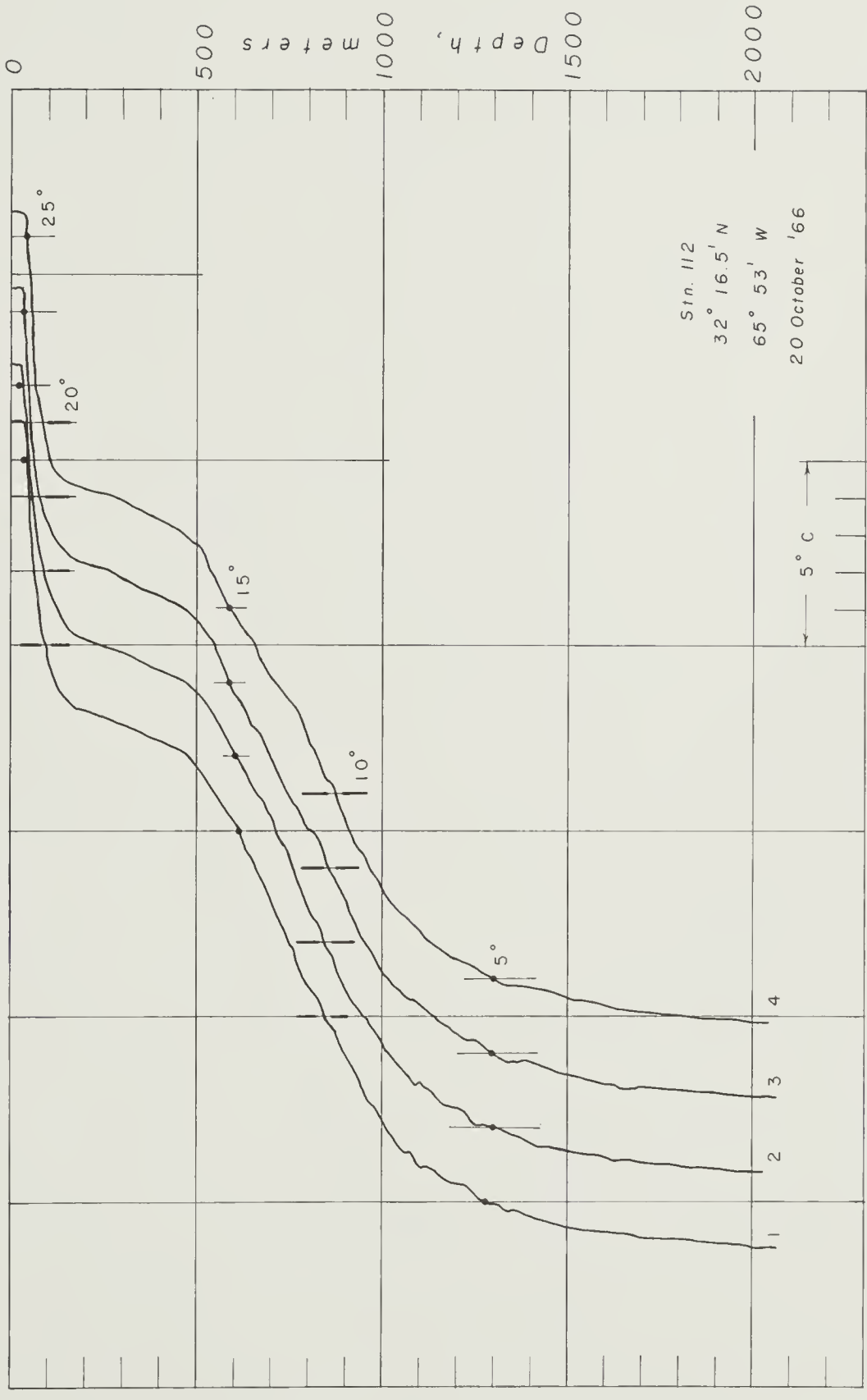


Fig. 19 Temperatures - Station 112

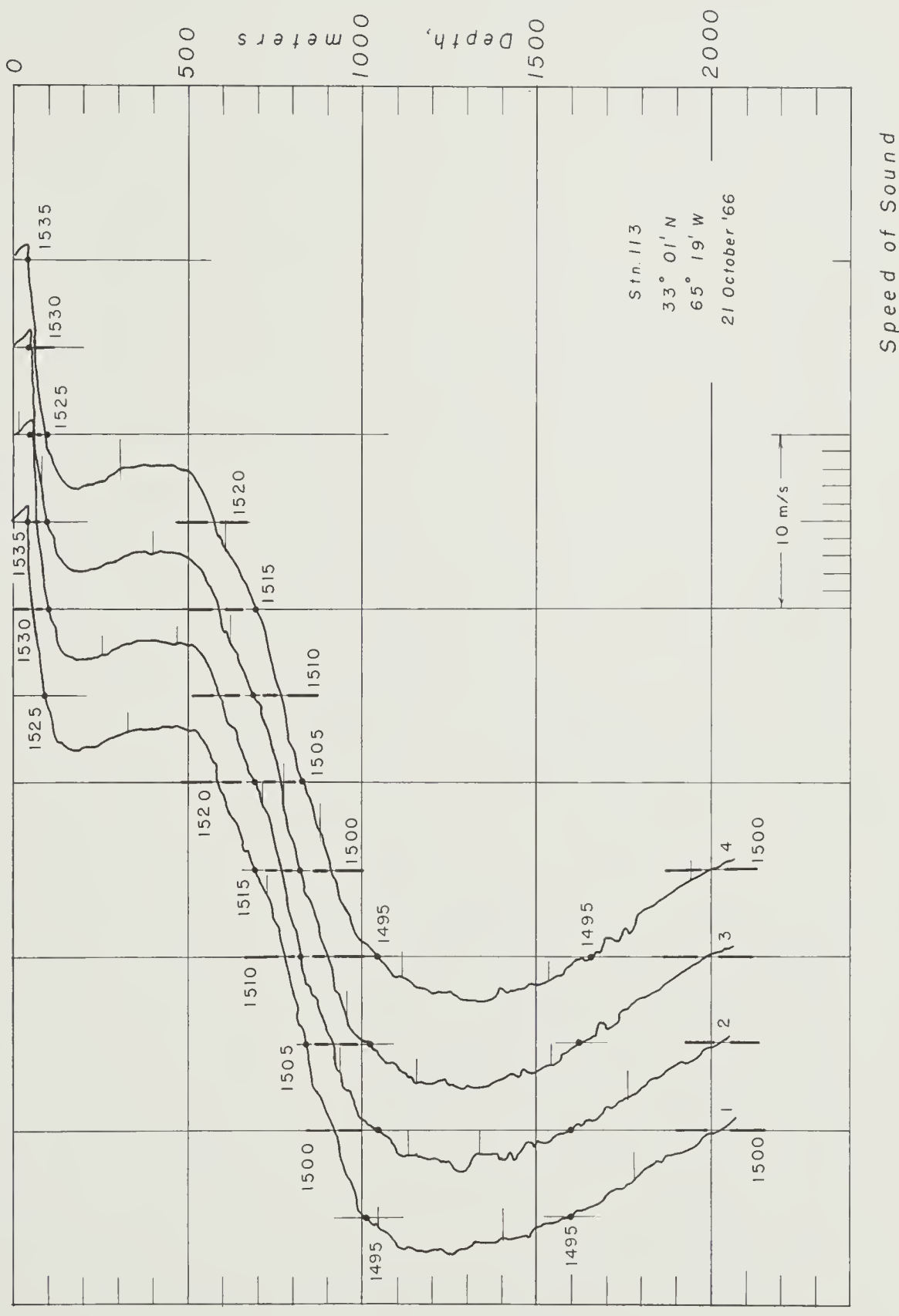


Fig. 20 Sound Speeds - Station 113

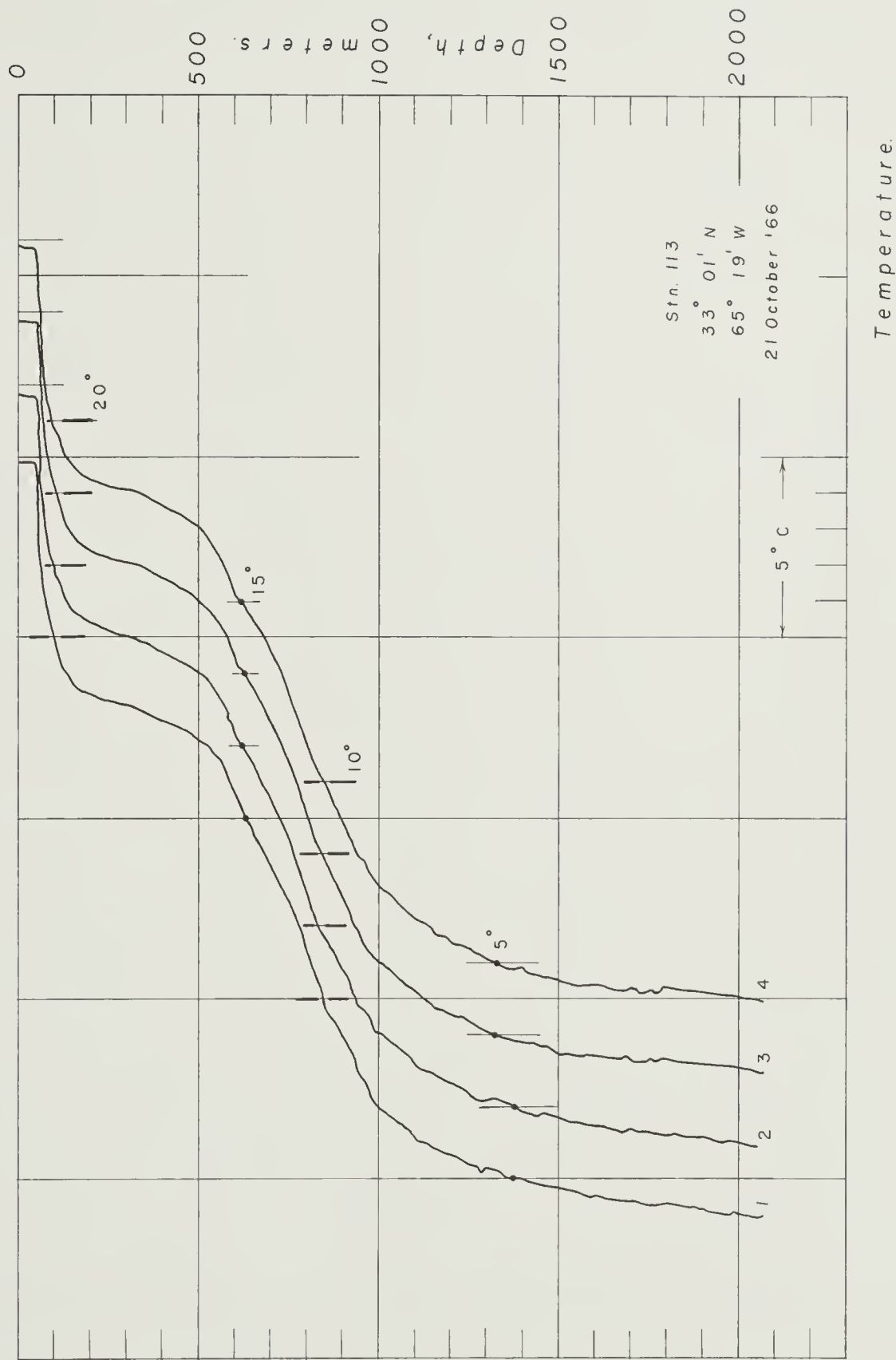


Fig. 21 Temperatures - Station 113

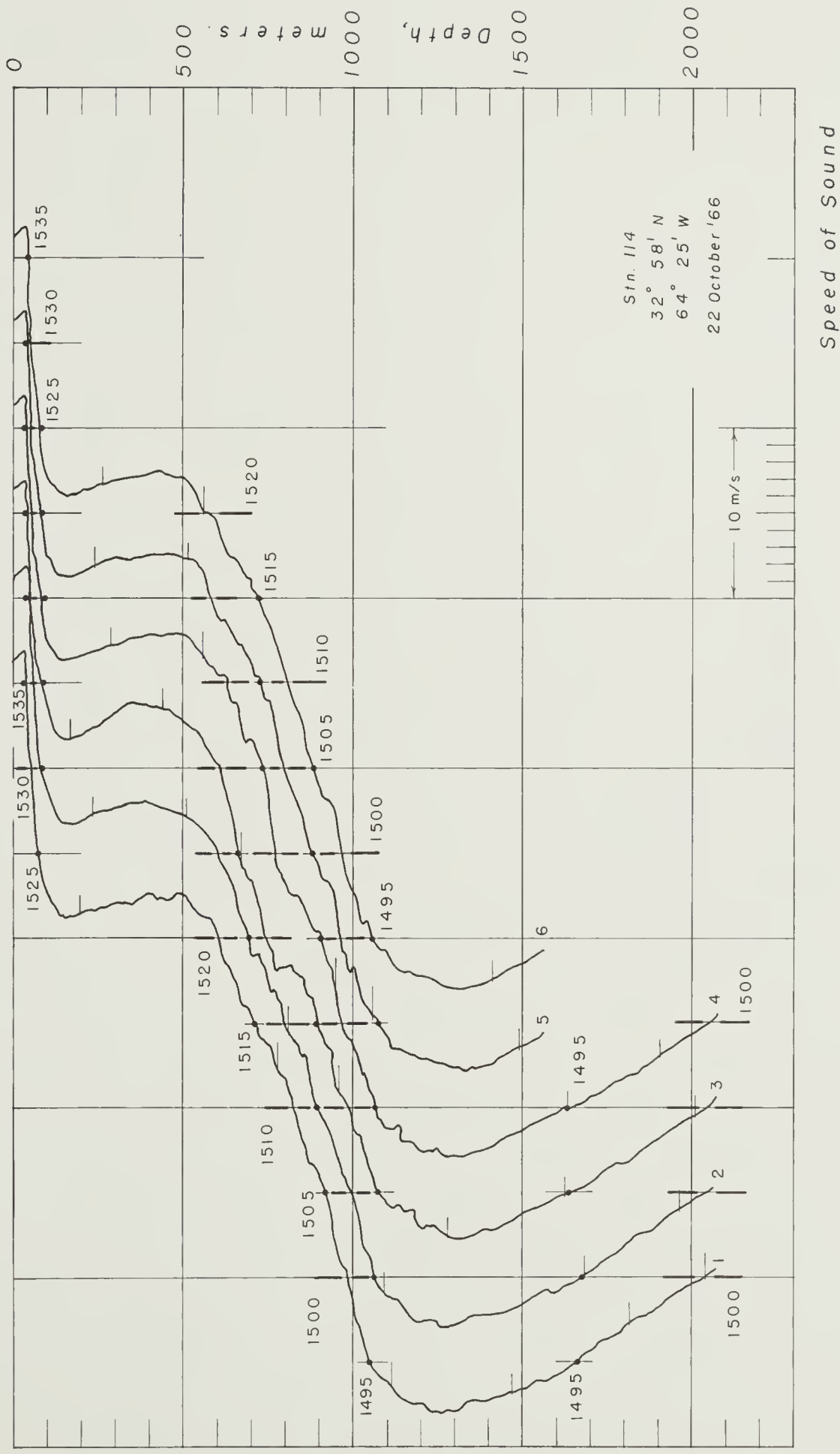


Fig. 22 Sound Speeds - Station 114

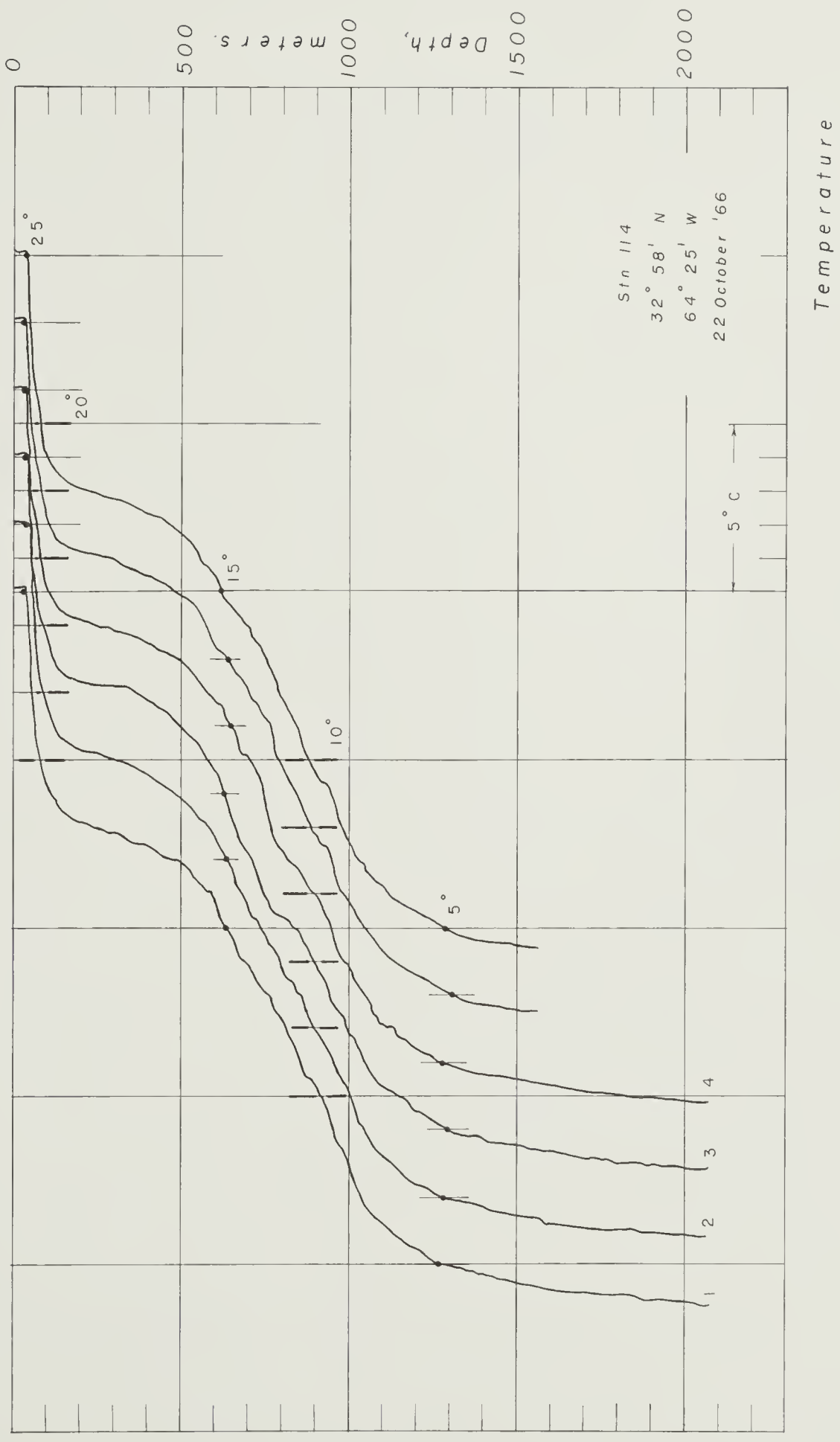


Fig. 23 Temperatures - Station 114

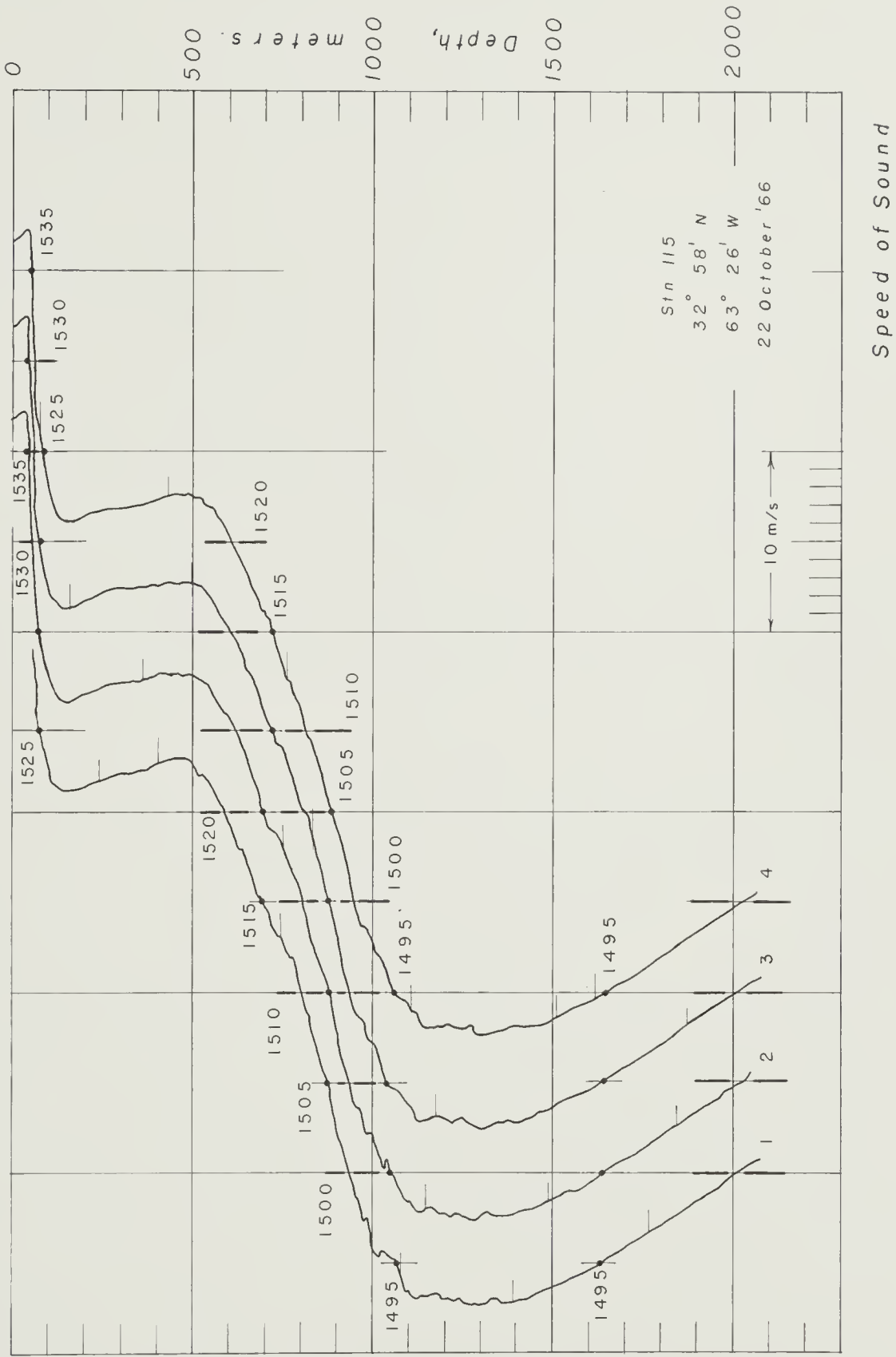


Fig. 24 Sound Speeds - Station 115

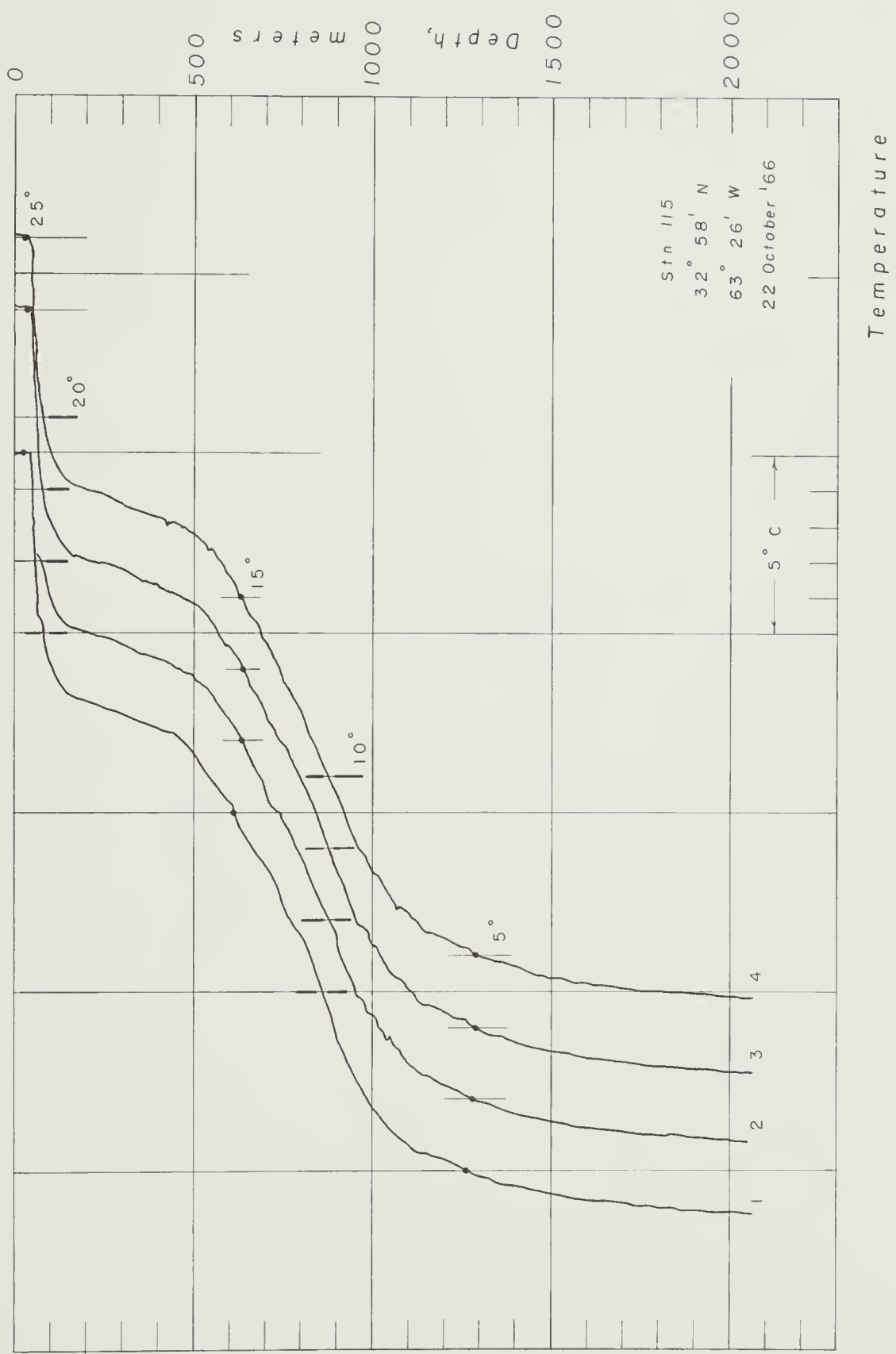


