MEASUREMENTS OF THERMAL STRUCTURE BETWEEN SOUTHERN CALIFORNIA AND HAWAII WITH THE THERMISTOR CHAIN

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THE PROBLEM

Investigate oceanographic factors pertinent to the behavior of underwater sound and to surface and subsurface navigation. Specifically, study the thermal structure of the upper sea layers by use of a towed thermistor chain.

RESULTS

1. The slopes, autocorrelation, and power spectra of isotherms obtained with the U. S. Navy Electronics Laboratory (NEL) thermistor chain in sections of detailed sea temperature structure from San Diego, California, to Honolulu, Hawaii, showed the median of the absolute values of vertical slope, in over 40,000 data samplings, to be 0°16' and the 70th percentile of the absolute values of slope to be 0°30'.

2. The autocorrelation of depth of encounter of isotherms in the sea at 30- and 60-minute lags has higher values near California than near Hawaii.

3. The significant high-frequency peaks in the power spectrum of isotherms are distributed in patches all the way from the California coast to the Hawaiian coast; however, they appear to be a little more numerous in the central part of the section.

RECOMMENDATIONS

1. Continue development of the thermistor chain to improve the quality, accuracy, and reliability of the data.

2. Make detailed studies of the thermocline and its associated internal waves by use of the chain. Include studies of the effects on the thermocline of islands, shoals, coastal configurations, tides, currents, upwelling, river runoff, water-mass boundaries, storms, and seasons. Particularly, acquire more data on the direction and speed of internal waves.

3. Investigate the use of other sensors, in conjunction with temperature on the thermistor chain, for current, sound velocity, and salinity.

ADMINISTRATIVE INFORMATION

Work was performed under S-R004 03 01, Task 0580 (NEL L4-4) by members of the Marine Environment Division. This report covers the period August 1961 to August 1963. It was approved for publication 7 February 1964. The authors wish to express appreciation to O. S. Lee and P. G. Hansen who led the cruise on which the data were collected and to G. H. Curl for reviewing this report. Thanks are also due Mrs. Rita Brown for the programming and machine computation, and to the Commanding Officer, LT John Baldwin, and other personnel of USS MARYSVILLE for making possible the collection of data.

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INTRODUCTION

The NEL thermistor chain has been in operation since 1961 and is capable of measuring and recording vertical sections of sea temperature structure from the surface down to a depth of 800 feet. USS MARYSVILLE (EPCE(R) 857), from which the chain is operated (fig. 1), conducted Cruise 1, the first test of this equipment, over the nearby San Diego Trough in June 1961, and the results have been reported.[1] Cruise 2 was made between 10 and 14 July 1961 off Southern California.[2] Cruise 3 entailed a test near San Clemente Island.

Cruise 4, the subject of this report, was from San Diego, California, to Honolulu, Hawaii (fig. 2). The purpose was to study the nature of vertical variations in temperature structure of internal waves in the deep ocean regions well away from shore,

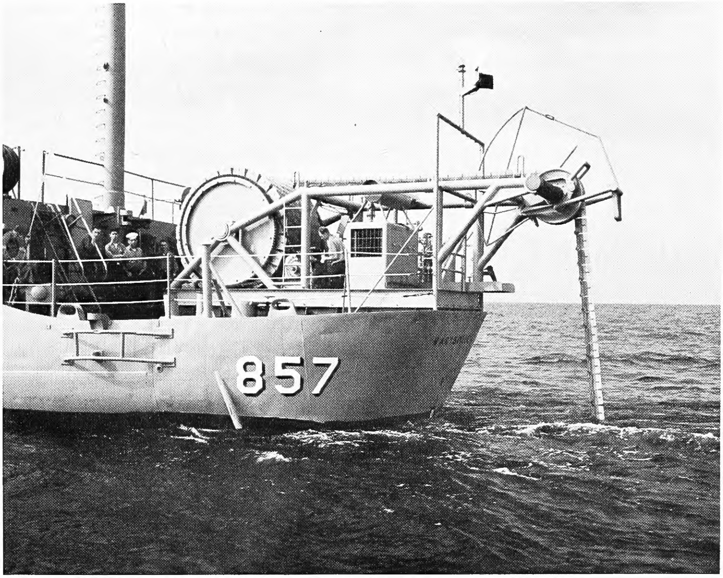


Figure 1. NEL thermistor chain hoist used on USS MARYSVILLE to obtain data.

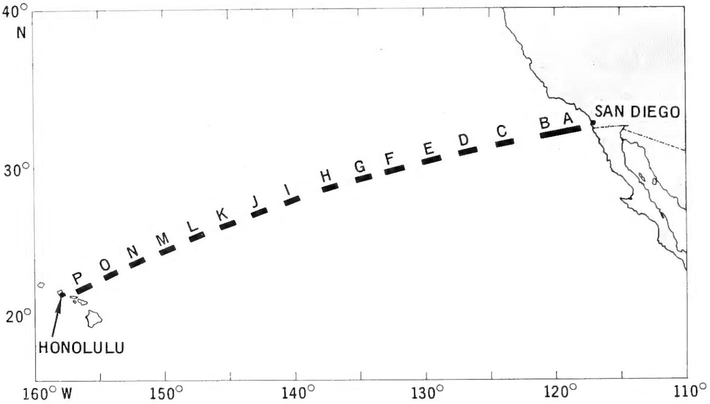


Figure 2. Track of USS MARYSVILLE showing locations A to P where data were collected between San Diego and Honolulu.

specifically, for each of two selected isotherms, to investigate the depth change or slope; the autocorrelation of successive depth measurements; and the power spectrum of the depth between San Diego and Honolulu.

EQUIPMENT

The NEL thermistor chain has been described in previous reports.[3-4] The sea and deck units consist of a chain hoist, chain links, and the drum on which the chain is wound. This large, rugged assembly weighs 37,500 pounds. The chain is composed of flat links about 1 foot long, 10 inches wide, and 1 inch thick. At the end of the chain is a 2,300-pound, streamlined weight, called a "fish," to hold it down.

About 100 pairs of insulated electrical leads fit through grooves inside the flat links. The electrical wires are connected, at intervals of 27 feet, to the temperature sensors, or thermistor beads.

The upper ends of the electrical leads are connected to a recorder located in the ship's laboratory. Signals from the leads are scanned electronically every 10 to 12 seconds, and lines showing the depths of isotherms are printed on 19-inch-wide tape. This procedure is equivalent to lowering a bathythermograph every 100 to 120 feet at a ship's speed of 6 knots. Also printed on the same tape are the depth of the fish at the end of the chain, which is the maximum depth of observation, and the temperature of the sea surface.

With the thermistor chain it is possible for USS MARYSVILLE to lower a string of temperature sensors into the water and then cruise ahead with the string suspended vertically from its fantail. Since elements are sensing from the surface down to about 800 feet while the ship is moving through the water horizontally, two dimensions of coverage, depth and distance, are achieved. However, time, a third dimension, must also be considered.

The thermal structure presented here is more properly the "structure of encounter," or "depth of encounter," of isotherms. The vertical scale is depth, but the horizontal scale may be considered as both time and distance. The amplitude of the vertical changes in isotherms is correct in either sense, but in 10 or 12 hours some time changes must certainly have occurred at the beginning of the section when the end is being recorded. The structures will in reality portray a spatial plot rather than time changes since the advective and vertical-oscillation changes caused by internal waves occur much more slowly than the movement of the ship across the section. Therefore the detailed thermal-structure data presented (fig. 3) can be described as vertical sections in the sea in the same manner as are other oceanographic sections derived from serial station data.

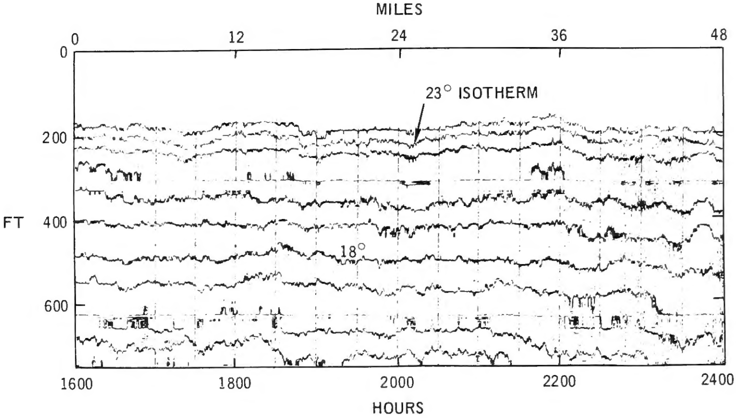


Figure 3. Example of temperature data taken with the thermistor chain between San Diego and Honolulu.

OBSERVATIONS AND DATA

Procedure

The ship's course on Cruise 4 consisted of a great circle tow between deep water off San Diego to deep water off Honolulu. The chain was towed the entire distance and recorded temperature from the surface to a maximum depth of about 750 feet at a speed of 6 knots. However, for one hour each day the ship's speed was increased to 8 knots, and thus the towing depth decreased for this period.

The long, continuous section of isotherms constituted the source of raw data. Inspection revealed that any given isotherm became progressively deeper as the ship proceeded westward and southward from the California coast. Also the surface water became warmer and the vertical gradients were weaker toward Hawaii.

During the tow some temperature sensors in the string of 34 developed electrical shorts and did not operate properly. This is shown by flat lines in the data. The shorts nullified detection of any isotherm passing through the depth of the faulty sensor. This did not, however, affect the recording of isotherms at other depths. It was feasible to choose and analyze the characteristics of isotherms at other valid depths. In the example of raw data (fig. 3), the 18- and 23-degree isotherms were chosen for analysis.

The data samples used were from an 8- or 12-hour continuous section each day for 16 consecutive days. Shown in figure 2 is the location of the sections used and in table 1 the specific times, positions, and sample size.

Nature of Vertical Oscillations

The nature of the detailed vertical changes in the isotherms has not been investigated in an open sea area before nor has the cause of vertical oscillations been established. It seems fairly certain that the density boundaries in the sea should have certain frequencies of oscillation and modes thereof. Eckart,[5] referring to Väisälä,[6] points out that a given density boundary may have its own normal oscillating frequency, the Väisälä frequency. Still another possibility is that strong winds may create convection cells and eddies in the upper layers of the sea, the circulation of which will cause the thermocline to be lowered more in one area than another. Tidal forces causing water movement around land boundaries and topographic features can start oscillation in the thermal structure. There is, however, reason to believe that the vertical variations observed with distance in the isotherms are internal waves moving in one or more directions. The progressive nature of these oscillations in shallow water has been determined by studies conducted from anchored ships and from the NEL Oceanographic Research Tower.[7]

The detailed recording of isotherm depths indicates the complicated character of oceanic thermal structure and emphasizes the exceedingly complex nature of the sea, not only in temperature, but in chemical, biological, and other aspects.

VARIABILITY

Changes in sea temperature at the surface and at various depths, which thus change the depth of isotherms, may be attributed to any of several factors, among which are the advection of water of different temperature into an area; radiation from the sun; mixing by the wind; tidal currents; internal waves; and others.[8-9] Since all the factors simultaneously exert influence, it is difficult to determine their individual effects.

Several investigators have made studies of the variability of surface and subsurface sea temperatures.[10-13] Others have developed methods for the statistical analysis of physical properties applicable to sea temperature variability.[14-20] In this report, three approaches to the study of isotherm depth variability are used: (1) differences in depth values; (2) autocorrelation of depth values; and (3) power spectrum of depth values.

