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SPEED OF SOUND IN UNCONSOLIDATED SEDIMENTS OF BOSTON HARBOR, MASSACHUSETTS

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by

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by

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by

Lloyd Frederick Lewis

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 discharge 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

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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.

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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], Hourz[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 3[illegible]0 kilocycle/second sound through various strata in deep sea cores obtained by the Wood's Hole Oceanographic Institution in 19[illegible]9. Assuming the ratio of sound speed in sediment to sound speed in water remained constant 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 frequencies in analyzing small samples in the laboratory for sound speed is possible using a technique developed by Toulis[49] and Shumway[44] in 19[illegible]6.

The sediment sample is placed in a compliant-walled cylinder and set into resonance by one acoustic probe. The frequency at which this resonance 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.

Eberson[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 10% 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):

$$V^2 = \frac{1}{[n\,d_1 + (1-n)d_s]\,[\,n\,C_1 + (1-n)C_s]} \qquad (2)$$

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

$$V^2 = \frac{1}{d_1 C_1} = V_1^2 \qquad (3)$$

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_1, 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 [illegible] 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

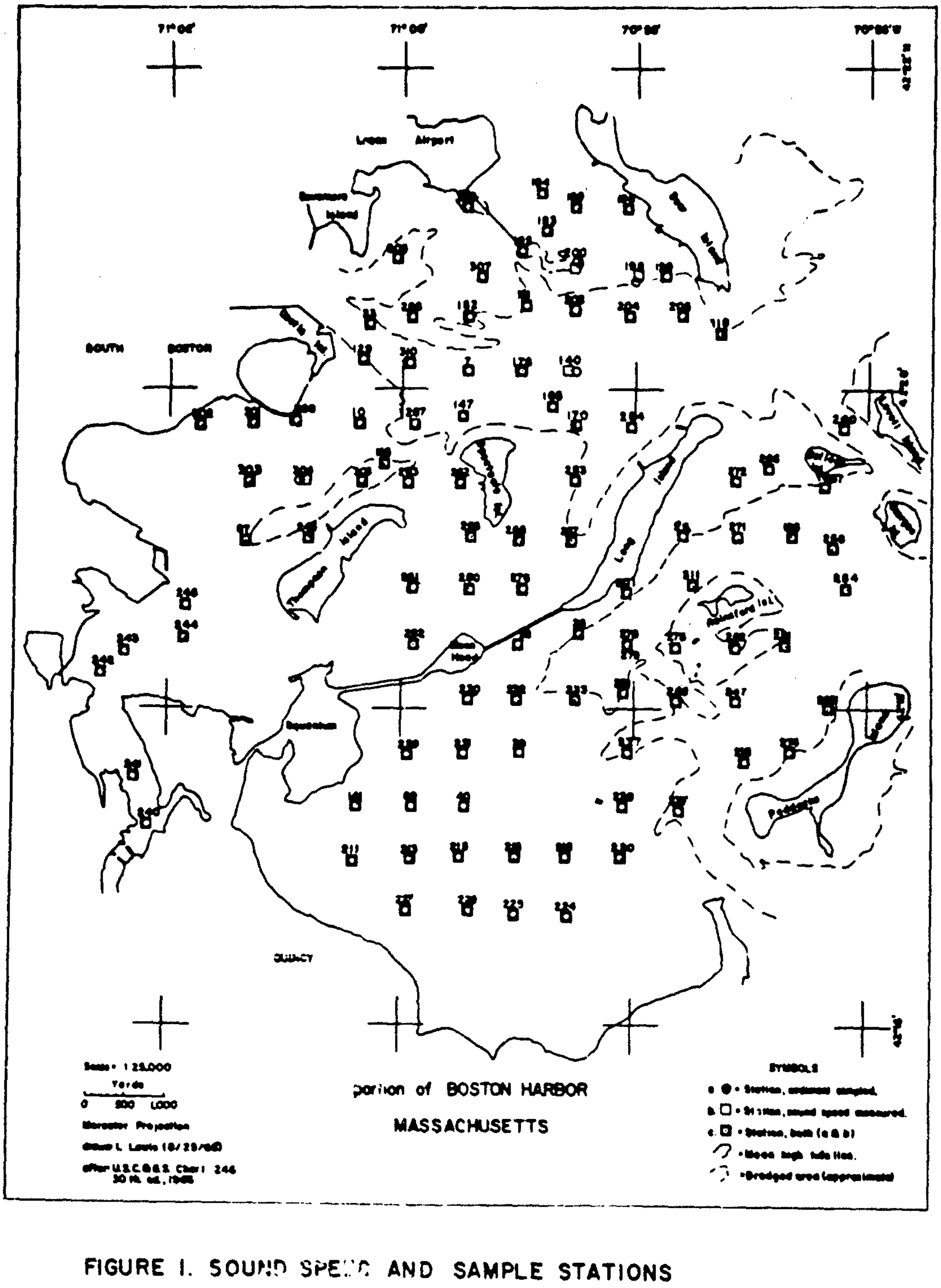


FIGURE I. SOUND SPEED AND SAMPLE STATIONS bottom is a nearly perfect reflector of sound energy. These two lithologies--the black mud and the Boston Blue Clay--in addition to an occasional sandy bottom in dredged areas were the materials most often encountered in surface sampling and sound speed measurements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

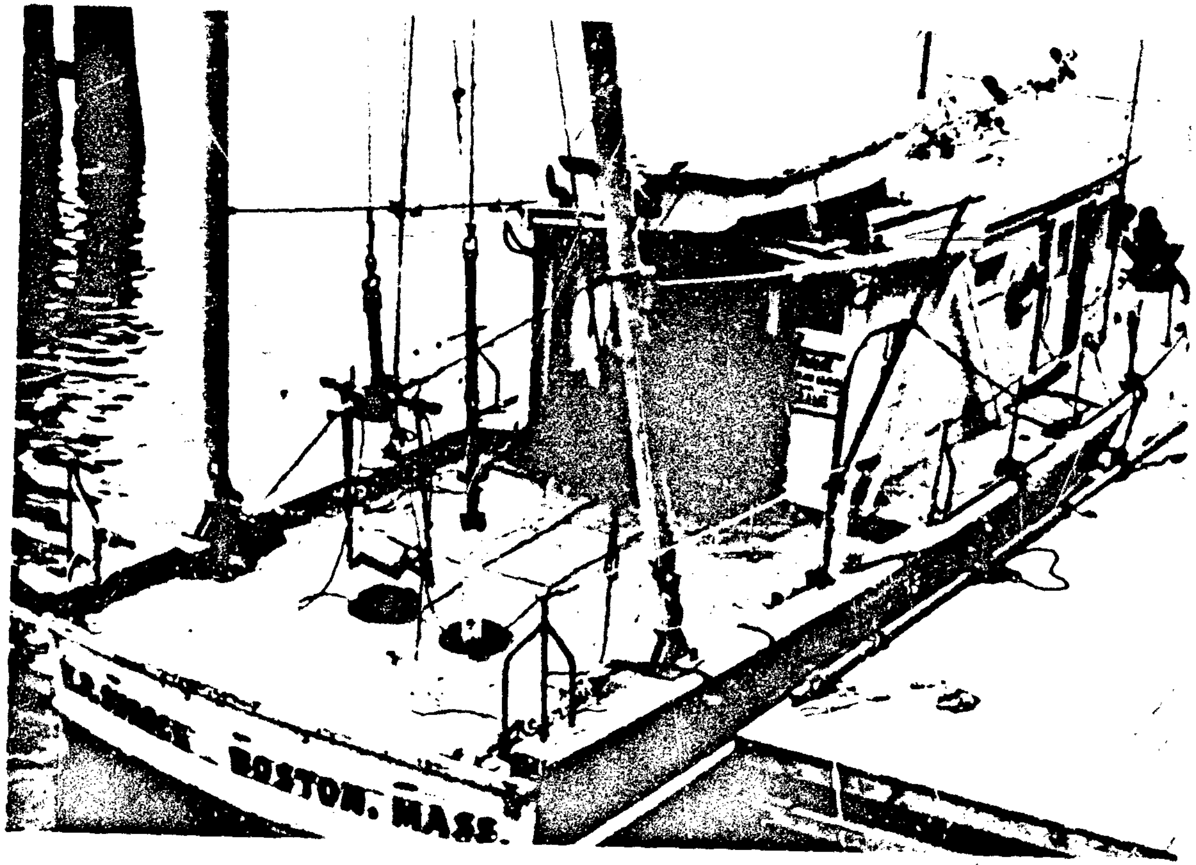
B. Sound Speed Measurements

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/inch² 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