Fig. 25 Temperatures - Station 115

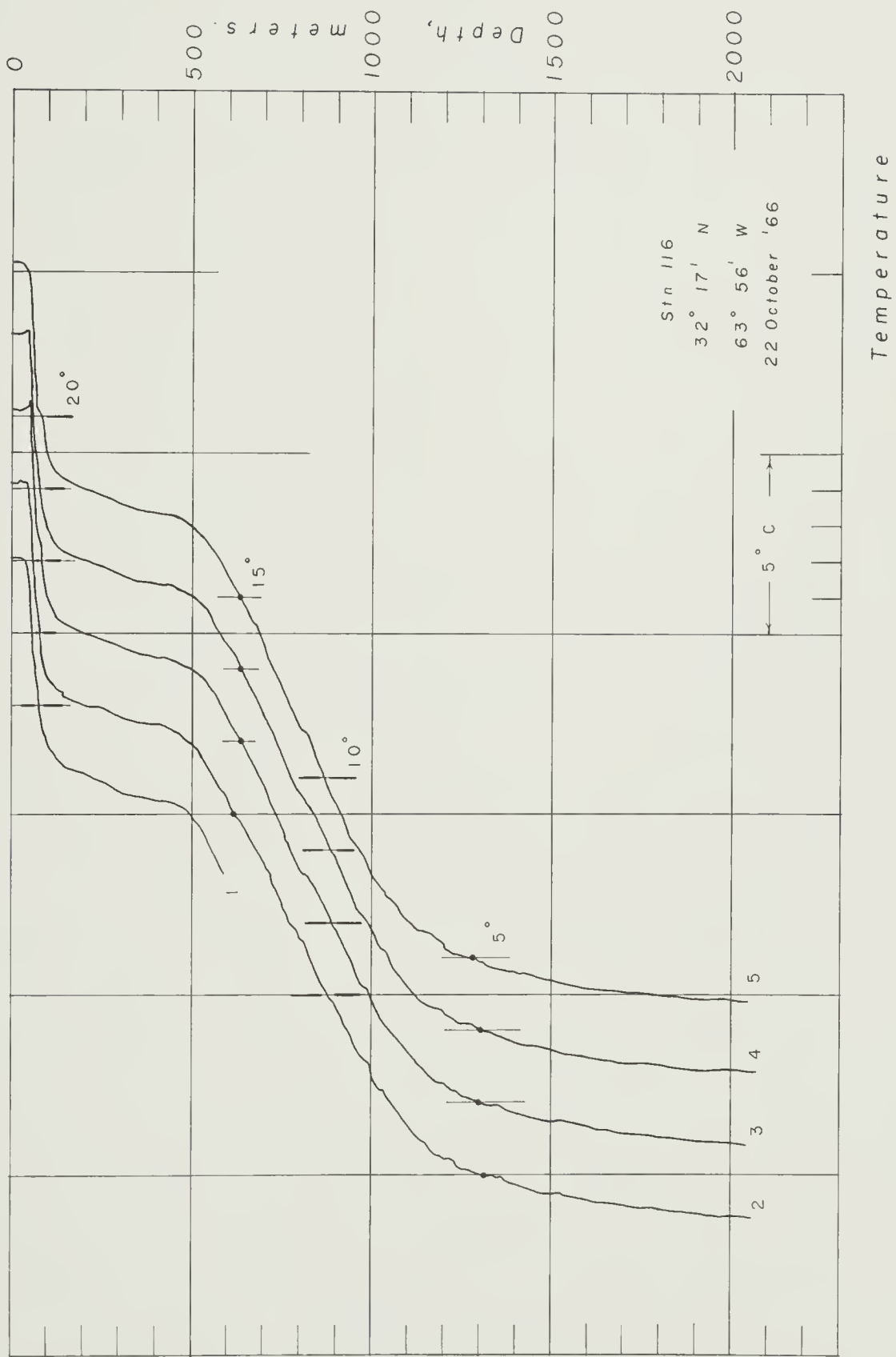


Fig. 27 Temperatures - Station 116

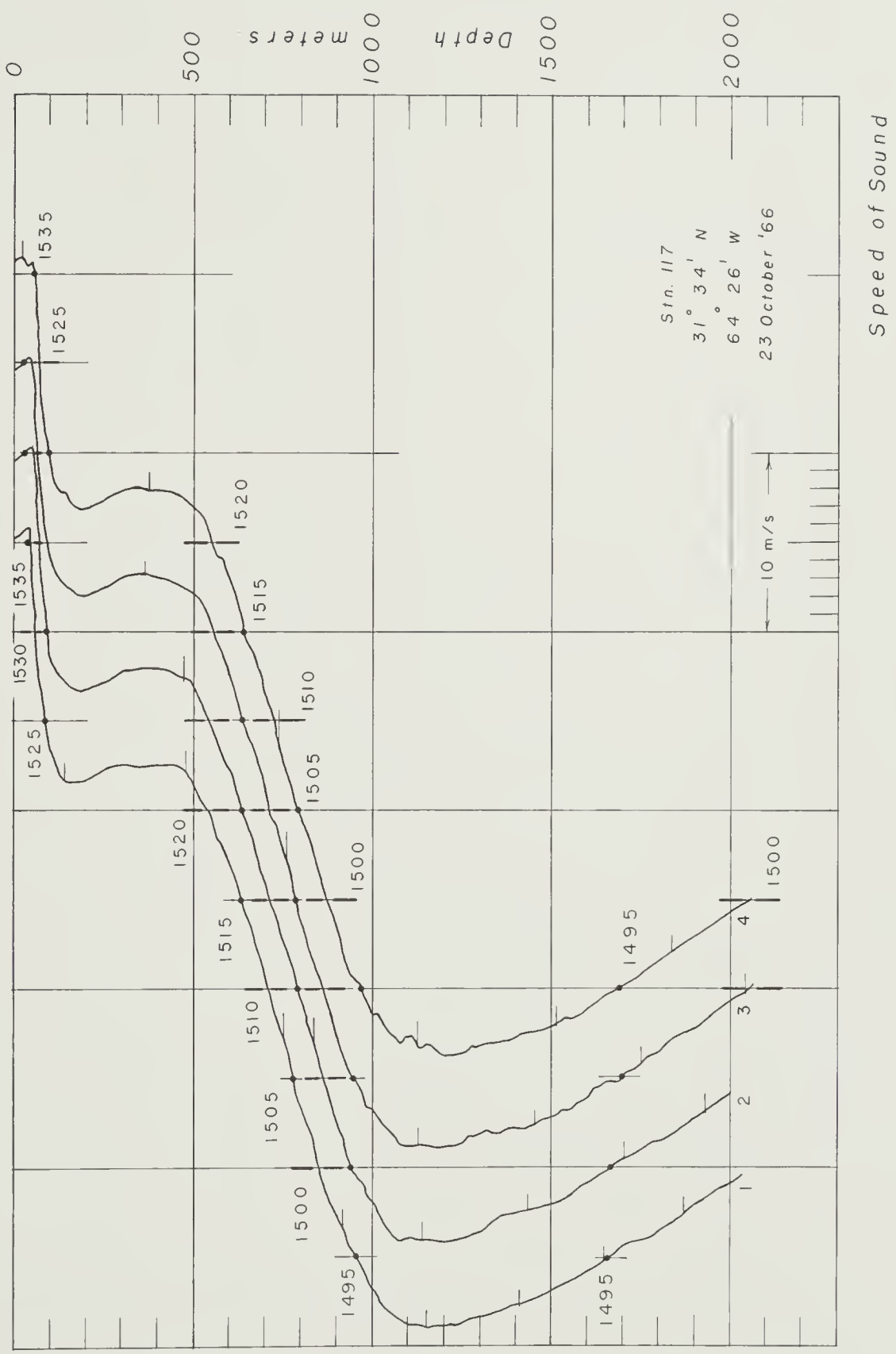


Fig. 28 Sound Speeds - Station 117

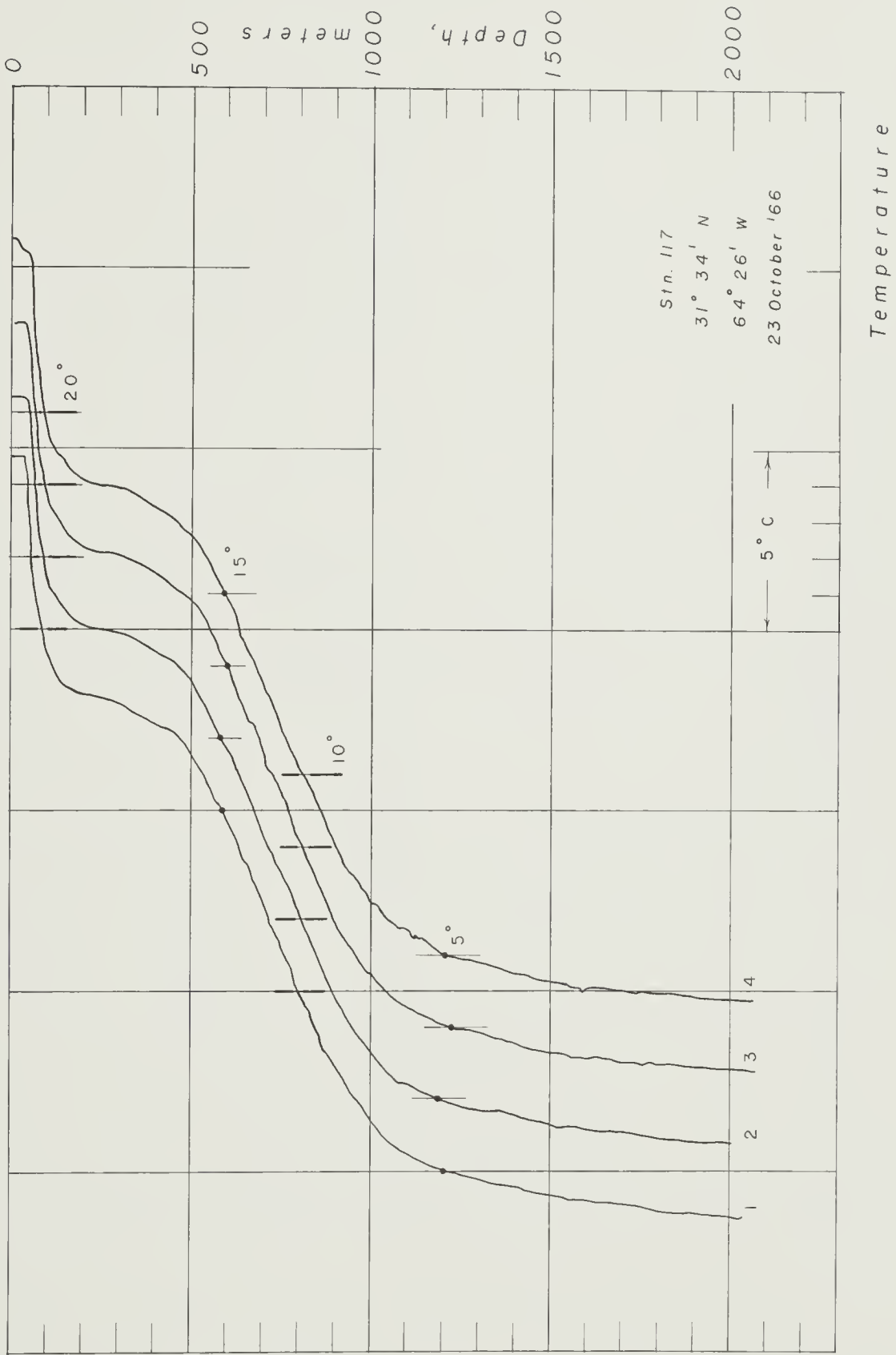


Fig. 29 Temperatures — Station 117

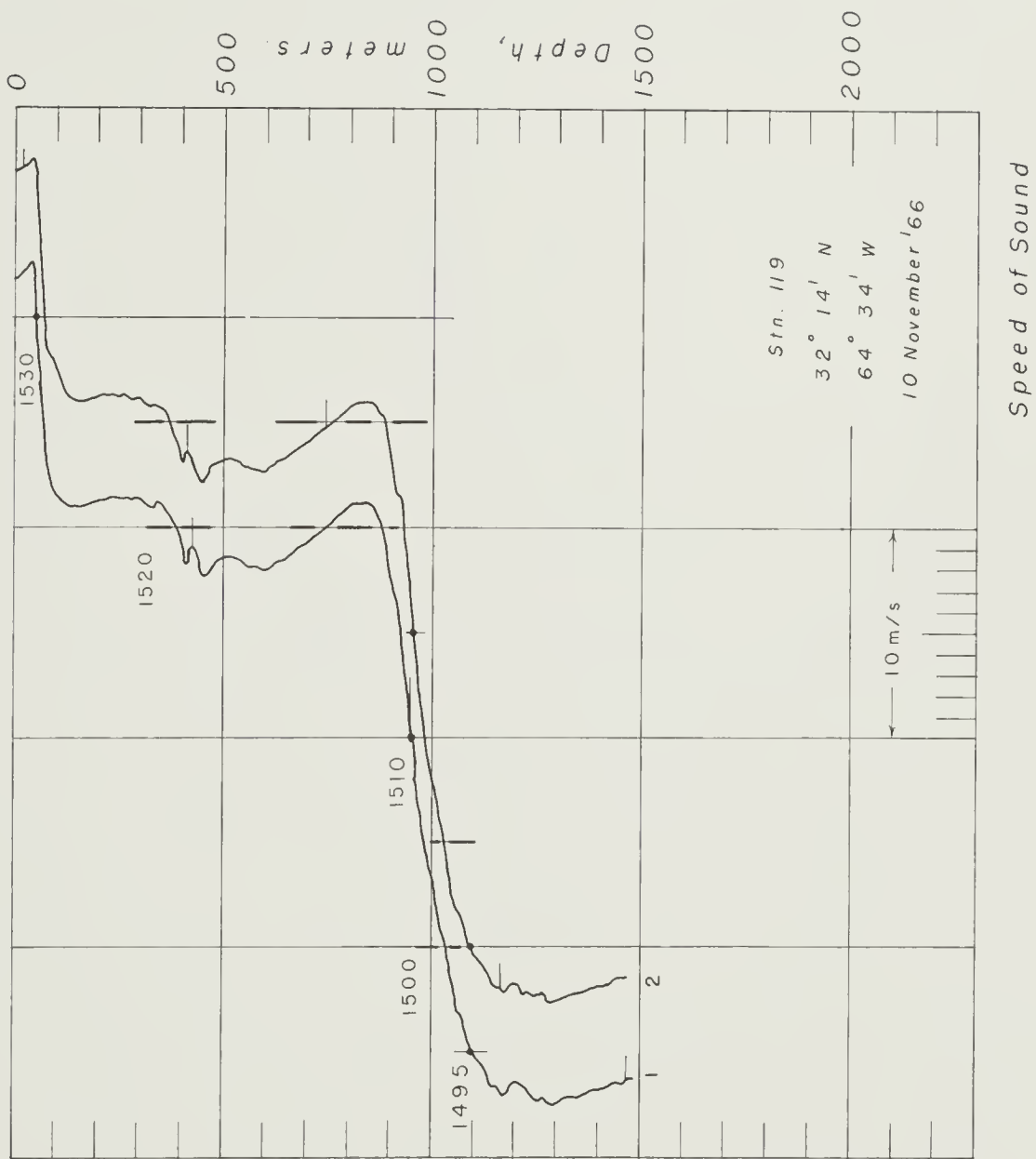


Fig. 30 Sound Speeds - Station 119

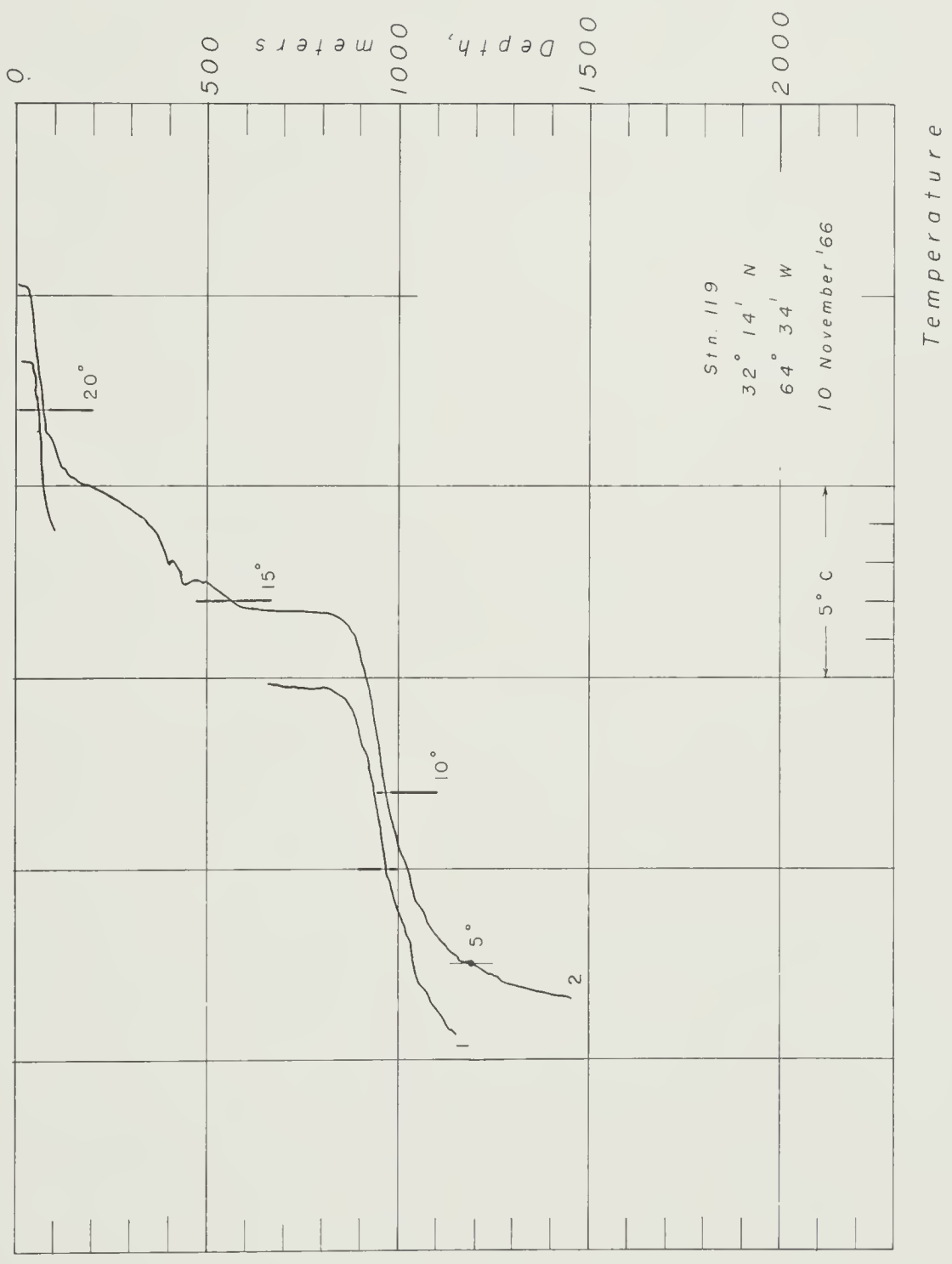


Fig. 31 Temperatures - Station 119

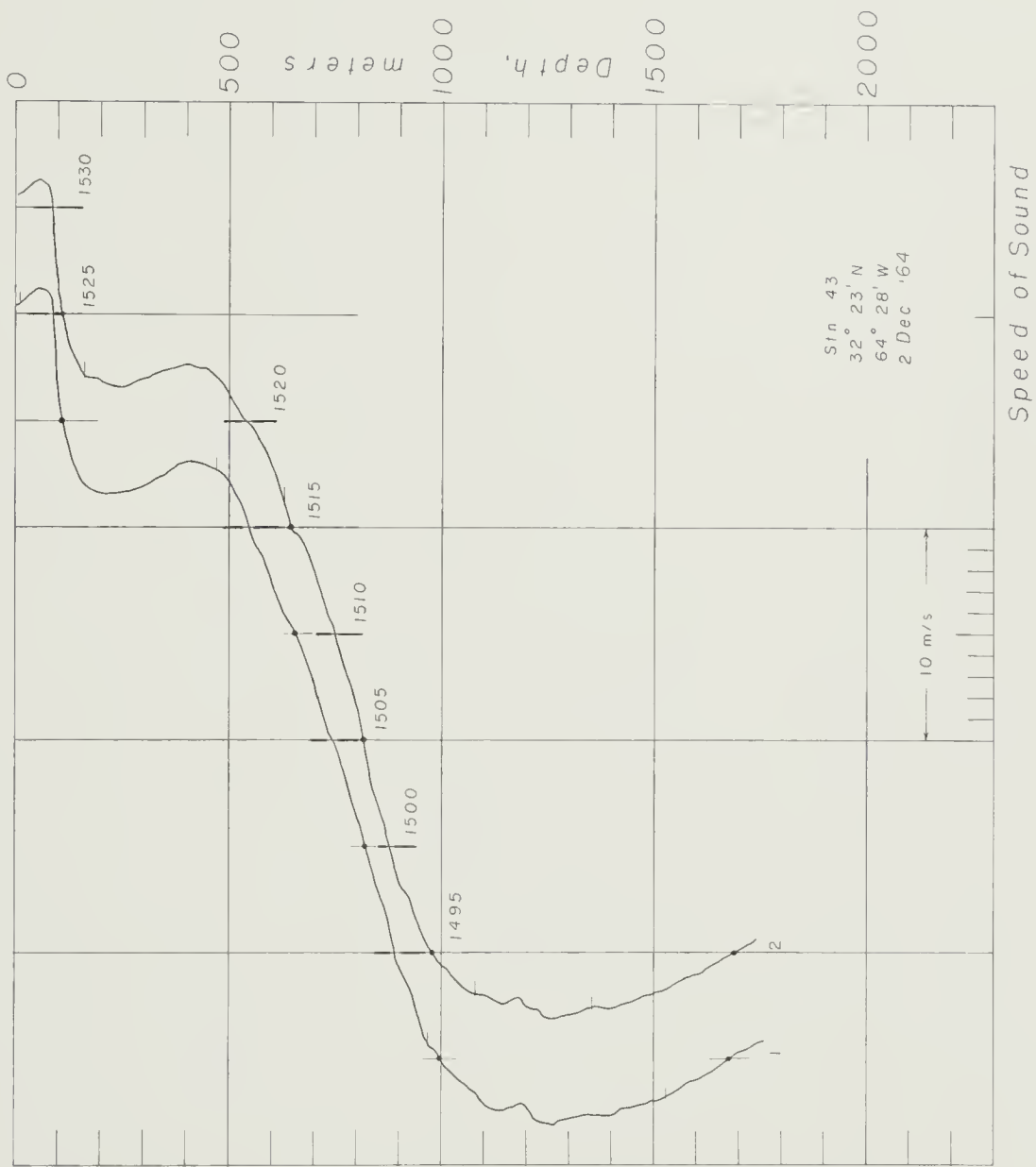


Fig. 32 Sound Speeds - Station 43

