# SPEED OF SOUND IN UNCONSOLIDATED SEDIMENTS OF BOSTON HARBOR, MASSACHUSETTS

by

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B.Sc., University of California (Berkeley)
(1965)

SUBMITTED IN PARTIAL FULFILLMENT

OF THE REQUIREMENTS FOR THE

DEGREE OF MASTER OF

SCIENCE

at the

MASSACHUSETTS INSTITUTE OF TECHNOLOGY

September, 1966

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Department of Geology and Geophysics, September 20, 1966

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Submitted to the Department of Geology and Geophysics on September 16, 1966 in partial fulfillment of the requirements for the degree of Master of Science.

## ABSTRACT

In situ measurements of the speed of sound in surfical marine sediments of Boston Harbor have been made at approximately 100 stations. A simple spark discharged of charged capacitors created the sound pulse which was received by a conventional hydrophone-amplifier-oscilloscope system. Photographs were taken of the trigger pulse as displayed on the oscilloscope screen. Detailed time records were obtained using a delay time base. First arrivals transmitted by the hydrophone appeared in the frequency range of 10 to 30 kilocycles/second while the sound source likely emitted a broad spectrum of frequencies.

Sediment samples at all stations have been obtained either by gravity coring (aided by hammar blows) or bucket grabs. Laboratory analyses of grain size distribution and water content have been made. Porosity was calculated assuming complete water saturation. The author attempted to correlate these various physical properties with in situ sound speed measurements and has compared his work to studies of similar sediments by other investigators. The presence of methane and hydrogen disulfide gases in the sediment limited the degree of simple correlation between sound transmission and other physical properties.

Thesis Supervisor: Dr. Harold E. Edgerton
Title: Professor of Electrical Engineering and
Institute Professor

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LIST OF FIGURES AND TABLES

# LIST OF SYMBOLS

| SYMBOL | DEFINITION | UNITS |
|---|---|---|
| a | Sound Signal Amplitude Ratio | ---- |
| B | Water Content | % |
| C | Compressibility | $[dynes/cm^2/cm^3]^{-1}$ |
| D | Grain Diameter | millimeters |
| d | Density | $gm/cm^3$ |
| G.M.S. | Graphic Mean Size | millimeters |
| k | Incompressibility | $[dynes/cm^2/cm^3]$ |
| l | Liquid Property(subscript) | ---- |
| m | Hydrometer Temperature Correction | ---- |
| N | Percentage of Sample Finer than 'D' | % |
| n | Porosity | % |
| R | Sound Speed Ratio | ---- |
| $R_h$ | Corrected Hydrometer Reading | ---- |
| s | Solids Property (subscript) | ---- |
| s.d. | Standard Deviation | ---- |
| t | Temperature | °C or °F |
| u | Rigidity | $dynes/cm^2$ |
| V | Sound Speed | km/sec/or ft/sec |
| W | Mass | grams |

## ACKNOWLEDGEMENTS

The author wishes to express his gratitude to Dr. Harold E. Edgerton for the advice and criticism which guided this thesis topic from beginning to end. Appreciation is offered to V. McRoberts for his suggestions on electronics and to Miss J. Mooney for her help in administrative affairs. Much of this work was accomplished with the instruments and facilities of the Stroboscopic Laboratory at M.I.T. and the patience of the personnel there is herein acknowledged.

Field work was accomplished in close co-operation with the Boston Harbor Group under the direction of Dr. Ely Mencher and supervision of R. Copeland and H. Payson Jr. The use of the Sedimentary Petrology Laboratory as well as the sharing of the use of the R/V R.R. Shrock is greatly appreciated.

Financial support was derived from U.S.Navy contract NONR 1841(71) administered by Dr. Frank Press and National Science Foundation Grant GP 2628 administered by Dr. Ely Mencher. Calibrated hydrophones were loaned by the U.S.Navy Underwater Sound Reference Laboratory, Orlando, Florida.

Finally, the author thanks his wife for her help in manuscript preparation and her patience throughout the project.

## I. Introduction

### A. Object of Research

This research was undertaken in an attempt by the author to relate the speed of propogation of acoustic energy through naturally occurring marine sediments to other physical properties of the sediment. Laboratory measurements of sound speed on core samples have yielded results in close agreement to in situ sound speed measurements only in those instances where the sediment was maintained in its original gas-free state and when due consideration was given to changes in pressure and temperature of the sample (Hamilton[22], Sykes[48]). In Boston Harbor the presence of an unknown amount of hydrogen disulfide and/or methane was obvious from the odor of samples collected. The temperature of the water and sediment varies a great deal in very shallow regions over a tidal period and daily with weather conditions. Considering the potential inconsistency in relating laboratory to in situ conditions, the author decided to make sound speed measurements in situ and obtain samples of sediment for laboratory analysis of physical properties which would be unaffected by transporting the sample to the laboratory.

Edgerton[13] has shown that penetration of 12 kilocycle/second sound is possible in Boston Harbor sediments only in those areas which are not covered by a black, fine-grained odoriferous mud. The latter acts as an almost perfect reflector of sound energy even when only inches thick. The author investigated this layer as well as the underlying compact clay and sand layers in an attempt to assign 'typical' sound speed values for use in accurately converting records of travel time(from continuous seismic profiles) to geological cross-sections.

From seismic investigations of deep-lying sediments, a refraction technique yields an average sound speed to use in computing depth (Ewing[14], Houtz[25], Shor[42]). This technique does not discriminate between layers of low acoustic contrast and effectively masks the distinction of thickness of these layers.

In the present study a horizontal variability in sound speed amounting to 40% or more is noted in the surfical sediments over the 30 square mile study area of Boston Harbor. Vertical variability in sound speed amounted to 30% in the first few feet at some locations, Assignment of sound speeds averaged over the Harbor would certainly produce significant errors in calculated layer depths locally.

A further application of sound speed measurements is in the field of soil mechanics. Once the speed of the compressional wave, the density and the compressivility of a sediment are determined, it is possible to calculate the other elastic properties including: Poison's Ratio, Shear Modulus, speed of shear wave, Young's Modulus, and Lame's constant (Jaeger [27]). Assumptions and techniques for carrying out these calculations have been given by Hamilton [18] and will not be repeated here.

B. Previous Investigations

Hamilton [22] reported in situ sound speed measurements in 1956 off San Diego. Operating in 90 feet of water, SCUBA divers inserted acoustic probes into the sediment and recording was done with oscilloscopes on a surface ship. Samples were collected and kept 'air-free' until laboratory analyses of density, porosity and grain size were completed. Hamilton noted that sound speed in sediments of high porosity was less than that in sea water and explained this by particle movement in a sound field causing frictional losses due to viscous drag. In situ sound speed measurements were conducted again in 1963 (Hamilton [20]) in 1000 feet of water using the bathyscaphe Trieste. Laboratory analyses of sediment properties were conducted as in the previous study. The general findings of these measurements are listed in Table III, Section V of this paper.

Sound speed measurements were made _in situ_ in a fresh water lake by Jones [28] in 1958. Two hydrophones were buried in the lake bottom to known depths and a known separation. The time delay in sensing a spark discharge in the water (at a known depth) indicated by an oscilloscope record of the hydrophone receptions provided a means of determining sound speed. Divers noted a great amount of organic debris decaying and generating free gas in the sediment. Using this two hydrophone technique, Jones was able to determine that the sound speed through the gas charged bottom was about one tenth the sound speed in the lake water.

Sykes[48] used acoustic probes (modified from Wood and Weston[54])of small radiating area to pulse 350 kilocycle/second sound through various strata in deep sea cores obtained by the Wood's Hole Oceanographic Institution in 1959. Assuming the ratio of sound speed in sediment to sound speed in water remained oonstant for _in situ_ and laboratory conditions, Sykes was able to calculate on the basis of salinity and temperature measurements (Albers[1]) the speed of sound in sea water _in situ_ and thus the speed of sound in sediments _in situ_.. The results thus obtained are listed in Table III, Section V of this paper. The basic difficulty with Sykes' system is in the probe size and inherent frequency limitations. In order to maintain the radiating area small with respect to core diameter and to emit sound whose wavelength was smaller than any particle size, Syke resorted to ultrasonic frequencies. Transmission was possible in highly porous fine clays but signal attenuation and scattering prohibited reception through silts and sands. [note: Figures 8 and 9 of this paper explain the size terms mentioned]. Sykes also determined water content, grain size, porosity and density assuming the cores had not dried appreciably over the year period between collection and analysis.

The use of lower requencies in analyzing small samples in the laboratory for sound speed is possible using a technique developed by Toulis[49] and Shumway[44] in 1956.

The sediment sample is placed in a compliant-walled cylinder and set into resonance by one acoustic probe. The frequency at which this resonznce occurs is measured by another probe and indicated accurately by a counter-amplifier voltmeter system. Over a frequency range of 25 to 35 kilocycles/second, the speed of sound was determined from frequency measurements and resonance mode assumptions. At the same time a sediment sound attenuation factor was determined from the 'Q' of the frequency resonance. An indication of Shumway's results is given in Table III, Section V of this paper. The major criticism of this technique is in that it does not provide for repeated measurements on the same sample. Invariably gas forms on decreasing pressure and increasing temperature as a result of setting the sample into resonance. With the gas present, the attenuation is much too high to repeat the measurement.

Nolle[37] worked with artifically compacted, sorted sands in an attempt to characterize their sound transmission properties. Sound speed was not measured in these experiments but when other factors were analyzed it became apparent that gas was coming out of solution and depositing on the sand grains, creating high attenuation and scattering coefficients at the operating frequencies of 400 to 1000 kilocycles/second. A solution to this difficulty was the continuous boiling of the sample during experimentation to maintain gas-free conditions. From an assumption of no rigidty (u = 0 for highly porous systems) the speed of a compressional wave is given by (Jaeger[27]):

$$V = \sqrt{k/d} = \sqrt{1/dC} \qquad (1)$$

Where V = sound speed, k = imcompressibility, d = density and, C = compressibility. If the system has a slight amount of gas entrainment it becomes highly compressible without a comparative density decrease and the net sound speed is reduced.

Berson[3] and Brandt[7] have shown by rather independent analytical means that a drastic reduction in sound speed occurs for only a small percentage of free gas by volume in a solid-liquid-gas system of components. The sound speed for a 0.2% fraction of gas in the void volume of a solid-liquid system is only 50% of the sound speed in the later. Physical reasoning points out that if gas is present as free bubbles, these bubbles will expand and contract absorbing sound energy and lengthening the time of propogation. In addition, the bubbles scatter and otherwise attenuate the signal.

Assuming the possiblilty of an ideal mixture of one solid (s) and one liquid (l) component, Officer[38] has derived an equation expressing the sound speed (V) in terms of porosity (n), density (d) and compressibility (c):

$$V^2 = \frac{1}{[n\,d_l + (1-n)d_s]\,[\,n\,C_l + (1-n)C_s]} \qquad (2)$$

For n = unity, that is all liquid, the sound speed reduces to that of the liquid (see one-component relation, equation 1)

$$V^2 = \frac{1}{d_l C_l} = V_l^2 \qquad (3)$$

For n = 0, that is all solid grains, the sound speed reduces to that of the solid (see one-component relation, equation 1)

$$V^2 = \frac{1}{d_s C_s} = V_s^2 \qquad (4)$$

As the porosity decreases slightly from unity, considering densities and compressibilities relatively unchanging, the denominator in (2) remains such that the sound speed decreases since the 'n' terms predominate and liquid compressibility is much greater than that of solids while liquid density is less than that of solid. Further decrease of porosity causes the '(1-n)' terms to become dominant and since $V_s$ is always greater than $V_l$, there occurs a minimum where the sound speed of the mixture is less than that in the liquid alone. This concept is further discussed in Section V of this paper in relation to the experiments of Nafe and Drake[36].

## II SCOPE OF PROJECT

This research was undertaken in co-operation with the Boston Harbor Group here at M.I.T. under the direction of Dr. Ely Mencher. The objective of this group was to sample the surfical sediments over most of Boston Harbor and using conventional laboratory techniques to work out the recent geological history of this area. The author originally intended to occupy a small number of stations with the Harbor Group and to develop a sound speed measurement technique. It soon became apparent that numerous stations would have to be occupied in order to find sites where similar sediments could be compared and to note significant trends in the results of the sediment analyses. The author therefore chose to work with the Harbor Group through the summer of 1966 to collect data at each of 100 stations as shown in Figure 1. The stations are on an arbitrary grid network and apparent gaps in the grid indicate sites where shallow water and/or a rocky bottom prohibited sound speed measurements.

The surficial geology of the Boston Harbor has been reviewed briefly by Phipps[40]. One or more glacial till layers occuring as drumlins or drifts are evidence of the last Pleistocene glaciation. The glacial till is an unsorted mixture of sands and gravels with fine clay-size rock flour, and some clay minerals. It is postulated that at the waning of the ice, the land rose and was eroded slightly and then sank to leave depressions in which fresh and salt water peats and black silty fossiliferous sediments were deposited. A high rate of discharge of organic wastes by man has helped to create the surfical, black, odoriferous, soft mud layer that covers most of the undredged area of the Harbor.

Probably the best sorted and most homogeneous deposit is the very stiff Boston Blue Clay (Lambe[31]) that occurs as thick as 100 feet under a layer of black mud or a layer of sand and gravel over most of the Harbor. Where the covering has been dredged, the clay acts as an acoustic absorber but where the black, gaseous mud is as thin as a few inches, the

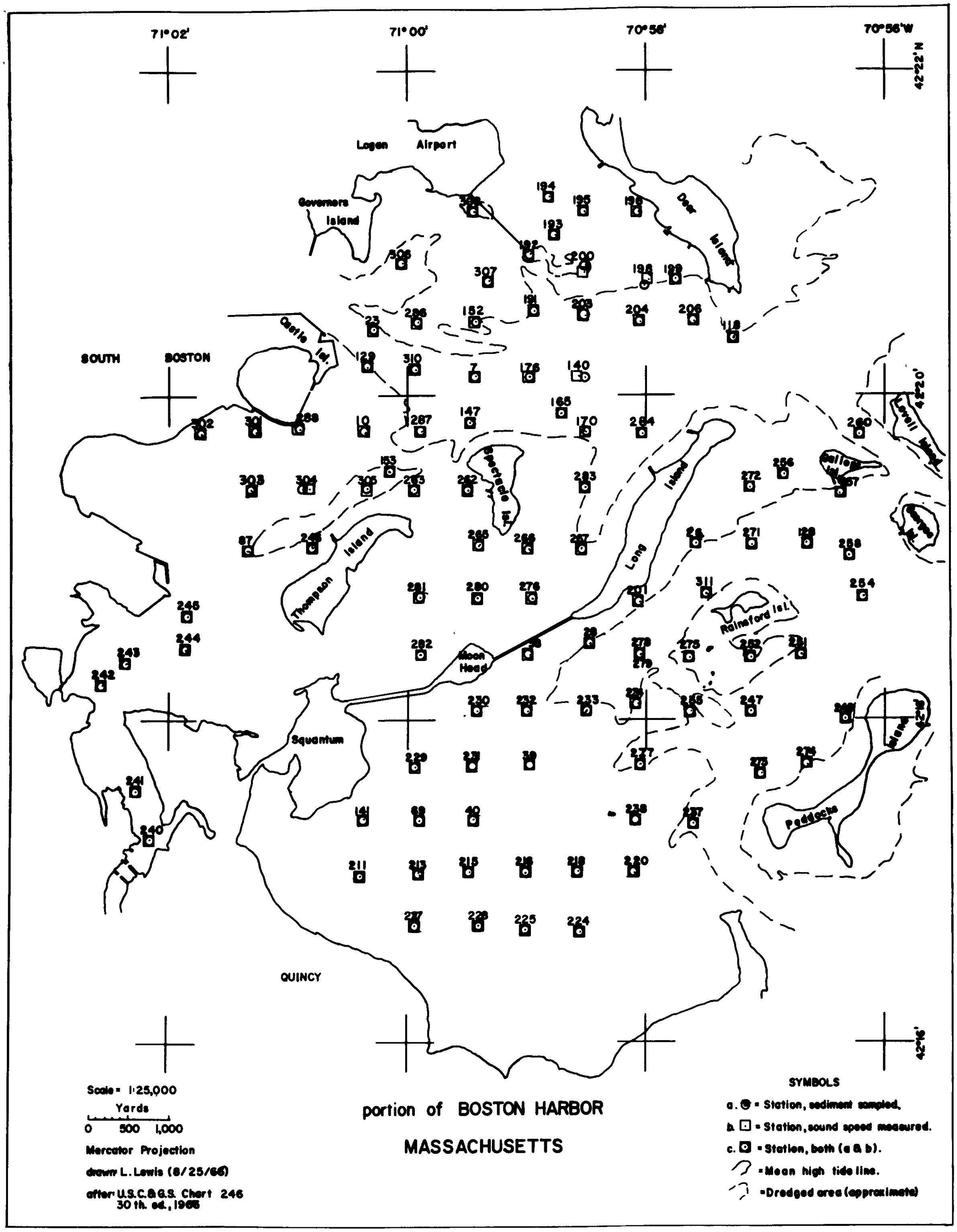



FIGURE 1. SOUND SPEED AND SAMPLE STATIONS

bottom is a nearly perfect reflector of sound energy. These two lithologies--the black mud and the Boston Blue Clay--in addition to an occasional sandy bottom in dredged areas were the materials most often encountered in surface sampling and sound speed measurements in this region.

## III. FIELD PROCEDURES

### A. Site Location

Most of the samples and all of the sound speed measurements were taken from the M.I.T. Research Vessel R.R.Shrock (Figure 2). With reference to an arbitrary grid network plotted on the United States Coast and Geodetic Survey Chart 246, the vessel was anchored at a proposed station and a position was established using sextant fixes on three visible landmarks and resection plotting using a three-arm protractor. The estimated accuracy of location by this technique is 25 yards and is fixed by the one minute reading precision of the sextant (H.Huges and Sons Ltd.1#12997) and scale of the chart. Several stations occurred adjacent channel bouys which facilitated location.

