Geothermal Measurements on Eniwetok and Bikini Atolls

GEOLOGICAL SURVEY PROFESSIONAL PAPER 260-U

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By J. H. SWARTZ

Bikini and Nearby Atolls, Marshall Islands

GEOLOGICAL SURVEY PROFESSIONAL PAPER 260-U

UNITED STATES GOVERNMENT PRINTING OFFICE, WASHINGTON : 1958

UNITED STATES DEPARTMENT OF THE INTERIOR

FRED A. SEATON, *Secretary*

GEOLOGICAL SURVEY

Thomas B. Nolan, ***Director***

For sale by the Superintendent of Documents, U. S. Government Printing Office
Washington 25, D. C. - Price 30 cents (paper cover)

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By J. H. Swartz

ABSTRACT

Geothermal measurements in two deep holes drilled in the summer of 1952 on Eniwetok Atoll showed that the atoll temperature profiles differ greatly from those in continental areas. In continental drill holes, the temperatures below the zone of annual change rise steadily with increasing depth. In the atoll drill holes, temperatures below the zone of annual change decrease steadily with increasing depth until a minimum is reached at a depth of several thousand feet (6.4° C between 3,180 and 3,380 feet in drill hole E–1, July 1955). Below this depth the curve reverses, and temperatures increase with further increase in depth, as in continental drill holes.

In both Eniwetok drill holes the temperature decreases rapidly to a depth of 1,000 to 1,400 feet, below which the rate of temperature decrease becomes much slower down to the depth of minimum temperature.

The temperatures of Marshall Islands ocean water, as determined in October and November 1952 by the Capricorn Expedition of the Scripps Institution of Oceanography, showed the same type of temperature profile: a rapid decrease to a depth of 800 feet, followed by a continued but much slower decrease with increasing depths. The close parallelism between the thermal profiles in the drill hole and the ocean leaves little question that the character of the thermal profile in the atoll is largely a result of cooling by the adjacent ocean.

Additional support for this hypothesis is afforded by measurements of the fluctuations of the water levels in the drill holes. In both drill holes there was evidence of tidal motion. In drill hole E–1, which was cased to a depth of 4,109 feet, the tidal amplitude was small and there was a phase lag of 9½ hours. In drill hole F–1, which was cased to a depth of 1,973 feet, the tidal variations agreed in both amplitude and phase with those measured simultaneously in the ocean offshore. Such evidence of high permeability in the reef sediments emphasizes the probability of heat transfer from sediments to ocean.

Further support for these conclusions was found in temperature and tidal measurements made in a drill hole on the island of Bikini, Bikini Atoll. The temperature curve there showed the same continuing temperature drop as in the Eniwetok drill holes. Water-level measurements showed a tidal fluctuation approximately one-half the amplitude of the ocean tide and with a phase lag of 1 hour.

The rise of temperature with increasing depth below the point of minimum temperature was observed only in one drill hole, where the rate of rise, 20° C per km, is only about half that observed in drill holes along the California coast. As the rise begins near the bottom of the drill hole it may be that the curve is still affected by the ocean and that a normal gradient would be found if measurements extended deep enough.

The average temperature gradient for the upper, steep-gradient part of the thermal profile was −51.5° C per km in the Eniwetok drill holes, −35.2° C per km in the Bikini drill hole, and −94.2° C per km in the ocean. The average gradient in the lower part of the profile was −7.5° C per km in the Eniwetok drill holes, −18.1° C per km in the Bikini drill hole, and −6.6° C per km in the ocean.

INTRODUCTION

PURPOSE OF STUDY

The drilling of two deep holes on Eniwetok Atoll in 1952 (Ladd, Ingerson, Townsend, and others, 1953) offered an opportunity for a study of geothermal profiles and the thermal regime under a coral atoll. The investigation was undertaken by the U. S. Geological Survey for the U. S. Atomic Energy Commission in cooperation with the Office of Naval Research and was carried out in cooperation with H. S. Ladd, of the Geological Survey, who directed the drilling, and with H. K. Stephenson, of the Los Alamos Scientific Laboratory, who had general responsibility for the project.

A hole drilled on Bikini island in 1947 to a depth of 2,556 feet (Ladd, Tracey, and Lill, 1948) was found to be still open in 1952 to a depth of 1,430 feet, and its thermal profile was measured for comparison with the Eniwetok data.

LOCATION

The Marshall Islands (fig. 235) lie in eastern Micronesia, approximately 2,900 miles west of Hawaii and 1,200 miles southeast of Guam. Eniwetok and Bikini Atolls (fig. 236) lie in the northwest corner of the group, Eniwetok at lat 11°30′ N., long 162°15′ E., and Bikini approximately 165 nautical miles to the east at lat 11°35′ N., long 165°25′ E.

The first Eniwetok drill hole, F–1, was drilled near the west end of Elugelab island [1], at the north end of the atoll where it is joined by a guyot or flat-topped seamount extending to the north and northwest. The second, E–1, was drilled near the south end of Parry Island on the southeast flank of the atoll.

[1] The island was subsequently destroyed, and this drill hole is no longer available for study.

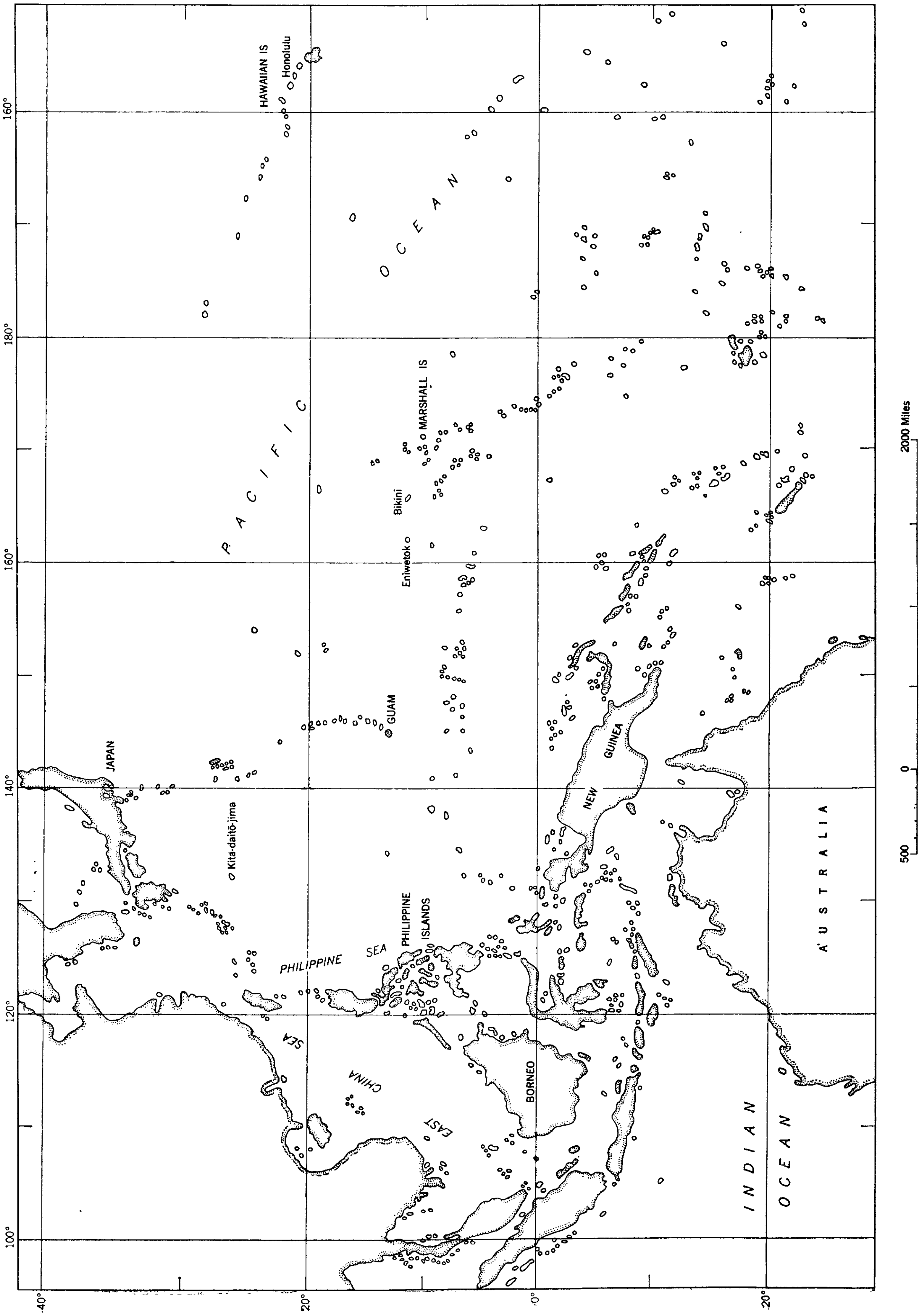

FIGURE 235.—Map of the west Pacific Ocean showing the location of the Marshall Islands.

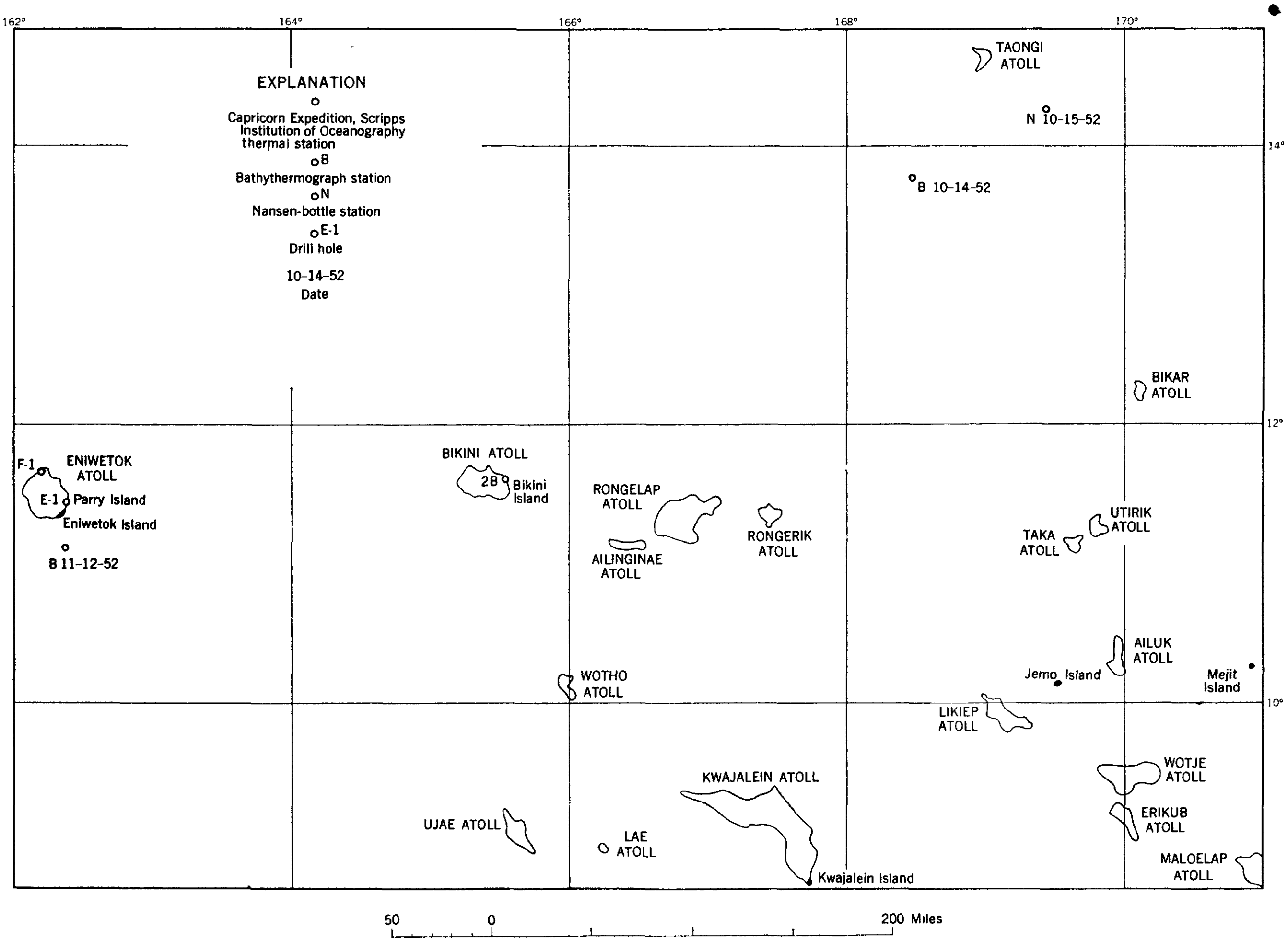

FIGURE 236.—Map of northwestern Marshall Islands showing the location of Eniwetok and Bikini Atolls and of ocean-temperature observations.

Drill hole 2B, on Bikini Atoll, is near the center of the lagoon side of Bikini island. It lies on the northeast side of the road that parallels the lagoon, near the native graveyard, and approximately 240 feet inland from the break in vegetation at the top of the beach.

ACKNOWLEDGMENTS

The cooperation of C. T. Cooper and H. H. Lewis, resident engineers for the U. S. Atomic Energy Commission, and of C. L. Coray and J. M. Lloyd, resident managers of the Holmes and Narver Co., made possible the smooth functioning of the program. Rudolph Raspet and W. L. Smith, of the Geological Survey, and Alan C. Jones, of the Atomic Energy Commission, assisted with thermal measurements at Eniwetok and Bikini Atolls respectively; and J. L. Moore, R. D. Blenck, Kai Hendricksen, V. A. DiTomaso, F. H. Delpino, and L. J. Casiano, all of the Holmes and Narver Co., and SP/3 C. J. Spengler, U. S. Army Signal Corps, have continued the thermal measurements in drill hole E-1 since the writer's departure from Eniwetok.

EQUIPMENT AND TECHNIQUES

THERMISTORS

All temperature measurements were made by means of thermistors mounted in multiconductor cables. A thermistor is a thermally sensitive resistor, a semiconductor, characterized by a high, negative temperature coefficient of resistance (Becker, Green, and Pearson, 1946; Shockley, 1950). At room temperatures the thermistors used in this study have a resistance of approximately 1,000 ohms and a rate of change of resistance of approximately 4.4 percent per degree centigrade change in temperature.

CABLES

In constructing the cables the thermistors were inserted at regular intervals and vulcanized in place. The circuit used (fig. 237) was one designed by the writer in 1949 for thermal measurements in the Arctic (Swartz, 1954). Distances in feet from a carefully marked zero point were either stamped into the vulcanized joint at each thermistor or shown by carefully

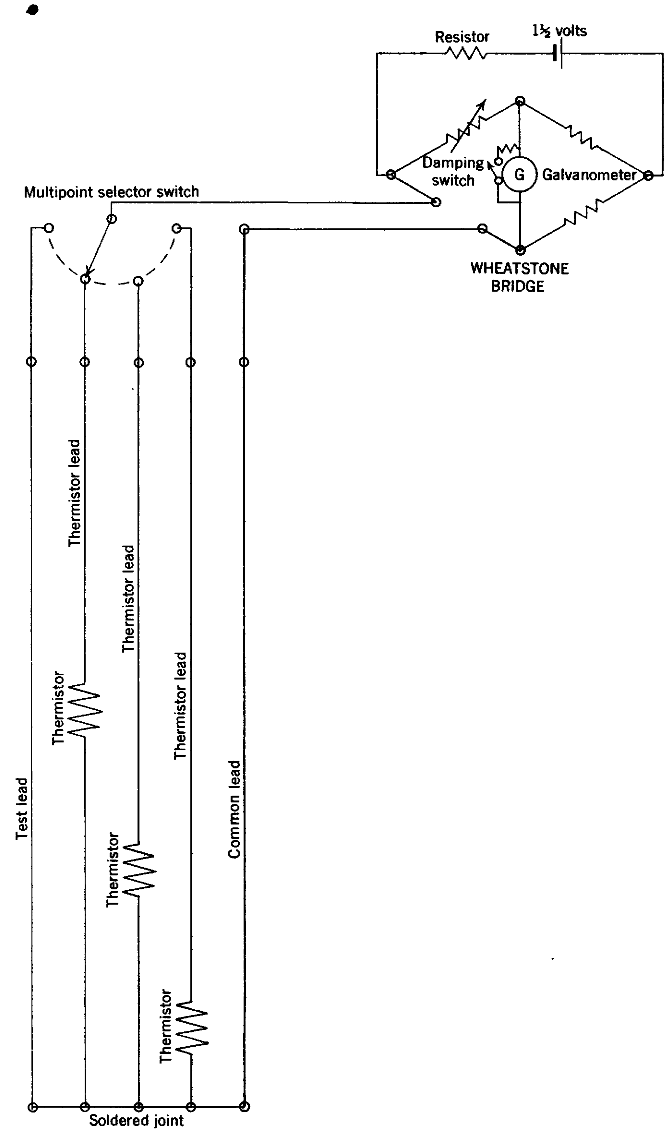

FIGURE 237.—Circuit diagram for a multithermistor cable.

positioned rings of vinylite tape. Several feet of free cable extended as a lead from the zero mark to a multiconductor connector enclosed in a waterproof cap.

Four cables were used in the present study. Measurements in June, July, and August, 1952, were made with a 3-conductor cable, 5,000 feet long, loaned by Prof. Francis Birch of Harvard University when delivery on other cables was delayed. With this cable only one thermistor could be used, as the remaining circuits were required for other equipment. The longest of the other 3 cables, which became available in October 1952, was 4,200 feet long and contained a steel strength-member 5/32 inch in diameter and carried 15 thermistors. The 2 shorter cables, 400 and 2,000 feet long respectively, carried 17 thermistors each and had cadmium-bronze conductors for greater strength, but did not contain a strength-member.

