(2)

Pressure Attenuation and Geotechnical Properties in Surficial Marine Sediments: Gulf of Mexico Continental Shelf

June 1992

ID 020:360:92

R. H. Bennett
W. B. Sawyer
D. J. Walter
Seafloor Geosciences Division
Ocean Science Directorate
Naval Oceanographic and Atmospheric Research Laboratory
Stennis Space Center, MS 39529-5004

E. N. Litman
Planning Systems, Inc.
Long Beach, MS 39560

Prepared for:
Gregory Page
Naval Surface Warfare Center, Code U-42
White Oak, Silver Spring, MD 20903

NSWC Reference
NAVCOMPT Work Request No. N6092191WRW0247

421485

36pp

PRESSURE ATTENUATION AND GEOTECHNICAL PROPERTIES IN SURFICIAL MARINE SEDIMENTS: GULF OF MEXICO CONTINENTAL SHELF

Richard H. Bennett
William B. Sawyer
Donald J. Walter
SEAFLOOR GEOSCIENCES DIVISION
NAVAL RESEARCH LABORATORY
STENNIS SPACE CENTER, MS 39529

AND

Eric N. Litman
PLANNING SYSTEMS, INC
LONG BEACH, MS 39560

JUNE 1992

Prepared for
Gregory Page
NAVAL SURFACE WARFARE CENTER, CODE U-42
WHITE OAK, SILVER SPRING, MD 20903

NSWC Reference
NAVCOMPT WORK REQUEST NO. N6092191WRW0247

PRESSURE ATTENUATION AND GEOTECHNICAL PROPERTIES IN SURFICIAL MARINE SEDIMENTS: GULF OF MEXICO CONTINENTAL SHELF

BACKGROUND

During September and October 1991, The Naval Research Laboratory, Stennis Space Center (NRLSSC) (formerly the Naval Oceanographic and Atmospheric Research Laboratory, (NOARL)) conducted an in situ geotechnical test and coring of surficial marine sediments on the continental shelf in the Gulf of Mexico. The purpose of the NRLSSC field exercise was to conduct initial test of a newly developed Seafloor Lander (platform). As part of the field work, the Naval Surface Warfare Center, White Oak, (Code U-42, POC: Gregory Page), requested a task be added to assess the effects of marine sediment on subbottom pressure attenuation (surface wave activity and pressure generated by a passing vessel). The task was performed with the exception of the objective to record pressure signals from passing vessels. A malfunction of one of the data recording subsystems approximately 30 hours into the field test terminated data collection prior to accomplishing this task. This task, however, could be performed during the next NRLSSC field exercise. In addition to the Lander measurements, five (5) sediment cores were collected and tested for selected geotechnical (mass physical and mechanical) properties. The sediment properties are required by G. Page as input parameters in the modeling of pressure attenuation in marine sediments using a Biot-Yamamoto poro-elastic model provided by R. Bennett (Yamamoto, Koning, Sellmeijer, and van Hijum, 1978). Preliminary pore pressure data were sent to G. Page. This report contains mostly sediment core data with information concerning the instrumentation and Seafloor Lander. Preliminary analysis of subbottom pressure attenuation was made for selected waves with periods of 5.3 to 12.0 sec. Additional pore pressure data is presently being transferred from the data acquisition system onto floppy disks for additional analyses as required.

INSTRUMENTATION

The Lander is designed to be placed on the seafloor and to serve as a system for various types of seafloor and oceanographic data collection for periods of up to several weeks. Instrumentation capabilities include: in situ ambient sediment pore water pressure, dynamic pore pressures driven by surface wave activity and subbottom pressure attenuation measurements using a device called a piezometer (multi-sensor probe), bottom pressure from wave activity, water and sediment temperature, current speed and direction. The Lander also has cameras for photographing the sea floor and a heading sensor to determine the relative direction of the Lander with respect to magnetic north (Table 1). Other types of instrumentation can be added depending upon project requirements. All data are recorded on two digital, 8-channel 200

Table 1 List of Sensors and Instrumentation that are Major Components of the Seafloor Lander (see Table 2 for Specifications).

INSTRUMENTATION / SENSORS

- PIEZOMETER PROBE (MULTI SENSOR)
- BOTTOM PRESSURE SENSOR
- X–Y CURRENT METER
- TEMPERATURE PROBES (2)
- CAMERAS (8 mm AND 110 STILL)
- PLATFORM ORIENTATION
- ACOUSTIC RELEASES
- DATA ACQUISITION

21d-69-1

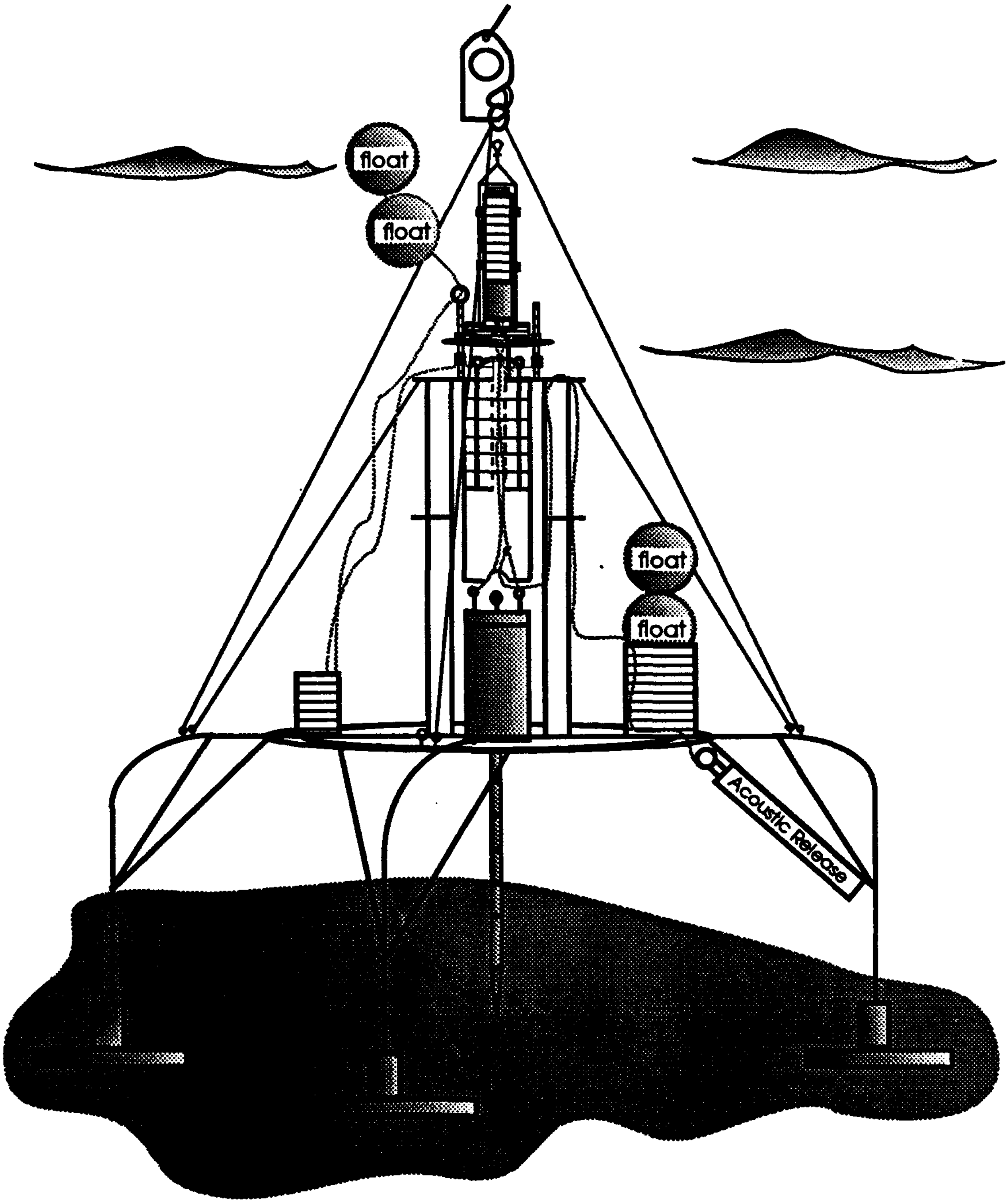
megabyte, data loggers. An acoustic transponder releases buoys for the return of a recovery line at the end of each field test.

The Lander and piezometer configurations are depicted in Figures 1A, 1B and 2. The piezometer is driven into the seafloor sediment on command to an acoustic transponder which releases the probe and driving weights (Figure 1A). When the piezometer is implanted, the probe is physically detached from the Lander with the exception of a data transmission line (electrical cable) which is connected to the data acquisition system located about 6 feet above the seabed. Also a steel cable is connected to the piezometer for return of the Lander system at the end of each test. The piezometer measures sediment pore water pressure at five subbottom depths (6.5"[16.51cm], 15"[38.10cm], 23.5"[59.69cm], 32.0"[81.28cm], and 40.5"[102.87cm]. The sensor located at 40.5" subbottom did not function during the field exercise, however, the remaining four pore water pressure sensors performed excellently providing high resolution data (Figure 2). Free water column "bottom" pressure is measured at 27.55"[69.95cm] and at approximately 6.5 feet above the sea floor.

Thirty-inch diameter foot pads prevent the Lander from excessive settlement into the seabed. Table 2 includes the core data that was provided by the Mississippi National Guard that was obtained from test ran by a commercial firm. This core data were used for the lander pad design. This one core was available prior to the field test when five gravity cores were collected in proximity to the Lander. NRLSSC core data are presented in this report. The various instruments are listed in Table 1 and the system specifications also are given in Table 2. The Seafloor Lander is designed to operate in virtually all continental shelf water depths.