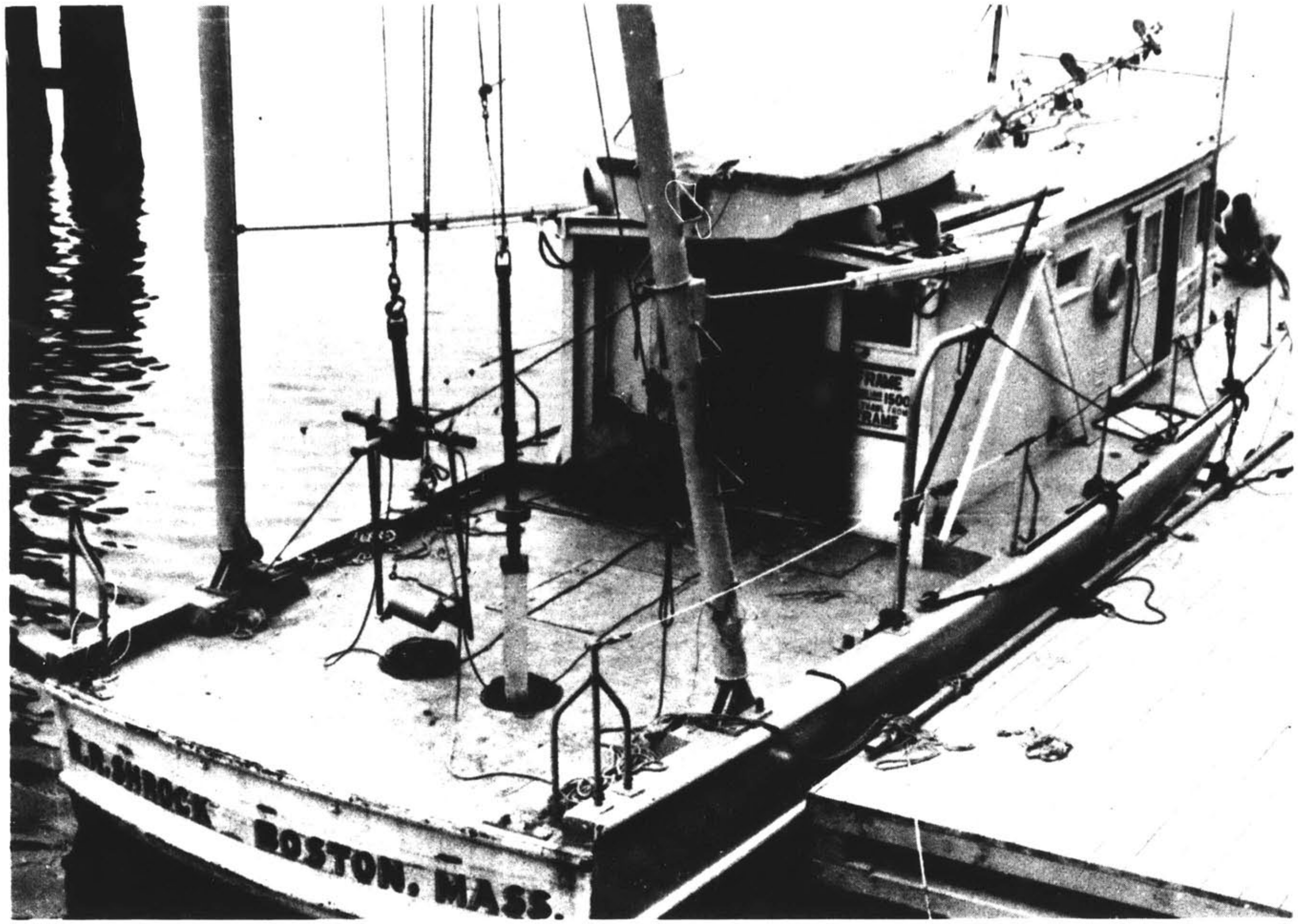
### B. Sound Speed Measurements

Equipment used on the vessel is shown in figure 3. The sonic probe and sampling instruments were suspended from the ship's A-frame as shown in Figure 2. Having anchored and obtained a position, a grab sample using the Van Veen ('g',Figure 3)or a core using the square corer ('a',Figure 3) was obtained to determine the coarseness of the bottom and to obtain a sediment sample. If a sample was taken, the sonic probe was lowered aft and sound speed measurements were made.

The sonic probe (f, Figure 3) was constructed of $2\frac{1}{2}$" diameter cast iron pipe with 1" probes of C.I.P.. threaded into 'T' couplings spaced approximately two feet apart on the 2 1/2" c.i.p. cross member. The supporting members were weighted with approximately 120 pounds of lead'doughnuts' providing a total weight of 190 pounds and a bearing pressure of approximately 110 pounds/inch$^2$ at the end of each probe (in air). This weight and configuration was found to be sufficiently stable to maintain the probes in a vertical position in the bottom except when the tidal current was at

FIGURE 2 RESEARCH VESSEL

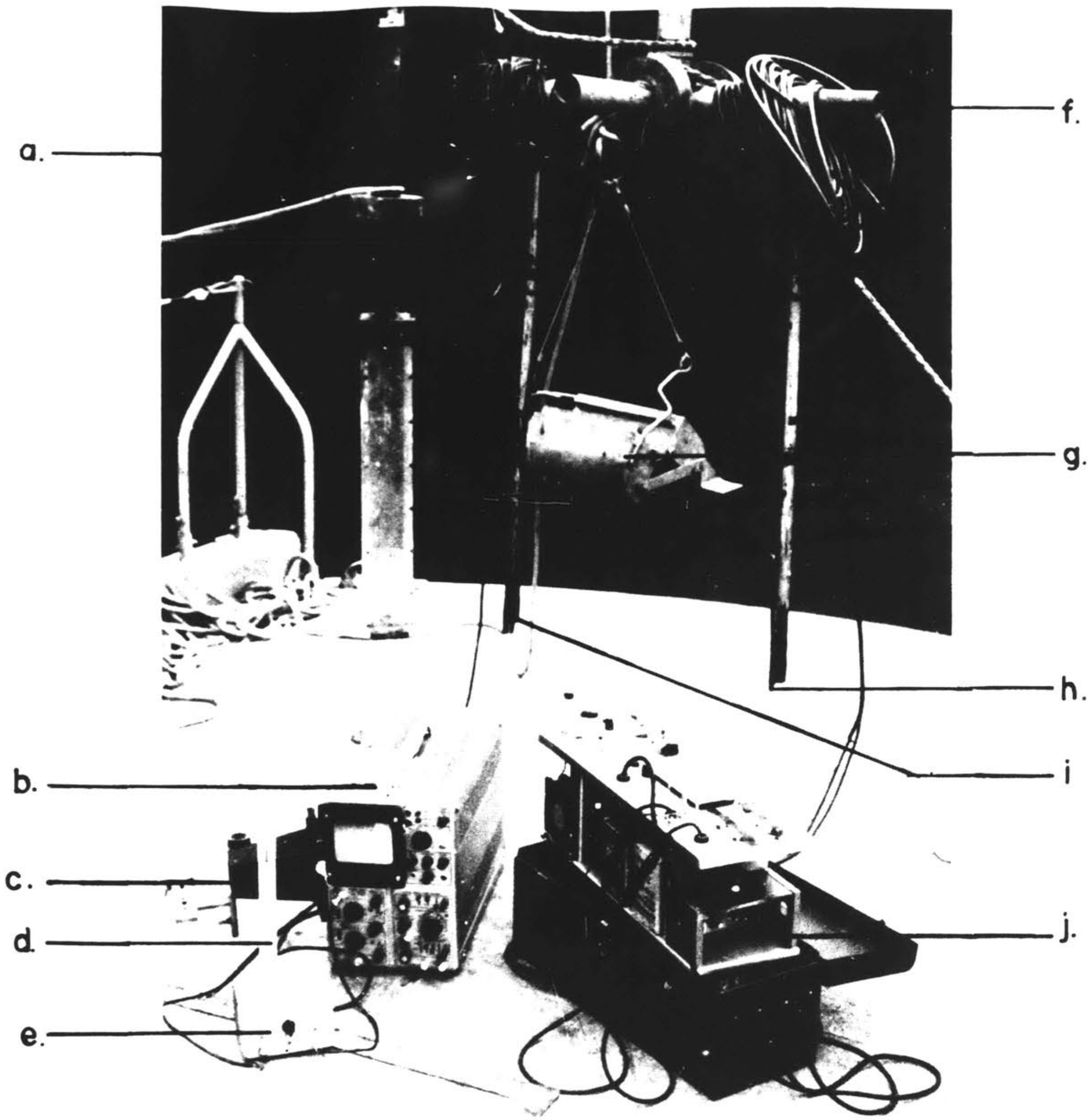
FIGURE 3 FIELD EQUIPMENT




R/V R.R. SHROCK

**August 23, 1966**

FIGURE 2




# EQUIPMENT

a. square corer
b. oscilloscope
c. camera mount
d. 12" scale
e. amplifier

f. sonic probe
g. Van Veen sampler
h. spark cable
i. hydrophone
j spark source

FIGURE 3

a maximum and/or the surface wind caused the vessel to swing rapidly and tighten the cable pulling the probes out of the sediment. A heavier probe arrangement and better anchoring technique would solve these problems.

Fixed to the end of one probe was a two-conductor, shielded, No. 14 copper wire cable ('h', Figure 3). Approximately 100 feet of this cable led back to the ship and was connected to the spark source ('j' Figure 3). The latter is a high voltage capacative discharge device designed by V. McRoberts, Stroboscopic Laboratory, M.I.T. It was operated at an electrical energy output of about 80 watt-seconds (3200 volts across 4 microfarads) which, when triggered once per second, provided 80 watts of acoustic power at the short circuit discharge in sea water across the two #14 wire leads ('h', Figure 3)

At the end of the other probe ('i', Figure 3 and LC32) a hydrophone (Atlantic Research Corporation, Serial #152) was fitted into a groove cut into the 1" c.i.p. The hydrophone is a piezoelectric device (Hueter[26]) constructed of coaxially mounted lead zirconate-lead titanate cylinders in a neoprene rubber sheath with an overall length of 4.3" and diameter of 0.75". When caused to contract and expand by the acoutic pressure wave from the shock associated with the spark discharge, the cylinders set up a potential difference across face-mounted electrodes. The voltage was transmitted back up to the surface by a two-conductor, low-impedance cable and to the vertical input of an oscilloscope. Accordinto to its specifications (UNSUSRL[50])the hydrophone has an omnidirectional sensitivity in the X-Y plane if held such that its long axis is in the Z direction. Since its free field voltage sensitivity (over the frequency range 10-100 kilocycles/second) is-106 decibels relative to 1 volt/microbar and the voltage received at the oscilloscope was approximately 0.8 volts (a maximum), the acoustic wave transmitted over two feet of sea water had a pressure effect at the hydrophone of about 1.75 pounds/inch$^2$ (approximately 0.12 bars).

When sound was transmitted through particularly 'lossy' sediment, the signal from the hydrophone was sent through a 10X or 100X voltage amplifier (Hewlett Packard Model 466A). The amplifier('e', Figure 3) could be used only in those instances where the received voltage was 50 millivolts or less since signal clipping occured for higher voltages.

The received signal was further amplified and displayed by the oscilloscope(Tektronix Model 564, #003378; Dual Trace Amplifier #006623; 3A3 Delayed Time Base #002295 as shown 'b', Figure 3). The received signal, together with the trigger signal from the spark source were displayed in the 0.1 millisecond 'normal' time mode and then the received signal only was displayed in the 10 microsecond 'delayed'time mode. In both cases a photographic record was obtained on 35 mm film using the camera mount(author's design; 'c', Figure 3)and a single-lens reflex camera with close focus rings (Nikkorex Model F,#399935; Nikkor Model H 50 mm f1.2 lens; not shown in Figure 3).

The technique used in making the sound speed measurement will be reviewed briefly with reference to the data recorded at Station 283 and shown in Figures 4 through 6. The probe was lowered slowly through the water column with the ship's hydraulic winch. The spark was discharged once per second and a record was made of the sound transmission in sea water (Figure 4), having noted the voltage, time and time delay settings on the oscilloscope and the original spark-hydrophone separation at the probes. The probe was lowered until the winch cable slacked and a measurement was made in the sediment (Figure 5) noting voltage and time. After being raised again to the surface, note was made of the penetration from the sediment marks on the probes, the probe spacing was checked and the probe was lowered again to obtain a measurement nearer the depth from which the sample was taken (Figure 6). Comparison of strata was also possible since the probes were open-ended pipes and collected cores from their point of deepest penetration. Finally the probes were raised, hosed, the spacing was checked again and the equipment was secured for the move to the next station.

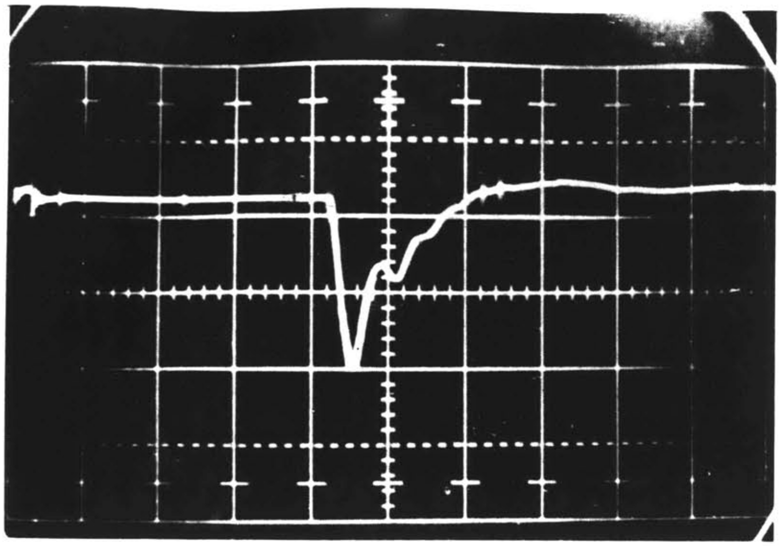
In the example shown in Figures 4 through 6, the deeper measurement (48") showed the speed of sound transmission to be 9% greater than that in water, while the shallower measurement (20") showed the speed to be actually 3% less than that in water. A moderate amount of hydrogen disulfide gas was noted in the core sample from the surface layer but none was noted at depth.

Table I with explanation summarizes the data and resulting sound speeds calculated for the various stations occupied. An estimate of the maximum signal voltage in both sediment and water was recorded but this is only an estimate since the power output of the spark source varied by as much as 10% between discharges.

C. Sediment Sampling

The sediment sample was obtained with either the Van Veen grab sampler ('g', Figure 3) or square corer ('a', Figure 3). As the Van Veen struck the bottom the trip bar released and the jaws closed to a depth of about six inches. The instrument was simple to operate and gave a quick indication of the coarseness of the sediment surface. The square corer, designed by H. Payson, Department of Geology and Geophysics, M.I.T., was used where samples of both the surface and immediately underlying sediment were desired. This device was lowered over the stern, held vertically at the sediment surface and pounded into the bottom with a 30 pound lead 'doughnut' drop weight.

Samples from either instrument were examined and placed in glass jars, capped, and labeled. Note was made on a core log of the estimated gas content(strength of odor), the coarseness of grain, method of sampling, location of station and other pertinent information. The sample was then taken to the laboratory for further analysis.

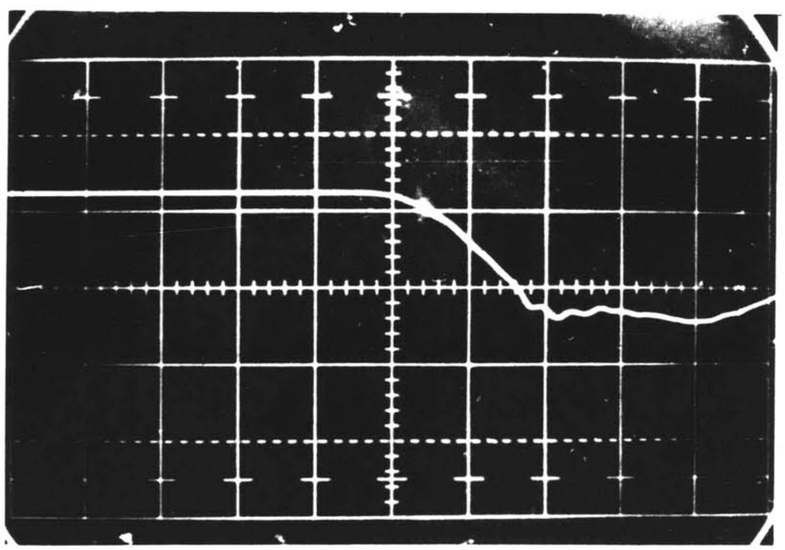


(a)

0.2 volts

0.1 milliseconds

0 time delay



(b)

0.2 volts

10 microseconds

0.375 milliseconds delay

FIGURE 4

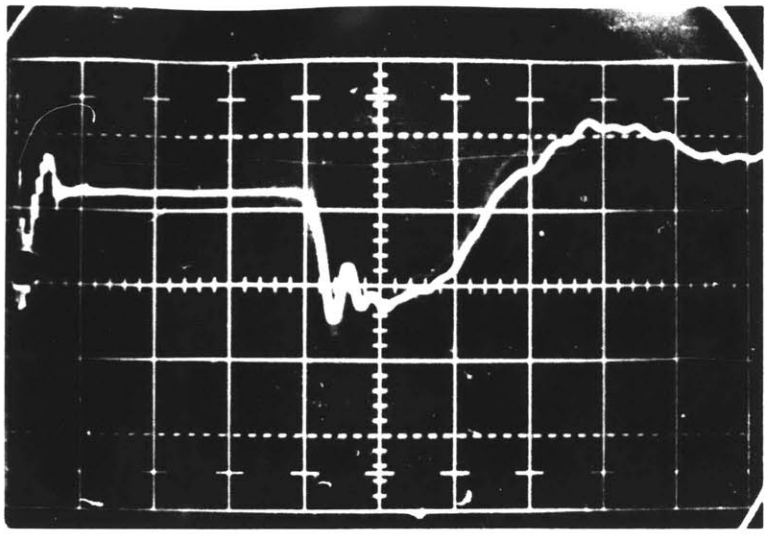
Station 283: Water Path Oscillographs

Initial arrival time = 0.423 milliseconds

Probe spacing = 2.00 feet

Sound speed = 4,730 feet/second

Maximum signal voltage = 0.44 volts

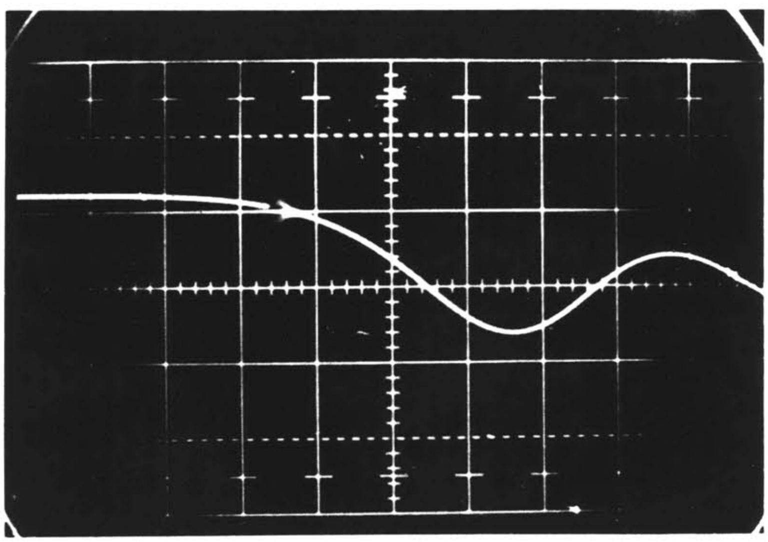


(a)