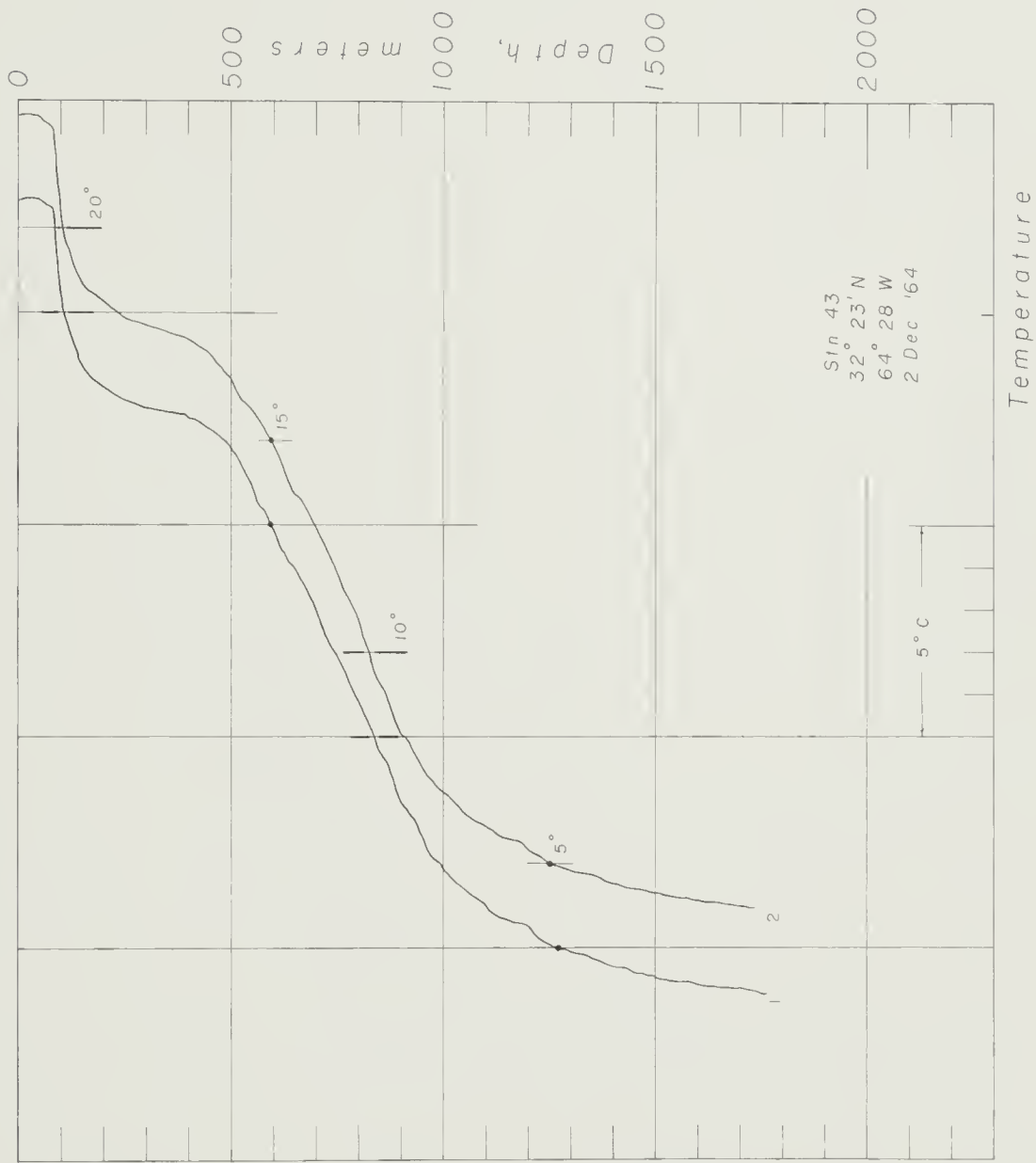


Fig. 33 Temperatures - Station 43

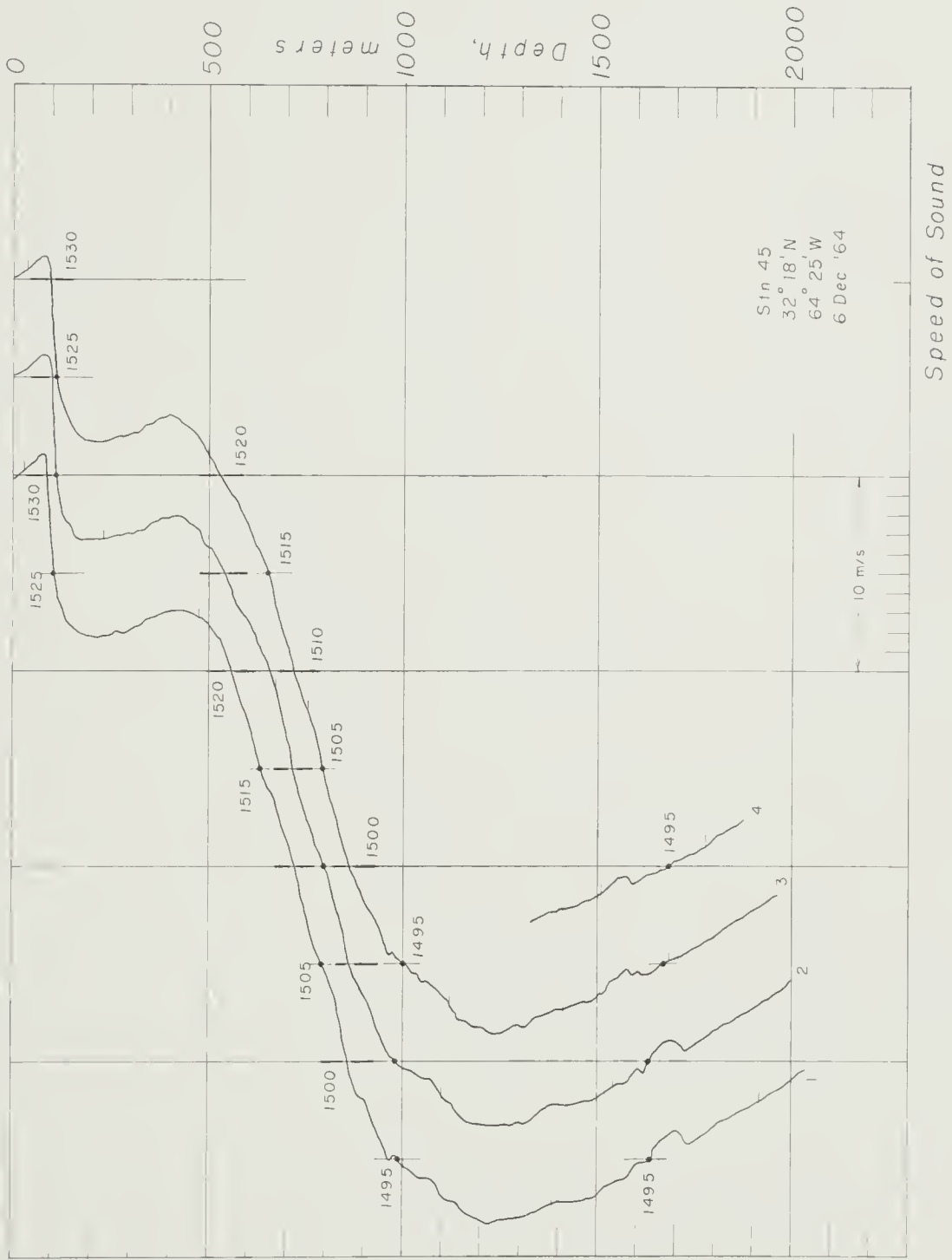


Fig. 34 Sound Speeds - Station 45



Fig. 35 Temperatures - Station 45

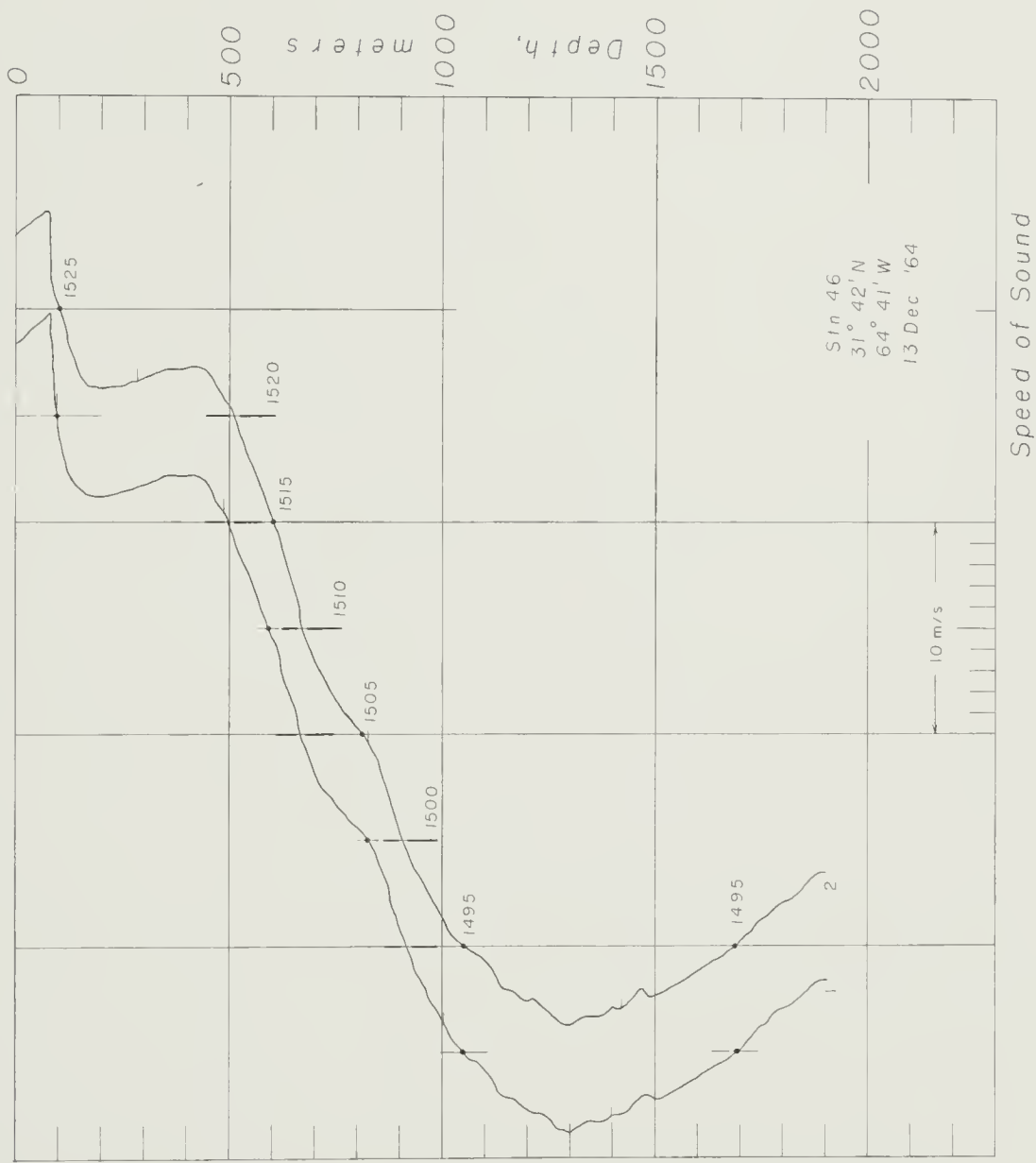


Fig. 36 Sound Speeds - Station 46

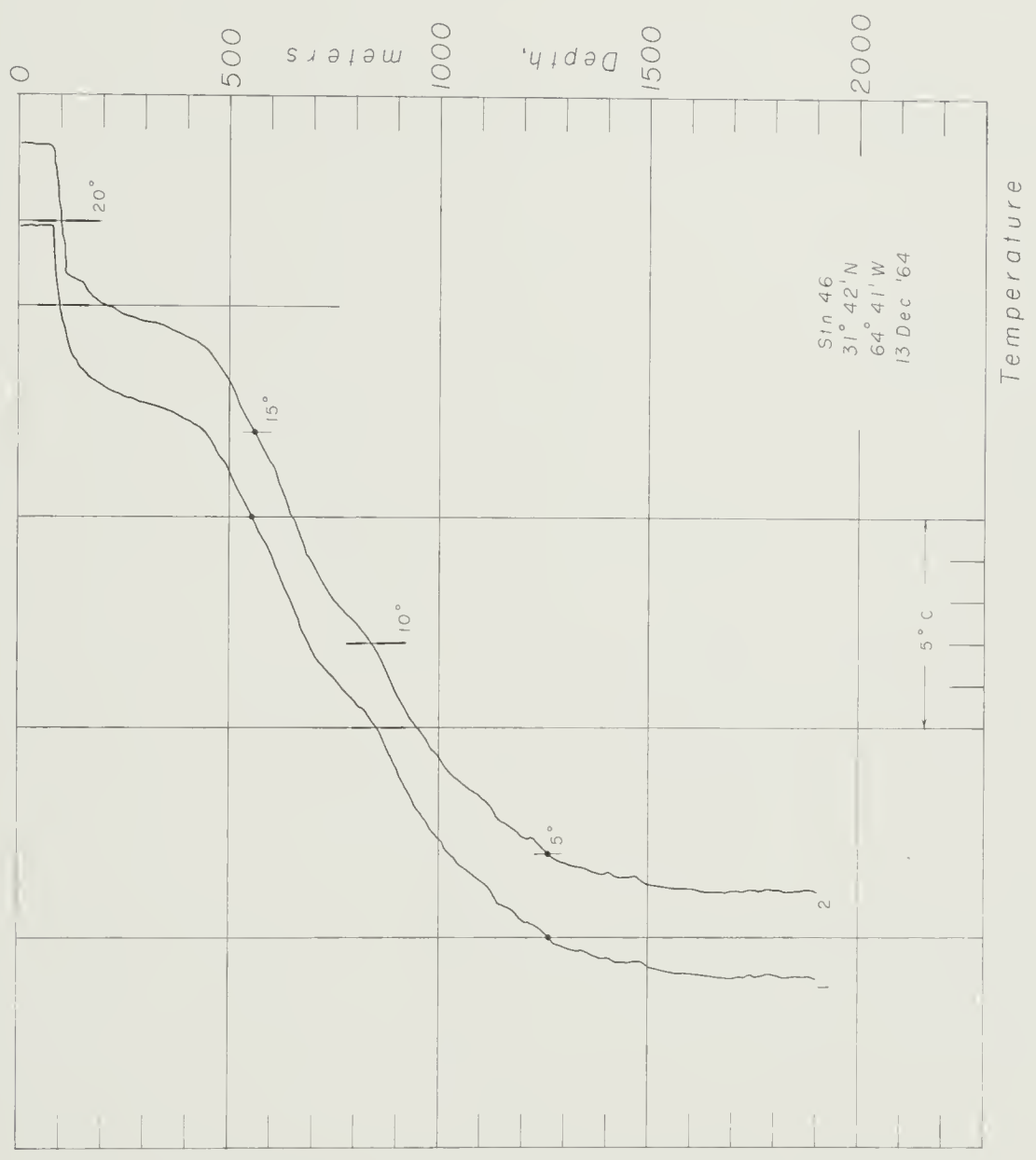


Fig. 37 Temperatures - Station 46

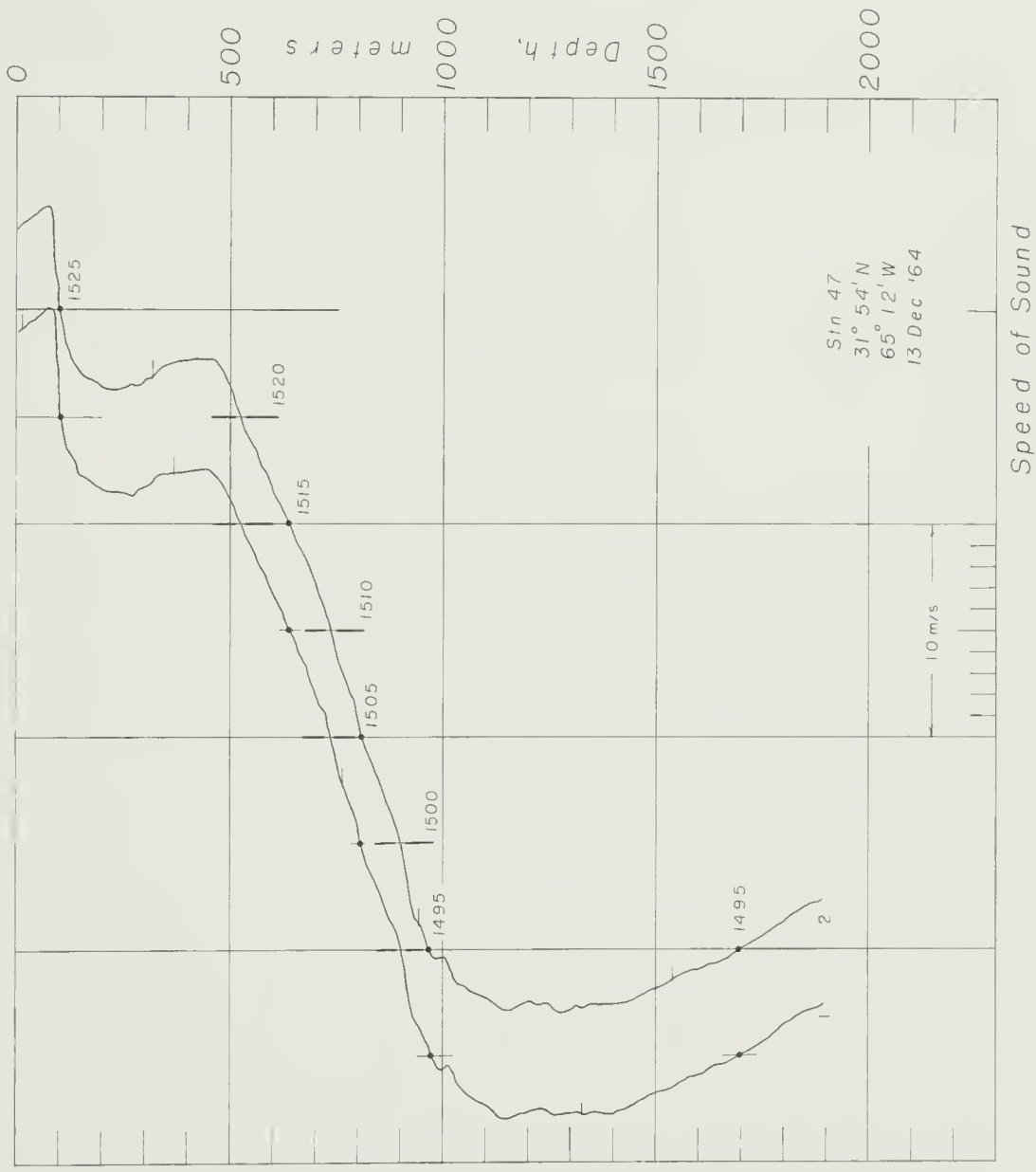


Fig. 38 Sound Speeds - Station 47



Fig. 39 Temperatures - Station 47

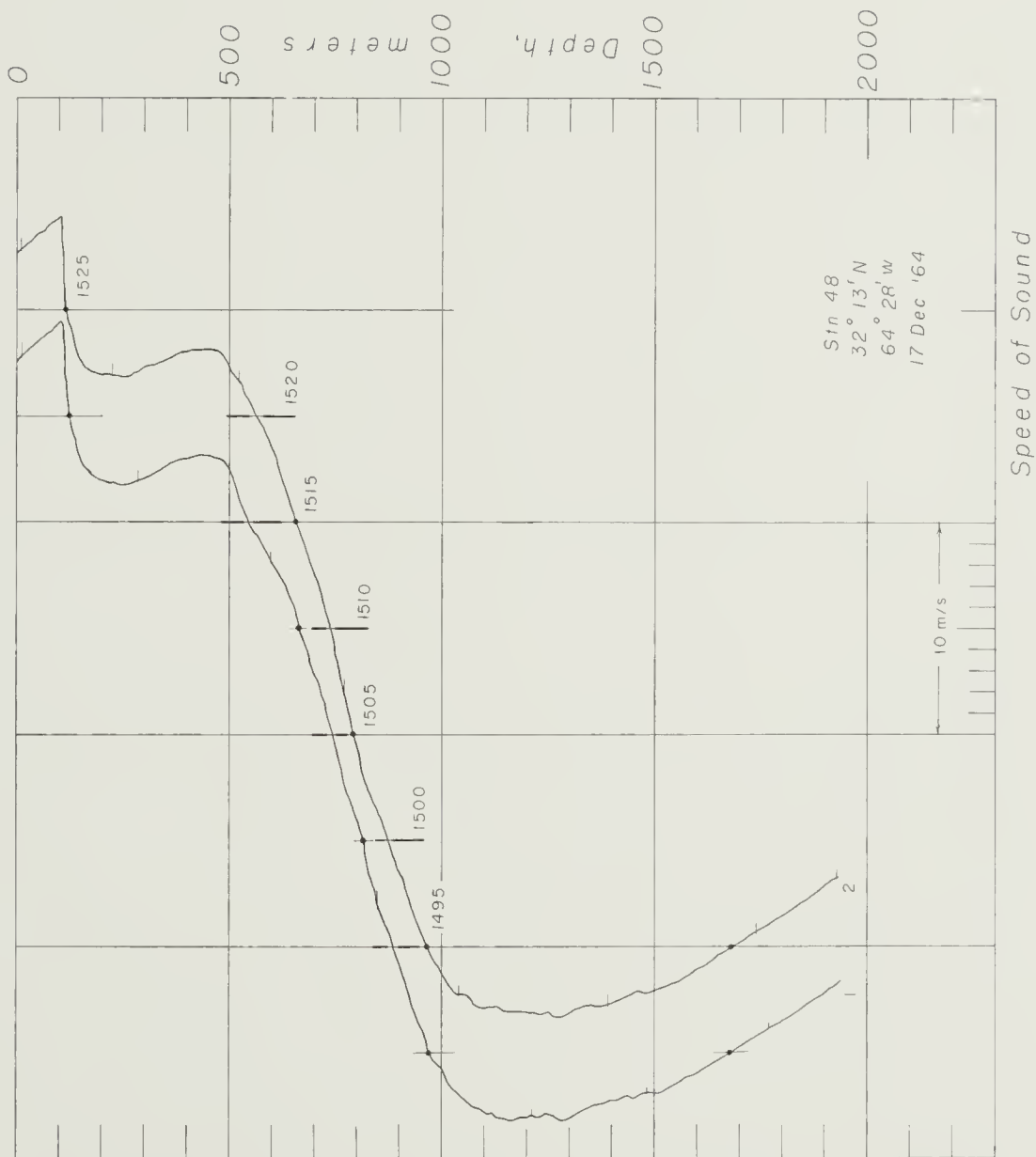