Differences in Depth Values

The first method of presenting the isotherm variability is by depth differences from point to point along the isotherm. For this the depths of isotherms were scaled from the original record in each section at half-minute intervals.

The selected sections are listed in table 1. One of the isotherms chosen for analysis was located in the main thermocline and the other below the main thermocline. These must also be at a level where the sensors were operating properly. Those chosen in the data section (fig. 3) were the 18° and 23°C isotherms.

The depth differences from point to point along the isotherms were determined from the formula:

$$X_i - X_{i+1} = Y_k$$

$$1 \leq k \leq N$$

TABLE 1. DATE, TIME, AND LOCATION OF TEMPERATURE DATA

	Date		Time		Start		End		Central Position			
No.	From Aug. 1961	To Aug. 1961	From	To	N Lat	W Long	N Lat	W Long	N Lat	W Long	Isotherm (°C)	Data Points (N)
A-1	3	4	2000	0800	32°27.8'	118°21.0'	32°16.9'	119°47.1'	32°22.4'	119°04.1'	15°	1440
A-2	3	4	2000	0800							8°	1440
B-1	4	4	0700	1900	32°17.0'	119°41.5'	32°04.9'	121°14.2'	32°11.0'	120°27.9'	14°	1440
B-2	4	4	0800	1830							8°	1260
C-1	5	5	1200	2400	31°41.5'	123°07.7'	31°25.8'	124°33.0'	31°33.7'	123°50.4'	16°	1440
C-2	5	5	1200	2400							9°	1440
D-1	6	6	1200	2400	31°10.7'	125°57.0'	30°56.5'	127°23.4'	31°03.6'	126°40.2'	16°	1440
D-2	6	6	1200	2400							10°	1440
E-1	7	7	1200	2400	30°41.0'	128°47.8'	30°21.3'	130°09.1'	30°31.2'	129°28.5'	18°	1440
E-2	7	7	1200	2400							14°	1440
F-1	8	8	1200	2400	30°03.0'	131°32.4'	29°35.0'	133°07.0'	29°49.0'	132°19.7'	17°	1440
F-2	8	8	1200	2400							16°	1440
G-1	9	9	1200	2400	29°21.9'	134°22.0'	29°03.6'	135°45.2'	29°12.8'	135°03.6'	18°	1440
G-2	9	9	1200	2400							16°	1440
H-1	10	10	1200	2400	28°44.0'	137°00.9'	28°20.2'	138°17.0'	28°32.1'	137°39.0'	20°	1440
H-2	10	10	1200	2400							17°	1440
I-1	11	11	1200	2400	27°59.9'	139°35.2'	27°38.9'	140°49.7'	27°49.4'	140°12.5'	20°	1440
I-2	11	11	1200	2400							17°	1440
J-1	12	12	1200	2400	27°13.8'	142°07.0'	26°53.0'	143°18.3'	27°03.4'	142°42.7'	20°	1440
J-2	12	12	1200	2400							17°	1440

Table 1. (Continued)

No.	Date		Time		Start		End		Central Position		Isotherm (°C)	Data Points (N)
	From Aug. 1961	To Aug. 1961	From	To	N Lat	W Long	N Lat	W Long	N Lat	W Long		
K-1	13	13	1200	2400	26°30.0'	144°31.0'	26°01.6'	145°43.4'	26°15.8'	145°07.2'	21°	1440
K-2	13	13	1200	2400							18°	1440
L-1	14	14	1200	2400	25°37.6'	146°54.0'	25°11.5'	148°05.1'	25°24.6'	147°29.6'	19°	1440
L-2	14	14	1200	2400							17°	1440
M-1	15	15	1200	2400	24°40.8'	149°12.9'	24°18.9'	150°25.9'	24°29.9'	149°49.4'	22°	1440
M-2	15	15	1200	2400							18°	1440
N-1	16	16	1200	2400	23°46.8'	151°32.0'	23°23.2'	152°42.0'	23°35.0'	152°07.0'	23°	1440
N-2	16	16	1200	2400							18°	1440
O-1	17	17	1200	2025	22°53.0'	153°43.0'	22°38.0'	154°33.8'	22°45.5'	154°08.4'	23°	1010
O-2	17	17	1200	2026							19°	1012
P-1	18	18	1200	2038	21°52.5'	156°05.8'	21°38.2'	156°41.0'	21°45.4'	156°23.4'	25°	1036
P-2	18	18	1200	2037							20°	1034

X_i and X_{i+1} are depths (feet) of a given isotherm at the beginning and end of the ith distance (or time) interval along the track; Y_k is the depth difference (feet). When the isotherm is falling, the difference is negative.

From the speed of the ship and depth differences, approximate slopes can be obtained. At a speed of 6 knots, the ship traveled 304 feet in each half-minute interval; therefore the dividing of the depth differences by 304 feet gave the slope of the isothermal surface in the direction of the ship's motion. This slope could also be expressed by the angle having this slope for a tangent.

From 1010 to 1440 consecutive observations of isotherm depths were made on each sample section of Cruise 4. The distributions of depth changes and slopes for each selected isotherm on each 8-12 hour section of the cruise are diagrammed as a cumulative frequency curve of depth changes and slope angle in Appendix A.

Appendix A shows that half-minute depth changes as great as plus or minus 30 feet were observed over a distance of 304 feet in several of the isotherms. This corresponds to a vertical angle of 5°45'. On the other hand 58 per cent of all the adjacent half-minute readings showed changes of less than one foot for the shallow isotherm, and 51 per cent for the deep isotherm. An example of the S-shaped nature of the cumulative frequency curve (or per cent of observations) is shown in figure 4.

The change in depth of this 20°C isotherm may be plus or minus. In figure 4 the 25th and 75th percentile depth changes are -1.3 and +1.4 feet; thus in 50 per cent of the cases the change is less than about 1.35 feet (in absolute value) in a horizontal distance of 304 feet. The 15th and 85th percentile changes occur at -2.3 and +2.7 feet with 70 per cent of the data in this range. The corresponding vertical angles are less than 0°15' (in absolute value) for the central 50 per cent of the cases and less than 0°28' for the central 70 per cent of the data. This example is a nearly typical case since the median of the absolute values of 44,000 data samplings is 0°16', and the 70th percentile of the absolute values of slope is 0°30'.

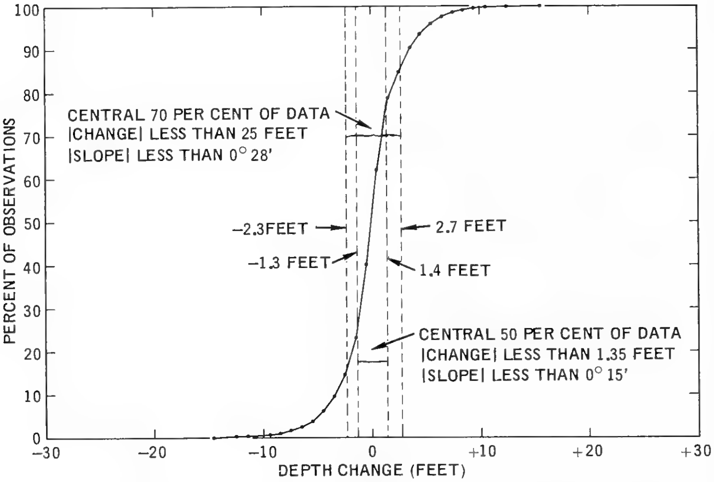


Figure 4. Example of cumulative percentage distribution of differences in depth between half-minute or 304-foot spaced readings of 20°C isotherm on section H. The 25 and 75 percentile delineating the central 50% of Data and the 15 and 85 percentile delineating the central 70% of Data.

To summarize the variability of depth changes (Appendix A), points were scaled from each of the cumulative percentage distributions of changes in depth per 304 feet, which corresponded to the 25th and 75th percentile of depth change and the absolute values averaged. Similarly the 15th and 85th percentiles were also determined and averaged. The latter average is somewhat analogous to the "significant wave" method whereby the upper 30 per cent is "average." However, here the value represents a depth change greater in absolute value than 70 per cent of the observations.

As an alternate treatment of the data, a cumulative percentage distribution curve for the *absolute* values of depth differences could be plotted. The new 70th percentile change would agree almost exactly with the average of the absolute values of the 15th and 85th percentiles discussed above. Hence, that average will be designated 70th percentile of absolute value of depth change (70th percentile - depth change). Likewise the 50th percentile in the alternate treatment would agree with the average of the absolute values of the 25th and 75th percentiles discussed in the previous paragraph, and that average will be designated 50th percentile - depth change.

In order to compare with other sample sections, the 70th percentiles and 50th percentiles of absolute values of slope were plotted in figure 5 for both the selected isotherm in the main thermocline and the isotherm below the main thermocline. All of these angles, of which half of the depth changes were greater and half less in absolute values, are shown (fig. 5, bottom section) with reference to longitude.

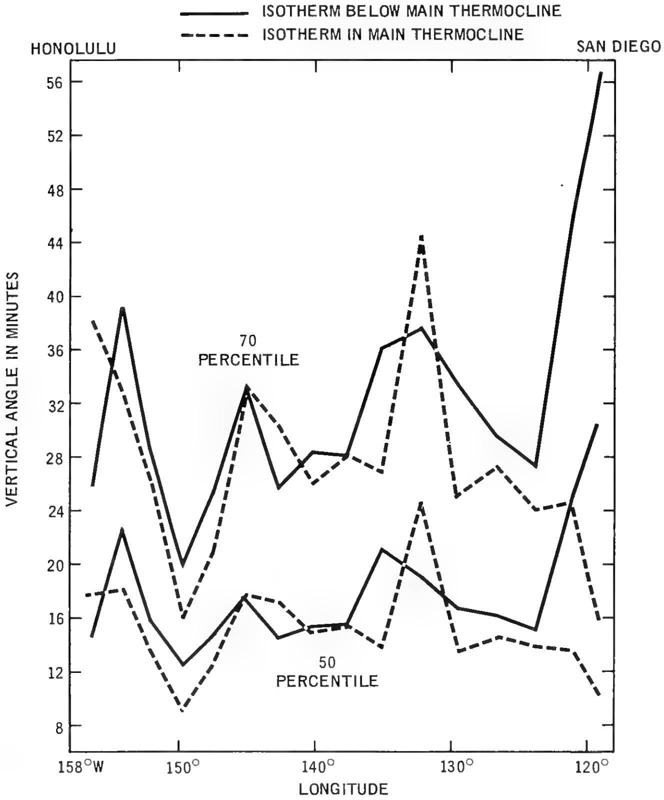


Figure 5. Summary of differences in depth of between half-minute or 304-foot-spaced depth readings of isotherms between San Diego and Honolulu.

Upper: Seventy percentile of absolute value of slope of an isotherm in the main thermocline and an isotherm below the main thermocline.

Lower: Fifty percentile of absolute value of slope of an isotherm in the main thermocline and an isotherm below the main thermocline.

Although there was considerable variability in changes in the vertical angle expressed in the 70th and 50th percentiles - slope, the results show that the 70th percentile - angle varies from 16 to 56 minutes. In general the slope becomes a little less when running from San Diego toward Honolulu where the vertical gradients are weaker and the internal waves are larger. The slopes of the deeper isotherm are usually less than the one in the main thermocline where the vertical gradients are stronger. The average slope of the latter is around half a degree.