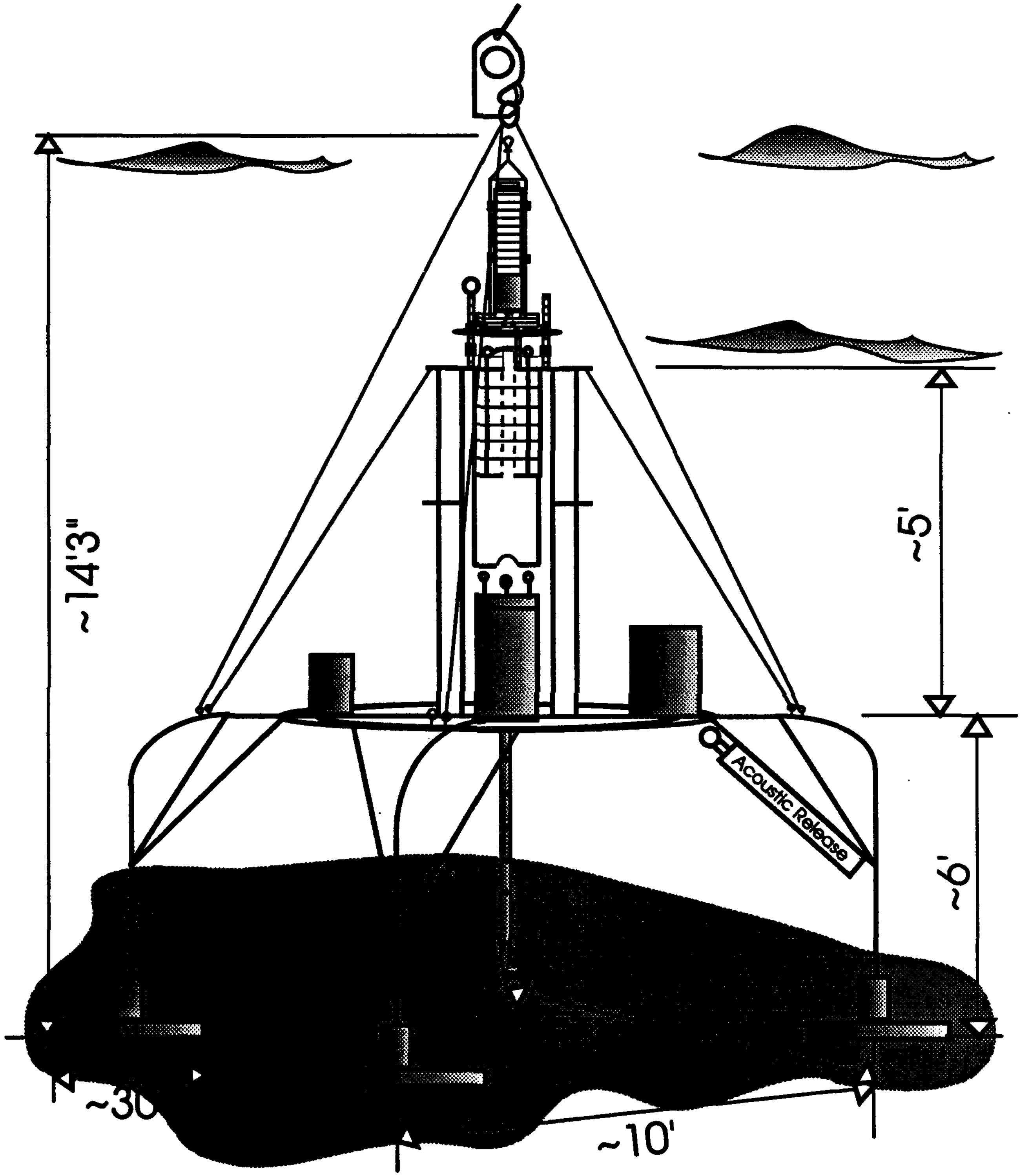
LANDER DEPLOYMENT AND RECOVERY AND CORE LOCATIONS

The site selected for the Lander test was located 30 mi. southeast of Biloxi, MS in 80 ft of water (Figure 3). The Lander was deployed September 23, 1991 and recovered October 4, 1991. Five cores were collected and selected geotechnical properties tests were performed on each core. Three cores, 1-3, were recovered in September 1991 and two cores, 4-5, were collected in April 1992 for additional tests. Cores 3, 4, and 5 were located about 6 ft. from the Lander and cores 1 and 2 were recovered 18 ft. and 28 ft. respectively from the Lander position (Figure 3). The Seafloor Lander test was performed in a relatively soft sandy-silty-clay deposit. Deployment and recovery were carried out aboard the R/V Kit Jones, a 65 foot vessel owned and operated by the State of Mississippi. The vessel easily handled the Lander on both deployment and recovery operations. Divers inspected and video recorded the Lander immediately after deployment. Prior to recovery of the Lander on October 4, 1991 the divers again made a video recording of the relative positions of the Seafloor Lander and the piezometer. Pictures indicated that the platform had not settled



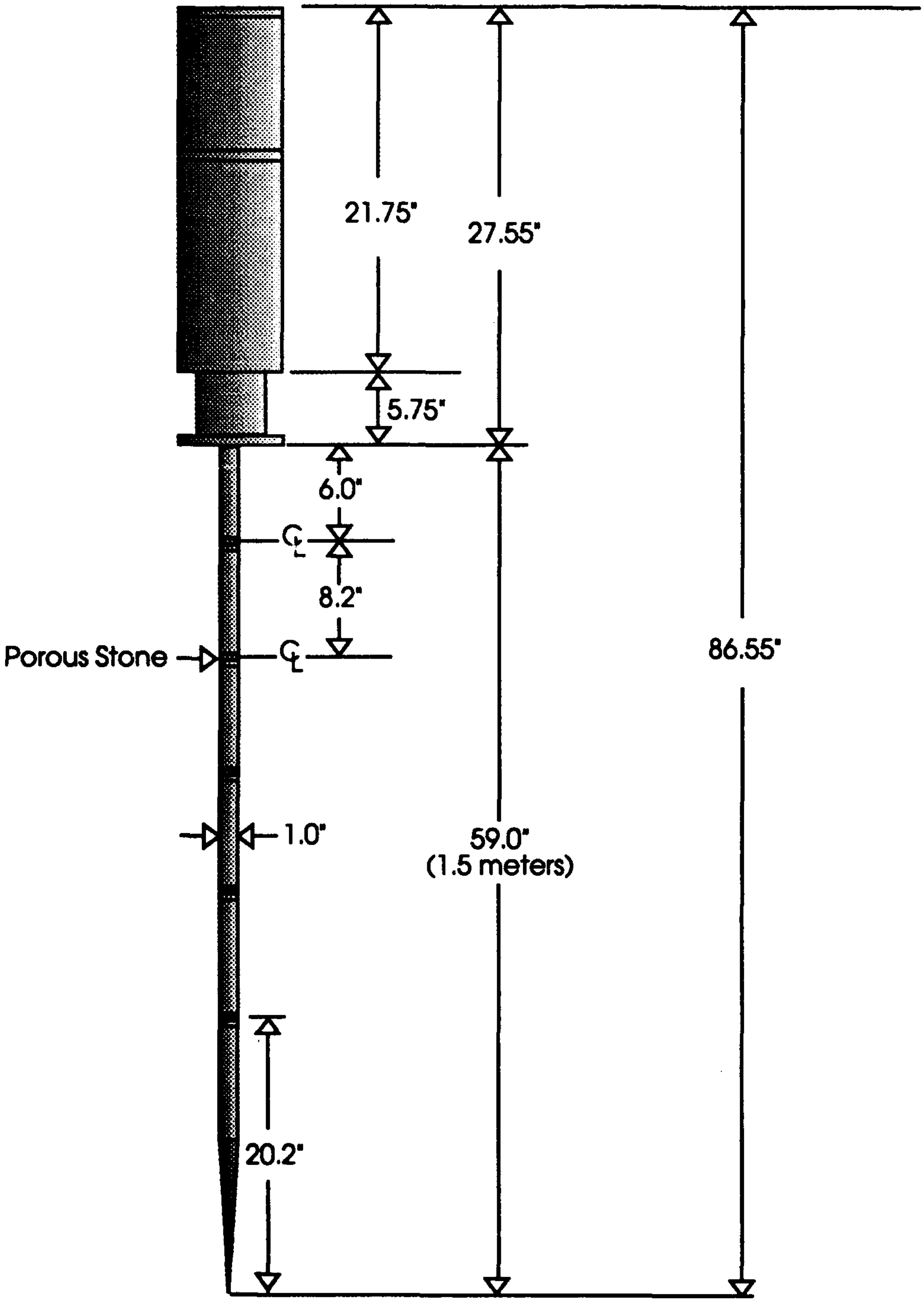
SEAFLOOR LANDER

Figure 1A Seafloor Lander Configuration Depicting Floats, Acoustic Releases, and Rigging of Lines and Cables.



SEAFLOOR LANDER

Figure 1B Seafloor Lander Configuration Depicting Sizes of Pads, Distance Between Pads and Height.



PIEZOMETER PROBE

Figure 2 Piezometer Probe Dimension Depicting Relative Positions of Porous Stones.

Table 2 Specifications of Lander, Sensors, and Instrumentation.

SEAFLOOR LANDER/INSTRUMENTATION/SENSORS

Deployed Sept. 23, 1991; recovered Oct. 4, 1991, 29° 58.89'N 88° 34.97' W.; 30 miles Southeast of Biloxi, MS

Lander: 1425 lbs in air, #5086 Aluminum, 4 1/2 " O.D. sch. 40, Pads 30" diameter, 3" skirt.

Piezometer: 125-150lbs., Nitronic 50 stainless steel probe, spacer and weights 250 lbs., variable reluctance pressure transducers +/- 5v. output. 12 v input power. Sampling rate at 10 samples per sec. (10/sec.). Fused Alum. oxide porous stones with 256 um pore size k = 1.7-2.0 and 10^{-1} cm/sec., N = 35-40 %; ceramic stones k = 3.1 x 10^{-5} cm/sec. pore size 6.0 um, N=50%, Saturation device 12 lbs.

Paroscientific Digiquartz pressure transducer (bottom pressure), quartz crystal resonator, frequency varies with pressure, repeatability .0005% full scale; has RS232 serial interface with data acquisition system, sampling at 10/sec. first two hrs., 5/sec. for 8 sec. then 10/sec for 2 sec., (checking variable data rates).

Data acquisition system: digital 400MB 16 channel max. capacity, control system for all sensors, max. sampling rate 100Hz, pressure case 3000 psi depth rating, Electrical cables with glass filled epoxy connectors

Pressure cases: Alum. 6061-T6 hard coat anodized.

Soil/sediment shear strength *0.42 psi = 60 lbs/sq. ft.* , soft clay, 0-10 ft. subbottom, silty clay. bulk density 84 lbs/cu ft. (initial data used to calc. bearing capacity). F.S. = 4 Factor of Safety bearing capacity. To be revised.

Buoys/Acoustic Releases: 44 lbs. buoyancy (each), acoustic transponder releases, Data Sonics

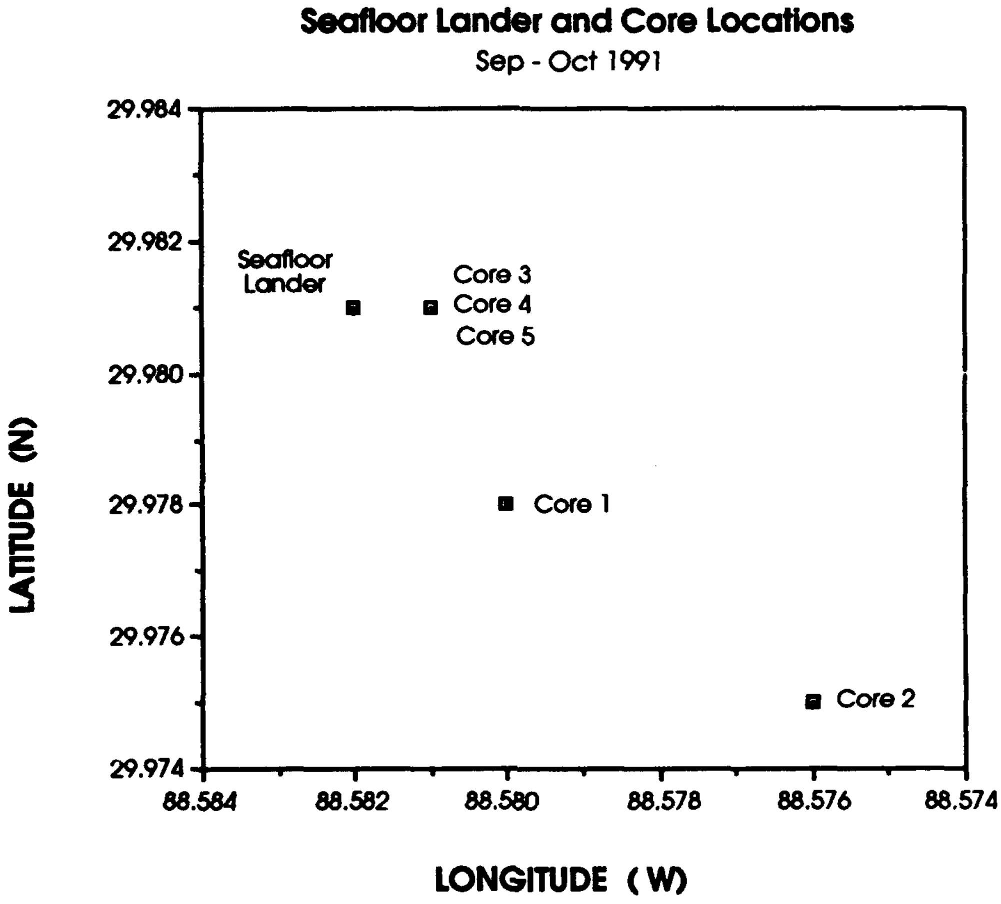
Cameras: 110 still camera, 8000m water depth, movie camera 8mm, 1800 water depth. Camera sampling every 24hrs, also on demand from data acq. system.

