NRL REPORT S-3392

THE MICROTHERMAL STRUCTURE OF THE OCEAN NEAR KEY WEST, FLORIDA

PART I - DESCRIPTION

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ABSTRACT

By means of a specially-developed sensitive fast-acting thermopile mounted on a submarine, microthermal variations at constant depth in the ocean have been investigated. Several days' operations were carried out in the coastal and Gulf Stream waters off Key West, Florida, and in the water north of the Cuba Coast. The prevailing bathythermograph condition was an isothermal layer down to a depth of approximately 100 feet, with a gradient layer below. In addition, slow oblique ascents of the submarine demonstrated the presence of a slightly warm near-surface layer about 20 feet thick.

Most of the data obtained consist of records of thermal fluctuation at several constant depths while the ship was under way at a slow speed. Representative examples have been transcribed and placed in a single figure according to depth so as to represent microthermal cross-sections of the ocean.

This report is a description of the thermopile, its location on the submarine, and a qualitative presentation of the records obtained; a report to appear at a later date will present a statistical analysis of some of the records and some discussion of the effects of the inhomogeneities on the propagation of sound in the ocean.

The three temperature layers mentioned above exhibit great differences in horizontal homogeneity. In the surface-heated diurnal layer 20 feet thick, small-scale small-amplitude fluctuations are found that presumably are the result of active and incomplete mixing, by wind action, of surface-heated water. Below this layer, to a depth of 100 to 120 feet (in the Key West area), is the "isothermal" layer in which comparatively slight lateral inhomogeneity is present. In the thermocline below, however, great differences of temperature at constant depth were found, amounting to several degrees fahrenheit with a patch size of the order of a few hundred yards. Only occasionally was a suggestion of regular periodicity observed such as would be produced by a simple system of internal waves in the thermocline.

PROBLEM STATUS

This is the first of a series of two interim reports on one phase of the problem. Work is continuing on other phases of the study of sound propagation in the ocean.

AUTHORIZATION

NRL Problem S02-03R

THE MICROTHERMAL STRUCTURE OF THE OCEAN NEAR KEY WEST, FLORIDA
PART I - DESCRIPTION

INTRODUCTION

The existence of small-scale lateral temperature differences in the ocean was suspected during the last war when the taking of bathythermograms (BT's) by Navy ships became routine practice. Many or most of the BT's were found to have double traces; that is, the temperature-depth trace was different for lowering and for raising the instrument. The obvious explanation--hysteresis of the instrument--failed when it was found that the double traces were not eliminated by very slow raising or lowering. In fact it was shown[1] that records of sound velocity versus depth, taken by a fast-acting interferometer and recorder, duplicated the double traces obtained simultaneously with a lowered BT. If the reality of the double traces is admitted, it follows that differences of temperature exist between the time and place of lowering and raising the instrument.

The existence of horizontal temperature variations in the ocean was definitely determined by Holter, and some records of them were presented in a USNR&SL report.[2] This work done during the war was of a preliminary nature, and so suffered from a number of deficiencies. For instance, the records were not adequately analyzed, different depths were not explored systematically, and a fast-acting temperature-measuring device was lacking. More recently the effect of the small-scale thermal structure of the ocean

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[1] USNR&SL Report S-18, "An Acoustic Interferometer for the Measurement of Sound Velocity in the Ocean," R. J. Urick, 1944.

[2] USNR&SL Report S-17, "Measurements of the Horizontal Structure of the Ocean," N. J. Holter, 1944.

on the propagation of sound was realized, and certain techniques in the analysis of random processes were developed. It was also during the war that it was shown by Ufford [3] that internal waves in the thermocline produce comparatively large temperature changes with time at a fixed location.

METHOD OF MEASUREMENT

It is apparent that a fast-responding thermal indicator is necessary in order to record temperature fluctuations when used on a ship travelling at any reasonable speed. This requirement of good thermal contact, in an electrical device in which high electrical insulation from the water is mandatory, is not an easy one to meet, as no substance is apparently both an electrical insulator and a thermal conductor. In the thermopile used for most of the work, this condition was approached by allowing the thermocouple wires to protrude out a short distance, where they would be surrounded by the sea, and by relying on a thin baked-on coating of vinylite varnish to provide electrical insulation.

Disassembled and assembled views of the thermopile are shown in Figures 1 and 2, respectively. Eight copper-constantan series-connected thermojunctions of No. 33 wire extend outward from a pair of rubber disks cemented together with Vulcalock cement. The wires lead from the junctions inward between the discs to the inner, or reference, junctions, which are located near the axis and are surrounded by cotton to secure relative constancy of temperature. Drift of the reference-junction temperature is not important when relatively short-period thermal changes are of interest.

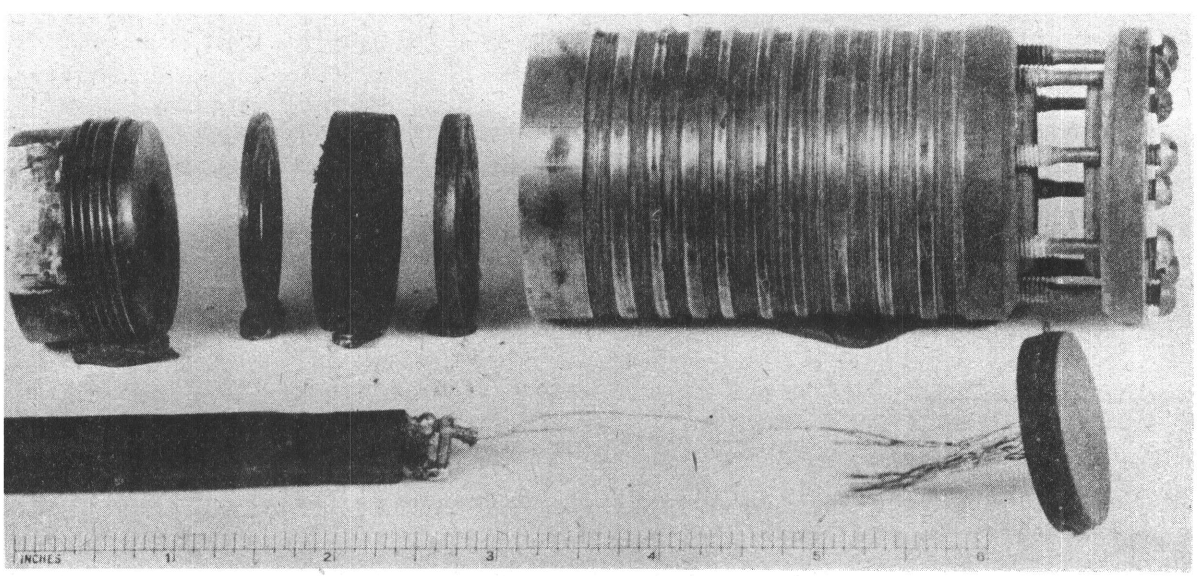


Figure 1. Unassembled View of Exposed-Junction Thermopile

[3] C. W. Ufford, "Internal Waves in the Ocean" (3 papers) Trans. Amer. Geoph. Union 28, 79-102, (Feb. 1947)

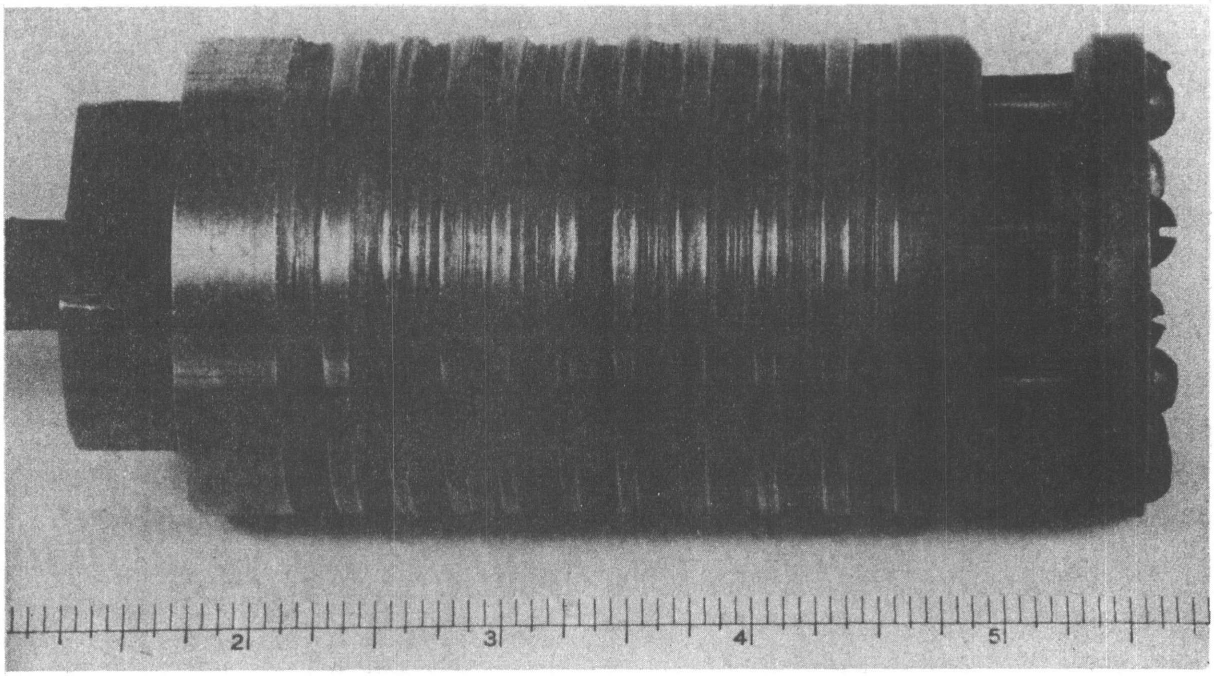


Figure 2- Assembled View of Exposed-Junction Thermopile

The thermopile was connected by rubber covered cable to a General Motors chopper-type dc amplifier having a voltage gain of 140 db into a 500 ohm load, and records were obtained with a 5-ma Esterline-Angus recorder. Although the sensitivity of the thermopile-amplifier-recorder combination was such that at maximum gain full-scale deflection of the recorder represented a temperature change of about .003°C, this much gain could never be used at sea. Calibration of the thermopile was made in the laboratory in terms of a voltage at the input to the amplifier. At sea, similar small fixed voltages were inserted on every record to permit their subsequent conversion into temperature.

The time constant of the outer junctions of the thermopile, plus recorder, was measured to be 0.4 second, and that of the inner junctions 3.7 minutes. These figures determine the amplitude spectrum of the system, and thus indicate the range of size of water bodies, assumed sinusoidal, that the system will faithfully record at a given ship speed. This spectrum is shown in Figure 3. It is seen that at a speed of 5 knots, sinusoidal patches having a half-wave length, or "patch size," between 5 and 1500 yards are recordable with less than 3 db attenuation. This response spectrum is also of value as a means of correcting the spectrum of a particular record obtained by a Fourier or an auto-correlation analysis. The method of obtaining experimentally the response spectrum for a thermopile-recorder system is outlined in the Appendix.