In practice, the cable was lowered into the drill hole and, except as noted, allowed to remain there until thermal equilibrium was attained. Measurements of thermistor resistance were then made with a Wheatstone bridge.

Both temporary and permanent cable installations were made. In the temporary installations the cables, lowered by hand or by winch, were allowed to remain in place as long as possible before measurements were made and the cable removed. In the permanent installation the cables were lowered to the required depth, the zero mark positioned, and the free lead tied in a clove hitch to a 24-inch length of 2½-inch-diameter propeller shafting resting across the mouth of the casing. These cables were left in the hole indefinitely and measurements continued at regular intervals. To protect the installation a small hut was placed over the mouth of the drill hole.

In making measurements the connector at the upper end of the cable was plugged into a multiple-selector switchbox (fig. 238) and the selected circuit connected to a four-dial Wheatstone bridge. Because of the high humidity and salt content of the air, the bridge, the switchbox, and the connecting leads were kept in a hot

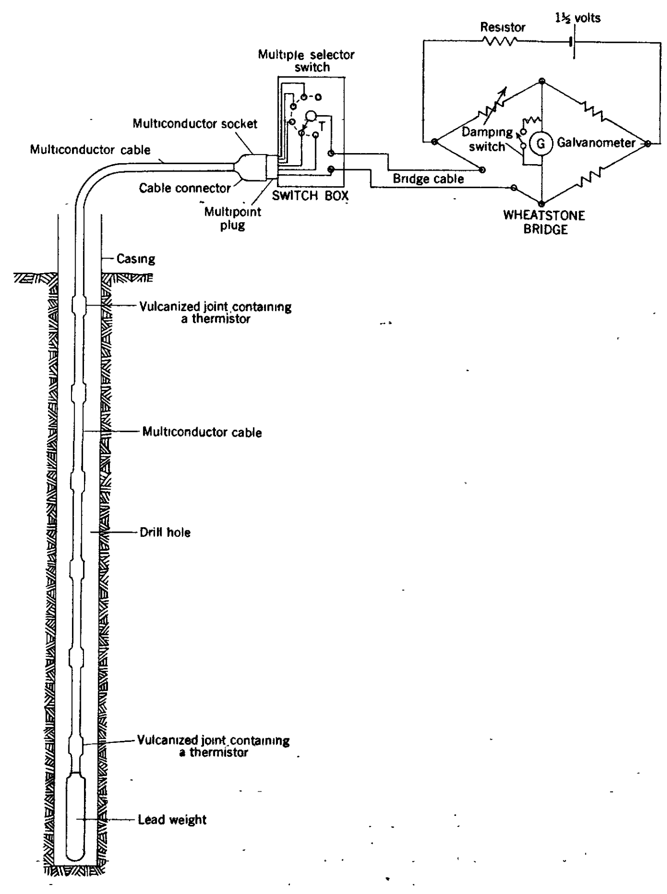

FIGURE 238.—Diagram of measurement setup for measuring temperatures in drill holes.

locker when not in use, and the waterproof caps of the cable connectors were removed only while measurements were being made.

CONVERSION OF RESISTANCE TO TEMPERATURE

The resistance of the thermistor, R, is found by subtracting the resistance of the thermistor circuit leads, R_L, from the measured resistance, R_M, of the thermistor plus the measurement circuit. Thus,

$$R=R_M-R_L. \quad (1)$$

The temperature, T, of the thermistor is then computed from the equation

$$T=[a/(b+\log R)]-c \quad (2)$$

where a, b, and c are constants, differing slightly for different thermistors, which have been determined by careful prior laboratory calibration.

The resistance R_L is determined by the resistance of the test circuit, R_T, in the multithermistor cables. As has been shown elsewhere (Swartz, 1954),

$$R_L=kR_T \quad (3)$$

where

$$k=R_{LC}/R_{TC} \quad (4)$$

and R_{LC} and R_{TC} are the resistances of thermistor lead and test lead, respectively, as measured by prior laboratory calibration.

If the cable, as in the single-thermistor cable, does not have a test lead, the resistance R_L must be computed from the equation

$$R_L=R_o(1+\alpha T_{LA}) \quad (5)$$

where α is the temperature coefficient of resistance of the conductor wire, R_o is the resistance of the conductor at 0° C, and T_{LA} is the average temperature of the cable as determined by successive approximations from the temperature-measurement data. Inserting the values of these constants for the present equipment, equation 5 reduces to

$$R_L=164.6+0.6296T_{LA} \quad (6)$$

for the single-thermistor cable.

RELIABILITY OF DATA

By the reliability of the measurements is meant their degree of freedom from error. Several factors affect the reliability of the measurements: the sensitivity of the instruments, the precision of the measurements, and the occurrence of systematic errors.

SENSITIVITY OF INSTRUMENTS

The thermal sensitivity of the instruments may be defined quantitatively as the change in temperature required to produce a unit deflection of the bridge galvanometer. It thus represents in a sense the resolving power of the measuring equipment used.

The sensitivity varied somewhat depending upon the particular equipment in use at a particular time. It ranged from 0.015° to 0.595°C per millimeter deflection with changes in the galvanometer and bridge multiplier. Somewhat limited experimental data indicate that with the particular equipment and observational techniques used, changes of 0.003–0.007°C could be detected in the July and August 1952 measurements, changes of 0.002°C in the October 1952 to March 16, 1953 measurements, and changes of 0.001°C in later measurements.

PRECISION OF MEASUREMENTS

The precision of the measurements represents the closeness with which they can be repeated and is dependent solely on the random errors of measurement. It is measured by the magnitude of the median error; that is, the one whose magnitude is such that the probability of the occurrence of a larger error exactly equals that of the occurrence of a smaller.

The precision of the measurements in the present survey varied somewhat with the skill and experience of the operator and with the particular equipment being used. The probable errors computed for the measurements from their beginning in June 1952 to October 1953 are listed in table 1.

TABLE 1.—*Precision of geothermal measurements in drill holes in the Marshall Islands, June 1952 to October 1953*

Cable	Atoll	Drill hole	Date	Probable error (°C) when thermistor resistance is—	
				<1,000 ohms	>1,000 ohms
Single thermistor.	Eniwetok	F–1	June 1952		±0.020
	do	E–1	July and Aug. 1952.		±.020
	Bikini	2B	Nov. 1952		±.007
Multi-thermistor.	Eniwetok	F–1	Oct. 1952	±0.003	±.002
	do	E–1	Dec. 1952–Mar. 16, 1953.	[1] ±.011	±.002
	do	E–1	Mar. 31, 1953–Oct. 1953.	±.003	±.001
	Bikini	2B	Nov. 1952	±.003	

[1] The majority of the multiple readings on which this figure is based were made when the bridge galvanometer was relatively insensitive. This value of the probable error is therefore regarded as probably too large.

It was not feasible, because of operating conditions, to make several readings at any one depth, so the probable errors given in table 1 are computed from a series of pairs of readings clustered about different means rather than a similar number of readings clustered about a single mean. It can be shown that the probable error so obtained will in general be somewhat smaller than that computed from the same number of readings clustered about a single mean.

ACCURACY OF MEASUREMENTS

EFFECTS OF SYSTEMATIC ERRORS

Systematic errors are those which affect all readings alike and are the major factor in determining the accuracy of the measurements. Accuracy is the closeness of approach of the measured value to the true value of the measured quantity; that is, the limiting value that would be approached by the mean of a series of very careful measurements free of all systematic error as the number of such measurements is greatly increased.

Systematic errors can be eliminated or reduced by careful instrumentation and operational techniques. When systematic errors can be quantitatively evaluated their effects can be removed by corresponding corrections. If they cannot be removed or evaluated it is possible only to estimate their probable size.

The following discussion will deal with those sources of systematic error found in the present investigation: bridge temperature, conductor temperature, thermistor heating, insufficient equilibrium time, accuracy of thermistor calibrations, and thermistor stability.

BRIDGE TEMPERATURE

Although the bridge resistors are made of an alloy with a low temperature coefficient of resistance, temperature changes may be sufficient to introduce changes in the calibration of the bridge. When not in use the bridge is kept in a heated locker at a temperature higher than the maximum ambient temperature to guard against moisture, mildew, and other sources of trouble. Prior to use the bridge must be cooled to the ambient temperature so that the bridge temperature and the calibration will remain constant during the measurement run. If the ambient temperature is not sufficiently close to that for which the bridge is calibrated, the actual calibration, while constant, will differ from the original by a certain factor which may be called the bridge-temperature error. Errors from this source have been found to be as much as 0.01° C if uncorrected. They may, however, be corrected as discussed below.

To determine both when the bridge temperature has become constant and what the bridge-temperature correction factor is, use is made of the standard resistor unit whose circuit is shown in figure 239. The resistors

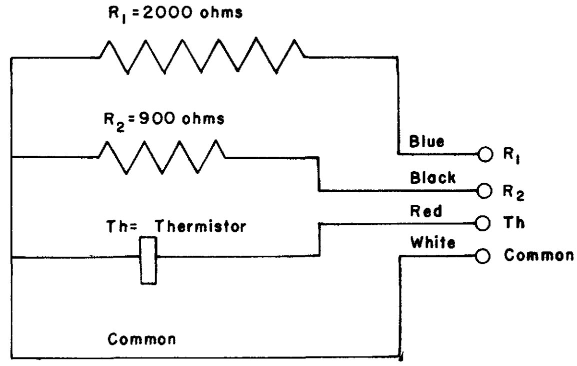

FIGURE 239.—Circuit for standard resistor unit used in determining bridge-temperature correction.

R_1 and R_2 are precision resistors of a very low temperature coefficient alloy. Both are very carefully calibrated in the laboratory between the extremes of the temperature range to be expected in the field, and then mounted in a micarta block, together with a calibrated thermistor to measure the temperature of the standard resistors. The resistances of the standards are so chosen as to fall within the two bridge ranges used for the thermistor measurements and to approximate the mean values of the thermistor resistances to be read in those ranges.

In operation the unit is attached to the bridge measurement terminals and the resistance of the thermistor checked until it has become nearly constant. Because the temperature coefficient of the bridge resistors is very small compared to that of the thermistor, absolute constancy is not required. When a sufficient constancy is reached, the bridge reading of the resistances R_1 and R_2 and of the thermistor are recorded. From the resistance of the thermistor the temperature of the standards is computed and their correct resistances determined from the laboratory calibration data. The bridge correction factor is then given by the ratio of the correct resistance to the reading of the bridge. Seventeen readings gave an average bridge correction of 0.011° C for one set of measurements.

CONDUCTOR TEMPERATURE

The resistance of the conductors in the cables varied considerably with temperature. Errors due to this source were eliminated in the multiconductor cables by the use of a test circuit described in a previous paper (Swartz, 1954).

This method was not applicable, however, to the single-thermistor cable. With this cable the conductor resistance had to be computed from the temperature coefficient of resistance of the wire, using the measured drill-hole temperatures and a method of successive approximations to determine the mean temperature of the cable. Any residual error from this source is believed to be small, as an error of 1° C in the cable temperature would mean an error of only 0.63 ohm in the conductor resistance, which would correspond to a temperature error of only 0.009°–0.016° C in the range of temperatures involved in the present study.

THERMISTOR HEATING

Because thermistors are so highly sensitive to temperature change, self-heating by the bridge current can be a source of error. To obviate this the bridge battery supply was reduced to 1½ volts and a series resistor of 1,000 ohms was used to reduce the bridge current still further. In addition a special measurement technique was employed to minimize the time of bridge-current flow. With these precautions a careful operator could reduce the error from this source to approximately 0.001° C. An incautious operator, who permitted the bridge current to flow during bridge adjustments, could, however, introduce an error of 0.01° C or more from this source.

INCOMPLETE EQUILIBRIUM

Measurements in 1952 with the single-thermistor cable ordinarily had to be made within 15 to 30 minutes after installation and before the cable could reach complete thermal equilibrium with the drill hole. Errors from this source were found to average 0.1° C.

The multiconductor cables in the temporary installation at Eniwetok drill hole F–1 in October 1952 could not be left in the hole long enough to reach complete equilibrium. However, as the cables were in place for 3½ to 6 hours before readings were taken, the errors from this source were much smaller than those for the single-thermistor cable. The time-temperature graphs from measurements made during the waiting period indicate an error on the order of 0.04° C.

THERMISTOR CALIBRATION

All thermistors used were calibrated in a precision-controlled temperature bath. Three factors could affect the accuracy of the calibration: stability of the bath, stability of the master standard, and accuracy of the computed thermistor constants. The bath temperature usually did not change more than 0.001° C between two successive readings of the master standard during a single set of measurements.

Recalibrations of the master standard through the courtesy of the National Bureau of Standards have shown a more or less regular decrease in the indicated temperature of approximately 0.02° C per year during a 5-year period.

Errors in the computed constants of the thermistors are small, so that differences between observed and computed temperatures are believed in general to average less than 0.004° C.

THERMISTOR STABILITY

Extensive measurements in the Arctic on certain thermistors permanently installed in the ground at points of constant temperature have shown a temperature drift from all causes—calibration drift, climatic change, and the like—not exceeding approximately 0.01° C per year. However, there is a growing body of evidence that thermistors that have been subjected to sudden large temperature changes, as during vulcanization, exhibit a form of thermal hysteresis. Recent measurements on 56 thermistors vulcanized into 2 cables have indicated an average initial temperature error from this cause of +0.17° C. Following vulcanization and during a period in which the cables were subjected to temperatures of 0°–32° C, the error slowly decreased to zero and then reversed in sign so that after 2 years the error due to drift was approximately −0.17° C.

Occasional thermistors may be found that show much greater error. Thus the ice-point resistance of one thermistor decreased from 3,209 to 3,197 ohms upon calibration at the steam point. During the following year it increased in resistance approximately exponentially to 3,290 ohms, a change of 93 ohms or of almost 0.5° C from the prehypsometer test value. However, such a change after heating seems exceptional and its effect can usually be recognized in the field data by abnormal and persistent kinks in the thermal profiles.

Because the thermistors in drill hole E–1 on Parry Island are permanently installed at points of essentially constant temperature, their calibration drift may be expected to be a minimum. It is difficult to differentiate in the field data between the effects of cooling of the drill hole and calibration drift of the thermistors. The rather meager evidence as yet available suggests a calibration drift of approximately −0.04° C per year for these thermistors. Errors from this source may therefore be expected to be small and to be less than 0.2° C for the period of measurement here covered.

EFFECT OF PRESSURE

A moderate amount of experimental evidence indicates that hydrostatic pressure has an effect on the resistance of thermistors. Investigations by Misener and Thompson (1952) and by Tavernier and Prache (1952) show a small but definite decrease in thermistor resistance with increasing pressure. The resultant error would therefore take the form of an apparent increase in temperature, and a correction for the effect of pressure would reduce slightly the apparent temperatures.

However, as there is disagreement as to the form of the pressure-resistance function and the value of the pressure coefficient, no pressure corrections have been applied to the data presented here.

ACCURACY OF DATA

TEMPERATURE

As previously noted, accuracy means the closeness of approach of the measured value to the true value of the measured quantity. Care must be taken to distinguish between the accuracy of the measured values of individual temperatures and that of the values of the change of temperature with time.

Measurements of individual temperatures are subject to a series of systematic errors which may enter in a variety of ways. If uncorrected, and if the effects should be additive (which in general will not be true), the total error for the single-thermistor cable, when not in equilibrium with the drill hole, could reach or slightly exceed 0.3° C. On the other hand the total error for the multiconductor cable, which would be in thermal equilibrium with the drill hole, probably would not exceed 0.2° C.

Measurements of the change of temperature with time are, in contrast, much more accurate, because systematic errors not due to time cancel out in taking the differences. Corrections can be applied for systematic errors that are time dependent, such as calibration drift. Experience in the field has indicated that such measurements, when carefully made with multiconductor cables permanently installed at points of constant temperature, may be accurate to 0.01° C or better. A moderate amount of evidence indicates that calibration drifts in such values may be expected to be as little as 0.04° C per year.

DEPTH

Each cable when inserted in the drill hole was positioned with its zero point at the top of the casing. All depths are therefore referred to the top of the casing as their zero point.

Cable 205, the 4,200-foot cable, had a central airplane-steel cable, 5/32 inch in diameter, as a strength-member. A high degree of dimensional stability is claimed for it by the manufacturer. The single-thermistor cable also had a steel strength-member, but of much smaller size. The cable, however, was much lighter in weight and is believed to have good dimensional stability. Cables 193 and 204, the 400- and 2,000-foot cables, had no strength-members. However, the conductors of these cables are of cadmium bronze, which greatly reduces their distensibility.

It is recognized that all of these cables when hanging in the drill hole will stretch to some extent under their own weight. The amount of stretch will be decreased, although not entirely eliminated, by the buoyancy of the water in the drill hole.

Adequate experimental data are not available for computing the stretch of these cables under their own weight, so no attempt has been made to correct the measured depths for this effect. The depths given here are the apparent depths as measured by the thermistor positions in the cable.

TEMPERATURE OBSERVATIONS

ENIWETOK ATOLL

DRILL HOLE F-1, ELUGELAB ISLAND

Drill hole F–1, near the west end of Elugelab island (fig. 240), was begun May 12, 1952, and bottomed June 10 at 4,630 feet in a hard, slow-drilling rock that was struck at 4,610 feet and is believed to be basalt. At that depth the tools were lost by collapse of a part of the overlying hole, and the drill pipe was eventually shot off at 3,750 feet. The hole was open to a depth of approximately 3,500 feet and was cased to a depth of 1,973 feet.

The lithologic sequence above the basalt comprised largely unconsolidated coral sediments (Ladd, Ingerson, Townsend, and others, 1953), with soft beds and cavities forming about 70 percent of the section. Cavities, some open, some filled with loose coral sand, totaled 122 feet in thickness and were found to a depth of more than 2,700 feet. Somewhat harder rock was found below 3,980 feet. Between 4,300 and 4,600 feet the section consisted largely of dolomite or dolomitic limestone.

