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PRECISION SOUND VELOCITY PROFILES IN THE OCEAN

VOLUME III

31 HOURS IN THE TONGUE OF THE OCEAN: SOUND SPEED, TEMPERATURE, ETC.

(March 1965)

by

Ants T. Piip

Columbia University Geophysical Field Station
St. David's, Bermuda

Technical Report No. 5
CU-5-67

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December 1967

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ABSTRACT

This report covers a 31-hour anchor station in the Tongue of the Ocean, in extremely calm weather. 34 consecutive, detailed, high-precision profiles and their 10, 20 and 31-hour envelopes are presented for both sound speed and temperature, from the sea surface to the bottom; and graphs showing the gradual changes of constant sound speed and isotherm depths. The sound speed and temperature structure is found to be relatively stable, as in an open ocean. Small, rapid variations abound in the thermocline region; a slight slow rise in deep isotherms occurs, but no tidal effects can be seen.

The ship's motions at anchor are described: a composite of diurnal east-west and semidiurnal north-south oscillations.

Results of a derivation of salinity from sound speed - temperature - depth data are shown to be in good agreement with published data.

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INTRODUCTION

This report covers Station 54, 9-11 March 1965, of our Sound Velocimeter Program. At this station we obtained 34 consecutive sets of high precision sound speed and temperature profiles from the surface to the bottom, in 31 hours. For the duration of the station our R/V SIR HORACE LAMB was anchored in the Tongue of the Ocean, 15 nm NE from Salvador Point, at approximately 1750 m (955 fathoms) depth.

THE TONGUE OF THE OCEAN

The Tongue of the Ocean (TOTO) is a large, protected mile-deep basin in the Bahamas (NavOceanO SP-94, 1967). The 20 by 120 mile basin is open to the deep ocean only in the north, at one of its narrow ends. In the west it is bounded by Andros Island, in the south and east it is virtually cut off from the ocean by wide expanses of the Great Bahama Bank, only a few fathoms deep. The dropoff from the banks to the deep is generally very steep.

The bottom of the basin is quite smooth, with a slight downwards slope to the north.

The topography is such that TOTO is practically an ocean in miniature. The deep northern passage ensures that the deep waters conform to the normal oceanic structure, whereas the barriers on the other sides isolate the basin from currents and other (deep) water motions. This makes the waters in TOTO quite stable, as in the middle of a large ocean, far from any disturbances. There still is sufficient water exchange to keep the water from stagnating or acquiring abnormal characteristics. The surface of TOTO , although open to tides and wind-driven seas, is protected from large oceanic waves and swells by the surrounding shallows. After a period of strong winds it calms down very rapidly.

Acoustically, TOTO is quiet and isolated from oceanic noise. It has a well developed sound channel, the region of minimum sound speed, connected to the oceanic sound channel only through the narrow gap in the north.

In recent years the U.S. Navy, with the cooperation of the govermnents of the U.K. and the Bahamas, has started taking advantage of the unique properties of TOTO for underwater research. TOTO has become the site of the Atlantic Undersea Test and Evaluation Center (AUTEC) for acoustic and weapons systems.

STATION 54: WEATHER, ANCHORING, ETC.

The week before this station had been very cold, according to Bahamian standards for the time of the year, and windy. While our

ship was at Nassau waiting for the weather to improve, there were 10-15 foot seas in TOTO. These had subsided to about a foot or two and the winds were down to about 10 knots from northerly directions by the time the SIR HORACE arrived at station. By nightfall 9 March it was practically calm, and remained so throughout the station. The sea finally became glassy, so calm indeed that the reflection of the half moon was as clear as the moon itself. The moon at the time of the station was at first quarter - a period of minimum tides. The equinoctial full moon occurred on 17 March, a week after the station.

The very calm weather made anchoring easy. The ground tackle was as follows: a 50-pound Danforth anchor; 50 feet of 1/2-inch chain; a block of iron of about 200 pounds; 20 feet of 1/2-inch chain; a 600-pound block of iron; another 20 feet of chain, shackled to the 3/4-inch diameter polypropylene anchor rode. About twice the depth of water was paid out and made fast to the bows of the ship. A tensiometer was connected across a bight of the outgoing anchor rode. Most of the time, the tension on the anchor line was only a few hundred pounds: an extremely low value for a 136 X 25 foot ship, a converted WW II coastal minesweeper. This might give the reader an idea of the utter calm encountered at the station, and the lack of any appreciable currents.

SHIP'S MOTION AT ANCHOR

While at anchor, the ship's position was monitored and recorded by means of the local Decca Hi-Fix system, whose facilities had been made available to us by the AUTEC administration.

The ship's motions are shown, in a somewhat smoothed form, in Fig. 1A. The open circles are surface turnarounds between upcoming and downgoing profiles (the numbers alongside refer to the downgoing profile starting at that point), the black dots on the track are hourly positions.

The ship's heading during the whole station was near-northerly, varying between 290° and 50°.

The ship's motion while at anchor turns out to have been an oscillation back and forth along a reasonably half-elliptical track, centered at 24° 36.0 N, 77° 35.0 W. The long axis of this half ellipse seems to lie along an azimuth 120°. The line connecting the extremes of the observed ship's motion, between turnarounds 17 and 31, is not too far from the axis of the apparent ellipse and lies at an azimuth 106° and is about 3.5 km long.

In Fig. 1B we have plotted the components of the ship's track parallel and normal to azimuth 106°, as a function of time. A very curious picture emerges:

The track for the first 7 hours is somewhat random. This we can explain by the ground tackle settling, and the slight and variable breeze we had during the first hours at station.

The last 24 hours show regular oscillations along both axes,

at different frequencies: parallel to the long axis, a near-perfect sine at a period of about 26 hours; along the short axis, the period is only about 13 hours, and the wave form reminiscent of a rectified sine wave.

The semi-diurnal north-south oscillation must be due to tidal currents - the tides in TOTO are predominantly semidiurnal. We cannot at this time offer a good explanation for the diurnal east-west oscillation, except that it might be a local resonant current system.

In our opinion the ship during the last 24 hours at anchor was faithfully following the surface waters: absolutely calm seas, no appreciable wind. Even the ground tackle did not impose any restoring force on the ship: the polypropylene rode had a total net buoyancy of 2-300 pounds and could be observed floating on the surface for several hundred yards from the ship.

