A New York Bight Sewage Sludge Dumping Experiment

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ABSTRACT

An experiment was carried out in New York Bight to study the influence of oceanic stratification on the space-time evolution of a dumped artificial tracer, sewage sludge. The dumped tracer generated "thermocline particle-fluid currents" with an initial velocity of 38 cm/sec, which exponentially decayed with distance and produced mode two internal gravity waves. A turbulent drag type coefficient of about 10^{-3} was determined for the particle currents. This experiment demonstrates the importance of water column density structure in understanding the dilution of potentially toxic substances placed in the ocean.

INTRODUCTION

It has been shown (Proni et al., 1976a) that acoustic signals may be used to determine the space-time distribution of material such as sewage sludge dumped into the ocean. It has also been shown (Drake, 1971; Proni et al., 1976b) that the presence and location of a near-surface thermocline has an important effect on the horizontal and vertical transport of particulate matter in the ocean. An important question remains to be investigated. What is the effect of a well-developed thermocline on the movement of sewage dumped into the ocean? In July 1976, a team of scientific investigators from the Atlantic Oceanographic and Meteorological Laboratories (AOML) of the National Oceanographic and Meteorological Laboratories (NOAA) and from other laboratories[1] undertook such an investigation using acoustic returns and water bottle samples.

EXPERIMENTAL DESIGN

A vessel carrying sewage was directed to a specific location within the EPA designated dump zone (40°23'30"N, 73°43'45"W). The NOAA Ships *George B. Kelez* and the R/V *Black Coral* were used to direct and study the dumping. The *Kelez* was the "on-station" vessel, used primarily for chemical sampling, while the vessel *Black Coral* was operating in a roving mode in order to obtain as much data as possible on the space-time growth of the dumped material.

The acoustic equipment, the primary source of data for this report, used aboard the *Black Coral* was essentially a commercially available but modified 200 KHz narrow-beam (12°) echo-sounder. The acoustic (80 watt) transducer was located in a streamlined tow body and emmitted a 0.1 millisecond-long pulse of acoustic energy at a rate of 267 pulse/min. The acoustic data were recorded for real-time use on paper records and, for later analysis, on analog magnetic tapes.

OBSERVATIONS

On July 15, 1976 at 0935 L.T., contact was made by the *Black Coral* with the dumping vessel *North River*. The *North River* was carrying 102,000 ft^3 of sludge from the Newton Creek Processing Plant (N.Y.C.) (Hatcher). The temperature of the sludge mixture was 34°C. At 0958 L.T. the sludge vessel dumped its load all at once and departed. The bulk density of the sludge was near that of water.

The *Black Coral* first crossed the dump at 1000 L.T. The first four passes over the dumped material are shown in Figure 1. The *Black Coral* proceeded south to north from 100 L.T. to 1002 L.T.; then she changed course and proceeded in a westward direction from 1002 L.T. to 1006 L.T.; then she changed course to a general eastward direction which she followed until 1011 L.T. Figure 2 shows the acoustic record obtained from 1012 L.T. to 1027 L.T. Figure 3 shows the track of the *Black Coral* from 1012 L.T. to 1027 L.T.

Figure 1 shows that within three minutes after the dumping, a portion of the dumped material had reached a depth of at least 16 m and that within nine minutes a portion of the dumped material had made its way to the bottom[2]. Sludge material thus remains throughout the water column, providing a source of material for acoustically tracing horizontal spreading.

Sludge material does not behave as a single geometrically limited (in the vertical) well-defined volume of fluid. Between 1005 L.T. and 1008 L.T. three distinct layers of particles may be seen. Because the ship reversed course (roughly), it becomes clear that the layers are emanating from the center of the dump.

Oscillations (internal gravity waves) are clearly present in the layers. For example, an oscillation exceeding 2 m peak-to-peak occurs at 1024 L.T. (Figure 2)[3]. The three layers seen between 1015 L.T. and 1018 L.T. appear to be oscillating closely in phase. The same may be said of the two layers which remain between 1022 L.T.

It may be observed by studying Figure 3 that the sludge material appears to propagate in a predominantly westward direction. The horizontal speed of propagation of the particle layers was measured (some of these speeds are given in Table 1). It shows that the horizontal speed of advance of the particle layers (sometimes called surges) decreases with distance from the centroid of concentration. The measured horizontal speeds ranges from 38.0 cm/sec to 31.0 cm/sec. It is possible to make an estimate of the vertical component of velocity of the leading edge[4] of the upper particulate surge shown in Figure 2 (the surge is seen between 1022 L.T. and 1026 L.T.). Since the dump occurred at 0958 L.T. and the leading edge of the upper surge has gone from a depth of 6 m to 9.5 m at 1022 L.T., the vertical-setting component is roughly 0.24 cm/sec downward.

The vertical extent of a horizontal layer does not appear to exceed one meter. The vertical resolution of the acoustic system used in the experiment is about 10 cm. The particulate surges and external gravity waves are both seen in the 2 m to 12 m depth range.

Background currents were measured by drogues at 2 m and 18 m. The 2 m drogue indicated a westward current of about 6.5 cm/sec and the drogue at 18 m indicated a current of 10 cm/sec in a northwest direction. Evidently, particle velocities are not exclusively due to background currents.

The dumped plume's motion appears to occur in three principal phases, which may or may not occur concurrently, These will be referred to as the gravitational descent phase, the dynamically active phase, and the passive phase (Koh and Chang). Significant chemical effects and physical changes in the dumped material may be occurring simultaneously with the general plume motion and could conceivably alter that motion. The gravitational descent phase is characterized by a vertical downward velocity of the leading edge of the plume. The dynamically active phase consists of two parts: the generation of internal gravity waves and the thermocline-limited decaying horizontal particulate current. During the passive phase of the dump, the particles' surges have evolved simply into regions (laminae) of excess density in which presumably gradual settling processes and diffusion occur.

Figure 4 shows another pass over the dump at a later time. The thermocline is now laden with particulate matter from the dump at a distance of up to 1.5 km.

Figure 5 shows two passes over yet another dump. From about 1435 to 1443 the ship was progressing towards the center of the dump; from 1443 on, the ship is moving away from the center of the dump.

The gravitational descent particles are comparable to falling solid spheres whose terminal velocity can be calculated by noting that (Daily):

weight of sphere = drag + buoyant force

or $$\frac{4}{3}\pi a \ \gamma_s = 6\pi a \mu V_3 + \frac{4}{3}\pi a^3 \gamma$$

where a = radius of particle

μ = dynamic molecular viscosity $\left(\frac{\text{force-time}}{\text{area}}\right)$,

γ_s = specific weight of solid $\left(\frac{\text{weight}}{\text{volume}}\right)$,

γ = specific weight of fluid,

then the terminal fall velocity[5] is $V_{oTerm} = \frac{2}{9}\frac{a^2}{\mu}(\gamma_s - \gamma)$.

Many particles are vertically stopped at the thermocline; their specific weight is approximately that of the water column's at that depth. Figure 6 shows expendable bathythermograph records (XBT's) taken at 1011, 1014, and 1034 L.T. Note the sharp temperature decrease ($6^{o}C$) in going from about 8m depth to 11 m depth, i.e., a rate of change of temperature with depth of 2^{o} c/m. This results in a density increment with depth of perhaps 0.002 gm/cm^3. This sharp vertical temperature (and hence density) gradient in the water column is apparently responsible for fast lateral motion of dumped material remaining at that depth. An effect seen neither for particles settling above or below the thermocline, these particles undergo the usual lateral diffusion as is discussed in Proni et al., (1976a)