The slopes of the 50th percentile - slope plotted in the lower part of figure 5 necessarily show lower angles with an average slope of around 16 minutes. This condition undergoes a great deal of variation with a tendency for lower median angles toward Honolulu.

Autocorrelation of Depth Values

Another approach to measuring subsurface temperature variability is by means of autocorrelation coefficients.[18] By using the same half-minute isotherm depth data, autocorrelations were computed for each leg of the cruise and each selected isotherm. Successive pairs of points at equal but overlapping time intervals were correlated with each other and the process repeated for each time interval, increasing by one-half minute steps from one half a minute to 72 minutes, or 144 lags. Autocorrelation, R_λ, was computed for increasing intervals, λ, of 304 feet (half minute), using the expression:

$$R_\lambda = \frac{(N-\lambda)\sum_{i=1}^{N-\lambda} X_i X_{i+\lambda} - \sum_{i=1}^{N-\lambda} X_i \sum_{i=1}^{N-\lambda} X_{i+\lambda}}{\left\{(N-\lambda)\sum_{i=1}^{N-\lambda} X_i^2 - \left[\sum_{i=1}^{N-\lambda} X_i\right]^2\right\}^{\frac{1}{2}} \left\{(N-\lambda)\sum_{i=1}^{N-\lambda} X_{i+\lambda}^2 - \left[\sum_{i=1}^{N-\lambda} X_{i+\lambda}\right]^2\right\}^{\frac{1}{2}}}$$

where $\lambda = 0, 1, 2, \ldots\ldots 144$ lag intervals, N = total number of depth recordings in a run. N is usually 1440, and λ is $\frac{N}{10}$.

The computed autocorrelations of all the selected isotherms on each sample section of the cruise were plotted for comparison in Appendix B.

One example of the autocorrelation is shown in figure 6. Starting with zero lags (0 minutes) the autocorrelation R_λ is 1.0, but as the lags increase the correlation becomes less and in some cases negative. In this example, after 60 lags the value of R_λ is reduced to 0.76; 120 lags, 0.64; and 144 lags, 0.61.

In order to summarize the autocorrelation of successive depth changes with time and distance, two points were scaled off the individual plots of autocorrelation, one at 60 lags (30 minutes) and another at 120 lags (60 minutes). Then, in order to compare these autocorrelations with those of other sample sections they were plotted with reference to longitude on the section between San Diego and Honolulu (fig. 7).

The upper part of figure 7, identified as A, shows the autocorrelations for the lags at 60 and 120 half-minute stops (is $\lambda = 60$ and 120) for the isotherm in the main thermocline whereas the lower figure, B, is a similar presentation for the isotherm chosen

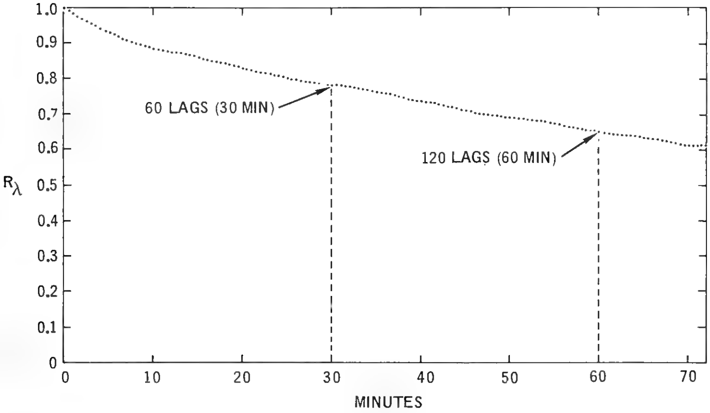
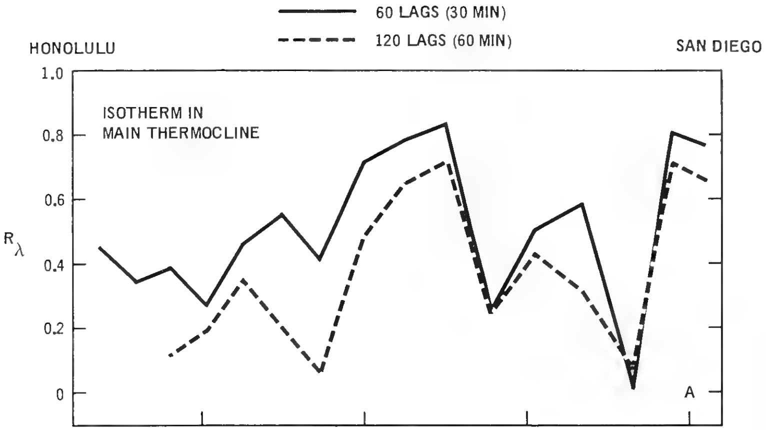
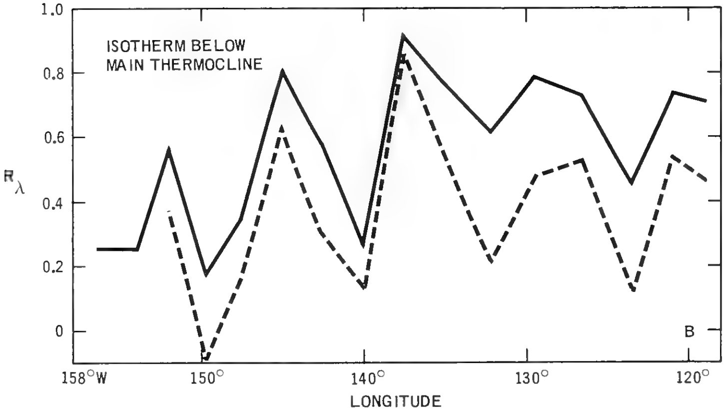


Figure 6. Example of autocorrelation of successive half-minute readings of the depth of 20° C isotherm on section H. The 60-lag (30-minute) and 120-lag (60-minute) values are indicated. ($\lambda = 60$ and 120 respectively).



A. *Isotherm in main thermocline.*



B. *Isotherm below main thermocline.*

Figure 7. Summary of autocorrelation of selected isotherm depth values at 60 lags (30 minutes, $\lambda = 60$) solid line and 120 lags (60 minutes, $\lambda = 120$) dashed line for each set of data between San Diego and Honolulu.

below the main thermocline. Both A and B contain considerable variation in the autocorrelation values with reference to longitude. However, there is some similarity in the fluctuation. As might be expected, the value of R_λ is nearly always less for the greater lags (120) than for the fewer lags (60). The values of autocorrelation (fig. 7), like those of the slopes (fig. 5), decrease slightly from the San Diego area toward Honolulu.

Power Spectrum of Depth Values

The third method of representing variability is by the power spectrum.[12,15,17,19-20] The power spectrum $U(h)$ is given by the Fourier transform of the autocorrelation, R. It is the energy per unit bandwidth and thus designed to emphasize the dominant frequencies, since the amplitudes are squared. The smoothed power spectrum values were obtained as follows:

$$U(h) = \frac{1}{n}\left[R(o) + \sum_{\lambda=1}^{\lambda=n-1} R(\lambda)\,(1 + \cos\frac{\pi\lambda}{n})\cos\frac{\pi\lambda h}{n}\right]$$

where $h = 0, 1, 2, 3 \ldots.\ n$ index number of frequency (actual frequencies are given by $h/(2\Delta t)$ cycles/min, $\Delta t = 1/2$ min), and

$\lambda = 0, 1, 2, 3 \ldots.\ n$ is the lag number

The results of the computed power spectra of all the selected isotherms on each section of the cruise were plotted for comparison in Appendix C.

One example of the computed power spectrum is shown in figure 8. The importance of the power spectrum lies in the peaks in the curve that indicate frequencies (or periods) in the original data which may have been obscured by "background noise." Of significance is the fact that this example of power spectrum has a large number of peaks or peak zones ranging in frequency* of

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*Here the sampling chain is moving through a quasi-stationary field of internal waves and the frequencies discussed are "frequencies of encounter." The wave lengths are nominal ones computed from the ship speed of 6 knots assuming that the internal waves are essentially stationary, i.e. are moving much slower than 6 knots. One should expect broad peaks or "peak zones" as often as narrow peaks if the internal waves are traveling in all directions; e.g. if internal waves of only a *very narrow* band of frequencies arrived from *all* directions, the straight track of the ship would intercept apparent wavelengths corresponding to a *broad band* of frequencies.

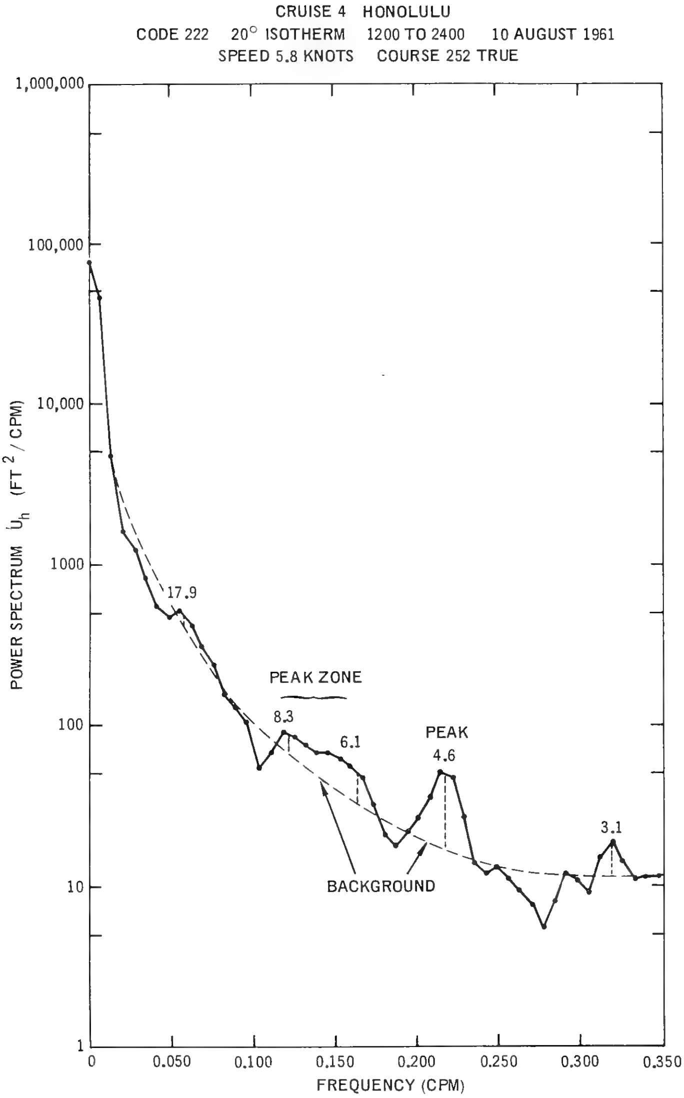


Figure 8. Example of power spectrum from successive half-minute readings of the depth of 20° C on section H. The peaks and zones of higher power are indicated.

0.056 to 0.318 cycle per minute, which is equivalent to a period of 17.9 to 3.1 minutes or a wave length of 1.8 to 0.3 miles. When the peaks are wide they are considered as zones; for example, 0.121 to 0.163 cycle per minute (or 0.8- to 0.6-mile wave lengths) is considered a zone.