Geothermal measurements were begun with the single-thermistor cable on June 19, 1952, 9 days after completion of the hole. The temperatures are given in table 2 and figure 241. Because of other equipment mounted in

TABLE 2.—*Temperature measurements with single-thermistor cable in drill hole F–1, Elugelab island, Eniwetok Atoll, June 19–26, 1952*

Depth (feet)	Temp (° C)	Day (June)	Depth (feet)	Temp (° C)	Day (June)
45	28.7	26	1,745	12.6	20
95	28.7	26	1,845	14.3	20
145	28.6	26	1,945	12.0	20
245	27.5	26	2,045	11.1	20
345	26.9	19	2,145	9.6	20
345	26.4	26	2,245	10.7	20
445	16.5	19	2,245	10.8	23
545	13.0	19	2,345	10.9	23
645	11.1	19	2,445	11.1	24
745	14.5	19	2,445	11.2	24
845	13.2	19	2,545	11.1	23
845	13.3	20	2,645	11.0	23
845	13.3	20	2,745	12.8	23
945	11.5	26	2,845	13.0	23
1,045	11.2	20	2,945	13.5	23
1,145	10.9	20	3,045	13.5	23
1,245	10.5	20	3,145	13.4	23
1,345	10.2	20	3,245	13.8	24
1,445	10.1	20	3,345	14.3	24
1,545	9.8	20	3,445	15.2	24
1,645	12.6	20	3,445	15.3	25

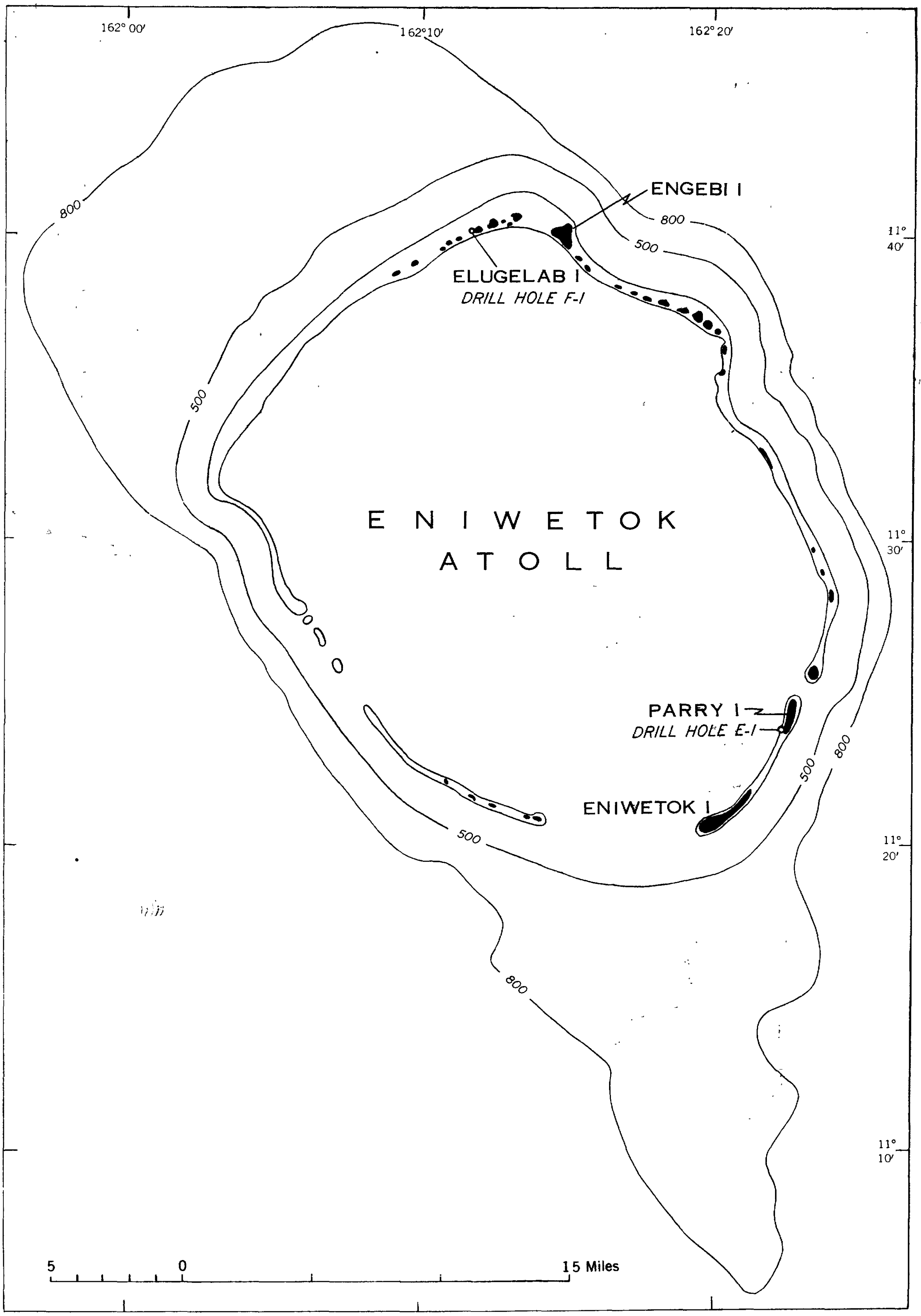

Figure 240.—Map of Eniwetok Atoll showing the location of the island of Elugelab and Parry Island, and of drill holes E-1 and F-1. Water depths in fathoms.

the cable, only two conductors were available for the thermistor circuit, and a test circuit could not be used. Circumstances seldom allowed more than 30 minutes for the cable to remain in place before measurements had to be begun, a period too short for the thermistor to reach complete thermal equilibrium with the drill hole. A series of tests, however, showed that the resultant error averages only 0.1° C.

The top of the casing, which served as zero point for the depth measurements, was 4⅜ inches above the surrounding ground level and 10.695 feet above mean low tide as determined by precise leveling. It was 6.15 feet below the drilling table which constituted the zero point for drill-log depths.

In October 1952 these measurements were repeated with two multithermistor cables temporarily installed. The results are given in table 3 and figure 241. Although the cables remained in the hole for 3½ to 6 hours before readings were taken, it was not possible to allow enough time for them to reach complete thermal equi-

TABLE 3.—*Temperature measurements with multithermistor cable in drill hole F-1, Elugelab island, Eniwetok Atoll, October 1952*

Depth (feet)	Temp (°C)	Depth (feet)	Temp (°C)	Depth (feet)	Temp (°C)
24.1	29. 1	500.5	22. 0	1,600	10. 0
28.1	28. 9	549.8	20. 3	1,649.8	10. 0
73.1	28. 5	600.5	19. 0	1,700	10. 1
98.1	28. 1	649.8	17. 2	1,800	9. 8
123.1	27. 9	700.5	14. 8	1,849.8	10. 4
148.1	27. 7	749.8	14. 0	1,900	9. 8
173.1	27. 6	800.5	13. 2	2,000	9. 7
198.1	27. 3	849.8	12. 8	2,049.8	9. 6
223.1	27. 3	900.5	11. 9	2,100	9. 3
248.1	27. 0	949.8	11. 5	2,249.8	8. 9
273.1	26. 4	1,049.8	10. 6	2,300	8. 6
298.1	26. 0	1,100.5	10. 4	2,500	8. 7
323.1	25. 7	1,149.8	10. 2	2,700	8. 7
348.1	25. 3	1,249.8	10. 0	2,900	8. 9
373.1	24. 8	1,300	9. 7	3,100	8. 8
398.1	24. 2	1,400	9. 6	3,300	9. 8(?)
423.1	23. 6	1,449.8	9. 7		
449.8	23. 5	1,500	9. 7		

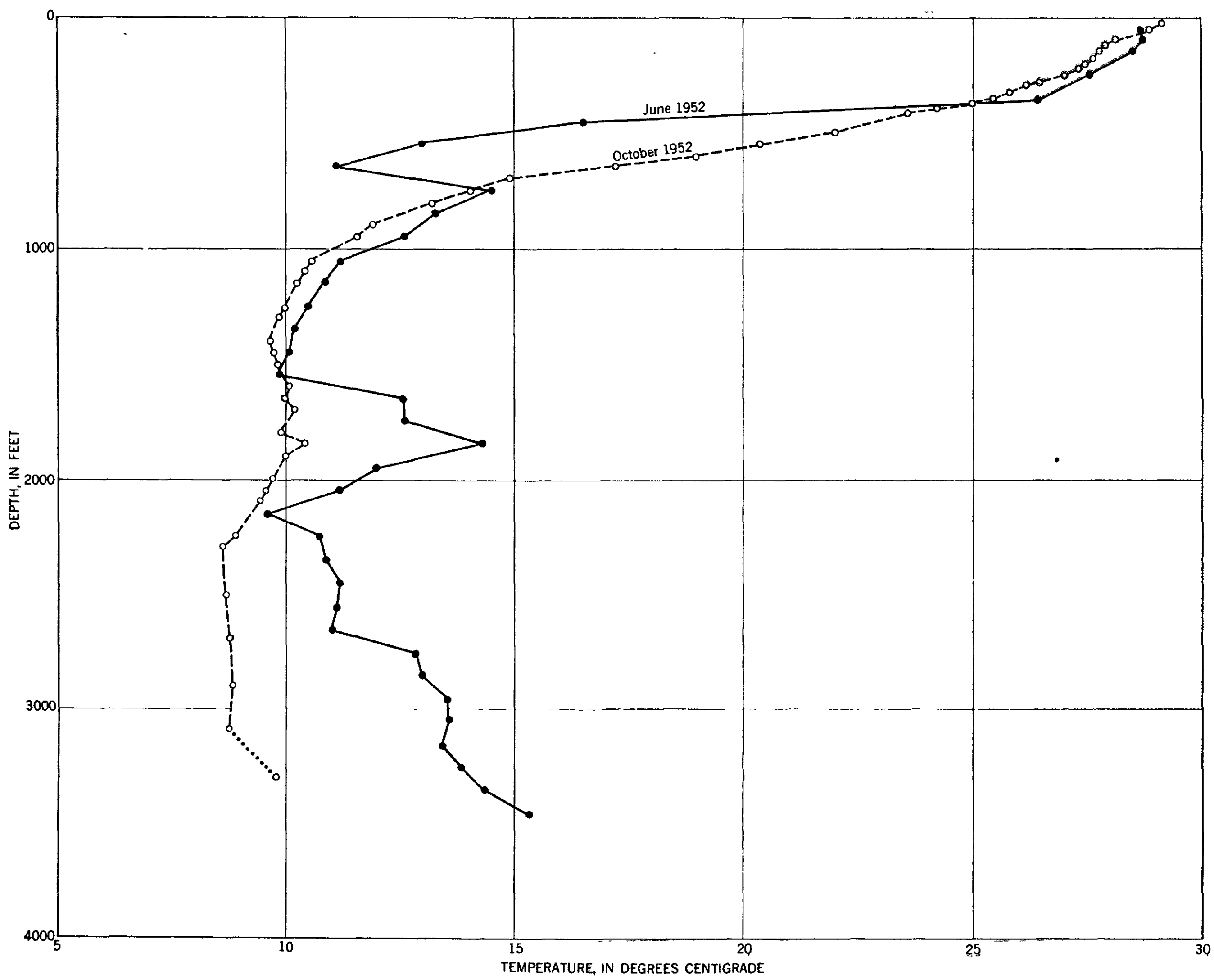

FIGURE 241.—Temperature profiles in drill hole F-1, Elugelab island, Eniwetok Atoll, June and October 1952.

librium with the drill hole. Measurements made during the waiting period indicate that the resultant error was on the order of 0.04° C.

Both curves of figure 241 show the same general trends, the most striking feature of which is the continuing decrease in temperature to great depths. The significance of this and of the differences between the two curves is discussed later.

DRILL HOLE E-1, PARRY ISLAND

Eniwetok drill hole E–1 is near the south end of Parry Island, approximately 1,200 feet from the south end and 175 feet from the west shore of the island (fig. 240). Drilling was begun on June 24, 1952, and the hole was completed in olivine basalt at a depth of 4,222 feet on July 12, 1952. The hole was cased with 7-inch casing to a depth of 4,109 feet. The lowermost 113 feet was uncased.

The stratigraphic sequence to a depth of 1,400 feet is similar to that of drill hole F–1 (Ladd, Ingerson, Townsend, and others, 1953). Below that depth, although the strata are still reef sediments, there are marked differences in lithology and organic constitution. Only 55 percent of the section was soft or cavernous and only 2 small cavities, totaling 8 feet in drilling distance, were observed. No dolomite was found in this drill hole. Basalt cuttings were first observed at 4,154 feet and olivine basalt was cored from 4,208 to 4,222 feet.

Thermal measurements were begun on July 24, 1952, 12 days after drilling was completed, and were continued through August 7, 1952. The results are given in table 4 and figure 242. The measurements were made with

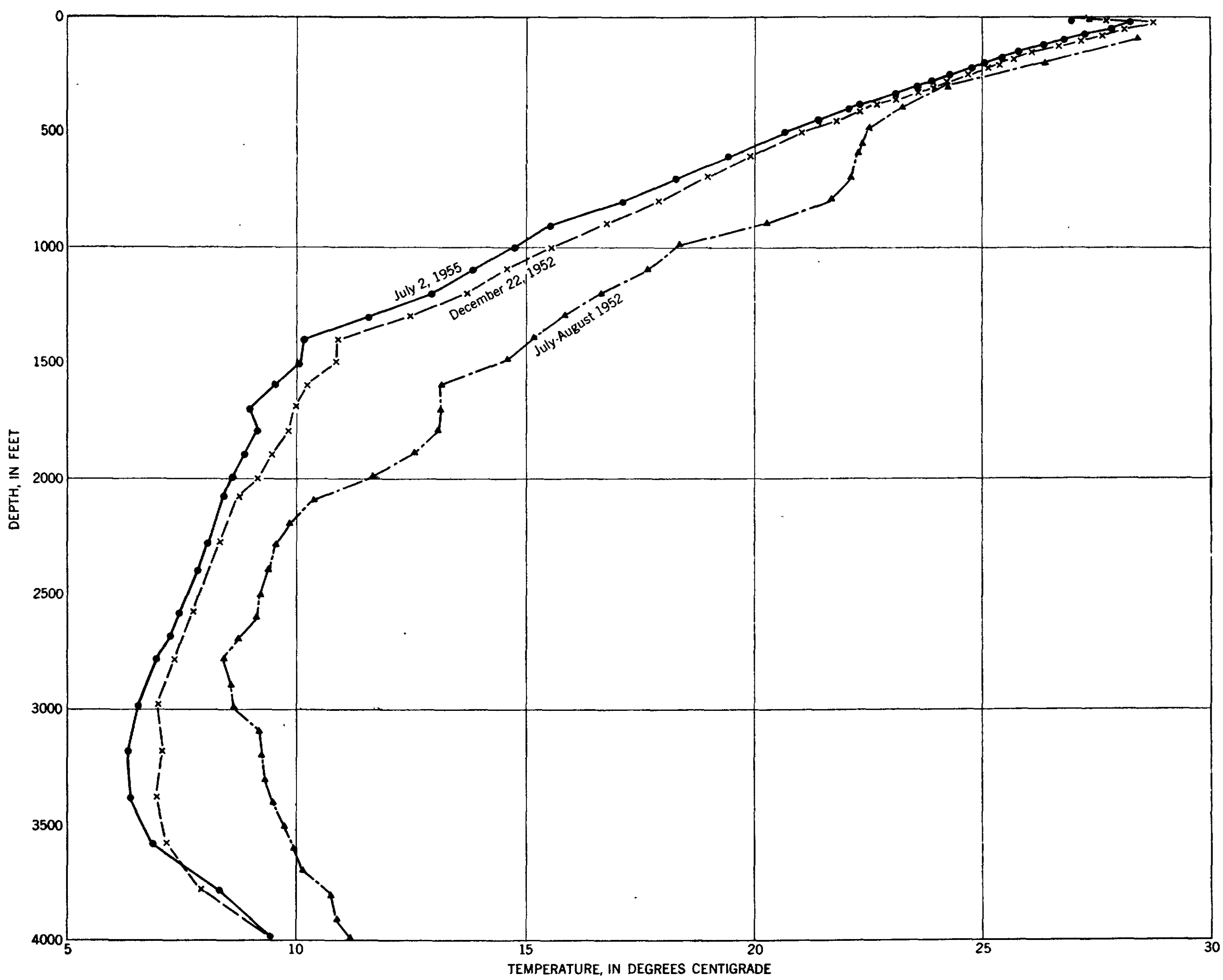

FIGURE 242.—Temperature profiles in drill hole E–1, Parry Island, Eniwetok Atoll, July and August 1952, December 22, 1952, and July 2, 1955.

TABLE 4.—*Temperature measurements in drill hole E–1, Parry Island, Eniwetok Atoll, July and August 1952*

Depth (feet)	Temp (°C)	Depth (feet)	Temp (°C)	Depth (feet)	Temp (°C)
95	28. 5	1,495	14. 6	2,995	8. 7
195	26. 4	1,595	13. 1	3.095	9. 2
295	24. 3	1,695	13. 2	3,195	9. 3
395	23. 3	1,795	13. 1	3,295	9. 3
495	22. 5	1,895	12. 6	3,395	9. 5
545	22. 4	1,995	11. 6	3,495	9. 7
595	22. 3	2.095	10. 4	3,595	9. 9
695	22. 2	2,195	9. 9	3,695	10. 1
795	21. 7	2.295	9. 5	3,795	10. 7
895	20. 3	2,395	9. 4	3,895	10. 8
995	18. 5	2,495	9. 2	3.995	11. 1
1,095	17. 7	2,595	9. 1	4.045	11. 4
1.195	16. 7	2,695	8. 7	4,095	11. 4
1,295	15. 8	2,795	8. 4	4,145	12. 2
1,395	15. 2	2,895	8. 6	4,195	11. 9

the single-thermistor cable used for the June 1952 measurements in drill hole F–1. As in the latter, no test circuit was available and conductor resistances had to be computed from drill-hole temperatures.