A simplistic usage of the conservation of mass could help account for the vertical falling speed becoming faster than background horizontal speed (although the background appears to direct the particle flow). From diagram 1 and the conservation of mass we get the following equation:

$$\rho_1 v_1 L_1 w_1 = \rho_2 v_2 L_2 w_2 = \rho_3 v_3 w_3 h$$

where ρ_s = density at position s

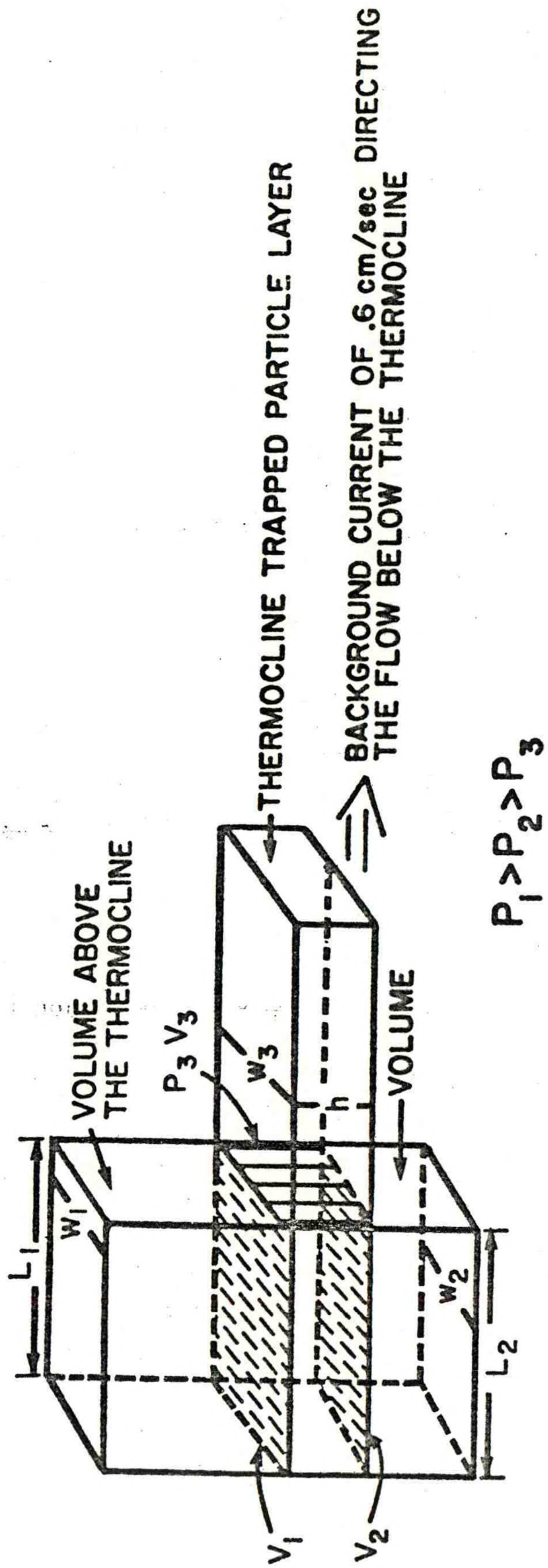
v_s = velocity at position s

w_s = width at position s

L_s = length at position s

h = height of particle layer

DIAGRAM 1


THERMOCLINE TRAPPED PARTICLE LAYER
BACKGROUND CURRENT OF .6 cm/sec DIRECTING THE FLOW BELOW THE THERMOCLINE
VOLUME ABOVE THE THERMOCLINE
VOLUME
P_3 V_3
w_3
h
L_1
w_1
w_2
L_2
P_1 V_1
P_2 V_2
$P_1 > P_2 > P_3$

from our observations let $V_1 \sim V_2 \sim 10$ cm/sec, $V_3 \sim 30$ cm/sec, $L_1 = L_2 = 120$ meters, h = 1 meter and as we shall explain next $w_1 = w_2 = w_3$. Then,

$$\frac{\rho_1 - \rho_2}{\rho_3} \approx .025$$

The width of the particle surge appears fairly constant or grows slowly, proceeding from the leading edge of the surge towards its source. This indicates that little turbulent mixing is occurring. The Richardson number R_i (an indicator of possible turbulence), may be written as

$$R_i = \frac{\left(\frac{-a_o}{\rho}\right)\left(\frac{\Delta\rho}{\Delta z}\right)}{\left(\frac{u}{z}\right)^2} .$$

We shall use the following estimates: g (gravitational acceleration) +980 cm/sec^2, Δu (the difference between the surge velocity and background current) = 30 cm/sec, $\Delta\rho$ (excess density sustainable by the thermocline) = .002 gm/cm^3, and Δz = 1 m. With these values R_i = .22 obtained. This is a borderline value because it is known that R_i = 0.25 marks the line between stable stratified flows and flows which may be, but are not necessarily, unstable.

The horizontal velocity of the leading edge of the surge tends to slow down as it moves away from its source (see Appendix A). Here we hypothesize the existence of a turbulent drag force acting between the thermocline-trapped particles and neighboring sections of the water column. Based on the value of the bulk Richardson number (0.22), it is likely that there exists some turbulence in the flow (there will be small zones within the flow of even a smaller Richardson number). From our values in Table 1 and equations in Appendix A, $C_D = .7 \times 10^{-3}$, which is slightly smaller than the C_{100} values (4×10^{-3} - 2.1×10^{-3}) that Sternberg obtained for water flowing over various bottom conditions (rock, gravel and sand).

We now consider the internal wave field. From the acoustic record, such as that shown in Figure 2, two facts are evident: (1) the internal oscillations occur at least within the vertical range 4 m to 12 m (i.e., the thermocline), and (2) the internal oscillations are in phase in that region. This doesn't mean that oscillations are not occurring below 12 m., but it does mean that only oscillations detectable acoustically occur within the 4 m to 12 m depth range.

The mode structure present in the internal wave field is indicated in Figure 7. The XBT at 1011 L.T. was taken during a period of low level internal wave motion, whereas that at 1014 L.T. was taken at or near a trough in the internal wave field. The difference[7] between the two tracers should yield a measure of water column displacement (in fact a slight underestimate of peak amplitude will result, a fact which can be ascertained by examination of the acoustic record). The data in Figure 7 shows that the first 11 or so meters of the water column oscillate in phase.

The maximum possible horizontal velocity contribution due to internal gravity waves is about .8 cm/sec. This estimate can be acquired by use of such formulas[8] as:

$$Cg_x = \pm N \frac{(K_z^2)}{K_n K^3} K_x$$

and assume all k's are of the same order of magnitude and is approximately $1m^{-1}$ and N (Brunt-Vaisala frequency) is approximately[9] $\frac{1}{120 \text{ sec.}}$.

It is beleived that the internal wave field is generated by the downward surge of sewage sludge penetrating the water column. In order to assure that the dumping vessel itself did not generate an internal wave field, the dump ship was requested to come on-station and carry out a "spot" dump. The water column density structure is essentially geverned by the temperature (see Fig A-1 and Table 2). The water column is viewed as being basically a two-layer system. The division between layers occurs in the 7 m to 10 m depth range where $\Delta\rho$ of 0.002 gm/cm^3 occurs. This stratification is in agreement with the general behavior of the internal wave field[9].

As the particle surge continuously gives up energy as it proceeds and is slowing down, its bulk motion characteristics decrease and individual particle dispersion predominates. For the data shown in Figure 2, it appears that individual particle dispersion may be occurring in the water column volume located between 8 m and 12 m depth and was passed over by the Black Coral between 8 m and 12 m and in the time interval 1451 to 1455 L.T. The acoustic records in both these figures indicate reflection occuring from a geometrically diffuse water mass in contrast to the spatially well-defined surge present at shallower depths and at earlier times. Note also that in the zone of supposed particle dispersion occurring in Figure 2 between 1016 and 1017 L.T. the acoustic reflected intensity has decreased substantially in the next ship's pass occuring between 1022 and 1024 L.T.

SUMMARY AND CONCLUSIONS

The experiments described in this paper were designed to study the practical problem of the space-time diffusion of sewage sludge dumped into a stratified oceanic environment. A wealth of information of the fluid dynamical aspects of dumping was obtained. The main results are:

(1) The dumping of sewage material into a stratified oceanic environment produces fast moving (38-30 cm/sec) but steadily slowing, horizontally flowing, "thermocline particle-laden fluid currents."

(2) Large amplitude (e.g. 1-2 m) internal waves are also produced. The internal waves, made visible at various depth in the upper half (i.e. first 12 m) of the water column by the presence of thermocline particulate surges, oscillate in phase throughout the upper water column.

(3) A portion of the sewage sludge material penetrates the thermocline and reaches the bottom, having passed through the water column with a speed of at least 10 cm/sec.

(4) Above and below the strong thermocline region no particle currents are observed, and the material appears to be undergoing "classical" diffusion.

(5) "Large scale" vertical dispersion (i.e. mixing on the scale of a few meters or larger) does not appear to occur in the thermocline particle currents until the currents either "slowed down" and/or "descended" to a sufficiently low speed and depth. "Small" scale vertical mixing (i.e., on the order of half a meter or less) could possibly occur, as a Richardson number of order of 0.22 may reasonably be calculated for at least the early (e.g., first twenty or so minutes) portion of particle current lifetime.