The power spectrum curve shows that the greatest power is in the low frequencies which show no peaks. The number of degrees of freedom is given by $\upsilon = \frac{2N}{n} - \frac{1}{2}$. When using 1440 consecutive depth sample values and 144 lags, $\upsilon = 19.5$. The corresponding ratio of computed to true value[19] falls between 0.54 and 1.60 for 90-percent confidence limits.

The ratio of background to peak height was determined by constructing a base line and vertical height (fig. 8). For example the 4.6-minute-period peak of this 20°C isotherm depth has a peak-to-background of 52 to 17, or a ratio of 3.06, which is significant, whereas the 17.9-minute-period peak (fig. 8) has a ratio of 1.21, which is not significant.

To summarize the power spectrum, the peaks and peak zones were read from the individual power spectrum graphs, and the peak-to-background ratio was computed and plotted (fig. 9A) for the data sections in an isotherm in the thermocline and (fig. 9B) for data sections in the isotherm below the thermocline. In both graphs the values were arranged with reference to longitude and frequency. Thus figures 9A and 9B are similarly portrayed as a longitude section from near San Diego to near Honolulu.

In addition a contour was drawn for ratio values of 1.6 and, when present, 2.0. Values greater than 1.6 are considered significant in accordance with the 95-per cent confidence limits.

The contours show that zones of significant frequencies of vertical changes in isotherm depths vary widely from sample to sample. No value exceeds 3.1. The higher or more significant values appear to be distributed in patches. However, for the shallow isotherm in the thermocline (fig. 9A) the higher values are a little more frequent near a midway zone and nearly to Hawaii.

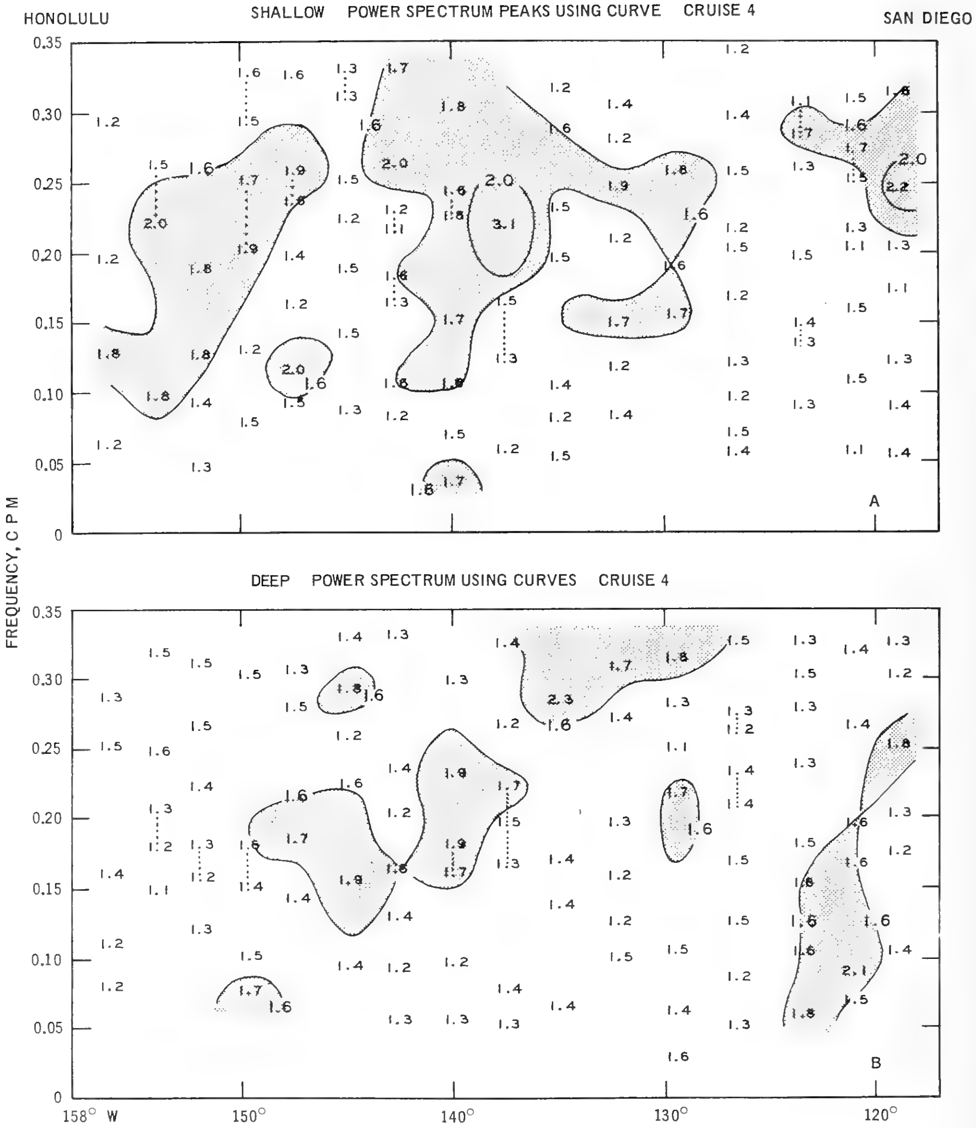


Figure 9. A. Ratio of peak values to background in power spectrum (in main thermocline).
B. Ratio of peak values to background in power spectrum (below main thermocline).

The similar plot of power spectrum peak to background of the deeper isotherm (fig. 9B) also shows more high values in a midway zone to Hawaii. The most persistent significant values occurred between 140 and 150°W where the frequency was 0.15-0.23 cycles per minute (cpm) or a wavelength of 0.7 to 0.4 miles. However, in general no single frequency persists over great distances. There are, however, a number of peaks with ratios greater than 1.6 all along the entire section.

RECOMMENDATIONS

1. Continue development of the thermistor chain to improve the quality, accuracy, and reliability of the data.

2. Make detailed studies of the thermocline and its associated internal waves by use of the chain. Include studies of the effects on the thermocline of islands, shoals, coastal configurations, tides, currents, upwelling, river runoff, water-mass boundaries, storms, and seasons. Particularly, acquire more data on the direction and speed of internal waves.

3. Investigate the use of other sensors, in conjunction with temperature on the thermistor chain, for current, sound velocity, and salinity.

SUMMARY AND CONCLUSIONS

The sections of temperature structure between a point off San Diego to Honolulu provided new detailed data of the upper layers of the sea.

The slope of the isotherms in two levels at 16 locations revealed that the median absolute value generally became less steep away from the California coast. Similarly, the deeper of the two isotherms, selected where the vertical temperature gradient was weak, had a greater number of larger vertical angles than the shallow one.

The autocorrelation of successive depth values of given isotherms became smaller more rapidly with increased distance from the California coast. The power spectrum of the depth of isotherms showed peaks at varying frequencies. The higher and more significant peaks appear to be most numerous in a zone half way to Hawaii than in other parts of the section.

REFERENCES

1. LaFond, E.C., "Two-Dimensional Oceanography," Bureau of Ships Journal, v.10, p.3-5, December 1961

2. Navy Electronics Laboratory Report 1130, Measurements of Thermal Structure Off Southern California With the USNEL Thermistor Chain, by E.C. LaFond and A.T. Moore, 28 August 1962

3. Richardson, W.S. and Hubbard, C.J., "The Contouring Temperature Recorder," Deep-Sea Research, v.6, p.239-244, 1959-1960

4. LaFond, E.C., "Towed Sea Temperature Structure Profiler," p.53-59 in Symposium on Transducers for Oceanic Research, San Diego, California, 1962. Proceedings, Plenum Press, 1963

5. Eckart, C.H., Hydrodynamics of Oceans and Atmospheres, Pergamon Press, 1960

6. Väisälä, V., "Über die Wirkung der Windschwankungen auf die Pilot Beobachtungen," Finska Vetenskaps-Societeten, Helsingfors, Commentationes Physico-Mathematicae, v.2, p.37, 1925

7. Lee, O.S., "Observations on Internal Waves in Shallow Water," Limnology and Oceanography, v.6, p.312-321, July 1961

8. LaFond, E.C., "Factors Affecting Vertical Temperature Gradients in the Upper Layers of the Sea," Scientific Monthly, v.78, p.243-253, April 1954

9. LaFond, E.C., "Detailed Temperature Structures of the Sea Off Baja California," Limnology and Oceanography, v.8, p.417-425, October 1963

REFERENCES (Continued)

10. LaFond, E.C. and Moore, A.T., "Short Period Variations in Sea Water Temperature," Indian Journal of Meteorology and Geophysics, v.11, p.163-166, April 1960

11. Roden, G.I. and Groves, G.W., "On the Statistical Prediction of Ocean Temperatures," Journal of Geophysical Research, v.65, p.249-263, January 1960

12. Pierson, W.J. and Marks, W., "The Power Spectrum Analysis of Ocean-Wave Records," American Geophysical Union. Transactions, v.33, p.834-844, December 1952

13. Roden, G.I., "Spectral Analysis of a Sea-Surface Temperature and Atmospheric Pressure Record Off Southern California," Journal of Marine Research, v.16, p.90-95, 1957-1958

14. Navy Electronics Laboratory Report 831, Information Recovery From Finite-Sample Fluctuation Data, by C.A. Potter, 26 February 1958

15. Tukey, J.W., "The Sampling Theory of Power Spectrum Estimates," p.47-67 in Woods Hole Oceanographic Institution, Symposium on Applications of Autocorrelation Analysis to Physical Problems, 13-14 June 1949

16. New York University. Meteorology and Oceanography Department, A Study of Wave Forecasting Methods and of the Height of a Fully Developed Sea on the Basis of Some Wave Records Obtained by the O.W.S. WEATHER EXPLORER During a Storm at Sea, by W.J. Pierson, June 1959

17. Navy Electronics Laboratory Technical Memorandum 296, Cross Spectrum Analysis With Certain Applications to Geophysical and Electromagnetic Problems, by E.E. Gossard, 9 July 1958

18. Mode, E.B., Elements of Statistics, 2d ed., p.246, 328, Prentice-Hall, 1951

REFERENCES (Continued)

19. Navy Electronics Laboratory Technical Memorandum 600, A Review of Power Spectrum and Cross Spectrum Analysis by Digital Methods, by E. E. Gossard, 15 April 1963

20. Panofsky, H.A. and Brier, G.W., Some Applications of Statistics to Meteorology, p. 144-145, Pennsylvania State University, 1958

APPENDIX A: FIGURES A-1 TO A-32 (DIFFERENCES)

FIGURE	SECTION	TEMPERATURE °C	
A–1	A–1	15	SHALLOW
A–2	A–2	8	DEEP
A–3	B–1	14	SHALLOW
A–4	B–2	8	DEEP
A–5	C–1	16	SHALLOW
A–6	C–2	9	DEEP

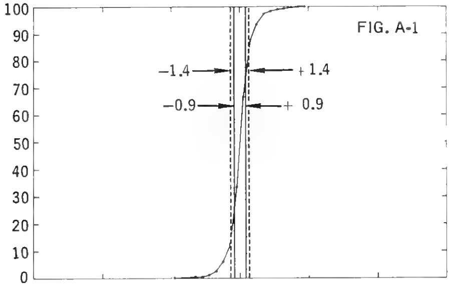
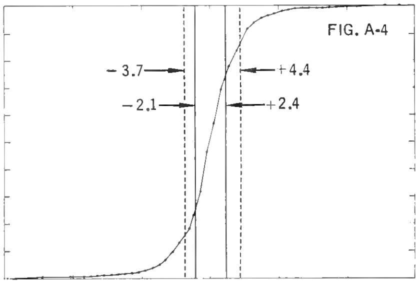