Fig. 40 Sound Speeds - Station 48

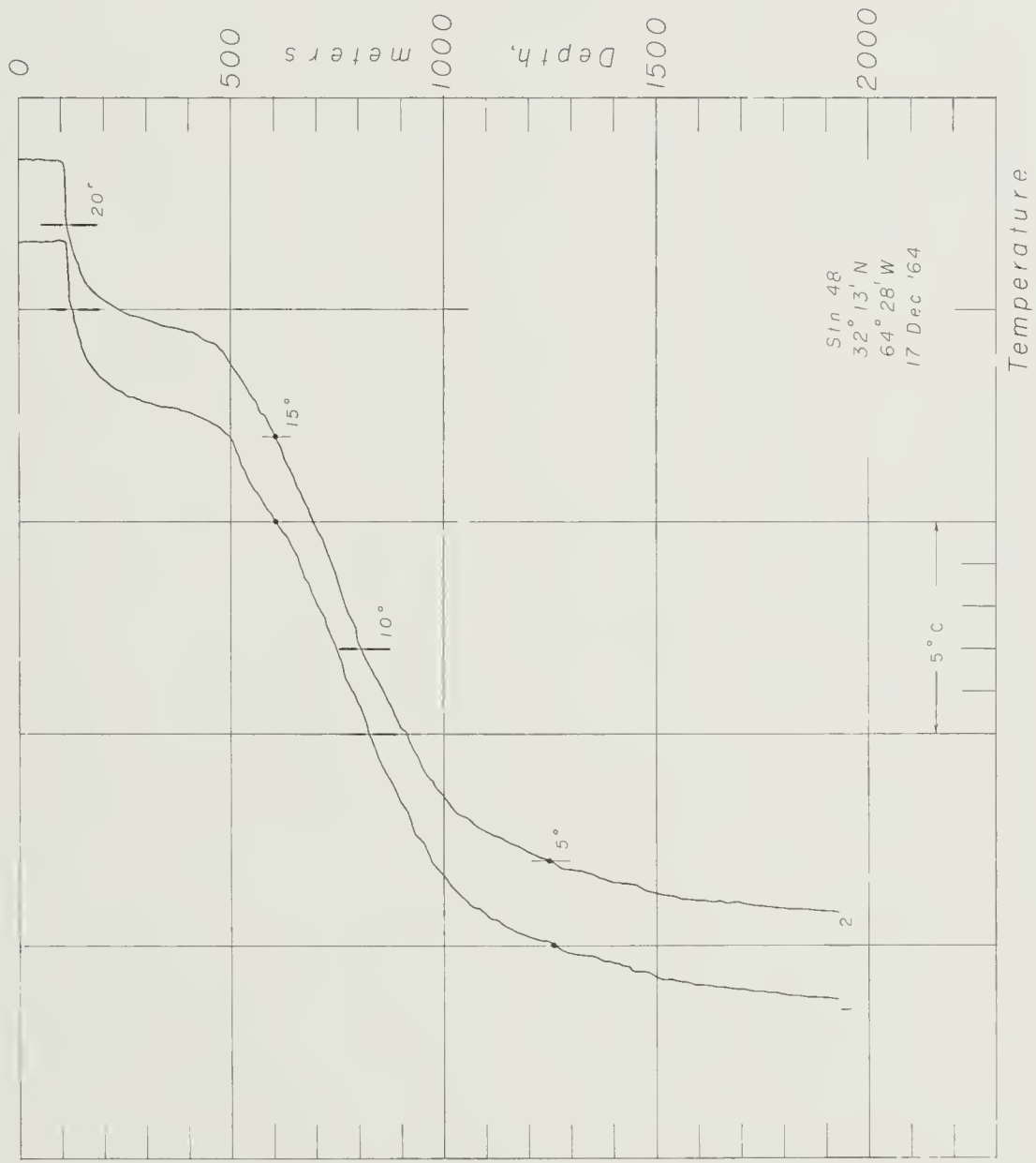


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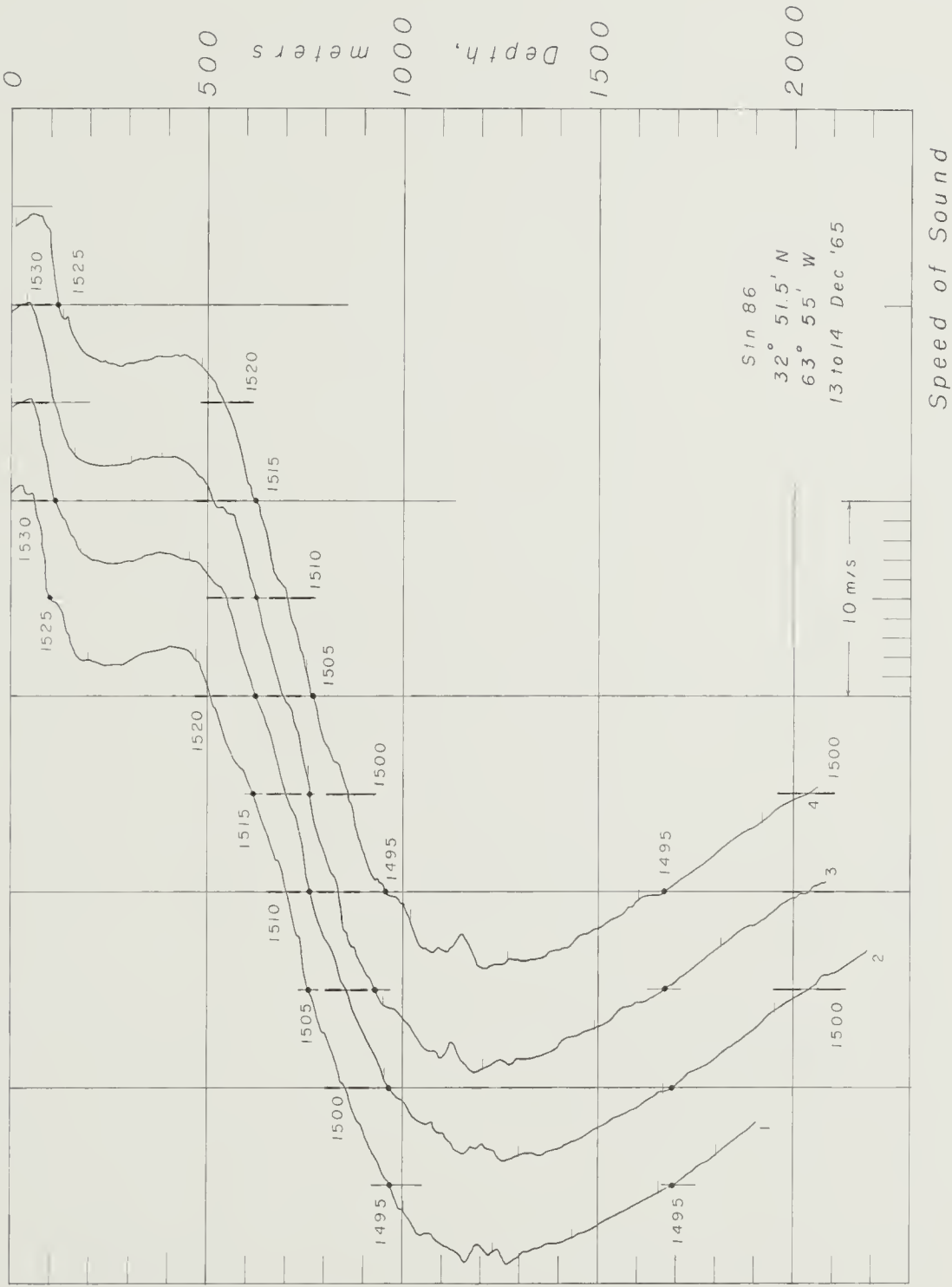


Fig. 42 Sound Speeds - Station 86

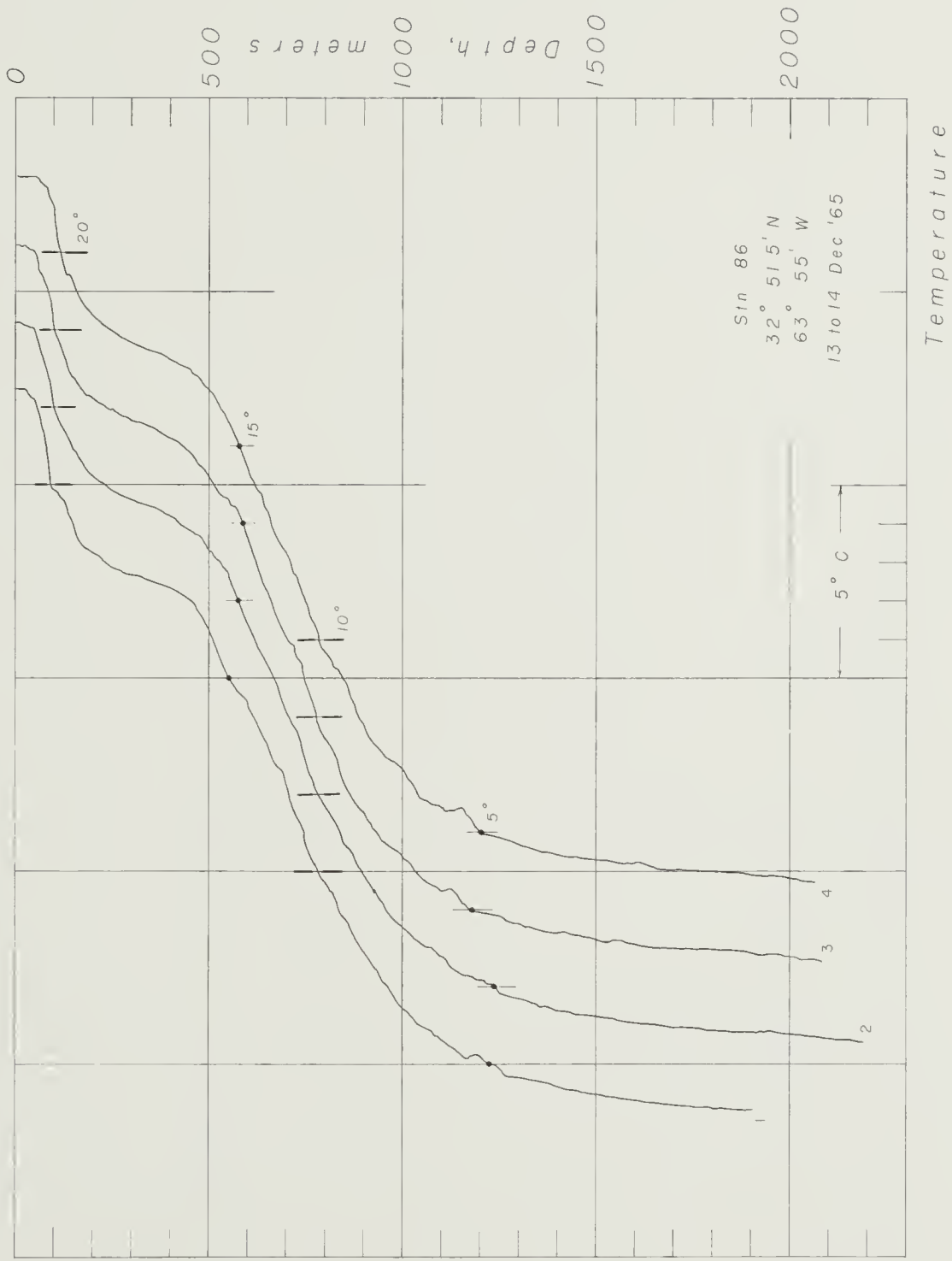


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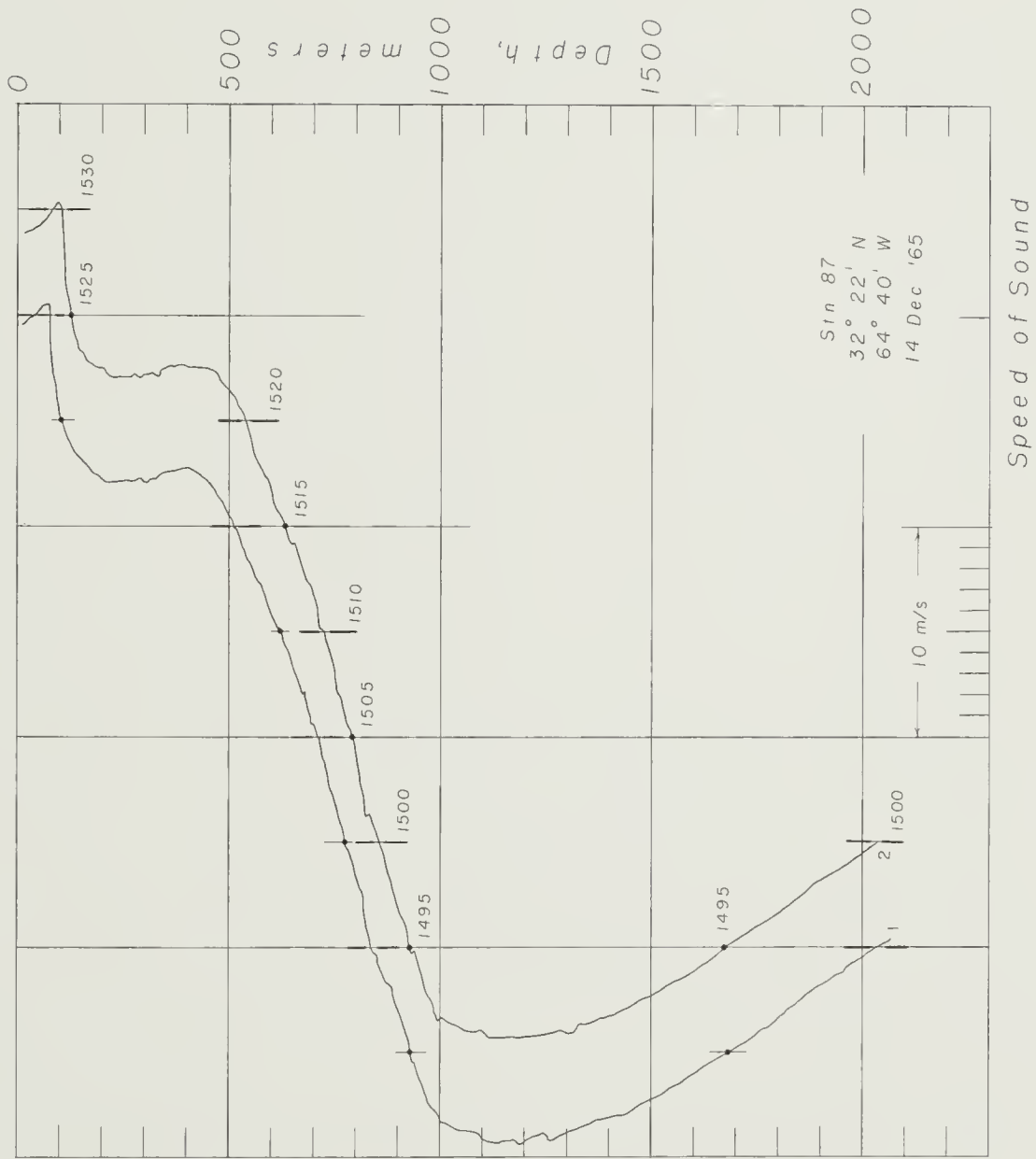


Fig. 44 Sound Speeds - Station 87

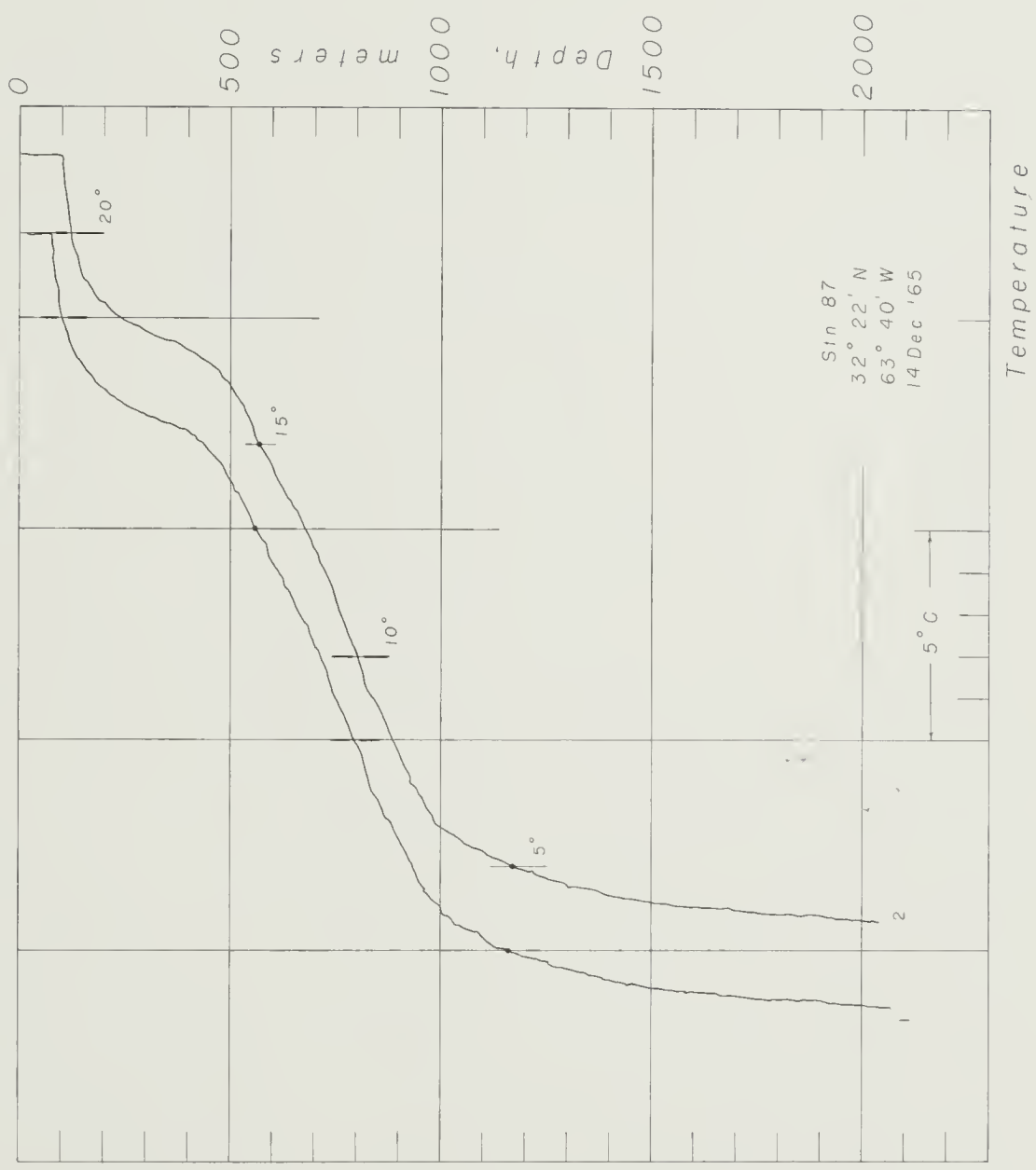


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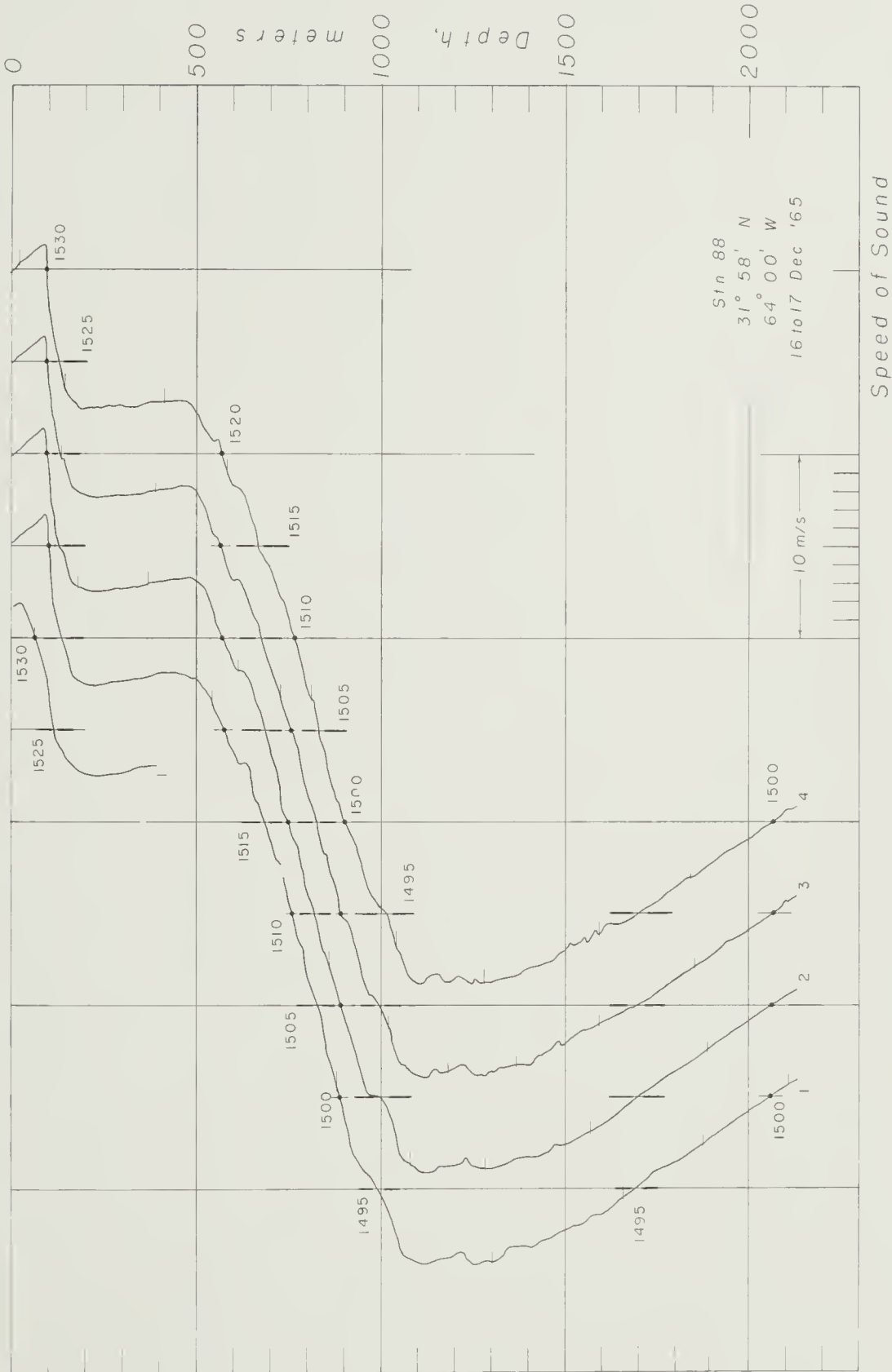