(6) Penetration to deeper depths by thermocline particle surges may occur when the particle concentration becomes high enough to overcome a supportive water column density increase.

(7) A simplified model of the particle current leads to an estimate of approximately 0.7×10^3 for the turbulent drag coefficient.

ACKNOWLEDGMENTS

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FOOTNOTES

1. The State University of New York (Marine Science Center, Stony Brook); the National Marine Fisheries Service (Sandy Hook).

2. The white areas in the center of the dump (such as the one centered at 1009 L.T.) are caused by severe acoustic signal attenuation in the upper portion of the dumped material. The signal is attenuated by at least 15 db (the dynamical range of the paper record); however, the signal is still detectable in the magnetic tape records which have a much larger dynamic range (in excess of 100 db). The attenuation caused by the sewage is (acoustic) frequency dependent, so multiple frequency acoustic systems are normally used in sludge tracking (Proni, 1976a).

3. The time axis on Figures 1 and 2 can be converted to a distance axis by multiplying by the ship's speed of 2 m/sec (for distance separation in units of meters multiply time differences by 120 cm/min).

4. See Appendix B for a detailed discussion of the vertical motion of the leading edge.

5. Future dump experiments will verify this for particular μ's and a's.

6. See for instance Newman and Pierson.

7. This XBT differencing procedure used to obtain the mode structure loses accuracy below 10 m depth.

8. See Roberts.

9. See Fig. A-1 noting $N^2 \equiv - \frac{g}{\rho} \frac{d\bar{\rho}}{dz}$.

APPENDIX A

The following is a heuristic solution for the average horizontal velocity. It is here that we introduce the drag coefficient. The Reynolds Equation (Le Mehaute) for the vertical direction is:

$$\rho \left(\frac{\partial}{\partial w} \overline{w} + \overline{u} \frac{\partial}{\partial x} \overline{w} + v \frac{\partial}{\partial y} \overline{w} + \overline{w} \frac{\partial}{\partial z} \overline{w} \right)$$

$$= - \frac{\partial}{\partial z} (\overline{p} + \rho g z) + \nabla^2 \overline{w} - \rho \left(\frac{\partial}{\partial x} \overline{u'v'} + \frac{\partial}{\partial y} \overline{v'w'} + \frac{\partial}{\partial z} \overline{w'^2} \right)$$

where u, v, and w are the x, y, and z components of the velocity respectively; z being the vertical and x and 4 being the horizontal directions; p, ρ, μ, and g are the pressure, the density, the viscosity and the acceleration due to gravity, respectively. The bars[a] denote time-averaged quantities and the primes denote turbulent perturbation. The main plume has no average vertical velocity and we will not consider variations in the y direction so

$$- \frac{\partial}{\partial z} (\overline{p} + \rho g z) - \rho \left(\frac{\partial \overline{u'w'}}{\partial x} + \frac{\partial \overline{w'^2}}{\partial z} \right) = 0.$$

Next, we let the vertical rate of change of average pressure force balance that of the gravity force. We are left with the result that the turbulent fluctuation[b] forces must balance themselves. Thus,

$$\frac{\partial \overline{u'w'}}{\partial x} + \frac{\partial \overline{w'^2}}{\partial z} = 0.$$

Using the concept that increases in the fluctuating velocities are proportional to increases in the mean velocity (Komar; Stanley and Swift, page 93) $u' \alpha \overline{u}$ and $w' \alpha u' \alpha \overline{u}$ or (α indicates proportionality)

$$0 = \left(\frac{\partial}{\partial x} \overline{u^2} C_{xz} + \frac{\partial}{\partial z} \overline{u^2} C_{zz} \right)$$

where C_{xz} and C_{zz} are products of proportionality constants.

Integrating over the vertical extent of the plumes

$$0 = \frac{\partial}{\partial z} \int_{z_o}^{z_h} \overline{u^2} C_{xz} \, dz + \int_{z_o}^{z_h} \frac{\partial}{\partial z} \overline{u^2} C_{zz} \, dz$$

let $\int_{z_o}^{z_h} \overline{u^2} \, dz = \langle \overline{u^2} \rangle_z (z_h - z_o) = \langle \overline{u^2} \rangle h$

$$0 = \frac{\partial}{\partial x} C_{xz} \langle \overline{u^2} \rangle h + \left[\overline{u^2}(z_h) - \overline{u^2}(z_o) \right] C_{zz}$$

for these plumes $\frac{\overline{u^2}(z_h) - \overline{u^2}(z_o)}{z}$ is approximately $<\overline{u^2}>_z$

hence $$0 = \frac{\partial}{\partial x} C_{xz} <\overline{u^2}>_z h - C_{zz} 2 <\overline{u^2}>z$$

$$\frac{\partial}{\partial x} <\overline{u^2}>_z h = -2 \frac{C_{zz}}{C_{xz}} <\overline{u^2}>_z$$

$\frac{C_{zz}}{C}$ will be C_D, the drag coefficient

$$\frac{\partial}{\partial x} <\overline{u^2}>_z h = -2 C_D <\overline{u^2}>_z$$

$$<\overline{u}>_z = <\overline{u}_o>_z \exp \left[-C_D/h (x-x_o)\right]$$

We have used $<\overline{u}^2>_z$ and $<\overline{u^2}>_z$ interchangably.

[a]This calculation is unaffected by internal gravity waves because this effect "averages out".

[b]We do have a borderline Richardson number.

APPENDIX B

For completeness, this appendix is an analysis of the vertical descent of the thermocline-trapped particle surge. Figure 8 shows smoothed internal gravity waves averaged out. The plume depth is referenced from Figure 2. A plot of θ (angle the resulting curves of Figure 8 make with the horizontal) and M (distance away from maximum concentration) is shown in Figure 9.

It is clear from Figure 9 that the particle currents flow horizontally to within the measurement capability of the acoustic system (a 0-3^{o} slope can be determined providing it exists over a sufficiently long horizontal distance, for example, 50 meters). The particle current angle, θpc is largest, of order 1^{o}, when a vertical descent has onset. We have chosen to call the vertical descent stage of particle current flow a "transition" stage. While in the act of transition (which is preceeded by short section of evolving into transition stages) θpc is of order 1^{o} (in the present data set).

APPENDIX C

Table 1: Measurements of Speed of Thermocline Surge

Time of Event	Length of Event	Centroid To Advanced Edge Of Thermocline Plume	Velocity Of Leading Edge With Relation To Centroid
1007-1009.6	2.6 minutes 325 meters	1.8 minutes 225 meters	10 minutes .38 m/sec
1014-1018	4 minutes 500 meters	3 minutes 375 meters	19 minutes .33 m/sec
1022-1026.5	4.5 minutes 562.5 meters	4 minutes 500 meters	27 minutes .31 m/sec
1437-1455	18 minutes 320 meters		.30 m sec