0.05 volts

0.1 millseconds

0 time delay



(b)

0.05 volts

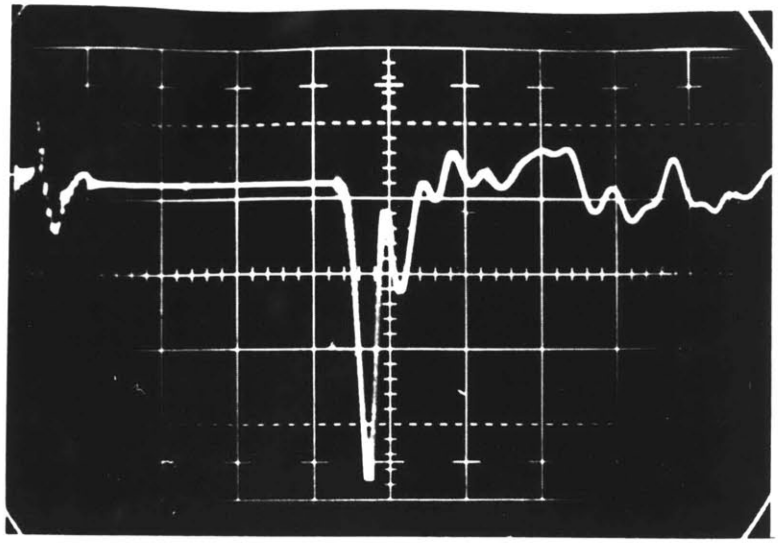
10 microseconds

0.375 milliseconds delay

FIGURE 5

Station 283 = Sediment Path (48" deep) Oscillographs

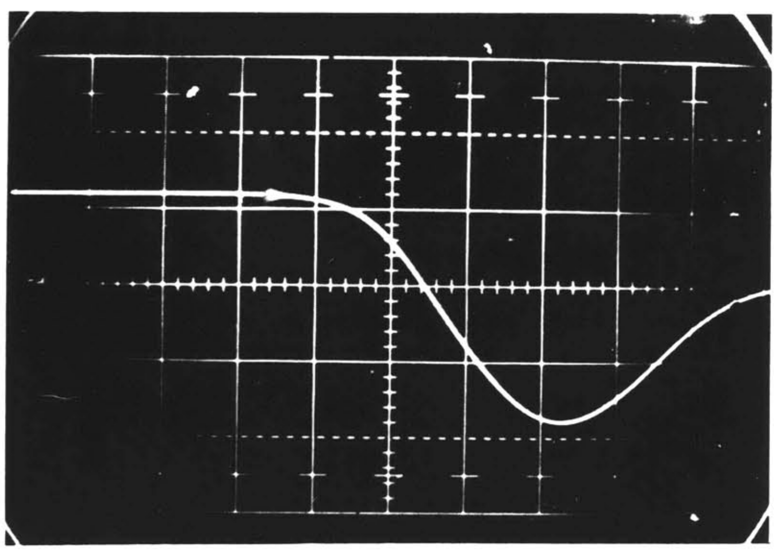
| | |
|---|---|
| Initial arrival time= | 0.395 milliseconds |
| Probe spacing= | 2.00 feet |
| Sound speed = | 5,060 feet/second |
| Maximum signal voltage= | 0.09 volts |



(a)

0.05 volts
0.1 milliseconds

0 time delay



(b)

0.05 volts
10 microseconds

0.400 milliseconds delay

FIGURE 6

Station 283: Sediment Path (20" deep) Oscillographs

| | |
|---|---|
| Initial arrival time | = 0.434 milliseconds |
| Probe spacing | = 2.00 feet |
| Sound speed | = 4,610 feet / second |
| Maximum signal voltage | = 0.20 volts |

## TABLE I: SOUND SPEED DATA AND RESULTS

| Symbol | Explanation |
|---|---|
| No. | Station number as snown on Figure 1. 'b' indicates stations are at same location. Station 26: changed to Station 202. Station 140: changed to Station 205. |
| Location | Approximate co-ordinates as shown on Figure 1. |
| Date | Date of sound speed measurement. Not necessarily same date as sample collected. |
| Depth | Penetration in inches of sound speed probes. 'a' indicates no change in sound speed over depth. |
| $V_s$ | Sound speed in feet/second through the sediment at the Station and Depth shown. May be more than one sediment sound speed at a given station. |
| $V_1$ | Sound speed in feet/second through the sea water at the Station. |
| R | The ratio: $V_s/V_1$ at a Depth at a Station. |
| a | The approximate ratio of signal amplitude in sediment to that in water at a Depth and Station |
| Gas Content | Subjective decision on intensity of odor of hydrogen disulfide. A few stations had a weak methane odor. |
| Comment | Estimate of the coarseness and or consistency of the sediment adhering to the probes. |

TABLE I: Sound Speed Data Results

| No. | Location Long. ° | ' | Lat. ° | ' | Date | Depth (inches) | $V_s$ (ft/sec) | $V_1$ (ft/sec) | R | a | Gas Content | Comments |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 7 | 71 | 00 | 42 | 20 | 8/03/66 | 12 | 4650 | 4760 | 0.98 | 0.43 | absent | crse. sand, blu clay |
| 10 | 71 | 00 | 42 | 20 | 8/09/66 | 18 | 4990 | 4830 | 1.03 | 0.40 | weak ($CH_4$?) | silty mud |
| | | | | | | 10 | 4550 | | 0.91 | 0.02 | strong | soft, shelly mud |
| 23 | 71 | 00 | 42 | 20 | 7/01/66 | 43 | 4780 | 4990 | 0.96 | 0.08 | strong | black mud |
| | | | | | | 7 | 4510 | | 0.94 | 0.66 | strong | black mud |
| | | | | | 8/22/66 | 20 | 6000 | 4810 | 1.24 | 0.16 | absent | black mud |
| 28 | 70 | 58 | 42 | 18 | 7/04/66 | 8 | 5940 | 4930 | 1.20 | 0.88 | absent | black mud |
| | | | | | | 7 | 4560 | | 0.95 | 0.05 | strong | black mud |
| | | | | | 8/22/66 | 25[a] | 4600 | 4800 | 0.95 | 0.006 | strong | black mud |
| 38 | 70 | 59 | 42 | 18 | 7/04/66 | 31[a] | 4500 | 4890 | 0.92 | 0.002 | strong | grey-black mud |
| 39 | 70 | 59 | 42 | 17 | 7/30/66 | 40[a] | 4710 | 4850 | 0.98 | 0.66 | moderate | silty blk mud |
| 40 | 71 | 00 | 42 | 17 | 7/29/66 | 40[a] | 4590 | 4860 | 0.94 | - | strong | mussel bed |
| 69 | 71 | 00 | 42 | 17 | 7/29/66 | 10 | 4700 | 4810 | 0.97 | 0.03 | moderate | black mud |
| | | | | | 8/06/66 | 27 | 4780 | 4760 | 1.00 | 0.61 | weak | black mud |
| 87 | 71 | 01 | 42 | 17 | 8/12/66 | 48 | 4980 | 4800 | 1.03 | 0.33 | weak | clayey mud |
| 118 | 70 | 57 | 42 | 20 | 7/01/66 | 10 | 6060 | 4910 | 1.23 | - | absent | sand |
| 128 | 70 | 56 | 42 | 19 | 7/04/66 | 10 | 5950 | 5050 | 1.18 | 0.35 | absent | fine silt |
| 129 | 71 | 00 | 42 | 20 | 7/01/66 | 8 | 6600 | 4980 | 1.32 | 0.08 | absent | black mud |
| 141 | 71 | 00 | 42 | 17 | 7/29/66 | 40 | 4670 | 4830 | 0.96 | 0.58 | weak | blk mud, blu clay |
| 147 | 71 | 00 | 42 | 20 | 7/01/66 | 8 | 6260 | 4990 | 1.26 | 0.25 | absent | coarse sand |
| 152 | 71 | 00 | 42 | 20 | 8/17/66 | 20 | 4640 | 4820 | 0.97 | 0.50 | strong | blk mud, blu clay |
| | | | | | | 15 | 4530 | | 0.94 | 0.05 | moderate | black mud |
| 153 | 71 | 00 | 42 | 20 | 8/22/66 | 30 | 4510 | 4820 | 0.94 | 0.05 | moderate | black mud |
| 165 | 70 | 59 | 42 | 20 | 8/22/66 | 8 | 5310 | 4780 | 1.11 | 0.50 | absent | sandy gravel |
| 170 | 70 | 58 | 42 | 20 | 7/03/66 | 8 | 5240 | 4960 | 1.05 | 0.90 | absent | peb grn blk sand |

TABLE I: Sound Speed Data and Results (cont.)

| No. | Location Long. ° | ' | Lat. ° | ' | Date | Depth (inches) | $V_s$ (ft/sec) | $V_l$ (ft/sec) | R | a | Gas Content | Comments |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 176 | 70 | 59 | 42 | 20 | 7/01/66 | 12 | 4810 | 5010 | 0.96 | 0.77 | moderate | grn blk sandy mud |
| 191 | 70 | 59 | 42 | 20 | 7/01/66 | 15 | 4210 | 5010 | 0.84 | 0.04 | strong | black mud |
| | | | | | | 18 | 4450 | | 0.93 | 0.70 | moderate | oily clay |
| 192 | 70 | 59 | 42 | 21 | 8/17/66 | 26 | 4770 | 4760 | 1.00 | 0.50 | absent | black mud |
| 193 | 70 | 59 | 42 | 21 | 7/03/66 | 46[a] | 4740 | 4910 | 0.97 | 0.10 | strong | black mud |
| 194 | 70 | 59 | 42 | 21 | 7/03/66 | 31[a] | 5000 | 4960 | 1.00 | 0.40 | weak | black mud |
| 195 | 70 | 59 | 42 | 21 | 8/17/66 | 15 | 4560 | 4820 | 0.95 | 0.70 | strong | black mud |
| 196 | 70 | 58 | 42 | 21 | 7/03/66 | 14 | 4560 | 4910 | 0.94 | 0.60 | weak | stiff black mud |
| 198 | 70 | 58 | 42 | 21 | 8/17/66 | 7 | 4720 | 4830 | 0.97 | 0.66 | weak | clayey stiff mud |
| 199 | 70 | 58 | 42 | 21 | 7/03/66 | 23 | 4610 | 4940 | 0.93 | - | weak | blk mud, blu clay |
| 200 | 70 | 58 | 42 | 21 | 8/17/66 | 10 | 4530 | 4760 | 0.95 | 0.20 | strong | ox. clay on mud |
| 201 | 70 | 58 | 42 | 19 | 7/04/66 | 8 | 5220 | 4920 | 1.06 | 1.00 | absent | lumpy black mud |
| 202 (26) | 50 | 58 | 42 | 19 | 7/04/66 | 8 | 8390 | 4960 | 1.69 | 0.08 | absent | grey clay |
| 203 | 70 | 59 | 42 | 20 | 8/17/66 | 15 | 4760 | 4820 | 0.99 | 0.04 | weak | clayey sand |
| 204 | 70 | 58 | 42 | 20 | 8/19/66 | 8 | 5010 | 4810 | 1.04 | 0.05 | absent | sand |
| 205 (140) | 70 | 58 | 42 | 20 | 8/17/66 | 14 | 4710 | 4800 | 0.98 | 0.80 | weak | silt, blu clay |
| | | | | | | 4 | 4700 | | 0.98 | 0.02 | absent | black mud |
| 206 | 70 | 58 | 42 | 20 | 8/19/66 | 10 | 4950 | 4790 | 1.05 | 1.00 | absent | sand |
| | | | | | | 8 | 4940 | | 0.99 | 0.52 | moderate | black mud |
| 211 | 71 | 00 | 42 | 17 | 6/28/66 | 23 | 4820 | 4990 | 0.97 | 0.02 | moderate | black mud |
| 213 | 71 | 00 | 42 | 17 | 6/28/66 | 34[a] | 4470 | 4990 | 0.89 | 0.24 | strong | coarse silt |

TABLE I: Sound Speed Data and Results (cont.)

| No. | Location Long. ° ' | Lat. ° ' | Date | Depth (inches) | $V_s$ (ft/sec) | $V_1$ (ft/sec) | R | a | Gas Content | Comments |
|---|---|---|---|---|---|---|---|---|---|---|
| 215 | 71 00 | 42 17 | 6/28/66 | 15 | 4930 | 4990 | 0.99 | 0.37 | moderate | grey silty clay |
| 216 | 70 59 | 42 17 | 6/28/66 | 15 | 4820 | 5080 | 0.95 | 0.46 | moderate | blk mud, bluclay |
| 218[b] | | | | 10 | 4920 | | 0.97 | 0.65 | weak | shelly grn blk mud |
| 219 | 70 59 | 42 17 | 6/28/66 | 40 | 4240 | 5060 | 0.83 | 0.54 | strong | black mud |
| 220 | 70 58 | 42 17 | 6/30/66 | 13 | 5320 | 5060 | 1.05 | 0.37 | weak | black mud |
| 224 | 70 58 | 42 17 | 6/30/66 | 27 | 4510 | 5040 | 0.90 | 0.08 | strong | grey blk mud |
| 225 | 70 59 | 42 17 | 6/30/66 | 6 | 5220 | 4990 | 1.04 | 0.36 | weak | black mud |
| 227 | 71 00 | 42 17 | 7/12/66 | 12 | 5780 | 4960 | 1.16 | 0.33 | absent | silty grn mud |
| 228 | 70 59 | 42 17 | 7/12/66 | 35[a] | 4830 | 5000 | 0.96 | 0.73 | weak | grn blk mud |
| 229 | 71 00 | 42 18 | 7/12/66 | 43[a] | 4590 | 5180 | 0.88 | - | strong | grn blk mud |
| 230 | 70 59 | 42 18 | 7/12/66 | 45[a] | 4570 | 5140 | 0.89 | 0.50 | strong | black mud |
| | | | | 10 | 4780 | | 0.93 | 0.16 | weak | black mud |
| 231 | 70 59 | 42 18 | 7/12/66 | 20 | 4480 | 5130 | 0.88 | 0.005 | strong | black mud |
| 232 | 70 59 | 42 18 | 7/12/66 | 43[a] | 5060 | 5160 | 0.98 | 1.00 | moderate | black mud |
| 233 | 70 58 | 42 18 | 7/12/66 | 23[a] | 5170 | 5170 | 1.00 | 0.08 | absent | grey silty mud |
| 234 | 70 58 | 42 18 | 7/12/66 | 32[a] | 5010 | 5240 | 0.96 | 0.21 | moderate | black mud |
| 235 | 70 58 | 42 18 | 7/12/66 | 20[a] | 4960 | 4960 | 1.00 | 0.10 | weak | black mud |
| 237 | 70 58 | 42 17 | 7/13/66 | 10 | 5710 | 4880 | 1.17 | 0.55 | absent | sandy mud |
| 238 | 70 58 | 42 17 | 7/13/66 | 8 | 5010 | 4890 | 1.02 | 1.00 | absent | grn silty sand |
| 240 | 71 02 | 42 17 | 7/13/66 | 25[a] | 4670 | 4920 | 0.95 | 0.02 | weak | shelly mud |
| 241 | 71 02 | 42 18 | 7/13/66 | 8 | 5010 | 4940 | 1.02 | 0.33 | absent | shelly mud |
| 242 | 71 02 | 42 18 | 7/13/66 | 30[a] | 4760 | 4950 | 0.96 | 0.71 | moderate | shelly mud |
| 243 | 71 02 | 42 18 | 7/13/66 | 29[a] | 5530 | 4950 | 1.12 | 0.25 | absent | snelly mud |
| 244 | 71 02 | 42 18 | 7/13/66 | 10 | 5020 | 5010 | 1.00 | 0.02 | moderate | black mud |
| | | | 7/16/66 | 26 | 4460 | 4760 | 0.94 | 0.002 | strong | black mud |
| 245 | 71 02 | 42 18 | 7/13/66 | 10 | 4700 | 4990 | 0.94 | 0.01 | strong | black mud |

TABLE I: Sound Speed Data and Results (cont.)