Temp. probes: IC Temp. Transducer 0.1°C precision, 1uA/°K, 12 v input power. Model AD 590 PN Transducer, probe 316 stainless steel. range set for 0 - 35 °C, 10° = 0v and 35° = 5v output. Water temp. 70-80°F or 21-27°C. Samples at 2/sec. for 15 sec. duration on demand every 15 min.

X-Y direction Current Meter: Marsh-McBurney 12v input +/-5v = 10'/sec. Samples at 2/sec. for 15 sec. duration on demand every 15 min.

Heading Sensor: KVH Industries Model PC-103, 0-3.590v sensor output, 0.01 v = 1° , field strength sensitivity 0.5 - 45 Telsa, weight 20 oz., 4.8"D X 4.0"H. good to about 1° of rotation. Samples at 2/sec. for 15 sec. on demand every 15 min.

Batteries: Deep Sea Power and Light (2), 12 v 76 A-H each, 150mA average current drain.



Core 1: 29° 58.7' N
88° 34.8' W

Core 2: 29° 58.5' N
88° 34.6' W

Core 3: 29° 58.9' N
88° 34.9' W

Core 4: 29° 58.9' N
88° 34.9' W

Core 5: 29° 58.9' N
88° 34.9' W

Lander: 29° 58.9' N
88° 34.9' W

Figure 3 Core Locations Relative to the Seafloor Lander Position in a Water Depth of 80 feet (-24.4 m).

below the top of the pads but the platform had moved about 3 ft. relative to the piezometer. Piezometer records indicated that the platform had moved within the first hour after the probe was implanted. A line deployed next to the platform during diver inspection appeared to be the cause of the movement. The line apparently snagged the current meter when the line was pulled onto the ship. The movement did not affect the integrity of the data and actually added technical information regarding the efficiency of Lander recovery when the piezometer is offset from the Lander by a few feet.

SEDIMENT PROPERTIES

Extensive analyses were carried out on all cores recovered. Analyses included physical and mechanical properties and core descriptions with grains size (textures). Emphasis in this report is on the sediment properties most important to the modeling of pressure attenuation below the sea floor. The most important parameters are: shear modulus, permeability, porosity and percent saturation (Yamamoto, et al., 1978). Other properties included in this report but of lesser significance in the modeling are, water content, wet bulk density, and derived properties such as overburden stress and effective stress which are important in stability analysis, acoustic modeling, and consolidation studies. Effective stress analysis becomes important when consideration is given to time effects and pore pressure changes driven by surface wave activity in shallow water environments (continental shelf water depths).

Sediments: The marine sediments at the Seafloor Lander site are classified as sandy-silty-clays and grain size analyses indicate that the predominant occurrence of sand is in the upper 0-30 cm although considerable silt and clay is present throughout the entire deposit. Some biogenic shell debris is present but scattered throughout the material. The presence of large amounts of sand relative to silt and clay in the upper 30 cm is responsible for the lowest water contents and porosities and highest wet bulk densities. The low water contents also impart high shear strengths to the near surface sediments. Changes in properties with depth below the sediment-water interface are <u>atypical</u> of many marine sedimentary deposits. Typically, in relatively homogeneous deposits, water contents and porosities are highest near the interface and decrease with depth of burial. Sediment shear strength in normally consolidated deposits are generally lowest (associated with high water contents) near the surface and increase with depth of burial. Changes in the physical and mechanical properties occur with depth as a function of consolidation and overburden stress; variations are commonly due to differences in grain size that occurs laterally and vertically. Grain size data for cores 1, 2, and 3 are found in Tables 3, 4, and 5. Graphs for the grain size distribution with burial depth are found in Figures 4, 5, and 6. Grain size ranges from: Sand 0.0625 mm to 2.0 mm, silt < 0 .0625 mm to .0039 mm, and clay < 0.0039mm.

Table 3 Weight Percent of Sand, Silt, and Clay In Core 1.

NRL CORE #1

DEPTH (cm)	SIZE	WT. MAT'L IN SZ RANGE (gm)	CUMMULATIVE WT. (gm)	WT. %	CUMMLATIVE WT. %
0-1.5	SAND	4.52	4.52	43.91	43.91
	SILT	2.71	7.23	26.34	70.26
	CLAY	3.06	10.29	29.74	100.00
2-4.5	SAND	4.20	4.20	41.24	41.24
	SILT	2.82	7.02	27.71	68.95
	CLAY	3.16	10.18	31.05	100.00
15-19	SAND	3.53	3.53	37.47	37.47
	SILT	2.84	6.37	30.20	67.67
	CLAY	3.05	9.42	32.33	100.00
56-60	SAND	0.20	0.20	2.86	2.86
	SILT	2.09	2.29	29.21	32.07
	CLAY	4.86	7.15	67.93	100.00
77.5-80	SAND	0.37	0.37	6.14	6.14
	SILT	1.41	1.78	23.09	29.24
	CLAY	4.30	6.08	70.76	100.00
90-100	SAND	0.02	0.02	0.25	0.25
	SILT	0.63	O.65	8.81	9.06
	CLAY	6.51	7.15	90.94	100.00
100-105	SAND	0.37	0.37	6.65	6.65
	SILT	1.03	1.40	18.80	25.45
	CLAY	4.11	5.51	74.55	100.00

Table 4 Weight Percent of Sand, Silt, and Clay in Core 2.

NRL CORE #2

DEPTH (cm)	SIZE	WT. MAT'L IN SZ RANGE (gm)	CUMMULATIVE WT. (gm)	WT. %	CUMMLATIVE WT. %
1.5-4.0	SAND	5.24	5.24	53.40	53.40
	SILT	1.80	7.04	18.30	71.70
	CLAY	2.78	9.81	28.30	100.00
4-7	SAND	2.09	2.09	24.71	24.71
	SILT	2.82	2.82	33.34	58.05
	CLAY	3.56	6.38	41.95	100.00
9-22	SAND	1.90	1.90	21.65	21.65
	SILT	2.53	4.43	28.83	50.48
	CLAY	4.36	8.79	49.52	100.00
27-30	SAND	2.45	2.45	30.55	30.55
	SILT	2.61	5.06	32.60	63.15
	CLAY	2.95	8.01	36.85	100.00
57-60	SAND	0.09	0.09	1.67	1.67
	SILT	1.36	1.45	24.79	26.46
	CLAY	4.02	5.47	73.54	100.00
104-107	SAND	0.01	0.01	0.20	0.20
	SILT	0.82	0.83	13.85	14.05
	CLAY	5.09	5.92	85.95	100.00
145-158	SAND	0.15	0.15	1.96	1.96
	SILT	0.61	0.76	7.81	9.76
	CLAY	7.05	7.81	90.24	100.00
161.5-164	SAND	0.08	0.08	1.27	1.27
	SILT	0.96	1.04	15.43	16.70
	CLAY	5.15	6.19	83.30	100.00

Table 5 Weight Percent of Sand, Silt, and Clay in Core 3.

NRL CORE #3

DEPTH (cm)	SIZE	WT. MAT'L IN SZ RANGE (gm)	CUMMULATIVE WT. (gm)	WT. %	CUMMLATIVE WT. %
6 - 9	SAND	5.27	5.27	51.46	51.46
	SILT	2.25	7.52	22.00	73.46
	CLAY	2.72	10.25	26.54	100.00
10-20	SAND	1.18	1.18	12.31	12.31
	SILT	3.74	5.29	39.02	51.33
	CLAY	4.67	9.59	48.67	100.00
28-31	SAND	0.42	0.42	5.37	5.37
	SILT	2.59	3.01	33.03	38.40
	CLAY	4.84	7.86	61.60	100.00
58-61	SAND	0.03	0.03	0.51	0.51
	SILT	0.72	0.75	14.03	14.54
	CLAY	4.39	5.13	85.46	100.00
66-69	SAND	0.17	0.17	2.78	2.78
	SILT	1.26	1.43	20.73	23.51
	CLAY	4.65	6.08	76.49	100.00
75-85	SAND	0.29	0.29	4.04	4.04
	SILT	1.05	1.34	14.52	18.56
	CLAY	5.86	7.20	81.44	100.00
105-108	SAND	0.03	0.03	0.55	0.55
	SILT	0.71	0.74	11.37	11.92
	CLAY	5.50	6.24	88.08	100.00
127-131	SAND	0.34	0.34	4.69	4.69
	SILT	1.40	1.74	19.27	23.96
	CLAY	5.53	7.27	76.04	100.00

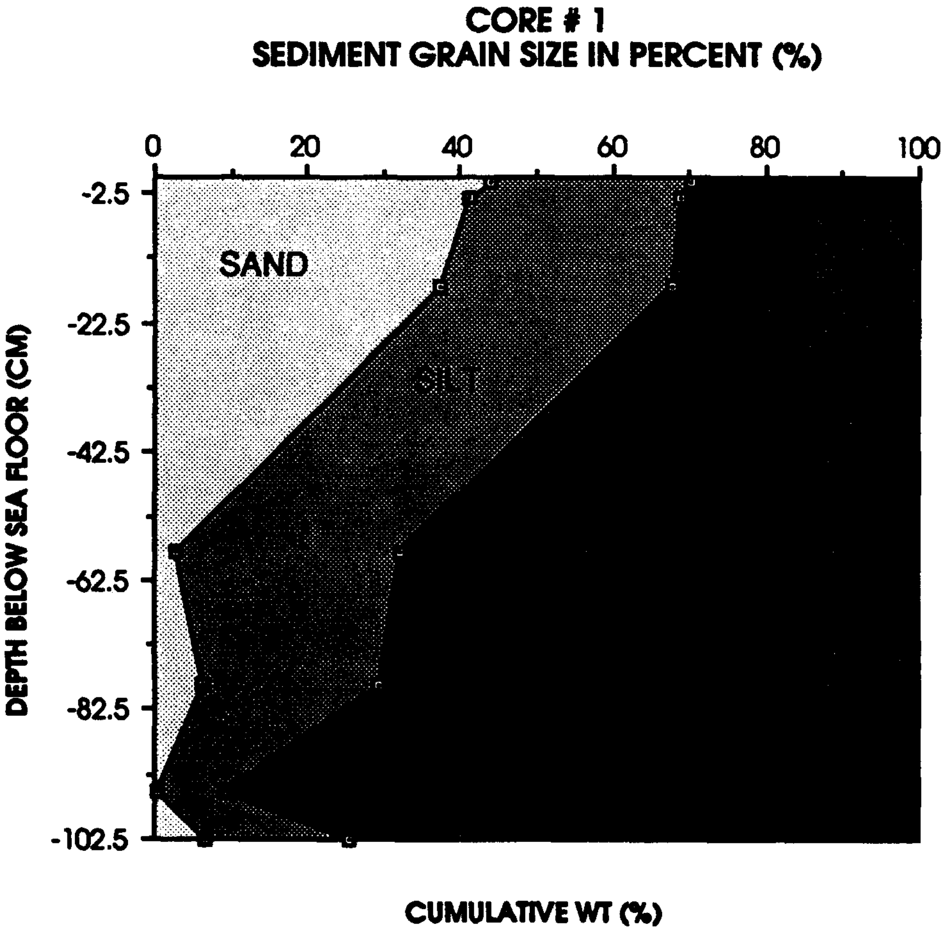


Figure 4 Plot of Sediment Grain Size with Depth Below the Sea Floor in Core 1.