Another thermopile, developed prior to the one just described, had its active junctions appressed tightly by a cylindrical spring to the inside of a thin-walled stainless-steel tube, and insulated electrically from it by extremely thin mica spacers. This unit had a time constant of 1.5 seconds, a time-response considered too slow to be satisfactory. The appearance of

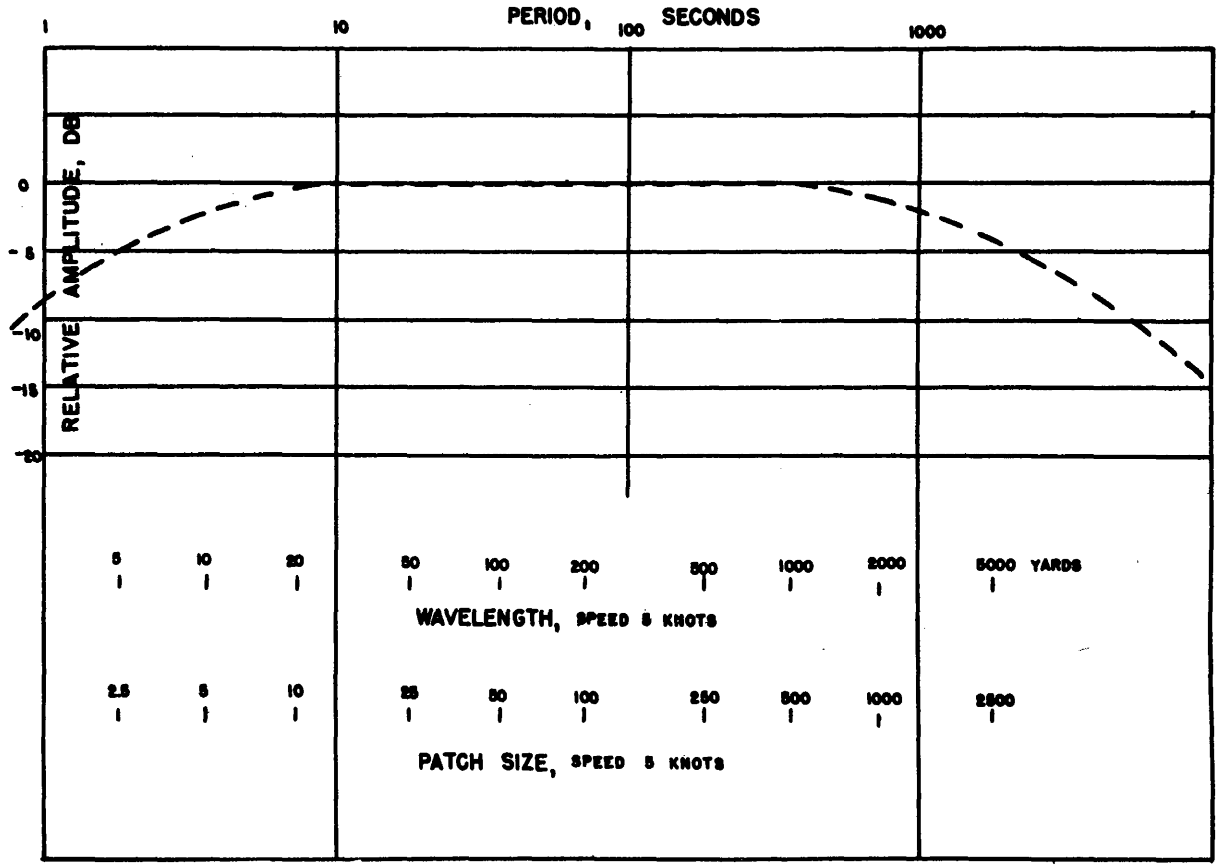


Figure 3- Spectrum of Exposed-Junction Thermopile

this unit is shown in Figure 4. Although superseded by the exposed-junction thermopile, it was used for one day's operations to check the absence of spurious electrochemical or salinity effects on the exposed-junction type.

The thermopile was mounted as far forward toward the bow as possible on the USS TRUMPETFISH, a guppy-schnorkel submarine. As this type of ship is completely streamlined while submerged, a 4-foot tripod was welded to the deck to support the thermopile. Photographs of this installation are shown in Figure 5. About 100 feet of cable led from the thermopile to the amplifier-recorder located in the forward part of the forward torpedo room. This installation was employed operationally for five days during the week of July 26, 1948. For two days in the succeeding week, a conning-tower mount was used on the USS COBBLER, a conventional submarine. A photograph of the latter installation, with the enclosed-junction thermopile in place, constitutes Figure 6.

Much of the work was done in the easily accessible coastal waters off Key West, Florida, in depths between 50 and 100 fathoms. These areas are designated A and B on the nautical chart of the Key West-Cuba area reproduced in Figure 7. A half-day's operations were carried out in Area C in about 350-fathom water, and an overnight trip permitted an examination of Area D at the center of the Gulf Stream, and of Area E just off the north coast of Cuba.

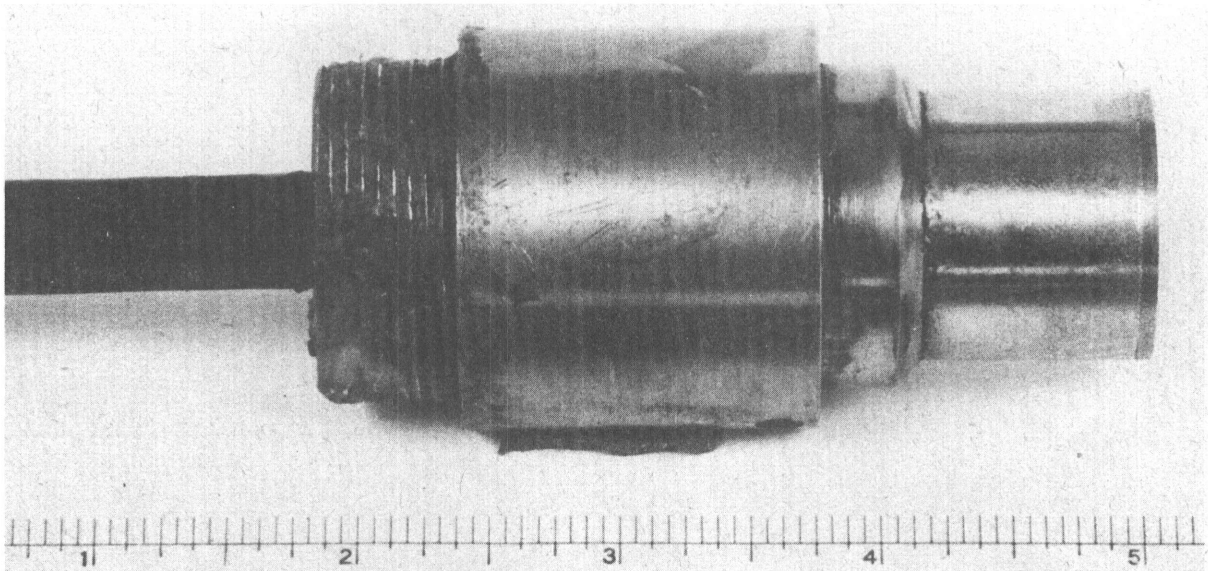


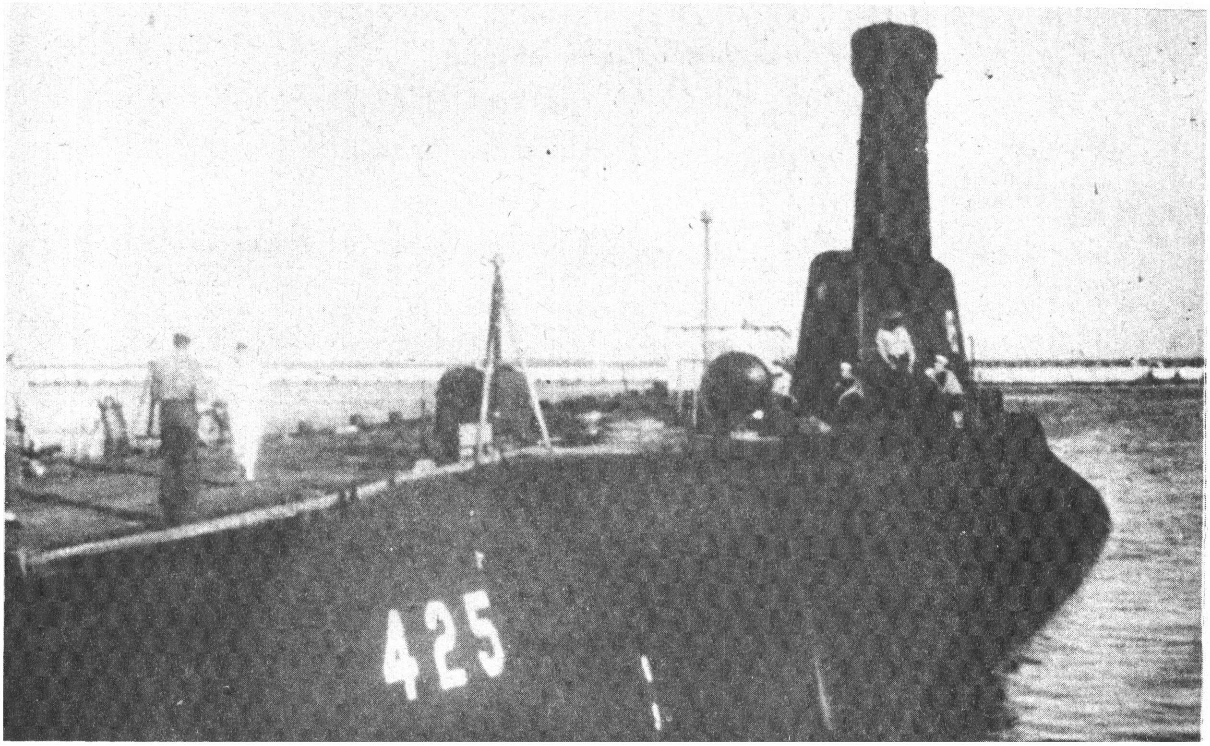
Figure 4- Enclosed-Junction Thermopile

The normal field operation consisted merely in making runs at several-to-many constant depths, and recording the temperature fluctuations. Since a strictly constant depth cannot be maintained by a submarine, especially at slow speeds, the depth and bubble angle (tilt) of the submarine were relayed from the control room and entered on the record. These deviations seldom exceeded 2 feet in depth and 1½ degrees of tilt, and the records at depths in the thermocline were later corrected by assuming an average temperature-depth gradient in the thermocline. Such corrections were found to be quite small. With the thermopile mounted forward, depth and tilt deviations tend to compensate, since a downward deviation from constant depth is corrected by the diving officer with an immediate upward tilt of the ship.

In addition to the constant depth runs, a few oblique ascent runs were made, in which the ship slowly came to the surface while maintaining a forward speed of 5 knots.

Bathythermograms were obtained with the submarine's BT at convenient times during a day's operations. They have been replotted in Figure 8, grouped by geographical areas. In the Coastal Areas A and B (BT's No. 1-7 of Figure 8) nearly isothermal water was found down to a depth near 100 feet. Below this is a sharp thermocline with a gradient of 1/10°F per foot. In the 350-fathom water of Area C, a similar condition exists. More nearly isothermal water is found in the Gulf Stream and Cuba Coast Areas (D and E), where the thermocline is less marked and of smaller gradient. The submarine BT, being located on the keel, yields no information, however, about the upper 20 feet of ocean water.

No wide variation of meteorological conditions was encountered on the days the runs were made. The usual weather condition was a partly cloudy sky of cirro-stratus and cumulus clouds, with gentle to moderate winds (6-20 knots) giving sea states of 1 to 3. No special or detailed meterological observations were made.