R/V BLACK CORAL

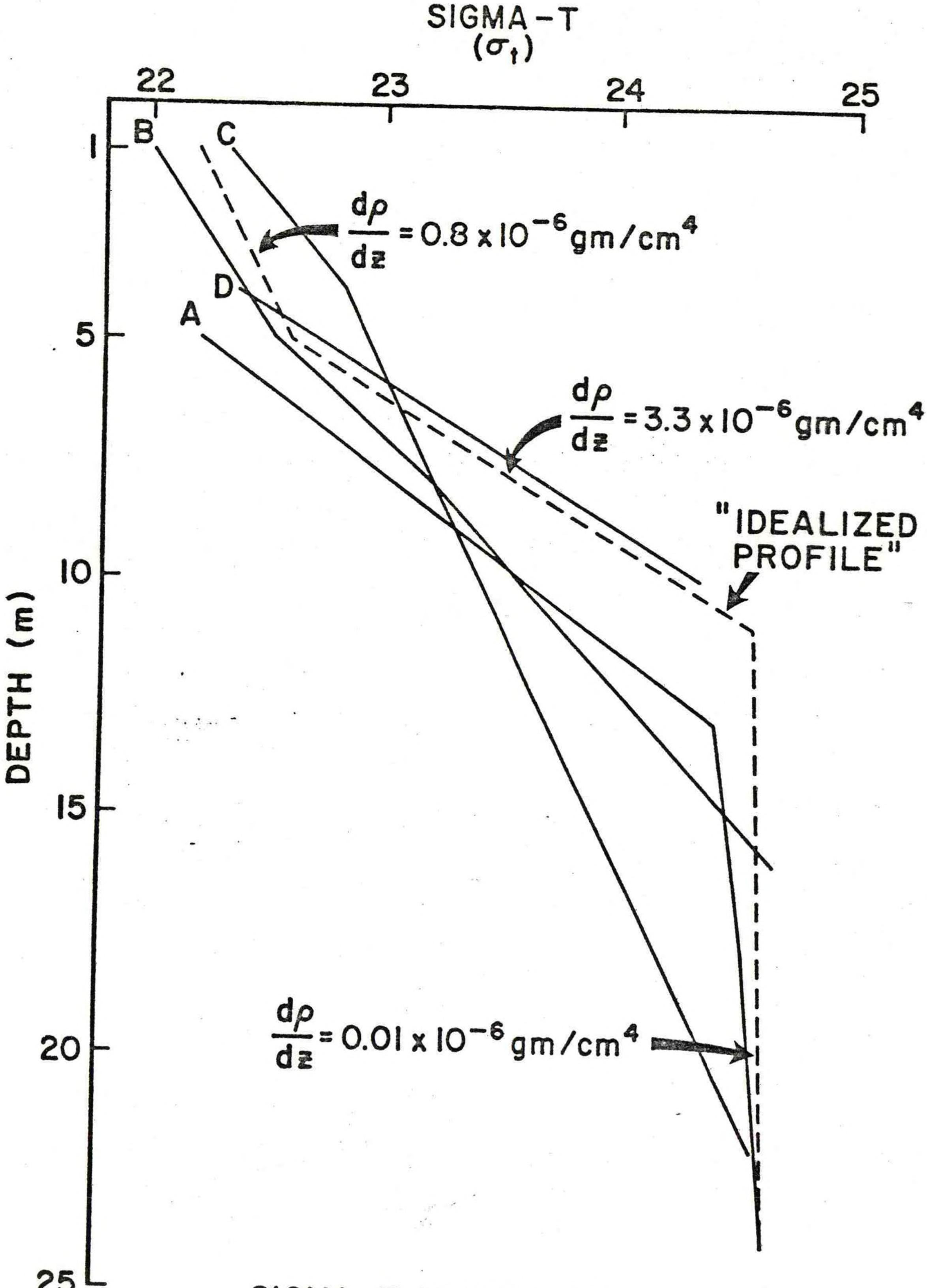
15 JULY 1976

SLUDGE TRACKING EXPERIMENT II

APPENDIX D

Table 2: Typical Salinity Profiles

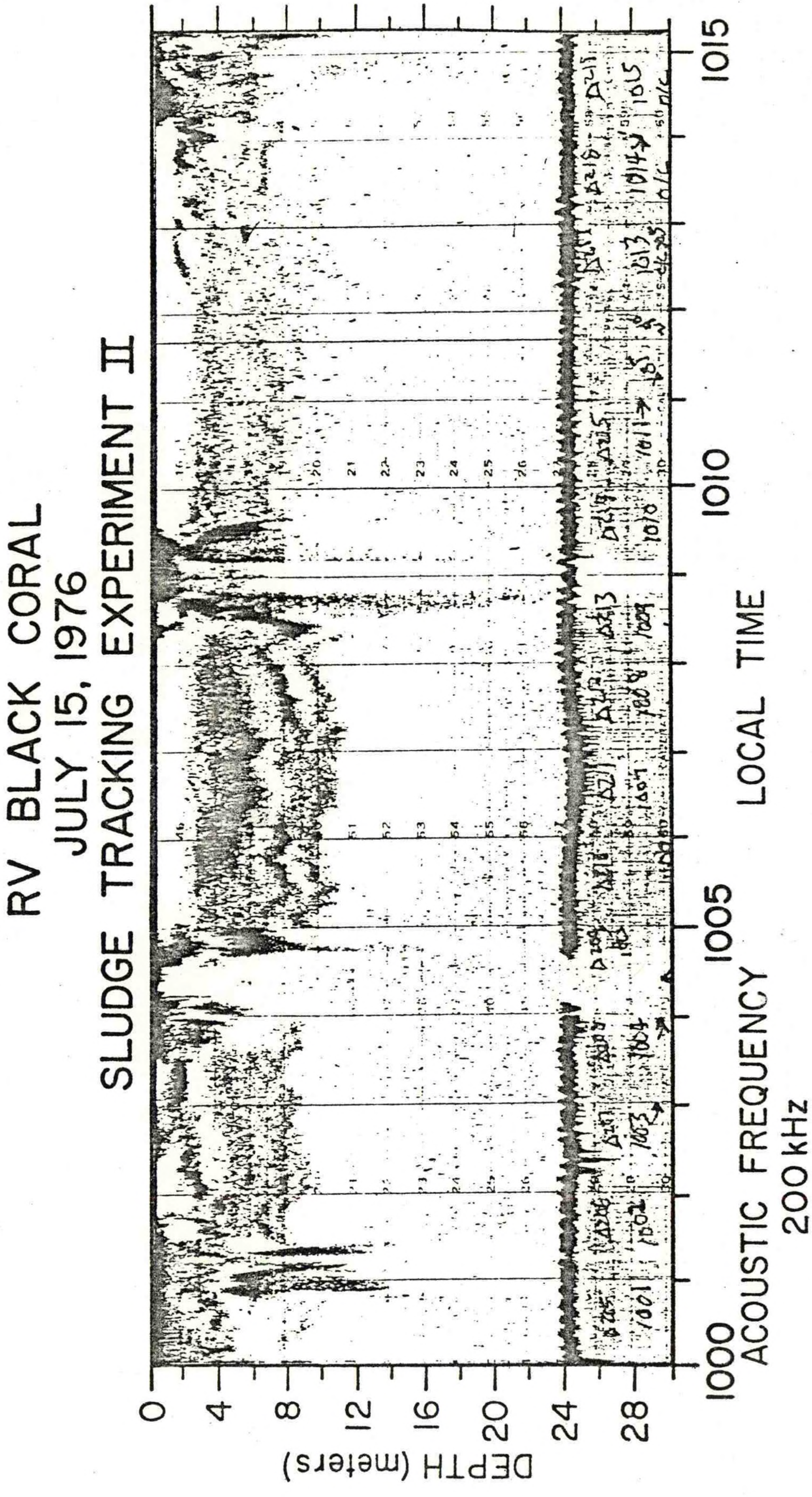
Station	Depth (m)	Temperature	Salinity	ρ
A	5	16.5	31.08	22.21
A	13	10.9	31.94	24.44
A	18	10.5	32.02	24.57
A	24	10.4	32.13	24.66
B	1	19.0	31.14	22.00
B	5	18.0	31.36	22.53
B	8	15.0	31.39	23.22
B	16	10.4	31.90	24.49
C	1	16.5	30.67	22.33
C	4	15.7	31.09	22.84
C	22	10.0	31.96	24.61
D	4	15.5	30.52	22.38
D	10	11.0	31.86	24.35