| No. | Location Long. ° | ' | Lat ° | ' | Date | Depth (inches) | $V_s$ (ft/sec) | $V_1$ (ft/sec) | R | a | Gas Content | Comments |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | 8 | 4810 | | 0.96 | 0.60 | moderate | sandy mud |
| 246 | 71 | 01 | 42 | 19 | 7/13/66 | 23 | 5250 | 5010 | 1.04 | 0.65 | weak | sandy mud |
| | | | | | 7/16/66 | 6 | 5770 | 4860 | 1.19 | 0.82 | absent | sandy mud |
| 247 | 70 | 57 | 42 | 18 | 8/22/66 | 8 | 5100 | 4830 | 1.05 | 0.33 | weak | sandy mud |
| 249 | 70 | 56 | 42 | 18 | 7/16/66 | 8 | 5260 | 4870 | 1.08 | 0.50 | absent | pebbly mud |
| 251 | 70 | 56 | 42 | 18 | 7/16/66 | 8 | 5410 | 4860 | 1.11 | 0.55 | absent | pebbly mud |
| 252 | 7057 | | 42 | 18 | 7/16/66 | 20 | 4260 | 4870 | 0.88 | 0.65 | moderate | black mud |
| 254 | 70 | 56 | 42 | 19 | 8/19/66 | 15 | 5110 | 4780 | 1.07 | 0.75 | absent | black mud |
| 256 | 70 | 57 | 42 | 19 | 8/07/66 | 12 | 5160 | 4760 | 1.08 | 0.50 | absent | pebbly mud |
| 257 | 70 | 56 | 42 | 19 | 8/07/66 | 12 | 4960 | 4760 | 1.04 | 0.30 | absent | pebbly mud |
| 258 | 70 | 56 | 42 | 18 | 7/19/66 | 15 | 5180 | 4780 | 1.08 | 0.20 | absent | pebbly clayey mud |
| 260 | 70 | 56 | 42 | 20 | 8/19/66 | 8 | 5310 | 4810 | 1.10 | 0.05 | absent | coarse sand |
| 262 | 71 | 00 | 42 | 19 | 8/06/66 | 24 | 4820 | 4730 | 1.02 | 0.66 | weak | black mud |
| 263 | 71 | 00 | 42 | 19 | 8/06/66 | 18 | 4300 | 4770 | 0.90 | 0.06 | strong | black mud |
| 265 | 71 | 00 | 42 | 19 | 8/06/66 | 11 | 4690 | 4750 | 0.99 | 0.80 | moderate | black mud |
| 266 | 70 | 59 | 42 | 19 | 8/06/66 | 24 | 5110 | 4810 | 1.06 | 0.56 | absent | black mud |
| | | | | | | 24 | 4710 | | 0.97 | 0.005 | moderate | black mud |
| 267 | 70 | 58 | 42 | 19 | 8/06/66 | 44 | 5550 | 4830 | 1.15 | 0.26 | absent | black mud |
| 271 | 70 | 57 | 42 | 19 | 7/24/66 | 16 | 5170 | 4880 | 1.06 | 0.25 | weak | silty mud |
| 272 | 70 | 57 | 42 | 20 | 7/24/66 | 36[a] | 4490 | 4830 | 0.93 | 0.60 | strong | tan grey silt |
| 273 | 70 | 57 | 42 | 18 | 7/24/66 | 8 | 5550 | 4840 | 1.14 | 0.18 | absent | shelly sand |
| 274 | 70 | 56 | 42 | 18 | 7/24/66 | 7 | 6210 | 4900 | 1.27 | 0.70 | absent | rocks, sand |
| 275 | 70 | 58 | 42 | 20 | 7/24/66 | 8 | 5220 | 4920 | 1.13 | 0.30 | absent | shelly sand |
| 276 | 70 | 59 | 42 | 19 | 7/29/66 | 39[a] | 4520 | 4810 | 0.94 | 0.72 | strong | soft black mud |
| 277 | 70 | 58 | 42 | 18 | 7/30/66 | 20 | 5670 | 4850 | 1.17 | 0.20 | absent | shelly blk mud |
| 278[b] | | | | | | 20 | 5200 | | 1.08 | 0.60 | weak | shelly silt |
| 279 | 70 | 58 | 42 | 18 | 7/30/66 | 10 | 4710 | 4810 | 0.98 | 1.00 | moderate | shelly mud |

TABLE I: Sound Speed Data and Results (cont.)

| No. | Location Long. ° ' | Lat. ° ' | Date | Depth (inches) | $V_s$ (ft/sec) | $V_1$ (ft/sec) | R | a | Gas Content | Comments |
|---|---|---|---|---|---|---|---|---|---|---|
| 280 | 70 59 | 42 19 | 8/03/66 | 20 | 4550 | 4850 | 0.94 | 0.01 | strong | black mud |
| | | | | 20 | 4820 | | 1.01 | 0.30 | moderate | black mud |
| 281 | 71 00 | 42 19 | 8/03/66 | 46 | 4530 | 4770 | 0.95 | 0.25 | moderate | tan black mud |
| | | | | 16 | 4650 | | 0.98 | 1.00 | moderate | black mud |
| 282 | 71 00 | 42 18 | 8/03/66 | 48 | 4310 | 4750 | 0.91 | 0.001 | strong | black mud |
| | | | | 20 | 4610 | | 0.97 | 0.50 | moderate | black mud |
| 283 | 70 58 | 42 19 | 8/03/66 | 48 | 5060 | 4730 | 1.07 | 0.25 | weak | black mud |
| 284 | 70 58 | 42 20 | 8/03/66 | 8 | 5160 | 4750 | 1.08 | 0.50 | absent | pebbly silty mud |
| | | | | 10 | 5150 | | 1.08 | 0.90 | moderate | silty mud |
| 286 | 71 00 | 42 20 | 8/09/66 | 16 | 4990 | 4750 | 1.05 | 0.70 | moderate | silty mud |
| 287 | 71 00 | 42 20 | 8/09/66 | 10 | 5090 | 4780 | 1.07 | 0.08 | absent | shelly blk mud |
| | | | | 10 | 4940 | | 1.03 | 0.32 | weak | silty shelly mud |
| 288 | 71 01 | 42 20 | 8/09/66 | 16 | 4710 | 4800 | 0.98 | 0.51 | weak($CH_4$?) | black mud |
| 301 | 71 01 | 42 20 | 8/12/66 | 48[a] | 4740 | 4830 | 0.98 | 1.00 | absent | black mud |
| 302 | 71 02 | 42 20 | 8/12/66 | 26 | 4530 | 4830 | 0.94 | 0.30 | absent | mud, blu clay |
| 303 | 71 01 | 42 19 | 8/12/66 | 22 | 5100 | 4830 | 1.06 | 0.38 | absent | black tan mud |
| 304 | 71 01 | 42 19 | 8/12/66 | 10 | 4700 | 4810 | 0.97 | 0.90 | weak($CH_4$?) | clayey blk tan mud |
| 305 | 71 00 | 42 19 | 8/12/66 | 10 | 5410 | 4800 | 1.13 | 0.55 | absent | mussels, blk mud |
| | | | | 10 | 4800 | | 1.00 | 1.00 | absent | crse. blk sandy mud |
| 306 | 71 00 | 42 21 | 8/14/66 | 20[a] | 4800 | 4800 | 1.00 | 0.06 | absent | crse. blk sandy mud |
| 307 | 70 59 | 42 21 | 8/14/66 | 10 | 5000 | 4800 | 1.04 | 1.00 | absent | crse. silty mud |
| | | | | 15 | 4640 | | 0.96 | 0.005 | moderate | soft blk mud |
| 308 | 70 59 | 42 21 | 8/14/66 | 30 | 4640 | 4840 | 0.96 | 0.01 | moderate | silty blk mud |
| | | | | 10 | 4460 | | 0.92 | 0.06 | strong | 8" ox. clay over |
| 310 | 71 00 | 42 20 | 8/19/66 | 30 | 4920 | 4820 | 1.02 | 1.00 | absent | very fine mud |
| 311 | 70 58 | 42 19 | 8/19/66 | 14 | 5350 | 4790 | 1.12 | 0.75 | absent | rocks, shells, sand, mud |

## IV LABORATORY PROCEDURES

All samples collected in Boston Harbor were analyzed for water content, grain size distribution, total iron and carbon contents and clay minerology. Of these, water content and grain size analyses only are of relevance to the sound speed measurements. Sediment porosity was calculated from the masses and assumed densities of water and solids. No analysis technique was developed for determining the amount or kind of gases entrained in the sediment.

### A. Water Content

Form 'A', Part 'A' outlines the data collected in determining water content for sample #283. A representative sample of the jar contents was selected, weighed, dried at 10 °C. for 24 hours and weighed again. The water content is determined as the ratio of weight of water to weight of solids (Lambe[31]). Several samples collected prior to Summer, 1966, had to be discarded since they were improperly stored and had obviously undergone considerable drying before they were to be analyzed for water content. This is the reason for the breaks in number sequence as noted in Figure 1 and Tables I and II.

### B. Sieve Analysis

Form 'A', Part 'B' outlines the data collected in sieve analysis of Sample #283. A representative sample of the jar contents was selected and weighed. After weighing, the sample was mixed with distilled water in an electric mixer. This sample was then wet sieved through sieves selected for the size ranges: greater than 0.500 mm; 0.250 to 0.500 mm; 0.125 to 0.250 mm; 0.063 to 0.125 mm. The fraction collected on each sieve was weighed and the result entered in the table of Form 'A'. The fraction that passed through the 0.063 mm sieve was placed in a one liter graduated cylinder for a hydrometer analysis (discussion following). Once the hydrometer analysis was completed, a few milliliters

FORM A

# SAMPLE ANALYSIS SUMMARY

Sample # 283 — Location 70°58'N, 42°19'W

Date August 20, 1966 — Core Depth 0" to 20"

Analysis By B.H.G.

## A. Water Content

a. Weight of crucible — 16.7 g.

b. Weight of crucible + wet sample — 40.0 g.

c. Weight of crucible + dry sample — 27.6 g.

d. Water content = $\frac{(b)-(c)}{(c)-(a)} = \frac{(40.0)-(27.6)}{(27.6)-(16.7)} =$ 77 %

## B. Seive Analysis

e. Weight of dish — 41.6 g.

f. Weight of dish + wet sample — 82.0 g.

g. Weight of wet sample (f-e) — 40.4 g.

h. Weight of dish — 68.1 g.

i. Weight of dish + dry hydrometer column deposit — 82.8 g.

j. Weight of fraction less than 0.063 millimeters diameter (i - h) — 14.7 g.

| Seive Range mm | Dish Weight g | Dish+Sample Weight g | Sample Weight g | Weight % (of total weight) | % Finer |
|---|---|---|---|---|---|
| > 0.500 | 65.2 | 65.5 | 0.3 | 1.6 | 98.4 |
| 0.250 to 0.500 | 63.5 | 63.8 | 0.3 | 1.6 | 96.8 |
| 0.125 to 0.250 | 68.8 | 69.1 | 0.3 | 1.6 | 95.2 |
| 0.063 to 0.125 | 71.0 | 73.6 | 2.6 | 13.7 | 81.5 |
| < 0.063 (from j above) | | | 14.7 | 81.5 | by hydrometer |
| | | Total | 18.2 ($W_s$) | 100.0 | |

## C. Check on Dry Weight ($W_s$)

k. Weight of water = (d) x (g) = (0.53) x (40.4) = 21.5 g.

l Dry weight = (g) - (k) = (40.4) - (21.5) = 18.9 g.

## D. Comments : Hydrometer analysis completed. Water content accurate to ±5% due to nonuniform water distribution

of 6N HCL was added causing the suspension to flocculate and settle rapidly. The cylinder was decanted and the deposit dried and weighed. The latter amount, added to the sieve weighings gave the total dry weight of sediment analyzed ($W_s$).

At this point the 'porosity' was calculated for the unconsolidated sediment. Porosity is defined as the volume ratio of voids to total sample. A density in gm/cm³ of 2.75 for the sediment solids based on data from Lambe[31] was assumed: Boston Blue Clay = 2.79; quartz = 2.65; feldspar = 2.70. The density for sea water was taken as 1.03 (Sverdrup[46]). From these assumptions the porosity (n) is:

$$n = \frac{\text{void volume}}{\text{bulk volume}} = \frac{\dfrac{\text{mass of sea water}}{\text{density of sea water}}}{\dfrac{\text{mass of sea water}}{\text{density of sea water}} + \dfrac{\text{solid mass}}{\text{solid density}}} \quad (5)$$

and for sample #283, refering to From 'A':

$$n = \frac{\dfrac{'g' - W_s}{1.03}}{\dfrac{'g' - W_s}{1.03} + \dfrac{W_s}{2.75}} \; [100]$$

$$= \frac{\dfrac{40.4 - 18.2}{1.03}}{\dfrac{40.4 - 18.2}{1.03} + \dfrac{18.2}{2.75}} \; [100]$$

$$n = 77\%$$

This number should not be compared to the water content since porosity is an estimated volume ratio while water content is determined as a weight ratio.

C. Hydrometer Analysis

Form 'B' outlines the data collected in the hydrometer analysis of sample #283. That portion of the sample which was wet sieved through the 0.063 mm opening sieve was placed in a one liter graduated cylinder with 100 milliliters of sodium oxalate dispersing agent (approximately one part per thousand parts by weight) and distilled water to make one liter of suspension. The hydrometer (Fisher Scientific Instruments #864209) was read at the time intervals shown or until the least reading approached 1.0000 ± 0.0005. Temperature in °C. was read sufficiently often to monitor the temperature to ± 0.5°C. The hydrometer reading ($R_h$) was corrected for miniscus rise (constant for a given hydrometer) and to this was added a correction for temperature ('m'). The percentage ('N') of sample #283 finer than a given grain diameter for an equivalent sphere was found from the relation:

$$N = \left[ \frac{d_s}{d_s - d_l} \right] \left[ \frac{R_h + m}{W_s} \right] (100) \qquad (6)$$

$$= \left[ \frac{2.75}{2.75 - 1.03} \right] \left[ \frac{R_h + m}{18.2} \right] (100)$$

$$N = 8.79 \left[ R_h + m \right] \quad \text{in\%}$$

To determine the diameter 'D' of the equivalent spherical particle for which 'N' is the percentage finer, the nomographic chart, Form 'C' was used. A calibration was run for the hydrometer (Figure 7) as explained on Form 'C' and the resulting hydrometer readings were plotted on the scale "Height in Cm" on Form 'C'. Using the assumed density for solids and the temperature as measured, a point on the scale "B x 10³" was determined (see "Key", Form 'C'). Using the

# FORM B

## MASSACHUSETTS INSTITUTE OF TECHNOLOGY

### SOIL MECHANICS LABORATORY

## HYDROMETER ANALYSIS

SOIL SAMPLE *Black silty mud, moderate smell ($H_2S$ ?)*

LOCATION *Long. 70°58', Lat. 42°19'*

BORING NO. *283* SAMPLE DEPTH *0-20"*

SAMPLE NO. *283*

SPECIFIC GRAVITY, G, *2.75 (assumed)*

SOIL SAMPLE WEIGHT

CONTAINER NO. *283*

WT. CONTAINER + DRY SOIL IN g *82.8*

WT. CONTAINER IN g *68.1*

WT DRY SOIL, $W_s$, IN g *14.7 (<63μ) + 3.5 (>63μ) = 18.2 total*

TEST NO. */*

DATE *8/20/66*

TESTED BY *B.H.G.*

HYDROMETER NO. *864209*

MENISCUS CORRECTION *+0.0004*

$$N\% = \frac{G}{G-1}\frac{V}{W_s}\gamma_c(r-r_w) \times 100 = \_\_\_(R-R_w) \;;\; N' = \%\text{ FINER NO. 200} \times N = \_\_\_ N \text{ (FOR COMBINED ANALYSIS ONLY)}$$

$$= \frac{2.75}{1.75}\frac{(100)(R+m)}{18.2}$$

~~$D = \sqrt{\frac{18\mu}{\gamma_s-\gamma_w}}\sqrt{\frac{Z_r}{t}}$~~ ; D IN mm = ~~$\sqrt{\frac{Z_r \text{ IN cm}}{t \text{ IN min.}}}$~~ *(D from Nomograph)*

| DATE | TIME | ~~ELAPSED TIME IN min~~ *$R_h$* | R = 1000(R-1) *+0.4* | ~~$R_w$ = 1000($r_w$-1)~~ | TEMPERATURE IN °C | ~~R-$R_w$~~ *R+m* | N IN % | ~~$Z_r$ IN cm~~ | ~~$Z_r$ IN cm / t IN min~~ | D IN mm | ~~N'~~ |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 8/20/66 | 15 sec. | 1.0080 | 8.4 | | 25.0 | 9.4 | 78.0 | | | 0.093 | |
| | 30 " | 1.0079 | 8.3 | | " | 9.3 | 77.2 | | | 0.065 | |
| | 1 min. | 1.0076 | 8.0 | | " | 9.0 | 74.7 | | | 0.046 | |
| | 2 " | 1.0072 | 7.6 | | " | 8.6 | 71.5 | | | 0.033 | |
| | 4 " | 1.0063 | 6.7 | | " | 7.7 | 64.0 | | | 0.024 | |
| | 15 " | 1.0038 | 4.2 | | " | 5.2 | 43.2 | | | 0.013 | |
| | 30 " | 1.0030 | 3.4 | | " | 4.4 | 36.5 | | | 0.0092 | |
| | 1 hr | 1.0018 | 2.2 | | " | 3.2 | 26.6 | | | 0.0065 | |
| | 2 " | 1.0010 | 1.4 | | " | 2.4 | 19.9 | | | 0.0047 | |
| | 4 " | 1.0009 | 1.3 | | " | 2.3 | 19.1 | | | 0.0033 | |
| | 8 " | 1.0001 | 0.5 | | " | 1.5 | 12.5 | | | 0.0024 | |
| | 24 " | 1.0000 | 0.4 | | " | 1.4 | 11.6 | | | 0.0014 | |