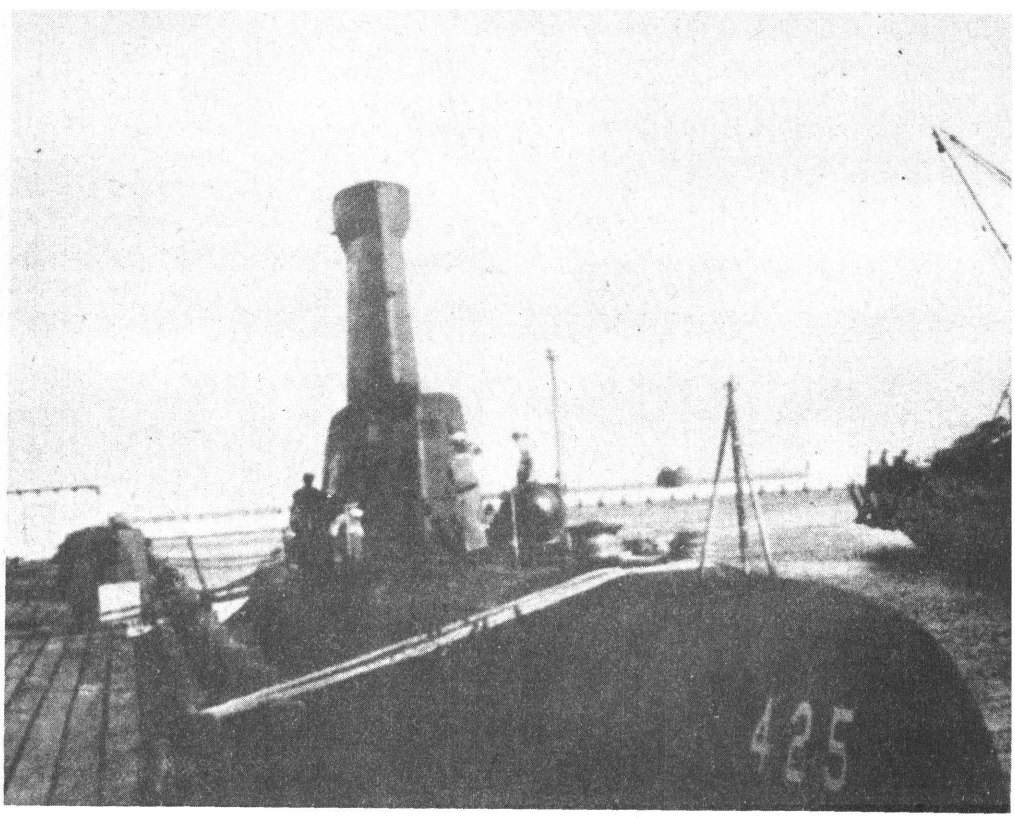


Figure 5- Views of Submarine Tripod Mount

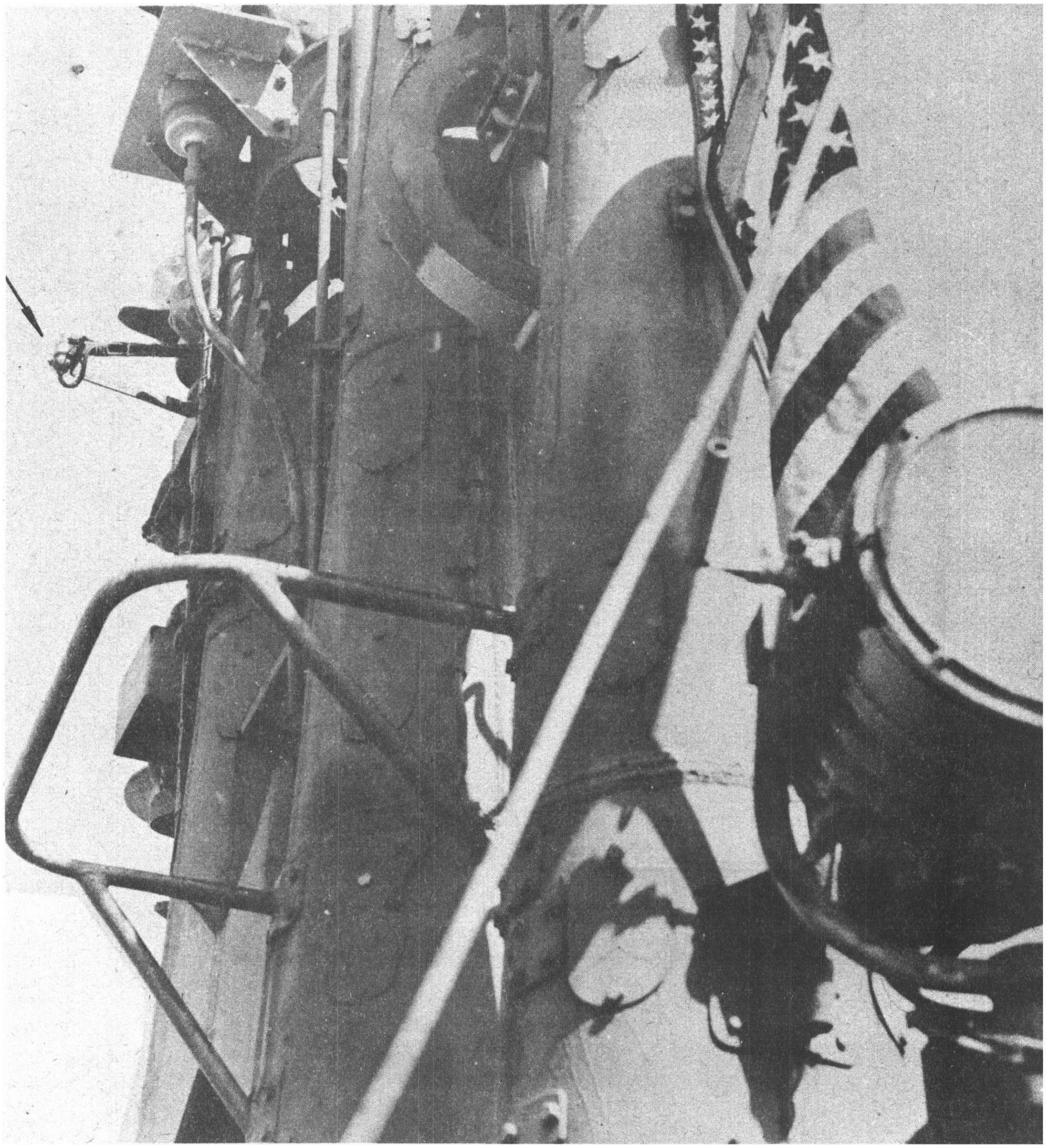


Figure 6- Conning Tower Mount of Enclosed-Junction Thermopile

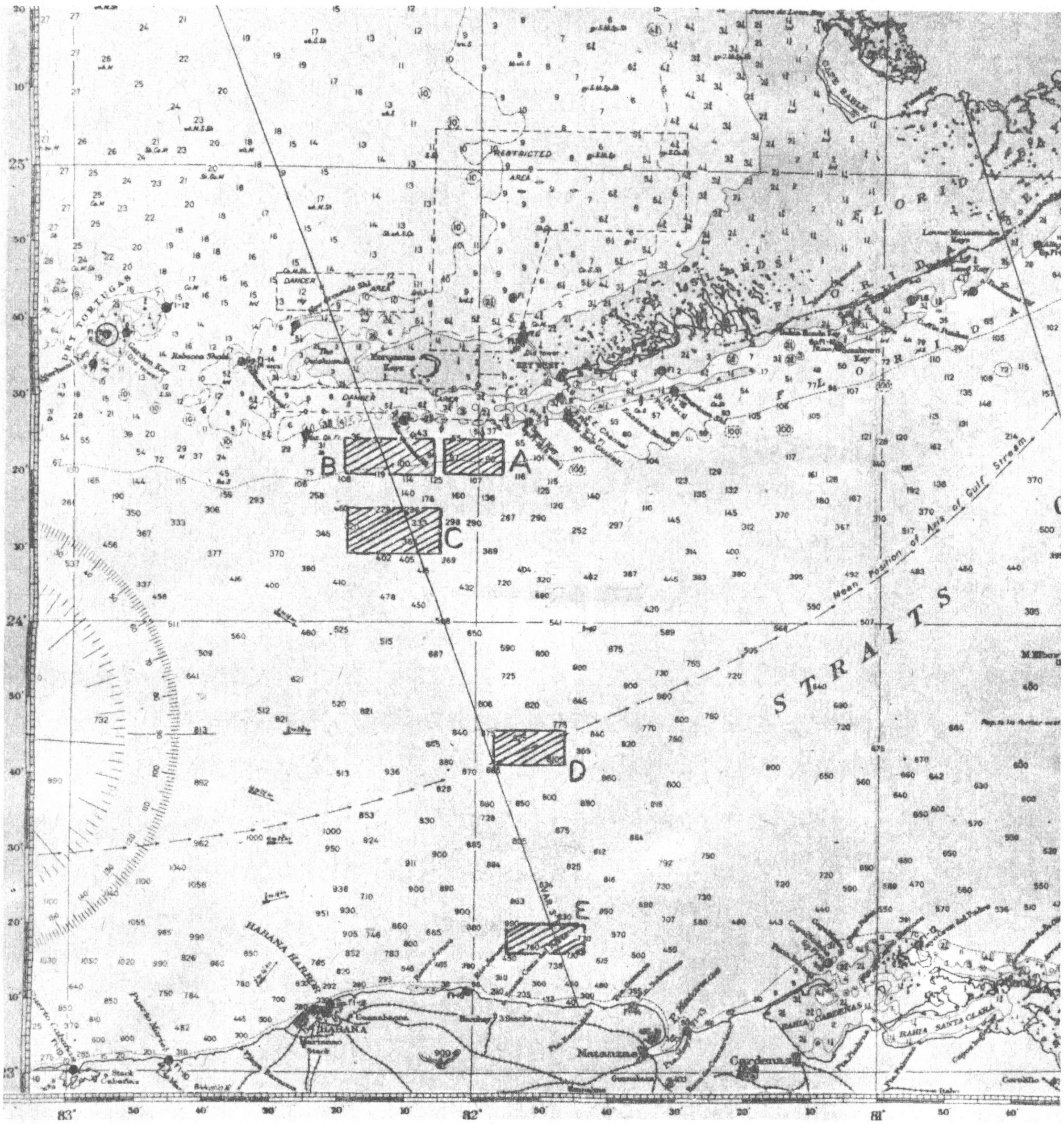
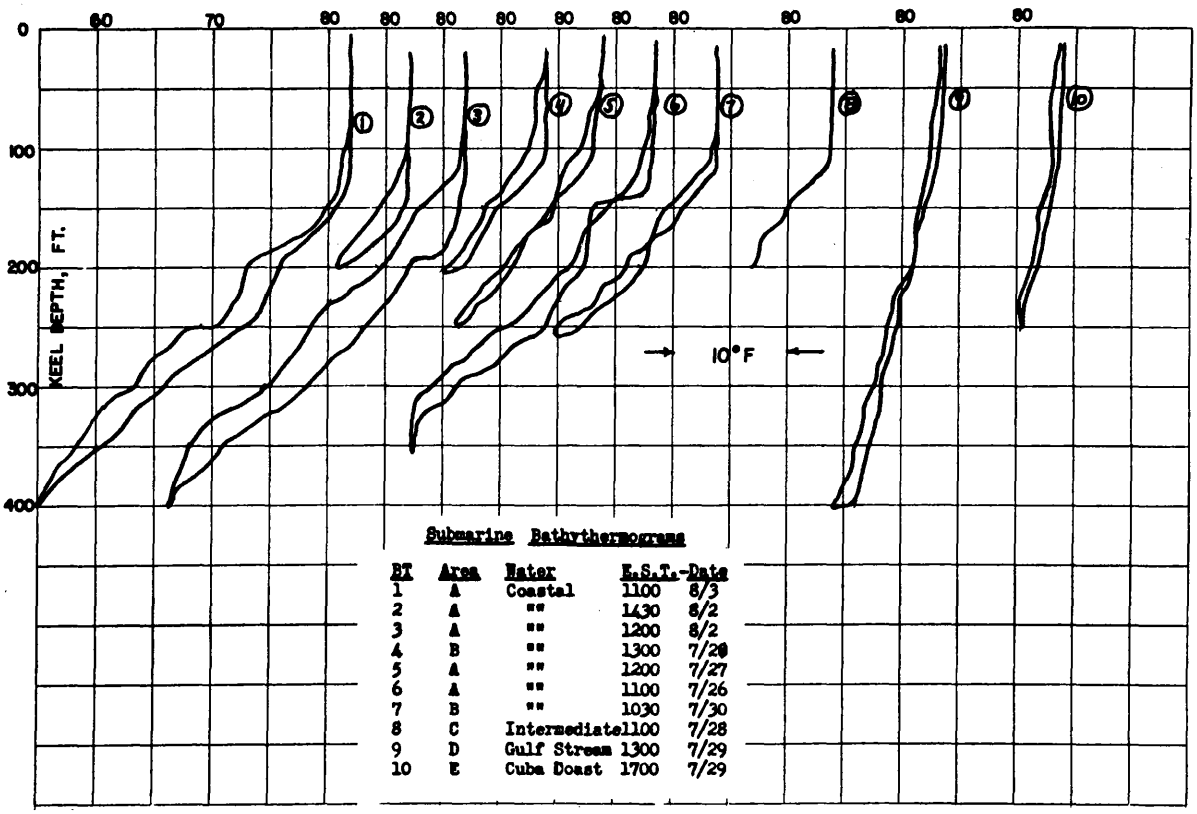


Figure 7- Chart of Key West Region Showing Operating Areas

The field records were obtained on Esterline-Angus tape. The records suffer from a number of faults, such as a non-Cartesian coordinate system, nonintegral and varying gain settings from run to run, and occasional places where the trace ran off-scale and was returned by a manual adjustment.