Fig. 46 Sound Speeds - Station 88

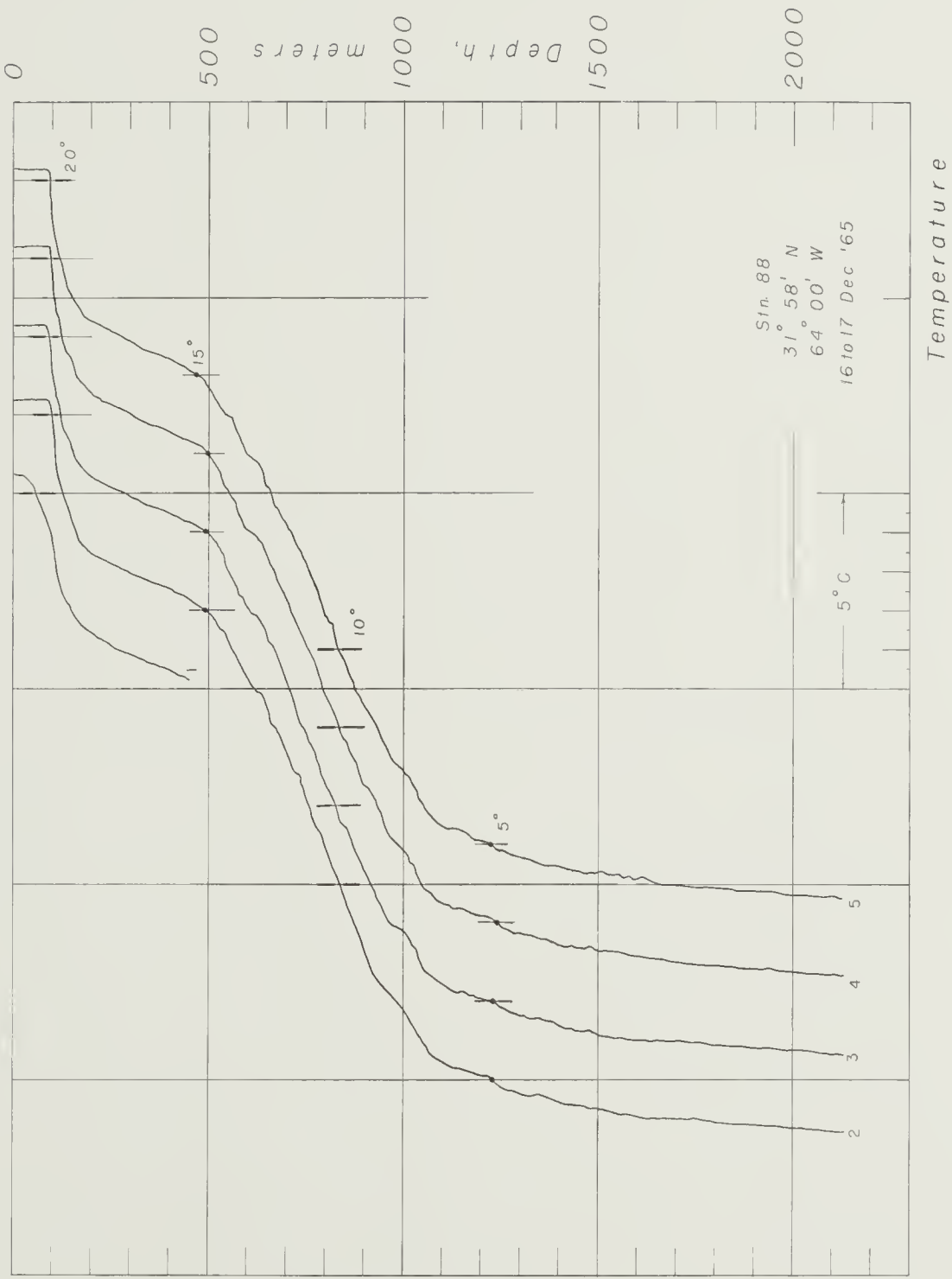


Fig. 47 Temperatures - Station 88

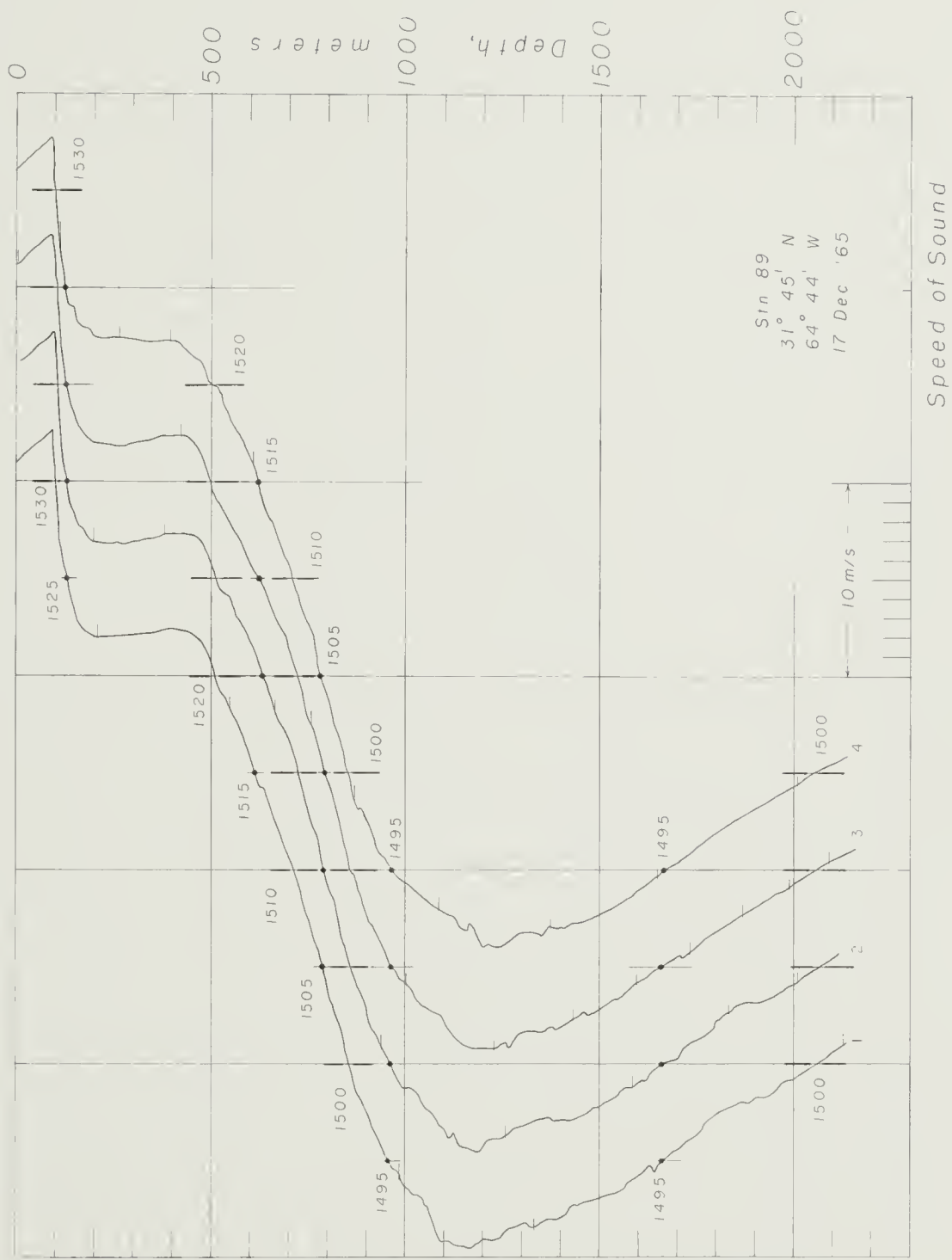


Fig. 48 Sound Speeds - Station 89

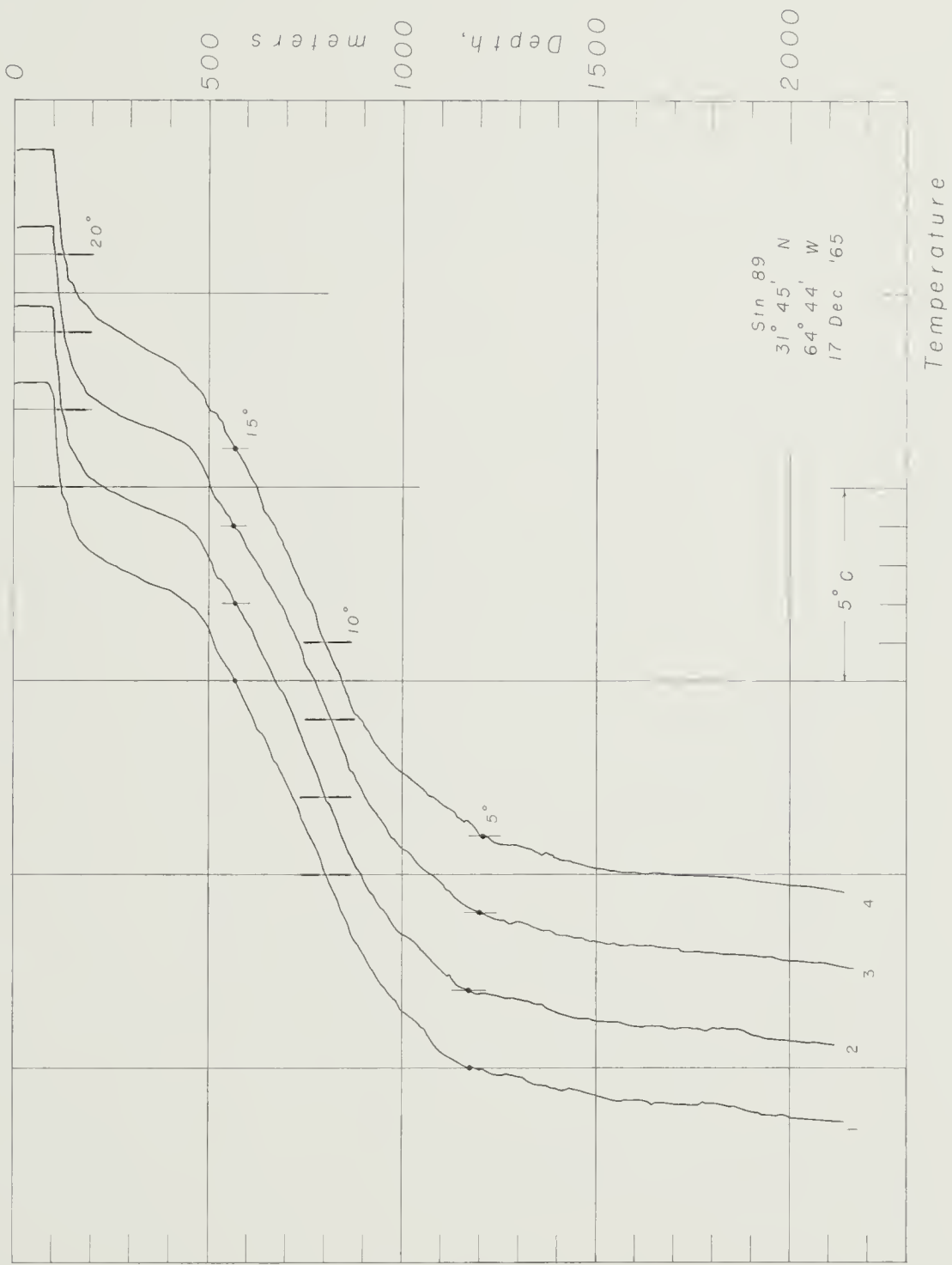


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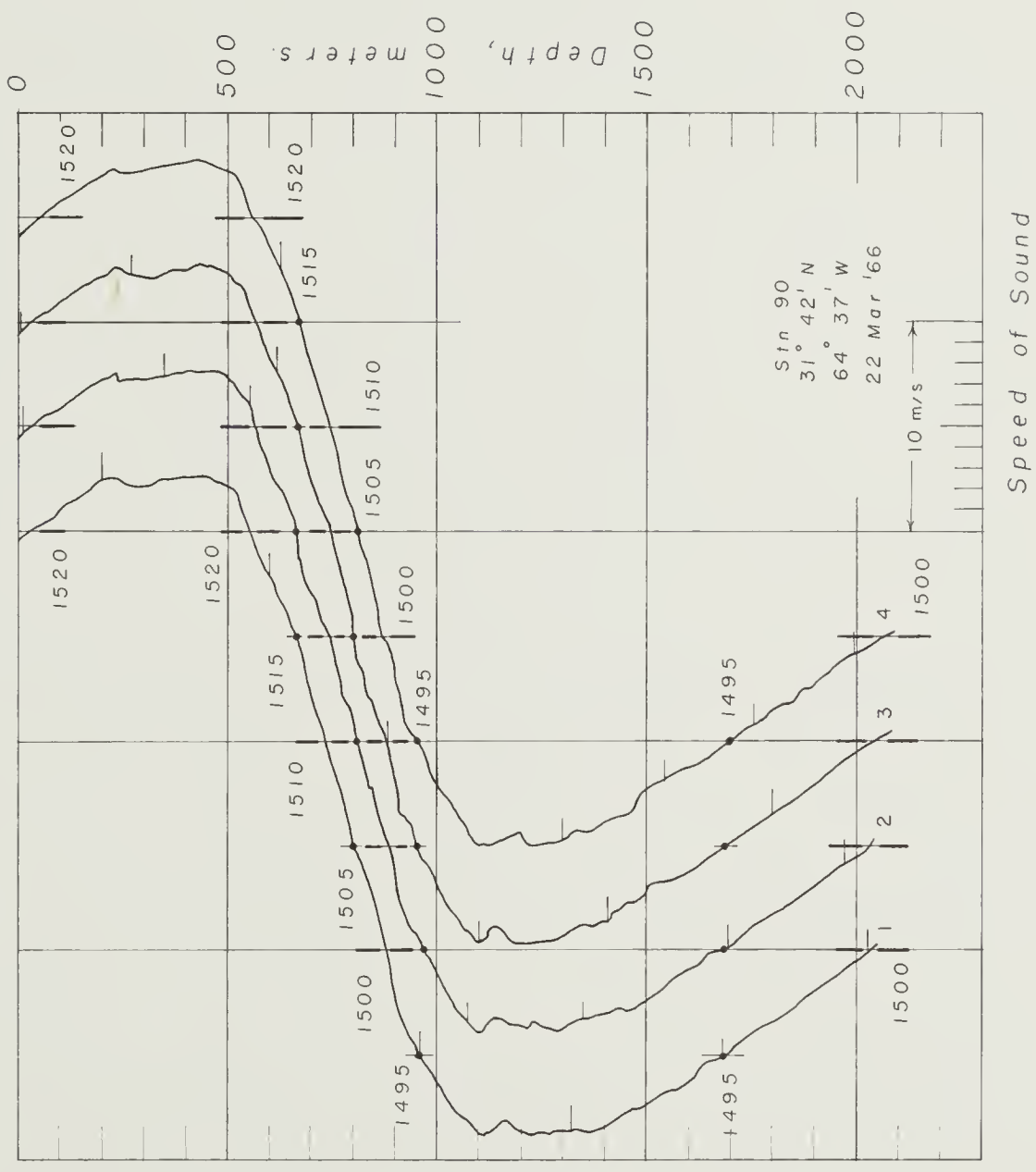


Fig. 50 Sound Speeds - Station 90

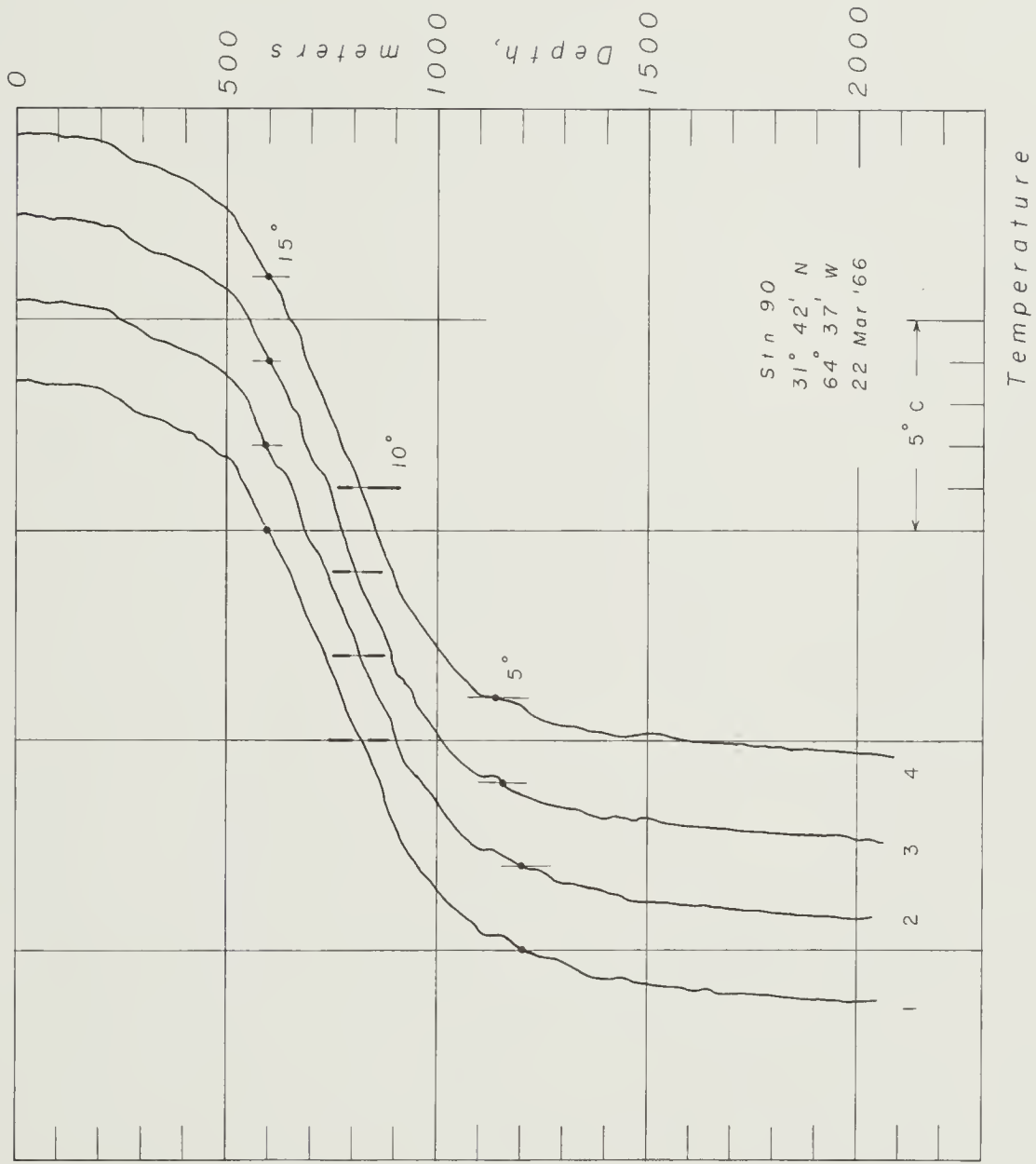


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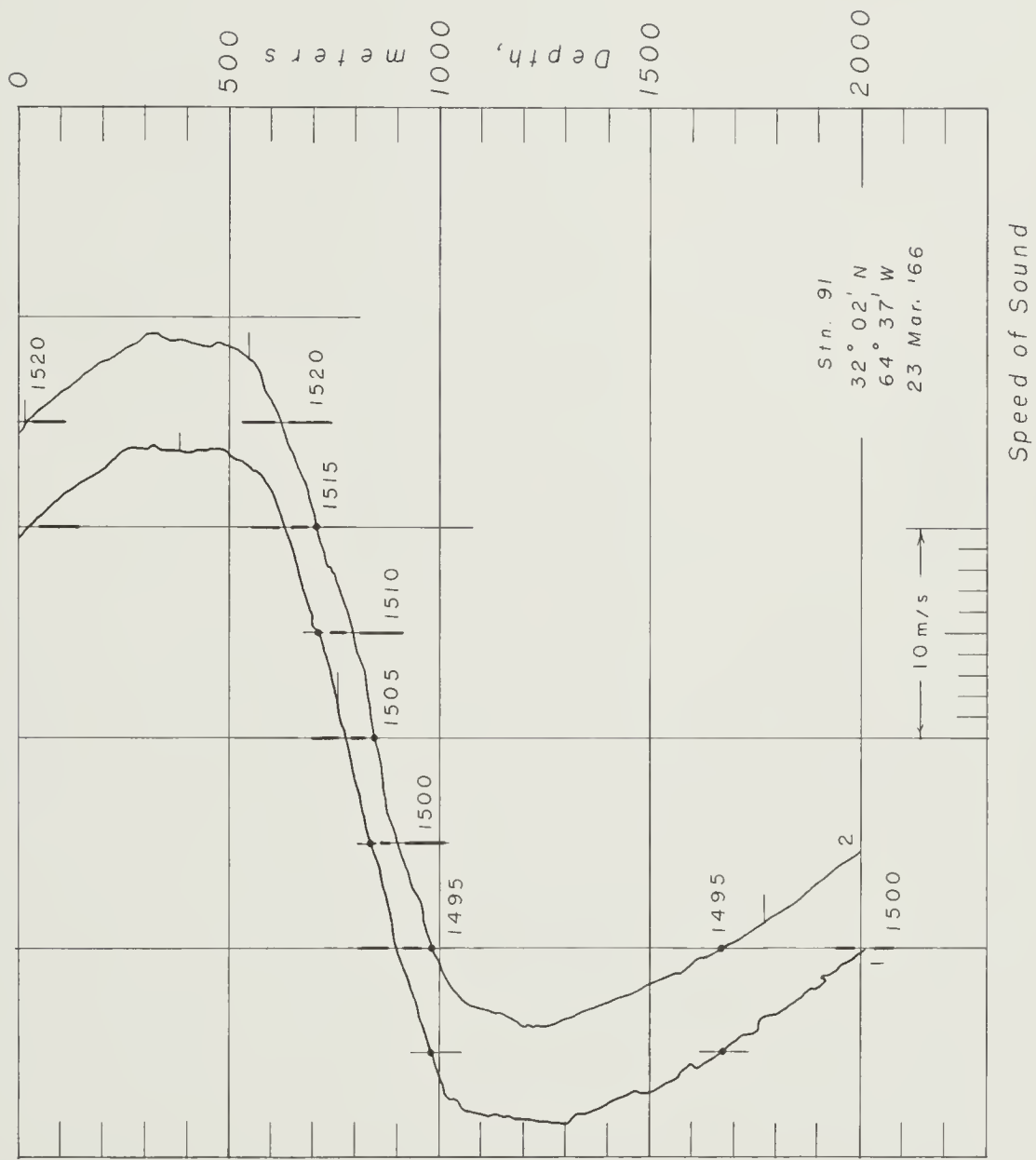