REMARKS : *m = 1.0 @ T = 25.0 °C*

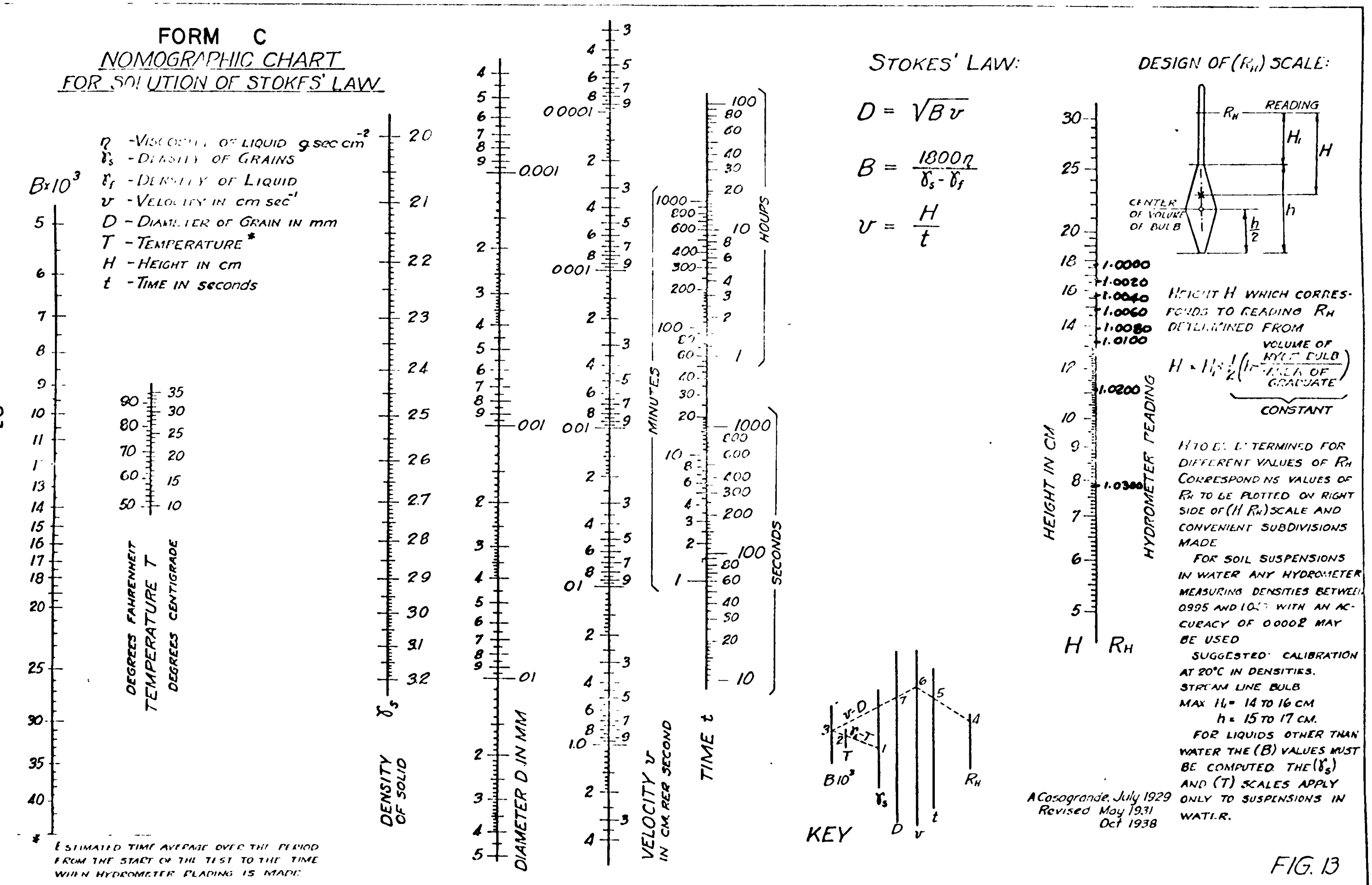
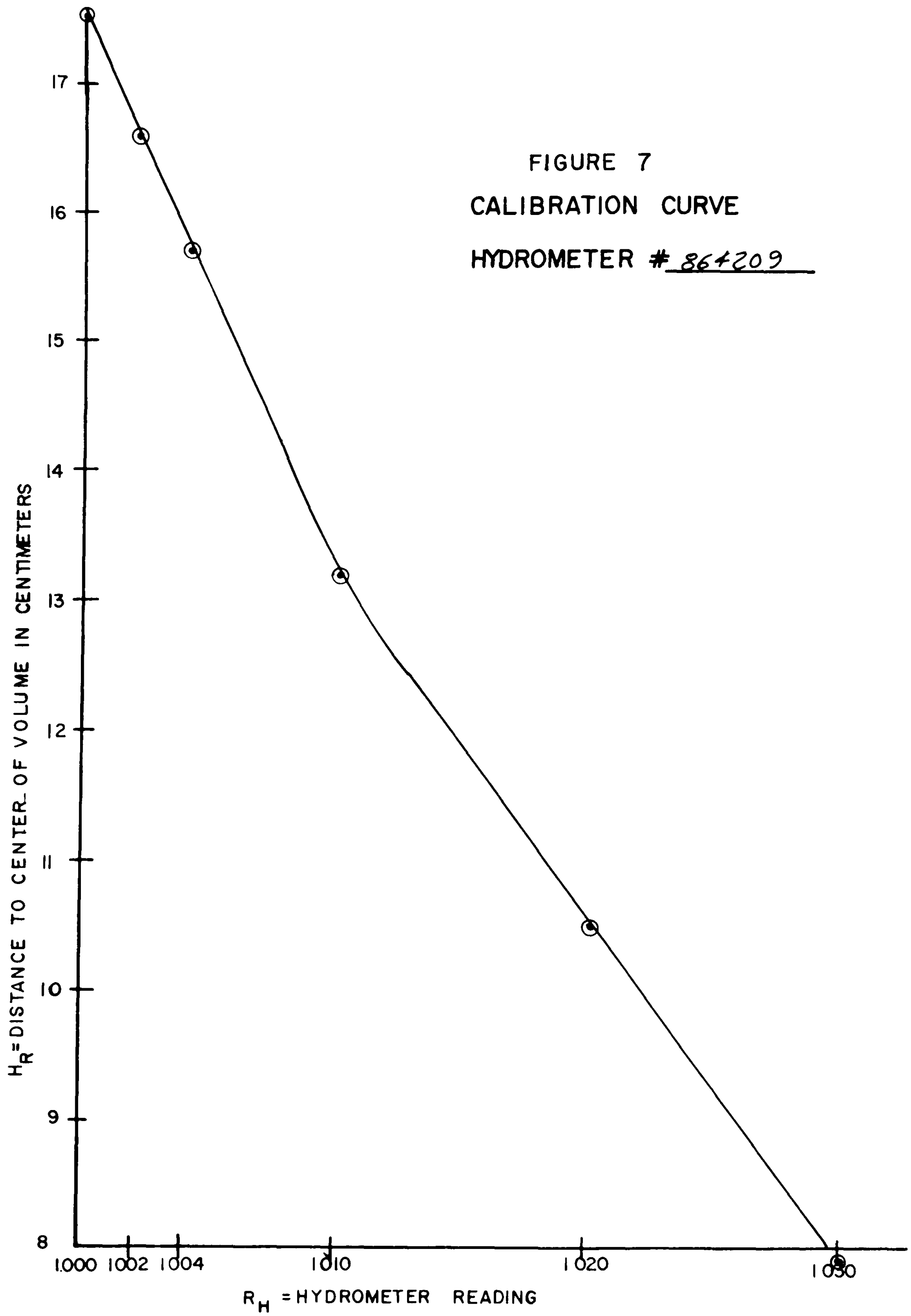

FORM C
NOMOGRAPHIC CHART
FOR SOLUTION OF STOKES' LAW
η - Viscosity of liquid g sec cm^-2
γs - Density of grains
γf - Density of liquid
v - Velocity in cm sec^-1
D - Diameter of grain in mm
T - Temperature *
H - Height in cm
t - Time in seconds
B×10^3
DEGREES FAHRENHEIT
TEMPERATURE T
DEGREES CENTIGRADE
DENSITY OF SOLID γs
DIAMETER D IN MM
VELOCITY v IN CM. PER SECOND
TIME t
MINUTES
HOURS
SECONDS
STOKES' LAW:
D = √(Bv)
B = 1800η / (γs - γf)
v = H / t
DESIGN OF (RH) SCALE:
READING
CENTER OF VOLUME OF BULB
HEIGHT IN CM
HYDROMETER READING
H
RH
CONSTANT
FOR SOIL SUSPENSIONS IN WATER ANY HYDROMETER MEASURING DENSITIES BETWEEN 0.995 AND 1.0 WITH AN ACCURACY OF 0.0002 MAY BE USED
SUGGESTED CALIBRATION AT 20°C IN DENSITIES.
STREAM LINE BULB
MAX H1 = 14 TO 16 CM
h = 15 TO 17 CM.
FOR LIQUIDS OTHER THAN WATER THE (B) VALUES MUST BE COMPUTED. THE (γs) AND (T) SCALES APPLY ONLY TO SUSPENSIONS IN WATER.
KEY
A Casagrande, July 1929
Revised May 1931
Oct 1938

FIG. 13

FIGURE 7

CALIBRATION CURVE

HYDROMETER # 864209



hydrometer reading corrected for miniscus rise (but not for temperature)and the measured time, a point on the "Velocity" scale was determined. Finally using the "Velocity" point and the "B x $10^3$" point, the diameter 'D' in millimeters was found.

D. Summary of Grain Size Distribution

Having completed the sieve and hydrometer analyses, a Grain Size Distribution (cumulative curve) was plotted as in Figure 8 for sample #283. This plot was made from the columns "% Finer" and "Sieve Range" (minimum size sieve used) on Form 'A' and columns 'N' and 'D' on Form 'B'. The final form gives the diameter of particles for which all lesser diameters form a given percentage finer by weight of the total wieght. From this cumulative distribution curve the sand, silt and clay percentage (M.I.T. classification) were read and a Graphic Mean Size was calculated. Since the diameter scale is logarithmic, conversion is made to phi units (Folk[15]) in calculating the G.M.S.:

$$D_{phi} = -\log_2 D_{mm} \qquad (7)$$

where for example; 0 phi = 1 mm, 1 phi = 1/2 mm, 2 phi = 1/4 mm. From Folk[15] the G.M.S. was calculated as:

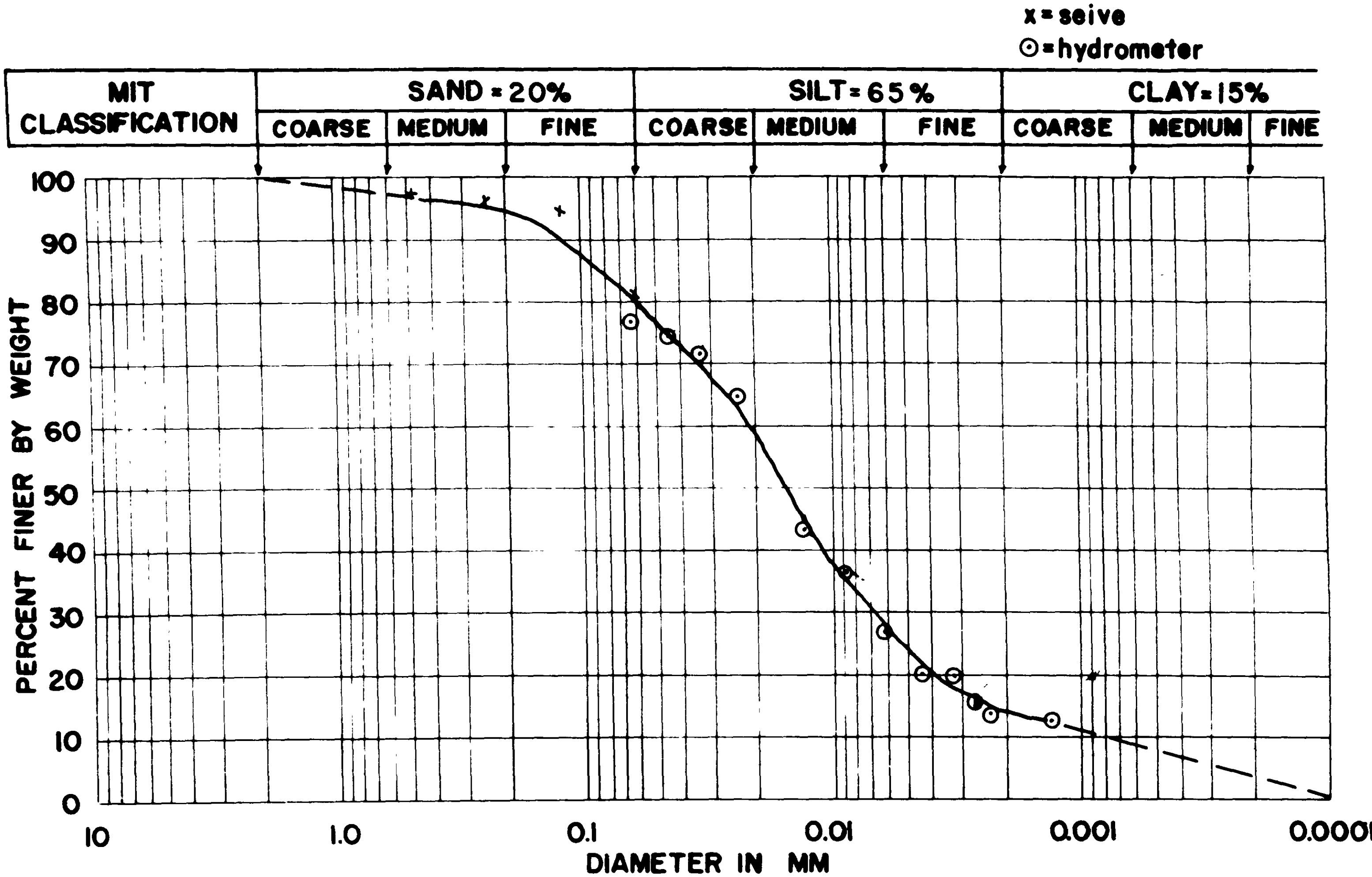
$$G.M.S. = \frac{D_{84\%} + D_{50\%} + D_{16\%}}{3} \qquad (8)$$

in phi units

where $D_{84\%}$ represents the diameter for the 84th percentile on the cumulative curve and from a scale converting mm to phi units, the graphic mean size for sample 283 (refer to Figure 8) is:

$$G.M.S. = \frac{3.6 + 6.1 + 8.9}{3} = 6.1 \text{ phi} = 0.015 \text{ mm.}$$

FIGURE 8. **GRAIN SIZE DISTRIBUTION**




SAMPLE: 283
COLLECTED: 8/3/66

GRAPHIC MEAN SIZE = 0.015 MM

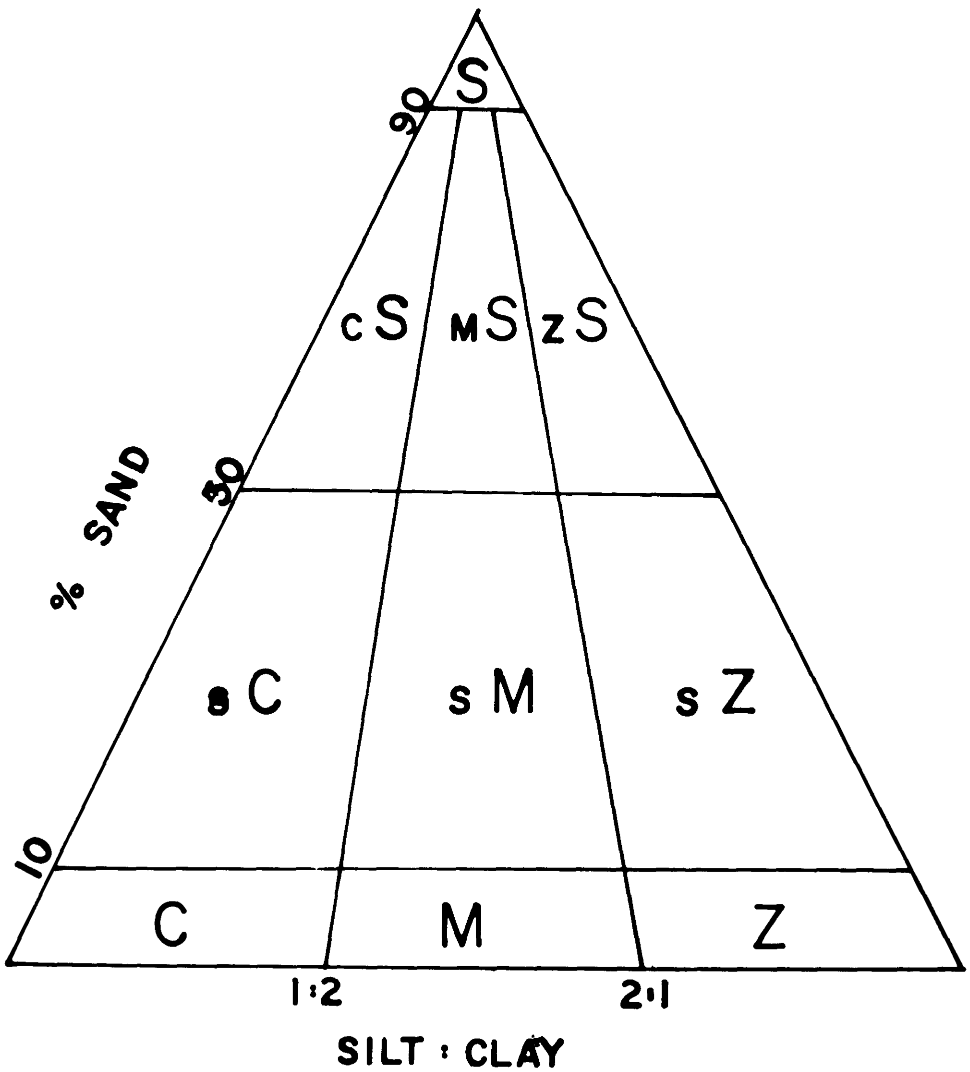
A sediment name was assigned the sample according to the scheme given by Folk[15] and shown in Figure 9. From the grain size distribution curve the percent sand is compared to the ratio of percent silt to percent clay. For sample #283:

% Sand = 20%

Silt:Clay = 4.3:1

and from Figure 9 the sediment name is "sandy silt". Since the core log did not indicate any pebbles or shells in the sample, this name is applicable.

Table II with explanation summarizes all the data for the field and laboratory seidment analyses.