In order to minimize resulting errors, representative and typical records were transcribed in the following manner: An Esterline-Angus recorder and a Brown Potentiometer recorder were connected by a resistance-battery network. The original record was fed into the E-A recorder and,

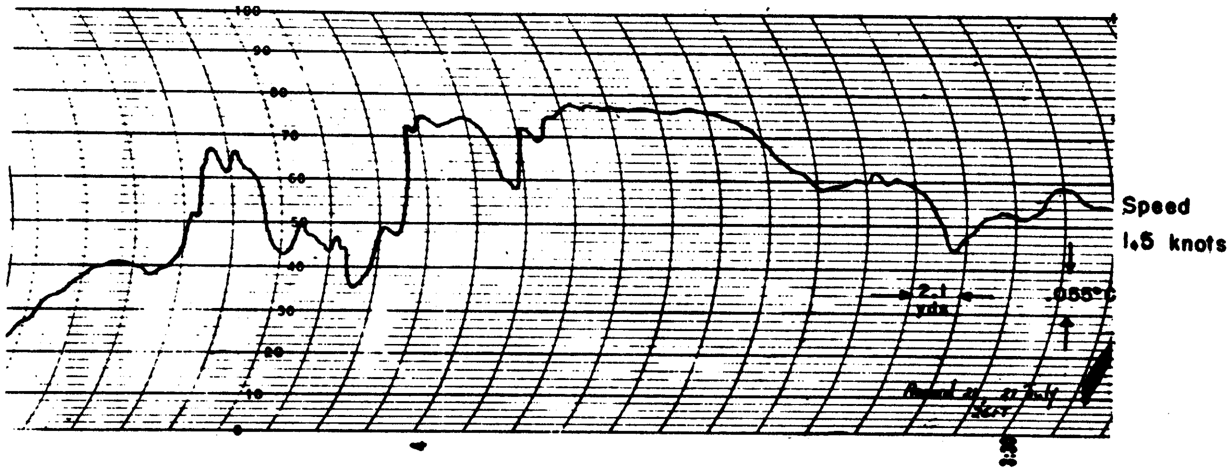


BT	Area	Water	E.S.T.-Date	
1	A	Coastal	1100	8/3
2	A	"	1430	8/2
3	A	"	1200	8/2
4	B	"	1300	7/28
5	A	"	1200	7/27
6	A	"	1100	7/26
7	B	"	1030	7/30
8	C	Intermediate	1100	7/28
9	D	Gulf Stream	1300	7/29
10	E	Cuba Doast	1700	7/29

Figure 8

as the chart-drive carried the record through, the trace was followed by varying the current through the instrument. Such variations were in turn recorded by the Brown recorder, and a record traced. The connecting network used permitted adjustments of the gain of the transcription so that an integral number of scale divisions could be made to represent an integral number of temperature units, and also enabled the off-scale wanderings of the original record to be eliminated. Also, the horizontal, or time, scale of the original could be changed by an integral factor.

Some evidence that the fluctuations observed represent real temperature changes is presented in Figures 9 and 10. Figure 9 shows two of the original records taken in quick succession at ship speeds of 1.5 and 5 knots, respectively. The upper record (1.5-knots) is seen to contain fewer fluctuations than the record (5-knots). The number of peaks and troughs is roughly proportionate to the speeds, indicating actual changes in the water temperature that are not significantly diminished at the higher speed by the time lag of the thermopile. Analogously, Figure 10 is a record obtained when the submarine slowed from two knots to near zero speed. The fact that no fluctuation was recorded at zero ship speed is evidence of the absence of electrochemical or spurious electrical effects. No attempt was made to detect temperature changes with time at a fixed position, such as the changes that would be produced by travelling internal waves in the thermocline.



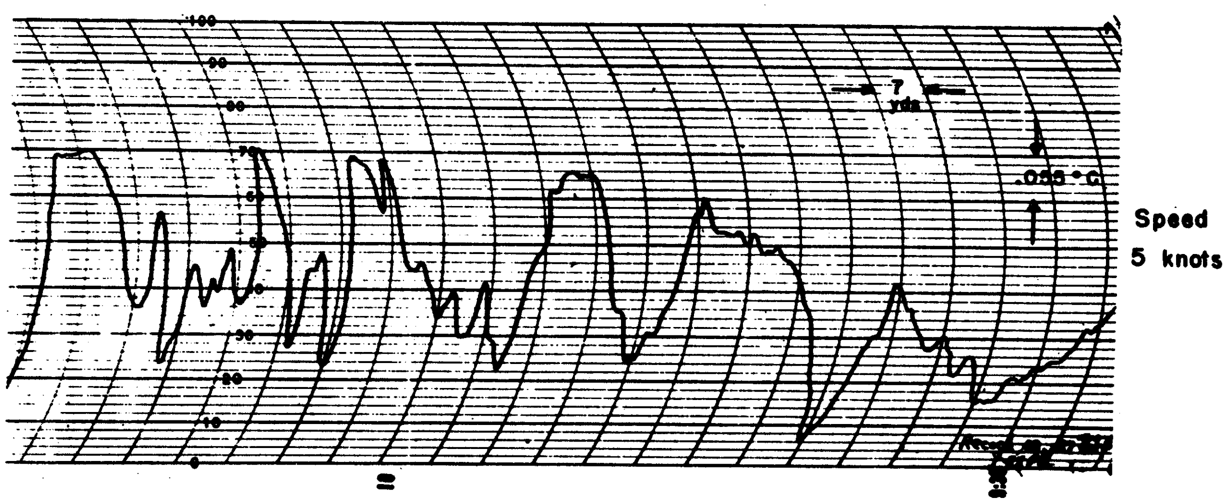


Figure 9— Comparison of 1.5 and 5 knot speeds

DESCRIPTION OF RESULTS

Figures 11 through 17 are some of the microtemperature cross sections obtained. Warmer temperatures are upward. Through each section (except that of Figure 14) a horizontal line has been drawn. Above this line each record is shown transcribed, as a pair, at two different vertical scales of temperature: The upper trace of each pair is to the same scale as the records below the line; the lower trace of each pair is at an amplification of 10 times the upper, and shows the details that are obscured by the lower magnification. Thus in perusing these figures, the upper trace of each pair above the line is to be compared with the traces below the line.

Such a comparison reveals the great difference in thermal uniformity at constant depth between levels above and below the top of the thermocline. In the isothermal water, above the thermocline, inhomogeneities of the order of a few yards in width and 1/10°C or less are present; in the thermocline, there are found much larger changes, both spatially and thermally, at constant depth. Near the surface, as evidenced by Figures 12 and 14, greater variations are sometimes observed than in the isothermal water below. This latter condition is present in Figure 14, but not in Figure 15, the records of which were obtained a few hours later in the same area.

The cross section of the water in Area E north of Cuba, (Figure 17), differs from those of Areas A, B, and C in that both the amplitude of the inhomogeneities and their transition with depth are less. This is in keeping with the BT, which indicates a more gradual thermocline of smaller gradient than in the more northern areas.

The thermopile with enclosed junctions was employed in one day's work in the Coastal Areas A and B, and a typical cross-section record is shown in Figure 18. The traces at depths in the thermocline are similar to those obtained with the exposed-junction unit, but the traces in the near-surface water are smoothed out to some extent by the slow response of this thermopile to thermal changes.

Figure 19 shows slow oblique ascents from a depth to the surface. In this set of traces only the center record reaches a depth in the thermocline. On that record the large temperature changes observed on the constant-depth records are obtained at depths in the thermocline; the great fluctuations just at the top of the thermocline were not encountered on other records. The smoothness of the traces between 30 and 100 feet in the isothermal layer is evident. All traces show a layer above 20-30 feet, warmer by 0.3°C than the water below, in which larger temperature changes are recorded. The nearly exponential trace in isothermal water is a result of incomplete thermal isolation of the reference junctions of the thermopile. It will be recalled that the near-surface layer is not recorded on any of the submarine BT's because of their poor location on the ship.

Figure 20 is a reproduction of three constant-depth records at a depth just at the base of the 25-foot surface layer. The upward, warmer deflections are evidence that the base of this layer is not at constant depth, so that the thermopile occasionally passes into the upper, warmer layer as it is moved horizontally.

Only occasionally was any pronounced periodicity in temperature observed at depths in the thermocline; such a case is shown by the 210-foot record of Figure 13. Because travelling waves in the thermocline, if simple, would be represented by periodic constant-depth traces, the usual absence of such periodicities in the recorded data indicates that internal waves are either absent, or exist as a complex wave system. Similarly no apparent difference in the records was made by changing the course of the run by 90°. To illustrate, a pair of traces at a depth of 230 feet for courses at 270° and 180° are reproduced in Figure 21.

SUMMARY

The following statements summarize briefly the results of the Key West experiments. Each of the three sections of the bathythermogram is characterized by its own distinct microthermal pattern. In the thermocline (in the Key West area in summer) there are comparatively large horizontal variations of temperature over a distance of a few hundred yards. It follows that the vertical temperature gradient in the thermocline is not laterally uniform. This nonuniformity of gradient may in part be influenced by internal waves, but as indicated by the usual absence of regularity, is more likely due to differences of origin or to variations in ocean currents. The isothermal water between a depth of 30 feet and the top of the thermocline is, in contrast, quite homogeneous--with no thermal differences normally greater than a few hundredths of a degree centigrade. Such homogeneity is the result of long-term mixing by surface winds. The upper 30 feet is characterized by slightly warmer, and usually less homogeneous, water representing the effect of surface heating and wind mixing.

No data has been obtained at night or during the early hours of the morning. By analogy with other areas, however, this surface layer may be assumed to be diurnal in existence and responsible to local and short-time changes in solar insolation and wind force. Such variability is present in the microtemperature records.

ACKNOWLEDGMENT

The help of the officers and men of the submarines USS TRUMPETFISH (SS 425) and USS COBBLER (SS 344), and of the subtender USS GILMORE (AS 16), is gratefully acknowledged; their willing cooperation materially assisted the conduct of the field work.