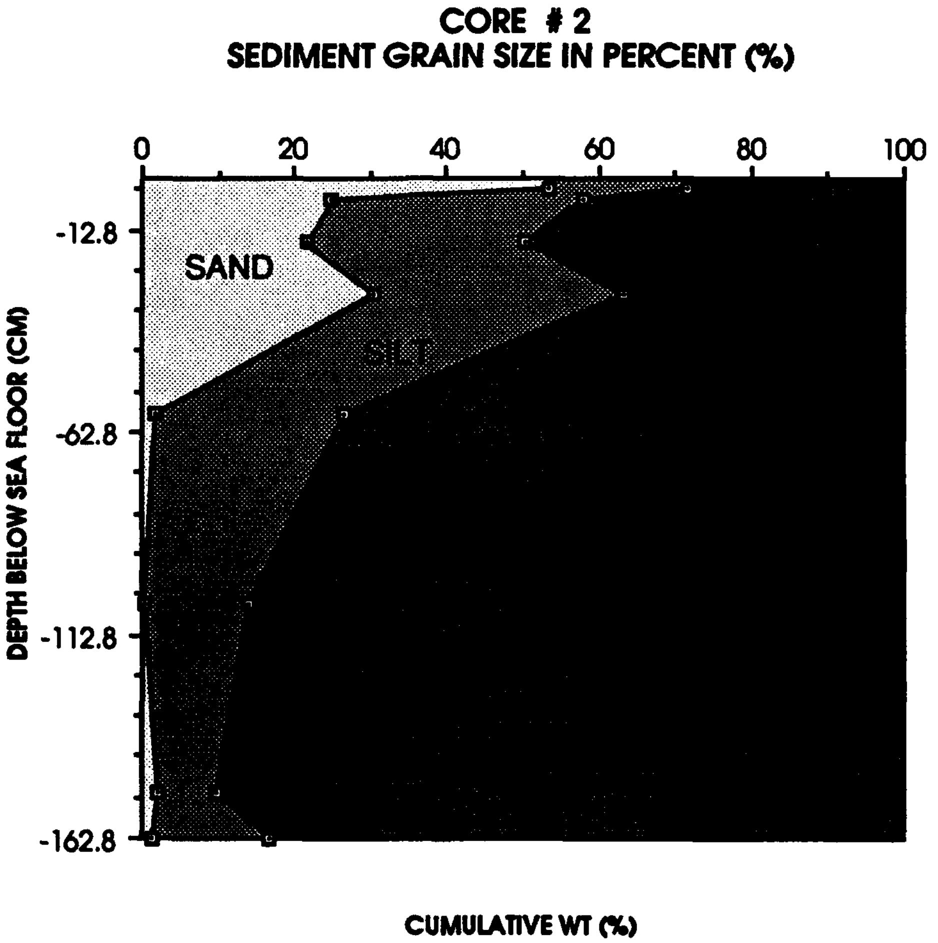


Figure 5 Plot of Sediment Grain Size with Depth Below the Sea Floor in Core 2.

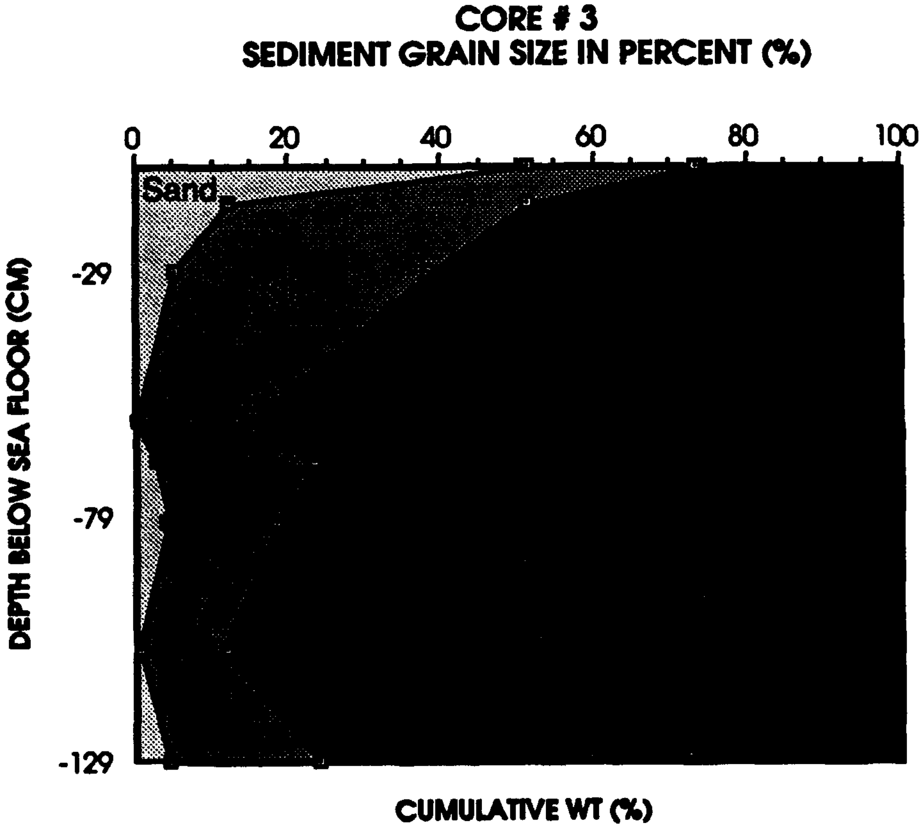


Figure 6 Plot of Sediment Grain Size with Depth Below the Sea Floor in Core 3.

Physical Properties: Wet bulk density is defined as mass per unit volume in units of gm/cc or Mg/m^3 and wet unit weight is the force per unit volume such as lbs./cu. ft. Data for the five cores are found in Table 6. The wet unit weight is used to calculate the total stress with depth below the seafloor and the total stress minus the total pore water pressure is the effective stress (Table 7). Stress is usually expressed in units of PSI or kPa where 1.0 PSI = 6.89 kPa.

Porosity (n) is defined as the ratio of the volume of the voids to the total volume or V_w/V_T and is determined volumetrically by laboratory techniques using calibrated tubes and laboratory measured average grain densities (Table 8, 9 and Figure 7). Water content (w%) is the ratio of the weight of the water to the weight of the dry solids x 100. Both porosity and water content are usually expressed as a percentage and water content is commonly greater than 100% in many fine-grained marine clays. Void ratio (e) is the volume of the voids to the volume of the solids. The relationship between porosity and void ratio is $n = e/1+e$. When sediments are 100% saturated the porosities and wet bulk densities can be determined using the average grain density and the water content data from subsamples; corrections for salt content can be applied if desired (Bennett and Lambert, 1971).

The degree of saturation, or amount of water contained within the sediment pore space, is expressed as the ratio of the volume of the water to the volume of the voids such as V_w/V_v x 100. The degree of saturation is determined by laboratory techniques using water content, average grain density (equal to specific gravity at 4°C), and a calibrated tube volume for each determination. All percent (%) saturation data presented here have been corrected for salt content (Table 9).

Permeabilities were determined on selected subsamples from cores 1 2, and 3. Data reported here were determined directly using the "falling-head" permeability technique. Values are expressed in terms of the coefficient of permeability k (cm/sec.) and intrinsic permeability K (cm^2). The relationship between the two permeability expressions is $K = k\mu/\delta$ where μ = viscosity (gm/cm sec) and δ = unit weight of water (g/cm^3). Data are found in Table 10 which gives the original water content (w%) and void ratio (e_o) values for each sample.

Shear Strength Parameters: Sediment shear strength was determined in the laboratory on cores using a standard miniature vane shear apparatus. Several shear strength tests were made on each core. The shear strength (S_u) reported here is equal to the cohesion (c) of the sediment and the relationship is expressed as $S_u = c + (p_t - p_w) \tan \phi$ where p_t is the total stress, p_w is the total pore water pressure, and $(p_t - p_w)$ is the effective stress and $\tan \phi$ is the angle of internal friction. When the sediment is stressed without loss of pore water then the effective stress term equals zero and $S_u = c$ where c is the cohesion. In fine-grained sediments (muds), such as the materials collected during this field work, the

Table 6 Selected Sediment Core Data.

PHYSICAL PROPERTIES DATA

CORE	DEPTH in Core (cm)	Wet Unit Wt (lbs/ft^3)	Wet Bulk Density (g/cc)
1	4.5-8.5	105.63	1.69
	38-41	88.59	1.42
	80-83	83.47	1.34
	105-108	82.40	1.32
2	5-8	94.21	1.51
	54-57	83.65	1.34
	101-104	82.40	1.32
	158-161	84.28	1.35
	164-167	84.90	1.36
3	35-38	89.15	1.42
	85-88	83.47	1.34
	108-112	88.65	1.42
	135.5-139	84.90	1.36
4	2-4	102.24	1.64
	4-7	104.25	1.67
	13-18	96.86	1.55
	30.5-34	98.07	1.57
	42-46	86.51	1.39
	70-73	82.81	1.33
	76-78	85.45	1.37
5	1-4	104.25	1.67
	9-12	103.54	1.66
	28-31.5	94.26	1.51
	39.5-42.5	86.62	1.39
	46-49	84.72	1.36
	58-61	91.14	1.46
	67-70	83.07	1.33

Table 7 Calculated Effective Overburden Stress and Total Overburden Stress (TOS) for Cores 1 - 5. Actual Values for Table 7 Total Stress Should Have Water Column Pressure Plus Atmospheric Pressure Added to TOS.

PHYSICAL PROPERTIES DATA

CORE	DEPTH (cm)	TOTAL* OVERBURDEN STRESS			EFFECTIVE OVERBURDEN STRESS		
		(Lbs/ft^2)	(PSI)	(kPa)	(Lbs/ft^2)	(PSI)	(kPa)
1	20	69.31	0.48	3.32	27.32	0.19	1.31
	60	185.57	1.29	8.88	59.59	0.41	2.85
	90	267.73	1.86	12.81	78.75	0.55	3.77
	110	321.80	2.23	15.39	90.82	0.63	4.36
2	30	92.73	0.64	4.44	29.74	0.21	1.42
	80	229.95	1.60	11.02	61.97	0.43	2.96
	130	365.51	2.53	17.47	92.54	0.64	4.43
	162	453.99	3.15	21.72	113.83	0.79	5.45
	170	476.27	3.31	22.79	119.31	0.83	5.71
3	60	175.49	1.22	8.40	49.51	0.34	2.37
	95	271.34	1.88	12.98	71.86	0.50	3.44
	120	344.05	2.39	16.46	92.08	0.64	4.41
	140	399.75	2.78	19.13	105.78	0.73	5.06
4	4	13.42	0.09	0.64	5.02	0.03	0.24
	10	33.94	0.24	1.62	12.94	0.09	0.62
	25	81.61	0.57	3.90	29.12	0.20	1.39
	35	113.79	0.79	5.44	40.30	0.28	1.93
	55	170.56	1.18	8.16	55.07	0.38	2.64
	75	224.90	1.56	10.76	67.42	0.47	3.23
	80	238.92	1.66	11.43	70.94	0.49	3.39
5	6	20.52	0.14	0.98	7.92	0.06	0.38
	20	68.08	0.47	3.25	26.09	0.18	1.25
	35	114.68	0.79	5.48	41.19	0.29	1.97
	45	143.10	0.99	6.84	48.61	0.34	2.33
	55	170.90	1.19	8.18	55.41	0.38	2.62
	65	200.80	1.39	9.58	64.32	0.45	3.08
	75	228.05	1.58	10.91	70.57	0.49	3.38

* *with water column pressure subtracted above sea floor*

80 ft of water = 35.5 psi
14.5 psi = atm. pressure

Table 8 Average Grain Density Data for Cores 1-5.