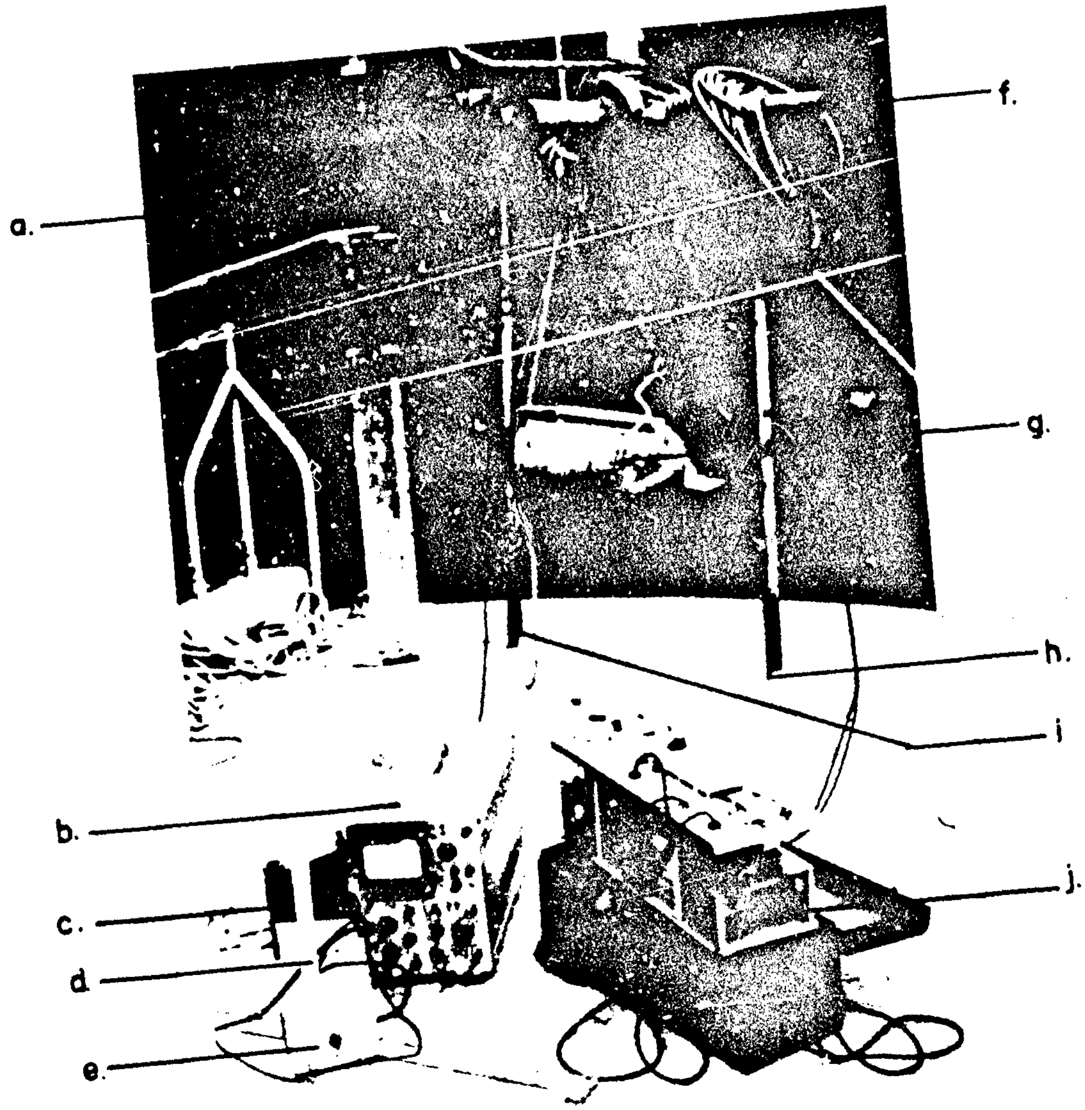
FIGURE 3 FIELD EQUIPMENT



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 piezeoelectric 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 #00229? 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.

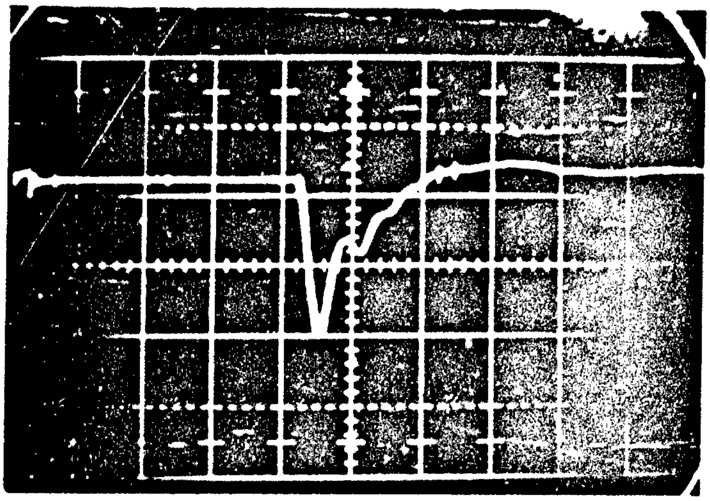
In the example shown in Figures 4 through 6, the deeper measurement (48") showed the speed of sound transmission to be 9% greater than that in water, while the shallower measurement (20") showed the speed to be actually 3% less than that in water. A moderate amount of hydrogen disulfide gas was noted 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.

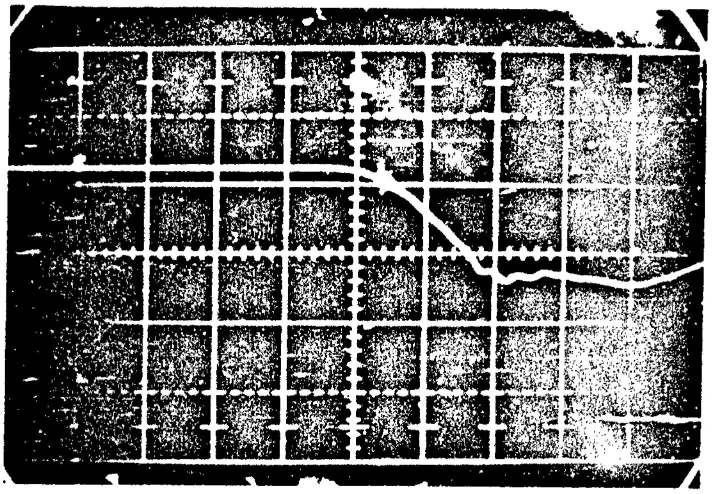


(a)

0.2 volts

0.1 milliseconds

0 time delay



(b)

0.2 volts

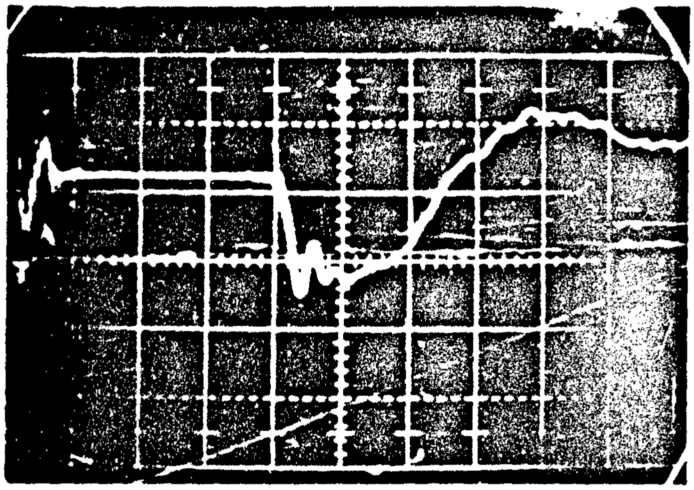
10 microseconds

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

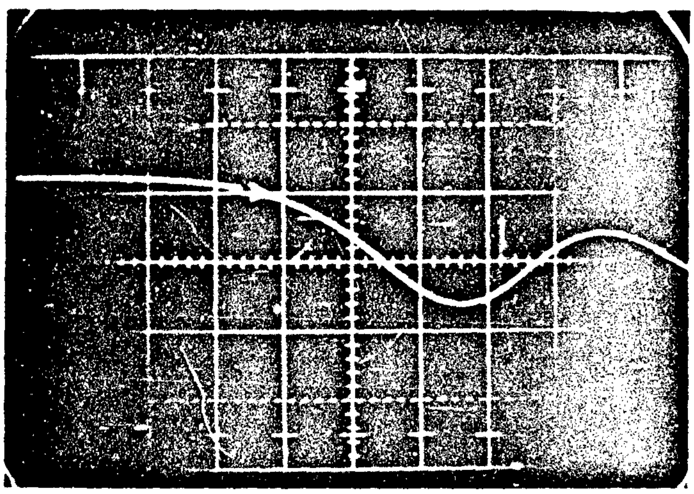


(a)