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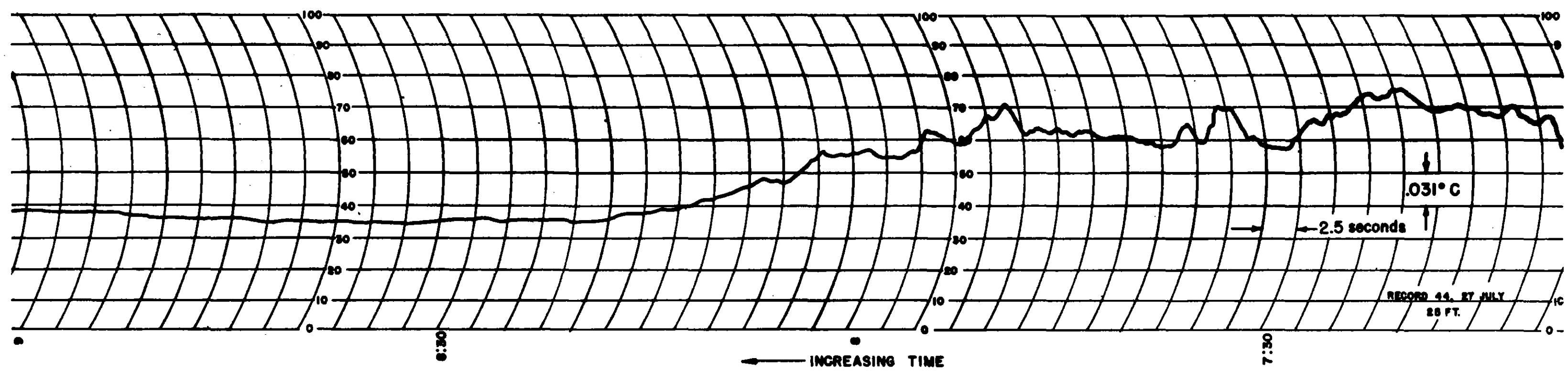

Figure 10— Record Obtained on Slowing from 2 Knots to Zero

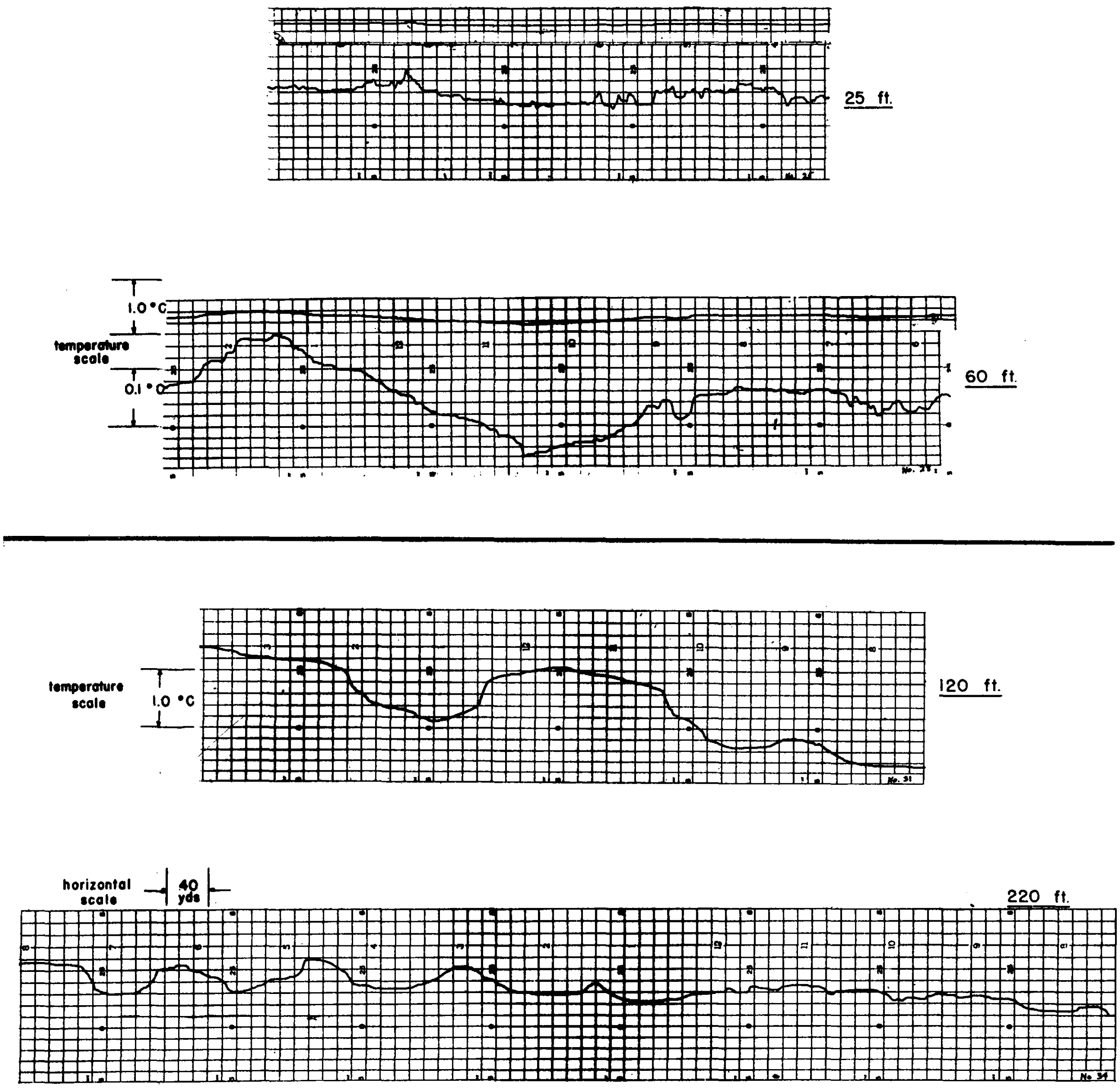

Figure 11 - Microthermal Cross Section
(Area A, 1100-1230 EST, 27 July 1948)

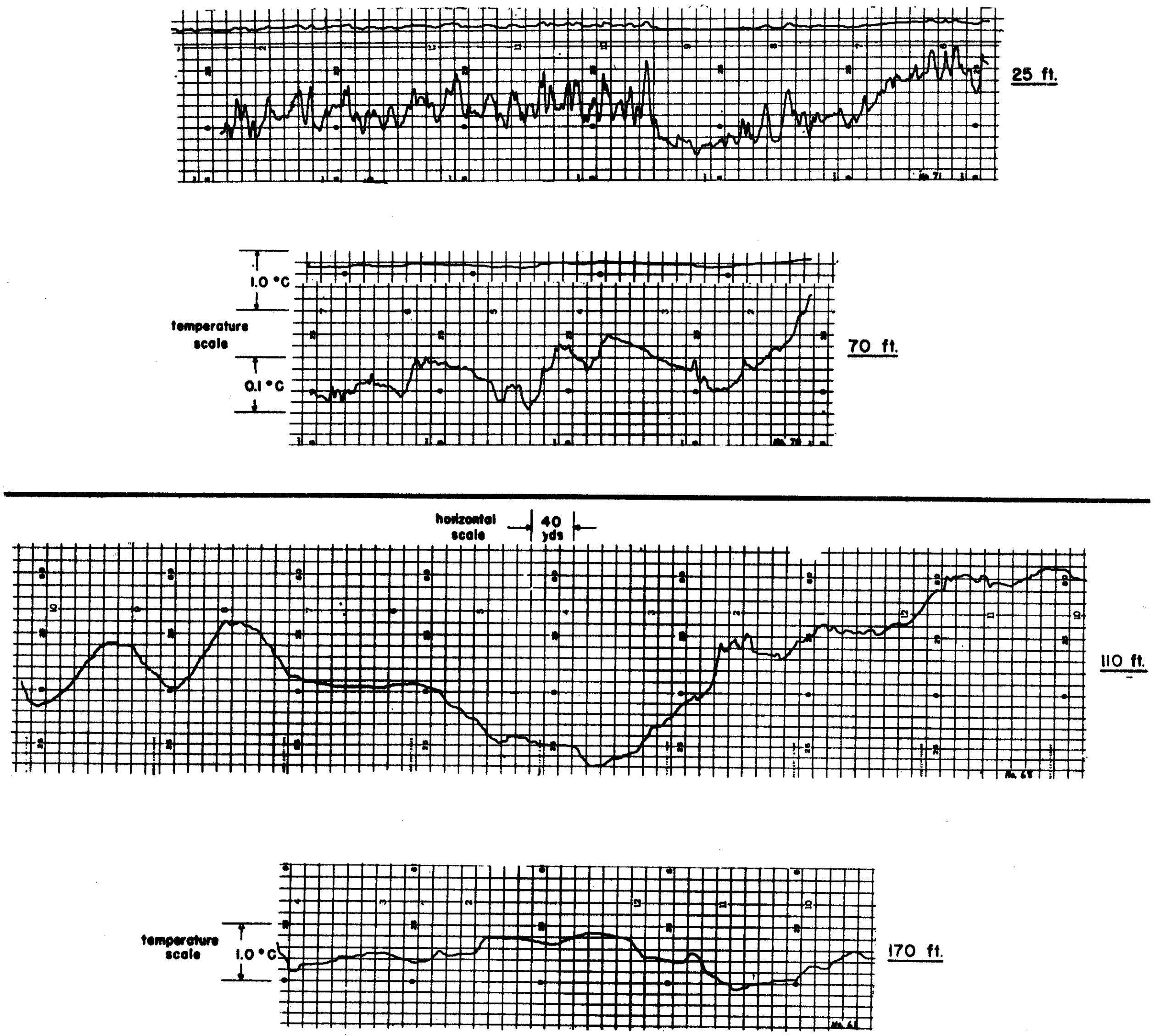

Figure 12 - Microthermal Cross Section
(Area B, 1230-1330 EST, 28 July 1948)

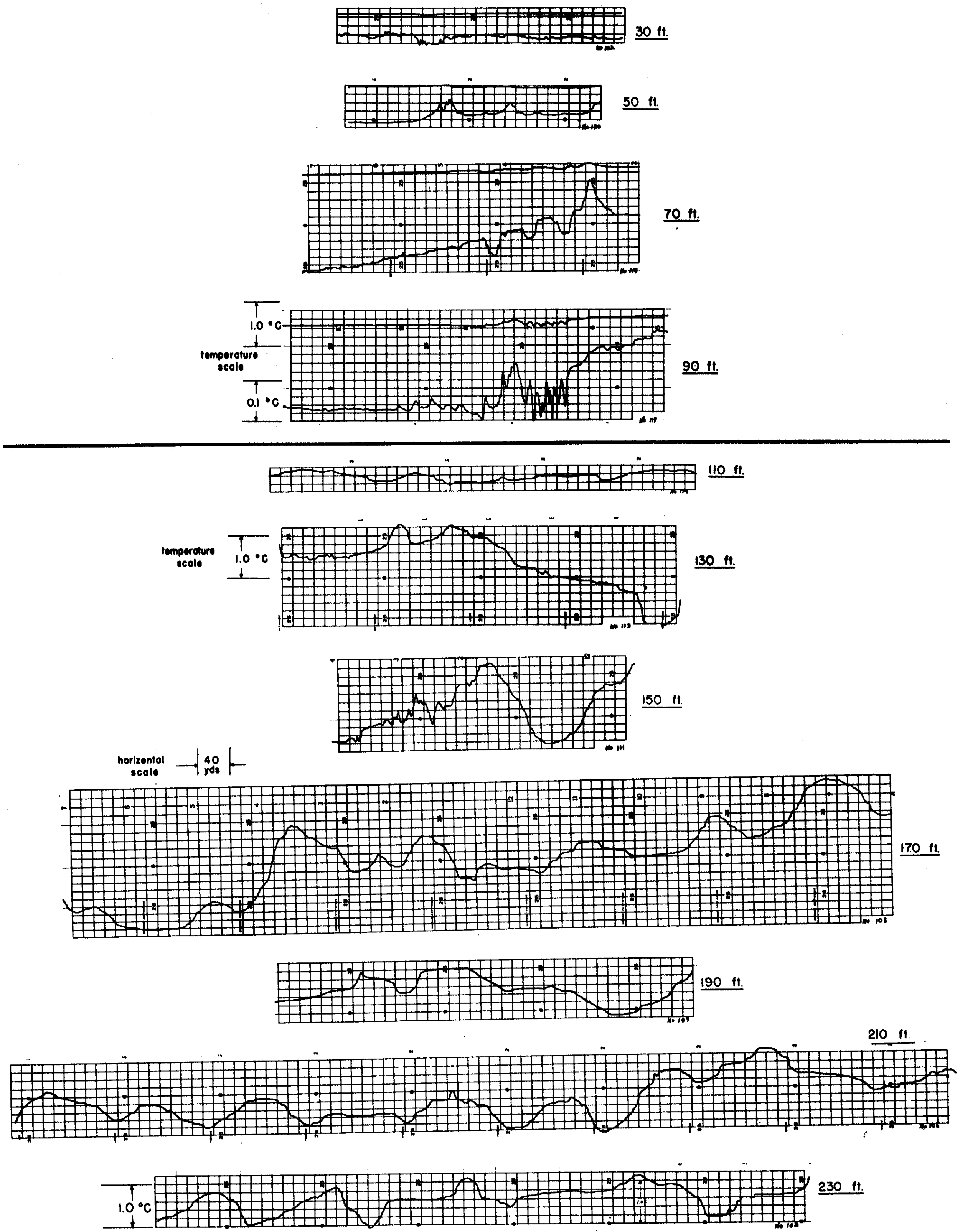

Figure 13 - Microthermal Cross Section
(Area A, 0830-1100 EST, 30 July 1948)