AVERAGE GRAIN DENSITY

(CORRECTED FOR SALT CONTENT)

CORE 1		CORE 2		CORE 3		CORE 4		CORE 5	
DEPTH (cm)	VALUE (g/cc)	DEPTH (cm)	VALUE (g/cc)	DEPTH (cm)	VALUE (g/cc)	DEPTH (cm)	VALUE (g/cc)	DEPTH (cm)	VALUE (g/cc)
0.0-1.5	2.64	0.0-1.0	2.65*	3.0-4.0	2.65*	2.0-4.0	2.61	1.0-4.0	2.62
2.0-4.5	2.61	1.5-4.0	2.63	6.5-9.0	2.72*	4.0-7.0	2.64	9.0-12.0	2.65
4.5-8.5	2.68	5.0-8.0	2.64*	22.0-23.0	2.65*	13.0-16.0	2.64	28.0-31.5	2.65
5.0-8.5	2.69*	8.0-9.0	2.65*	35.0-38.0	2.62	30.5-34.0	2.64	39.5-42.5	2.65
12.0-13.0	2.63	23.5-26.0	2.66*	35.0-38.0	2.65*	43.0-46.0	2.69	46.0-49.0	2.65
15.5-18.0	2.65	54.0-57.0	2.66	38.0-41.0	2.64*	70.0-73.0	2.65	58.0-61.0	2.60
21.0-22.0	2.64	54.0-57.0	2.63*	85.0-88.0	2.69*	76.0-78.0	2.66	67.0-70.0	2.62
34.0-35.0	2.62	101.0-104.0	2.58	108.0-112.0	2.69				
35.5-38.0	2.59	101.0-104.0	2.64*	108.0-112.0	2.66*				
38.0-41.0	2.64	158.0-161.0	2.69*	127.0-130.0	2.72*				
38.0-41.0	2.62*	164.0-167.0	2.57	135.5-139.0	2.68				
42.0-45.0	2.61	164.0-167.0	2.69*	135.5-139.0	2.67*				
50.0-51.0	2.62								
56.5-59.0	2.62								
64.0-65.0	2.62								
80.0-83.0	2.65								
80.0-83.0	2.62*								
105.0-108.5	2.67								
105.0-108.5	2.64*								
115.0-116.0	2.61								

* NRL DATA CORRECTED FOR SALT CONTENT
OTHER DATA NAVO - CORRECTED FOR SALT CONTENT

Table 9 Percent Saturation and Porosity Data for Core 1-5.

PERCENT SATURATION AND POROSITY DATA

CORE NUMBER	CORE DEPTH (cm)	PERCENT (%) SATURATION	POROSITY
1	4.5-8.5	95.0	58.1
1	38.0-41.0	99.7	75.3
1	80.0-83.0	99.0	80.2
1	105.0-108.5	97.4	80.4
2	1.5-4.5	100.0	69.8
2	54.0-57.0	99.2	80.0
2	101.0-104.0	99.1	81.2
2	158.0-161.0	98.0	79.5
2	164.0-167.0	97.4	78.5
3	35.0-38.0	100.0	75.4
3	85.0-88.0	100.0	81.2
3	108.0-112.0	100.0	76.2
3	135.5-139.0	100.0	79.3
4	2.0-4.0	100.0	62.7
4	4.0-7.0	99.0	59.5
4	13.0-16.0	100.0	67.7
4	30.5-34.0	100.0	66.2
4	43.0-46.0	97.6	77.1
4	70.0-73.0	95.9	79.3
4	76.0-78.0	99.5	77.2
5	1.0-4.0	100.0	60.0
5	9.0-12.0	100.0	61.1
5	28.0-31.5	100.0	70.1
5	39.5-42.5	98.4	76.8
5	46.0-49.0	99.2	78.4
5	58.0-61.0	99.0	72.2
5	67.0-70.0	97.0	79.6

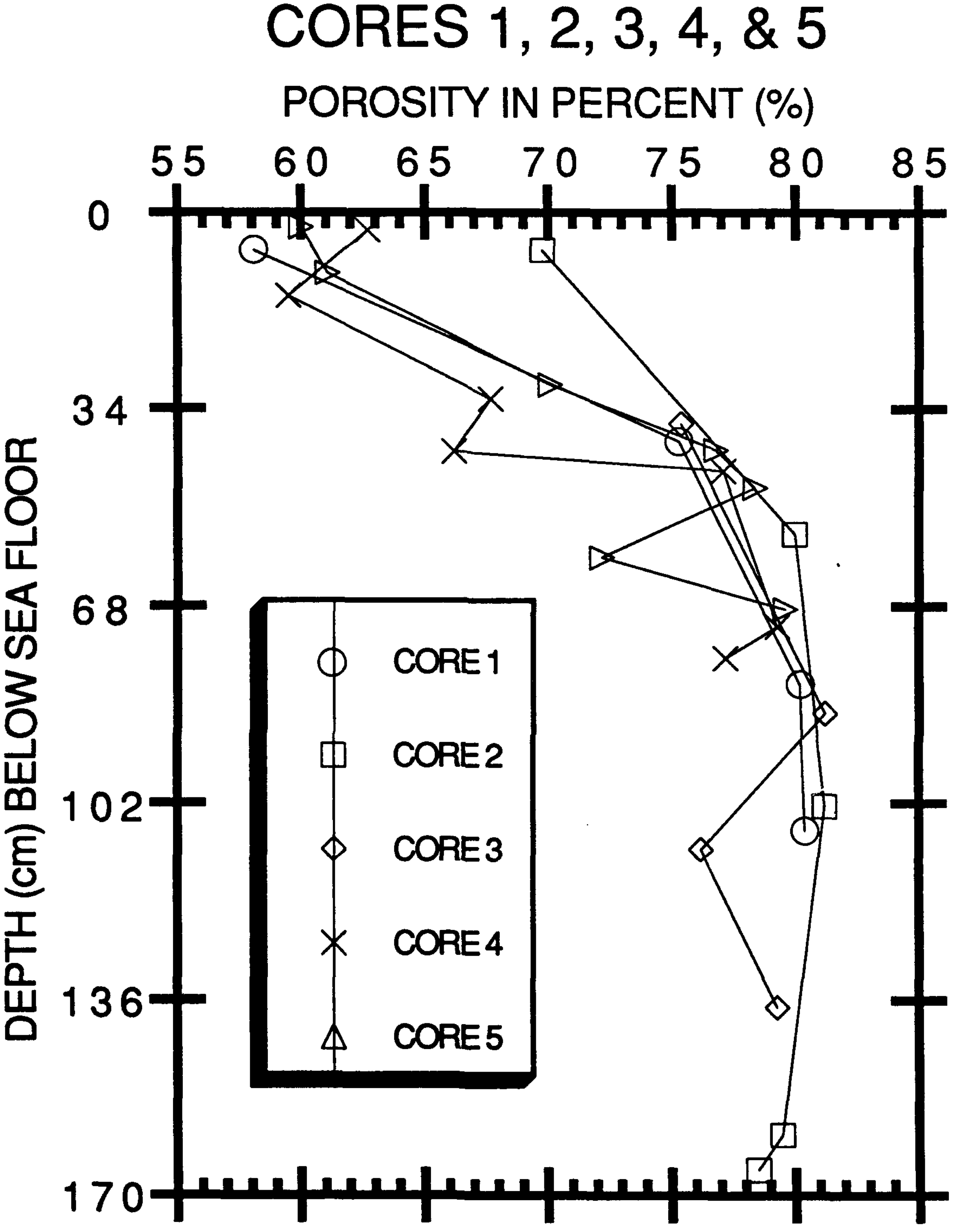


Figure 7 Porosity Profiles of Cores 1, 2, 3, 4, & 5.

Table 10 Permeability Data for Cores 1 - 3.

PHYSICAL PROPERTIES DATA

PERMEABILITY

CORE	DEPTH	k (cm/sec)	VOID RATIO * Original e_o	WATER CONTENT * Initial w_o	K (cm^2)
3	10 - 20(15cm)	1.51×10^{-6} cm/s	1.48	64.2	1.56×10^{-11} cm ^{2}
2	9 - 22(15.5cm)	8.66×10^{-7} cm/s	1.83	77.9	8.93×10^{-12} cm ^{2}
3	75 - 85(80cm)	4.14×10^{-7} cm/s	3.87	150.1	4.23×10^{-12} cm ^{2}
1	90 - 100(95cm)	4.42×10^{-6} cm/s	4.65	154.5	4.56×10^{-11} cm ^{2}
2	145 - 158(150cm)	5.41×10^{-7} cm/s	3.78	140.4	5.58×10^{-12} cm ^{2}

* *uncorrected for salt content*

cm/s x 1.031 x $10^{-5} = cm^2$

sediments have very low permeabilities and the use of a vane shear apparatus is standard geotechnical practice for the determination of sediment shear strength. The shear strength is depicted in Figure 8 for core 1-5 and a regression (third degree polynomial) is depicted in Figure 9 for all shear strength data. Values of shear strength in kPa and PSI are given in Tables 11 and 12.

The shear modulus (G) for cores 1-5 was calculated from a value for shear modulus ratio equal to 120. The shear modulus ratio is defined as the ratio of the shear modulus to the undrained shear strength or G/Su. The value of 120 has been used extensively for engineering design of offshore platforms in the Gulf of Mexico. Laboratory tests at Texas A&M University, Department of Geotechnical Engineering, have shown this ratio (value of 120) to be a reasonable estimate for continental shelf fine-grained sediments consisting predominantly of clay minerals (personal communication, 1992, Wayne A. Dunlap, TAMU). Plot of the shear modulus with depth below the seafloor is depicted in Figure 10. Figure 11 gives the third degree polynomial regression for the shear modulus with depth of burial.

Dynamic Pore Water Pressures and Pressure Attenuation in Sediment: Pore water pressures at four subbottom depths were measured for the duration of the experiment (approximately 30 hrs. when the data logging terminated). Dynamic pore water pressures were monitored synchronous with "bottom" pressure measurements. Excellent resolution of dynamic bottom pressures and pore water pressures with depth below the sea floor were obtained (Figure 12). Significant bottom pressure attenuation and phase shift is revealed in the data (Figures 12, 13, 14, 15). Preliminary analysis of the ratio p/p_0 of pore pressure amplitude (p) to bottom pressure amplitude (p_0) versus subbottom depth reveal significant attenuation for several bottom pressure wave periods (12.0 sec to 5.3 sec; and Table 13). Considerable energy is lost in the upper 1 - 2 feet subbottom for these short period waves. These data are plotted on an earlier graph (Figure 16) published by Yamamoto (1981) which showed the relationship of bottom pressure attenuation p/po with depth from theory and field data collected by Bennett for the Mississippi Delta coastal environment (Bennett and Faris 1979). Yamamoto's theory (1981) showed good agreement with the field data, however, some of his input parameters (sediment properties) were not in agreement with later core data reported by Bennett et al., (1986).

In contrast to the pressures generated by short period waves, long period tidal waves of only about a 1 1/2 ft. amplitude and having a pressures of approximately .6-.7 PSI are transmitted to depths of at least 51 feet below the seafloor in high porosity Mississippi Delta muds (Bennett and Faris, 1979). Even lower amplitude, lower pressure, tidal waves were found to transmit equivalent pressure and to be in phase to depths of 51 feet subbottom (ibid., Figure 17 from Bennett and Faris, 1979, and Bennett, et al. 1982).