SIGMA-T VERSUS DEPTH IN JULY IN THE N.Y. BIGHT

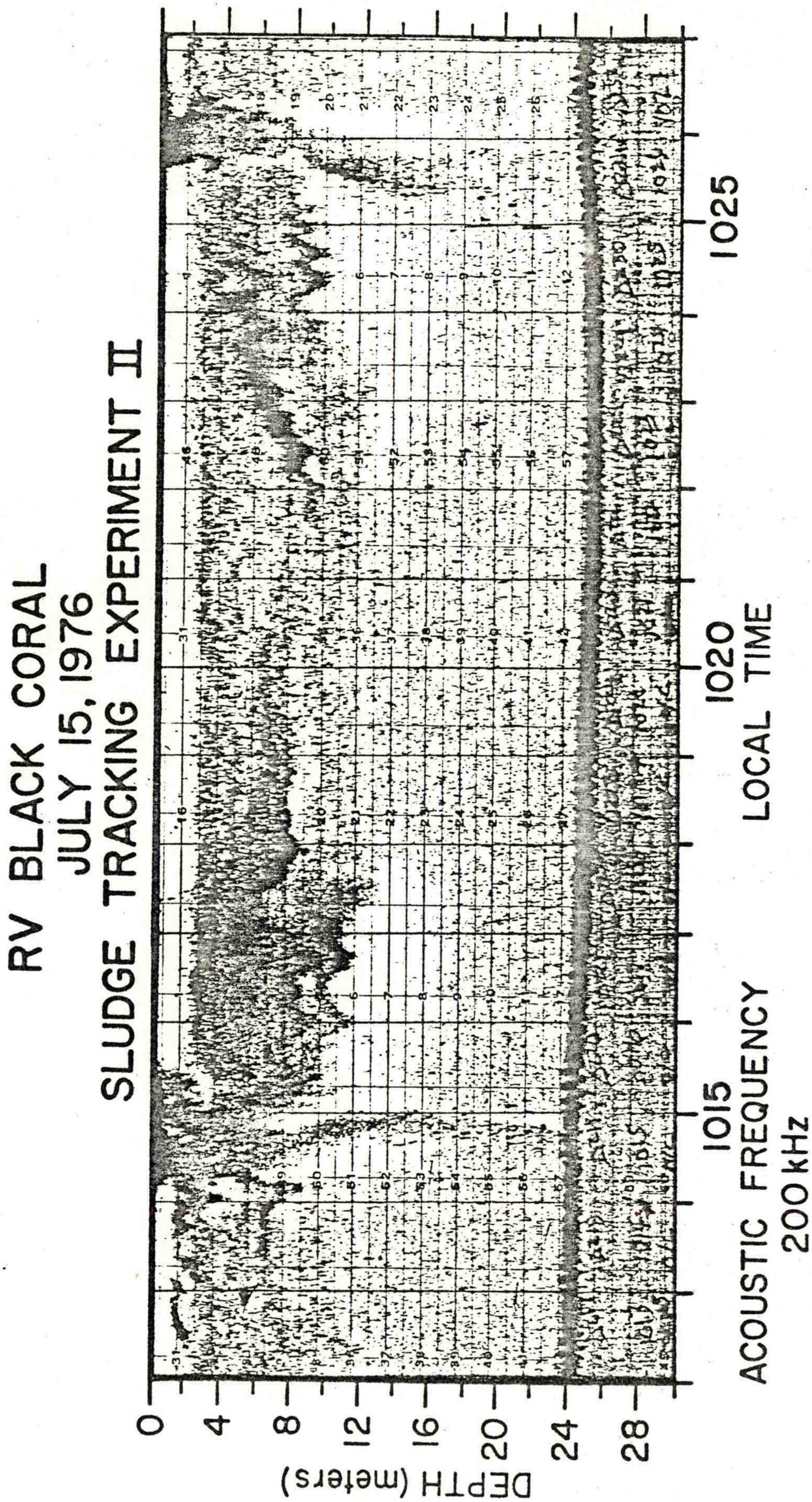
Fig. A-1

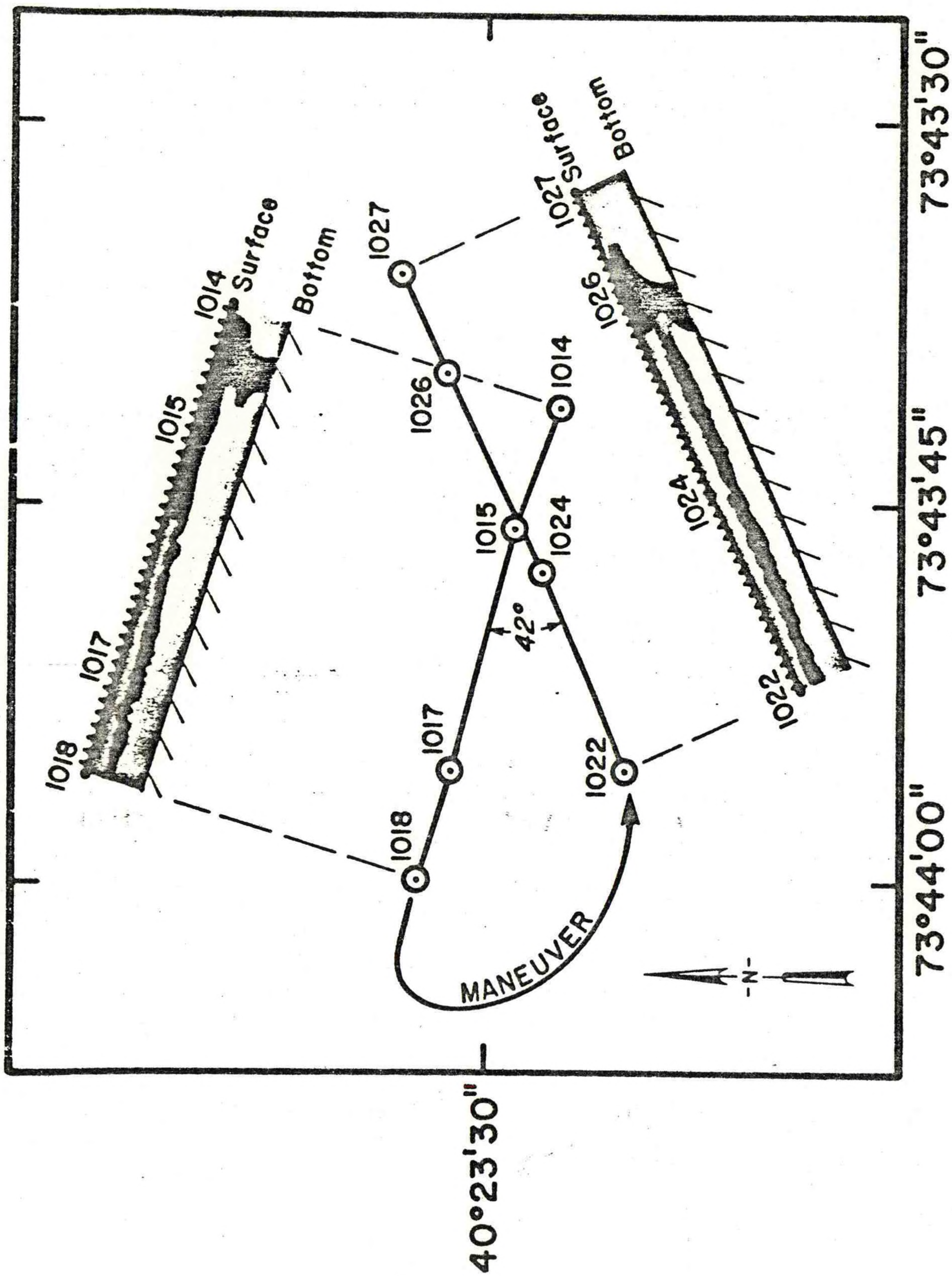
FIGURE 1



RV BLACK CORAL
JULY 15, 1976
SLUDGE TRACKING EXPERIMENT II
DEPTH (meters)
0
4
8
12
16
20
24
28
1000
1005
1010
1015
LOCAL TIME
ACOUSTIC FREQUENCY
200 kHz

FIGURE 2


RV BLACK CORAL
JULY 15, 1976
SLUDGE TRACKING EXPERIMENT II
DEPTH (meters)
0
4
8
12
16
20
24
28
1015
1020
1025
LOCAL TIME
ACOUSTIC FREQUENCY
200 kHz