S = SAND    s = SANDY

C = CLAY    c = CLAYEY

M = MUD    m = MUDDY

Z = SILT    z = SILTY

FIGURE 9. Sediment Nomenclature

Folk[15]

## TABLE II: SEDIMENT SAMPLE DATA AND ANALYSES

| Symbol | Explanation |
| --- | --- |
| No. | Station number as shown on Figure 1. See Figure 1 and Table 1 for co-ordinate location. |
| Date | Date sample was collected. Not necessarily the same date as sound speed taken. |
| Depth | Depth in inches into bottom from which sample taken. |
| Inst. | Sampler used as illustrated in Figure 3.<br>VV = Van Veen<br>SC = Square Corer<br>C = Corer(cylindrical tube used on square corer) |
| Sand<br>Silt<br>Clay | Percentages as determined from Figure 8. |
| Name | As determined from Sand, Silt, Clay % and Figure 9. |
| G.M.S. | Graphic mean size in mm x $10^{-3}$ (explained in text) |
| $W_s$ | Mass of dried solids in grams. |
| $W_1$ | Mass of liquids in grams. |
| B | Water content in % (explained in text). |
| n | 'porosity' in % ( explained in text). |

TABLE II: Sediment Sample Data and Analysis

| No. | Date | Depth (inches) | Inst. | Sand (%) | Silt (%) | Clay (%) | Name | G.M.S. ($x10^{-3}$mm) | $W_s$ (gm.) | $W_l$ (gm.) | B (%) | n (%) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 7 | 8/03/66 | 6 | SC | 75 | 15 | 10 | silty sand | 73.3 | 39.0 | 11.4 | 29 | 44 |
| 10 | 8/09/66 | 6 | SC | 50 | 25 | 15 | silty sand | 32.4 | 27.0 | 14.9 | 55 | 60 |
| 23 | 8/09/66 | 6 | SC | 20 | 65 | 15 | sandy silt | 15.7 | 21.3 | 26.4 | 129 | 77 |
| 28 | 7/04/66 | 6 | VV | 20 | 60 | 20 | sandy silt | 12.7 | 15.5 | 24.2 | 156 | 81 |
| 38 | 7/29/66 | 16 | SC | 10 | 70 | 20 | silt | 6.9 | 17.4 | 18.9 | 109 | 74 |
| 39 | 7/30/66 | 15 | SC | 10 | 60 | 30 | silt | 4.6 | 10.6 | 11.3 | 107 | 74 |
| 40 | 7/29/60 | 3 | VV | 20 | 65 | 15 | sandy silt | 21.2 | - | - | -high- | |
| 69 | 7/29/66 | 6 | VV | 10 | 60 | 30 | silt | 3.8 | 8.3 | 12.1 | 145 | 79 |
| 87 | 8/12/66 | 6 | VV | 20 | 45 | 35 | sandy clay | 5.5 | 10.7 | 10.1 | 94 | 73 |
| 118 | 12/10/66 | | VV | sample is very coarse rock-little coarse sand | | | | | | | -low- | |
| 128 | 7/08/66 | 72 | C | 5 | 80 | 15 | silt | 3.8 | 20.9 | 9.0 | 43 | 49 |
| 129 | 8/03/66 | 72 | C | 60 | 30 | 10 | silty sand | 87.2 | 15.0 | 5.2 | 35 | 55 |
| 141 | 7/29/66 | 6 | VV | 15 | 65 | 20 | sandy silty | 3.0 | 13.9 | 14.2 | 102 | 73 |
| 147 | 8/03/66 | Anchor sample, not enough for size analysis | | | | | | | | | | |
| 152 | 10/19/65 | 6 | VV | 10 | 85 | 5 | silt | 64.7 | - | - | - | - |
| 153 | 10/19/65 | 6 | VV | 35 | 50 | 15 | sandy silt | 14.5 | - | - | - | - |
| 165 | 10/23/65 | 6 | VV | 90 | 5 | 5 | pebbly sand | 717.0 | 23.9 | 8.5 | 35 | 49 |
| 170 | 10/23/65 | 6 | VV | 70 | 25 | 5 | silty sand | 122.4 | 30.6 | 14.5 | 47 | 54 |
| 176 | 10/23/65 | 6 | VV | 75 | 15 | 10 | muddy sand | 101.5 | 35.7 | 14.6 | 41 | 52 |
| 191 | 3/22/66 | 24 | SC | 45 | 40 | 15 | sandy silt | 23.5 | 17.6 | 21.5 | 122 | 80 |
| 192 | 3/22/66 | 6 | VV | 30 | 50 | 20 | sandy silt | 14.0 | 11.7 | 16.7 | 143 | 80 |
| | | | | 20 | 55 | 25 | sandy silt | 8.0 | 19.8 | 16.8 | 85 | 69 |
| 193[a] | 3/22/66 | 6 | VV | 15 | 60 | 25 | sandy silt | 8.9 | 10.1 | 18.1 | 180 | 82 |
| | | | | 55 | 25 | 20 | muddy sand | 21.9 | 9.8 | 12.7 | 129 | 78 |
| 194[a] | 3/22/66 | 6 | VV | 55 | 25 | 20 | muddy sand | 28.8 | 16.4 | 34.1 | 208 | 84 |

TABLE II: Sediment Sample Data and Analysis (cont.)

| No. | Date | Depth (inches) | Inst. | Sand (%) | Silt (%) | Clay (%) | Name | G.M.S. ($x10^{-3}$mm) | $W_s$ (gm.) | $W_l$ (gm.) | B (%) | n (%) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | 15 | 65 | 20 | sandy silt | 8.4 | 10.3 | 16.3 | 158 | 71 |
| 195[a] | 3/22/66 | 6 | VV | 15 | 60 | 25 | sandy silt | 6.6 | 11.8 | 18.1 | 153 | 83 |
| 196 | 3/22/66 | 6 | VV | 65 | 25 | 10 | silty sand | 43.6 | 20.8 | 14.5 | 70 | 56 |
| 198 | 3/22/66 | 6 | VV | 80 | 10 | 10 | muddy sand | 44.5 | 23.8 | 13.0 | 54 | 59 |
| 199 | 3/22/66 | 6 | VV | 10 | 65 | 25 | silt | 4.8 | 6.6 | 24.4 | 370 | 79 |
| 200 | 3/22/66 | 6 | VV | 20 | 65 | 15 | sandy silt | 10.5 | 12.1 | 17.5 | 145 | 75 |
| 201 | 3/28/66 | 6 | VV | 55 | 25 | | sandy silt | 9.4 | 6.8 | 23.6 | 348 | 66 |
| 202[b] (26) | 3/28/66 | 6 | VV | 80 | 10 | 10 | muddy sand | 57.5 | 17.2 | 12.1 | 70 | 44 |
| 203 | 4/19/66 | 18 | C | 70 | 10 | 20 | clayey sand | 24.3 | 14.1 | 5.3 | 37 | 61 |
| 204 | 4/19/66 | tried core: all rocks, fine grey sand (12") over very stiff clay | | | | | | | | | -low- | |
| 205[b] (140) | 4/19/66 | 36 | C | 10 | 70 | 20 | silt | 4.3 | 15.9 | 8.1 | 51 | 57 |
| 206 | 4/19/66 | tried core: all rocks, fine grey sand (12") | | | | | | | | | -low- | |
| 211 | 6/28/66 | 10 | SC | 35 | 50 | 15 | sandy silt | 42.7 | 14.3 | 7.1 | 50 | 47 |
| 213 | 6/23/66 | 18 | SC | 15 | 60 | 25 | sandy silt | 7.7 | 10.0 | 7.0 | 70 | 77 |
| 215 | 6/28/66 | 12 | SC | 45 | 40 | 15 | sandy silt | 30.8 | 11.8 | 6.3 | 53 | 51 |
| 216 | 6/28/66 | 10 | SC | 35 | 50 | 15 | sandy silt | 36.9 | 13.0 | 5.8 | 44 | 48 |
| 218 | 6/28/66 | 8 | SC | 30 | 60 | 10 | sandy silt | 18.6 | 7.9 | 6.3 | 80 | 52 |
| 219[c] | 6/28/66 | 14 | SC | 40 | 50 | 10 | sandy silt | 33.7 | 10.5 | 6.3 | 60 | 45 |
| 220 | 6/30/66 | 6 | SC | 30 | 50 | 20 | sandy silt | 13.8 | 7.0 | 6.8 | 97 | 57 |
| 224 | 6/30/66 | 30 | SC | 20 | 55 | 25 | sandy silt | 10.5 | 7.2 | 11.4 | 156 | 65 |
| 225 | 6/30/66 | 6 | SC | 60 | 30 | 10 | silty sand | 91.5 | 23.1 | 7.1 | 31 | 40 |
| 227 | 7/12/66 | 6 | VV | 70 | 20 | 10 | silty sand | 38.2 | 14.8 | 5.2 | 35 | 51 |
| 228 | 7/12/66 | 6 | VV | 40 | 45 | 15 | sandy silt | 22.7 | 12.3 | 7.5 | 61 | 59 |

TABLE II: Sediment Sample Data and Analysis (cont.)

| No. | Date | Depth (inches) | Inst. | Sand (%) | Silt (%) | Clay (%) | Name | G.M.S. ($x10^{-3}$mm) | $W_s$ (gm.) | $W_l$ (gm.) | B (%) | n (%) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 229 | 7/12/66 | 6 | VV | 40 | 45 | 15 | sandy silt | 39.6 | 25.5 | 11.6 | 45 | 55 |
| 230 | 7/12/66 | 6 | VV | 35 | 40 | 25 | sandy mud | 15.8 | 7.9 | 11.6 | 147 | 79 |
| 231 | 7/12/66 | 6 | VV | 10 | 65 | 25 | silt | 5.6 | 6.9 | 10.5 | 152 | 80 |
| 232 | 7/12/66 | 6 | VV | 10 | 65 | 25 | silt | 7.3 | 8.8 | 23.7 | 259 | 88 |
| 233 | 7/12/66 | 6 | VV | 30 | 55 | 15 | sandy silt | 18.2 | 8.6 | 13.5 | 157 | 81 |
| 234 | 7/12/66 | 6 | VV | 15 | 60 | 25 | sandy silt | 6.7 | 7.9 | 15.0 | 190 | 83 |
| 235 | 7/12/66 | 6 | VV | 50 | 30 | 20 | muddy sand | 32.1 | 12.2 | 10.4 | 85 | 70 |
| 237 | 7/13/66 | 6 | VV | 85 | 5 | 10 | clayey sand | 269.8 | 14.6 | 6.5 | 44 | 54 |
| 238 | 7/13/66 | 6 | VV | 60 | 30 | 10 | silty sand | 45.4 | 9.8 | 11.3 | 115 | 75 |
| 240 | 7/13/66 | 6 | VV | 70 | 25 | 5 | silty sand | 114.2 | 20.2 | 9.8 | 48 | 56 |
| 241 | 7/13/66 | 6 | VV | 75 | 20 | 5 | silty sand | 111.9 | 20.3 | 9.4 | 46 | 55 |
| 242 | 7/13/66 | 6 | VV | 55 | 30 | 15 | silty sand | 22.7 | 14.9 | 12.0 | 81 | 69 |
| 243 | 7/13/66 | 6 | VV | 40 | 50 | 10 | sandy silt | 25.2 | 14.2 | 11.7 | 83 | 68 |
| 244 | 7/13/66 | 6 | VV | 5 | 75 | 20 | silt | 6.2 | 9.6 | 21.6 | 227 | 86 |
| 245 | 7/13/66 | 6 | VV | 25 | 55 | 20 | sandy silt | 14.2 | 15.0 | 25.0 | 166 | 81 |
| 246 | 7/13/66 | 6 | VV | 25 | 60 | 15 | sandy silt | 12.9 | 21.7 | 21.7 | 100 | 73 |
| 247 | 8/22/66 | 8 | VV | 50 | 30 | 20 | muddy sand | 20.3 | 12.6 | 10.9 | 86 | 70 |
| 249 | 7/16/66 | 6 | VV | 30 | 55 | 15 | sandy silt | 20.8 | 15.9 | 16.0 | 101 | 73 |
| 251 | 7/16/66 | 6 | VV | 45 | 40 | 15 | sandy silt | 27.0 | 24.8 | 18.9 | 76 | 67 |
| 252 | 7/16/66 | 6 | VV | 50 | 35 | 15 | silty sand | 40.7 | 30.7 | 19.8 | 64 | 64 |
| 254 | 7/16/66 | 6 | VV | 45 | 45 | 10 | sandy silt | 25.2 | 19.1 | 15.6 | 82 | 68 |
| 256 | 7/17/66 | 6 | VV | 55 | 35 | 10 | silty sand | 36.7 | 32.4 | 6.6 | 20 | 35 |
| 257 | 7/17/66 | 6 | VV | 70 | 20 | 10 | silty sand | 135.8 | 35.9 | 20.2 | 56 | 60 |
| 258 | 7/17/66 | 6 | VV | 45 | 30 | 25 | sandy mud | 16.2 | 19.8 | 16.9 | 85 | 70 |

TABLE II: Sediment Sample Data and Analysis (cont.)

| No. | Date | Depth (inches) | Inst. | Sand (%) | Silt (%) | Clay (%) | Name | G.M.S. ($x10^{-3}$mm) | $W_s$ (gm.) | $W_l$ (gm.) | B (%) | n (%) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 260 | 7/17/66 | 4 | VV | 55 | 35 | 10 | silty sand | 50.1 | 25.6 | 14.2 | 56 | 58 |
| 262 | 7/23/66 | 15 | SC | 20 | 70 | 10 | sandy silt | 13.1 | 25.1 | 17.8 | 70 | 66 |
| 263 | 7/23/66 | 12 | SC | 15 | 80 | 5 | sandy silt | 23.8 | 18.2 | 28.1 | 155 | 80 |
| 265 | 7/23/66 | 10 | SC | 25 | 65 | 10 | sandy silt | 18.1 | 19.5 | 20.0 | 103 | 73 |
| 266 | 7/23/66 | 6 | VV | 40 | 50 | 10 | sandy silt | 26.5 | 22.0 | 19.7 | 90 | 70 |
| 267 | 7/23/66 | 6 | VV | 20 | 65 | 15 | sandy silt | 14.1 | 18.8 | 19.2 | 102 | 73 |
| 271 | 7/24/66 | 6 | VV | 55 | 35 | 10 | silty sand | 44.5 | 31.1 | 13.1 | 42 | 53 |
| 272 | 7/24/66 | 6 | VV | 75 | 15 | 10 | muddy sand | 81.9 | 16.8 | 8.6 | 51 | 58 |
| 273 | 7/24/66 | 6 | VV | 80 | 15 | 5 | silty sand | 267.9 | 37.3 | 15.3 | 41 | 52 |
| 274 | 7/24/66 | 6 | VV | 15 | 55 | 30 | sandy mud | 5.8 | 6.5 | 10.4 | 160 | 81 |
| 275 | 7/24/66 | 6 | VV | 60 | 25 | 15 | muddy sand | 60.8 | 27.9 | 17.0 | 61 | 60 |
| 276 | 7/29/66 | 24 | SC | 20 | 55 | 25 | sandy silt | 10.8 | 27.1 | 18.6 | 68 | 64 |
| 277 | 7/30/66 | 9 | SC | 30 | 55 | 15 | sandy silt | 19.6 | 15.5 | 15.9 | 102 | 74 |
| 278[c] | 7/30/66 | 10 | SC | 60 | 25 | 15 | muddy sand | 42.1 | 22.5 | 6.7 | 30 | 44 |
| 279 | 7/30/66 | 4 | SC | 20 | 50 | 30 | sandy silt | 9.2 | 14.9 | 15.5 | 104 | 73 |
| 280 | 8/03/66 | 12 | SC | 15 | 45 | 40 | sandy mud | 4.9 | 16.5 | 13.7 | 83 | 68 |
| 281 | 8/03/66 | 8 | SC | 20 | 50 | 30 | sandy mud | 6.5 | 17.0 | 13.6 | 80 | 67 |
| 282 | 8/03/66 | 7 | SC | 15 | 65 | 20 | sandy silt | 6.8 | 10.0 | 8.6 | 86 | 70 |
| 283 | 8/03/66 | 15 | SC | 20 | 65 | 15 | sandy silt | 15.5 | 18.2 | 22.2 | 122 | 77 |
| 284 | 8/03/66 | 6 | SC | 15 | 75 | 10 | sandy silt | 58.3 | 17.3 | 11.1 | 64 | 51 |
| 286 | 8/09/66 | 6 | SC | 45 | 40 | 15 | sandy silt | 22.4 | 27.8 | 17.7 | 64 | 63 |
| 287 | 8/09/66 | 6 | SC | 55 | 35 | 10 | silty sand | 40.1 | 31.1 | 16.7 | 54 | 59 |
| 288 | 8/09/66 | 6 | SC | 45 | 40 | 15 | sandy silt | 23.0 | 24.6 | 20.6 | 84 | 69 |
| 301 | 8/12/66 | 6 | VV | 10 | 60 | 30 | silt | 4.3 | 9.2 | 12.3 | 133 | 77 |
| 302 | 8/12/66 | 6 | VV | 5 | 55 | 40 | mud | 2.6 | 7.2 | 14.8 | 206 | 85 |

TABLE II: Sediment Sample Data and Analysis (cont.)

| No. | Date | Depth (inches) | Inst. | Sand (%) | Silt (%) | Clay (%) | Name | G.M.S. ($x10^{-3}$ mm.) | $W_s$ (gm.) | $W_l$ (gm.) | B (%) | n (%) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 303 | 8/12/66 | 6 | VV | 30 | 40 | 30 | sandy mud | 8.4 | 10.0 | 12.9 | 129 | 78 |
| 304 | 8/12/66 | 6 | VV | 15 | 55 | 30 | sandy mud | 5.4 | 8.9 | 12.8 | 144 | 79 |
| 305 | 8/12/66 | 6 | VV | 5 | 55 | 40 | mud | 2.1 | 8.1 | 10.7 | 132 | 75 |
| 306 | 8/14/66 | 6 | VV | 40 | 35 | 25 | sandy mud | 13.0 | 9.1 | 11.7 | 128 | 77 |
| 307 | 8/14/66 | 8 | SC | 70 | 15 | 15 | muddy sand | 45.1 | 21.0 | 7.2 | 34 | 49 |
| 308 | 8/14/66 | 6 | SC | 15 | 50 | 35 | sandy mud | 6.7 | 11.2 | 12.6 | 111 | 85 |
| 310 | 8/19/66 | 8 | VV | 45 | 35 | 20 | sandy mud | 19.1 | 13.5 | 12.9 | 96 | 72 |
| 311 | 8/19/66 | 8 | VV | 60 | 25 | 15 | muddy sand | 90.2 | 19.5 | 13.7 | 70 | 65 |

## V RESULTS AND DISCUSSION

Specific sound speed and sediment properties for each station are listed in Tables I and II of the preceeding sections. In Table I are found the sound speed ratio(R) of transmission in sediment to transmission in sea water; the signal attenuation ratio (a) and pertinent field data as to location, description, date measured and depth of penetration. Table II lists the sediment name, graphic mean size, water content and porosity as well as field and laboratory data concerning collection and sample analysis. The following is a discussion of these results with comparisons made to the work of other investigators.