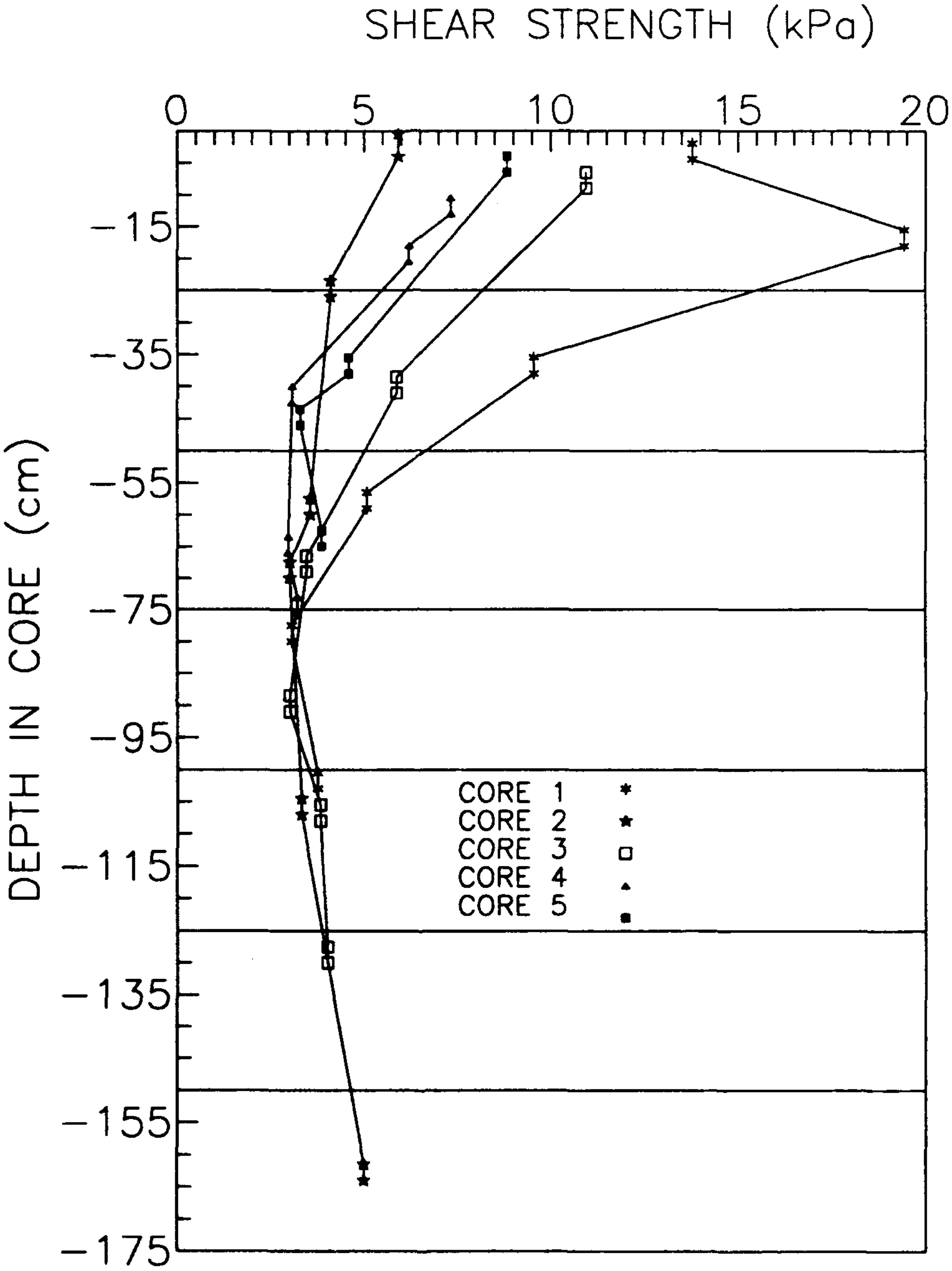


Figure 8 Undrained Shear Strength Versus Core Depth in Cores 1-5.

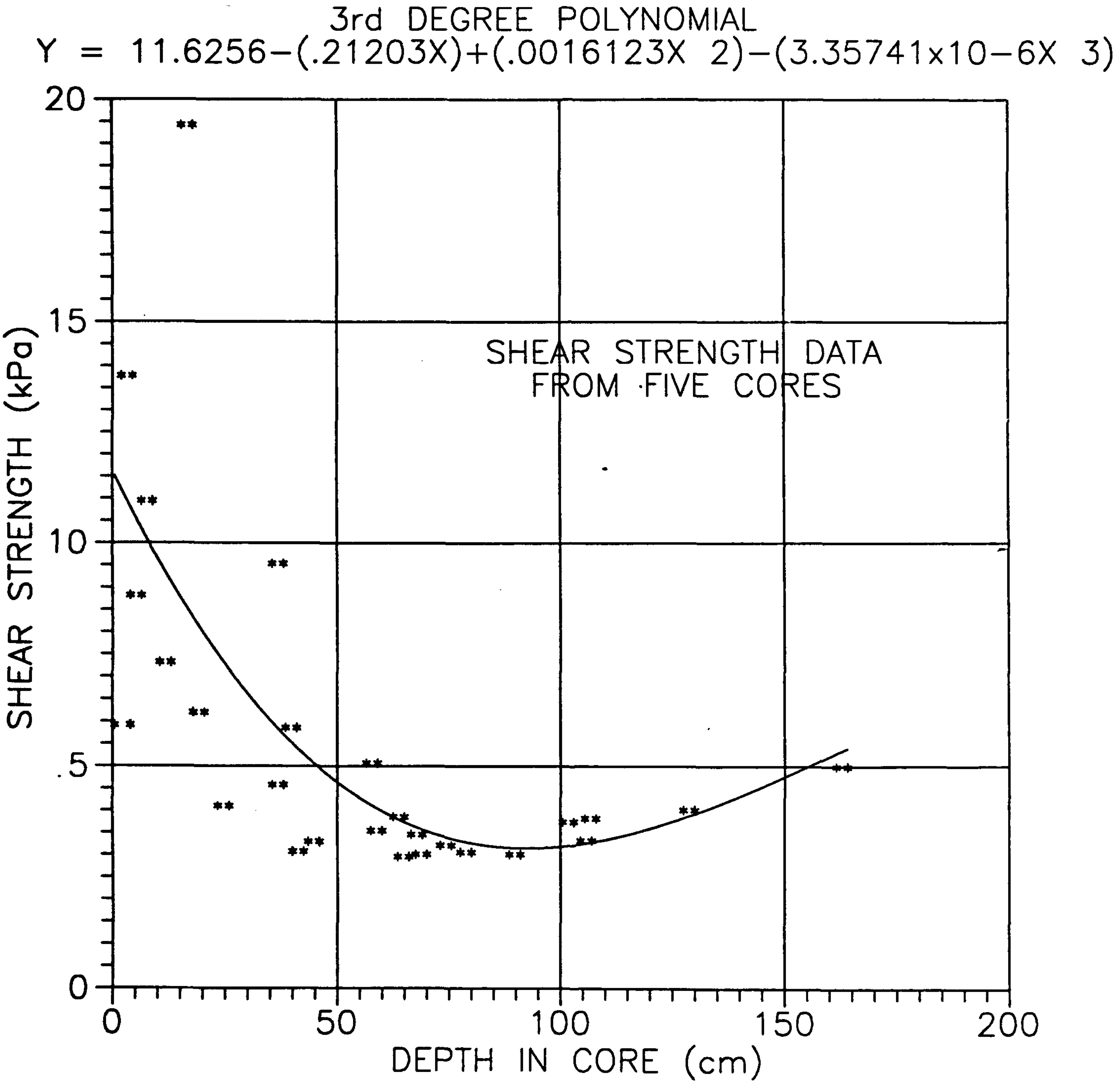


Figure 9 Shear Strength Versus Subbottom Depth in Cores 1-5 and 3rd Degree Polynomial Regression.

Table 11 Undrained Shear Strength (SS) and Shear Modulus for Cores 1-3.

CORE 1

DEPTH	SS (kPa)	SHEAR MODULUS (kPa)	(psi)
-2	13.78	1653.6	240
-4.5	13.78	1653.6	240
-15.5	19.4232	2330.78	338.3
-18	19.4232	2330.78	338.3
-35.5	9.53817	1144.58	166.1
-38	9.53817	1144.58	166.1
-56.5	5.07104	608.52	88.3
-59	5.07104	608.53	88.3
-77.5	3.05916	367.1	53.3
-80	3.05916	367.1	53.3
-100.5	3.74816	449.78	65.3
-103	3.74816	449.78	65.3

CORE 2

DEPTH	SS (kPa)	SHEAR MODULUS (kPa)	(psi)
-0.5	5.91575	709.9	103
-4	5.91575	709.9	103
-23.5	4.10196	492.24	71.4
-26	4.10196	492.24	71.4
-57.5	3.54387	425.27	61.7
-60	3.54387	425.27	61.7
-67.5	3.01369	361.64	52.5
-70	3.01369	361.64	52.5
-104.5	3.32064	398.47	57.8
-107	3.32064	398.47	57.8
-161.5	4.99491	599.39	87
-164	4.99491	599.39	87

CORE 3

DEPTH	SS (kPa)	SHEAR MODULUS (kPa)	(psi)
-6.5	10.9386	1312.63	190.5
-9	10.9386	1312.63	190.5
-38.5	5.85994	703.19	120.1
-41	5.85994	703.19	120.1
-66.5	3.46016	415.22	60.3
-69	3.46016	415.22	60.3
-88.5	3.01369	361.64	52.5
-91	3.01369	361.64	52.5
-105.5	3.82292	458.75	66.6
-108	3.82292	458.75	66.6
-127.5	4.01825	482.18	70
-130	4.01825	482.18	70

Table 12 Undrained Shear Strength (SS) and Shear Modulus for Cores 4 and 5.

CORE 4

DEPTH	SS (kPa)	SHEAR MODULUS (kPa)	SHEAR MODULUS (psi)
-10.5	7.3164	877.97	127.4
-13	7.3164	877.97	127.4
-18	6.1994	743.93	108
-20.5	6.1994	743.93	108
-40	3.0718	368.62	53.5
-42.5	3.0718	368.62	53.5
-63.5	2.96	355.2	51.6
-66	2.96	355.2	51.6
-73	3.2114	385.37	55.9
-75.5	3.2114	385.37	55.9

CORE 5

DEPTH	SS (kPa)	SHEAR MODULUS (kPa)	SHEAR MODULUS (psi)
-4	8.8243	1058.92	153.7
-6.5	8.8243	1058.92	153.7
-35.5	4.5797	549.56	79.8
-38	4.5797	549.56	79.8
-43.5	3.2952	395.23	57.4
-46	3.2952	395.23	57.4
-62.5	3.8536	462.43	67.1
-65	3.8536	462.43	67.1

(ALL DEPTHS IN cm.)