R/V BLACK CORAL
15 JULY 1976
SLUDGE TRACKING EXPERIMENT II

FIGURE 4

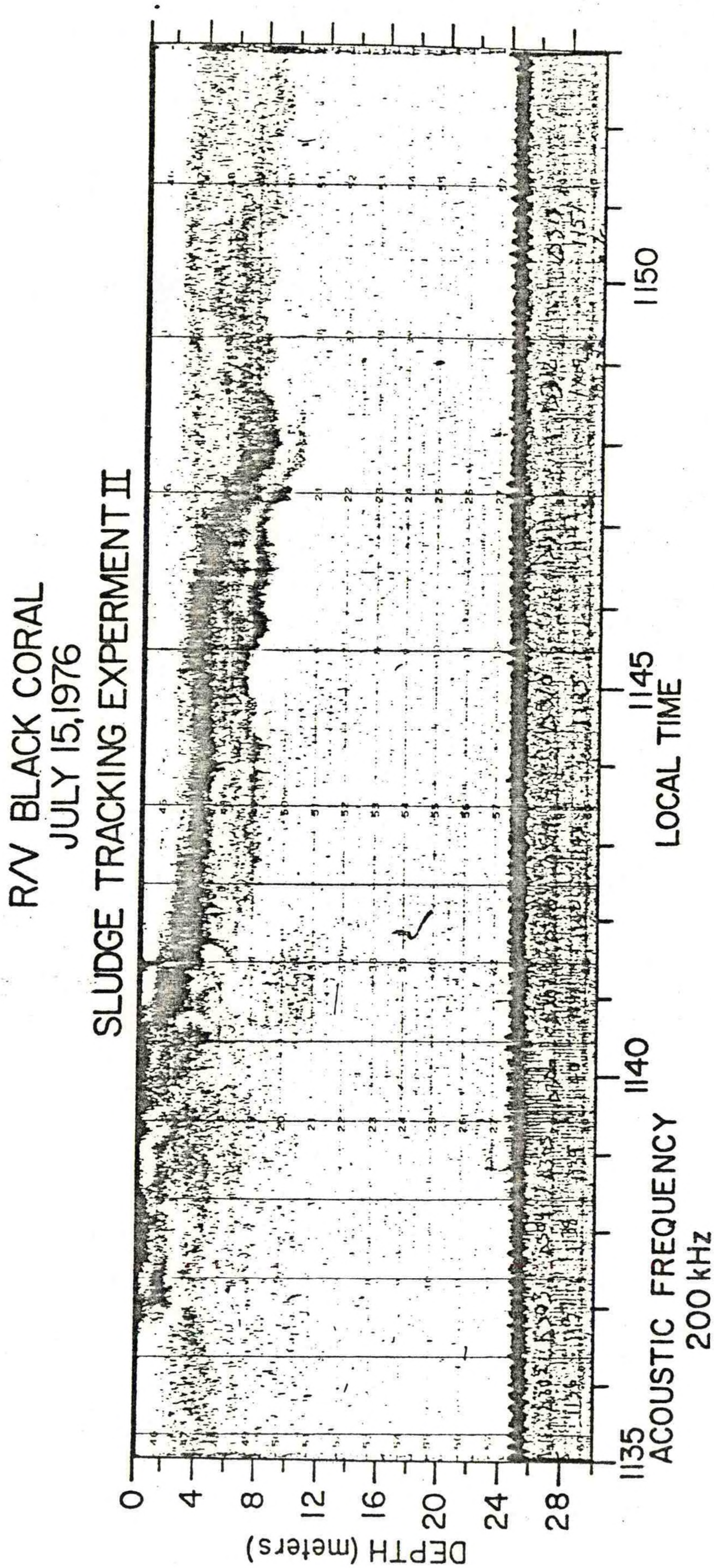
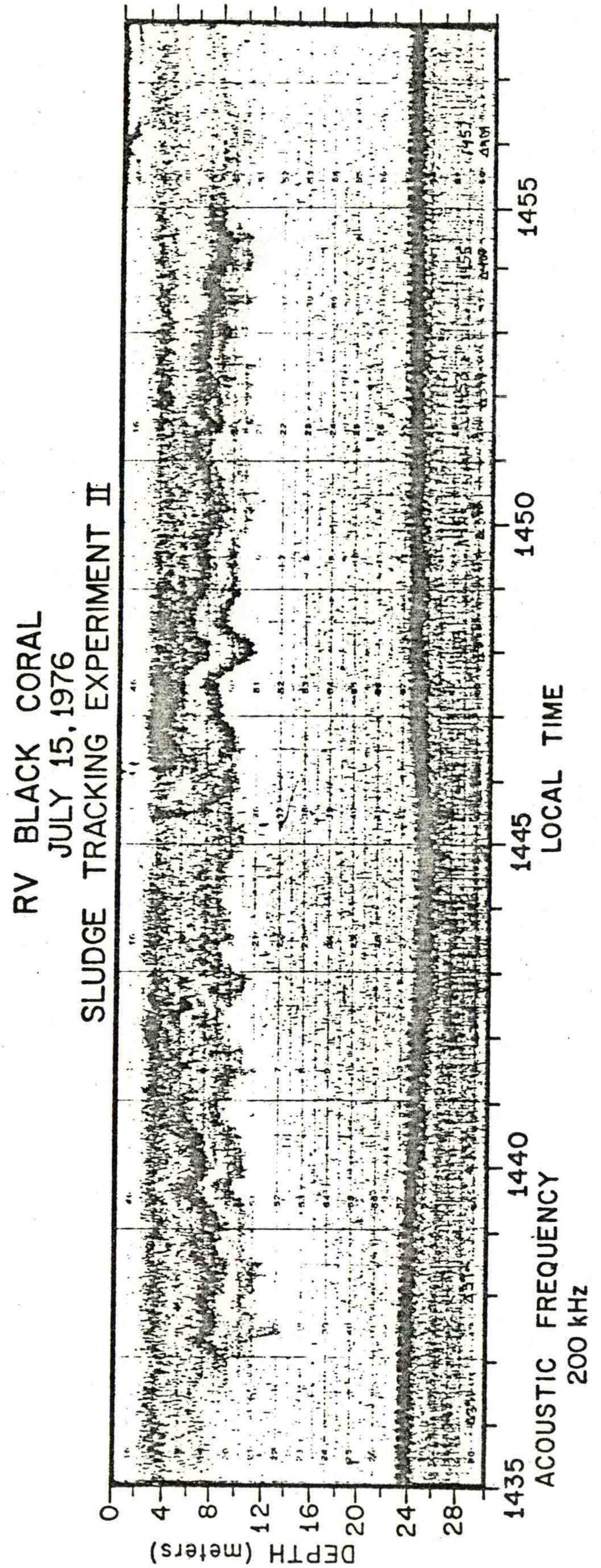
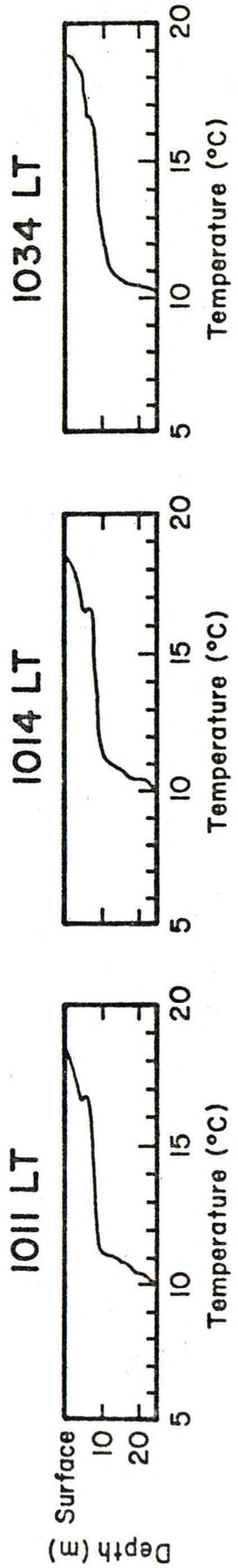
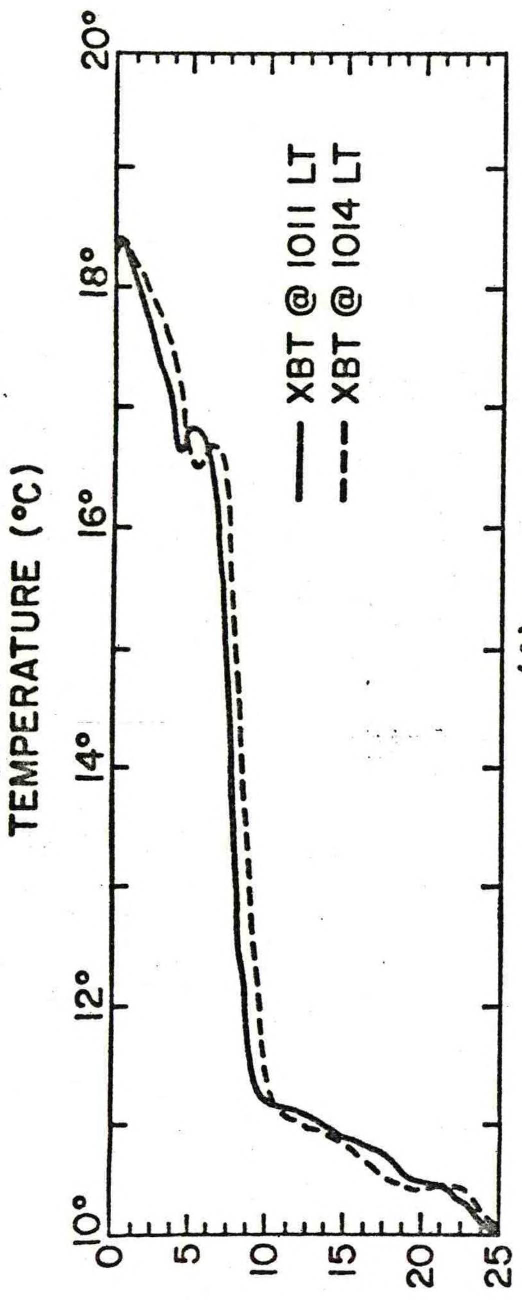