0.05volts

0.1 milliseconds

0 time delay



(b)

0.05volts

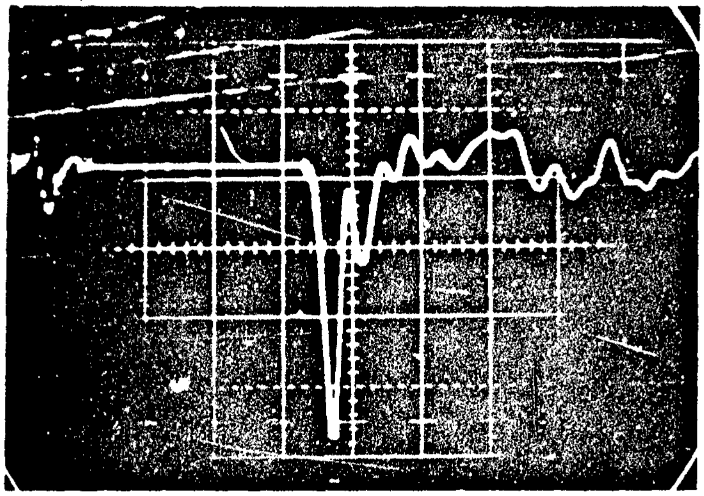
10 microseconds

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

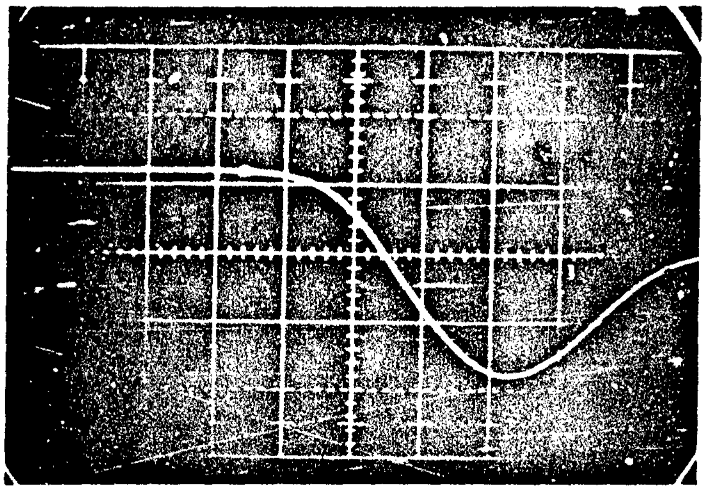


(a)

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 shown 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)	$\bar{n}$	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[a]	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. ° '	Location Lat. ° '	Date	Depth (inches)	V_s (ft/sec)	V_1 (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	1.60	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_l (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	shelly 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 1. [illegible]

No.	Location Long. ° '	Location Lat ° '	Date	Depth (inches)	V_s (ft/sec)	V_1 (ft/sec)	K	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[b]	70 58	42 18	7/30/66	20	5670	4850	1.17	0.20	absent	shelly blk mud
278				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. ° '	Location Lat. ° '	Date	Depth (inches)	V_s (ft/sec)	V_1 (ft/sec)	k	a	Gas Content	Comments
280	70 59	42 19	8/03/66	20	4550	4850	0.94	0.01	strong	black mud
281	71 00	42 19	8/03/66	20	4820		1.01	0.30	moderate	black mud
				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
283	70 58	42 19	8/03/66	20	4610		0.97	0.50	moderate	black mud
				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
286	71 00	42 20	8/09/66	10	5150		1.08	0.90	moderate	silty mud
				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
288	71 01	42 20	8/09/66	10	4940		1.03	0.32	weak	silty shelly mud
				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
306	71 00	42 21	8/14/66	10	4800		1.00	1.00	absent	crse. blk sandy mud
				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
308	70 59	42 21	8/14/66	15	4640		0.96	0.005	moderate	soft blk mud
				30	4640	4840	0.96	0.01	moderate	silty blk mud
310	71 00	42 20	8/19/66	10	4460		0.92	0.06	strong	8" ox. clay over
				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, 12°13'W
Date August 20, 1966 | Core Depth 0" to 20"
Analysis By D.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 = $\frac{(b)-(c)}{(a)-(a)} = \frac{(40.0)-(27.6)}{(27.6)-(16.7)} =$ 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/cm^3 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:

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

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

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

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

$$n = 77\%$$

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:

$$N = \left[\frac{d_s}{d_s - d_1} \right] \left[\frac{R_h + m}{W_s} \right] (100) \qquad (6)$$

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

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

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 C.M" on Form 'C'. Using the assumed density for solids and the temperature as measured, a point on the scale "B x 10^3" 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 *20'*

SAMPLE NO. *283*

SPECIFIC GRAVITY, G_s *2.75 (estimated)*

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. *1*

DATE *8/20/66*

TESTED BY *B.H.G.*

HYDROMETER NO. *864209*

MENISCUS CORRECTION *+0.0004*

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

$= \frac{2.75}{1.75}\frac{(100)(R+m)}{18.2}$; $D = \cancel{\sqrt{\frac{18\mu}{\gamma_s-\gamma_w}}\sqrt{\frac{z}{t}}}$; D IN mm = $\cancel{\sqrt{\frac{z_r \text{ IN cm}}{t \text{ IN min}}}}$ *(D from Nomograph)*

DATE	TIME	~~ELAPSED TIME IN min~~ *R_h*	$R = 1000(r-1)$ *$+C_t$*	~~$R_w = 1000(r_w-1)$~~	TEMPERATURE IN °C	$R-R_w$ *R+m*	N IN %	~~z_r IN cm~~	~~$\frac{z_r \text{ IN cm}}{t \text{ IN min}}$~~	D IN mm	~~N'~~
8/20/66	*15 sec*	*1.0080*	*8.6*		*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*