Fig. 52 Sound Speeds - Station 91

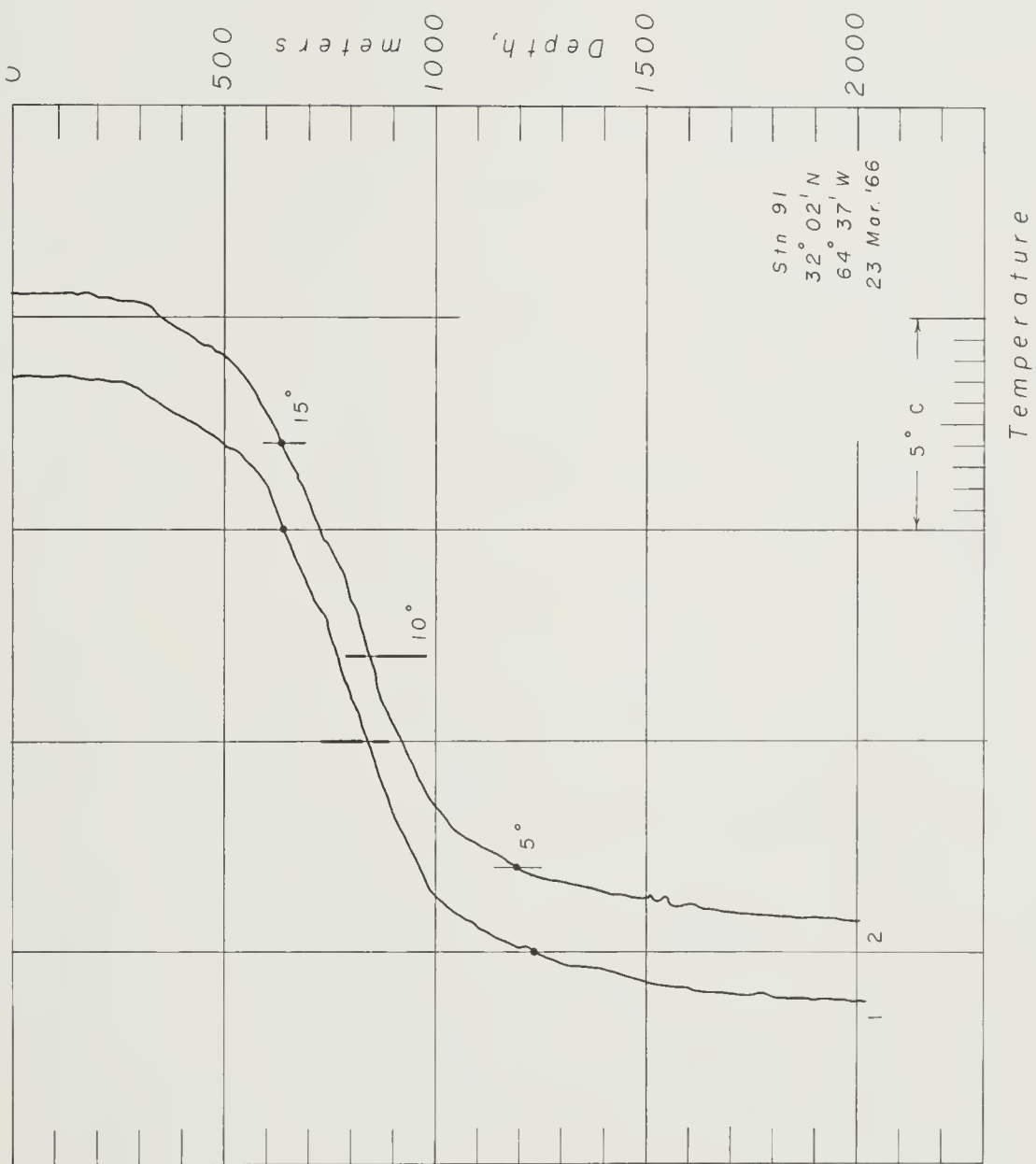


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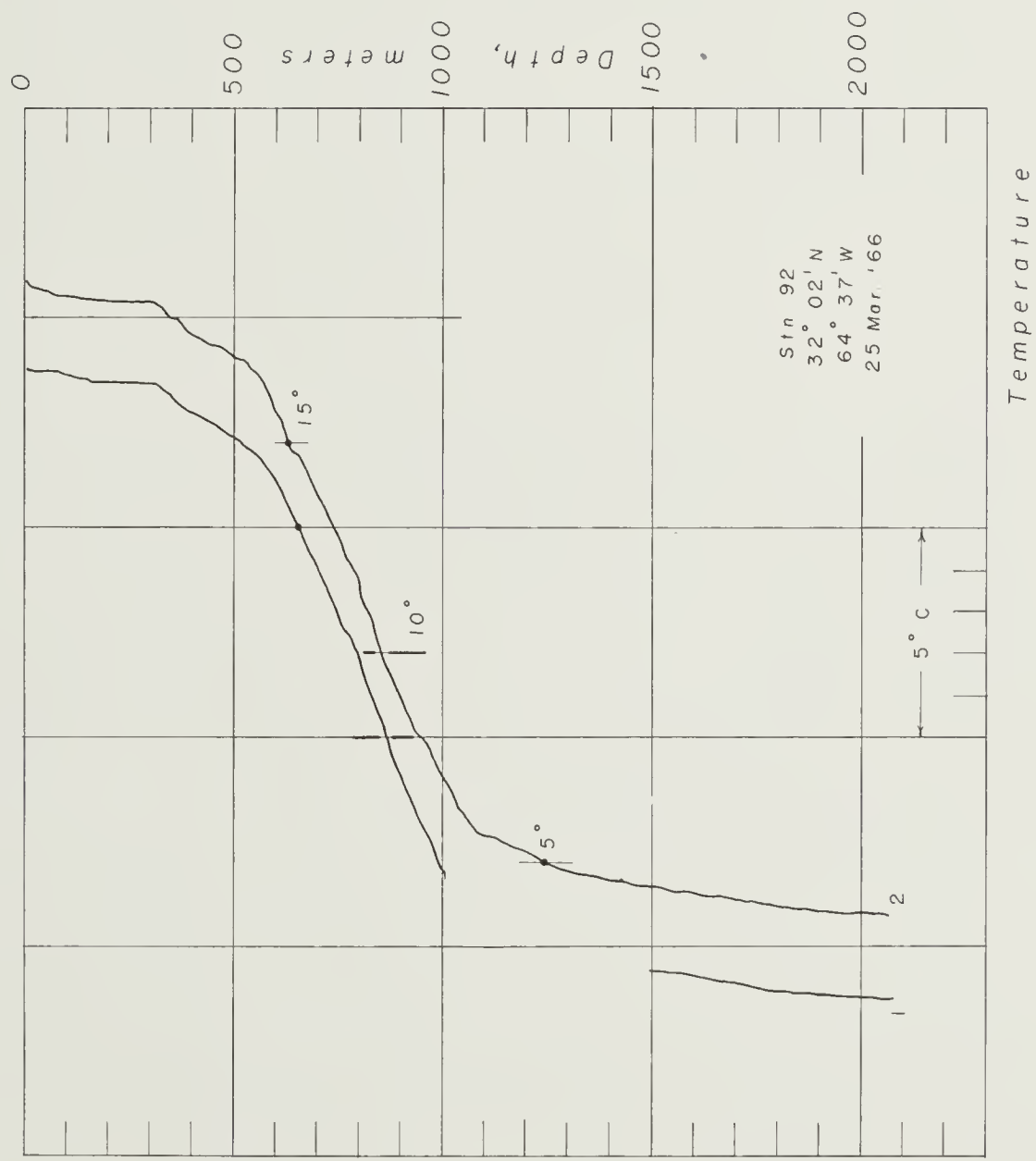