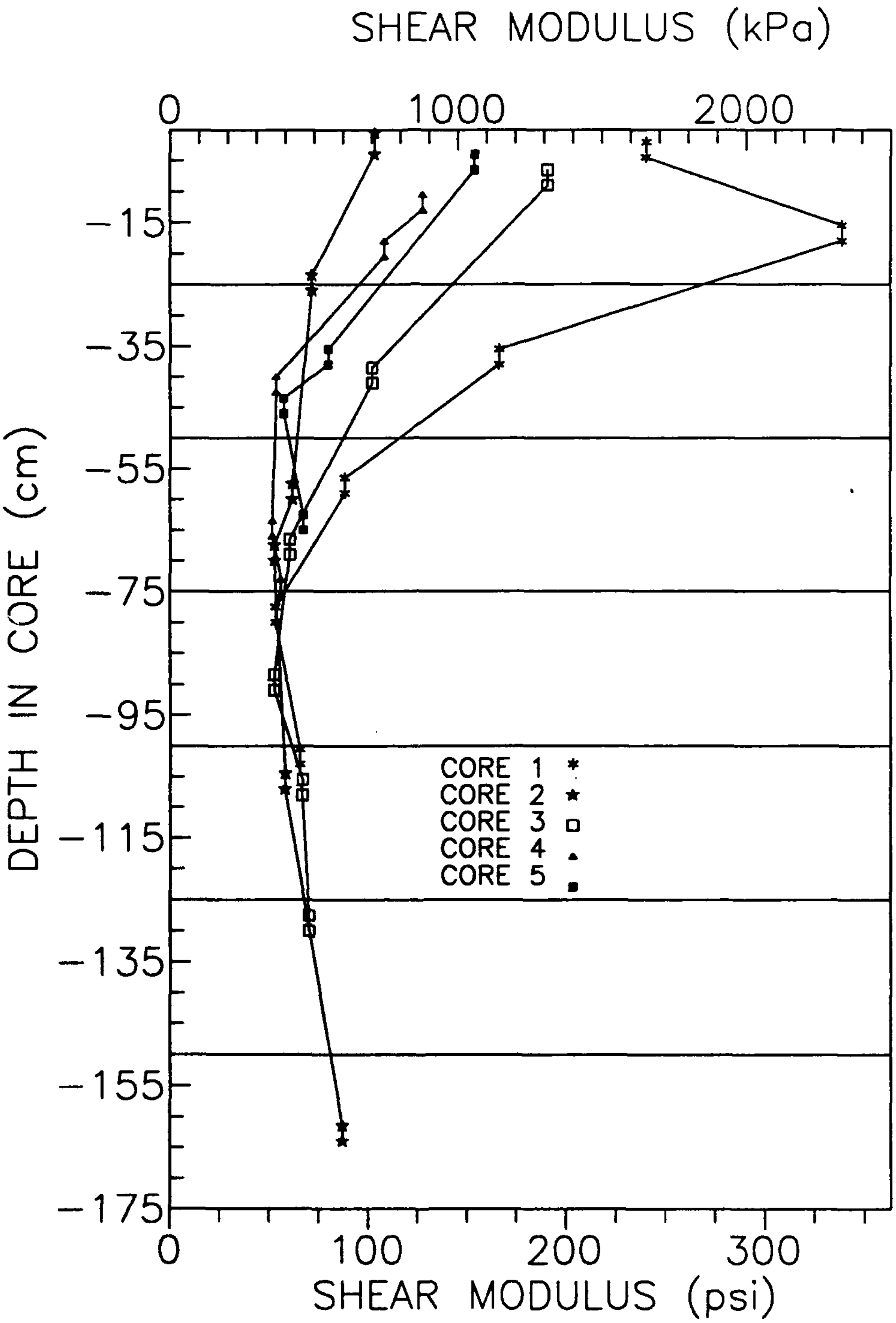


Figure 10 Shear Modulus Versus Core Depth (Cores 1-5).

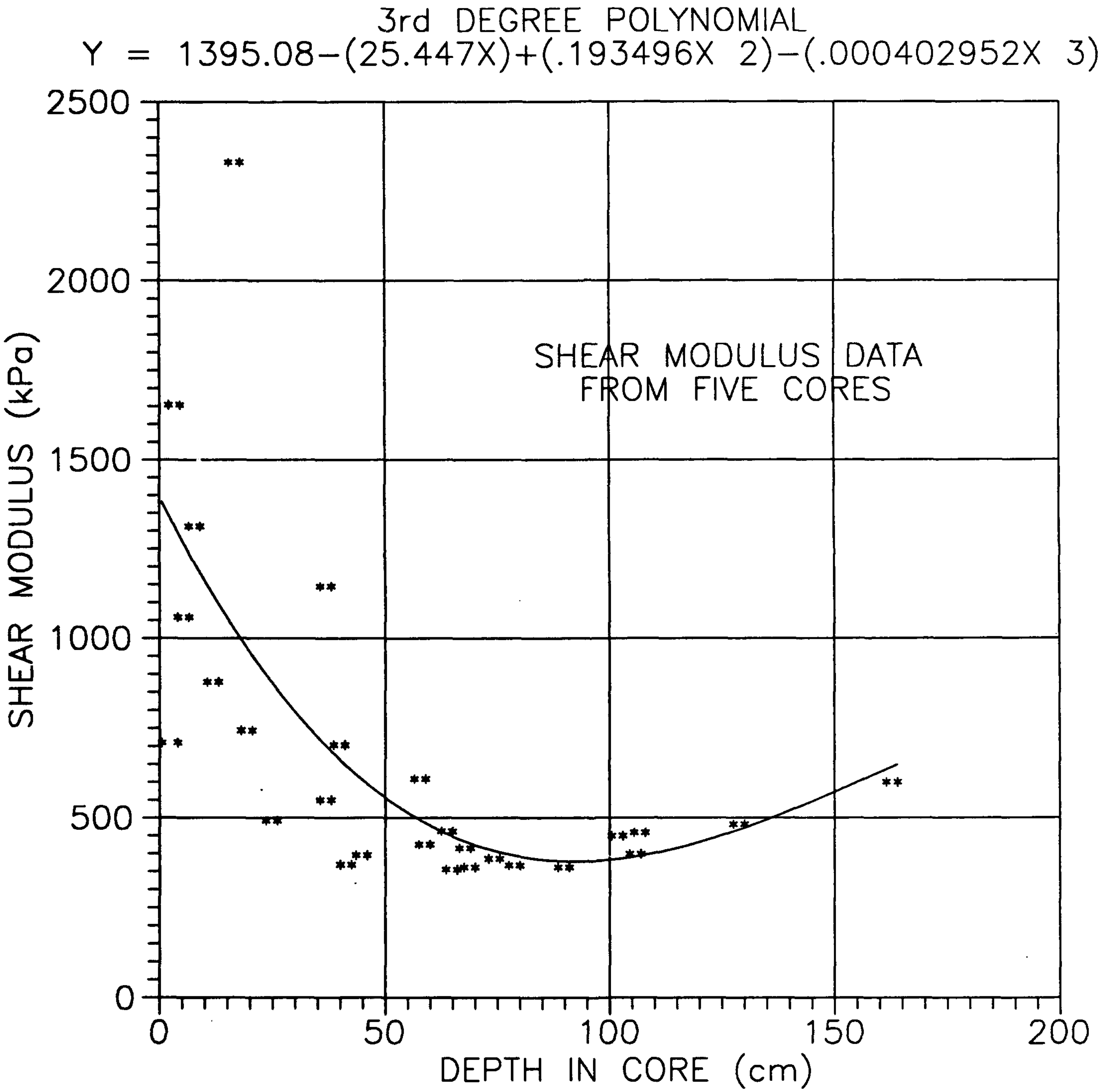
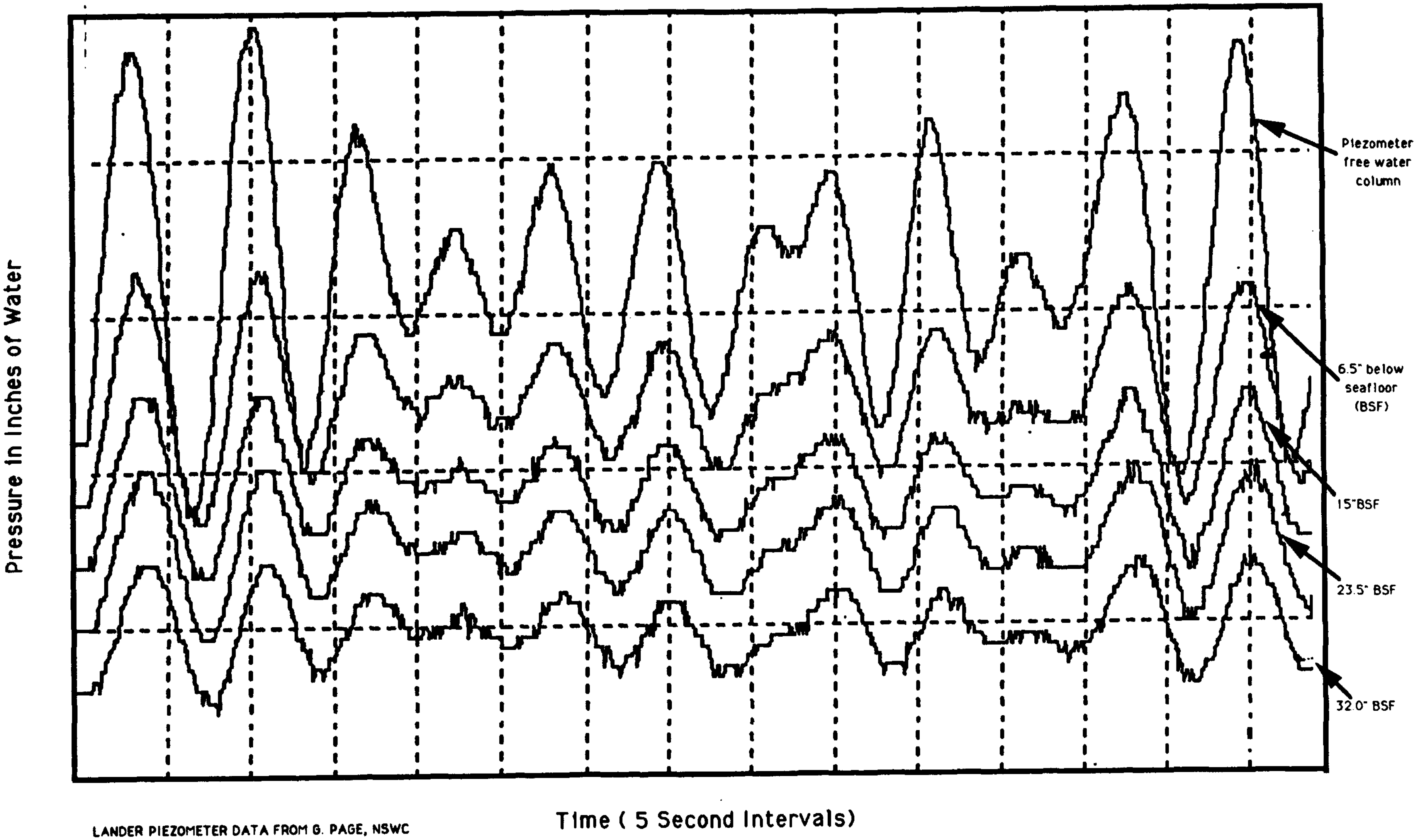


Figure 11 Best Fit 3rd Degree Polynomial of Shear Modulus Versus Depth in Cores 1-5.


UNCORRECTED PRELIMINARY DATA

22:40:10 09/23
Parosclentific Water Depth (Ft). 74
1 PSI = 27.03 Inches of Water Pressure
Piezometer water Depth Apporx. 78ft

LANDER PIEZOMETER DATA FROM G. PAGE, NSWC

Figure 12 Free Water Column Pressure and Pore Water Pressure Attenuation from Piezometer Probe Sensors with Depth Below the Seafloor.