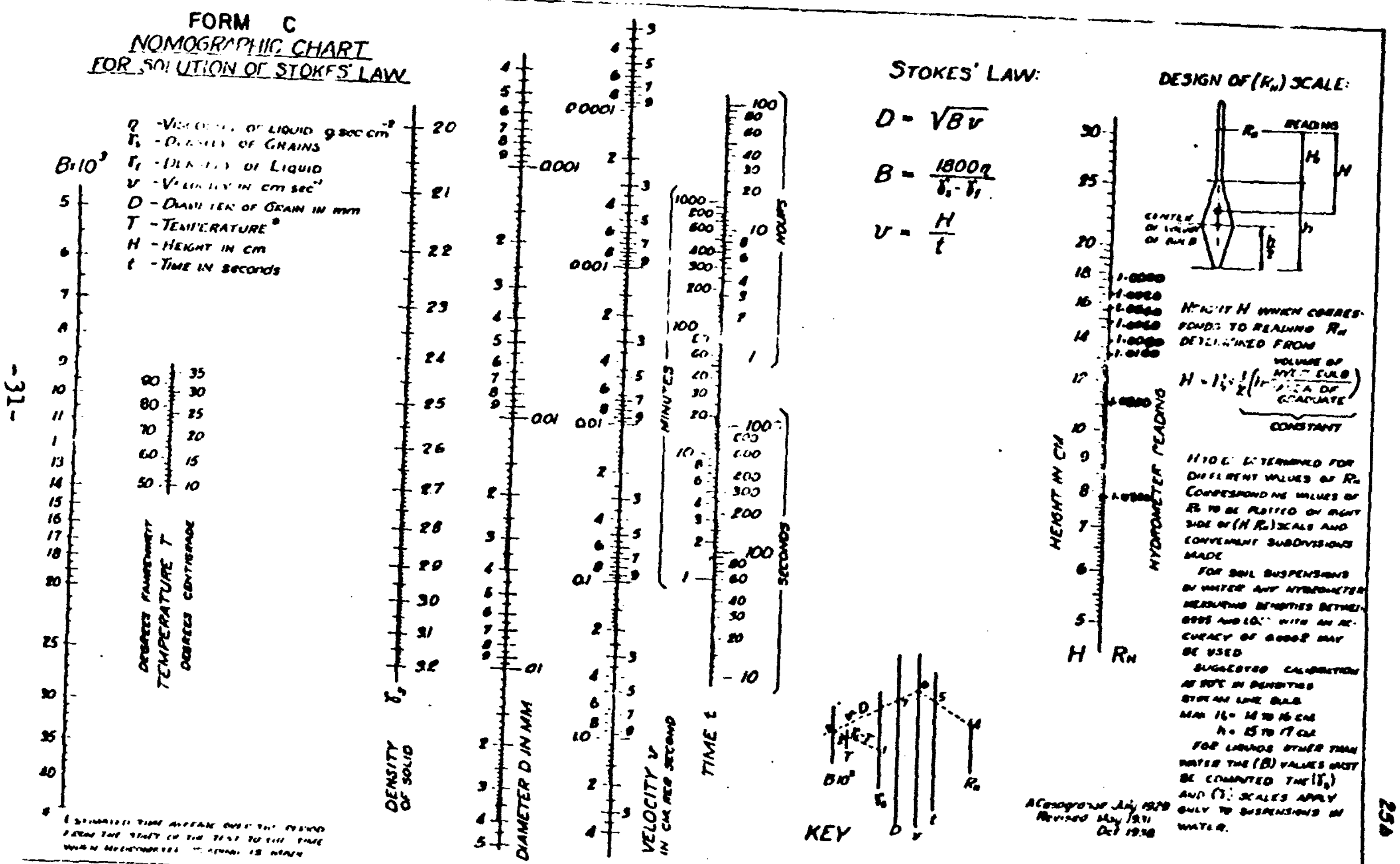
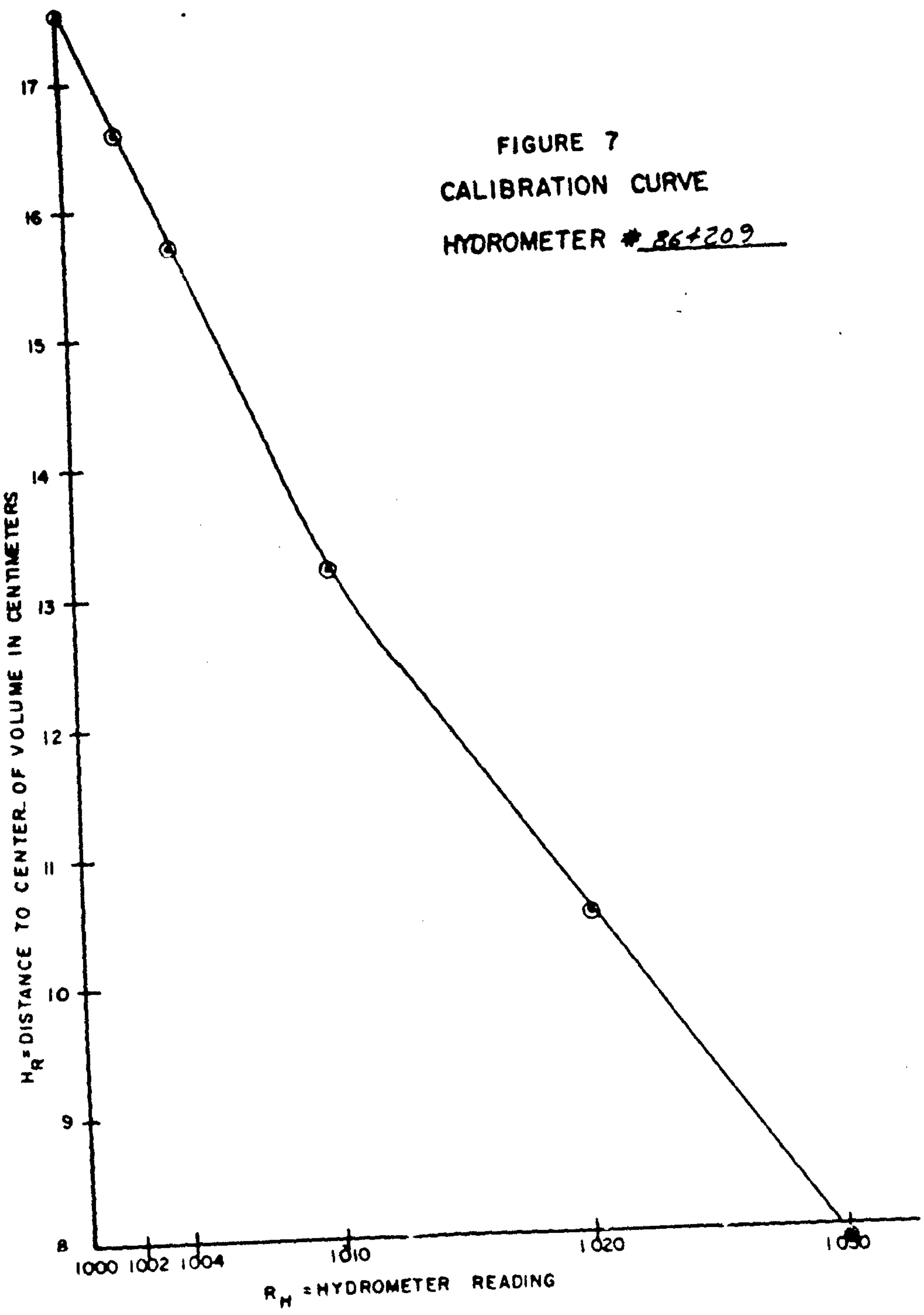

FORM C
NOMOGRAPHIC CHART
FOR SOLUTION OF STOKES' LAW
B·10³
DENSITY OF SOLID
DIAMETER D IN MM
VELOCITY v IN CM PER SECOND
TIME t
MINUTES
HOURS
SECONDS
TEMPERATURE T
DEGREES FAHRENHEIT
DEGREES CENTIGRADE
STOKES' LAW:
D = √(Bv)
B = 1800η / (γs − γl)
v = H / t
DESIGN OF (RH) SCALE:
READING
CENTER OF VOLUME OF BULB
HEIGHT IN CM
HYDROMETER READING
H
RH
KEY
CONSTANT
A Casagrande July 1929
Revised May 1931
Oct 1938

FIG. 13

FIGURE 7

CALIBRATION CURVE

HYDROMETER # 86+209



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.:

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

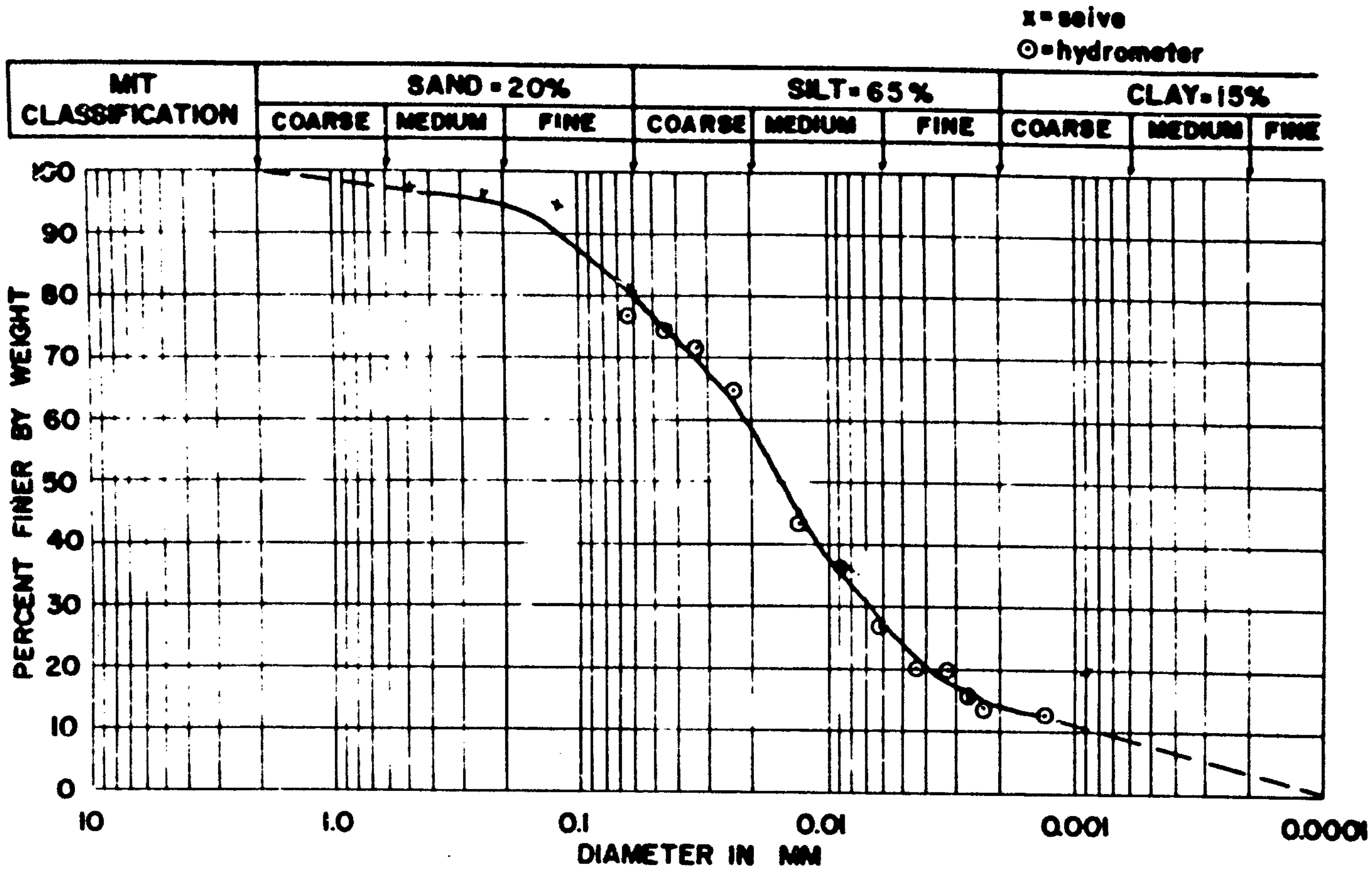
where for example; 0 phi = 1 mm, 1 phi = 1/2 mm, 2 phi = 1/4 mm. From Folk[15] the G.M.S. was calculated as:

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

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

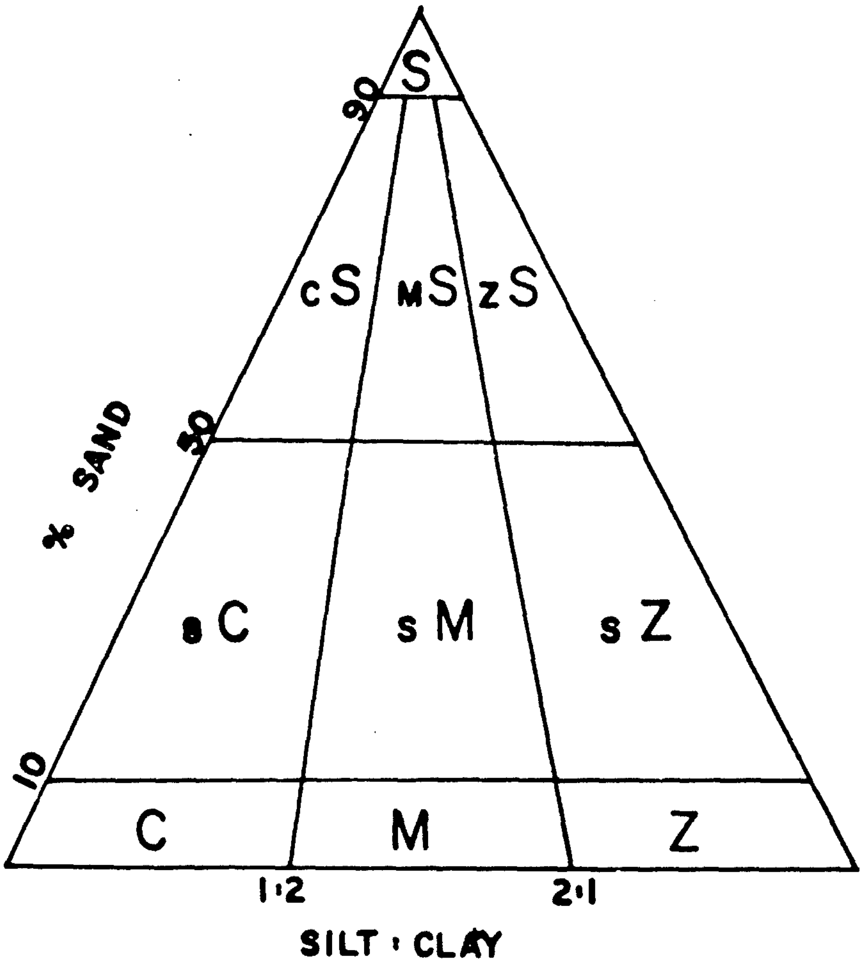
A sediment name was assigned the sample according to the scheme given by Folk[15] and shown in Figure 9. From the grain size distribution curve the percent sand is compared to the ratio of percent silt to percent clay. For sample #283:

% 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. VV = Van Veen SC = Square Corer C = Corer(cylindrical tube used on square corer)
Sand Silt 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 [illegible]

No.	Date	Depth (inches)	Inst.	Sand (%)	Silt (%)	Clay (%)	Name	G.M.S. ($x10^{-3}$mm)	σ_s (φm.)	σ_1 (φm.)	(%)	(%)
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	56	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	14.5	24.2	136	81
33	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-	
63	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.[illegible]	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
193[a]	3/22/66	6	VV	20	55	25	sandy silt	8.0	19.8	16.8	35	69
				15	60	25	sandy silt	8.9	10.1	18.1	180	82
194[a]	3/22/66	6	VV	55	25	20	muddy sand	21.9	9.8	12.7	129	78
				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 (cm.)	w_1 (cm.)	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	1[illegible].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	44
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.[illegible]	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	3[illegible].9	20.2	56	60
258	7/17/66	6	VV	45	30	25	sandy mud	16.2	19.8	16.9	8[illegible]	70

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

No.	Date	Depth (inches)	Inst.	Sand (%)	Silt (%)	Clay (%)	Name	G.M.S. ($x10^{-3}$mm)	σ_s (φm.)	W_1 (φm.)	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[c]	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_1 (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]:

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

where V_z comes from:

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

and d is:

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

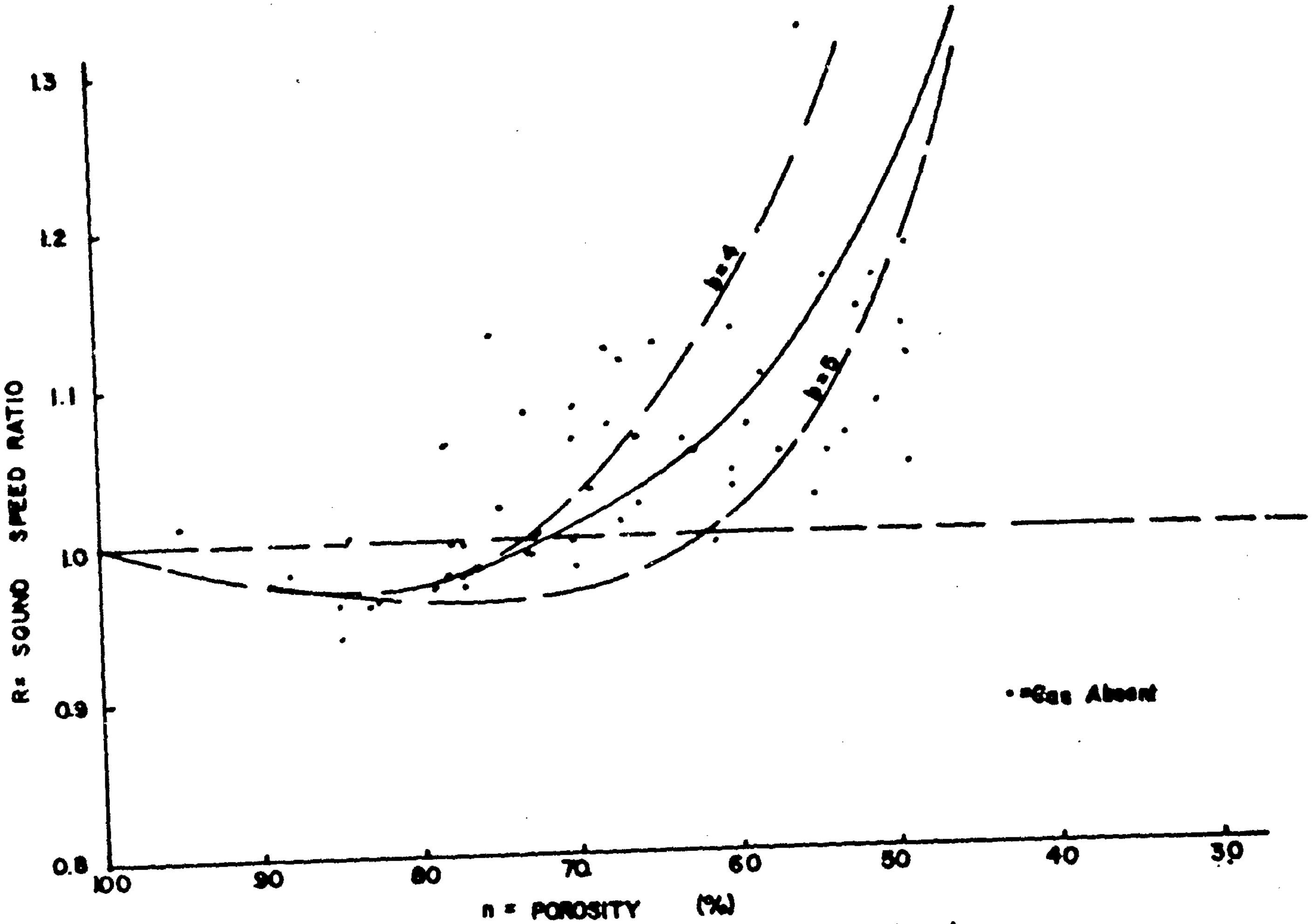


FIGURE 10 Sound Speed Ratio versus Porosity (gas absent)

V_1 = speed of sound in liquid = 1.52 km/sec
V_s = speed of sound in solid = 6.00 km/sec
d_s = denatty of solids = 2.65 gm/cm^3
d_1 = 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:

$$V_z^2 = 2.29 = V_1^2 = V^2$$

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

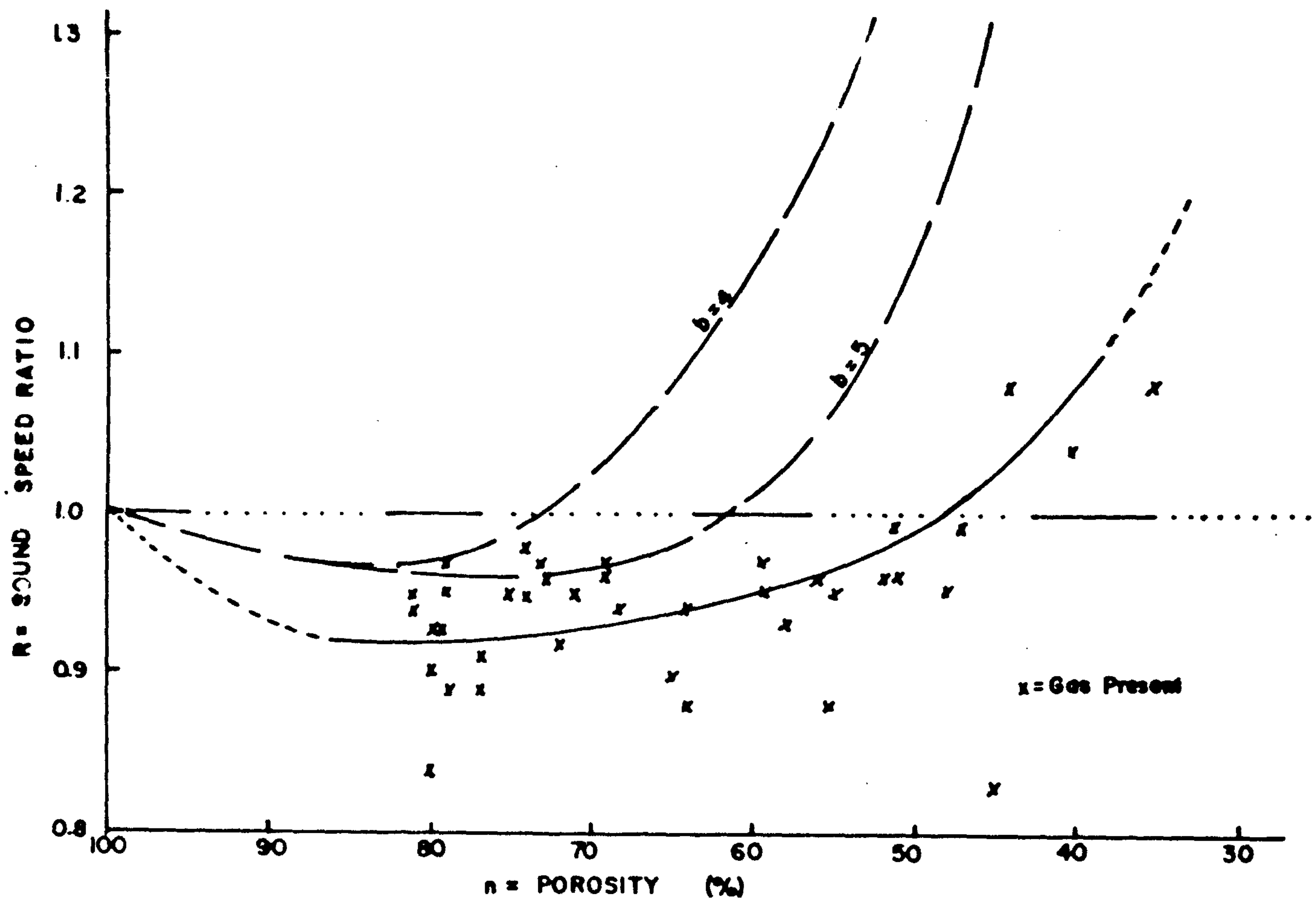


FIGURE 11. Sound Speed Ratio versus Porosity (gas present)

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 'n' is greater than unity. At 'n' equal to unity, 'n' 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 'n' 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 'n' versus water content. Although the scatter is severe, for those samples which are nongaseous, a relation similar to that for 'n' 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% 'n' is less than unity corresponding to the case for porosity greater than 65%.