All depths were measured from a zero point at the top of the casing, 28 inches above the general ground level at an elevation of 14.44 feet above mean low water. The top of the casing is 4.67 feet lower than the drill table (elevation 19.11 feet above mean low water), which was used as the zero point for the stratigraphic measurements in the drill log.

On December 18, 1952, three geothermal-measurement cables were permanently installed in drill hole E–1 to permit a continuing study of the thermal regime in the drill hole and surrounding strata. Such a permanent installation has the added advantage that the cable attains and will thereafter remain in thermal equilibrium with the drill hole so that the temperature of the thermistor is identical with the temperature in the drill hole and adjacent beds.

Initial readings were made on the night of December 18, 3 to 4 hours after the installation of each cable. These were taken purely to check the installation, as it was too early for the cables to have reached equilibrium with the drill hole. The measurements of the permanent sequence were begun 4 days later, on December 22, and have been continued at regular intervals since that date. Representative readings obtained from December 1952 to July 1955 are given in table 5.

The minimum temperature from 1952 to 1954 occurred at a depth of 3,380 feet. Since early 1954, however, the temperature at a depth of 3,180 feet has been dropping somewhat more rapidly than that at 3,380 feet, with the result that early in 1955 it finally became, and since then has remained, slightly less than at 3,380 feet. The point of minimum temperature has thus migrated a short distance upward in the 2½ years of observations.

The temperature profiles for December 22, 1952, and July 2, 1955, are shown graphically in figure 242, with the profile for July and August 1952.

TABLE 5.—*Temperature measurements in the permanent installation in drill hole E–1, Parry Island, Eniwetok Atoll, December 1952 to July 1955*

Depth (feet)	Temperature (°C)				Depth (feet)	Temperature (°C)			
	Dec. 22, 1952	July 5, 1953	July 15, 1954	July 2, 1955		Dec. 22, 1952	July 5, 1953	July 15, 1954	July 2, 1955
3.8	26. 96	28. 52	27. 86	27. 31	1,000.3	15. 54	15. 12	14. 89	14. 78
27.8	28. 70	28. 49	28. 41	28. 20	1,100.3	14. 52	14. 11	13. 90	13. 81
52.8	28. 02	27. 96	27. 94	27. 83	1,200.3	13. 70	13. 31	13. 08	12. 97
77.8	27. 59	27. 34	27. 30	27. 24	1,300.3	12. 43	11. 98	11. 76	11. 58
102.8	27. 10	26. 88	26. 82	26. 77	1,400.3	10. 90	10. 47	10. 21	10. 13
127.8	26. 62	26. 42	26. 37	26. 32	1,500.3	10. 87	10. 40	10. 16	10. 06
152.8	25. 99	25. 99	25. 82	25. 77	1,600.3	10. 20	9. 82	9. 64	9. 54
177.8	25. 62	25. 73	25. 47	25. 43	1,700.3	9. 96	------	9. 15	8. 95
202.8	25. 30	25. 43	25. 09	25. 03	1,800.3	9. 82	9. 42	9. 21	9. 12
227.8	25. 04	25. 13	24. 80	24. 76	1,900.3	9. 47	9. 08	8. 89	8. 83
252.8	24. 68	24. 64	24. 26	24. 26	2,000.3	9. 16	8. 81	8. 65	8. 58
277.8	24. 18	24. 17	23. 94	23. 90	2,080	8. 73	8. 53	8. 43	8. 40
302.8	23. 90	23. 80	23. 66	23. 59	2,280	8. 33	8. 21	8. 08	8. 05
327.8	23. 53	23. 28	23. 12	23. 10	2,380	------	7. 98	7. 88	7. 85
352.8	23. 07	22. 90	------	------	2,580	7. 72	7. 66	7. 53	7. 46
377.8	22. 60	22. 48	22. 29	22. 30	2,680	------	7. 51	7. 34	7. 27
402.8	22. 33	22. 22	22. 02	22. 04	2,780	7. 35	7. 26	7. 08	6. 99
450.3	21. 80	21. 66	21. 42	21. 40	2,980	6. 96	6. 88	6. 74	6. 54
500.3	21. 02	21. 04	20. 71	20. 66	3,180	7. 08	6. 79	6. 56	6. 36
600.3	19. 93	19. 67	19. 45	19. 46	3,380	6. 94	6. 68	6. 52	6. 41
700.3	18. 93	18. 56	18. 37	18. 29	3,580	7. 16	7. 03	6. 92	6. 89
800.3	17. 91	17. 45	17. 21	17. 11	3,780	7. 93	8. 38	8. 32	8. 30
900.3	16. 74	16. 18	15. 78	15. 56	3,980	9. 45	9. 52	9. 44	9. 42

BIKINI ATOLL—DRILL HOLE 2B, BIKINI ISLAND

Because the thermal profiles observed in the Eniwetok drill holes departed so radically from those observed elsewhere, it seemed highly desirable to make similar thermal measurements on other atolls. Fortunately, this was possible. In 1947 during a resurvey of Bikini Atoll, a year after Operation Crossroads, holes had been drilled on Bikini island, one (drill hole 2B) to a depth of 2,556 feet (Ladd, Tracey, and Lill, 1948; Emery, Tracey, and Ladd, 1954). In November 1952 drill hole 2B was relocated. No maps showing its exact position were available, but a description furnished by H. S. Ladd, who had had charge of the drilling project, made it possible to find it.

Three drill holes—2, 2A, and 2B—had been drilled close together near the center of the lagoon shore of Bikini island (fig. 243). Drill holes 2 and 2A were

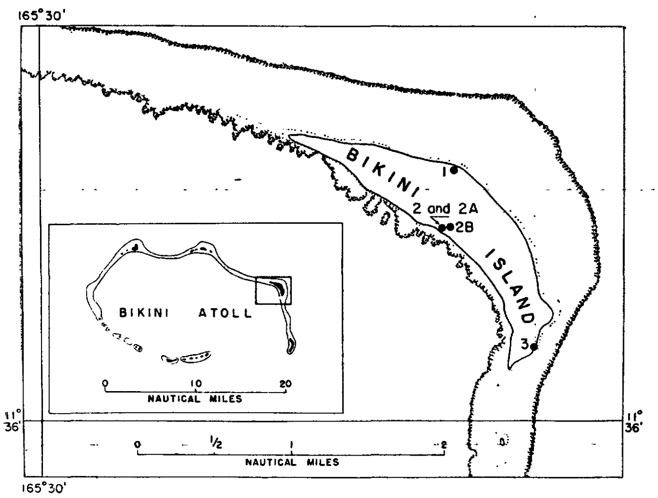

FIGURE 243.—Map of Bikini Atoll showing location of Bikini island and drill holes.

located 63 feet inland from the break in vegetation at the top of the beach, 130 feet seaward from the shore road along the lagoon side of the island, 54 feet northwest of the northwest fence of the native graveyard, and approximately 800 feet southeast of the Japanese monument at the landing near the center of the lagoon beach. Drill hole 2B is 179 feet N. 60° E. from drill holes 2 and 2A, and 49 feet north of the lagoon shore road. The drill hole is marked by its 4-inch casing, which projects about 14 inches above the ground, and by a protective fence recently placed around it. The hole was found to be still open to a depth of 1,430 feet, but to be bridged at a point between 1,430 and 1,450 feet below the top of the casing.

Cable 193 was inserted in drill hole 2B at 1400 hours on November 28, 1952, with its zero point 36 inches below the top of the casing and at the surface of the water table in the casing. It was allowed to remain overnight to reach thermal equilibrium and was read at 1000 hours on November 29.

No other multiconductor cable was available, so that it was necessary to use the single-thermistor cable for measurements at depths greater than 403 feet. This was installed in the drill hole to a depth of 500 feet at 1118 hours on November 29. Because there was only one thermistor in the cable, the thermistor had to be changed to a different depth after each reading. It was not possible to leave the thermistor at any given depth for more than about half an hour, so it could not reach complete thermal equilibrium with the hole. The length of time the thermistor remained at each depth was comparable to the length of time in the June, July, and August, 1952, measurements at drill holes F–1 and E–1 on Eniwetok. The same considerations of accuracy would therefore apply to the measurements in Bikini drill hole 2B for depths of 500 feet or more.

Cable 193 remained in place for 18 hours before measurements were begun, so that it had reached equilibrium with its surroundings; thus, the measurements from 0 to 403 feet may be regarded as equal in accuracy to those with the same cable on December 22 and afterward in drill hole E–1 on Eniwetok.

In all the measurements the resistance of the test circuit was determined and a correction for conductor resistances made. The observed temperatures are shown in table 6.

TABLE 6.—*Temperature measurements in drill hole 2B, Bikini island, Bikini Atoll, November 29, 1952* [1]

Depth (feet)	*Temp (°C)*	*Depth (feet)*	*Temp (°C)*	*Depth (feet)*	*Temp (°C)*
4	28. 7	228	26. 2	600	23. 1
28	28. 0	253	25. 9	700	22. 1
53	27. 6	278	25. 9	800	20. 5
78	27. 4	303	25. 7	1,000	18. 0
103	27. 2	328	25. 6	1,200	17. 0
128	27. 0	353	25. 5	1,400	15. 8
153	26. 8	378	25. 3	1,430	15. 7
178	26. 4	403	25. 2		
203	26. 4	500	24. 6		

[1] Multiconductor-cable 193 used to depth of 403 feet, the single-thermistor cable used below that depth.

The resultant temperature profile is shown in figure 244 together with those for Eniwetok drill holes E–1 and F–1 for comparison. All three exhibit the same continuous drop in temperature with increasing depth, although the temperatures for drill hole 2B are uniformly higher below a depth of 350 feet. A sharp decrease in the negative gradient for drill hole 2B occurs at a depth of 1,000 feet, but its significance cannot be determined. It may represent the base of the high-gradient zone observed at 1,050 feet in F–1 and 1,400 feet in E–1, although it occurs at a higher temperature and the break is less sharp.

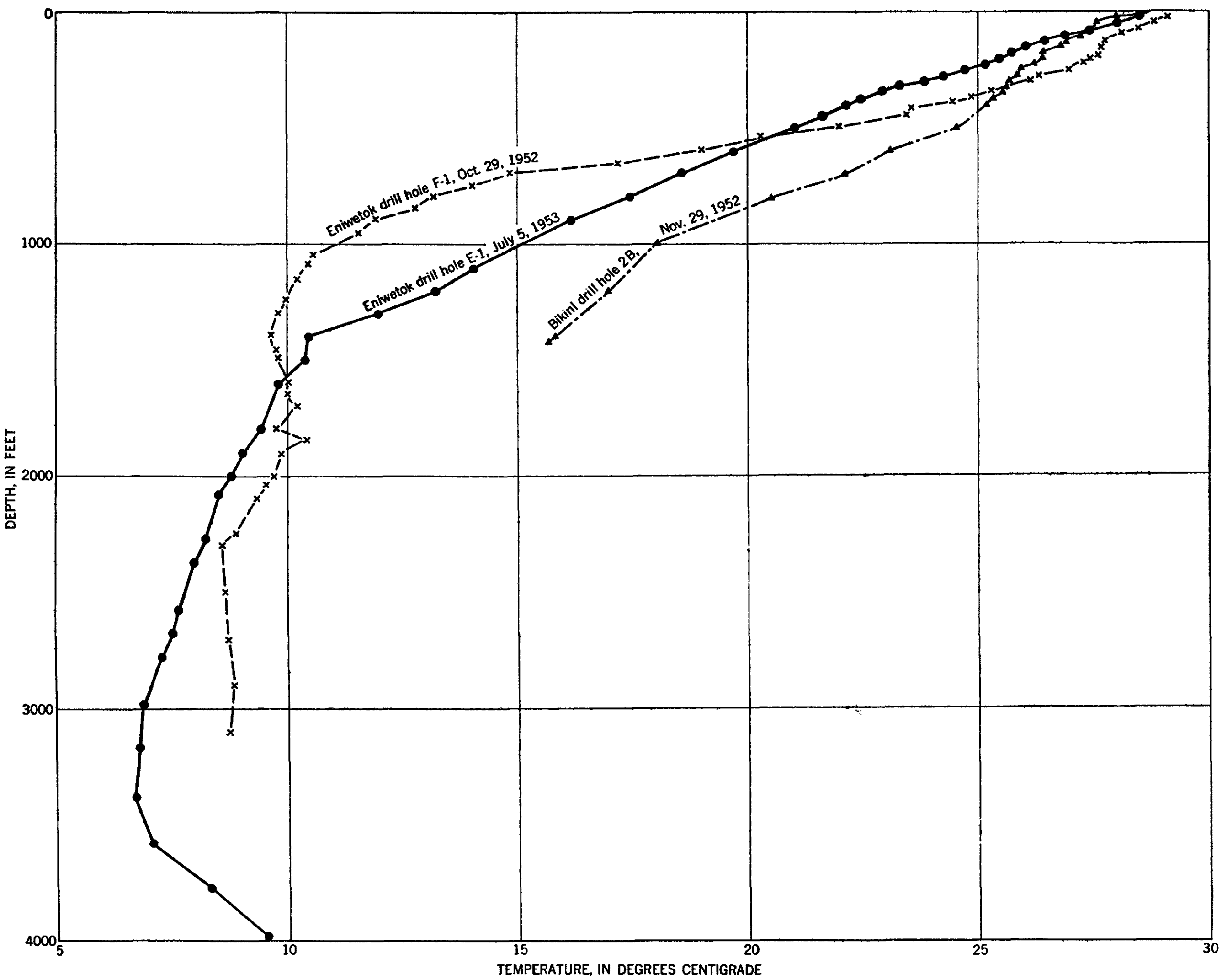

FIGURE 244.—Temperature profiles in drill holes E-1 and F-1, Eniwetok Atoll, and drill hole 2B, Bikini Atoll.

ANALYSIS OF OBSERVATIONS

EFFECTS OF HEAT OF DRILLING

The operation of a rotary drill, such as that used on Eniwetok, develops large amounts of frictional heat. In addition the water used on Eniwetok in preparing the drilling mud and in drilling the hole was pumped from the lagoon at a temperature of approximately 28° C. The average temperature of the rocks penetrated in drilling was on the order of 12° C. Thus, large volumes of water at a temperature approximately 16° C higher were pumped into the holes. The temperature of the hole and the rocks surrounding it must therefore have been considerably increased during the drilling. Temperatures in the hole should therefore be considerably above normal immediately after the completion of drilling and should gradually decrease with time, as the drilling heat is dissipated, until thermal equilibrium is reestablished.

That this has occurred in the Eniwetok drilling is shown in table 5 and by figures 241, 242, and 245. In figure 242 the thermal profiles in drill hole E–1 for December 22, 1952, and July 2, 1955, have been superimposed on that for July 24 to August 7, 1952, which was measured just after drilling was completed. There is a marked drop in temperature between the profile for July and August and that for December 22, 1952, and the latter curve has become smoother and more regular. The temperatures for the July 2, 1955, curve have in general decreased still further although the rate of decrease has become much less.

In figure 241, where the thermal profile in drill hole F–1 for October 1952, 4 months after drilling was ended, is superimposed on that for June 1952, measured a few days after drilling was completed, the divergence is even more pronounced than for drill hole E–1. This is probably due in part to the longer drilling time, 30 days for F–1 as compared with 19 days for E–1, and the greater thermal disturbance that might be expected as a result.

Two pronounced anomalies are evident in the June profile. A marked low, culminating at a depth of 650 feet, extends from 400 to 750 feet. This low had disappeared when the October measurements were made. The pronounced thermal high, centered at 1,850 feet and extending from 1,550 to 2,150 feet, was still present in October but had greatly decreased in amplitude, and concurrently had spread 150 feet farther up and down the hole (extending from 1,400 to 2,300 feet in October). The persistence of this anomaly indicates that equilibrium had not been reached 4 months after drilling was completed.

Figure 245 shows the change of temperature with time for a depth of 800 feet in drill hole E–1. It is apparent that thermal dissipation was still continuing more than a year after drilling was completed.

COMPARISON WITH PACIFIC COAST THERMAL PROFILES

It is of interest to compare the characteristics of the atoll thermal profiles with those of thermal profiles in drill holes in other areas of the Pacific Ocean. Figure 246 shows the profiles, taken from Van Orstrand (1939, figs. 3 and 4, p. 127–128), of three typical California coast drill holes: Nesa 11 at Long Beach, and Hobson 3 and Ferguson 3 at Ventura. Nesa 11 and Hobson 3 are near the coast, and Ferguson 3 is actually in the ocean offshore. All three are, therefore, in places similar to the Eniwetok drill holes, with respect to their distance from the ocean.

All three are characterized by a steadily rising temperature below the zone of annual change. This constant rise in temperature with increasing depth below a shallow surface zone is characteristic of continental thermal profiles, whether coastal or interior.

In figure 246 the thermal profile in Eniwetok drill hole E–1 for March 16, 1953 is superimposed on the profiles of the three California wells. It is at once apparent that the profile in the atoll represents a very different thermal condition. Instead of rising, the temperature decreases rapidly for the first 1,400 feet, its trend in this portion of the curve being nearly at a right angle to the trends of the California profiles. Below 1,400 feet it decreases less rapidly to a depth of 3,380 feet, where it reaches a minimum of approximately 6.7° C. Below 3,380 feet the temperature rises and continues to rise to the maximum depth attained.