FIG. A-1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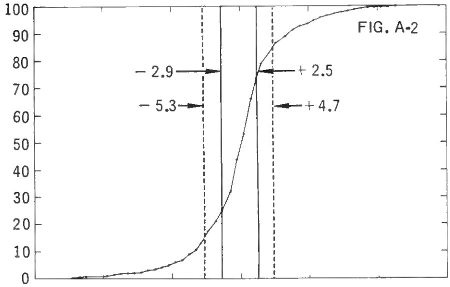
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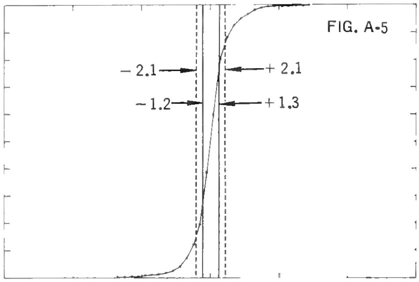
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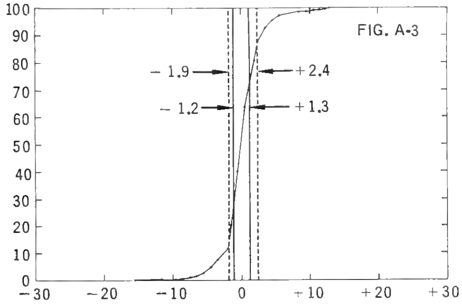
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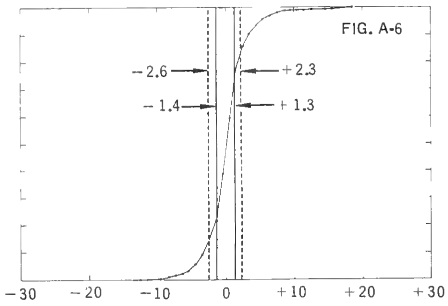
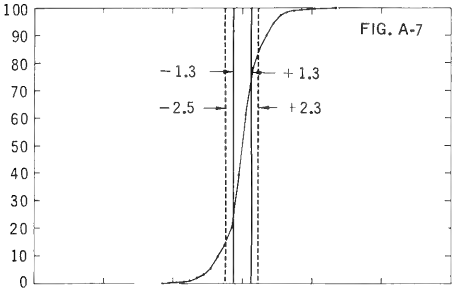


FIG. A-6

PERCENT OF OBSERVATIONS

DEPTH CHANGE (FT)

FIGURE	SECTION	TEMPERATURE °C	
A–7	D–1	16	SHALLOW
A–8	D–2	10	DEEP
A–9	E–1	18	SHALLOW
A–10	E–2	14	DEEP
A–11	F–1	17	SHALLOW
A–12	F–2	16	DEEP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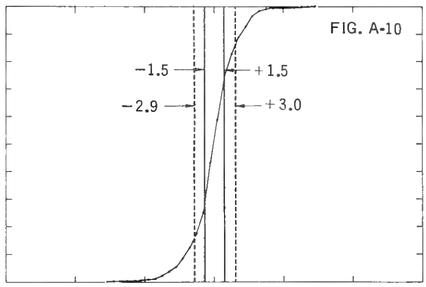
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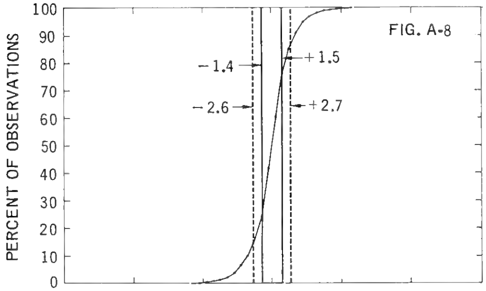
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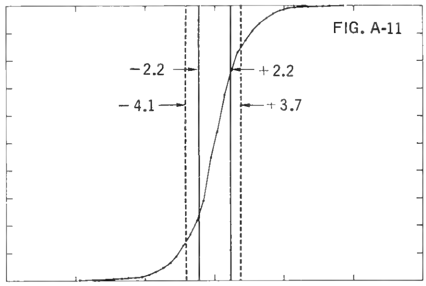


FIG. A-11

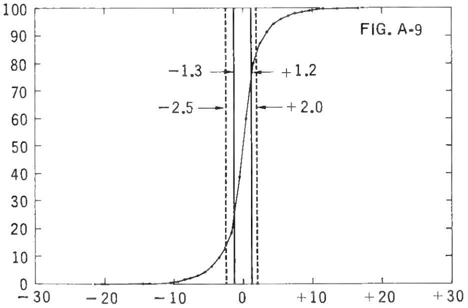


FIG. A-9

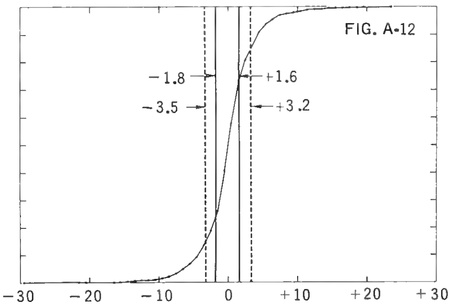
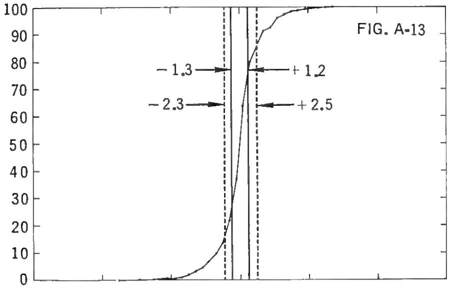


FIG. A-12

DEPTH CHANGE (FT)

FIGURE	SECTION	TEMPERATURE °C	
A–13	G–1	18	SHALLOW
A–14	G–2	16	DEEP
A–15	H–1	20	SHALLOW
A–16	H–2	17	DEEP
A–17	I–1	20	SHALLOW
A–18	I–2	17	DEEP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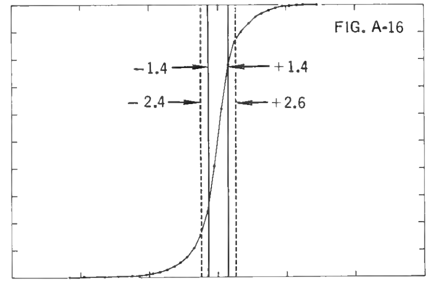
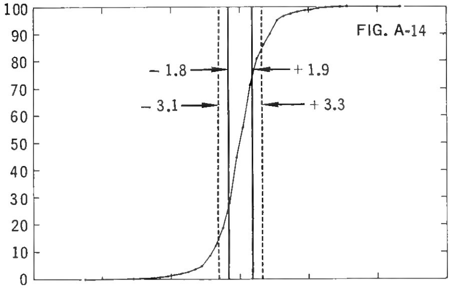


FIG. A-16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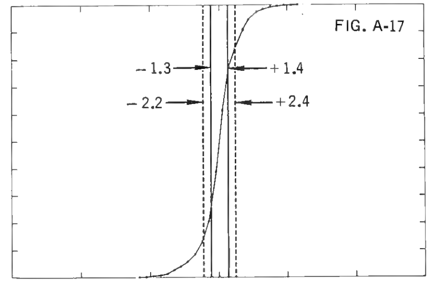
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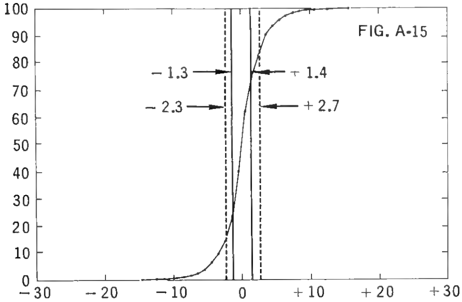
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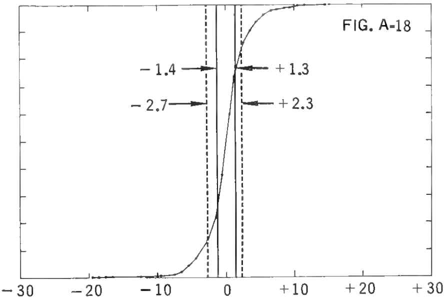
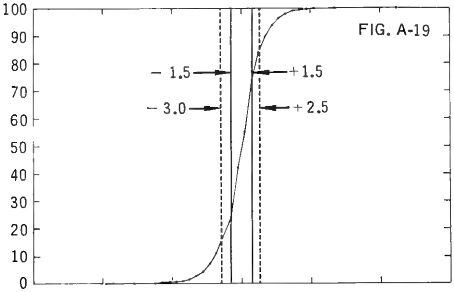


FIG. A-18

FIGURE	SECTION	TEMPERATURE °C	
A–19	J–1	20	SHALLOW
A–20	J–2	17	DEEP
A–21	K–1	21	SHALLOW
A–22	K–2	18	DEEP
A–23	L–1	19	SHALLOW
A–24	L–2	17	DEEP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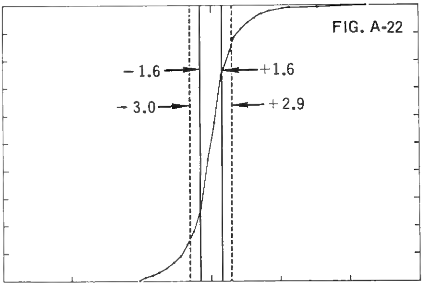
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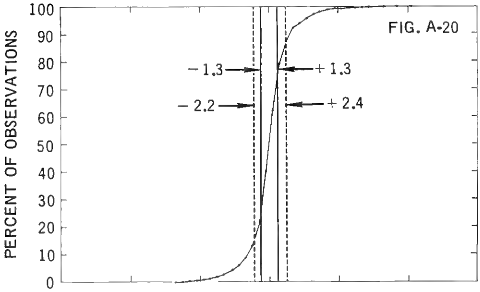
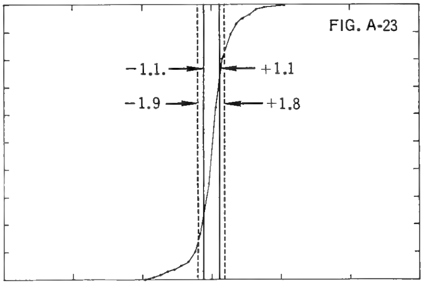


FIG. A-20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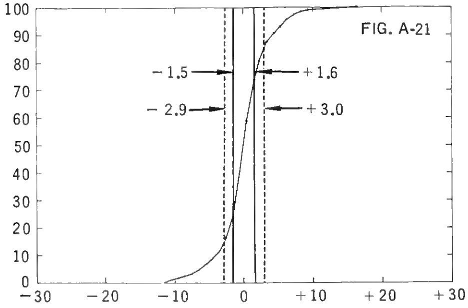
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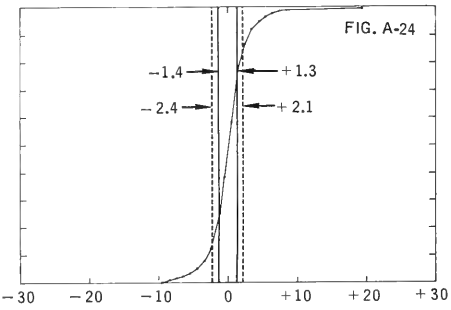
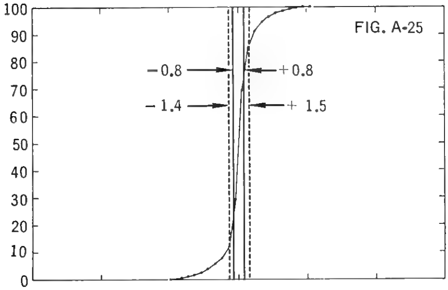