INSTRUMENTATION, DATA REDUCTION

Our instrumentation at this station was very similar to the one described in an earlier paper (Piip, 1964). Two NBS-type velocimeters on the submerged instrument package were read alternately every few seconds for sound speed. Temperature was measured by means of a Hytech Model 4002 telemetering thermometer. A precision pressure gauge, calibrated against an upside-down echo-sounder, provided depth information. A complete instrument reading sequence (depth - velocimeter 1 - depth - velocimeter 2 - depth - temperature) was obtained and printed on paper tape every 12 seconds. Winch speed was closely controlled and kept to about 1/2 m/s - thus, sound speed readings were recorded approximately every 3 m, temperature every 6 m of depth.

The instrument output frequencies (all our sensors were of the FM-type) were later processed ashore: the readings were transferred to IBM cards, and processed at the LGO computer center. Numerical and graphical computer outputs were generated: plots and listings of sound speed vs. depth (one for each velocimeter), and temperature vs. depth.

Most of the time the two velocimeters were operating properly, producing nearly coincident profiles. The visual average of these was used for the final profiles, as included in this report.

About a third through the station, however, it was noticed that one of the two velocimeters of the initial pair had developed a slow drift at shallow depths, in warm water. The suspected instrument was replaced by a spare. The new pair was found to track satisfactorily, proving that both instruments were now operating as they should, and justifying the use of data from the wellbehaved instrument alone from the previous, questionable pair as the final profile.

ACCURACY, CORRECTIONS TO THE PLOTS

The estimated accuracy of the sound speeds in the plots presented

herewith is ± 15 cm/sec, precision about ± 10 cm/sec. The speeds given in the plots pertain to a velocimeter standardized for + 10 °C. In order to obtain the true sound speed at other ambient temperatures, corrections have to be applied to the values given in the plots, because of the thermal expansion of the sound path in the instrument. The corrections are given in the following table.

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

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

where T: ambient temperature, °C

V_i: indicated sound speed

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

All sound speeds are based on Greenspan & Tschiegg (1957), whose tables for distilled water were used in our instrument calibrations in the laboratory.

Depths are true, corrected depths. A conservative estimate of their accuracy is ± 5 m ± 1/2 %, but no more than ± 10 m.

Temperatures are good to ± 0.05 °C.

RESULTS

Sound Speed

The results of our sound speed measurements are shown in Figures 2, 3, and 4. The 34 individual, consecutive profiles appear in Fig. 2. The profiles have been spaced by 2 m/s. To improve legibility, every fifth profile is shown dashed. Each profile carries reference marks at round sound speed values. Small horizontal ticks are 10-minute time marks; their depths and times are listed in the Appendix.

Successive envelopes of the sound speed profiles are given in Fig 3: one for each 10 hours of the 31 hour station, one for the first 20 hours, and one covering the whole station. This presentation probably is of more practical value than a string of individual profiles, all looking very much alike: an envelope immediately gives the total range of variability at each depth, and pinpoints stable and

unstable regions.

Fig. 4 shows the variation of selected constant sound speed depths as a function of time.

This is a smoothed picture: in order to get a better picture of the motion of these depths we have reduced the effects of small, short-time variations by taking the average of two successive profiles, in depth and time, for each point on the graph. This has about the same effect as using a low-pass filter with a cutoff at a few hours period.

The most conspicuous feature of the profiles is their uniformity. No really radical changes are seen to occur over the 31 hours. There are numerous small ripples on the profiles, indicating inhomogeneity. Most of these ripples can be followed through several, sometimes half a dozen or even more profiles. A "step" at about 950 m persists for the duration of the whole station. As usual, the fine structure is most concentrated in and above the sound channel, the foot of the main thermocline.

The vertical "wavelength" of the ripples, which really means the thickness of the various layers and cells of slightly different waters, varies between 20 and 100 meters. The maximum thickness of layers seems to be about the same as their vertical oscillation over their lifetime. The vertical thickness of the composite envelopes Fig. 3, after subtraction of slow trends, corresponds closely to the sum of layer thickness and its oscillation amplitude at each depth.

No diurnal or semidiurnal periodicities can be discerned.

The overall stability of the sound speed structure is a consequence of the isolated character of TOTO. It is too small for any really large or long-period internal waves or water motions to be generated inside, and none can enter from the open ocean.

A detailed look at the 34 profiles shows the following gradual changes among the profiles:

The mixing layer at 200 m depth deepens very slowly by about 20 m. A gradual development of a pronounced high-sound speed layer between 100-200 m can be observed. This looks like a settling down of the surface waters after having been churned up and well mixed during the week before our station.

The knee at about 400 m shows slight periodic flattening around profiles 8-16 (04-11 GMT), 20-23 (15-18 GMT), and 30-34 (01-04 GMT).

Between 500-1000 m depth the profiles gradually straighten from a rounded shape to near-linear gradient over this range. This is due to a low sound-speed layer developing around 950-1200 m.

The sound channel depth remains constant at around 1100 m. Its shape varies: round initially, it becomes quite sharply peaked in profiles 7-10, 22-26, 34. The minimum sound speed in the channel varies around 1490 m/s. There are two short periods where it was over this value, profiles 1-3 (22-24 GMT) and 10-13

(06-09 GMT). Over the whole 31 hours of our station, the minimum sound speed had a tendency of gradually decreasing.

Below the sound channel, everything is uniform and increasingly stable. After profile 10 (08 GMT), the incipient widening of the less than 1490 m/s region depresses the depth of the 1491 and 1492 m/s contours appreciably.

Towards the end of the station, a distinct step in the profiles becomes apparent at great depth: it moves upwards from 1700 m in profile 27 to 1600 m in profile 34.

Temperature

Our temperature data is displayed in Figures 5, 6, 7. These figures have been constructed similarly to the corresponding sound speed graphs: 34 individual profiles, spaced 1 °C, in Fig. 5; ten and twenty-hour envelopes and one for the whole station in Fig. 6; and depths of isotherms in Fig. 7.

At first glance, the temperature profiles in Fig. 5 look somewhat smoother than the sound speed ones of Fig. 2. This smoothness is only apparent, a consequence of the two times lower sampling rate.

Most of the comments about the sound speed structure and its changes are applicable to temperature as well: it is the temperature that determines the gross features of the sound speed structure, since salinity normally is rather stable, and its small variations have less effect on the sound speed than the normally encountered temperature structure.

The slow changes in isotherm depths around and below 1000 m explain the gradual decrease of the minimum sound speed in the sound channel: wherever the isotherms rise, the sound speed decreases. (A rising isotherm of course means that temperature at a given point is sinking in this region.)

The deep isotherms were more unstable in depth for the duration of our station than the shallower ones - in the 300-800 m range oscillations are discernible, but no long-term drift; the deep ones all show a gradual upwards trend.

Salinity

Salinity was not measured directly. Instead, as an experiment, we have turned the usual procedure around and tried to compute salinity values from our depth, temperature and sound speed values. Wilson's tables (Wilson, 1960) were used for this purpose. 6 profiles (2, 6, 10, 14, 17, 24) were analyzed at every 100 m depth. The mean of these salinity profiles is shown in Fig. 8, together with its TS diagram.