Because it shows fewer signs of thermal disturbance from drilling and has been observed for a longer period of time, the profile of drill hole E–1 has been used above for comparison with the California profiles. However, the same general features are evident in drill hole F–1 (fig. 241); there is an even more rapid initial drop in temperature which continues to about 1,050 feet, where the slowup in the rate of decrease begins. This slowup occurs in both drill holes F–1 and E–1 at approximately the same temperature rather than at the same depth.

The thermal profile for drill hole F–1 below this depth becomes quite irregular, owing to thermal disturbances which in October 1952 had not yet disappeared. As a result, the measured minimum temperature of 8.6° C is reached at a depth of 2,300 feet. The temperature remains nearly constant below this point to a depth of 3,100 feet. The apparent rise below that point is based on a single observation which itself is doubtful.

The thermal profile for Bikini drill hole 2B (fig. 244) shows the same long-continued drop in temperature with increasing depth, paralleling that in drill hole E–1 quite closely below 600 feet although its temperatures are uniformly higher below a depth of about 350 feet. If the decrease in the negative gradient at 1,000 feet is the same as that occurring at 1,050 feet in F–1 and 1,400 feet in E–1, which cannot be determined without deeper measurements, it occurs here at a higher temperature, 18.0° C, and is much less sharp a change.

All three atoll thermal profiles parallel each other but diverge widely from the continental-type profiles illustrated by drill holes on the California coast.

COMPARISON WITH OCEAN TEMPERATURES IN THE MARSHALL ISLANDS AREA

As the coral atolls represent isolated land masses of quite porous reef sediments, it seemed reasonable to believe that the marked divergence of the thermal profiles from normal continental profiles could be related to the temperatures in the adjacent ocean. An attempt to measure the thermal profile immediately off Eniwetok was unsuccessful because heavy weather damaged the equipment. However, during the 1952–53 Capricorn Expedition of the Scripps Institution of Oceanography three sets of thermal measurements were made in the Marshall Islands waters, from the SS. *Horizon*, as follows (see also fig. 236):

Run	*Date*	*Location*
Nansen-bottle cast.	Oct. 15, 1952	Lat 14°16′ N., long 169°27′ E.
Bathythermograph.	Oct. 14, 1952	Lat 13°45′ N., long 168°28′ E.
Bathythermograph.	Nov. 12, 1952	Lat 11°07′ N., long 162°22′ E.

The observations, as furnished by Walter H. Munk, are given in table 7.

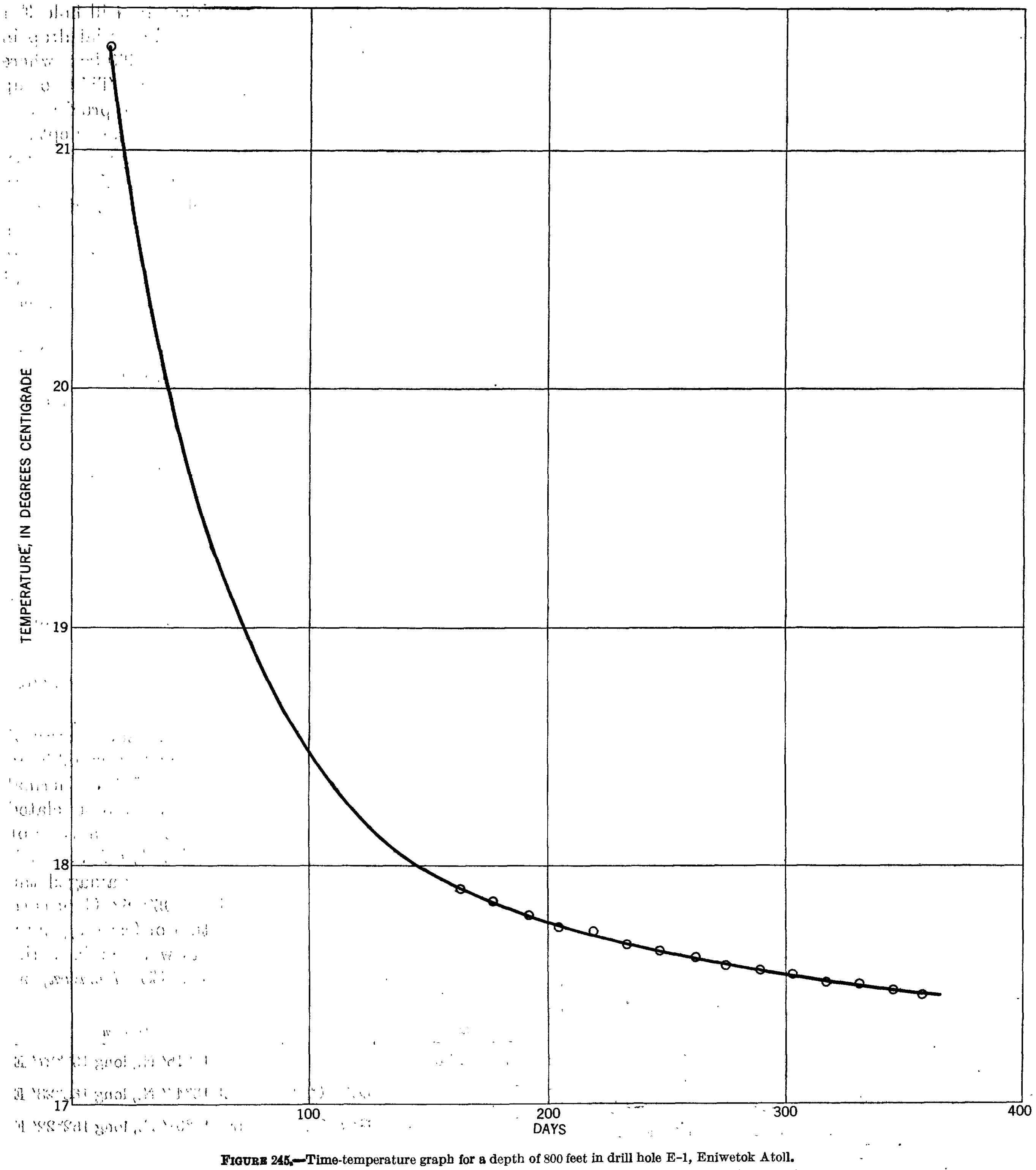

Figure 245.—Time-temperature graph for a depth of 800 feet in drill hole E-1, Eniwetok Atoll.

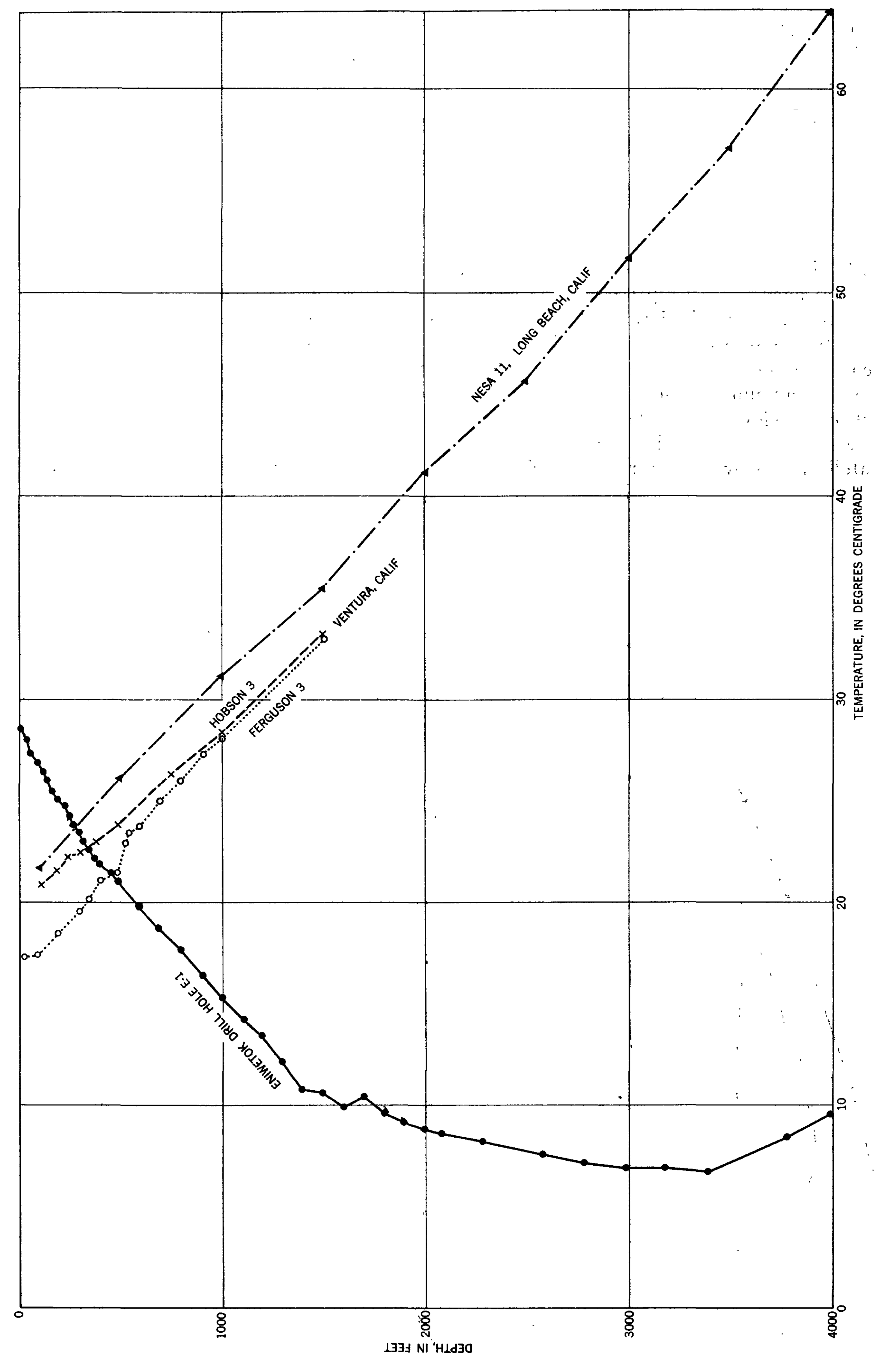

FIGURE 246.—Temperature profiles in drill hole E-1, Eniwetok Atoll, and in three drill holes on the California coast.

TABLE 7.—*Ocean-water temperatures in the Marshall Islands area; measured by the Capricorn Expedition, Scripps Institution of Oceanography, October and November 1952*

Depth (feet)	Temp. °F	Temp. °C	Depth (feet)	Temp. °F	Temp. °C
0–200 [1]	82	27.8	800	51	10.6
300	80	26.7	1,000	50	10.0
400	74	23.3	1,500	47.5	8.6
500	65	18.3	2,000	45.5	7.5
600	60	15.6	3,000	42.5	5.8
700	53	11.7	4,000	40	4.4

[1] Isothermal.

In figure 247 the thermal profiles in drill holes E–1, F–1, and 2B are shown superimposed on the ocean-temperature profile. The similarity of the ocean thermal profile to the atoll thermal profiles is immediately apparent. All four show the same rapid decrease in temperature in an upper zone (in the ocean to a depth of 800 feet) followed by a deeper zone of continued but less rapid decrease in temperature. Although the atoll profiles eventually reverse their trend and the ocean profile does not, continuing to become cooler with increasing depth, the close parallelism of all four is striking, leaving little doubt that the ocean temperatures are a major factor in controlling atoll temperatures, at least in the zone of reef sediments.

The zone of rapid temperature change has been called the thermocline. The zone of decreased rate of change immediately below it has been called the zone of weak gradient (Mao and Yoshida, 1953, p. 12). The term asthenocline (from the Greek *asthenos*, weak, and *klinein*, to incline) is here suggested for the latter.

The temperatures in drill hole F–1 down to depths of about 1,400 feet parallel those of the ocean more closely than do those in drill hole E–1. This relation suggests a closer access in that part of drill hole F–1 to the cooling effects of the ocean water. Drilling data indicated softer beds and more cavernous horizons in drill hole F–1 than in drill hole E–1, although nothing but a general relationship can be stated.

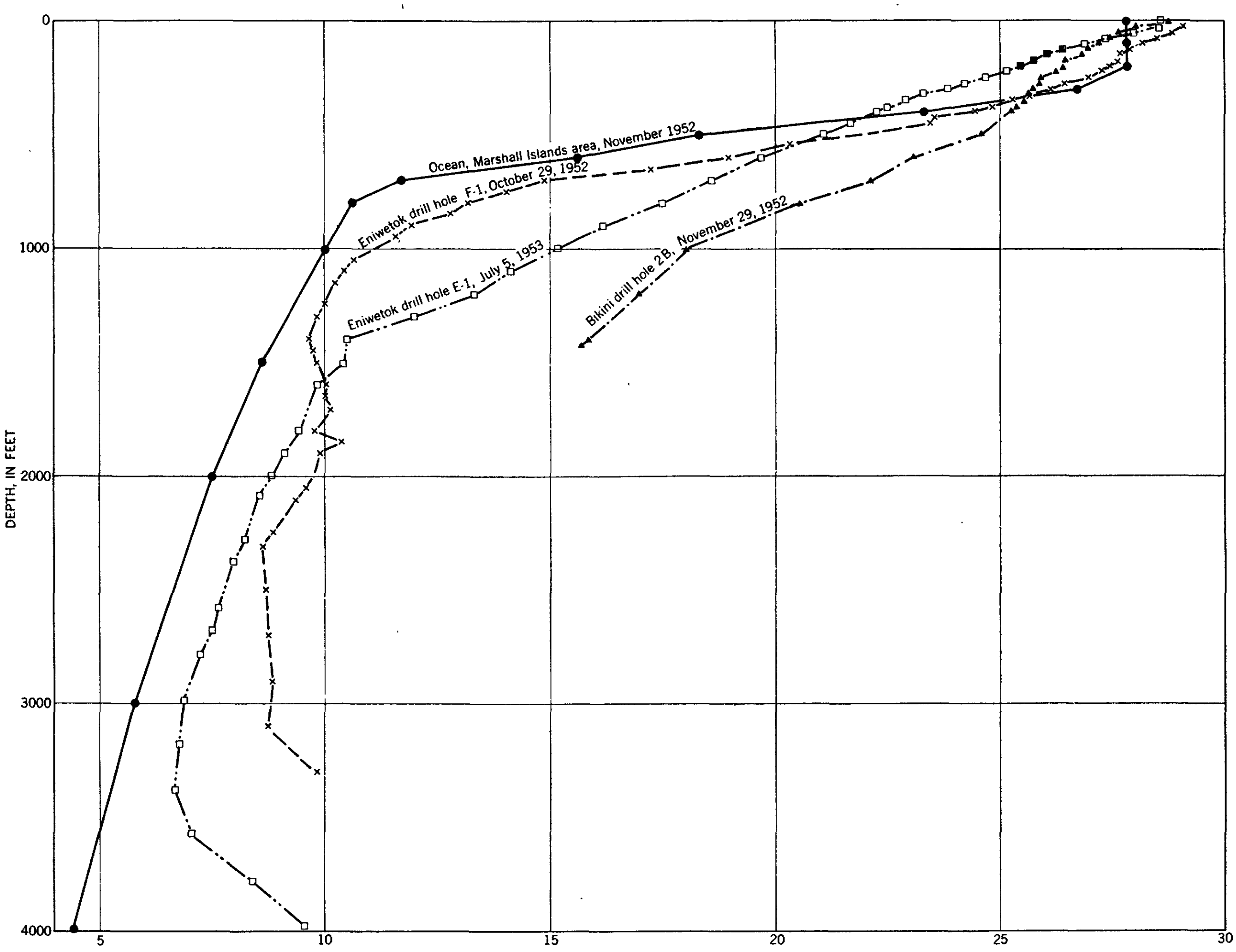

FIGURE 247.—Temperature profiles in drill holes E–1 and F–1, Eniwetok Atoll; drill hole 2B, Bikini Atoll; and in the ocean in the Marshall Islands area.

TIDAL FLUCTUATIONS IN THE DRILL HOLES

In October 1952, H. K. Stephenson and Walter H. Munk made a series of water-level measurements in drill hole F–1. At the same time measurements were made of the water level in the ocean offshore on the reef. The results, which have very kindly been furnished by Dr. Stephenson, are given in table 8.

These observations are shown graphically in figure 248, where they are compared with tide-table observations (U. S. Coast and Geodetic Survey, 1951). It is apparent that the water-level fluctuations in the drill hole agree in both phase and amplitude, as closely as can be determined, with the tide as measured just offshore and as given in the tide tables. This result was surprising, especially so because the drill hole was solidly cased to a depth of 1,973 feet. It indicates that the reef sediments surrounding drill hole F–1 are highly permeable to ocean water.

Similar measurements were made in drill hole E–1 by the writer in December 1952. At that time water in the

TABLE 8.—*Water-level measurements in drill hole F–1, Elugelab island, Eniwetok Atoll, October 21, 1952*

[Measured by H. K. Stephenson and W. H. Munk]

Time	Water level (feet) [1]		
	Drill hole	Ocean on reef	Tide tables
0458			4.2
0505	3.70		
0730	2.64		
0810	2.08	2.35	
0915	1.42	1.57	
1010	1.06	1.16	
1055	.98	1.03	.8
1215	1.46	1.28	
	[1] 2.80	[1] 2.80	[1] 2.8
1415	3.12	3.16	
1520	3.98	3.99	
1615	4.48	4.49	
1712			4.8
1715	4.62	4.57	
1800	4.48	4.41	
2336			.8

[1] Each set of measurements was referred to an individual arbitrary datum. Therefore, they are arbitrarily corrected here to a common midtide measurement of 2.8 feet to permit a more satisfactory comparison.