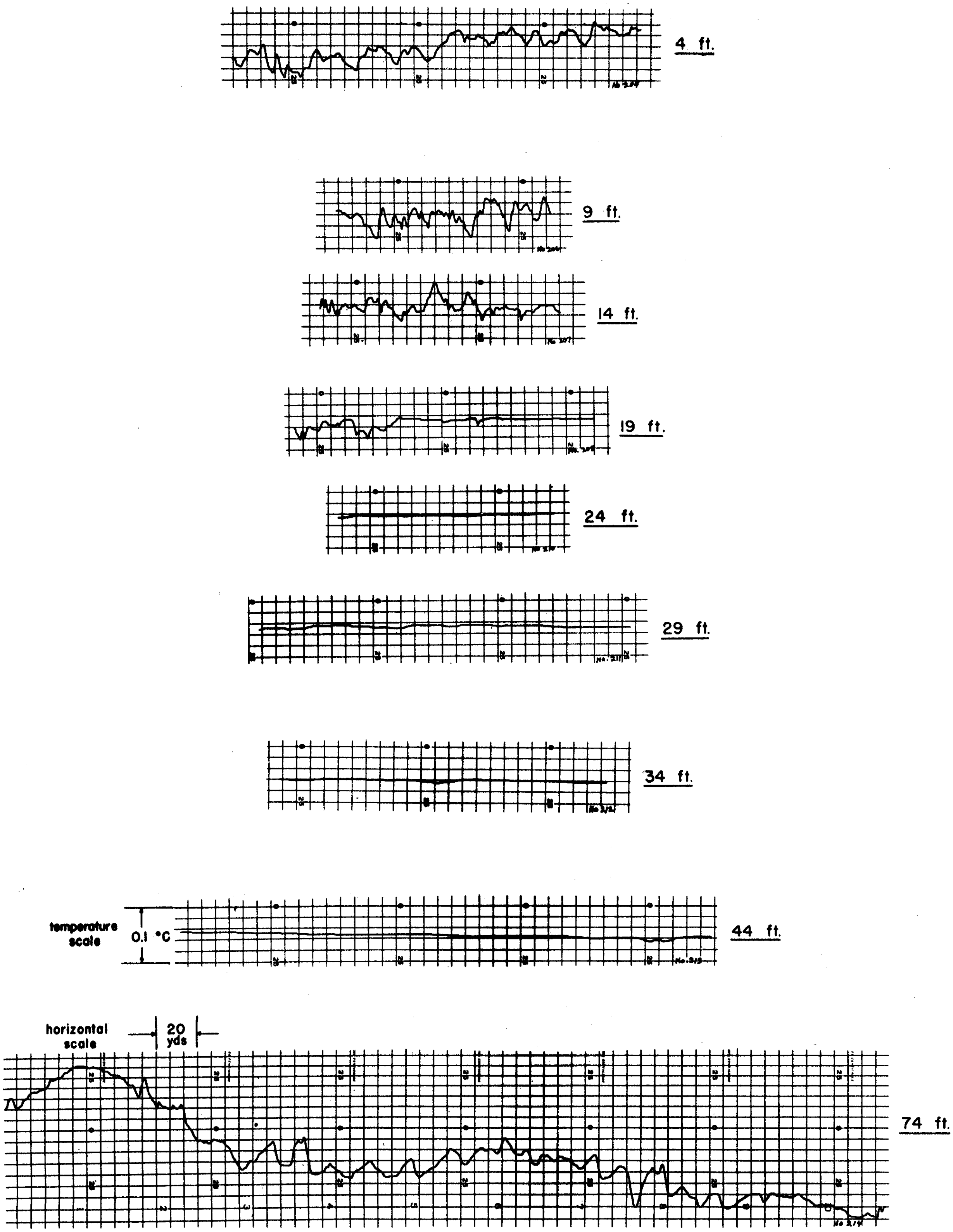

Figure 14 — Microthermal Cross Section
(Area A, 1030-1200 EST, 2 Aug. 1948)

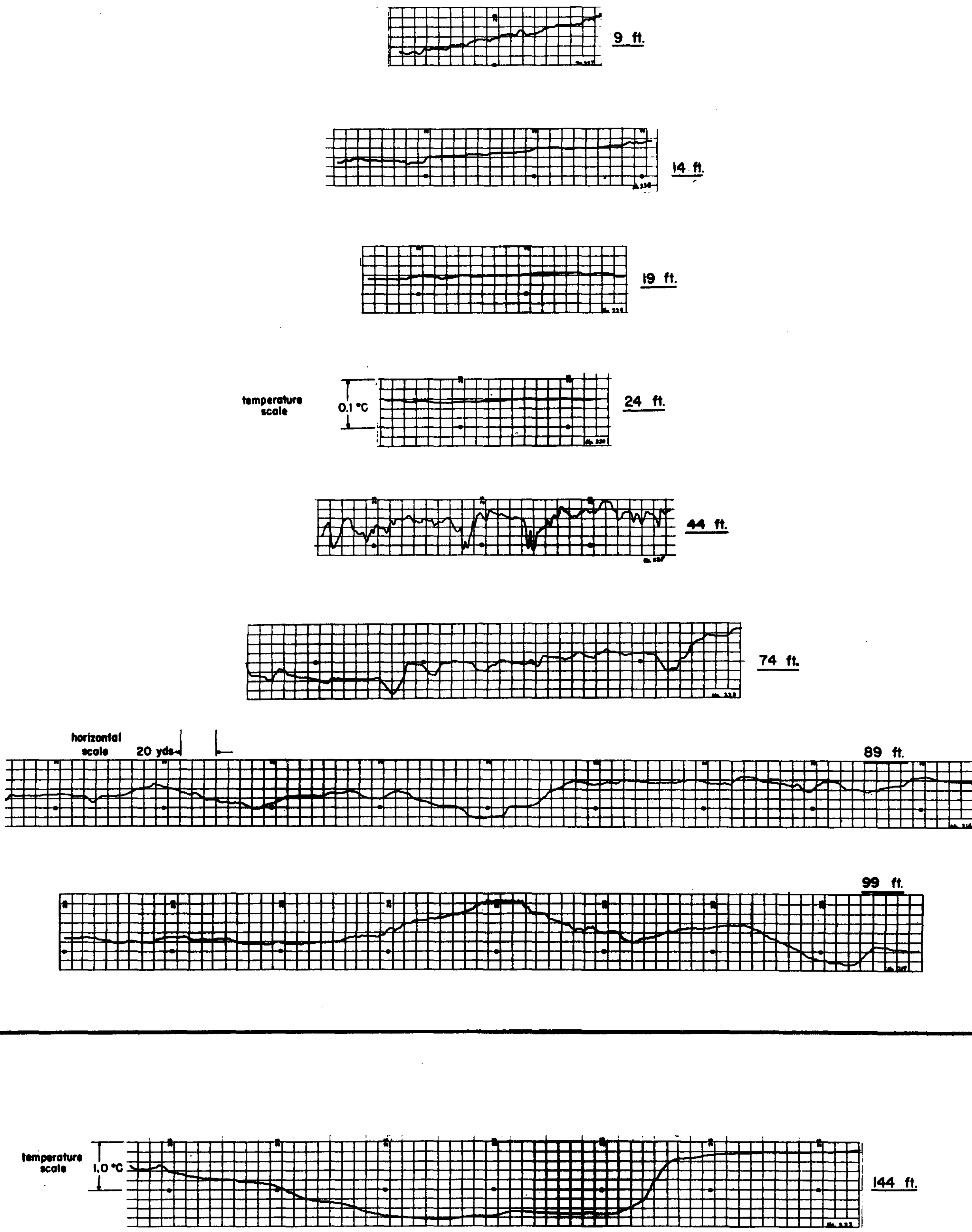

Figure 15 - Microthermal Cross Section
(Area A, 1300-1440 EST, 2 Aug. 1948)

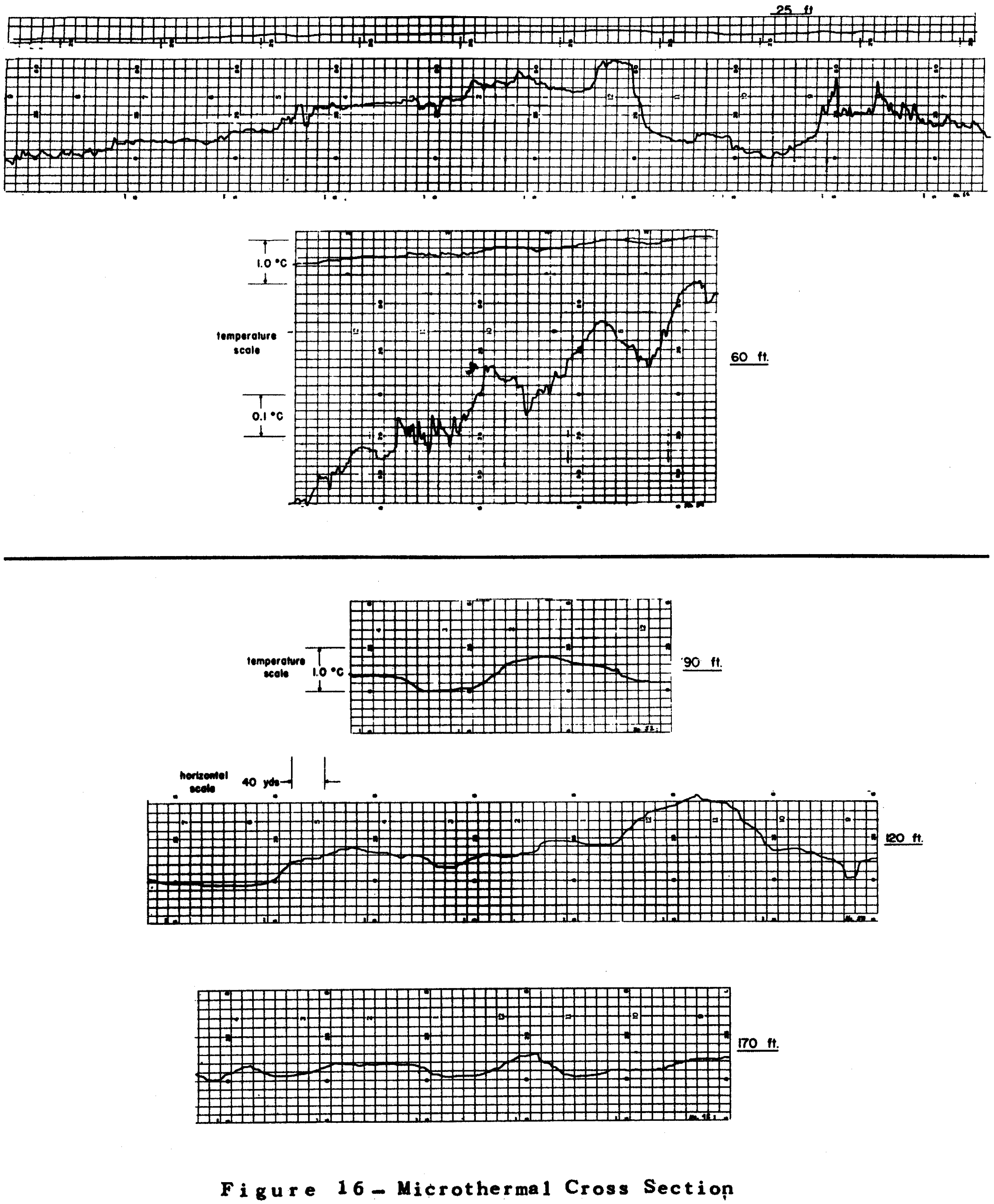

Figure 16 – Microthermal Cross Section
(Area C, 1000-1130 EST, 28 July 1948)