### A. Sound Speed versus Sediment Properties

Figure 10 is a plot of the sound speed ratio 'R' versus porosity 'n' for stations and samples investigated in this study. The solid line is a 'best fit' curve for the plotted points. Only those stations (55 in number) at which the odor in the sediments was estimated as weak or absent are plotted in Figure 10. Approximately 65 % of the points lie within or on the two curves labeled: "b=4" and "b=5", which are exponents in the following general equation(9) and defining relations (10, 11) after the statistical analysis of Nafe and Drake[36]:

$$V^2 = n V_z^2 \left[ 1 + \frac{d_1 (1-n)}{d} \right] + V_s^2 \left[ \frac{d_s (1-n)^b}{d} \right] \quad (9)$$

where $V_z$ comes from:

$$\frac{1}{d V_z^2} = \frac{n}{d_1 V_1^2} + \frac{[1-n] [1 + (4/3)(u_s/k_s)]}{d_s V_s^2} \quad (10)$$

and d is:

$$d = d_1 n + d_s(1 - n)$$

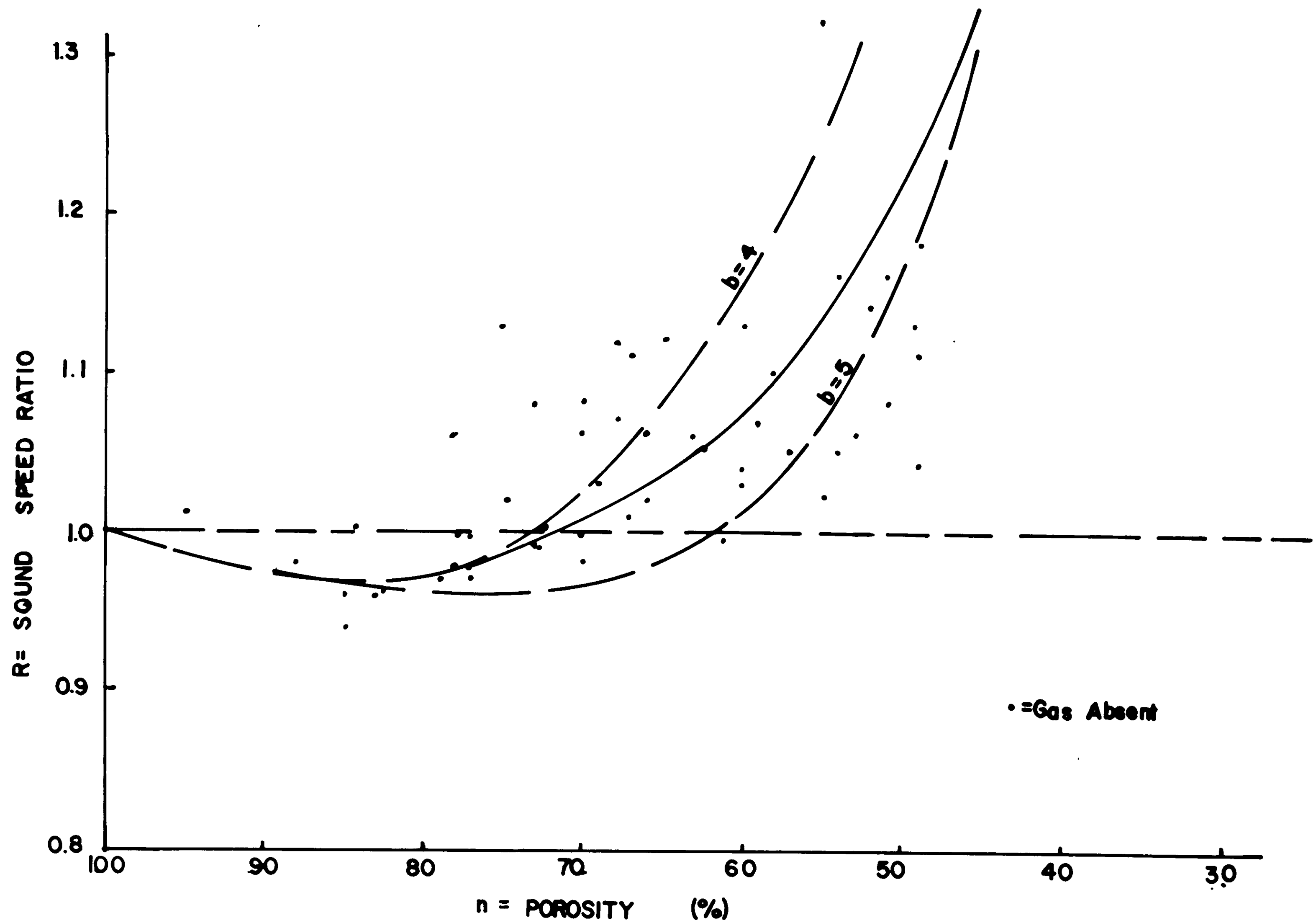



FIGURE 10 Sound Speed Ratio versus Porosity (gas absent)

$V_l$ = speed of sound in liquid = 1.52 km/sec
$V_s$ = speed of sound in solid = 6.00 km/sec
$d_s$ = density of solids = 2.65 gm/cm$^3$
$d_l$ = density of sea water = 1.03 gm/cm$^3$
$u_s/k_s$ = structure factor = 0.60

The above factors, used in equations (9,10,11) result in:

$$V^2 = V_z^2\left[ n + \frac{(1.03n)(1-n)}{(2.65 - 1.62n)} \right] + \left[ \frac{95.5}{2.65 - 1.62n} \right](1-n)^b \quad (12)$$

$$V_z^2 = \frac{1}{(2.65 - 1.62n)(0.405n + 0.019)} \quad (13)$$

Letting n = 1(liquid only), the bulk sound speed reduces to the liquid sound speed:

$$V_z^2 = 2.29 = V_l^2 = V^2$$

and letting n = 0(solids only), the bulk sound speed reduces to the solid sound speed:

$$V_z^2 = 2.00$$

$$V^2 = 36.00 = V_s^2$$

At intermediate porosities, the sound speed is as shown with a ratio 'R' less than unity over the porosity range: 65 % to 100%. This effect has been explained by Officer[38] and is discussed in the introduction to this paper.

Figure 11 is plotted in complete analogy to Figure 10 except that all the points represent stations where the gas odor was particularly pungent('moderate' to 'strong' in Table I). The solid line 'best fit' curve falls considerably below rather than intermediate to the Nafe, Drake[36] relations. The author postulates that since the sound speeds at these stations are low with respect to similar stations where no odor is present, the gas odor represents gases at least partially in a free bubble state. These bubbles are likely

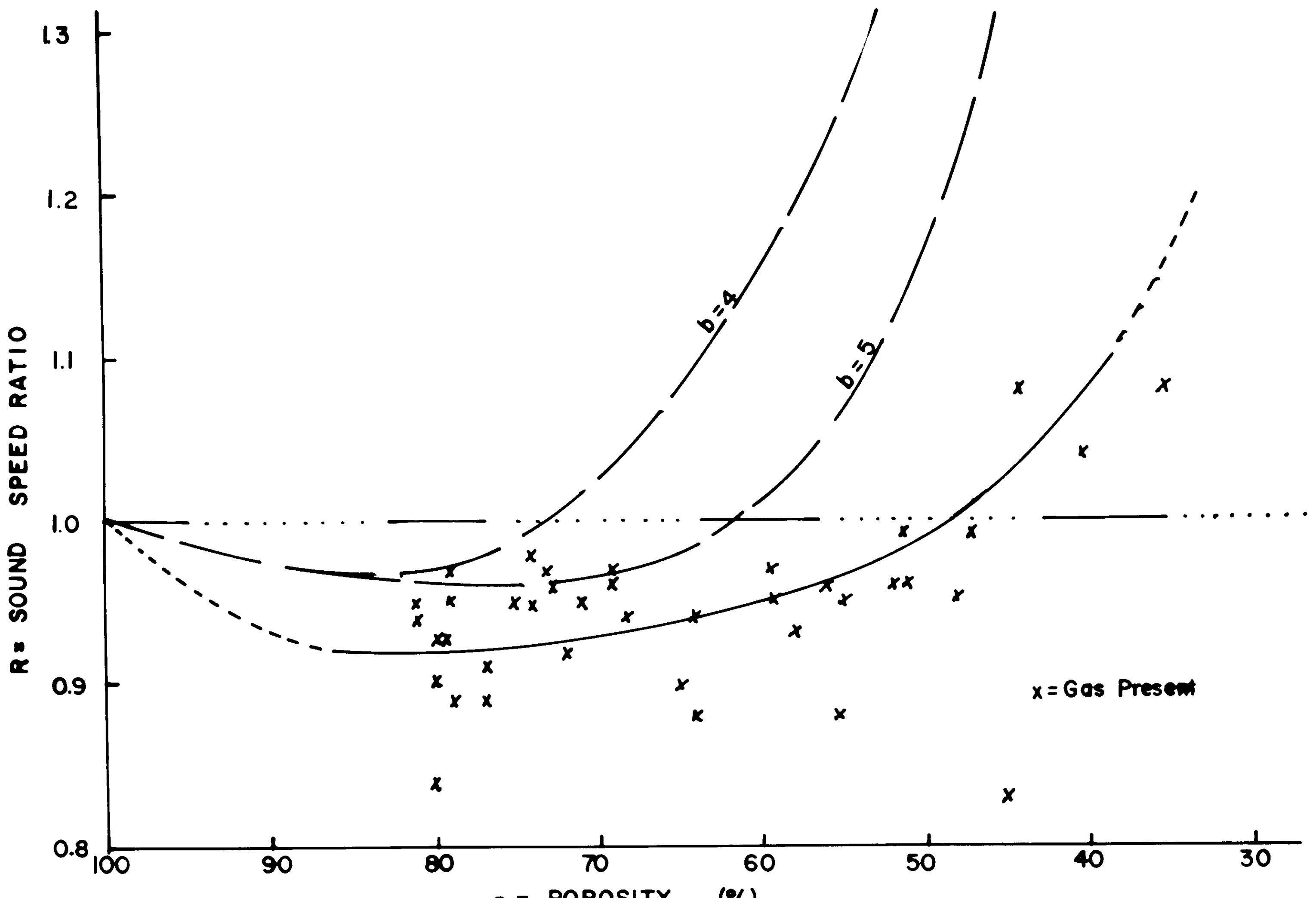



FIGURE 11. Sound Speed Ratio versus Porosity (gas present)

entrained in the soft organic ooze and are being generated by organic decay in an anerobic environment. The bubbles act as sound absorbers and effectively attenuate and otherwise slow the speed of propogation. The effect is pronounced over a wide range of porosities in comparison to the non-gaseous sediments: n from 48% to 100%. For much lower porosities(35% or less) compaction effects of grain to grain contact outweigh the gas presence and 'R' is greater than unity. At 'n' equal to unity, 'R' probably rises to unity since from density considerations, even in a gas saturated liquid, the gas would not appear as free bubbles. Since the gas would be in solution, it would have little sound transmission inhibiting effect.

An attempt was made to relate mean grain size to ratio of sound speeds. The resulting plot is a scatter diagram with no apparent relationship between the two factors. Again, gaseous sediments plotted well below the 'R' equal to unity ordinate and clustered in the finer grained region. The lack of correlation is explained by the unsorted nature of the sediments, characteristic of glacial tills and glacial drift. For these deposits, mean grain size has little real significance.

Figure 12 is a log-linear plot of 'R' versus water content. Although the scatter is severe, for those samples which are nongaseous, a relation similar to that for 'R' versus 'n' is distinguished(solid line in Figure 12 is best fit for nongaseous sediments only). At low water content, the sound speed approaches that of the solids and at high water contents near 100% 'R' is less than unity corresponding to the case for porosity greater than 65%.

B. Sound Speed Profiles

The heavy dotted lines in Figure 13 represent the locations of the sound speed profiles as plotted in Figures 14-17. The ordinate is the sound speed ratio 'R' and the