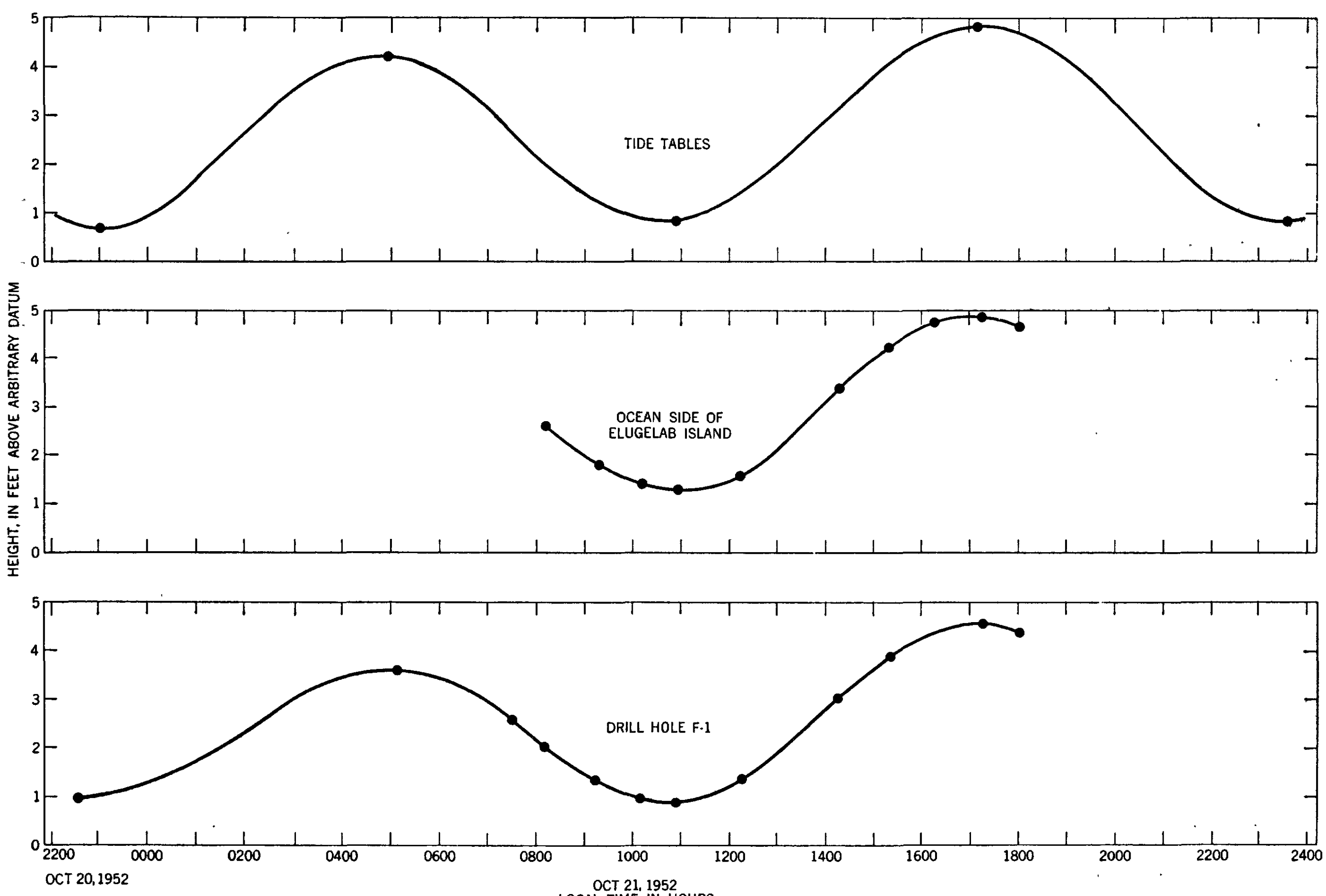

FIGURE 248.—Water-level fluctuations in drill hole F-1, Eniwetok Atoll; tidal fluctuations on the ocean side of Elugelab island; and tide-table values for Eniwetok Atoll.

drill hole was about 52 inches below the top of the casing. A piece of board with a sharp bottom knifelike edge was placed across the mouth of the casing and a 6-foot folding rule lowered slowly until its metal tip touched the surface of the water. The instant of contact was clearly and sharply shown by a slight disturbance wave in the water. The reading on the rule at the bottom of the board was recorded as the depth of the water surface below the top of the casing. Great care was exercised to keep the rule both straight and vertical so that contact was made by the entire end of the rule at the same time, and readings were immediately repeated one or more times as a check. Despite the apparent crudeness of the method, it was found possible, because of the sharpness of the disturbance signal, to repeat measurements to the nearest thirty-second of an inch. The measurements are shown in table 9.

In figure 249 water-level fluctuations in the drill hole are compared with those of the tide as given by the tide tables. The fluctuations in the drill hole are negligible when both are plotted to the same scale (fig. 249*A*). However, if the amplitude of the morning tidal wave is reduced to the amplitude of the fluctuation

TABLE 9.—*Water-level measurements in drill hole E-1, Parry Island, Eniwetok Atoll, December 14, 1952*

Time	Water level (inches)		Time	Water level (inches)	
	Depth below top of casing	Decimal equivalent height above minimum		Depth below top of casing	Decimal equivalent height above minimum
0838	$52\frac{16}{32}$	0.69	1406	$52\frac{24}{32}$	0.44
0908	$52\frac{18}{32}$	.63	1442	$52\frac{26}{32}$	.38
0941	$52\frac{18}{32}$	.63	1508	$52\frac{30}{32}$	.25
1007	$52\frac{18}{32}$	.63	1541	$53\frac{2}{32}$	.13
1032	$52\frac{16}{32}$	.69	1609	$53\frac{4}{32}$	.06
1102	$52\frac{16}{32}$	.69	1639	$53\frac{4}{32}$	.06
1132	$52\frac{16}{32}$	.69	1709	$53\frac{4}{32}$	.06
1201	$52\frac{16}{32}$	.69	1739	$53\frac{6}{32}$	0
1242	$52\frac{18}{32}$	.63	1809	$53\frac{6}{32}$	0
1302	$52\frac{20}{32}$	.56	1850	$53\frac{6}{32}$	.03
1333	$52\frac{22}{32}$	.50	1938	$53\frac{6}{32}$	0

in the drill hole and the phase is shifted so there is a lag of 9½ hours, quite satisfactory agreement between fluctuations of the tide and the water level in the drill hole is obtained (fig. 249*B*).

Both the small amplitude of the water-level fluctuation in drill hole E-1 and the time lag of 9½ hours indicate either a much longer hydraulic path, or a higher

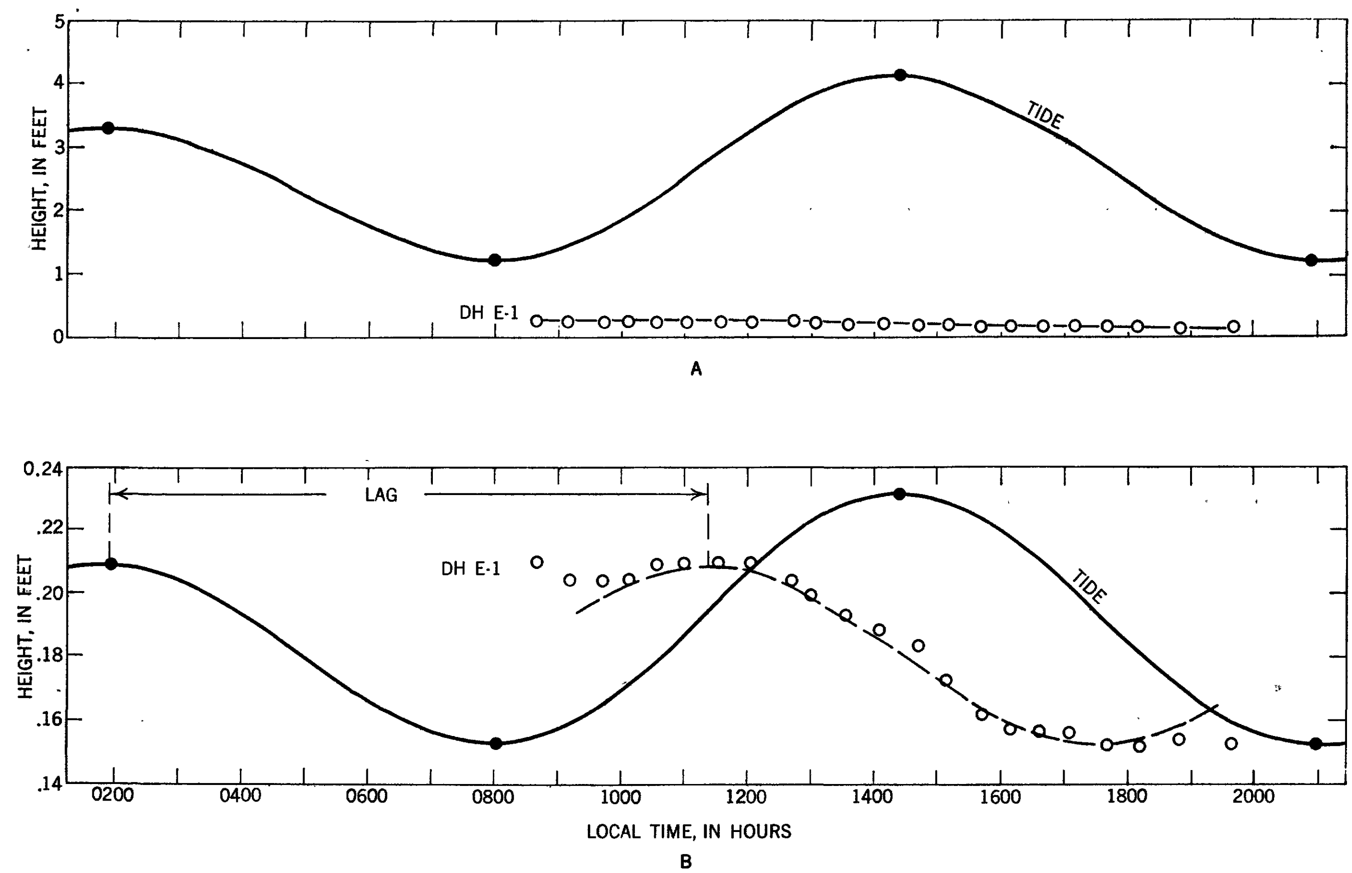

FIGURE 249.—Comparison of water-level fluctuations in drill hole E-1, Eniwetok Atoll, with tide-table values, December 14, 1952. *A*, Tide-table values (solid circles) and drill-hole values (open circles) plotted to same scale. *B*, Tide-table values (solid line) reduced to same amplitude as drill-hole values (open circles) and shifted in phase (broken line), with a lag of 9½ hours.

hydraulic resistance, or both. Drill hole E–1 is solidly cased to a depth of 4,109 feet, within 113 feet of the bottom of the hole and within 99 feet of the top of the basalt. A longer hydraulic path is, therefore, obvious. However, this in itself would not seem sufficient to account for the very small amplitude and longer time lag. A much less pervious rock would seem also to be required. Drilling indicated firmer rock and fewer cavities. This is also in accord with the temperature data, which shows less agreement in the upper 1,400 feet with the ocean profile than in drill hole F–1. However, the difference between the general conditions in the two holes seems less than the small amplitude and large time lag in drill hole E–1 would demand. It is quite reasonable to believe that the deeper part of the section will have in general a lower porosity and permeability. It is also quite possible that the longer hydraulic path may interpose in its course certain strata more consolidated and of much lower porosity and permeability than the average, and that these may cause a disproportionate change in the tidal fluctuations. If the hole were not cased below 2,000 feet, it is quite possible that a tidal fluctuation of large amplitude and little time lag might be observed. No data are available and no conclusions can be reached at present concerning these different possibilities. It may be safely stated, however, that all the evidence indicates a generally lower porosity and hydraulic permeability in the reef sediments around drill hole E–1 than around drill hole F–1.

Measurements were made of the fluctuations of water level in the Bikini drill hole at the same time that the temperature measurements were being taken (table 10).

TABLE 10.—*Water-level fluctuations in drill hole 2B, Bikini island, Bikini Atoll, November 1952*

Day	Time	Water level: Depth below top of casing (inches)	Water level: Height above arbitrary zero (feet)	Day	Time	Water level: Depth below top of casing (inches)	Water level: Height above arbitrary zero (feet)
Nov. 28	1400	36. 0	2. 40	Nov. 29	1415	31. 5	2. 77
29	1115	47. 0	1. 48	29	1436	30. 5	2. 85
29	1236	39. 5	2. 10	29	1440	30. 5	2. 85
29	1300	37. 0	2. 31	29	1457	29. 5	2. 94
29	1330	34. 5	2. 52	29	1502	30. 0	2. 90
29	1344	33. 5	2. 60	29	1530	29. 25	2. 96
29	1412	32. 5	2. 69				

These measurements are plotted in figure 250 for comparison with the tide tables (U. S. Coast and Geodetic Survey, 1951). It is evident that the water-level fluctuation in the drill hole has a smaller amplitude than the ocean tide (fig. 250*A*). A comparison of the two sets of data indicates that the amplitude in the drill hole is only 0.45 that of the ocean tide. That it is a true tidal fluctuation, however, is shown in figure 250*B* where the

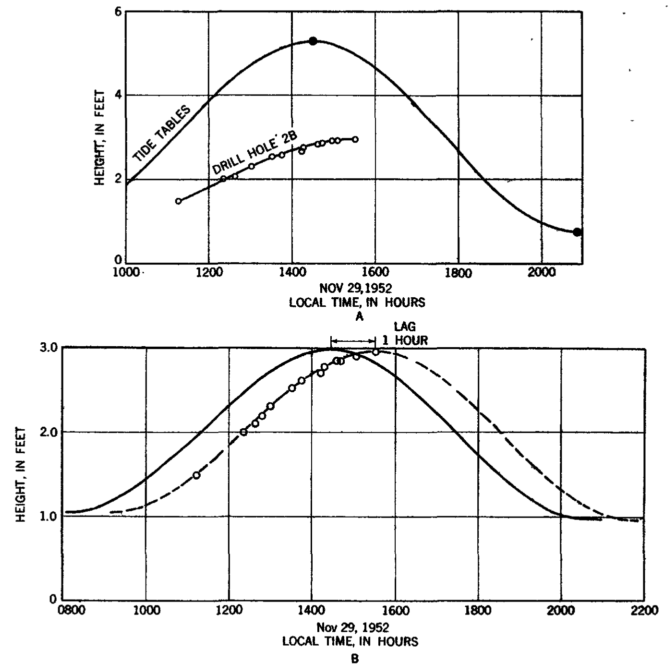

FIGURE 250.—Comparison of water-level fluctuations in drill hole 2B, Bikini Atoll, with tide-table values, November 29, 1952. *A*, Tide-table values (solid circles) and drill-hole values (open circles) plotted to same scale. *B*, Tide-table values (solid line) reduced to same amplitude as drill-hole values (open circles) and shifted in phase (broken line), with a lag of 1 hour.

amplitude of the tidal fluctuations in the ocean (solid line) is reduced to 0.45 of normal and referred to the same arbitrary zero as that for the fluctuations in the drill hole. If the tide curve is shifted in phase (broken line) so that there is a phase lag of 1 hour, it falls very satisfactorily on the curve of water-level fluctuations (open circles) in the drill hole.

The drill hole is solidly cased with 4-inch casing to a depth of 804 feet and seems to be bridged at a depth of approximately 1,430 feet. It is therefore known to be open from 804 to 1,430 feet but it is not known whether it is hydraulically blocked below 1,430 feet.

The lag and the decreased amplitude of the fluctuations in the drill hole indicate a lower permeability in the surrounding sediments than for Eniwetok drill hole F–1. Nevertheless, the presence of a tidal fluctuation in the drill hole with an amplitude of 45 percent of that in the open ocean indicates quite a high permeability for the Bikini sediments.

The evidence from tidal fluctuations of the movement of sea water through the coral sediments and the close parallelism of the atoll and ocean temperature profiles strongly suggests that the temperature of the atolls is a function of the temperature of the ocean water and its access to the atoll sediments.

COMPARISON WITH KITA-DAITŌ-JIMA

Since completing the manuscript for this report, the writer has received translations of two papers, published in Japanese, by Toshio Sugiyama (1934, 1936) describing temperature measurements in a test drill hole on Kita-daitō-jima, an island in the western Pacific Ocean, 200 miles east of the south end of Okinawa at lat 25° 57′ N., long 131° 18′ E., and believed to be an elevated coral atoll. To the best of the present writer's knowledge this is the only other place where systematic measurements have been made of inhole temperatures beneath a coral island.

A first test hole was put down to a depth of 686.6 feet (209.26 meters) in 1934 with a rotary drill. In 1936 this hole was deepened to a total of 1,416.2 feet (431.67 meters).

Temperature measurements were made by means of a copper-constantan thermocouple which was tied at several points to a wire cable and lowered through the drill rods to the desired depth. The thermocouple leads were enamel insulated and the inhole junction was protected by a very small diameter rubber tube. The cold junction of the thermocouple was formed by an ice bath at the surface, and the current in the thermocouple circuit was measured by a sensitive galvanometer read by telescope. Temperatures were obtained by means of a calibration curve previously prepared at the Earthquake Research Institute, Tokyo University.

Measurements made at 50-meter intervals between 1050 and 1150 hours on the 26th day of the first drilling are given in table 11.

TABLE 11.—*Temperature measurements during first Kita-daitō-jima drilling, 1934*

Depth: Meters	Depth: Feet	Temp (° C)	Remarks
1.55	5.1	20.80	Groundwater table.
50	164.0	19.80	
100	328.1	18.00	
150	492.1	15.86	
200	656.2	15.20	

In the second drilling the hole reached 1,305.8 feet (398.00 meters) on April 17, 1936. Temperature measurements were made on April 18, between 1400 and 1700 hours, using a copper-constantan thermocouple as before. The thermocouple leads were wrapped with rubber, but this insulation proved unsatisfactory and easily damaged. Although no statement is made concerning the measurement technique employed it is assumed to be the same as that for the first survey in 1934. The temperatures are given in table 12 and are shown in figure 251. Measurements were made at 10-meter intervals. After completing the temperature run, drilling was resumed and the hole finally bottomed at 431.67 meters (1,416.2 feet) on April 24, 1936.