E. 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 'n' and the

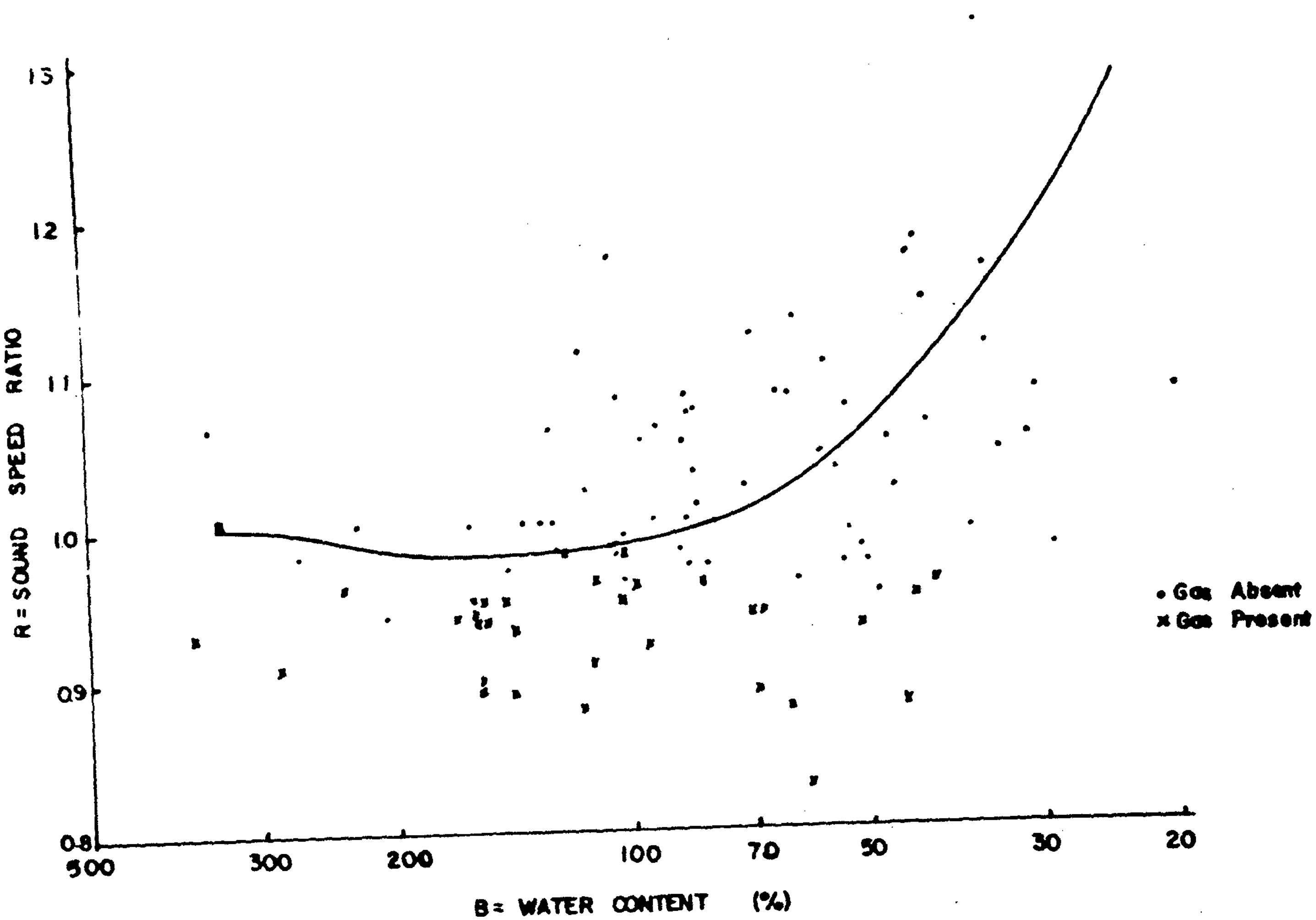


FIGURE 12. SOUND SPEED RATIO VERSUS WATER CONTENT

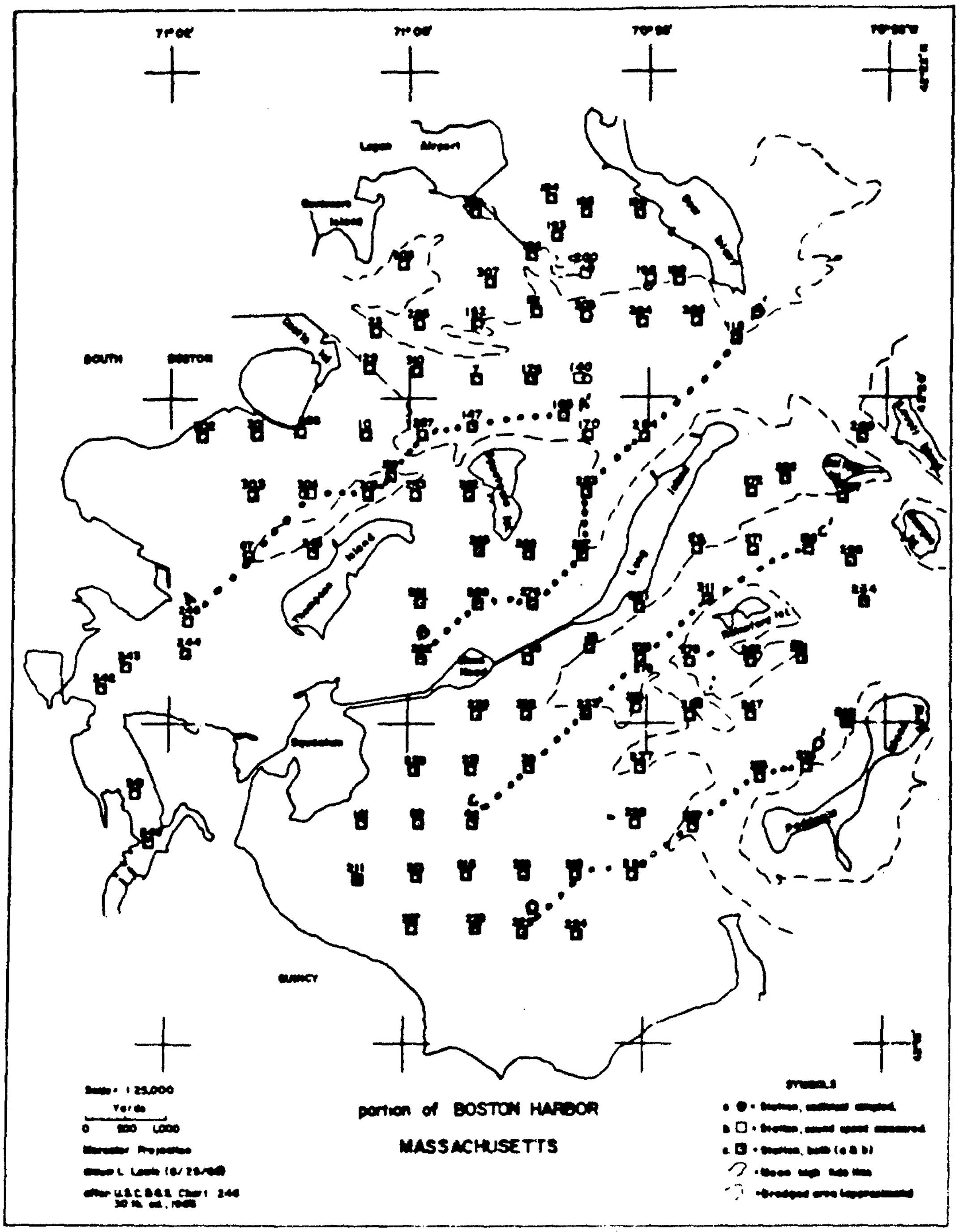


FIGURE 13 SOUND SPEED PROFILE LOCATIONS

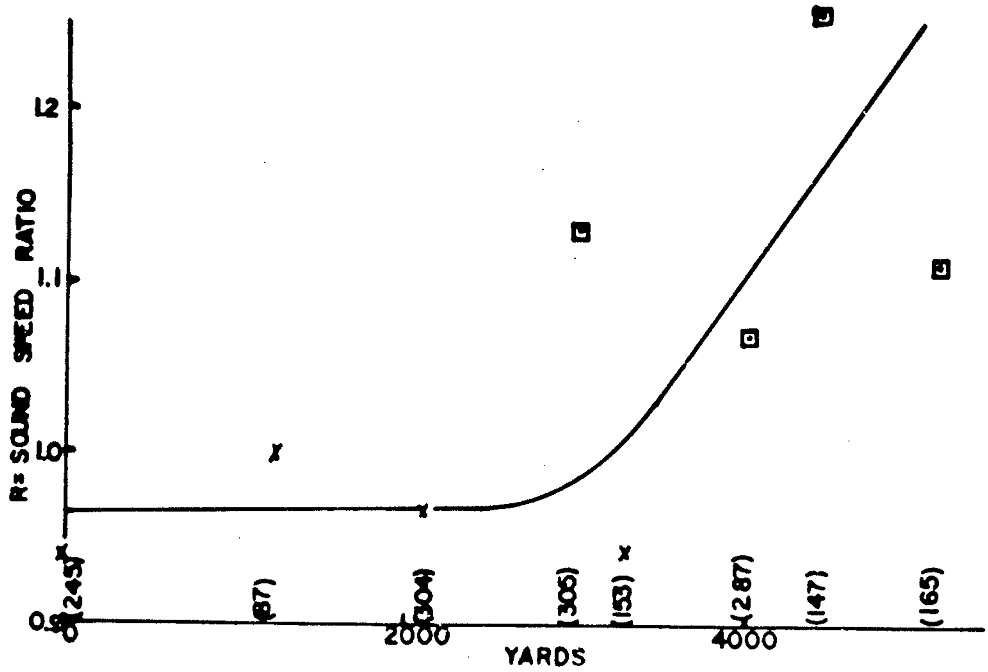


FIGURE 14. PROFILE A - A'