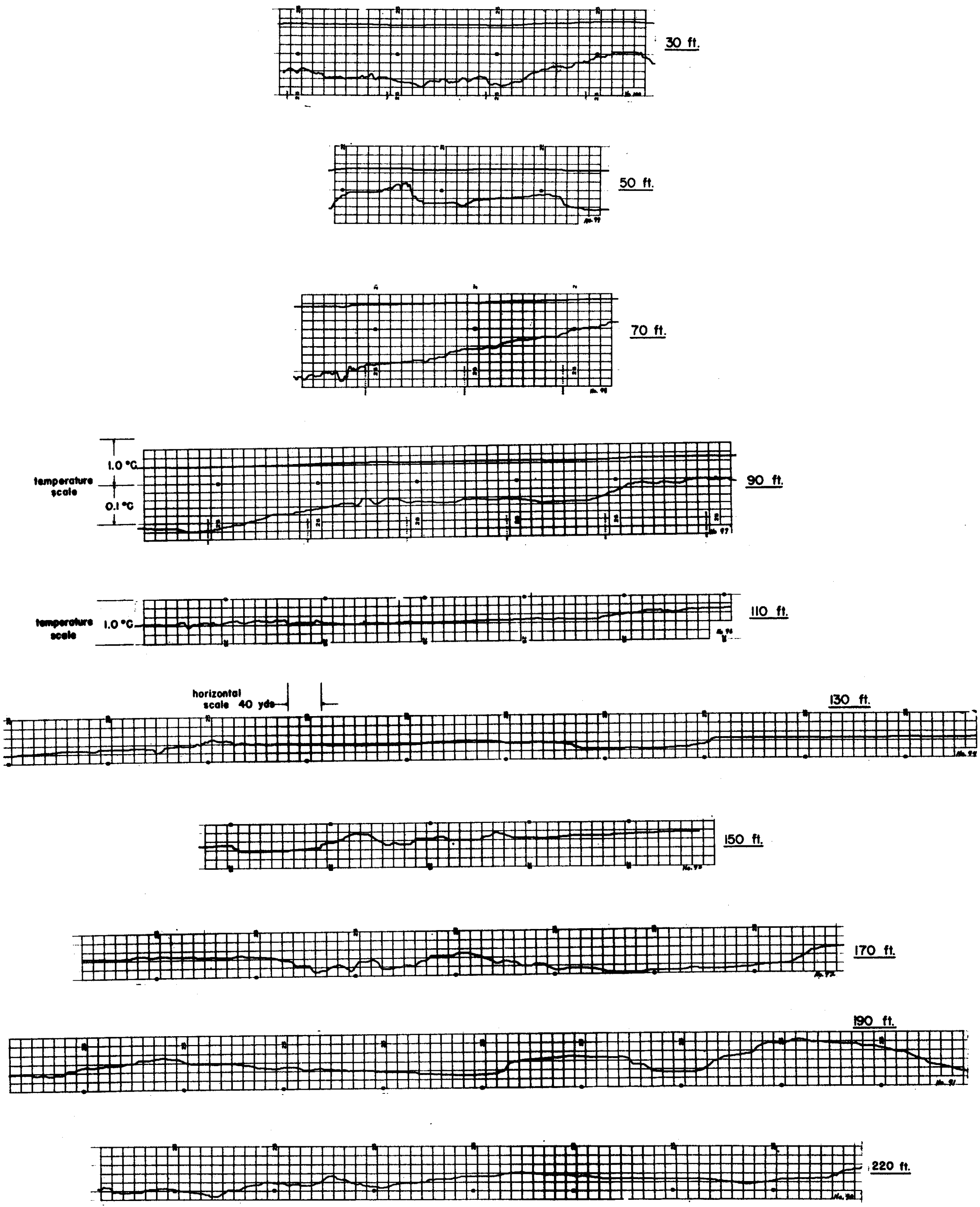

Figure 17 – Microthermal Cross Section
(Area E, 1630-1830 EST, 29 July 1948)

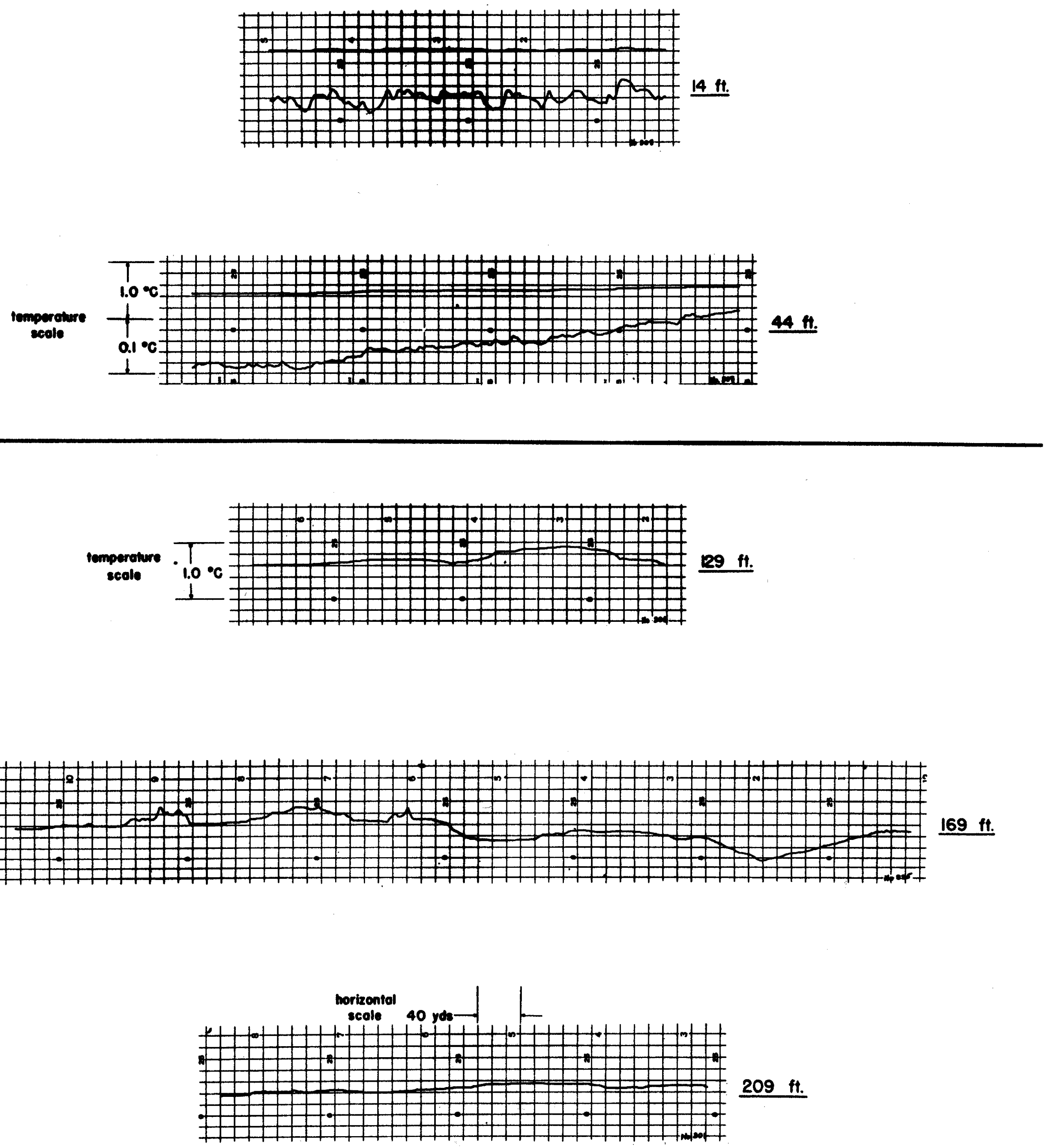

Figure 18 — Microthermal Cross Section Enclosed-Junction Thermopile (Area A, 1100-1300 EST, 3 Aug. 1948)