Fig. 55 Temperatures - Station 92

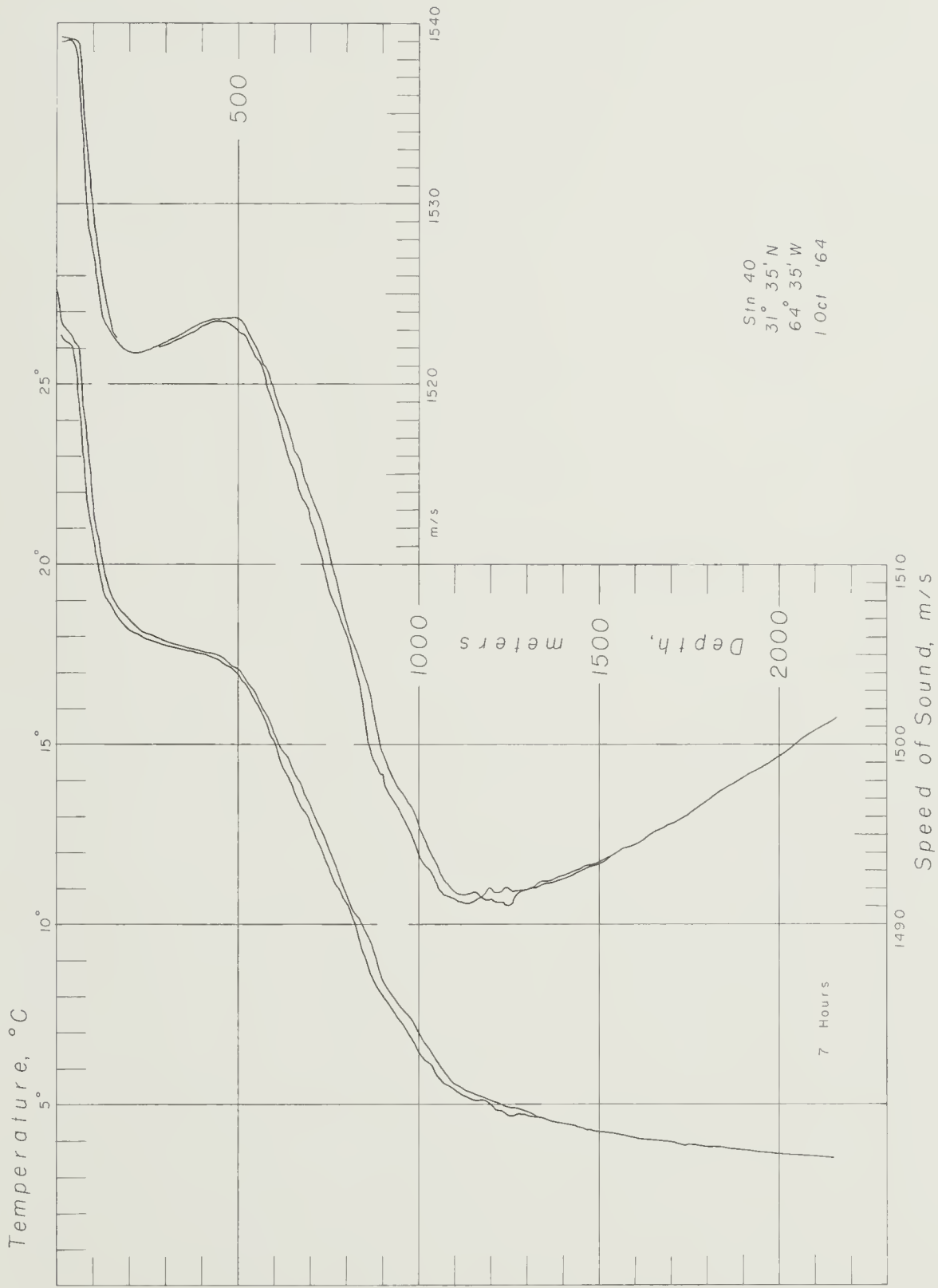


Fig. 56 Profile Envelopes - Station 40

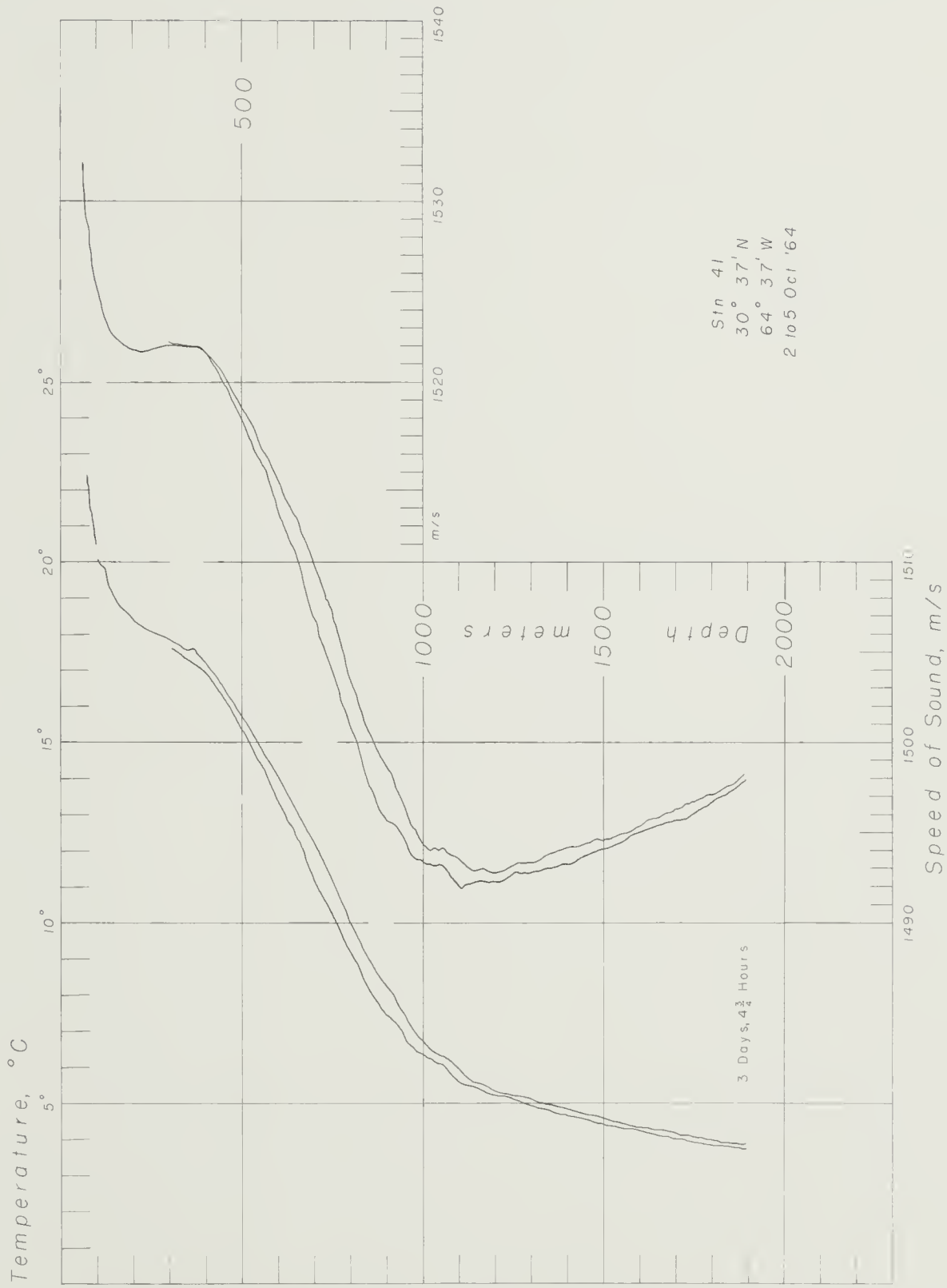


Fig. 57 Profile Envelopes - Station 41

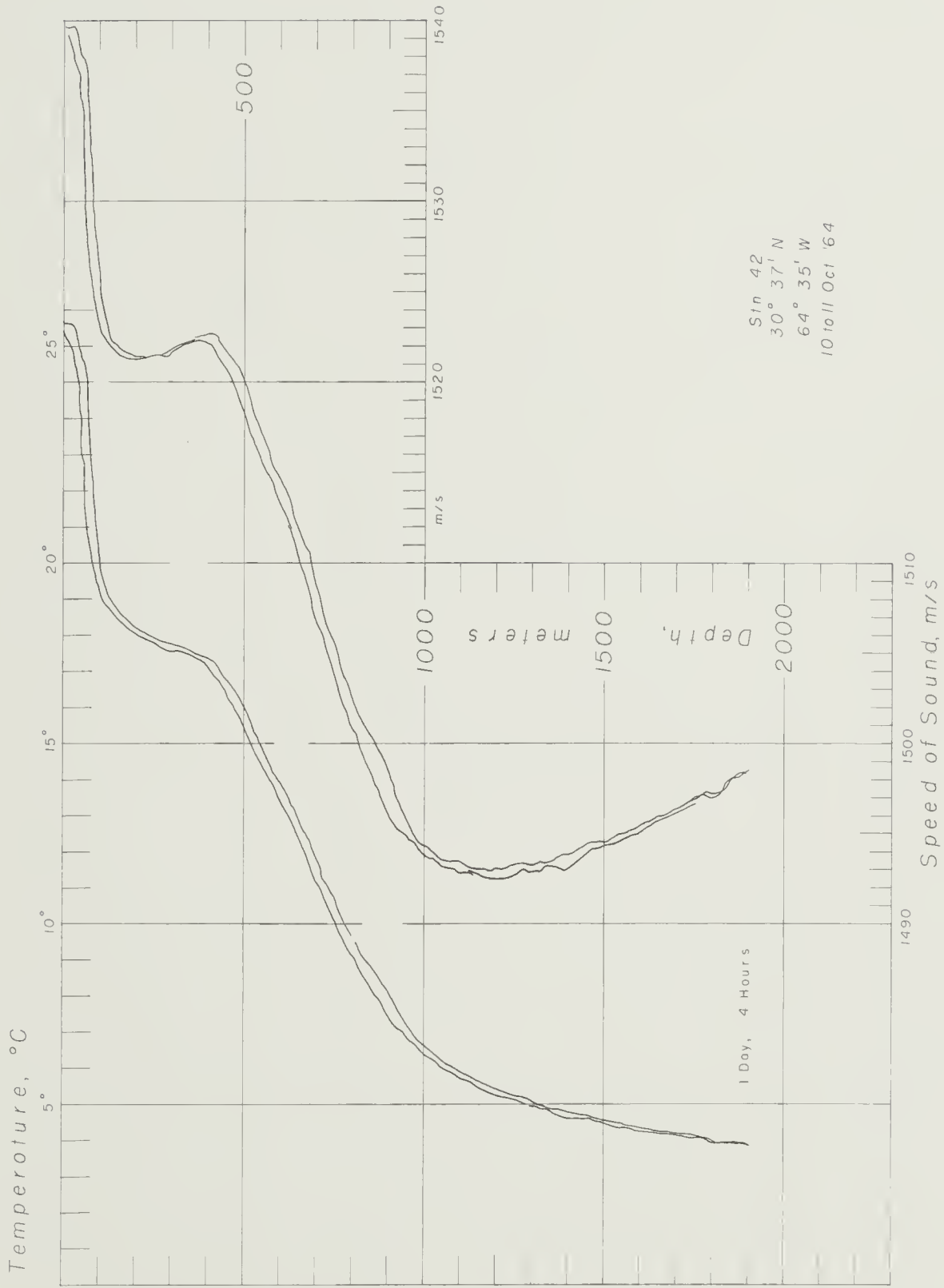


Fig. 58 Profile Envelopes - Station 42

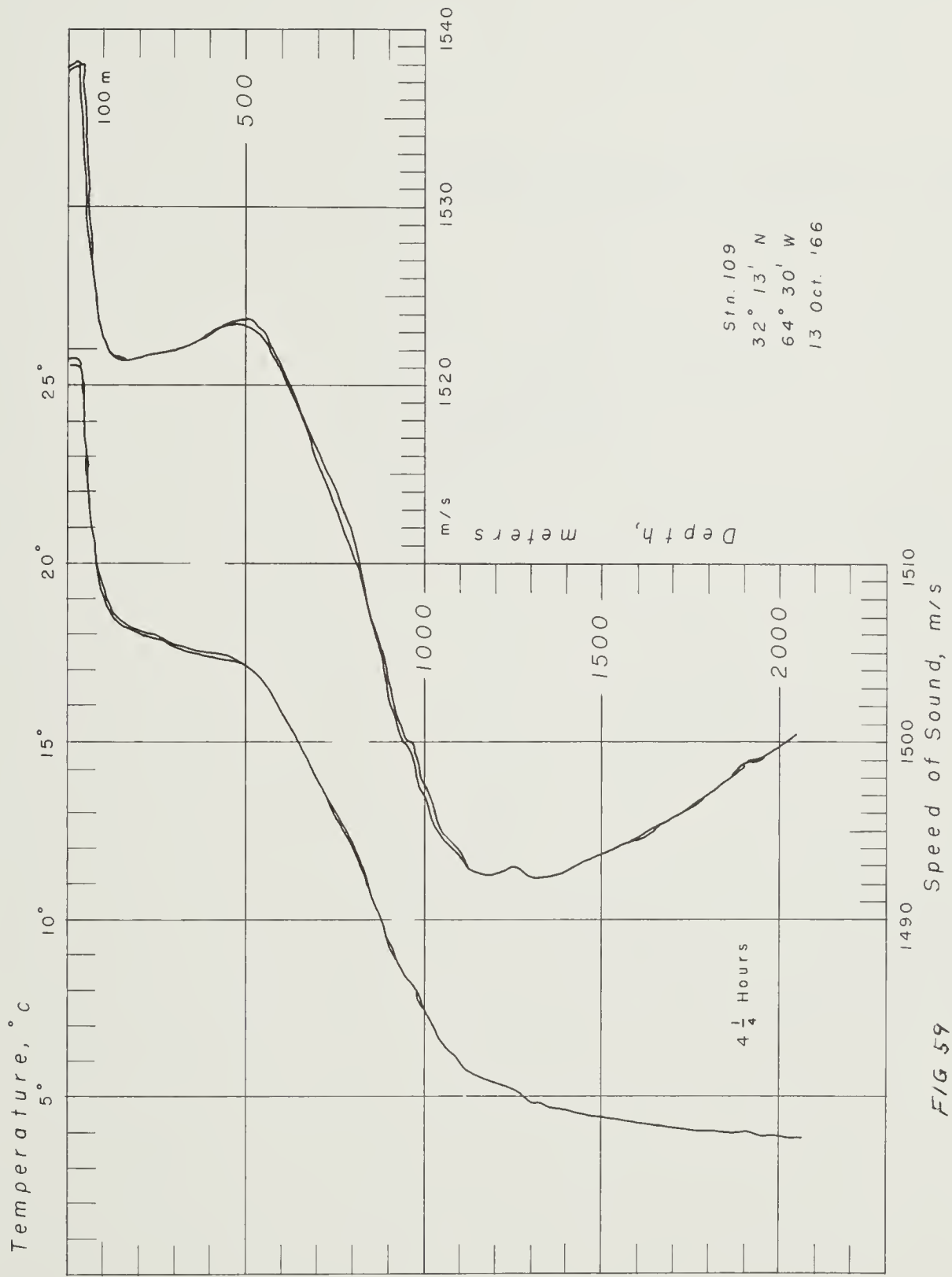


Fig. 59 Profile Envelopes - Station 109

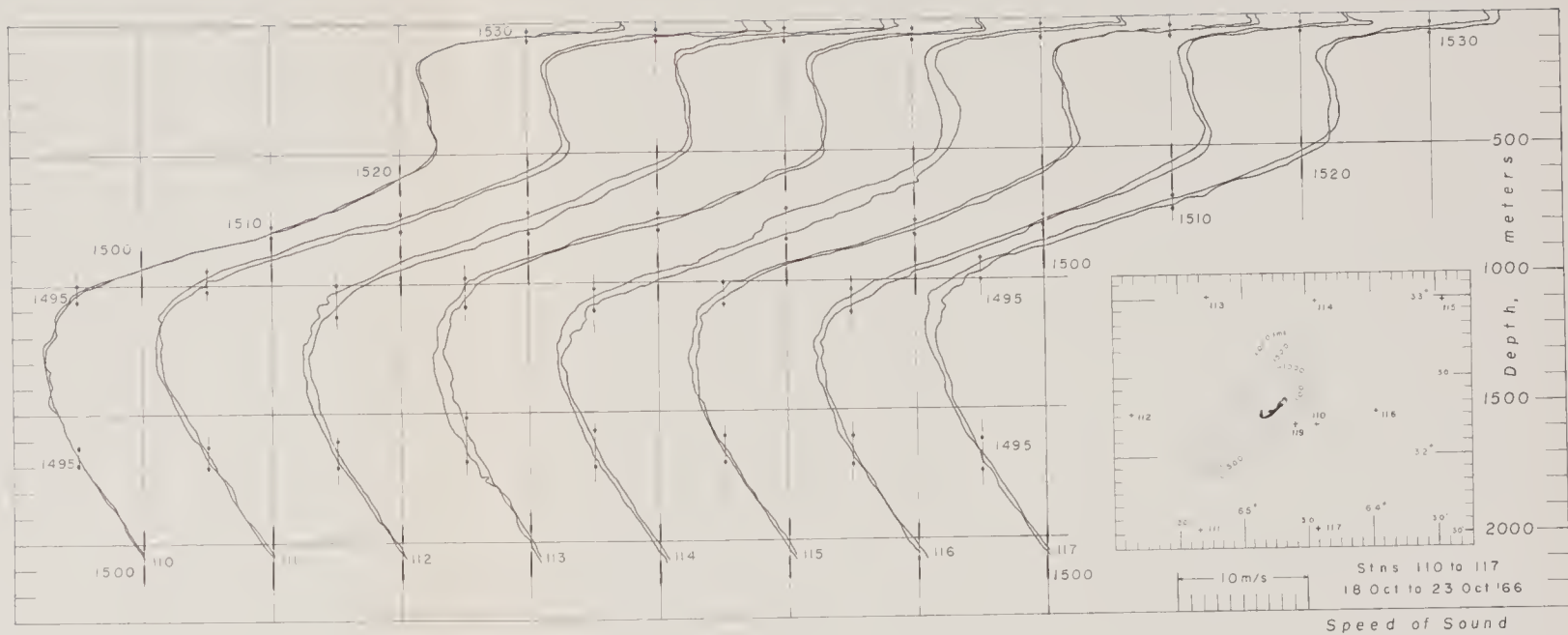


Fig. 60 Sound Speed Profile Envelopes – Stations 110 to 117



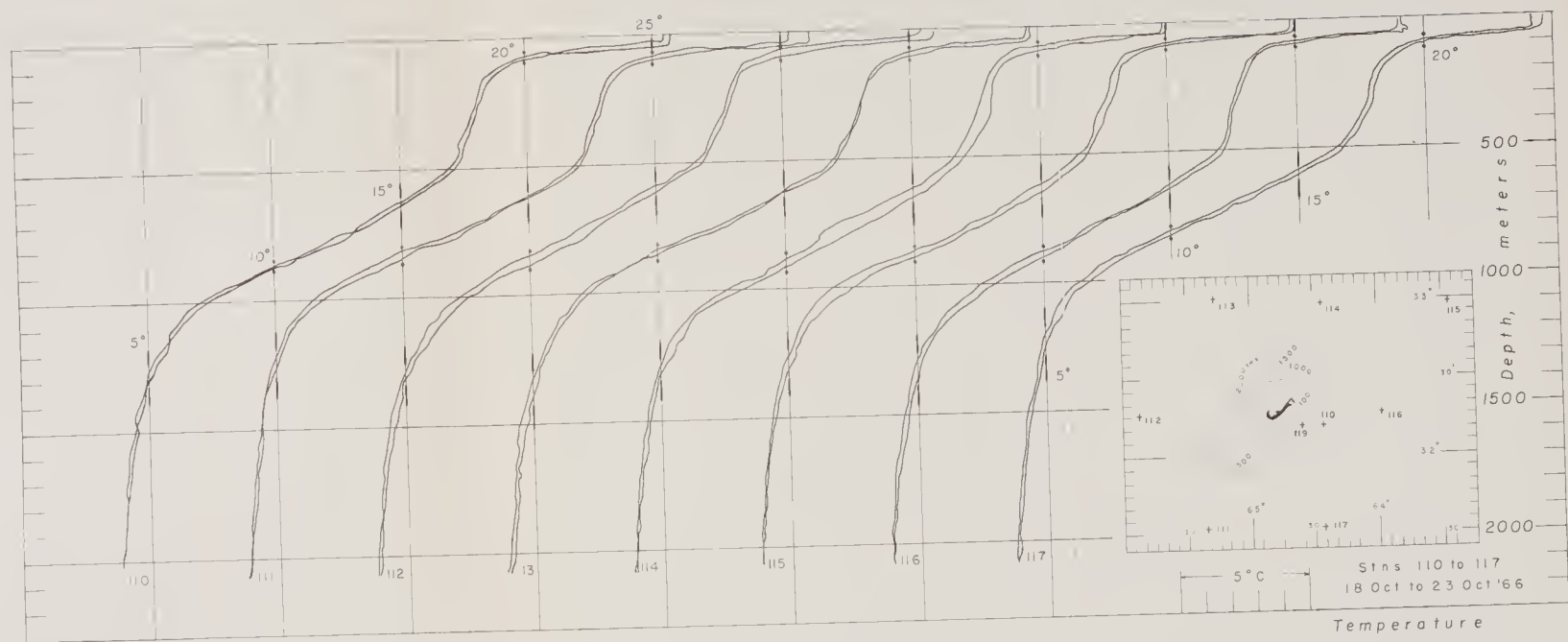


Fig. 61 Temperature Profile Envelopes — Stations 110 to 117



Fig. 62 Profile Envelopes - Station 119

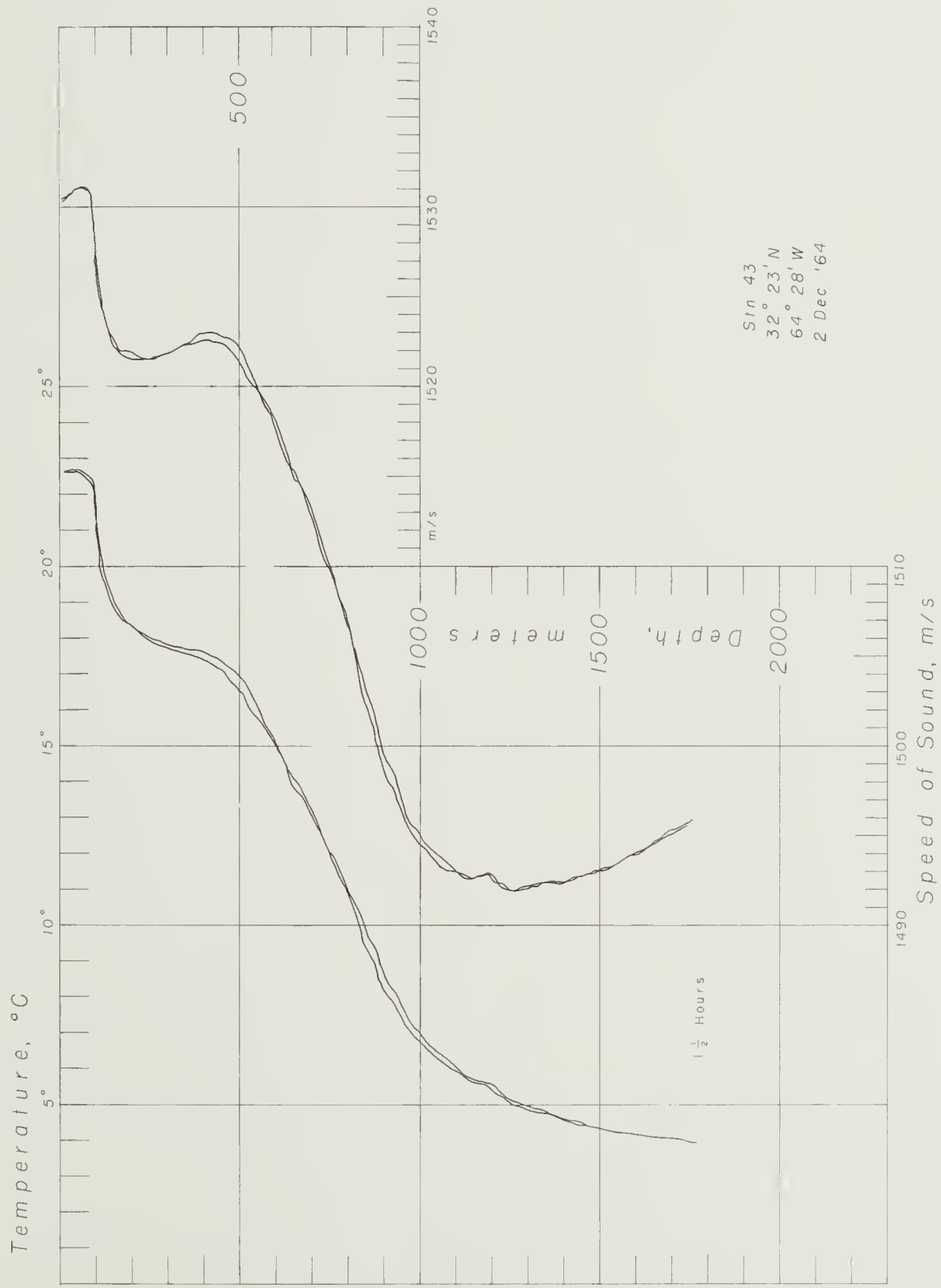


Fig. 63 Profile Envelopes - Station 43

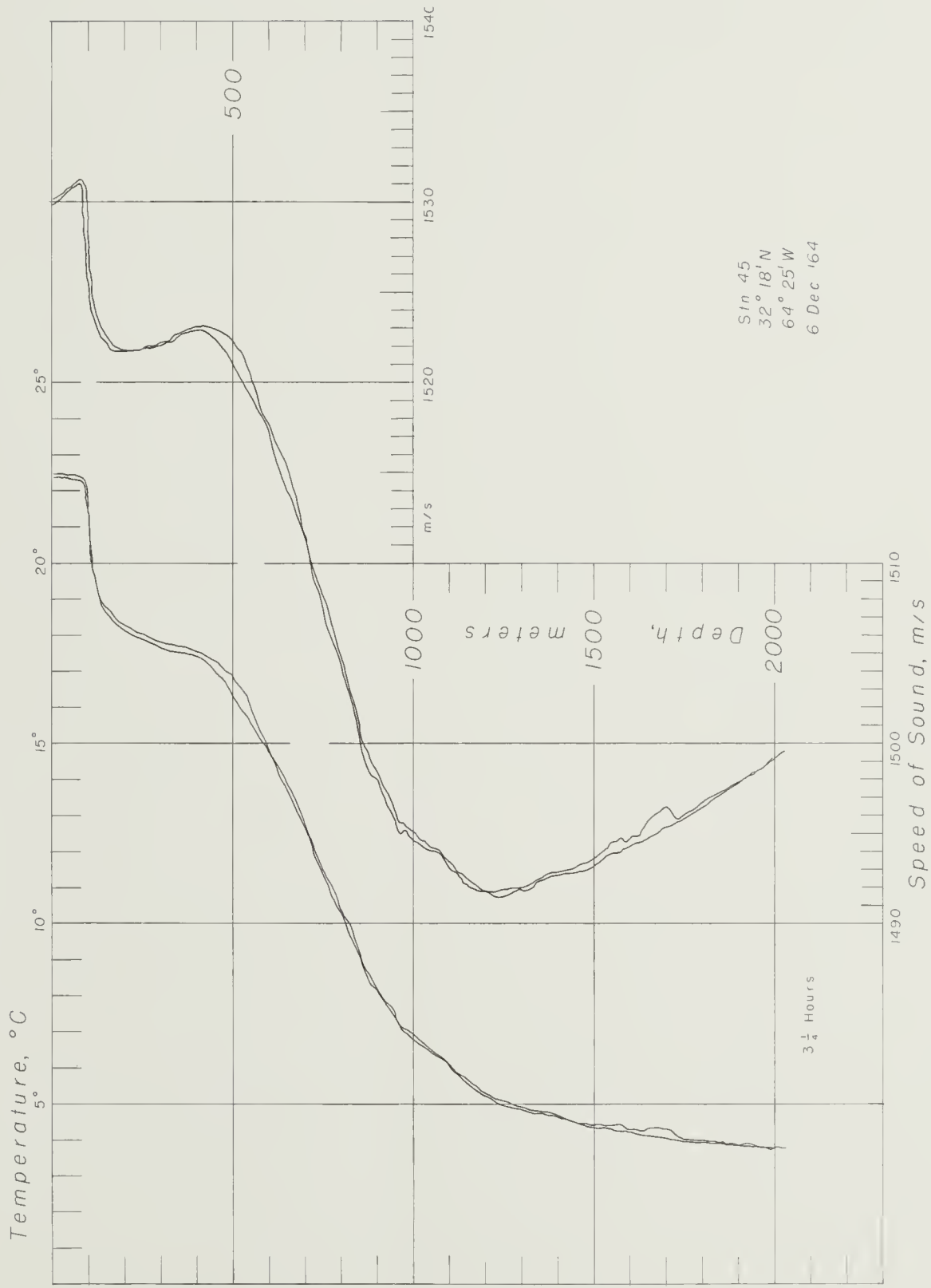
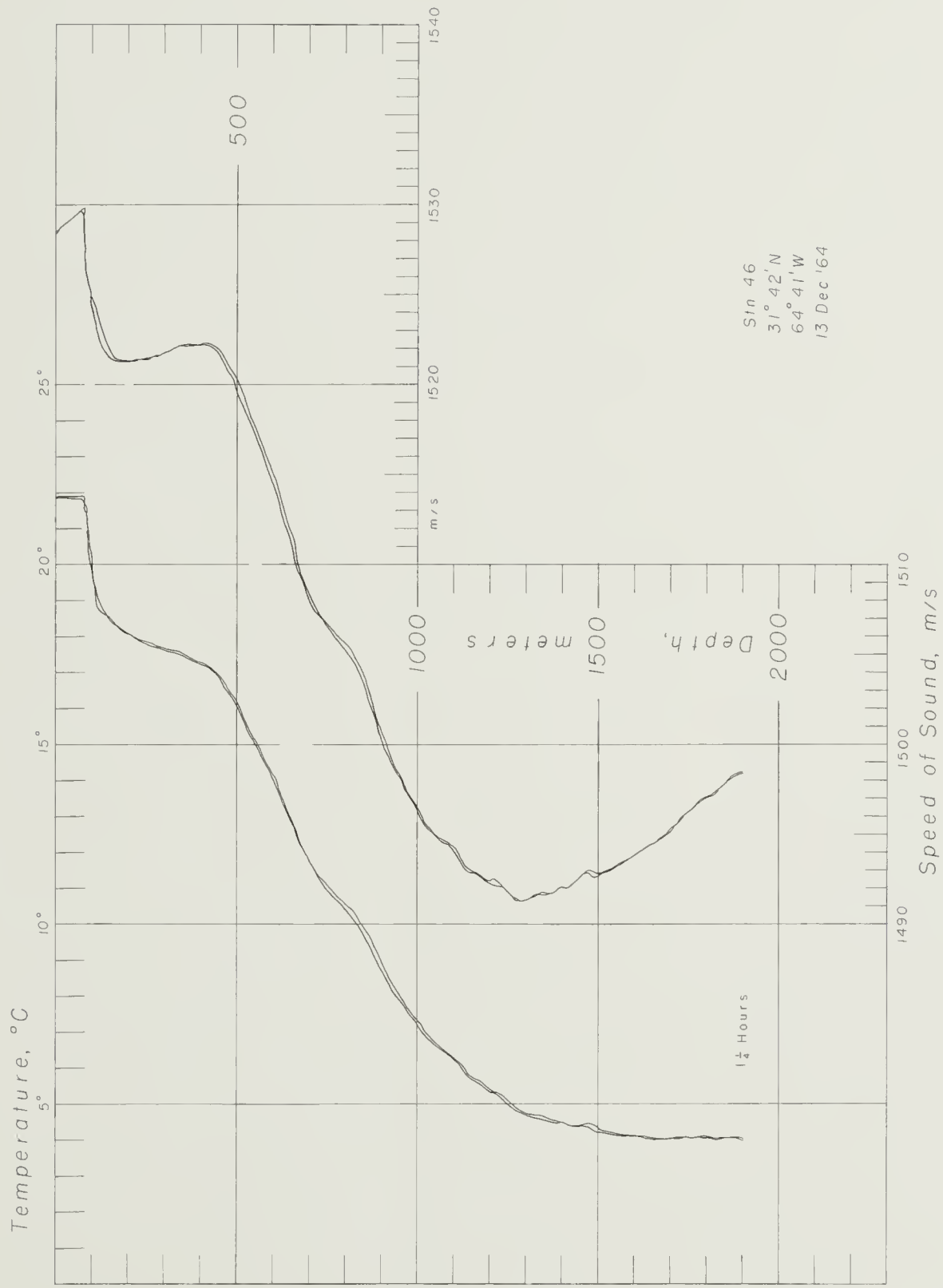
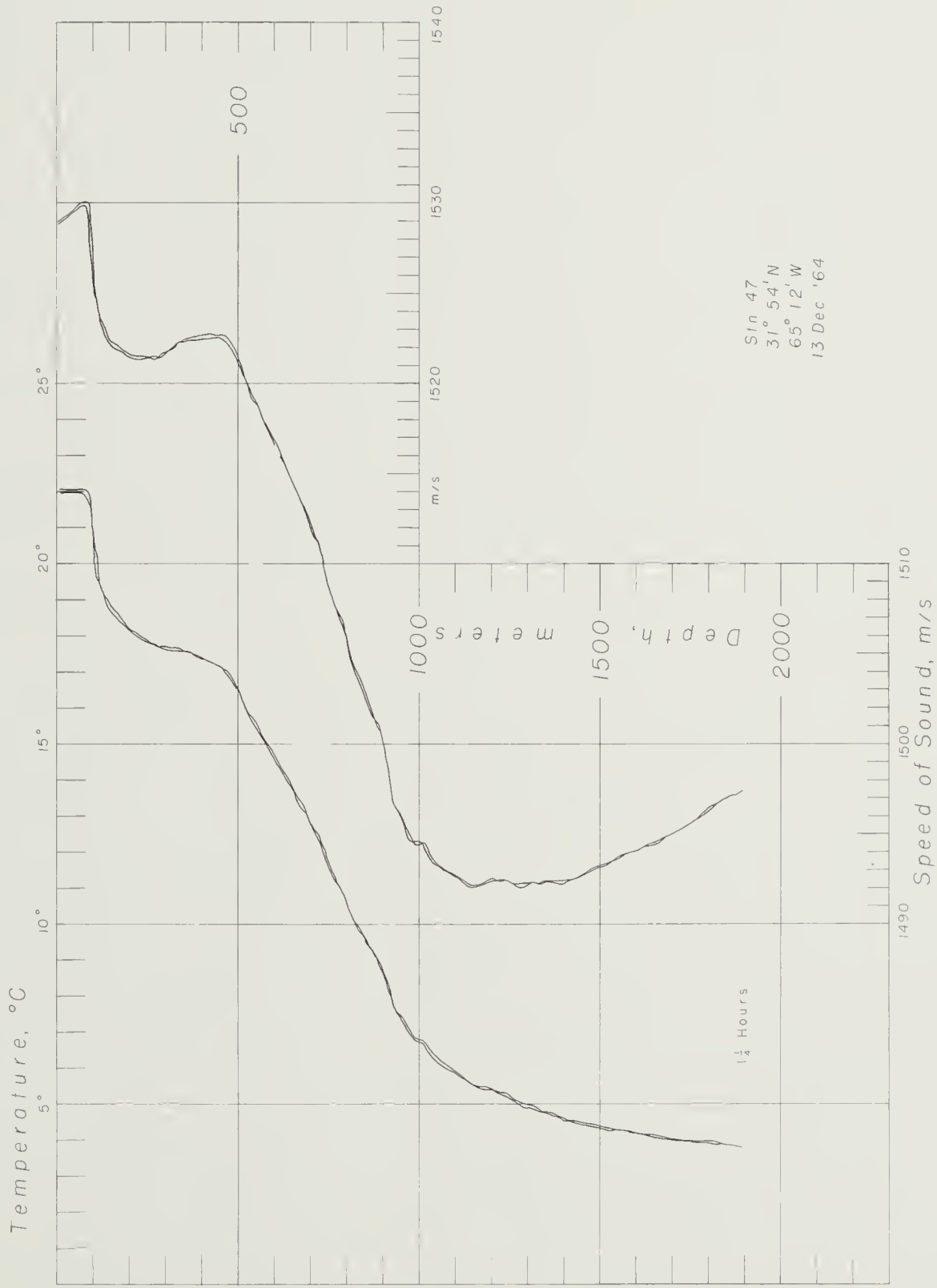