The quality of a salinity determination in this fashion is dependent on the uncertainties of the available depth - temperature - sound speed information. In our case, the instrument uncertainties are as follows:

Sound speed	± 15 cm/sec	=	± 0.11 o/oo	Salinity
Temperature	± 0.05 °C	=	± 0.13 o/oo	"
Depth (surface)	± 5 m	=	± 0.06 o/oo	"
Depth (deep)	± 10 m	=	± 0.12 o/oo	"
Total uncertainty, at surface		=	± 0.30 o/oo	"
below 1000 m		=	± 0.36 o/oo	"

Taking the mean of 6 observations reduces the random experimental errors by a factor of $\sqrt{6} \simeq 2.5$. Thus, our final salinity profile should be good to ± 0.12 o/oo S at shallow depths, and to ± 0.15 o/oo S deeper than 1000 m.

In addition to the instrument uncertainties, the tables are somewhat questionable, too, and not in perfect agreement with each other. E.g., at zero depth, zero salinity and 10 °C, Greenspan & Tschiegg's table gives 1447.59 m/s as the sound speed, Wilson 1447.40 m/s. (It is suspected that the sound speeds in Greenspan & Tschiegg's table are too high by about a foot/sec. (C.E. Tschiegg, personal communication.))

In spite of all the uncertainties, our salinity profile is in excellent agreement with published data, and falls well within the center 50 % band of most commonly observed values (NavOceanO SP-94, 1967). This seems to prove our contention that with good instruments and reasonable care useful salinity data can be deduced from sound speed - temperature - depth measurements.

SUMMARY

We have attempted to give a comprehensive description of a 30-hour period in the Tongue of the Ocean around the vernal equinox. Therefore, in addition to our prime purpose - describing the sound speed structure and its variations, we have included a description of the temperature structure as well as some curious aspects of the ship's motion at anchor, resulting from periodic currents, and an estimate of the salinity structure as deduced from our sound speed - temperature - depth measurements.

Although our results will in all probability be not exactly repeatable at other times of the year, or in other years, the picture given in this report should be construed as being typical of changes that occur in TOTO over a period slightly longer than a day.

We shall conclude with a short table of numerical results. Table I lists mean sound speeds and temperatures for every 100 m of the profiles used in our salinity determinations (2, 6, 10, 14, 17, 24); the total spread of sound speed and temperature values encountered in our 34 profiles in 31 hours; and our computed salinities and σ_T.

TABLE I

Mean Nunerical Values For Every 100 m Depth

D[m]	$\overline{V}$ [m/s]	ΔV [m/s]	$\overline{T}$ [°C]	ΔT [°C]	$\overline{S}$ [o/oo]	$\overline{\sigma_T}$
10	1533.21	0.4	23.54	0.30	36.82	25.08
100	1535.21	0.6	22.76	0.35	36.80	25.04
201	1532.62	5.4	22.10	1.85	36.94	25.61
300	1522.80	1.8	18.03	0.45	36.39	26.32
400	1520.06	2.0	16.61	0.55	36.03	26.41
502	1513.45	2.6	14.14	0.70	35.72	26.72
600	1506.98	2.2	11.80	0.55	35.37	26.93
700	1501.53	1.7	9.86	0.45	35.16	27.09
800	1497.84	1.4	8.47	0.40	35.01	27.22
900	1495.66	2.4	7.03	0.55	34.91	27.35
1000	1490.93	1.5	5.83	0.35	34.98	27.56
1104	1490.03	1.4	5.19	0.30	35.02	27.69
1200	1490.13	0.9	4.82	0.20	34.96	27.68
1300	1491.03	0.8	4.60	0.20	34.98	27.72
1400	1491.78	0.6	4.38	0,15	34.97	27.74
1502	1492.70	0.6	4.21	0.15	34.91	27.70
1600	1493.83	0.5	4.09	0.15	34.87	27.69
1704	1494.89	0.3	3.96	0.2	34.98	27.72

ACKNOWLEDGEMENTS

This work was performed under the aegis of Acoustics Programs, Code 468, U.S. Office of Naval Research.

Without the help of the AUTEC organization, particularly Mr. V.J. Prestipino, and the Bahamas Decca we never could have followed our ship's motions as well as we did.

Thanks also are due to my colleagues and collaborators at the Columbia University Geophysical Field Station, particularly Brian Turner, and Capt. McCann and the crew of our R/V SIR HORACE LAMB.

Dr. James Dorman's contributions to this program are gratefully acknowledged: he wrote the data reduction programs and assisted in operating the LGO computer.

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A. Piip, 1964: "Fine Structure and Stability of the Sound Channel in the Ocean," J. Acoust. Soc. Am. 36, 1948-53.

M. Greenspan and C.E. Tschiegg, 1957: "Speed of Sound in Water by a Direct Method," J. Res. Nat. Bur. Stds. 59, 249.

W.D. Wilson, 1960: "Equation for the Speed of Sound in Sea Water," J. Acoust. Soc. Am. 32, 1957 (L).