R/V BLACK CORAL
JULY 15,1976
SLUDGE TRACKING EXPERMENT II
DEPTH (meters)
0
4
8
12
16
20
24
28
1135
1140
1145
1150
LOCAL TIME
ACOUSTIC FREQUENCY
200 kHz

FIGURE 5


RV BLACK CORAL
JULY 15, 1976
SLUDGE TRACKING EXPERIMENT II
DEPTH (meters)
0
4
8
12
16
20
24
28
1435
1440
1445
1450
1455
LOCAL TIME
ACOUSTIC FREQUENCY
200 kHz

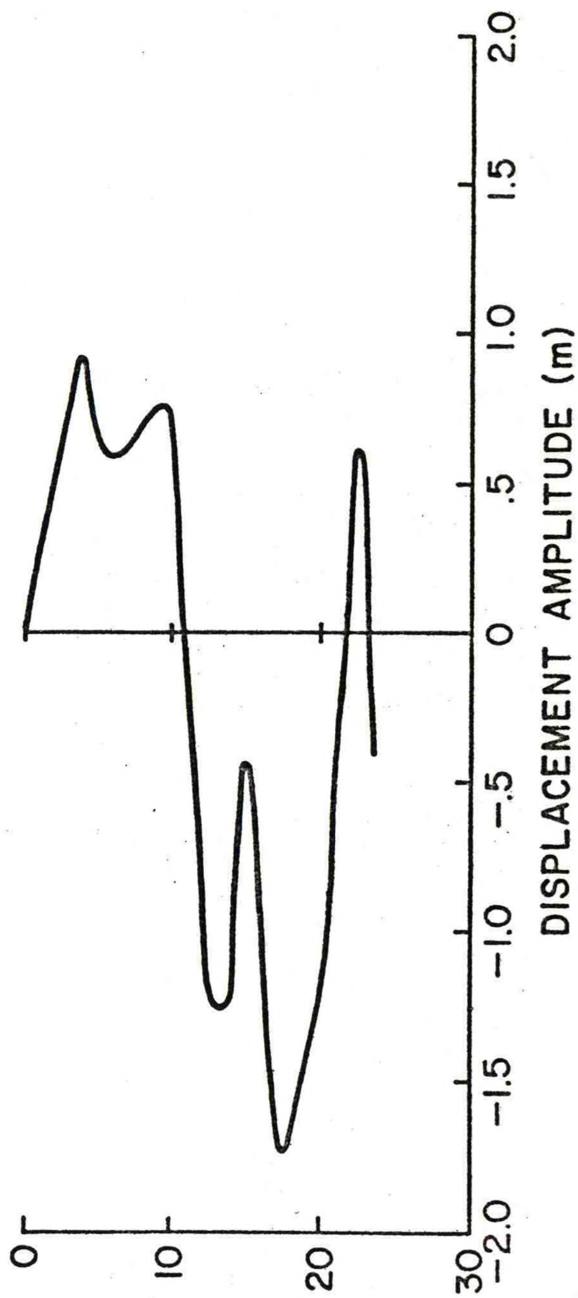


R/V BLACK CORAL
15 JULY 1976
SLUDGE TRACKING EXPERIMENT II



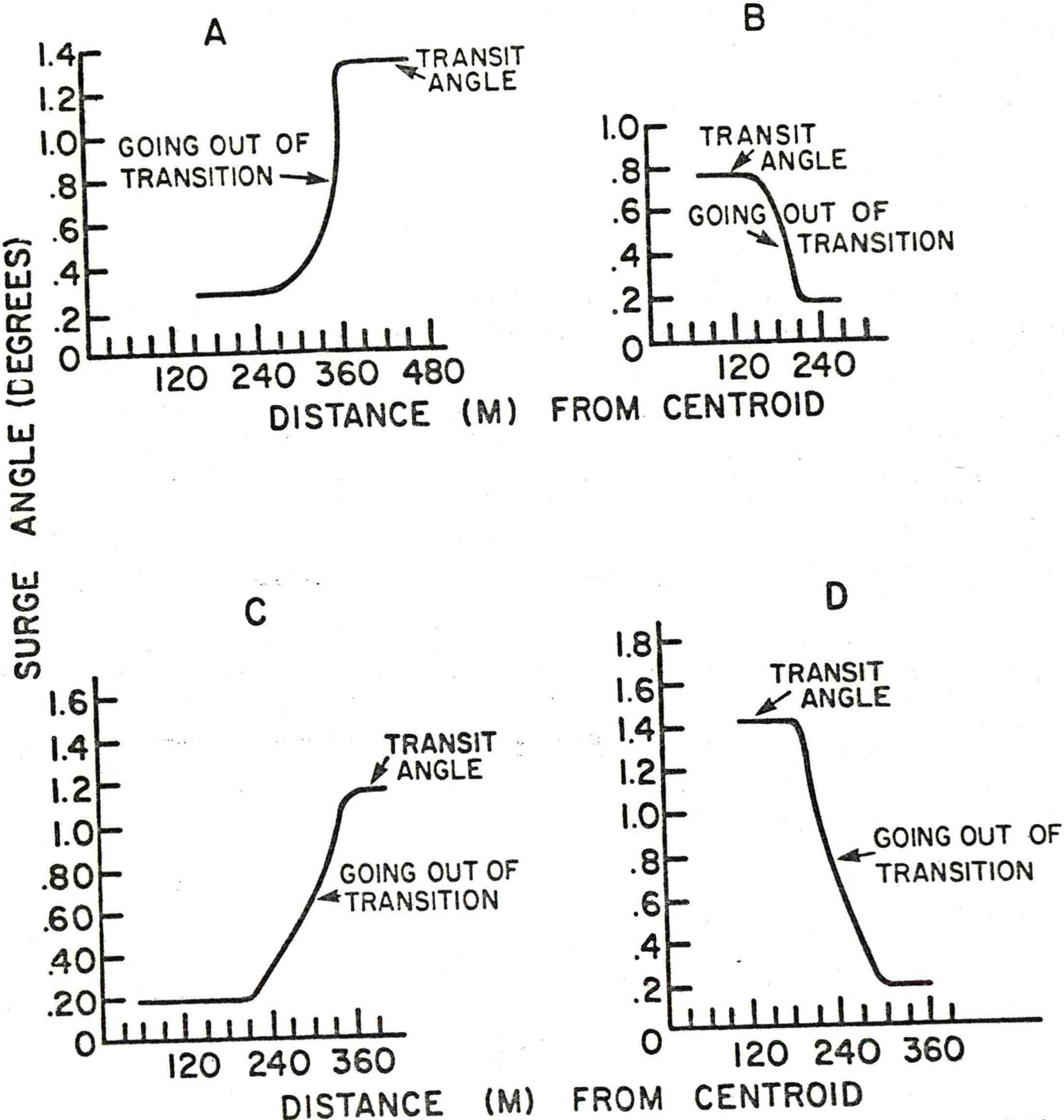
(A)

Expendable Bathythermograph (XBT) Records taken at 1011 and 1014 L.T. on 15 July 1976.