FIG. A-24

DEPTH CHANGE (FT)

FIGURE	SECTION	TEMPERATURE °C	
A–25	M–1	22	SHALLOW
A–26	M–2	18	DEEP
A–27	N–1	23	SHALLOW
A–28	N–2	18	DEEP
A–29	O–1	23	SHALLOW
A–30	O–2	19	DEEP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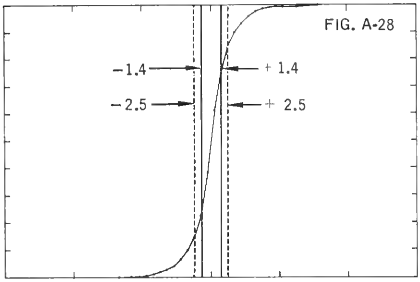


FIG. A-28

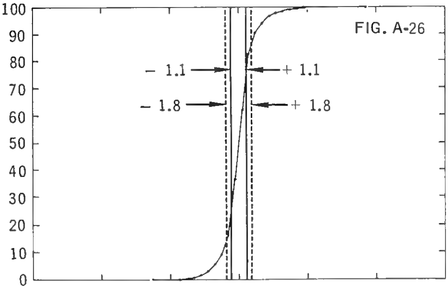
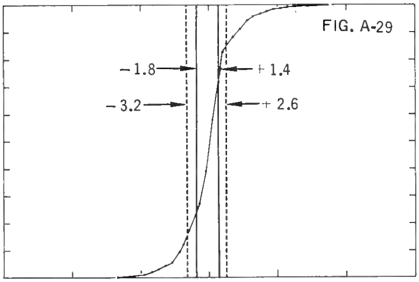


FIG. A-26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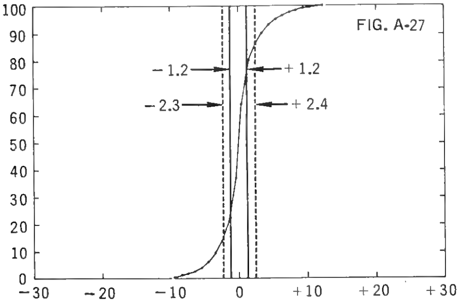
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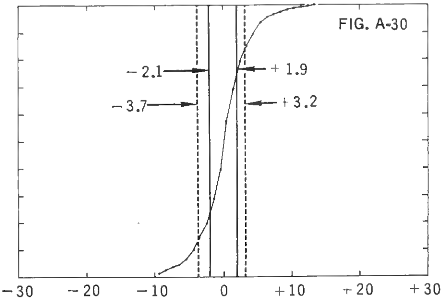
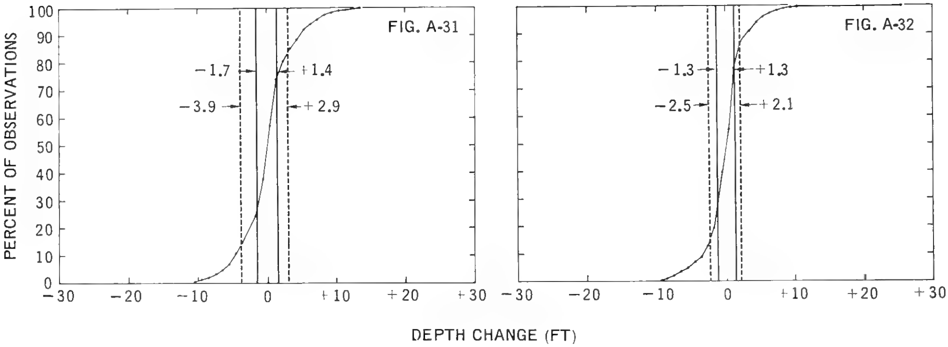


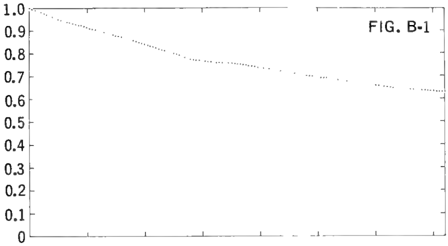
FIG. A-30

FIGURE	SECTION	TEMPERATURE °C	
A–31	P–1	25	SHALLOW
A–32	P–2	20	DEEP



APPENDIX B: FIGURES B-1 TO B-32 (AUTOCORRELATION)

FIGURE	SECTION	
B–1	A–1	SHALLOW
B–2	A–2	DEEP
B–3	B–1	SHALLOW
B–4	B–2	DEEP
B–5	C–1	SHALLOW
B–6	C–2	DEEP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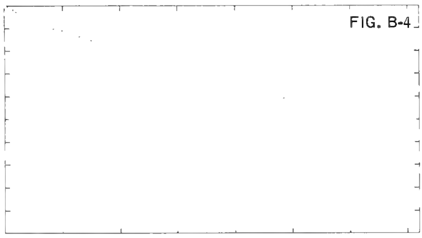
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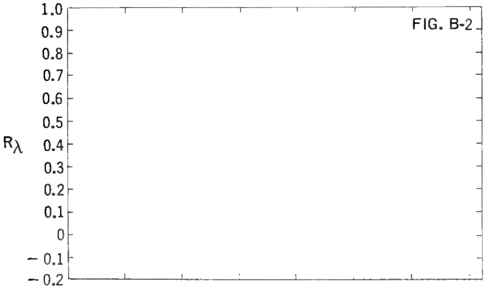
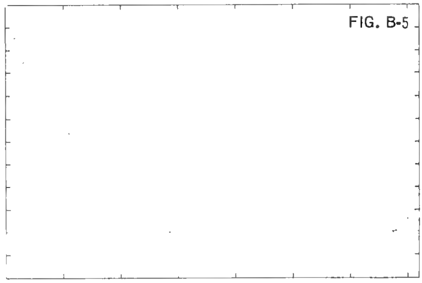


FIG. B-2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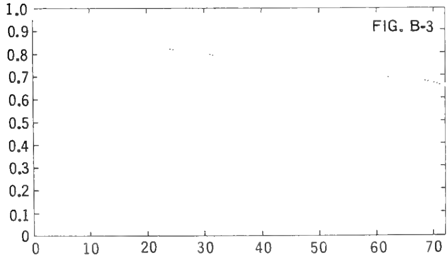
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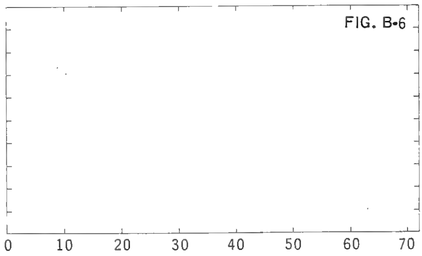
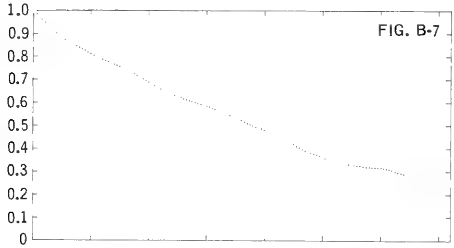


FIG. B-6

MINUTES

FIGURE	SECTION	
B–7	D–1	SHALLOW
B–8	D–2	DEEP
B–9	E–1	SHALLOW
B–10	E–2	DEEP
B–11	F–1	SHALLOW
B–12	F–2	DEEP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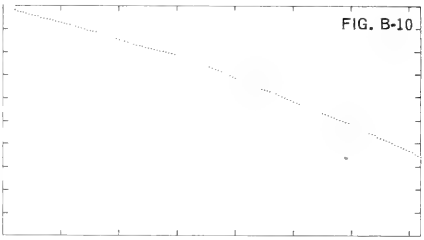
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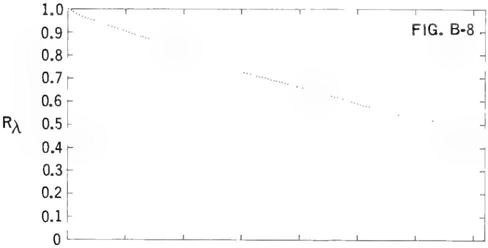
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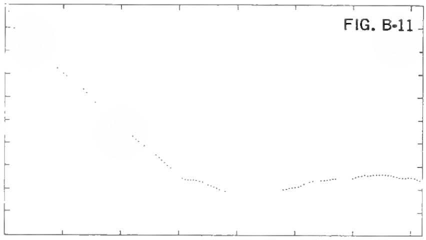
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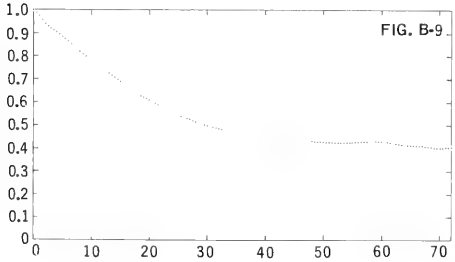
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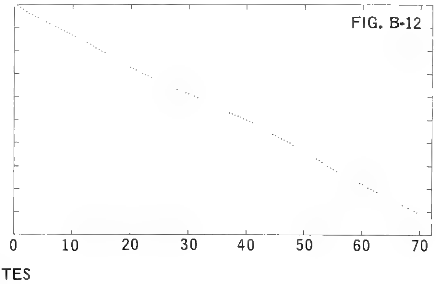
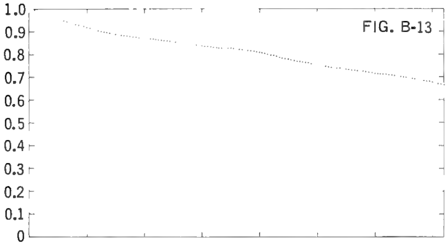


FIG. B-12

FIGURE	SECTION	
B–13	G–1	SHALLOW
B–14	G–2	DEEP
B–15	H–1	SHALLOW
B–16	H–2	DEEP
B–17	I–1	SHALLOW
B–18	I–2	DEEP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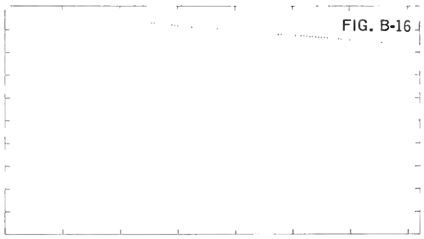
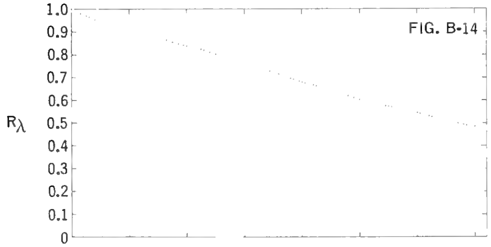