APPENDIX
Timing of Profiles

Prof.	D(m)	GMT	Prof.	D(m)	GMT	Prof.	D(m)	GMT	Prof.	D(m)	GMT	Prof.	D(m)	GMT
1	4	2128	7	1	0305	14	1754	0938	21	1	1626	27	2	2309
	7	2130		59	0310		1714	0940		124	1630		19	2310
	317	2140		355	0320		1346	0950		153	1640		399	2320
	728	2150		693	0330		954	1000		909	1650		596	2330
	1192	2200		1043	0340		528	1010		1269	1700		876	2340
	1614	2210		1338	0350		129	1020		1687	1710		997	2345
	1755	2214		1658	0400		1	1025		1749	1712	28	981	2349
2	1755	2219		1745	0404	15	441	1040	22	1750	1716		978	2350
	1716	2220	8	1746	0408		848	1050		1615	1720		664	0000
	1211	2230		1732	0410		1398	1100		1255	1730		372	0010
	883	2240		1528	0420		1754	1108		927	1740		108	0020
	495	2250		1263	0430	16	1756	1120		595	1750		1	0025
	106	2300		882	0440		1426	1130		168	1800	29	1	0026
	8	2305		567	0450		1017	1140		1	1804		103	0030
3	5	2309		276	0500		579	1150	23	1	1825		399	0040
	20	2310		45	0510		128	1200		193	1830		707	0050
	381	2320		1	0512		5	1203		467	1840		1024	0100
	709	2330	9	4	0514	17	3	1211		751	1850		1358	0110
	1018	2340		165	0520		332	1220		1061	1900		1687	0118
	1372	2350		469	0530		823	1230		1377	1910	30	1692	0120
	1746	2359		824	0540		1088	1240		1650	1920		1369	0130
4	1746	0001		1283	0550		1405	1250		1739	1924		930	0140
	1449	0010		1686	0600		1645	1300	24	1730	1934		436	0150
	1094	0020		1737	0602		1754	1304		1674	1940		4	0158
	755	0030	10	1737	0604	18	1754	1306		1452	1950	31	2	0201
	446	0040		1583	0610		1714	1310		1198	2000		353	0210
	159	0050		1187	0620		1522	1320		925	2010		927	0220
	3	0057		812	0630		1306	1330		622	2020		1434	0230
5	1	0059		412	0640		1064	1340		371	2030		1685	0235
	65	0100		26	0650		759	1350		112	2040	32	1687	0238
	382	0110		1	0651		429	1400		5	2044		1665	0240
	781	0120	11	1	0653		75	1410	25	3	2050		1431	0250
	1087	0130		77	0700		1	1412		268	2100		1084	0300
	1399	0140		387	0710	19	1	1414		512	2110		693	0310
	1655	0150		897	0720		108	1420		809	2120		263	0320
	1753	0155		1341	0730		447	1430		1116	2130		1	0326
6	1753	0158		1709	0740		815	1440		1360	2140	33	3	0329
	1723	0200		1750	0741		1187	1450		1609	2150		27	0330
	1538	0210	12	1749	0743		1526	1500		1711	2155		564	0340
	1344	0220		1631	0750		1750	1508	26	1712	2156		1066	0350
	1142	0230		1217	0800	20	1652	1517		1579	2200		1509	0400
	860	0240		735	0810		1632	1520		1303	2210		1685	0404
	512	0250		322	0820		1442	1530		1303	2220	34	1687	0406
	128	0300		1	0827		1236	1540		1089	2230		1608	0410
	1	0303	13	1	0849		1001	1550		743	2240		1226	0420
				6	0850		688	1600		368	2250		750	0430
				321	0900		332	1610		81	2300		284	0440
				690	0910		1	1618		1	2305		1	0447
				1200	0920									
				1676	0930									
				1755	0932									