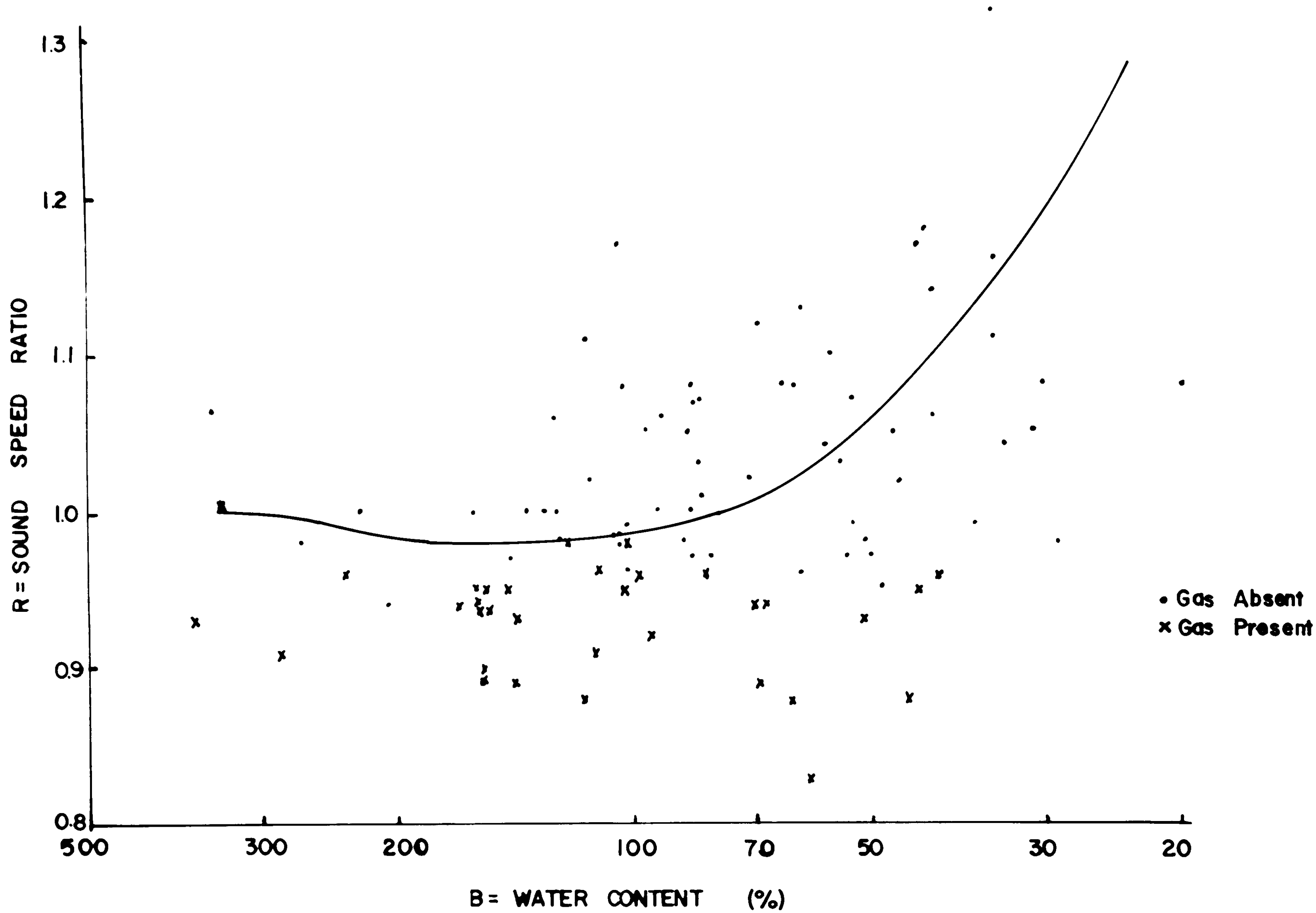



FIGURE 12. SOUND SPEED RATIO VERSUS WATER CONTENT

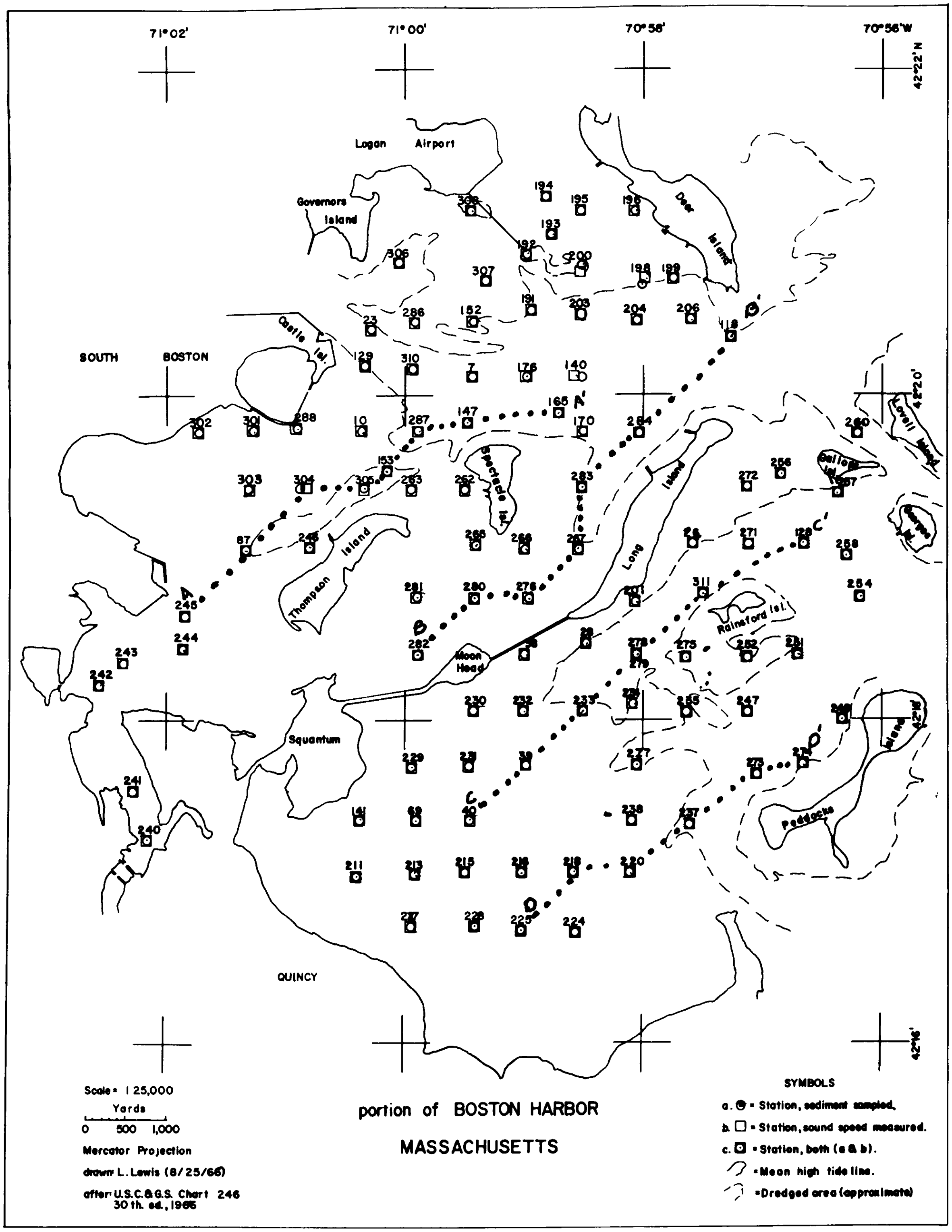



FIGURE 13. SOUND SPEED PROFILE LOCATIONS

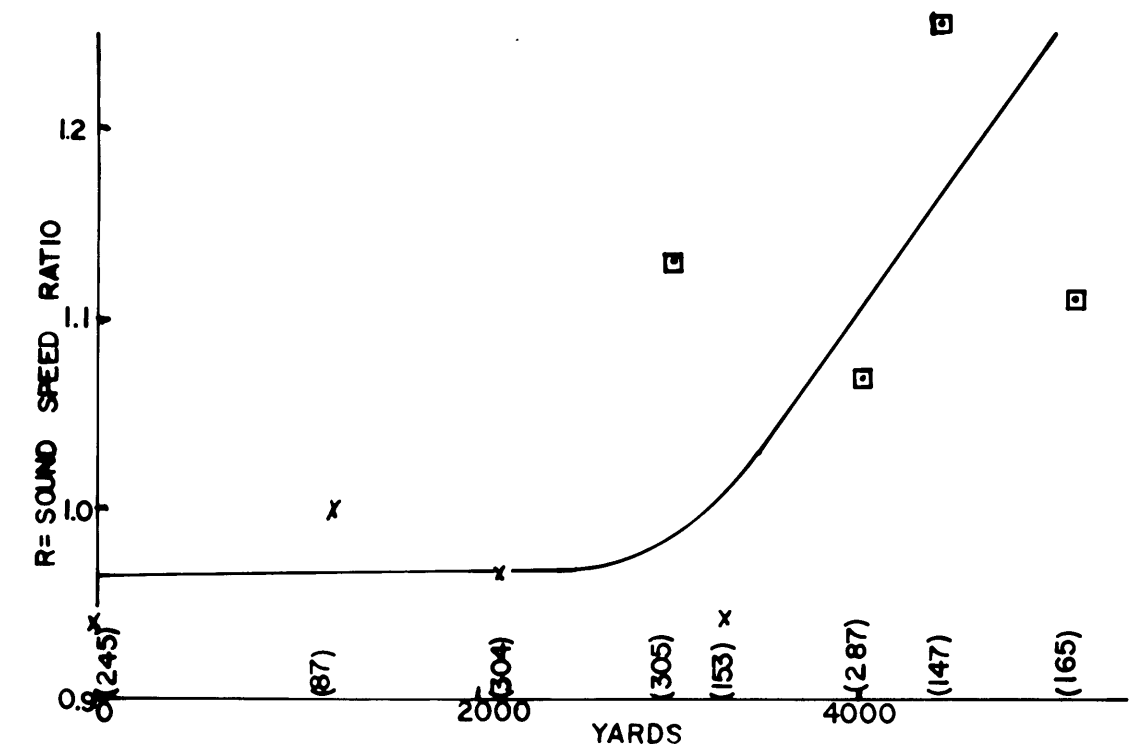



FIGURE 14. PROFILE A - A'

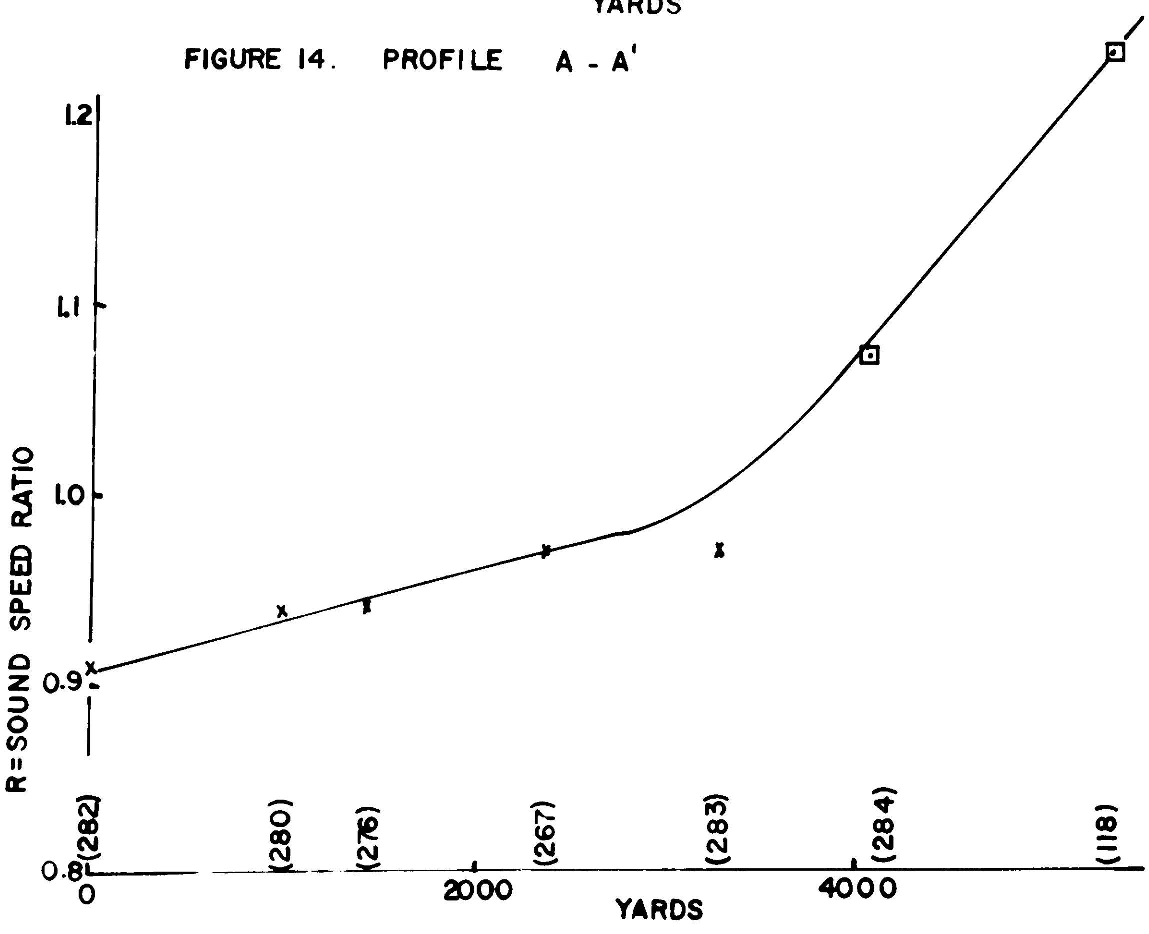



FIGURE 15. PROFILE B - B'

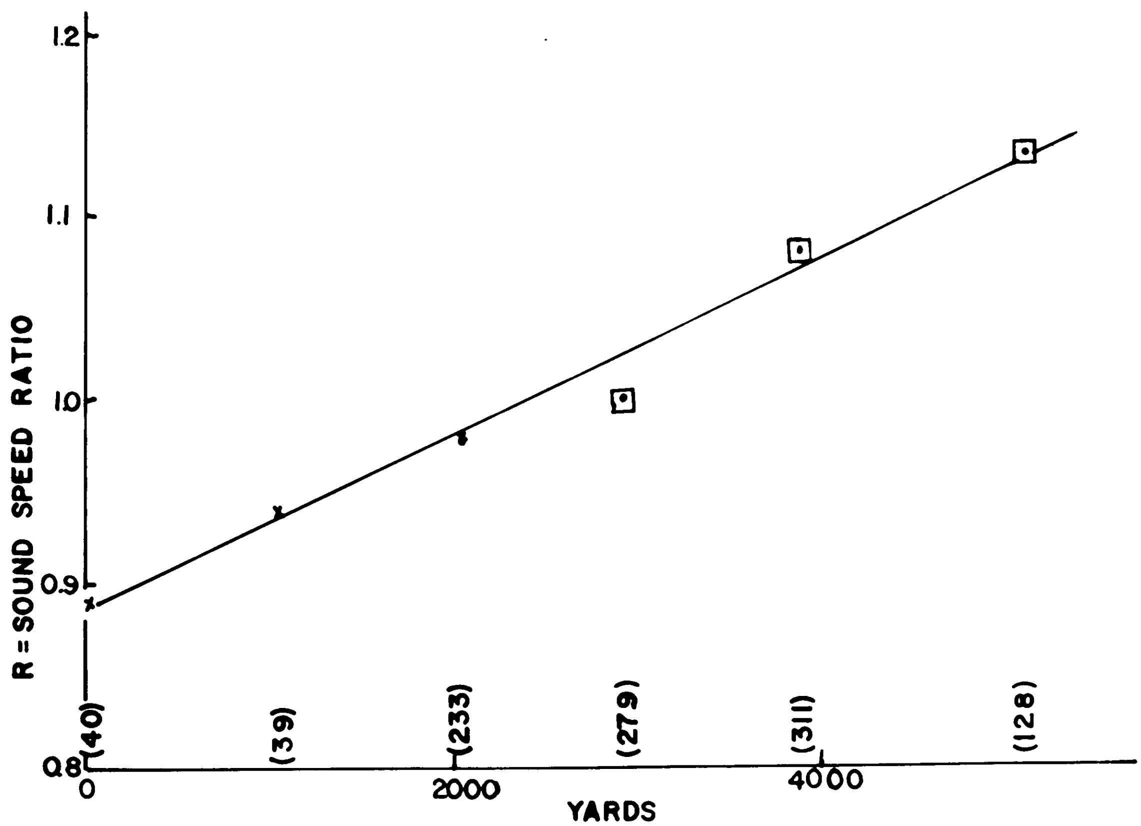



FIGURE 16. PROFILE C-C'

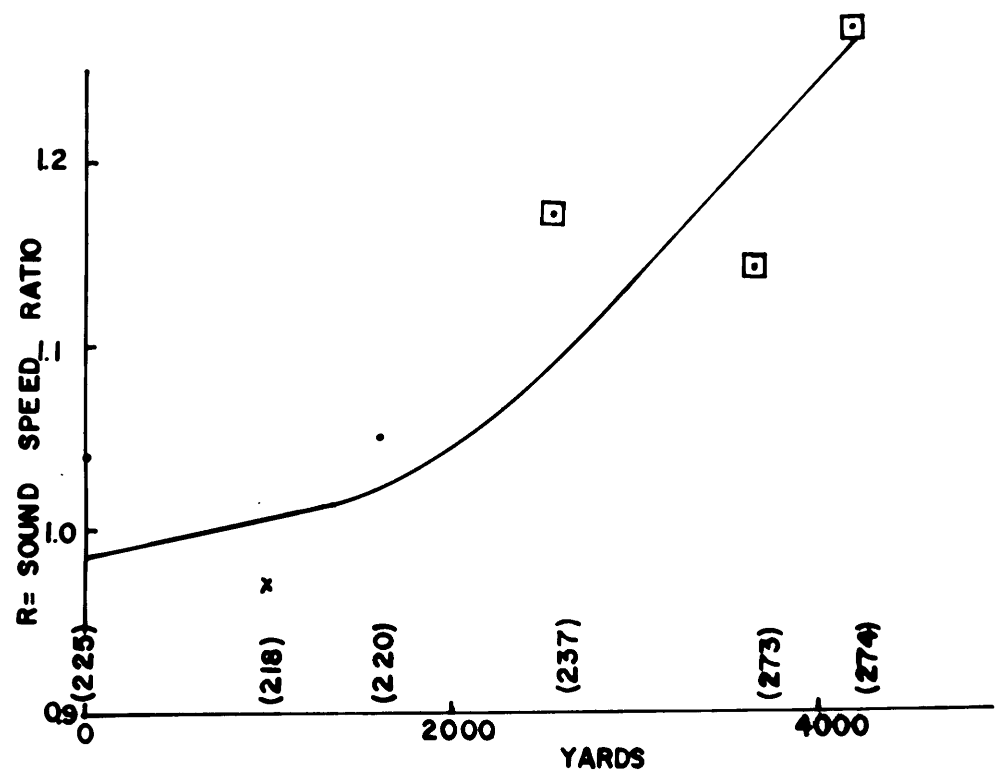



FIGURE 17. PROFILE D-D'

abscissa is distance in yards from the most westerly station on the profile. Points represent gas free stations, crosses are gaseous stations and boxes are stations in dredged areas. These profiles are remarkably smooth and indicate the rather abrupt increase in sound speed in passing from the gaseous black mud of the shallow bays to the gas free silts and sands of the dredged channels. This concept correlates with the findings of Edgerton[13] and Yules[56] that the sound penetration characteristics of shallow, undredged bays in Boston Harbor are much inferior to those of dredged channels.

C. Comparison to Other Work

Even though a plot of mean grain size versus 'R' for all stations showed no apparent correlation, if one groups the sound speed results in terms of sediment type, one finds sound speeds limited to rather specific numbers with rather small standard deviations. Table III expresses the sediment sound speed as determined from average 'R' values and an average sea water sound speed of 4880 ft/sec. Also listed are the mean and standard deviation in 'R' and the number of samples representing the sediment type, with parentheses indicating sediments specific to this study. Considering the rather high standard deviation given for the mean 'R' values listed, Table III shows a general agreement for mean sound speeds of broad sediment types among the various workers. All comparisons are made for sediments free of gas.

Of final note is the fact that both Yules[56] and Phipps[40] assumed in their Boston Harbor seismic work that the Boston Blue Clay had a sound propogation speed equivalent to that of sea water. This assumption was actually not far in error as shown by Table III. Depths to horizons within this clay as determined from their travel time curves were probably in error by less than 2% under this assumption.

TABLE III: SOUND SPEED COMPARISONS

| | Lewis (1966) | | | | Hamilton[22] (1956) | Hamilton[20] (1963) | Shumway[43] (1960) | Sykes[48] (1960) |
|---|---|---|---|---|---|---|---|---|
| SEDIMENT TYPE | No. | n | S.D. | $V_s$# | $V_s$ | $V_s$ | $V_s$ | $V_s$ |
| gaseous mud | 21 | 0.91 | 0.08 | 4440 | ---- | ---- | ---- | ---- |
| fine silt and clay (Boston Blue Clay, gas absent) | 7 | 0.96 | 0.02 | 4690 | 4800 | ---- | 4840 | ---- |
| silt and fine sand (less than $15\times10^{-3}$mm, gas absent) | 9 | 1.06 | 0.08 | 5170 | 5075 | 50[illegible]0 | ---- | 5130 |
| coarse sand (more than $100\times10^{-3}$mm, gas absent) | 11 | 1.15 | 0.07 | 5610 | 5640 | 5800 | 5680 | ---- |

#based on sea water sound speed average of 104 measurements: 4880 feet/second.
all $V_s$ are in feet/second.

D. Error Analysis and Measurement Consistency

The precision of any sound speed measurement in this study is limited by spark cable-hydrophone separation and thus by the relative spacing of the probes. The author assumed after repeated use that the probe spacing remained fixed to within 0.15 inches in 24.00 inches. Assuming a mean sound speed of 4880 feet/second, this spacing indicates that time measurements were accurate to four microseconds in 410 microseconds or approximately 1% which represents approximately 50 feet/second in 5000 feet/second. On the oscilloscope 10 microsecond delayed time base scale, time could be read easily to two microseconds.

A test of precision at a given station is represented in the 'R' value at each of four stations occupied on two different dates:

| Station | Date | Depth (inches) | R |
|---|---|---|---|
| 28 | 7/04/66 | 7 | 1.24 |
| | 8/22/66 | 20 | 1.20 |
| 38 | 7/04/66 | 25 | 0.95 |
| | 8/22/66 | 31 | 0.92 |
| 87 | 8/06/66 | 27 | 1.00 |
| | 8/12/66 | 48 | 1.03 |
| 245 | 7/12/66 | 10 | 0.94 |
| | 7/16/66 | 26 | 0.94 |

It is noted tha an 'R' value could be repeated to within 3% of its original value considering all the possible errors in relocating on station and sinking the probes to the same horizon.

The sea water sound speed was averaged from 104 measurements and found to be 4880 feet/second with a standard deviation of 110 feet/second. This discrepancy is explicable with respect to the area studied. Boston Harbor has several shallow bays that warm considerably compared to deeper ship's channels. The amount of sewage and other debris in the water both alter its temperature and its dispersive character with respect to sound transmission. The entire harbor also warmed somewhat over the summer during which this study was conducted. Various amounts of sewage and 'fresh' water effluent also alter the salinity of the water locally. Considering the increments of 5.7 feet/second per°F. increase in temperature and 4.3 feet/second per one thousandth part increase in salinity, it is not surprising that the water sound speed was variable within the limits of 4720 to 5050 feet/second over the summer in the Harbor.

As a test of consistency in laboratory procedures and results, sediment samples from three stations were chosen on which to carry out complete analyses by two different laboratory personnel. Samples 193, 194 and 195 as shown in Table II have duplicate readings for all parameters determined. Considering the unsorted nature of most samples collected, the comparisons of graphic mean sizes and percentages of sand, silt and clay are within reason. In the three comparisons, porosity varied by as much as 10% and water content by as much as 100%. The latter is due mainly to the difficulty in determining water content on a sample that is poorly sorted and not fully disaggregated. Estimates of accuracy considering the laboratory techniques used are as follows:

| Sand, Silt, Clay | G.M.S. | Water Content | Porosity |
|---|---|---|---|
| ± 5% | ± 10% | ± 25% | ± 5% |

This variation in percentage of size component does not affect the choice of sediment name. Mean size is not an appropriate characterization of unsorted materials. Water content was not a critical factor in this study and the technique used for its determination was not repeatable in the same sample. Porosity was calculated from accurately determined solid and liquid weights since complete disaggregation insured complete drying of solid components.

## VI CONCLUSIONS AND RECOMMENDATIONS

The object of this investigation was to relate the speed of sound transmission in marine sediment to other physical properties of the sediments. This goal was accomplished using the equipment and techniques herein described. Considering the unsorted and altered condition of the sediments examined in Boston Harbor, the correlation between sound speed and sediment properties is rather remarkable. Data obtained in this study compare favorably with analogous work of other investigations and results associated with particularly gaseous sediments have been explained. The general character of variation of sound speed in the surfical sediment layers over the Harbor has been described.

It is the author's opinion that the design of the sediment sound probe could be improved with respect to stability and better monitoring of depth of penetration. Comparison on the basis of physical properties would probably be much improved if care were taken to select samples from exactly the depth at which the sound speed is measured.

If a high energy, controlled-output sound source were used, transmissiion through gaseous sediments would be facilitated. If, in addition, a quantitive estimate of the free gas could be made, this could be correlated to the sound signal amplitude attenuation.

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