FIG. B-16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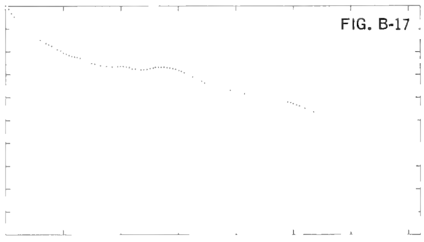
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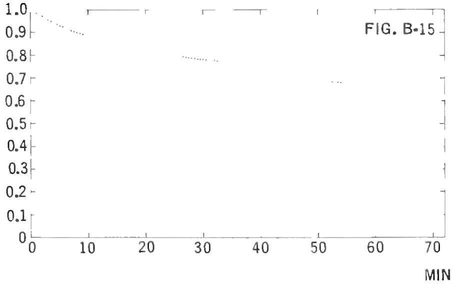


FIG. B-15

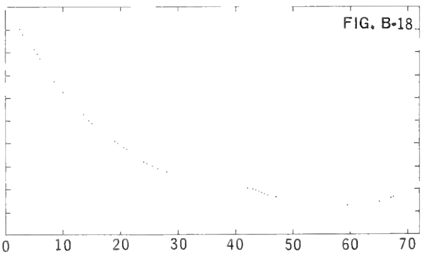


FIG. B-18

FIGURE	SECTION	
B–19	J–1	SHALLOW
B–20	J–2	DEEP
B–21	K–1	SHALLOW
B–22	K–2	DEEP
B–23	L–1	SHALLOW
B–24	L–2	DEEP

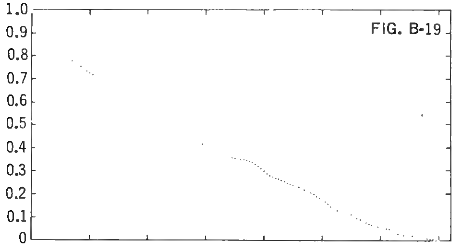


FIG. B-19

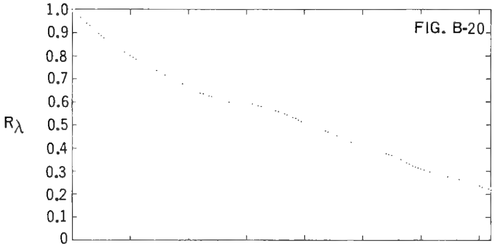


FIG. B-20

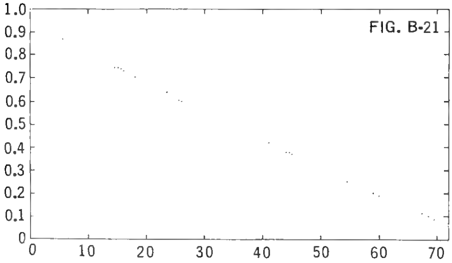


FIG. B-21

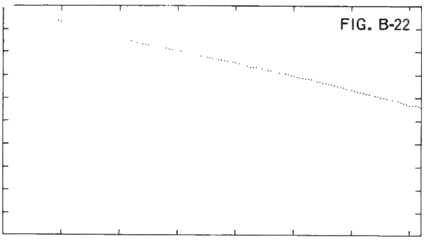


FIG. B-22

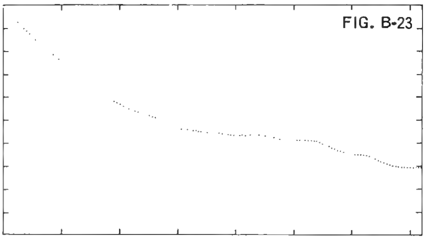


FIG. B-23

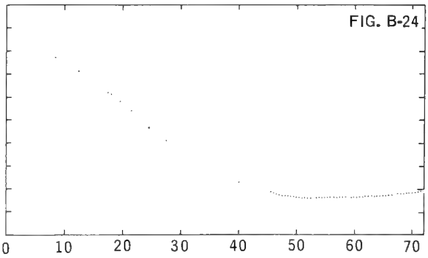


FIG. B-24

MINUTES

FIGURE	SECTION	
B–25	M–1	SHALLOW
B–26	M–2	DEEP
B–27	N–1	SHALLOW
B–28	N–2	DEEP
B–29	O–1	SHALLOW
B–30	O–2	DEEP

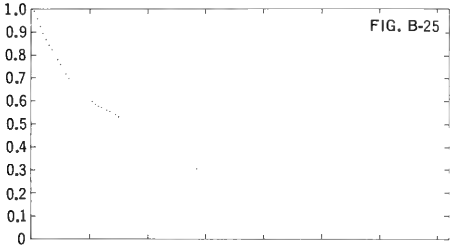


FIG. B-25

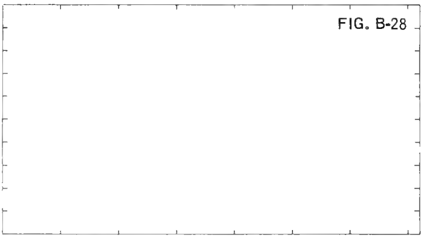


FIG. B-28

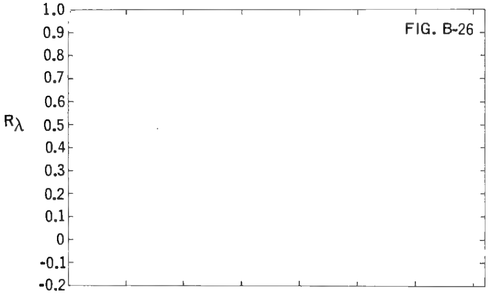


FIG. B-26

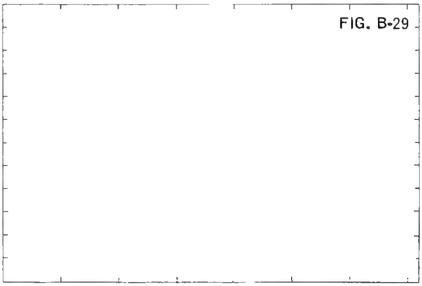


FIG. B-29

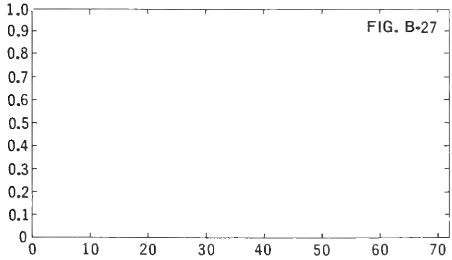


FIG. B-27

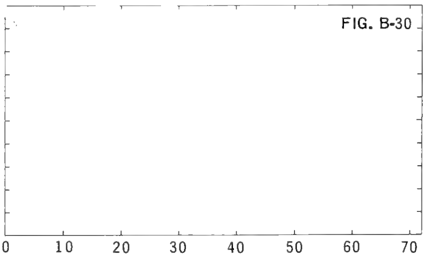


FIG. B-30

FIGURE	SECTION	
B–31	P–1	SHALLOW
B–32	P–2	DEEP

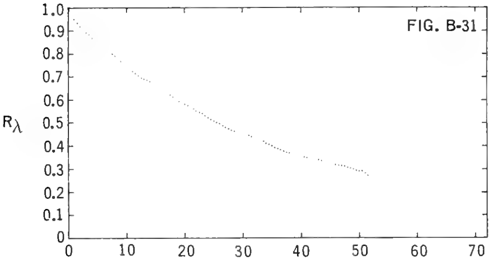


FIG. B-31

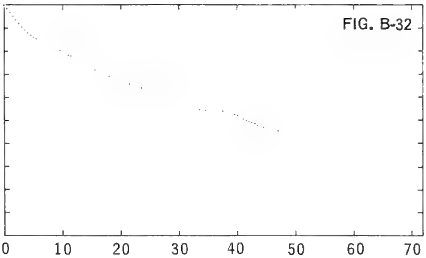


FIG. B-32

APPENDIX C: FIGURES C-1 TO C-32 (POWER SPECTRUM)