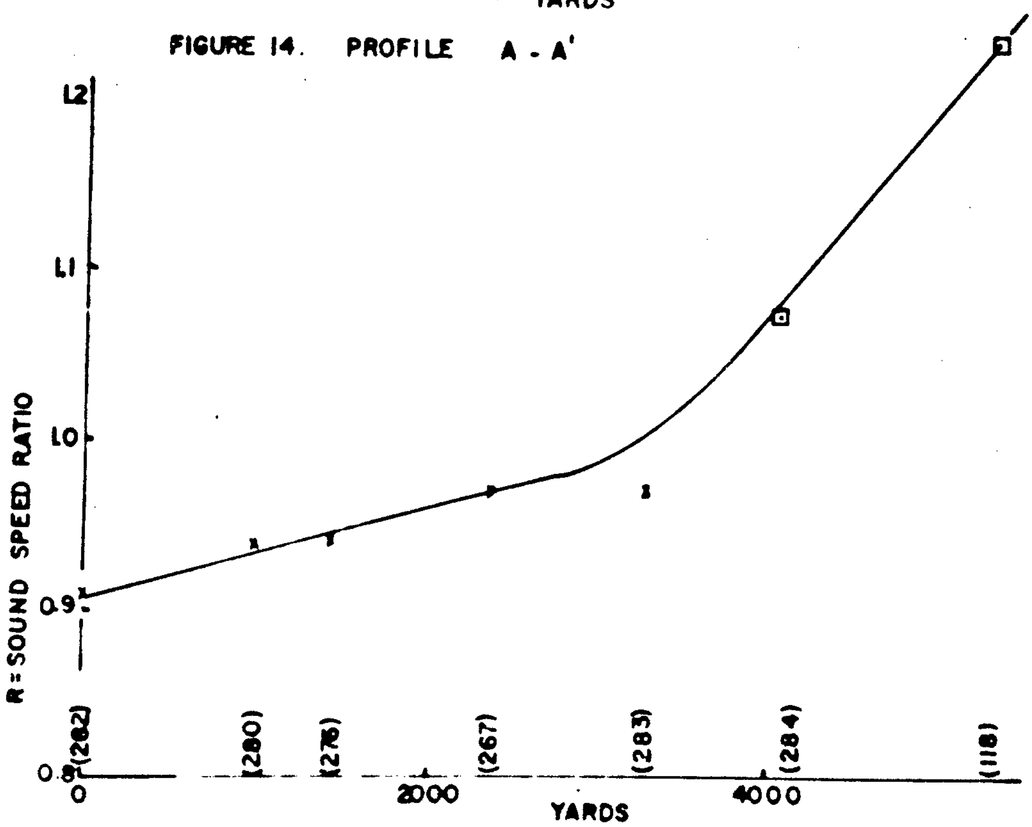


FIGURE 15 PROFILE B - B'

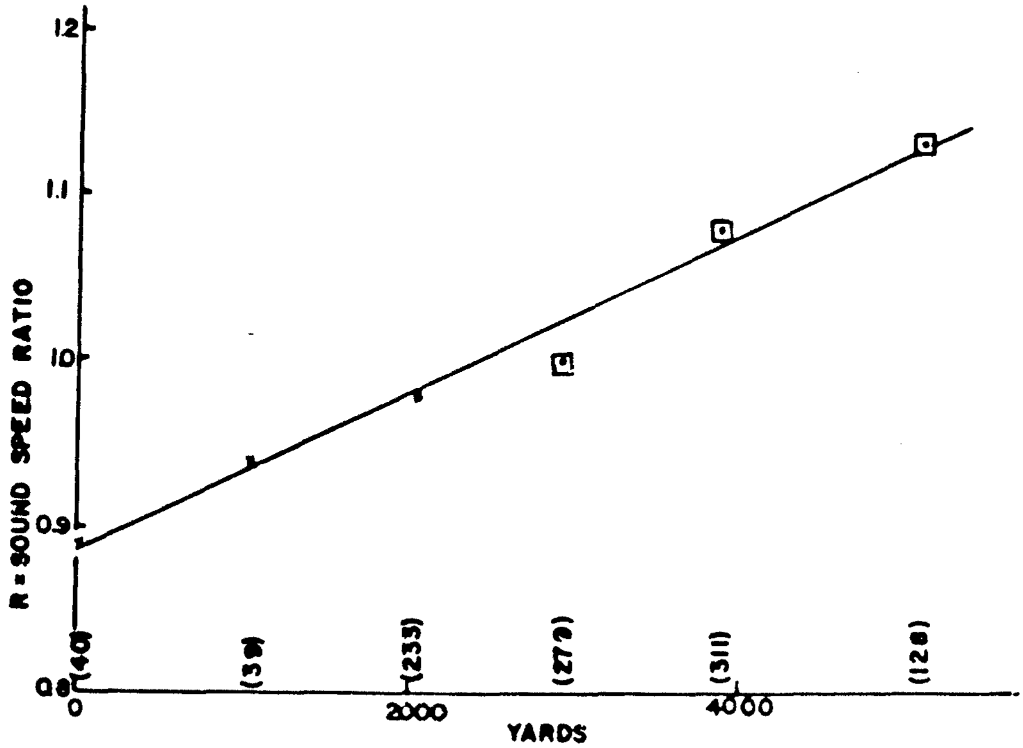


FIGURE 16. PROFILE C-C'

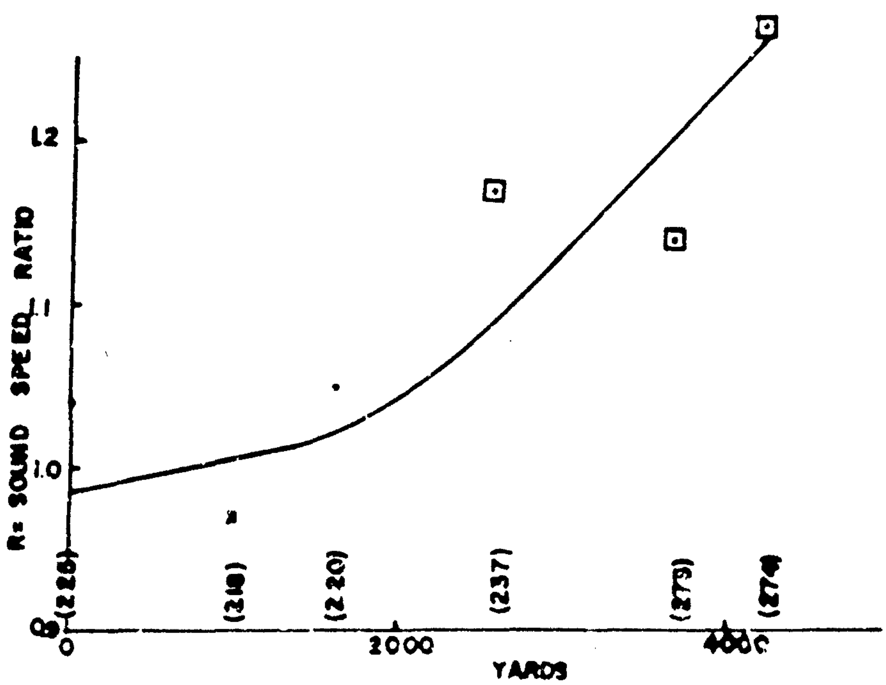


FIGURE 17. PROFILE D-D'

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 'N' 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 'N' values and an average sea water sound speed of 4880 ft/sec. Also listed are the mean and standard deviation in 'N' 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 'N' 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.

A 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

SEDIMENT TYPE	Lewis (1966) No.	n	S.D.	V_s #	Hamilton[22] (1956) V_s	Hamilton[20] (1963) V_s	Shumway[43] (1960) V_s	Sykes[45] (1960) 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	----	48[illegible]0	-
silt and fine sand (less than 15×10^{-3} mm, gas absent)	9	1.06	0.08	5170	507[illegible]	50[illegible]0	----	[illegible]13[illegible]
coarse sand (more than 100×10^{-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 sinkin 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 4.7 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, transmission 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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