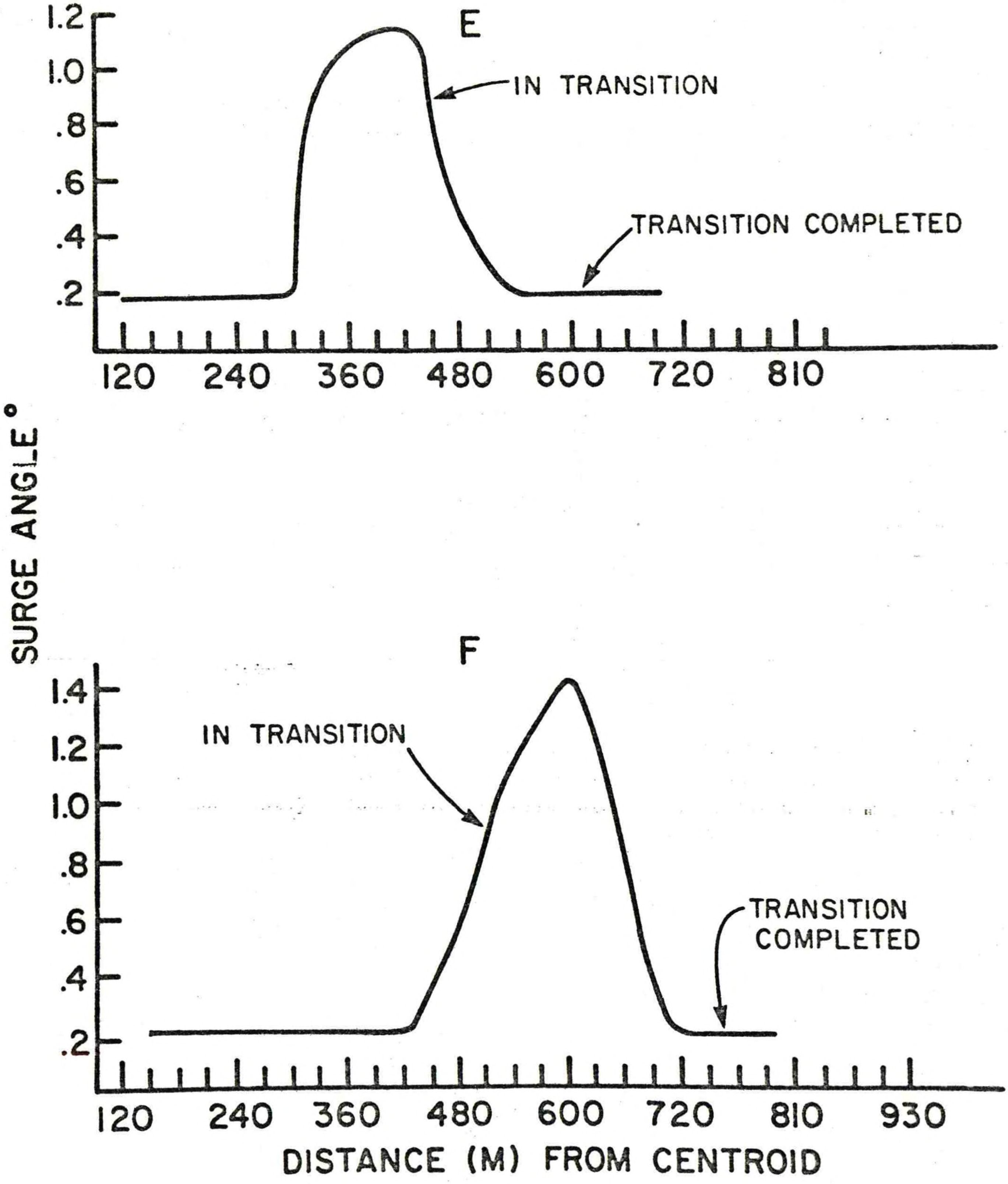


(B)

Displacement Amplitude obtained by taking the difference between the XBT Records in (A).



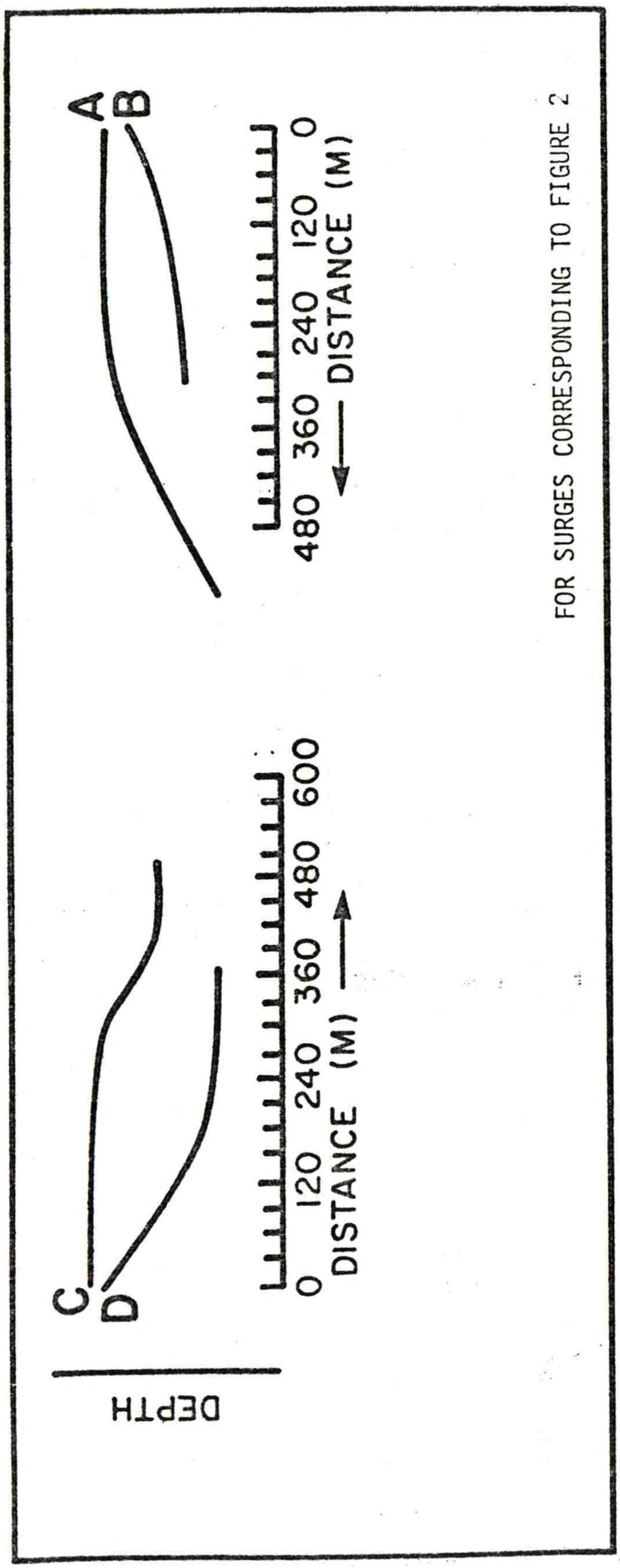
SURGE ANGLE AS A FUNCTION OF RANGE (MORNING DUMP 15 JULY 1976)

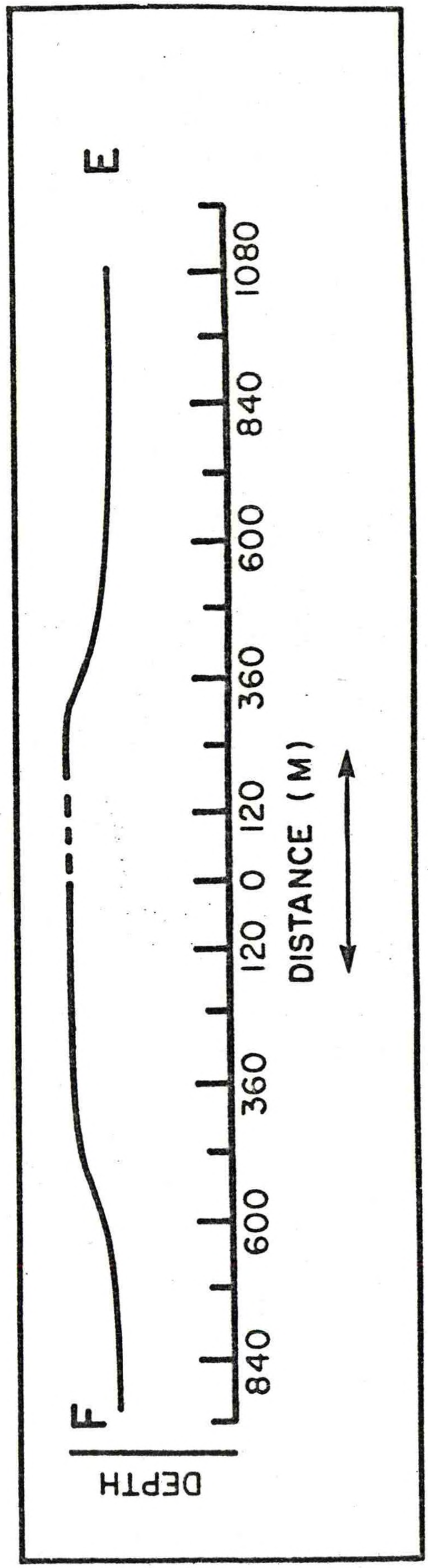


SURGE ANGLE AS A FUNCTION OF RANGE

(AFTERNOON DUMP 15 JULY 1976)

FIGURE 9


A
B
0 120 240 360 480
DISTANCE (M)
FOR SURGES CORRESPONDING TO FIGURE 2
C
D
0 120 240 360 480 600
DISTANCE (M)
DEPTH


E
1080 840 600 360 120 0 120 360 600 840
DISTANCE (M)
F
DEPTH