FIGURE	SECTION	
C–1	A–1	SHALLOW
C–2	A–2	DEEP
C–3	B–1	SHALLOW
C–4	B–2	DEEP
C–5	C–1	SHALLOW
C–6	C–2	DEEP

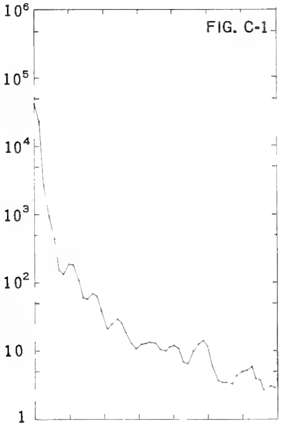


FIG. C-1

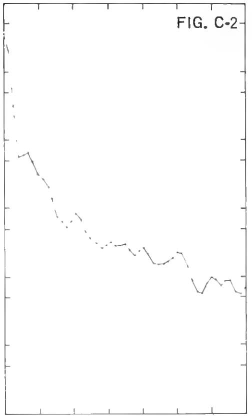


FIG. C-2

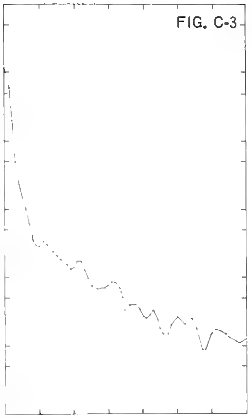


FIG. C-3

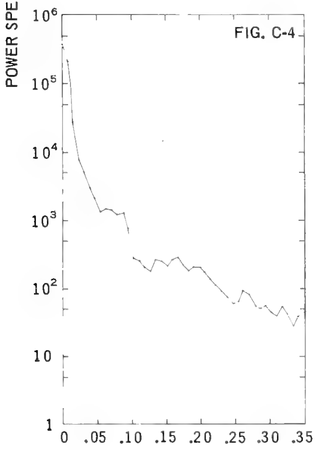


FIG. C-4

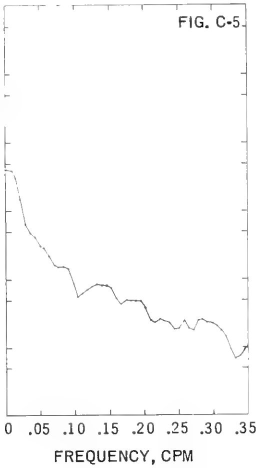


FIG. C-5

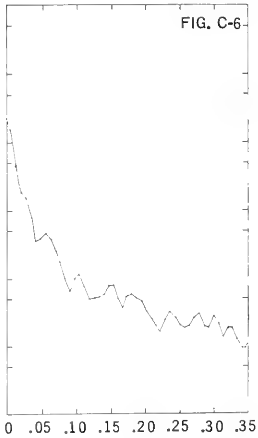


FIG. C-6

FIGURE	SECTION	
C–7	G–1	SHALLOW
C–8	D–2	DEEP
C–9	H–1	SHALLOW
C–10	E–2	DEEP
C–11	F–1	SHALLOW
C–12	F–2	DEEP

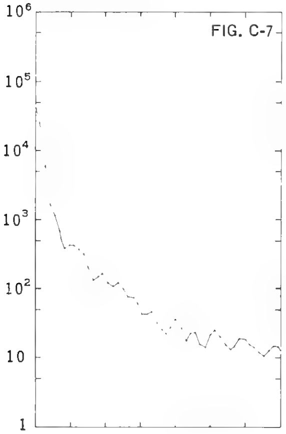


FIG. C-7

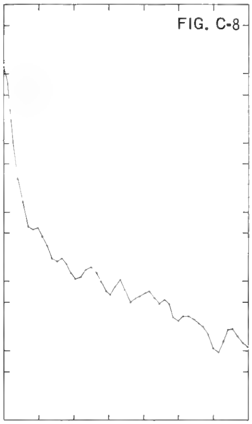


FIG. C-8

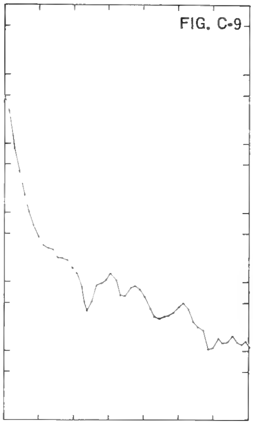


FIG. C-9

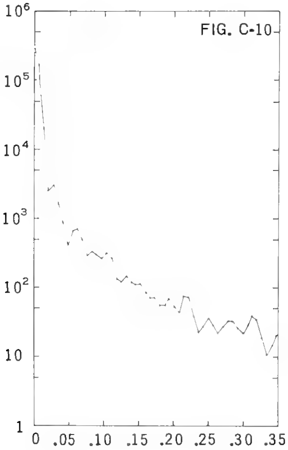


FIG. C-10

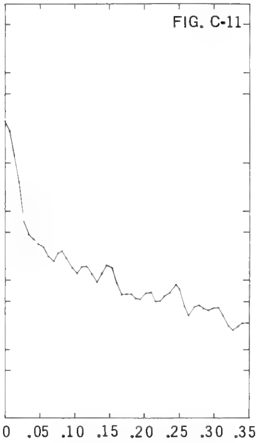


FIG. C-11

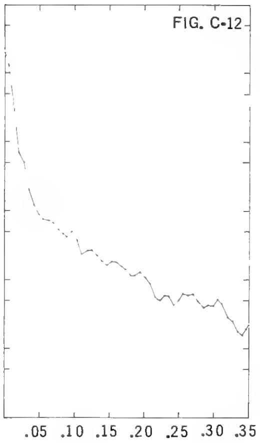
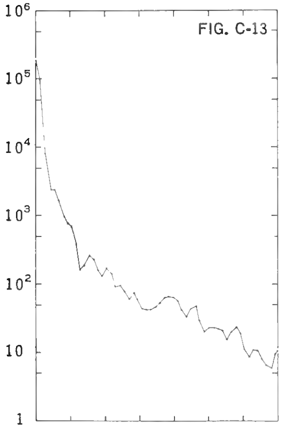
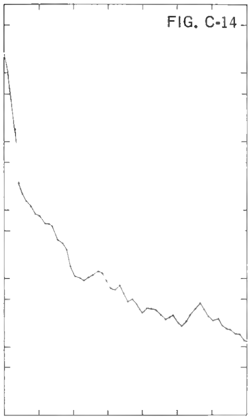
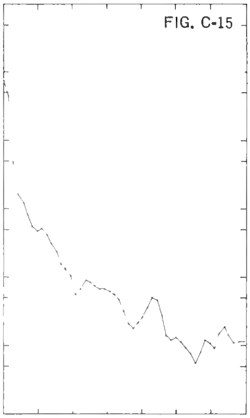


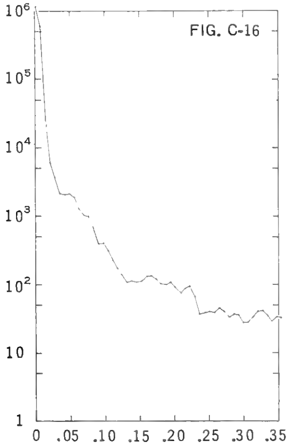
FIG. C-12

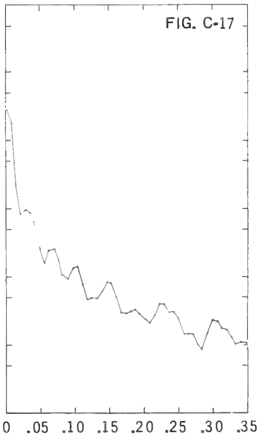
FIGURE	SECTION	
C–13	G–1	SHALLOW
C–14	G–2	DEEP
C–15	H–1	SHALLOW
C–16	H–2	DEEP
C–17	I–1	SHALLOW
C–18	I–2	DEEP











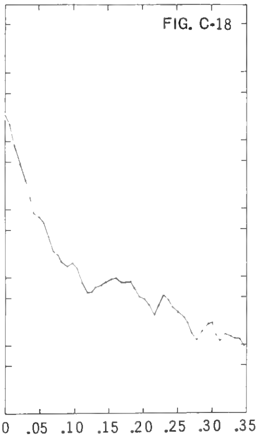


FIGURE	SECTION	
C–19	J–1	SHALLOW
C–20	J–2	DEEP
C–21	K–1	SHALLOW
C–22	K–2	DEEP
C–23	L–1	SHALLOW
C–24	L–2	DEEP

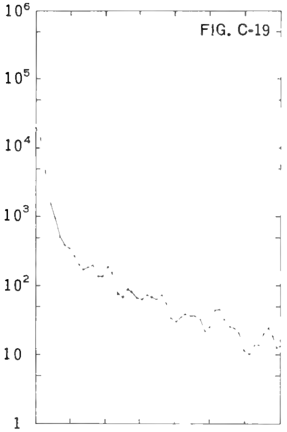


FIG. C-19

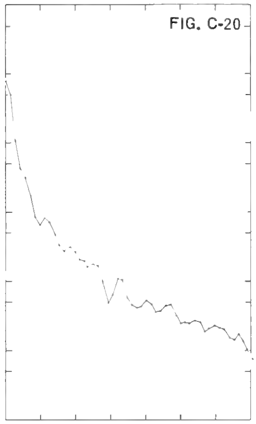
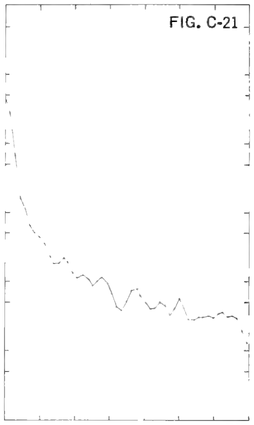


FIG. C-20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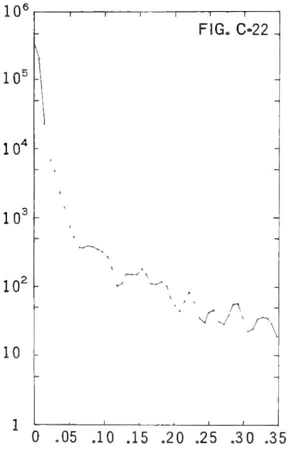
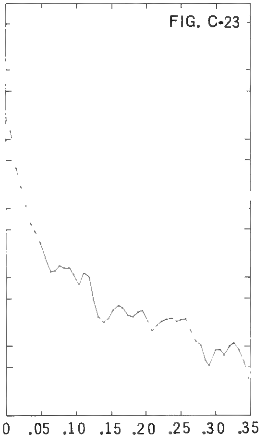


FIG. C-22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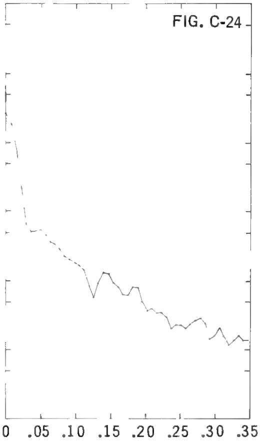


FIG. C-24

FIGURE	SECTION	
C–25	M–1	SHALLOW
C–26	M–2	DEEP
C–27	N–1	SHALLOW
C–28	N–2	DEEP
C–29	O–1	SHALLOW
C–30	O–2	DEEP

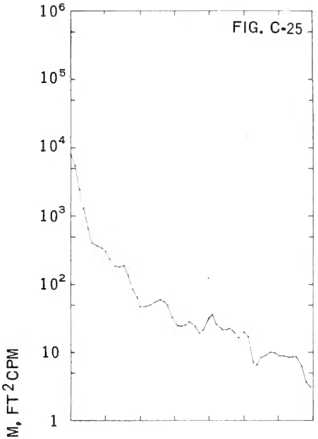


FIG. C-25

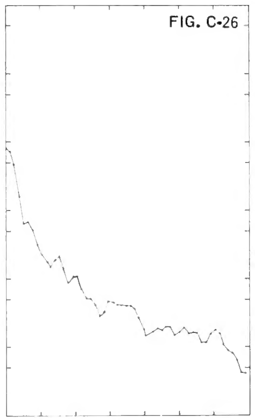


FIG. C-26

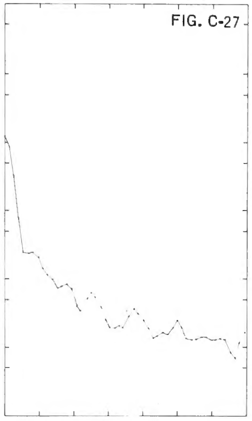


FIG. C-27

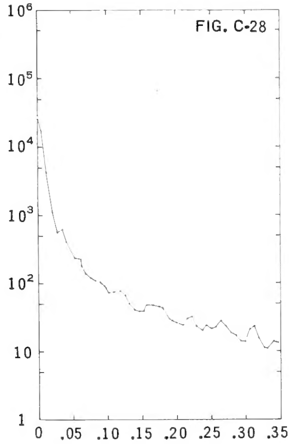


FIG. C-28

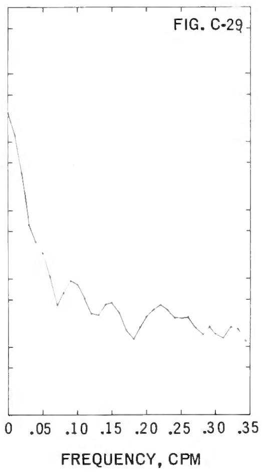


FIG. C-29

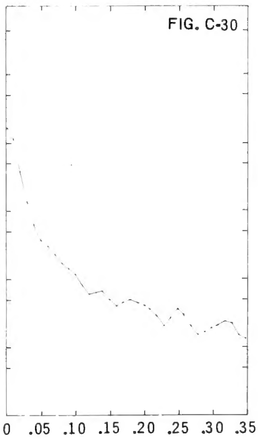
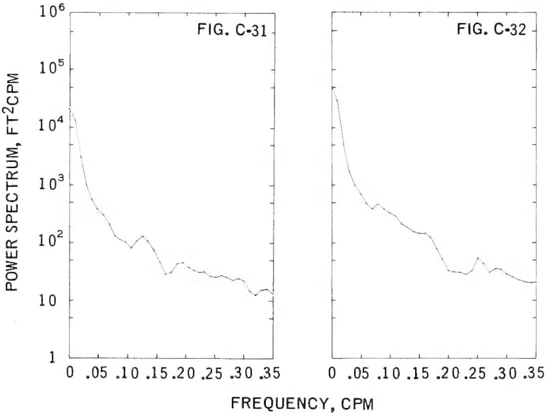


FIG. C-30

FIGURE	SECTION	
C–31	P–1	SHALLOW
C–32	P–2	DEEP



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