Both sets of measurements were made during the progress of drilling. As described previously, drilling

TABLE 12.—*Temperature measurements during second Kita-daitō-jima drilling, April 18, 1936*

Depth: Meters	Depth: Feet	Temp. (° C)	Depth: Meters	Depth: Feet	Temp. (° C)
0.44	1.4	22.50	210	689.0	13.75
10	32.8	21.60	220	721.8	13.50
20	65.6	21.00	230	754.6	13.20
30	98.4	20.10	240	787.4	12.85
40	131.2	19.85	250	820.2	12.60
50	164.0	19.35	260	853.0	12.00
60	196.9	19.10	270	885.8	11.95
70	229.7	18.85	280	918.6	11.70
80	262.5	18.38	290	951.4	11.40
90	295.3	18.30	300	984.3	11.10
100	328.1	17.30	310	1,017.1	10.85
110	360.9	17.10	320	1,049.9	10.55
120	393.7	16.80	330	1,082.7	10.30
130	426.5	16.30	340	1,115.5	10.15
140	459.3	16.30	350	1,148.3	9.95
150	492.1	16.00	360	1,181.1	9.70
160	524.9	15.80	370	1,213.9	9.50
170	557.7	15.55	380	1,246.7	9.25
180	590.6	15.05	390	1,279.5	9.00
190	623.4	14.80	395	1,295.9	8.75
200	656.2	14.20	398	[1] 1,305.8	-----

[1] Total depth of drill hole on April 18, 1936.

introduces a large amount of heat into the hole and the rocks surrounding it, especially when a rotary drill is used. In addition it is presumed, although not so stated by Sugiyama, that water for drilling was pumped from one of the ponds nearby. The temperature of the surface water of nearby Akaike pond was 26.4° C. at the time of the temperature measurements. This may be regarded as within a degree or two of the temperature of the drilling water. As this is well above the average temperature in the drill hole, a large amount of heat must have been added by the drilling water. Drill-hole temperatures a few days after the completion of drilling differ by some degrees from the normal equilibrium temperatures, and the disturbance would be even greater for measurements made during the drilling process. It is therefore believed that the Kita-daitō-jima measurements are probably a few degrees high.

Although error from this cause will differ for different depths, the general trends of the thermal profiles are not too greatly altered, and it is therefore probable that the general trends of the Kita-daitō-jima profiles are approximately correct.

The curves for Eniwetok drill hole F–1 (measured 4 months after drilling was completed), Eniwetok drill hole E–1 (measured a year after the completion of the drilling), Bikini drill hole 2B (measured a little more than 5 years after completion of drilling), and the Kita-daitō-jima drill hole, are in general much alike (fig. 251). All four show the same steady decrease in temperature with increasing depth. The trends for the Kita-daitō-jima profile rather closely parallel those of

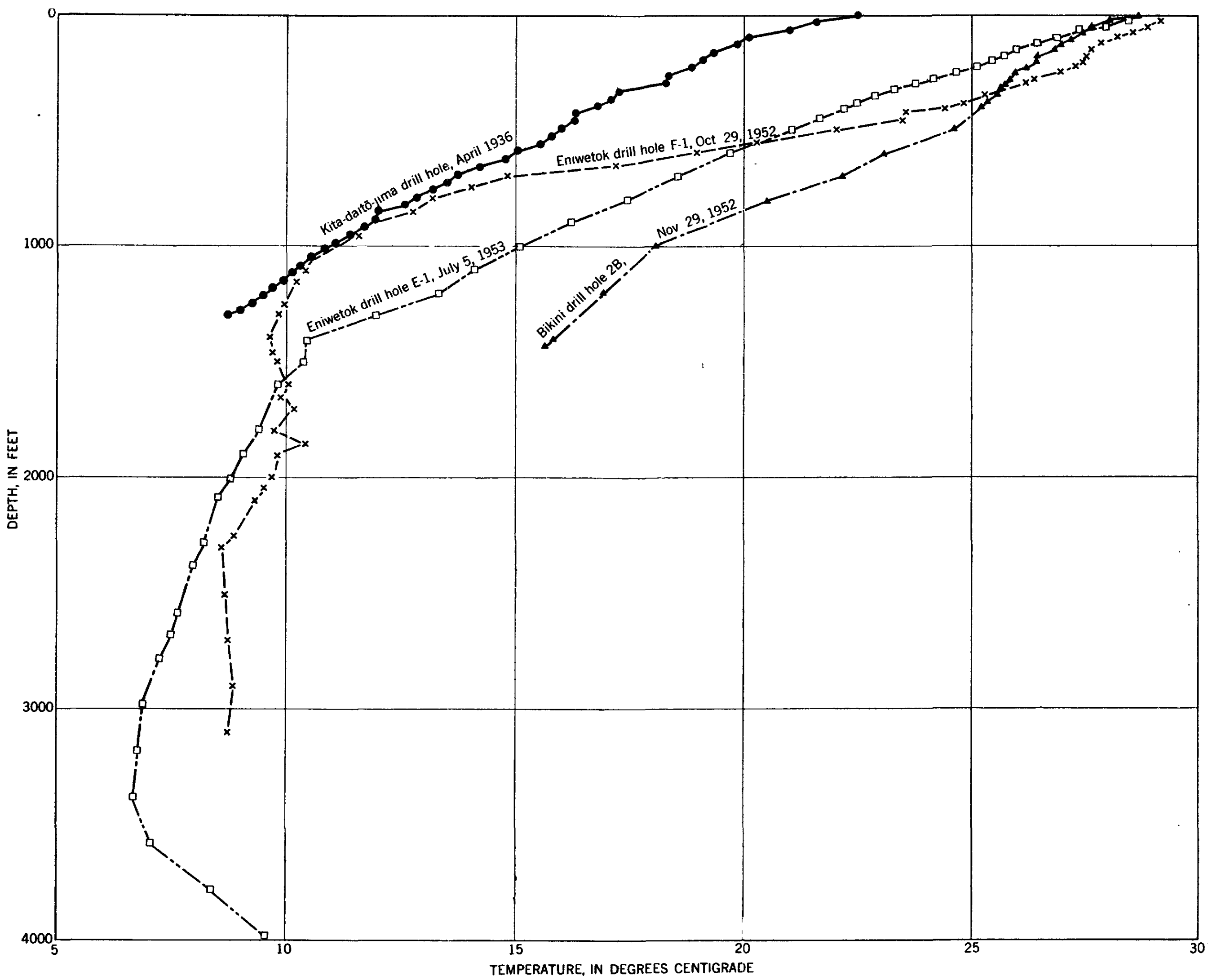

FIGURE 251.—Temperature profiles in drill hole on Kita-daitō-jima; drill holes E-1 and F-1, Eniwetok Atoll; and drill hole 2B, Bikini Atoll.

both Eniwetok drill hole E–1 and Bikini drill hole 2B. The rate of decrease is more rapid in the upper, thermocline segment of Eniwetok drill hole F–1 than in the other three although the F–1 curve closely parallels the Kita-daitō-jima curve between depths of 900 and 1,150 feet. As at Bikini, the measurements at Kita-daitō-jima were not made at great enough depths to determine certainly the sharp break observed in the Eniwetok curves at the base of the thermocline segment, unless the change in trend in the Bikini curve at a depth of 1,000 feet and in the Kita-daitō-jima curve at a depth of 850 feet can be regarded as the beginning of such a change. All four curves show the same sharp difference from the trends of the continental curves illustrated in figure 246.

In early December 1935 Sugiyama installed a tide gage in the original drill hole, then only 686.6 feet (209.26 meters) deep, and recorded the water-level fluctuations (Sugiyama, 1936, tables 8–11). A tidal fluctuation ranging from 0.78 to 3.70 feet (0.238 to 1.127 meters) was observed.

He attempted to make comparable tide measurements for the sea by installing a tide gage at the Minatoguchi coast nearby, but the first gage was swept into the sea and satisfactory records could not be obtained. An old well approximately 50 meters east of Minatoguchi was finally used. Although the well water is not in direct connection with the sea, its rise and fall is stated by Sugiyama (1936, p. 20) to be nearly the same as that of the adjacent sea level. Data from these various measurements are given in table 13.

The tidal amplitude in the original drill hole, before deepening, was 86 percent of the amplitude in the well and the average lag behind the latter was about 1.1 hours. No tidal measurements were made in the drill hole after it was deepened by the second drilling.

TABLE 13.—*Tidal fluctuations in the drill hole and in the old well at Minatoguchi, Kita-daitō-jima; measured by T. Sugiyama, December 1935*

[L, low tide; H, high tide]

Day	Tide stage	Observed data				Relative amplitude: drill hole / well	Lag of drill hole behind well	
		Time		Amplitude (H-L)				
		Drill hole	Well	Drill hole (meters)	Well (meters)		h	m
Dec. 9	L	1244	----	0.498	------	------	----	----
	H	1847	----	1.022	------	------	----	----
10	L	----	----	.865	------	------	----	----
	H	0847	----	.471	------	------	----	----
	L	1434	----	.576	------	------	----	----
	H	1939	----	1.127	------	------	----	----
11	L	0405	----	.969	------	------	----	----
	H	0938	----	.471	------	------	----	----
	L	1506	----	.603	------	------	----	----
	H	2027	----	1.100	------	------	----	----
12	L	0506	----	.943	------	------	----	----
	H	1034	----	.445	------	------	----	----
	L	1601	----	.576	------	------	----	----
	H	2132	----	[1] 1.074	------	------	----	----
13	L	0545	----	.917	------	------	----	----
	H	1119	----	.419	------	------	----	----
	L	1634	----	.550	------	------	----	----
	H	2214	----	.969	------	------	----	----
14	L	0614	----	.838	------	------	----	----
	H	1200	1030	.419	0.550	0.762	1	30
	L	1739	1636	.498	.629	.792	1	3
	H	2300	2150	.865	.917	.943	1	10
15	L	0653	----	.760	.786	.967	----	----
	H	1227	1142	------	.498	------		45
	L	----	1735	------	.524	------	----	----
	H	----	2257	------	.812	------	----	----
16	L	----	----	------	.786	------	----	----
	H	----	1222	.394	.445	.885	----	----
	L	----	1828	.367	.419	.876	----	----
	H	----	2349	.524	.655	.800	----	----
17	L	----	0705	.603	.734	.822	----	----
	H	----	1318	.367	.445	.825	----	----
	L	----	1928	.288	.341	.845	----	----
18	H	----	0052	.445	.498	.894	----	----
	L	----	0751	.498	.576	.865	----	----
	H	----	1357	.445	.524	.849	----	----
	L	----	2121	.288	[1] .288	1.000	----	----
19	H	----	0243	.301	.314	.958	----	----
	L	----	0859	------	.524	------	----	----
	H	----	1505	------	.576	------	----	----
	L	----	2310	------	.393	------	----	----
20	H	----	0450	------	.367?	------	----	----
	L	----	----	------	------	------	----	----
Average	--------	----	----	0.632	[2] 0.548	0.872	1	7

[1] The value given in Sugiyama's paper (1936) seems to be a typographic error; the value given here is probably correct.
[2] The amplitudes for the drill hole include spring-tide values of December 9–13, those for the old well at Minatoguchi do not. The average for the drill hole, approximately 0.632 meters (2.07 ft), seems reasonably correct. The average for the old well, approximately 0.548 meters, is obviously too low, as the value indicated by the average amplitude ratio of 0.872 would be 0.725 meters (2.38 ft).

These data present the same evidence for a high permeability of the reef sediments as did the water-level measurements in the Eniwetok and Bikini drill holes.

Sugiyama reached much the same conclusion for Kita-daitō-jima that the writer has reached independently for Eniwetok and Bikini Atolls, as indicated by the statement that "It is thought that the change of temperature is primarily governed by the free permeation of sea water into the limestone which underlies Kita-daitō-jima" (1936, p. 20).

TEMPERATURE GRADIENTS

It has been customary, in determining the temperature gradient of a continental drill hole, to pass a straight line through the points of observation of the temperature-depth graph by the method of least squares and to use the slope of this line as the mean temperature gradient for the hole. Although this method possesses some significance for drill holes with the continental-type profile, in which the temperatures increase more or less steadily with increasing depth, it would have no value for the atoll-type profile with its segments of radically different slope and its changes of gradient sign. It is possible, however, to subdivide the atoll temperature profiles into a series of segments which do not depart too greatly from a straight line and to determine by least squares the average gradient for each segment. These gradients are given in table 14, which also in-

TABLE 14.—*Average temperature gradients for approximately linear segments of Marshall Islands temperature profiles*

Depth (ft)	Temperature gradients [1]	
	°C per m	M per °C
Eniwetok drill hole E-1; Apr. 27, 1953		
27.7–127.8	−0.068	−14.7
127.8–227.8	−.039	−25.7
227.8–327.8	−.059	−16.9
327.8–1,400.3	−.039	−25.7
1,400.3–2,980	−.007	−138.5
2,980–3,380	−.002	−406.4
3,380–3,980	+.016	+61.3
Eniwetok drill hole F-1; Oct. 29, 1952		
24.1–123.1	−0.041	−24.2
123.1–223.1	−.018	−54.3
223.1–399.3	−.054	−18.6
399.3–700.5	−.101	−9.9
700.5–1,050.3	−.040	−25.1
1,050.3–1,400 [2]	−.009	−114.2
Bikini drill hole 2B; Nov. 29,1952		
4–28	−0.090	−11.1
28–253	−.029	−34.6
253–353	−.014	−72.6
353–500	−.021	−46.9
500–1,000	−.043	−23.4
1,000–1,430	−.018	−55.6
Ocean, Marshall Islands area; Nov. 1952		
0–200	0.000	∞
200–300	−.036	−27.7
300–700	−.124	−8.1
700–800	−.036	−27.7
800–1,500	−.009	−107.1
1,500–4,000	−.005	−183.1

[1] A negative gradient, as the term is used here, is one in which the temperature is decreasing downward, a positive gradient one in which the temperature is increasing downward. This convention has been selected so that the normal continental gradient is positive.
[2] Only the gradients for the upper 1,400 feet of Eniwetok drill hole F-1 are shown. Below that depth the temperatures were so disturbed by thermal anomalies still persisting from the drilling that the gradients have little significance.

cludes the gradients for similar segments of the ocean-temperature profile.

The selection of points to be included in a linear segment involves of necessity a certain subjective element. Moreover, such straight-line gradients are average values that conceal much local detail that may be of stratigraphic significance. A more satisfactory and objective method is to compute the gradient for each interval measured (Birch, 1954). This has been done, and the resultant gradients in the drill holes on Eniwetok and Bikini, and in the ocean in the Marshall Islands area, are given in table 15.

TABLE 15.—*Temperature gradient for each measured interval, Marshall Islands temperature profiles*

Depth interval (ft)	Temperature gradient	
	°C per m	M per °C
Eniwetok drill hole E-1; Sept. 16, 1953		
3.8–27.8	+0.030	+33.3
27.8–52.8	−.058	−17.3
52.8–77.8	−.083	−12.1
77.8–102.8	−.066	−15.2
102.8–127.8	−.060	−16.6
127.8–152.8	−.051	−19.5
152.8–177.8	−.034	−29.3
177.8–202.8	−.038	−26.3
202.8–227.8	−.035	−28.2
227.8–252.8	−.070	−14.4
252.8–277.8	−.058	−17.3
277.8–302.8	−.047	−21.2
302.8–327.8	−.070	−14.4
327.8–352.8	−.059	−16.9
352.8–377.8	−.047	−21.2
377.8–402.8	−.039	−25.4
402.8–450.3	−.038	−26.3
450.3–500.3	−.042	−23.8
500.3–600.3	−.047	−21.2
600.3–700.3	−.035	−28.2
700.3–800.3	−.037	−27.2
800.3–900.3	−.044	−22.8
900.3–1,000.3	−.033	−30.2
1,000.3–1,100.3	−.033	−30.8
1,100.3–1,200.3	−.026	−39.1
1,200.3–1,300.3	−.044	−22.6
1,300.3–1,400.3	−.050	−20.2
1,400.3–1,500.3	−.002	−435.4
1,500.3–1,600.3	−.018	−54.4
1,600.3–1,700.3	(−.011)	(−95.3)
1,700.3–1,800.3	(−.003)	(−304.8)
1,800.3–1,900.3	−.011	−92.4
1,900.3–2,000.3	−.008	−121.9
2,000.3–2,080	−.011	−93.4
2,080–2,280	−.005	−196.7
2,280–2,380	−.010	−98.3
2,380–2,580	−.003	−290.3
2,580–2,680	−.004	−234.5
2,680–2,780	−.008	−121.9
2,780–2,980	−.006	−169.3
2,980–3,180	−.003	−338.7
3,180–3,380	−.002	−508.0
3,380–3,580	+.006	+160.4
3,580–3,780	+.022	+44.8
3,780–3,980	+.018	+54.4

TABLE 15.—*Temperature gradient for each measured interval Marshall Islands temperature profiles*—Continued