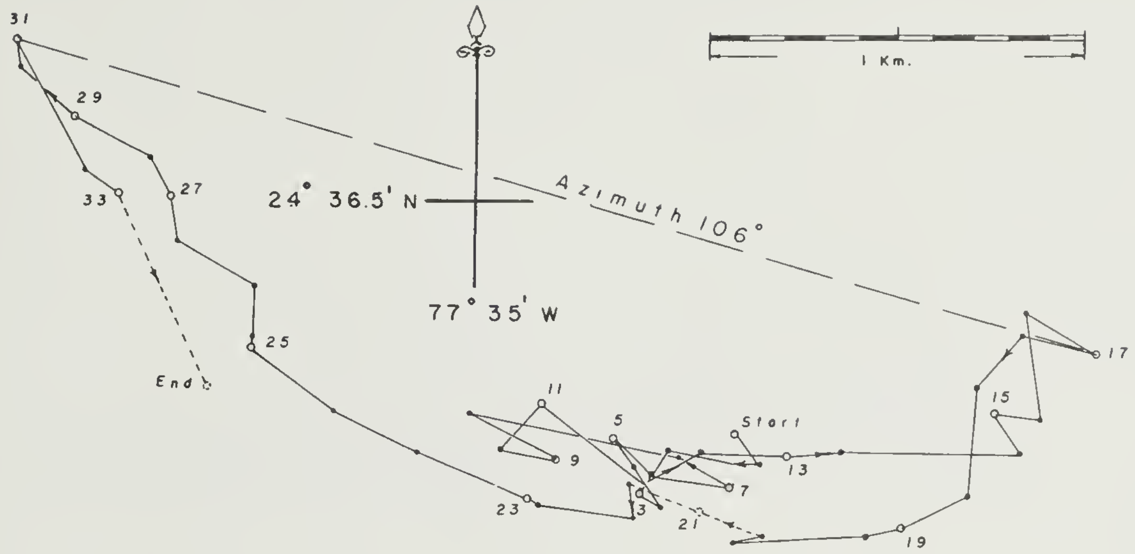


Fig. I-A: Ship's track at anchor

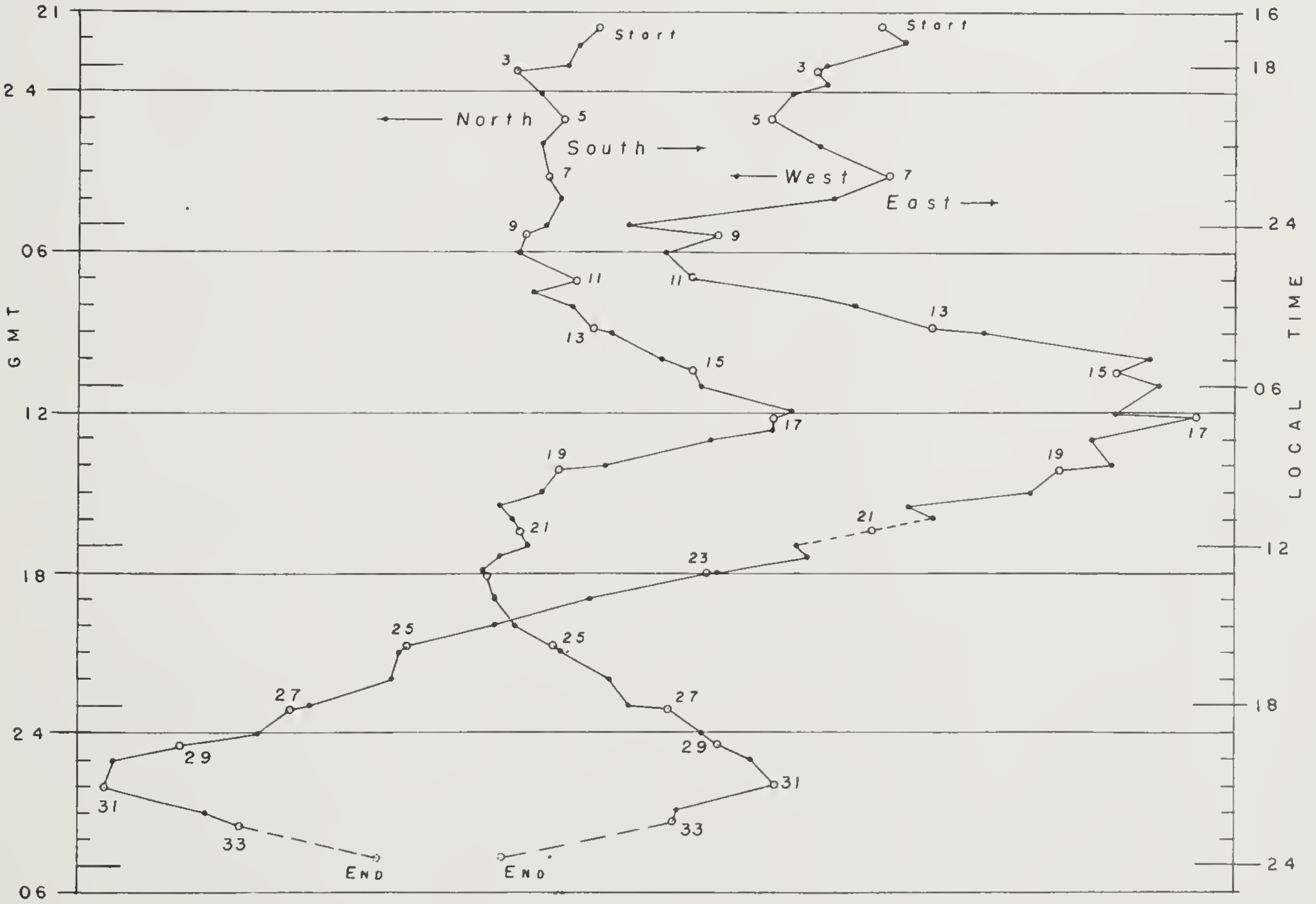


Fig. I-B: Components of ship's track
II and ⊥ to azimuth 106°

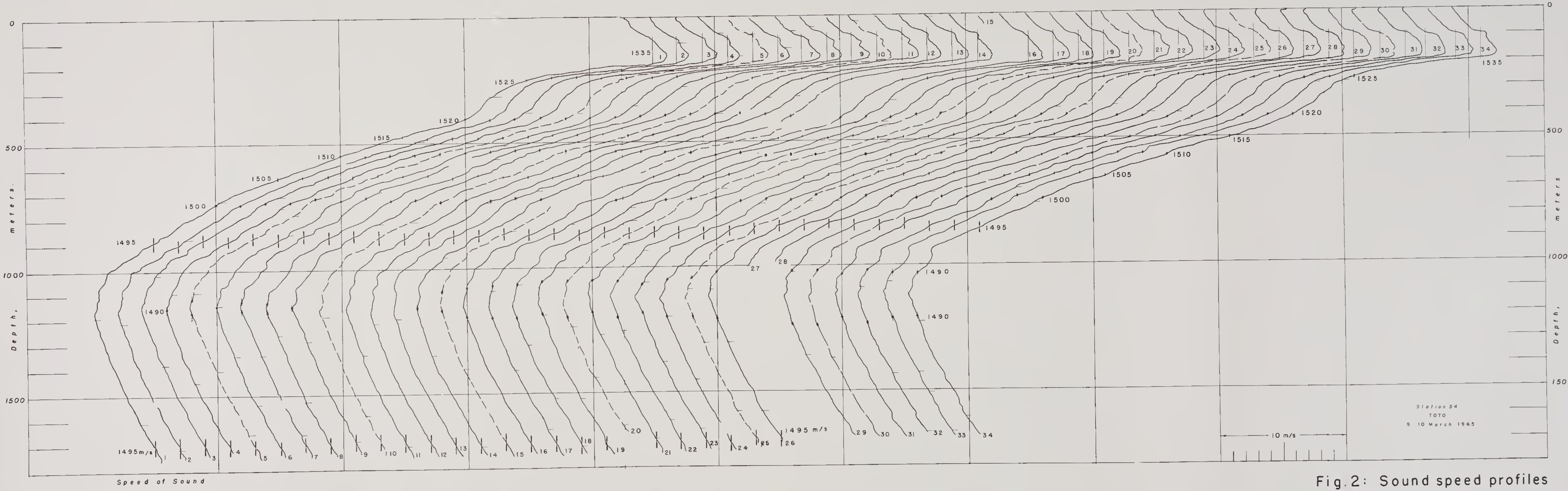


Fig. 2: Sound speed profiles

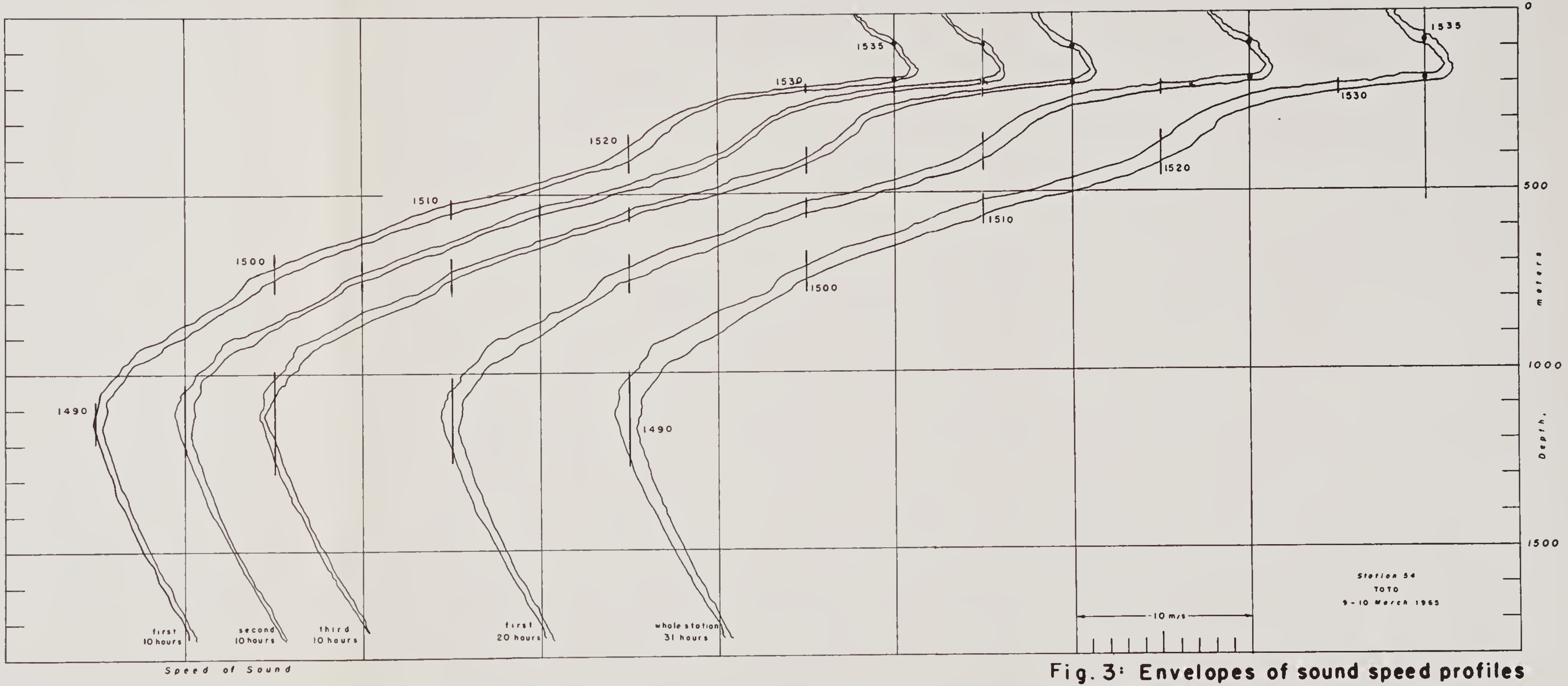


Fig. 3: Envelopes of sound speed profiles

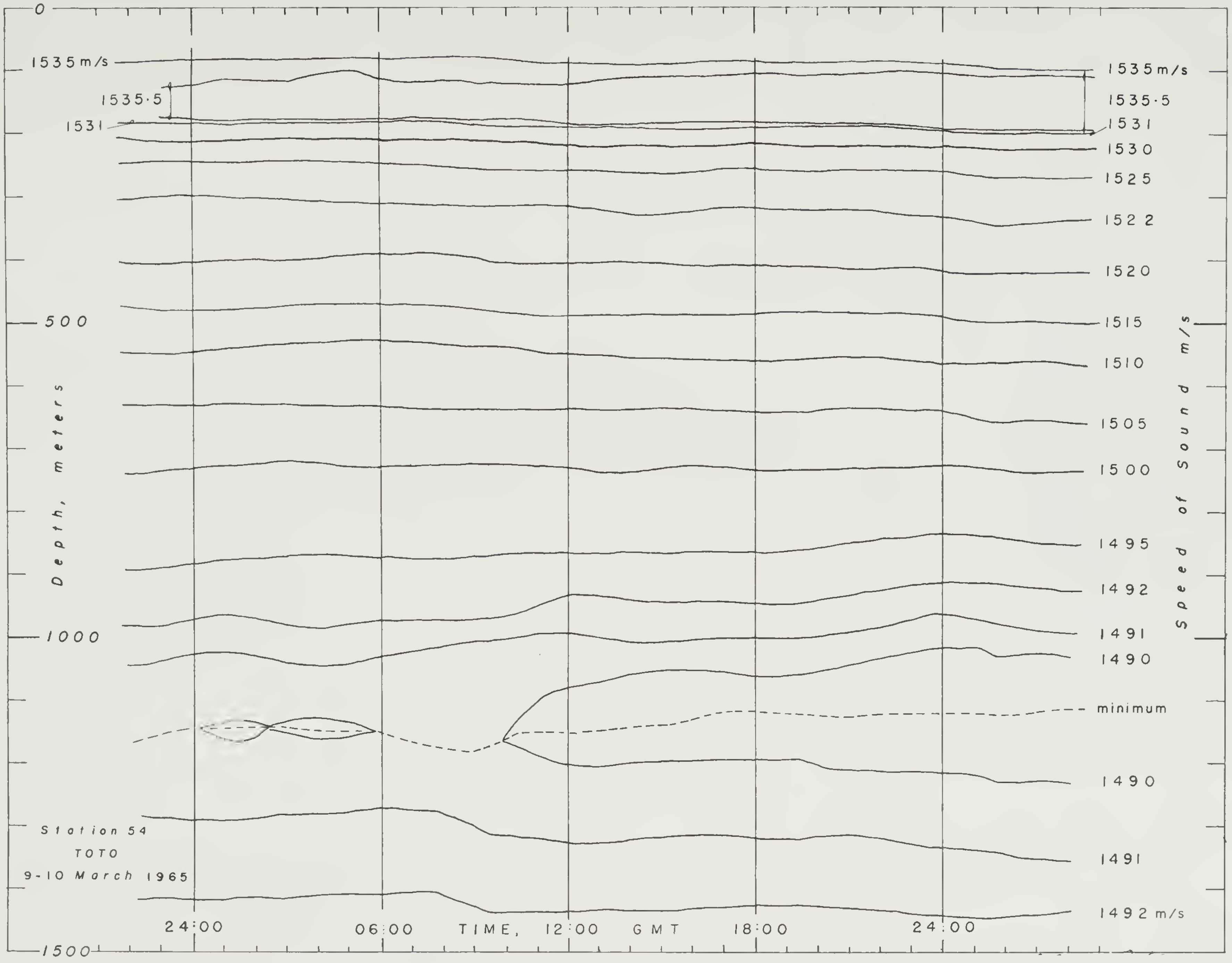


Fig. 4: Depths of constant sound speed levels

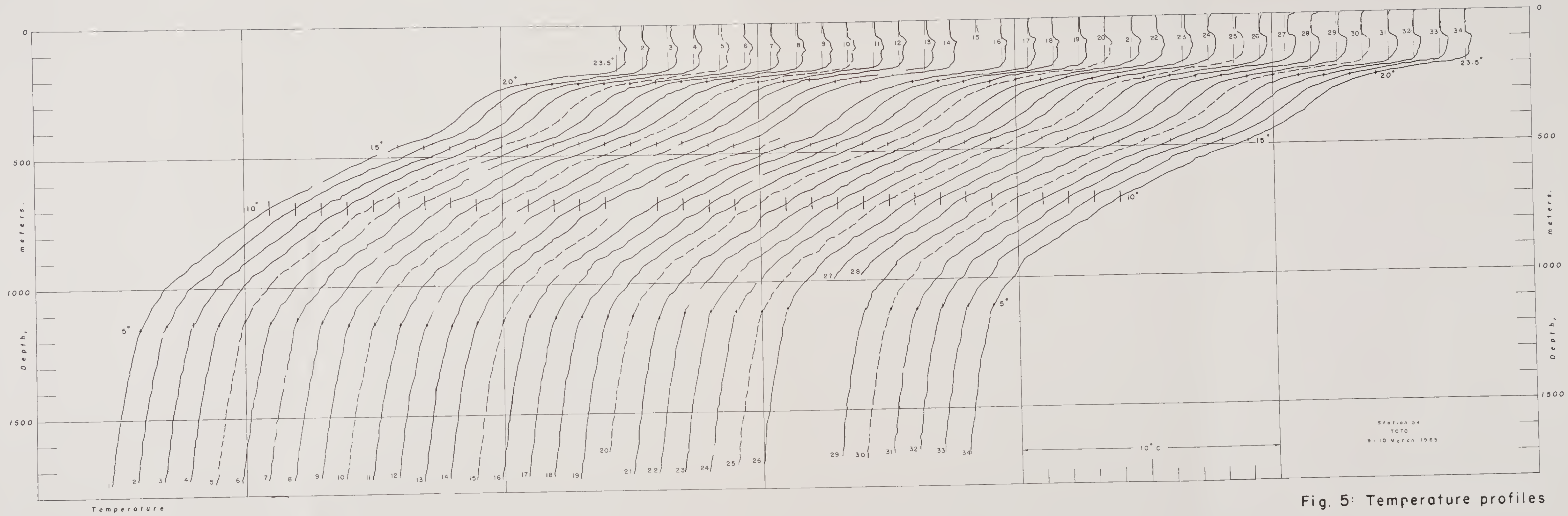