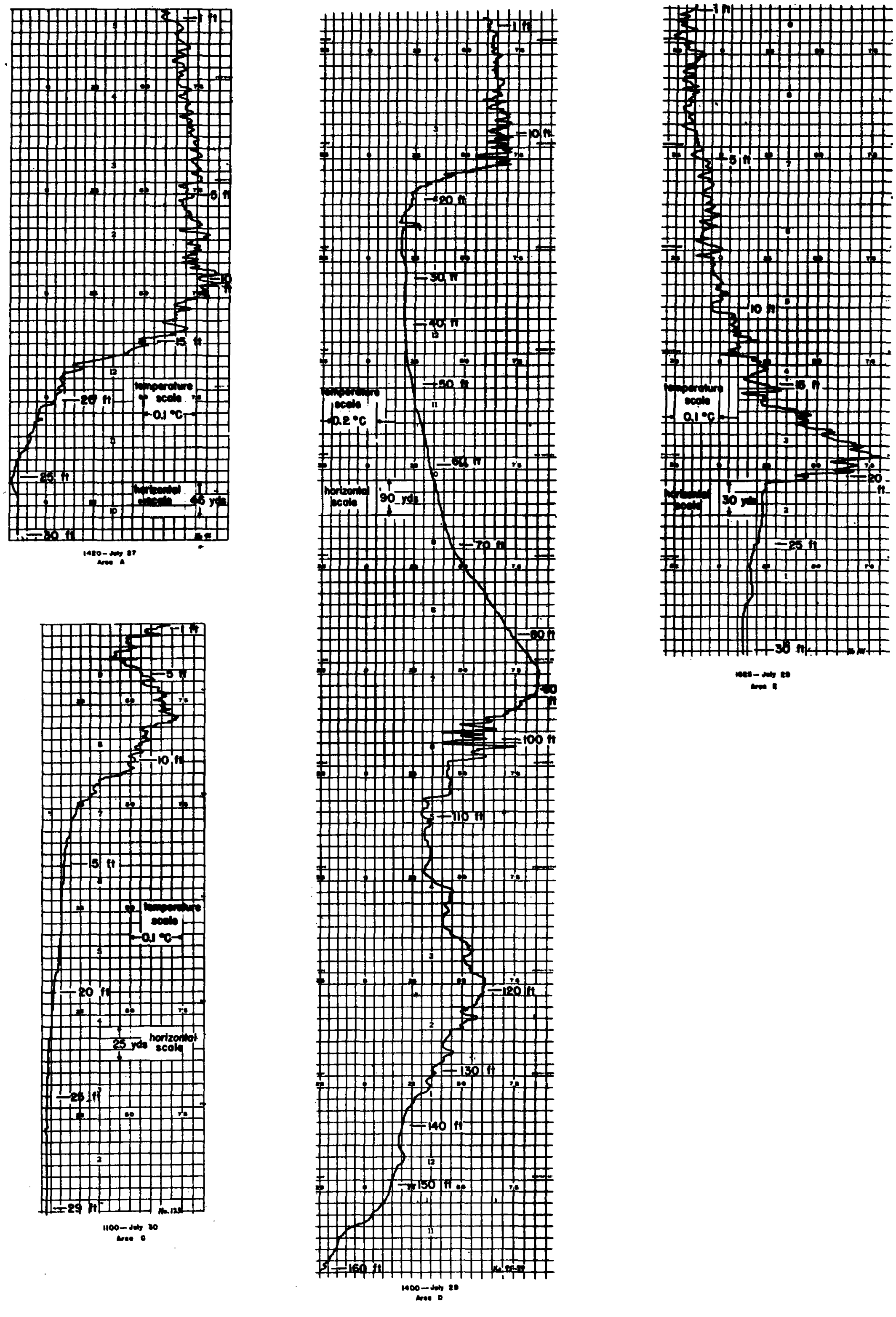

Figure 19 – Slow Oblique Ascent Records

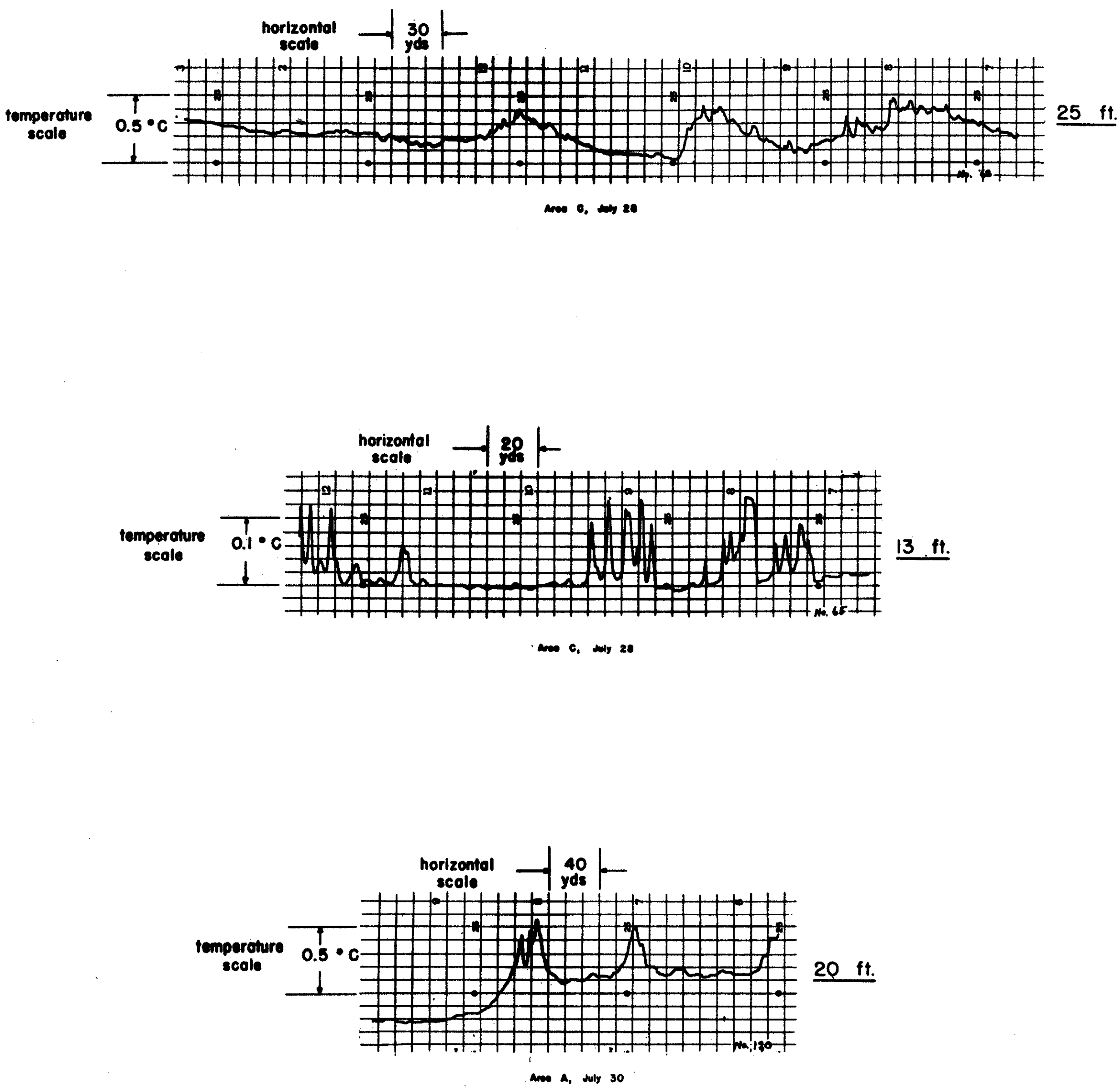

Figure 20 – Microthermal Variation at Shallow Depths, Showing Warmer-Water Patches

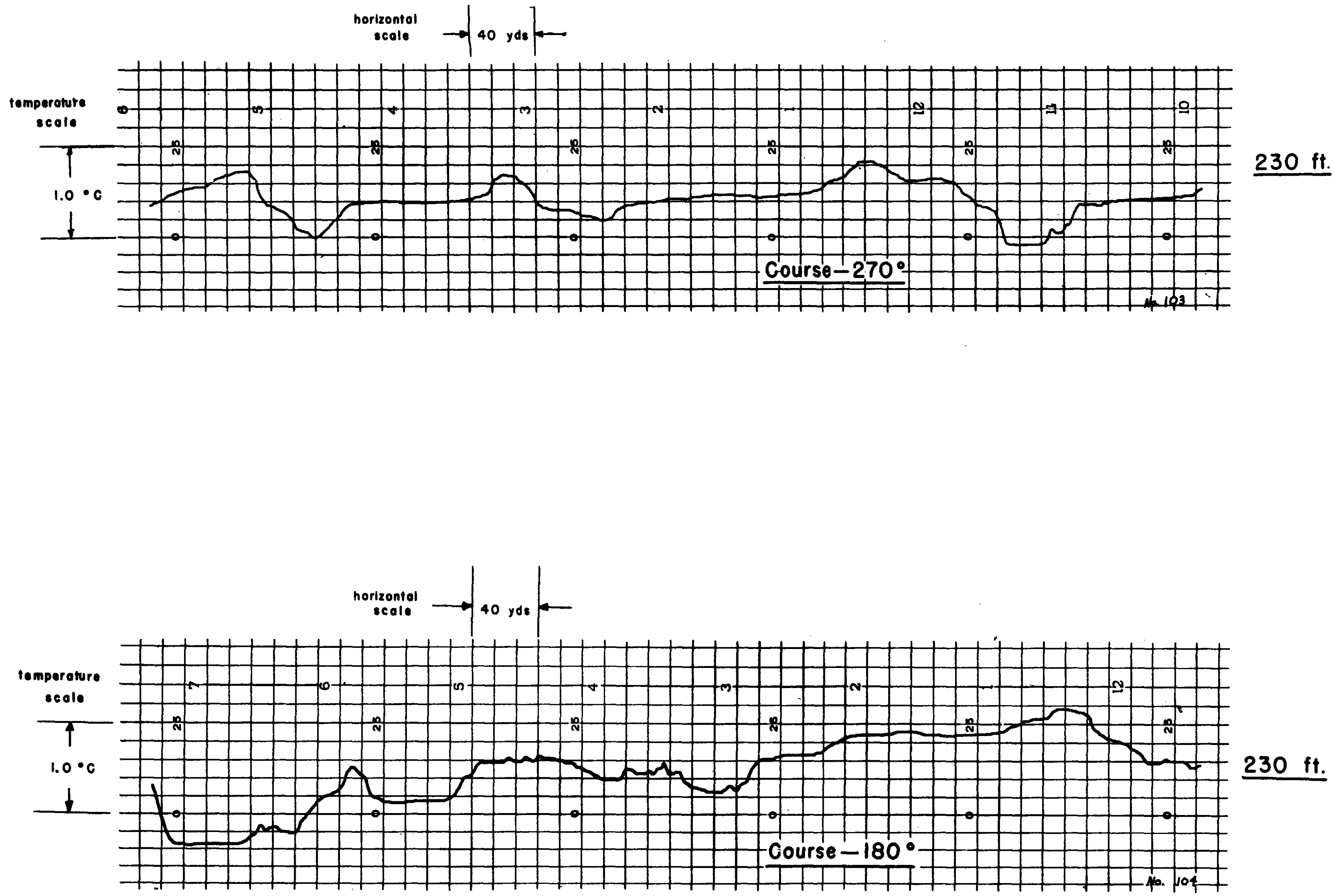

Figure 21—Comparison of Microthermal Variation on Two Courses 90° Apart

APPENDIX

Method for Obtaining the Response Spectrum of a Thermopile

Let a thermopile be suddenly plunged from air to a water bath of a slightly different constant temperature. If the thermopile is of the type described in this report, the record traced on a recorder can be observed to have a rapid exponential rise and a much slower exponential fall. The first part represents the response of the outer active junctions; the latter part is the result of incomplete thermal isolation of the reference junctions. This is the response to an "input" in the form of a "unit-step", and the spectrum, or frequency response, can be found by the method of the Laplace transform.

Let s represent the complex argument of the Laplace transform, and let E(s) denote the transform of the input excitation. Let the transform of the response to E(s) be R(s). Then if S(s) is the desired amplitude spectrum of the device, $S(s) = R(s)/E(s)$.

In the present case, the excitation can be taken to be the "unit-step" function, so that $E(s) = \frac{1}{s}$. The response to this excitation is observed to be of the form $R(t) = e^{-bt}(1-e^{-at})$, where the first factor is the slow exponential fall, and the second the rapid exponential rise, and where a and b can be evaluated from the record obtained. Its transform is

$$R(s) = \frac{1}{s+b} - \frac{1}{s+(b+a)} \approx \frac{1}{s+b} - \frac{1}{s+a}$$

since $b \ll a$. Thus

$$S(s) = \frac{s}{s+b} - \frac{s}{s+a}$$

the real part which is, if s is taken as $i\omega$,

$$Re = \frac{1}{1+\left(\frac{\omega}{a} - \frac{b}{\omega}\right)^2}$$

and its imaginary part

$$\mathrm{Im} = \frac{-\left(\frac{\omega}{a} - \frac{b}{\omega}\right)}{1 + \left(\frac{\omega}{a} - \frac{b}{\omega}\right)^2}$$

Then the amplitude spectrum is

$$\left[\overline{\mathrm{Re}}^2 + \overline{\mathrm{Im}}^2\right]^{1/2} = \left[1 + \left(\frac{\omega}{a} - \frac{b}{\omega}\right)^2\right]^{-1/2}$$

The active-junction time constant was measured to be 4/10 sec; thus $a = \frac{10}{4} = 2.5\ \mathrm{sec}^{-1}$; the reference-junction time constant was 3.7 min. = 222 seconds; thus $b = \frac{1}{222} = .0045\ \mathrm{sec}^{-1}$. With these values inserted, the above function is plotted in Figure 3.

* * *

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