Depth interval (ft)	Temperature gradient	
	°C per m	M per °C
Eniwetok drill hole F-1; Oct. 29, 1952		
24.1–48.1	−0.030	−33.3
48.1–73.1	−.046	−21.8
73.1–99.3	−.045	−22.2
99.3–123.1	−.039	−25.9
123.1–148.1	−.025	−40.1
148.1–173.1	−.012	−84.7
173.1–199.3	−.018	−57.0
199.3–223.1	−.023	−42.7
223.1–248.1	−.041	−24.6
248.1–273.1	−.075	−13.4
273.1–299.3	−.031	−31.9
299.3–323.1	−.070	−14.2
323.1–348.1	−.047	−21.2
348.1–373.1	−.062	−16.2
373.1–399.3	−.046	−21.6
399.3–423.1	−.120	−8.3
423.1–450.3	−.012	−82.9
450.3–500.5	−.096	−10.4
500.5–550.3	−.113	−8.9
550.3–600.5	−.086	−11.7
600.5–650.3	−.118	−8.5
650.3–700.5	−.155	−6.5
700.5–750.3	−.053	−18.7
750.3–800.5	−.056	−17.8
800.5–850.3	−.024	−42.2
850.3–900.5	−.059	−17.0
900.5–950.3	−.024	−42.2
950.3–1,050.3	−.032	−31.1
1,050.3–1,100.5	−.010	−102.0
1,100.5–1,150.3	−.013	−79.9
1,150.3–1,250.3	−.008	−127.0
1,250.3–1,300.3	−.011	−95.3
1,300.3–1,400.0	−.006	−168.8
Bikini drill hole 2B; Nov. 29, 1952		
4–28	−0.090	−11.1
28–53	−.052	−19.1
53–78	−.025	−40.1
78–103	−.032	−31.8
103–128	−.032	−31.8
128–153	−.020	−50.8
153–178	−.050	−20.1
178–203	−.000	∞
203–228	−.026	−38.1
228–253	−.041	−24.6
253–278	−.004	−254.0
278–303	−.021	−47.6
303–328	−.014	−69.3
328–353	−.012	−84.7
353–378	−.024	−42.3
378–403	−.014	−69.3
403–500	−.023	−44.1
500–600	−.049	−20.5
600–700	−.031	−32.1
700–800	−.053	−18.9
800–1,000	−.041	−24.4
1,000–1,200	−.017	−58.6
1,200–1,400	−.019	−53.5
1,400–1,430	−.019	−53.8

TABLE 15.—*Temperature gradient for each measured interval, Marshall Islands temperature profiles*—Continued

Depth interval (ft)	Temperature gradient	
	°C per m	M per °C
Ocean, Marshall Islands area; Nov. 1952		
0–200	0.000	∞
200–300	−.036	−27.7
300–400	−.112	−9.0
400–500	−.164	−6.1
500–600	−.089	−11.3
600–700	−.128	−7.8
700–800	−.036	−27.7
800–1,000	−.010	−101.6
1,000–1,500	−.009	−108.9
1,500–2,000	−.007	−138.6
2,000–3,000	−.006	−179.3
3,000–4,000	−.005	−217.7

The gradients of table 15 are shown graphically in figure 252. Certain general correlations can be noted. The higher gradients of the thermocline are apparent in each of the four curves, as well as the sharp decrease in gradient at the base of the thermocline, marked by the small arrows. All 3 drill holes show an early gradient decrease to a minimum value at depths of 150 to 200 feet, a correlation especially evident for the Eniwetok drill holes E–1 and F–1.

Despite these general points of agreement, however, the most striking feature of the four curves is not their similarity but their marked differences. Eniwetok drill hole F–1, with its high gradient maximum, matches most closely the general shape of the ocean gradient curve. For Eniwetok drill hole E–1, on the other hand, the gradients in the thermocline are relatively low and nearly uniform, with no sign of a gradient peak. However, the thermocline extends considerably deeper than for the other three curves. In Bikini drill hole 2B, the gradients are also low, but they are less uniform and there is some tendency toward a small gradient high. Such differences in gradients represent differences in subsurface heat flow. As the climate and ocean temperatures are essentially the same for both atolls, the sources of the differences must be sought within the atolls themselves.

Attention has already been called to the differences in the tidal motion in the three drill holes. It was originally presumed that these differences were largely a result of differences in casing length or inhole blocking. The gradient data suggest that the differences are more fundamental than this. The best gradient correlation between drill hole and ocean is that for Eniwetok drill hole F–1, which showed a tidal fluctuation agreeing both in amplitude and phase with that in the ocean offshore. The poorest correlation is that for Eniwetok drill hole E–1, which showed tidal motion of

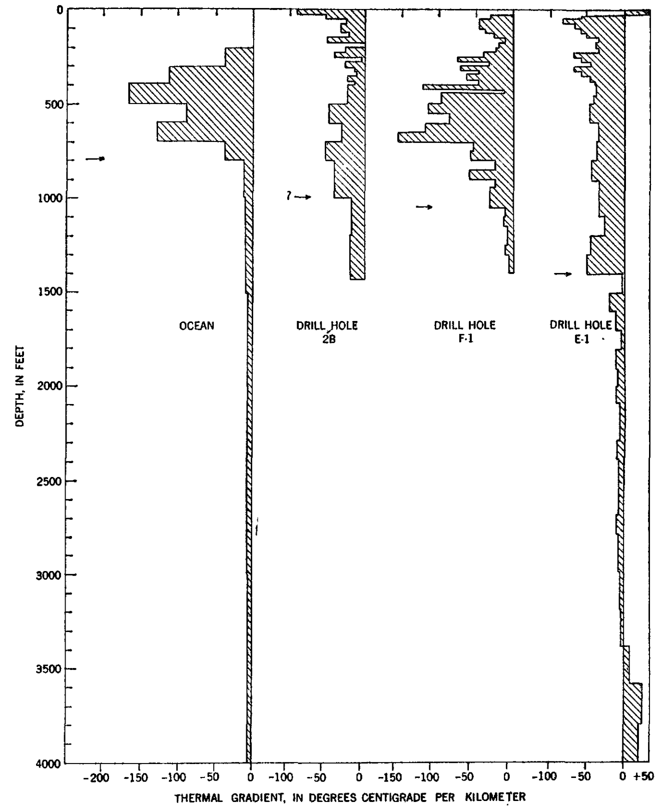

FIGURE 252.—Temperature gradients for each measured interval, Marshall Islands thermal profiles. Arrows indicate base of thermocline.

very small amplitude and a phase lag of 9½ hours. Bikini drill hole 2B is intermediate both in correlation and in tidal amplitude and lag.

These facts suggest that, although tidal fluctuations are undoubtedly affected by casing length, both tidal variations and thermal gradients are an expression of fundamental differences in lithology and permeability within the atolls themselves.

If near-surface temperatures are omitted, all three drill holes show negative gradients to considerable depths. The ocean gradients are negative throughout. Omitting anomalous gradients, only Eniwetok drill hole E–1 shows a positive gradient within the depths measured. It seems certain, however, that the positive gradient characteristic of continental thermal profiles would develop in all three drill holes if they were deepened sufficiently.

The thermal gradient for Eniwetok drill hole E–1 below 3,580 feet averages +0.020° C per meter or +49.6 meters per degree C. For 20 drill holes along the Pacific coast in California, Oregon, and Washington the average is +0.035° C per meter or +28.4 meters per degree C (Van Orstrand, 1939, p. 132, 135, 137). The positive thermal gradient at the bottom of drill hole E–1 is thus much lower than that for these Pacific coast wells. As the positive gradients in drill hole E–1 are for the part of the drill hole just below the point of curve reversal, it is quite possible that the gradient is still influenced by the cooling effect of the adjacent ocean water and therefore is less than the normal gradient at depth in a coral atoll.

Some idea of the direction of heat flow as well as of the general distribution of temperatures underground may be obtained through the preparation of an isogeotherm chart for a vertical section through one of the drill holes and approximately perpendicular to the atoll flank. If it is assumed, as seems reasonable, that the temperatures along the flank of the atoll are those of the adjacent ocean and that these are essentially those given by the Scripps Institution of Oceanography measurements, the isogeotherms shown in figure 253 are obtained for such a section through Eniwetok drill hole E–1. The lines of thermal flow are, of course, perpendicular to the isothermal lines. The general flow is therefore downward and outward above the point of minimum temperature and upward and outward below that point.

FORCED CONVECTION AS A METHOD OF HEAT TRANSFER IN CORAL ATOLLS

In discussing the temperature profiles for Eniwetok drill hole F–1, and in comparing the measurements for June with those for October 1952, it was noted that the June curve showed a pronounced thermal low of abnormal character extending from about 400 to about 750 feet in depth, with a minimum temperature of 11.1° C at 645 feet (see fig. 241).

Several features make this thermal low abnormal. Even though large amounts of heat are added by the drilling process to the drill hole and the strata surrounding it through drilling friction and by the use of warm lagoon waters for drilling and for drilling mud, this thermal low represents a heat deficiency. Between June and October, although there was a drop in temperature in the rest of the profile, the temperature rose in the thermal low— at 650 feet as much as 6° C. The atoll temperature curves closely parallel the temperature curve in the adjacent ocean and there seems little question that the atoll thermal profile owes its character to the cooling effect of the adjacent ocean. For this to

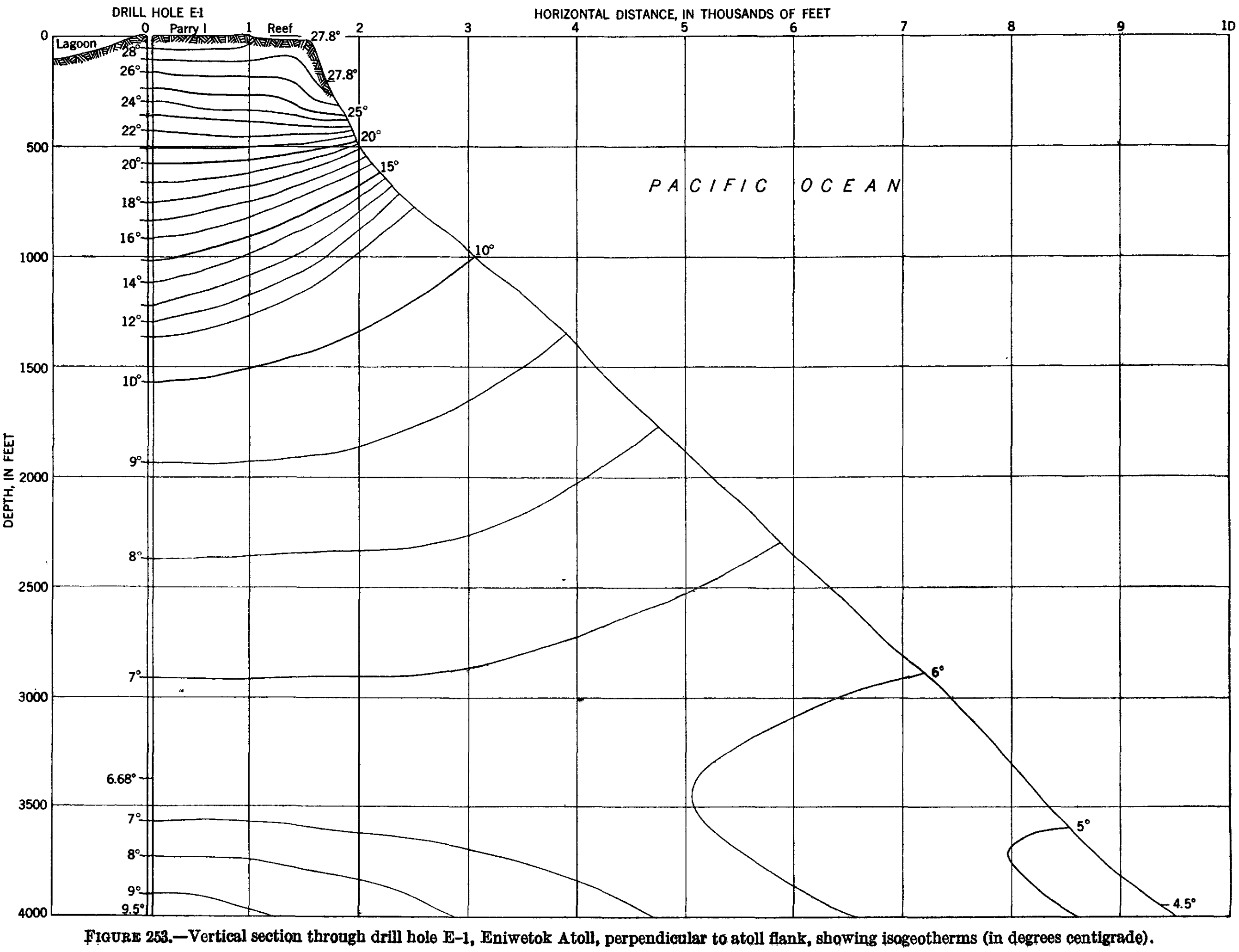

FIGURE 253.—Vertical section through drill hole E–1, Eniwetok Atoll, perpendicular to atoll flank, showing isogeotherms (in degrees centigrade).

occur the ocean temperatures must be lower than the corresponding atoll temperatures. Yet the temperatures of the atoll profile in this thermal low are lower than the ocean temperatures at the same depths. At 600 feet, for instance, the drill hole is 3.5° C colder than the adjacent ocean at that depth. The presence of the low immediately after the completion of drilling and its disappearance by October, 4 months later, indicate that it is an effect associated with the drilling, despite the fact that it represents a loss of heat.

The only explanation of these anomalies that seems tenable is that the stratigraphic zone from a depth of 400 to 750 feet is more porous than adjacent beds, or in any event gives more easy access to water from the drill hole, indicating that the maximum permeability is probably at or near a depth of 645 feet, which is the point of minimum temperature for the low; that water which was colder than the 11.1° C minimum temperature of the thermal low was flushed through the sediments in this zone and cooled them to this temperature; and that following the drilling this flushing process was reduced or discontinued so that the cooling effect disappeared and the beds were then reheated to the October level by the influx of heat from the adjacent sediments. This could occur if colder water from lower in the hole, perhaps with a temperature of 10° C or lower, was forced upward in the hole outside the casing and then outward away from the drill hole through this permeable horizon, as could happen if, after the casing was set at 1,973 feet, water was forced upward between the casing and the drill-hole wall. The October measurements showed that temperatures of 10° C and lower extended from a depth of 1,200 feet downward to the bottom of the hole, and that the temperature at the bottom of the casing was approximately 9.7° C. Even if the escaping drilling fluid had not been completely cooled by its descent to 1,973 feet through the casing, it should have been brought to or slightly below 10° C by its rise outside the casing through this zone.

This possibility is further supported by drilling information. Although 200 bags of cement were used in setting the 9⅝ inch casing at 1,973 feet, the seat obtained was not as good as had been hoped. The casing was later found to turn in the hole. It is therefore quite possible that water was circulated upward between the casing and the wall of the drill hole. This circulation would cease when the pumping ceased.

These facts all point to a sort of heat-flushing process—the removal during drilling of a large amount of heat from the sediments in this thermal low by cool water moving through the sediments.

The process of heat transfer in which heat is either removed from or transferred to the walls of a channel by a fluid moving through the channel is known in heat engineering as forced convection. The occurrence of this abnormal low indicates that forced convection can be an effective means of heat transfer in coral-reef sediments.

Both the effectiveness of the cooling in this case and the tidal data indicating a high permeability for the coral sediments suggest that the unusual character of the atoll thermal profiles and their close parallelism with the ocean temperatures are due in large part to cooling of the atoll sediments through forced convection by the movement of sea water through the pore channels of the sediments. Preliminary computations indicate that, for sea water moving through the pore channels at the average rate of rise and fall of the tide, a temperature difference of a few thousandths of a degree between wall and water would suffice to remove by forced convection all of the heat brought to the channel walls by conduction.

The evidence presented by these various considerations strongly suggests that forced convection in all probability constitutes a major factor in the transfer of heat from the coral atoll to the sea.

SUMMARY

The temperature profiles in a coral atoll are unusual in character, differing in striking fashion from thermal profiles in continental areas. The latter increase steadily in temperature with increasing depth below the zone of annual change. The atoll curves, on the other hand, decrease steadily in temperature below this shallow surface zone until a minimum value is reached at a depth of more than 3,000 feet.

The atoll curves show typically an upper zone of rapidly dropping temperatures. At or near a depth of 1,000 feet this trend is sharply altered so that below this point temperatures, while still dropping, decrease much more slowly.

The temperature profile in the ocean nearby shows a close parallelism with the atoll curves. It displays an upper zone, the thermocline, having the same rapid temperature drop. At a depth of about 800 feet the trend is sharply altered to a much slower rate of decrease, the zone of weak gradient or asthenocline. This parallelism strongly suggests that the atoll thermal profiles owe their unique character to the cooling effects of the adjacent ocean water.

This hypothesis is lent additional support by the presence of tidal motion in the water levels in the drill holes. This motion is slight with a long phase lag in deeply cased Eniwetok drill hole E–1. At Bikini, where there is only shallow casing in the hole, the amplitude of the variation is nearly half of the tidal amplitude and the lag is only 1 hour. In drill hole F–1, which has 1,973 feet of casing, the tidal fluctuation agrees in both

amplitude and phase with the tide in the adjacent ocean. These facts indicate a high permeability for the reef sediments and supports the feasibility of their cooling by the ocean water.

Below the point of minimum temperature in the atoll profiles the trend is reversed, and the temperatures begin to rise with increasing depth as in the continental drill holes. This reversal has been observed with certainty only in Eniwetok drill hole E–1. The positive gradient below the reversal point in that drill hole is about half the average gradient for 20 wells on the Pacific west coast of the continental United States. It is quite possible that the points of measurement in drill hole E–1 are so little below the point of trend reversal that the gradient is still modified by the cooling effect of the ocean waters and that at greater depth it may attain more nearly a normal value.

The tidal evidence of high permeability in the reef sediments and the abnormal cooling effect observed in Eniwetok drill hole F–1 point to the probability that forced convection by water moving through the reef sediments plays an important role in heat transfer in the atolls.

It is to be hoped that similar measurements may be continued in drill holes on other atolls and oceanic islands to determine how widespread and how characteristic this type of atoll temperature profile may be, to study the factors affecting it, and to determine what limiting effects may be present.

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