Fig. 5: Temperature profiles

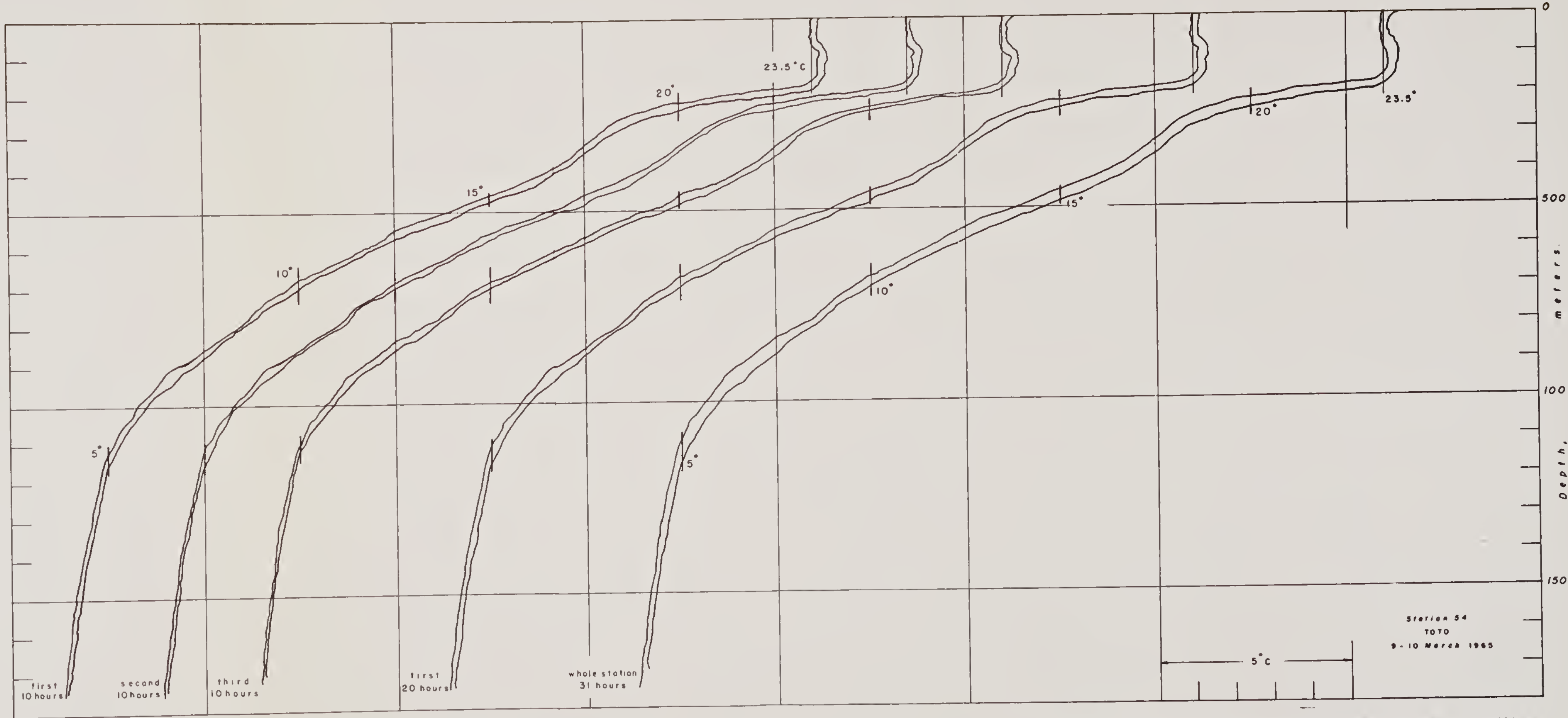


Fig. 6: Envelopes of temperature profiles

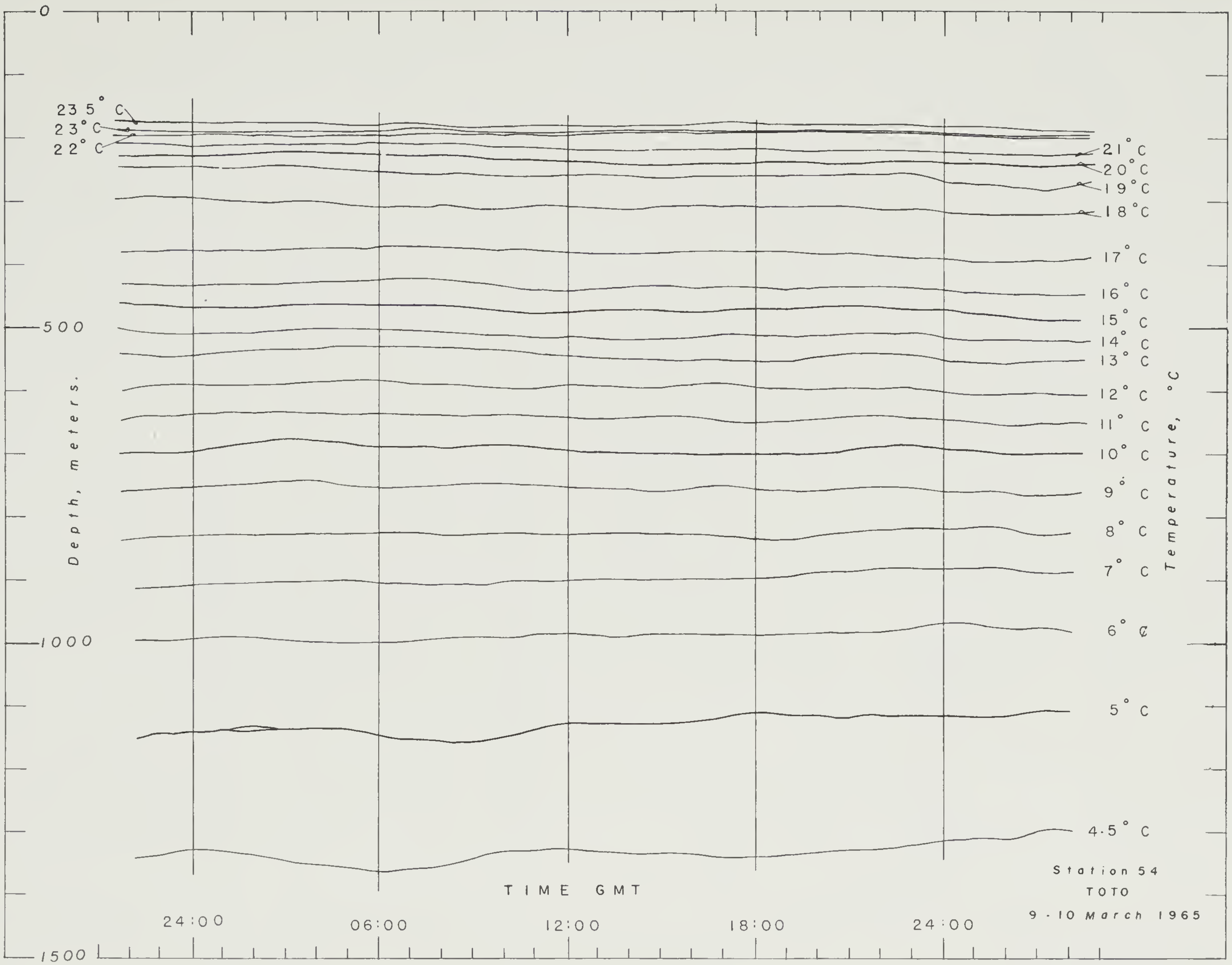
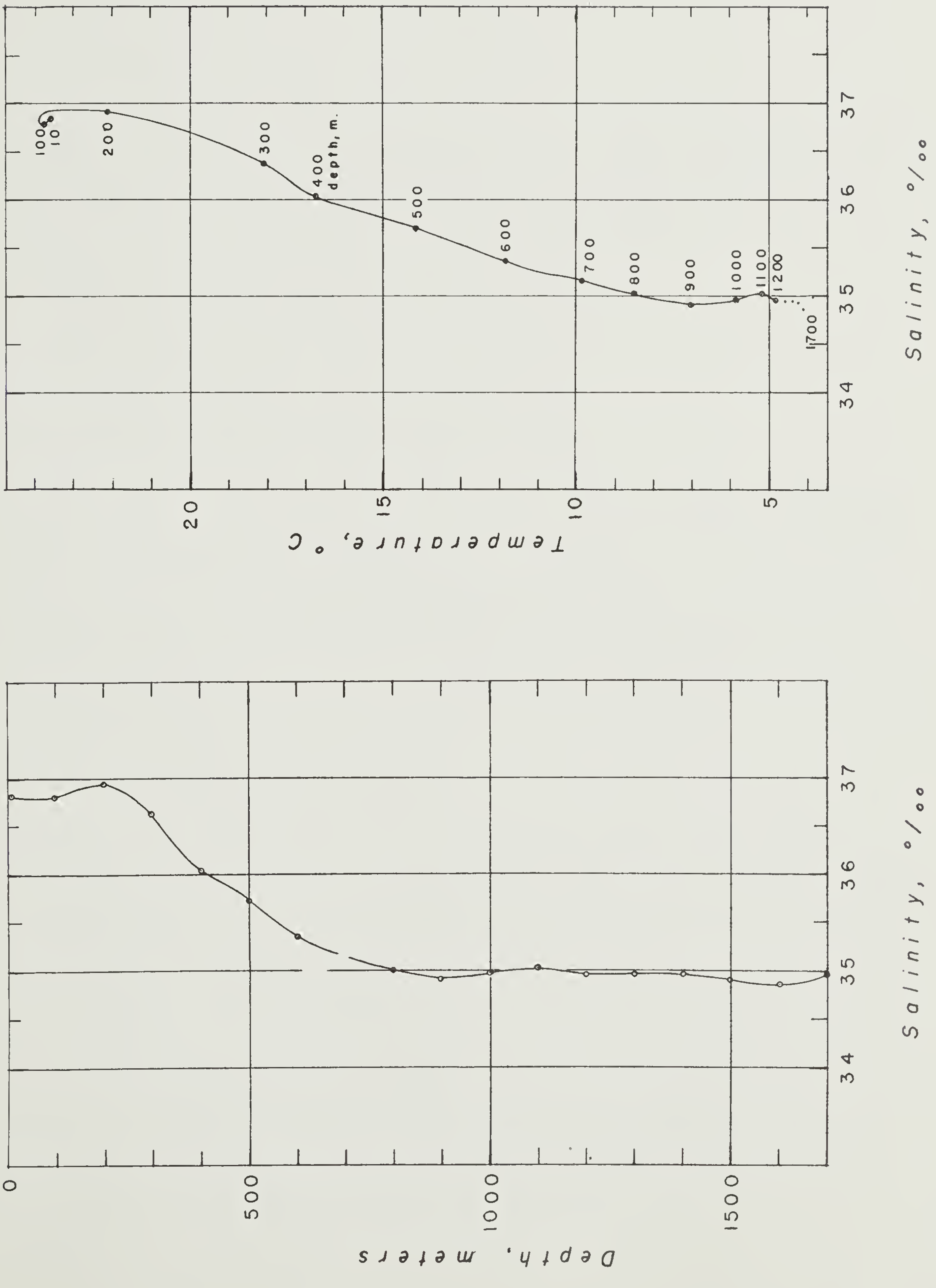


Fig. 7: Depths of isotherms

Fig. 8: Salinity derived from sound speed-temperature-depth



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This report covers a 31-hour anchor station in the Tongue of the Ocean, in extremely calm weather. 34 consecutive, detailed, high-precision profiles and their 10, 20 and 31-hour envelopes are presented for both sound speed and temperature, from the sea surface to the bottom; and the graphs showing the gradual changes of constant sound speed and isotherm depths. The sound speed and temperature structure is found to be relatively stable, as in the open ocean. Small, rapid variations abound in the thermocline region; a slight slow rise in deep isotherms occurs, but no tidal effects can be seen.

The ship's motions at anchor are described: a composite of diurnal east-west and semidiurnal north-south oscillations.

Results of a derivation of salinity from sound speed - temperature - depth data are shown to be in good agreement with published data. (U).

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Sound speed: envelopes of consecutive profiles						
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