Fig. 64 Profile Envelopes - Station 45



Stn 46
 31° 42' N
 64° 41' W
 13 Dec '64

Fig. 65 Profile Envelopes - Station 46



Stn 47
 31° 54' N
 65° 12' W
 13 Dec '64

Fig. 66 Profile Envelopes - Station 47

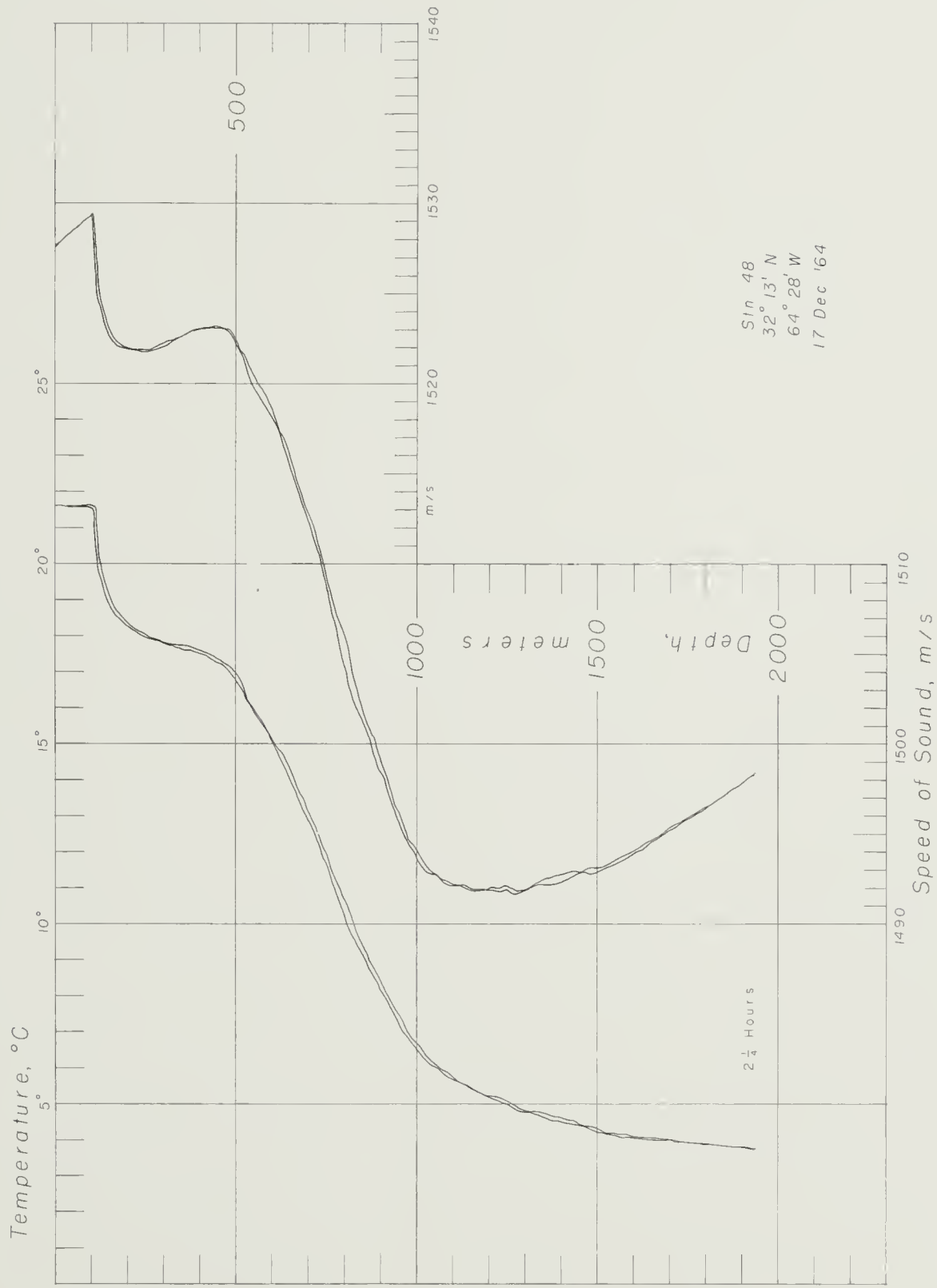


Fig. 67 Profile Envelopes - Station 48

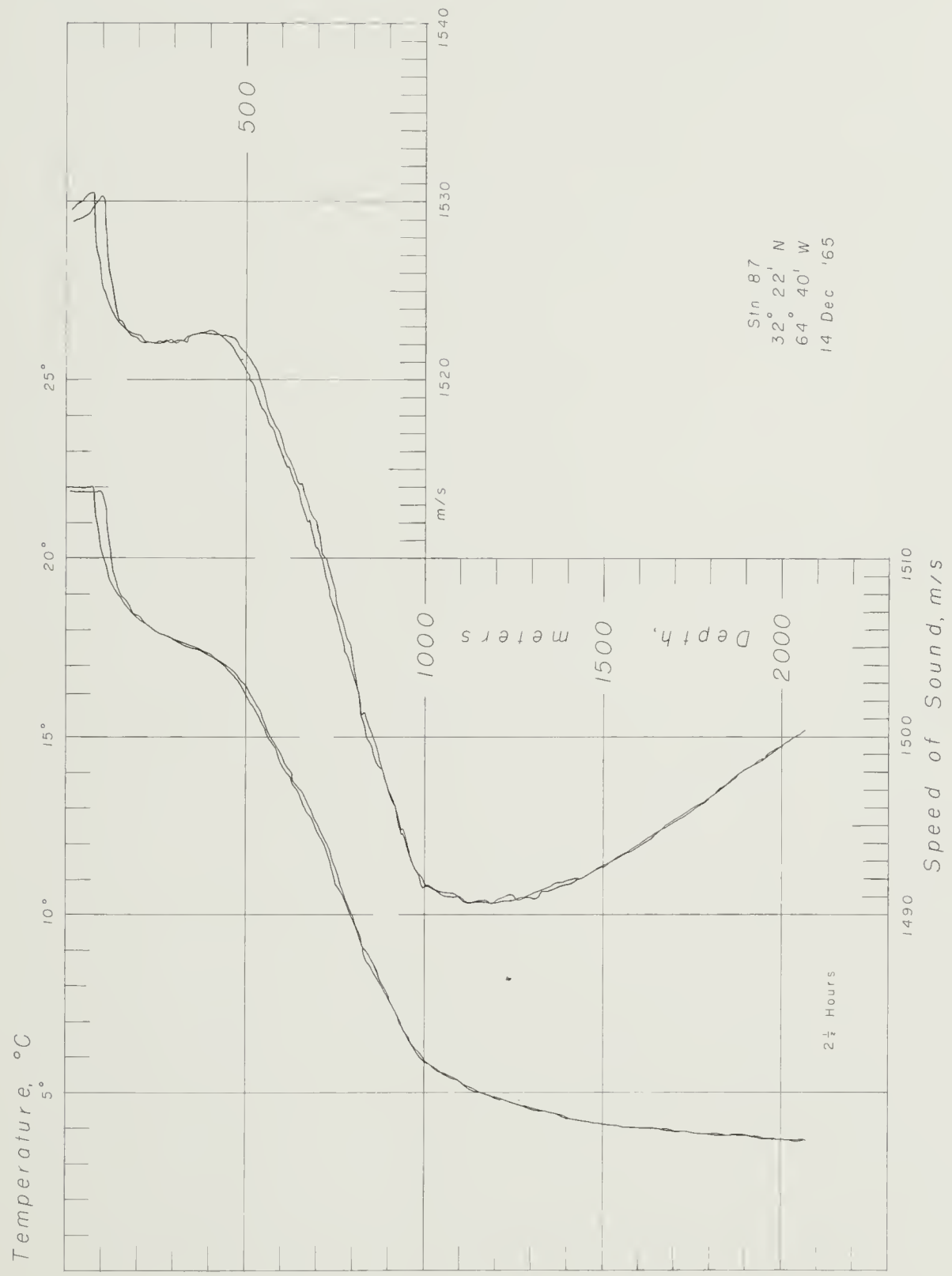


Fig. 69 Profile Envelopes - Station 87

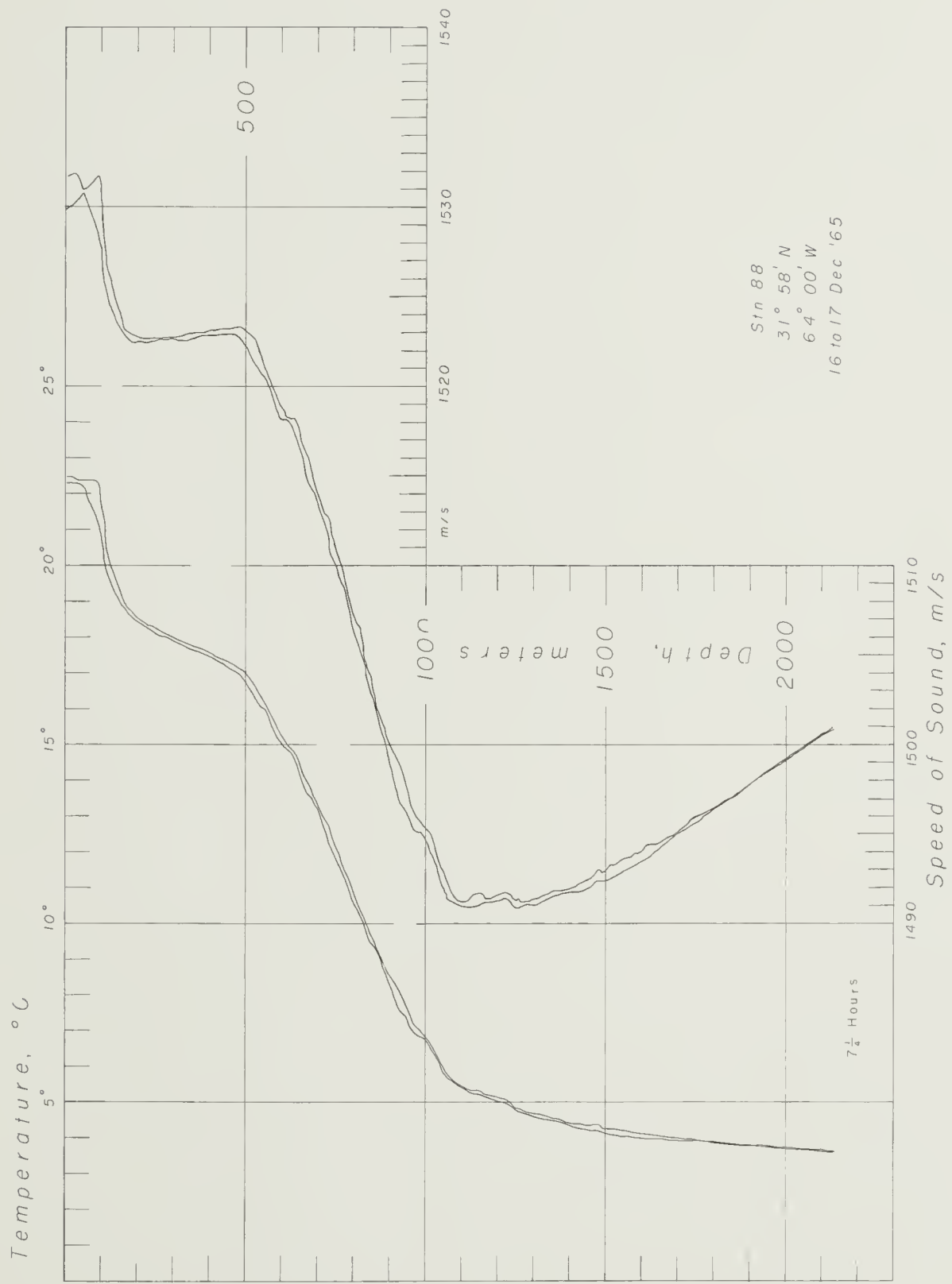


Fig. 70 Profile Envelopes - Station 88

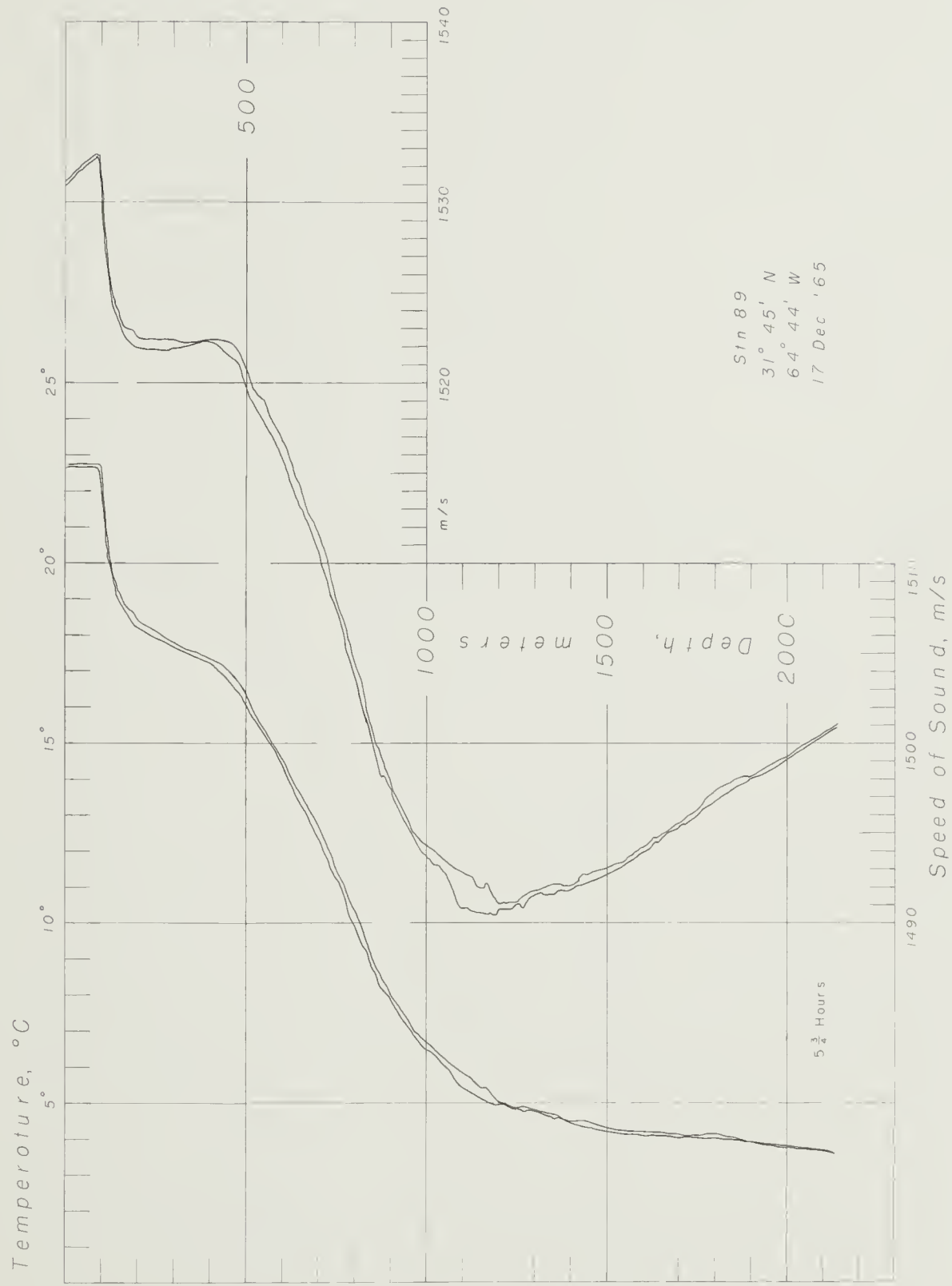


Fig. 71 Profile Envelopes - Station 89

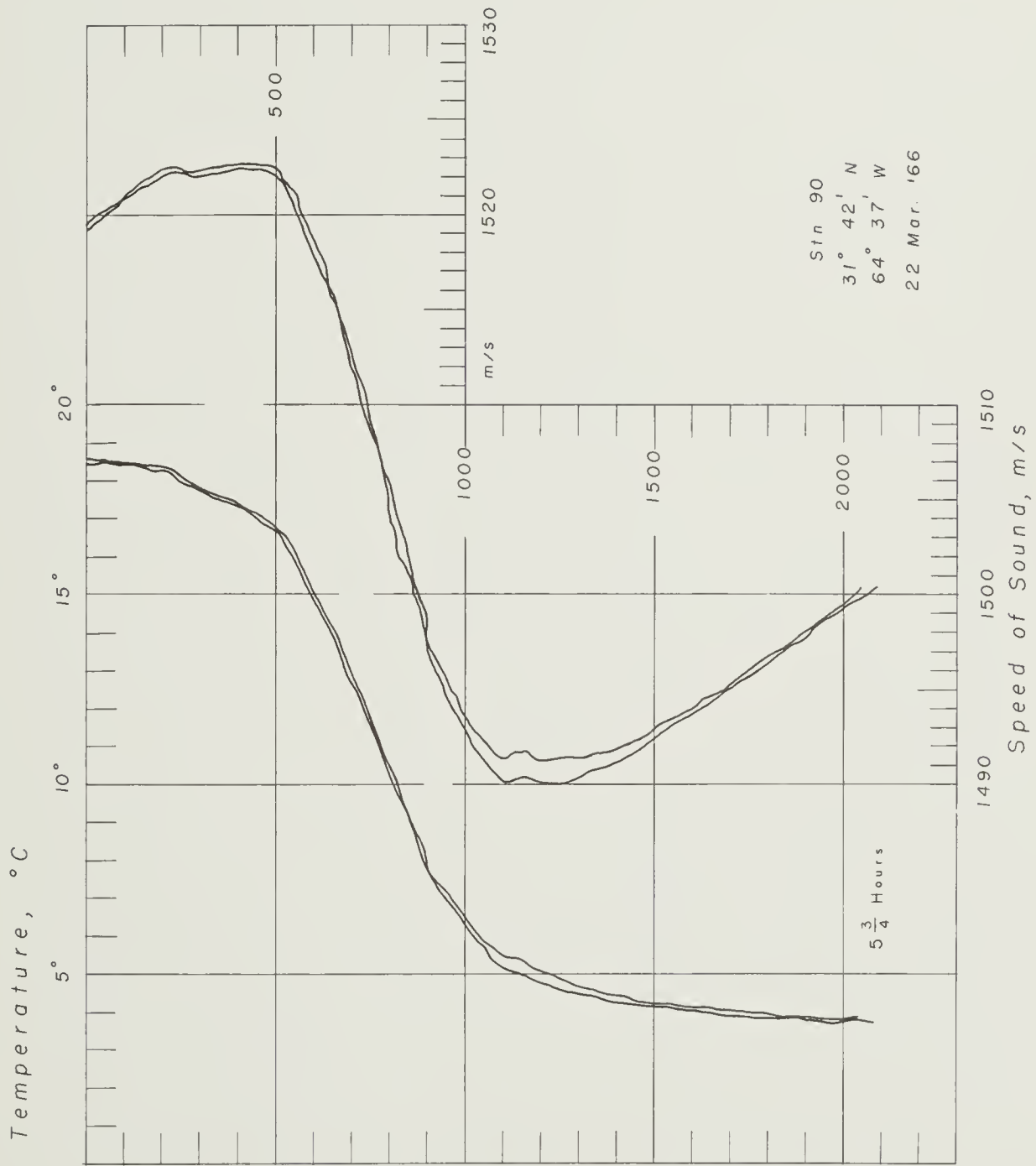


Fig. 72 Profile Envelopes - Station 90

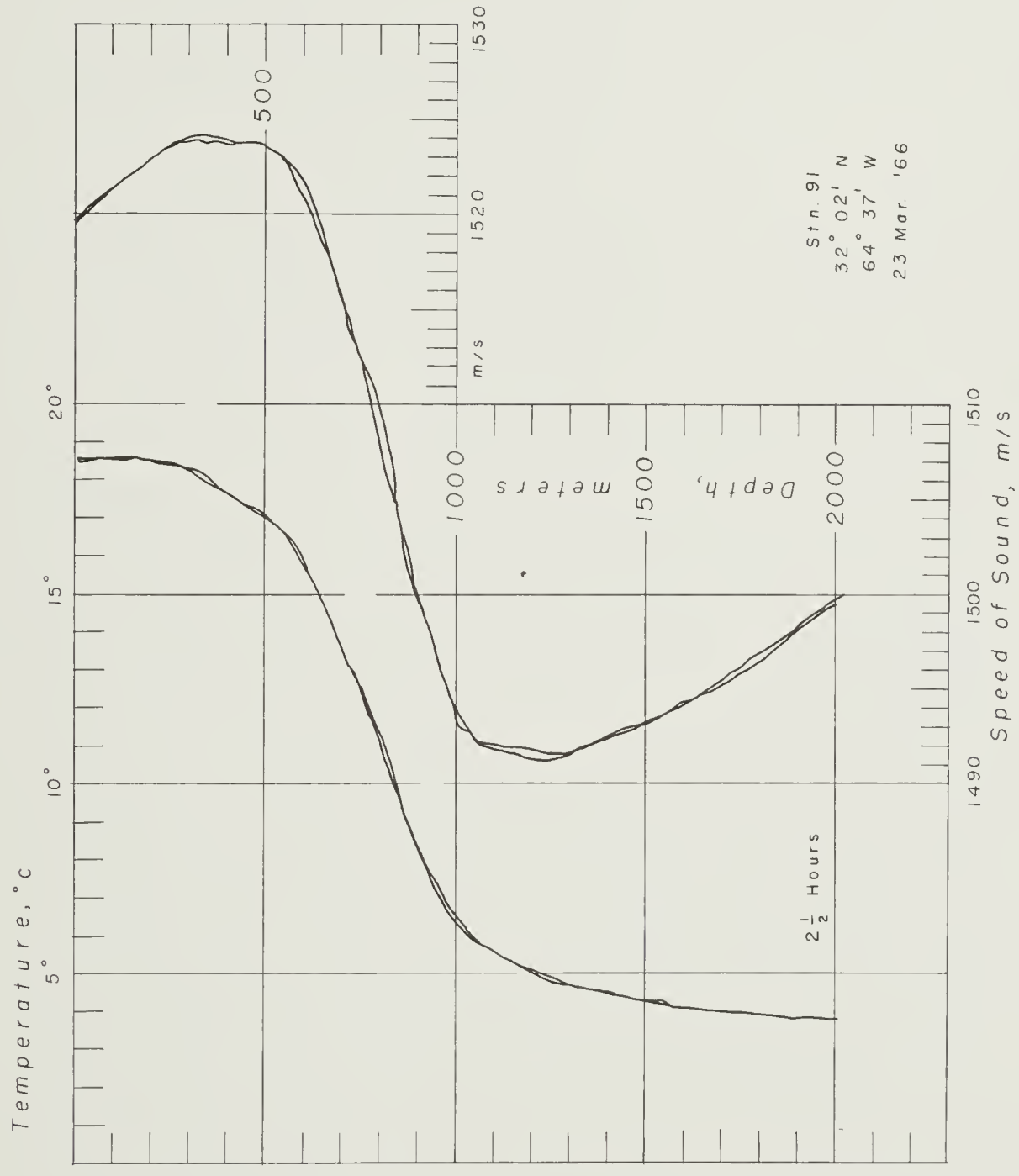


Fig. 73 Profile Envelopes - Station 91

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13. ABSTRACT A collection of high-resolution, precision simultaneous sound speed and temperature profiles to 2200m depth, and their envelopes for each station is presented for 25 stations in Bermudian waters in the months of October, December and March. The period October to March covers the full range of large seasonal changes in the near-surface waters from summer to winter, while the deep waters remain relatively stable and do not show any definite seasonal changes. For two long constant depth stations, in and below the main thermocline, time series and their power density spectra are shown for sound speeds and temperatures. A table of sound channel parameters at all stations concludes the report. The report emphasizes the variability and short-lived phenomena in oceanic waters around Bermuda.			

14. KEY WORDS	LINK A		LINK B		LINK C	
	ROLE	WT	ROLE	WT	ROLE	WT
Oceanography Underwater acoustics Sound Speed: consecutive, detailed profiles Sound Speed: envelopes of consecutive profiles Temperature: consecutive, detailed profiles Temperature: envelopes of consecutive profiles Internal waves Internal waves, power spectra Sound channel Bermuda Sargasso Sea						

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