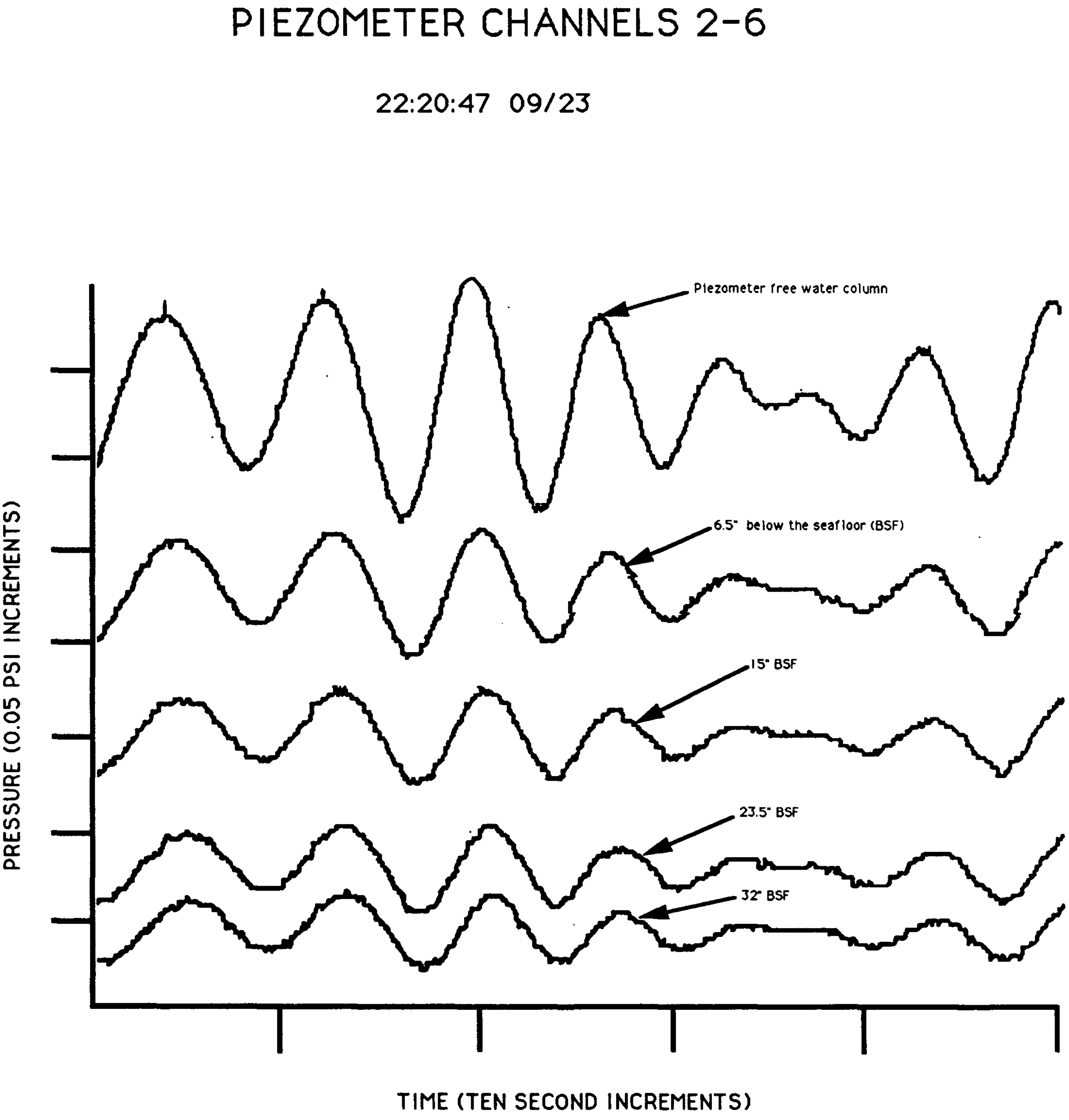


Figure 13 Free Water Column Pressure and Pore Water Attenuation with Depth Below the Seafloor.

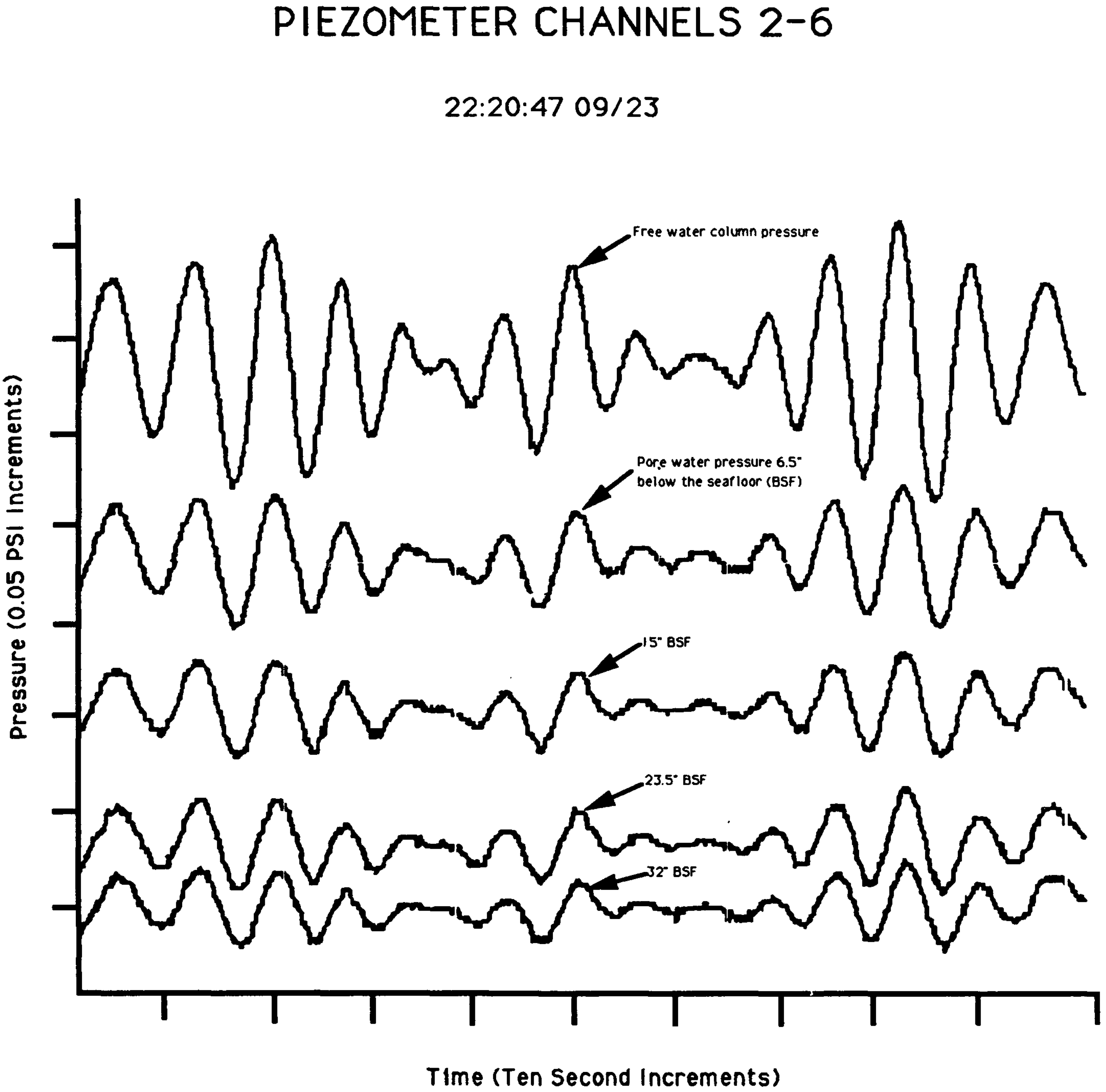
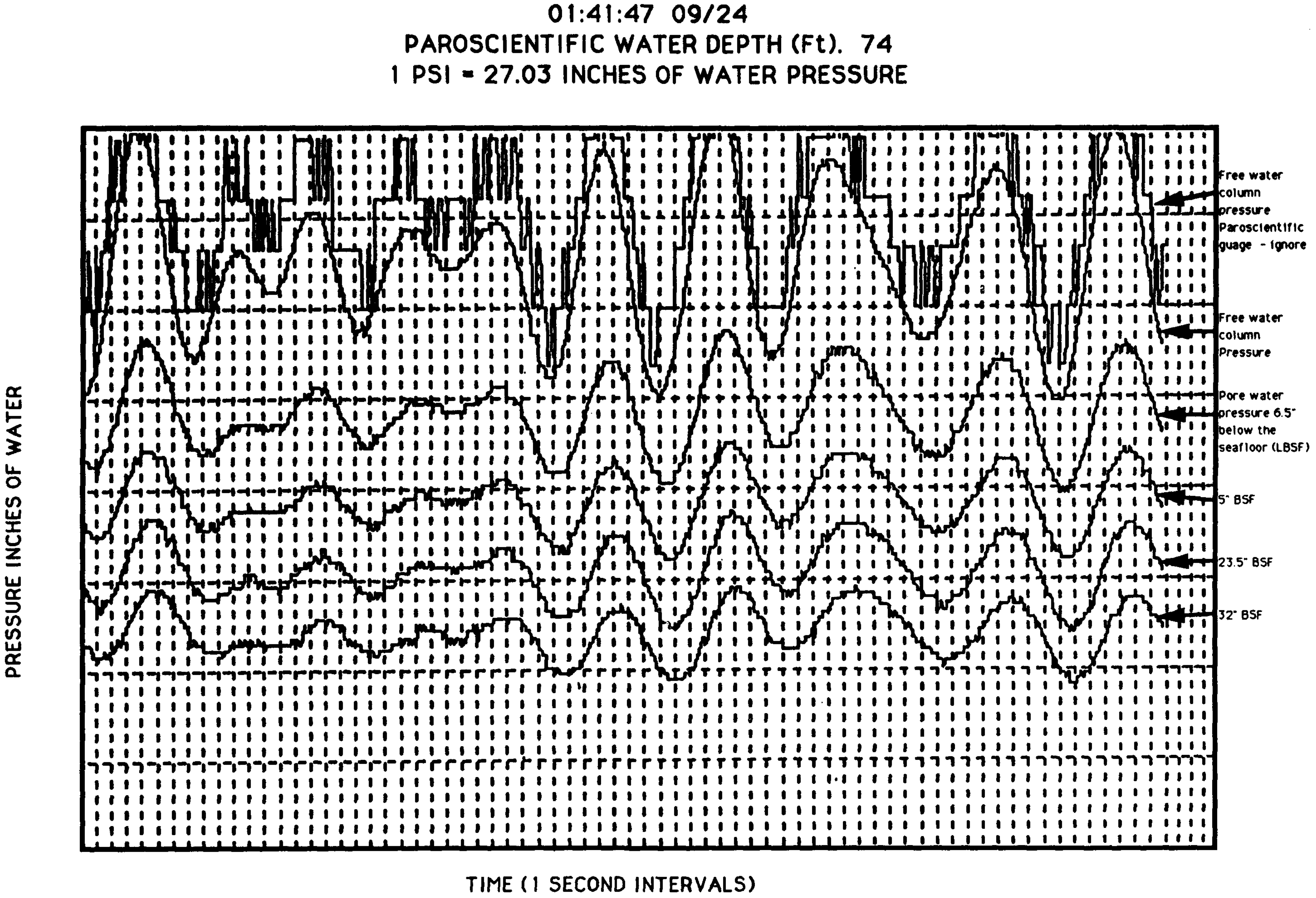


Figure 14 Free Water Column Pressure and Pore Water Pressure with Subbottom Depth Below the Seafloor.



01:41:47 09/24
PAROSCIENTIFIC WATER DEPTH (Ft). 74
1 PSI = 27.03 INCHES OF WATER PRESSURE

Figure 15 Free Water Column Pressure and Pore Water Pressure Below the Seafloor (Note Attenuation with Subbottom Depth). Disreguard Paroscientific Guage "Free Water Column Pressure".

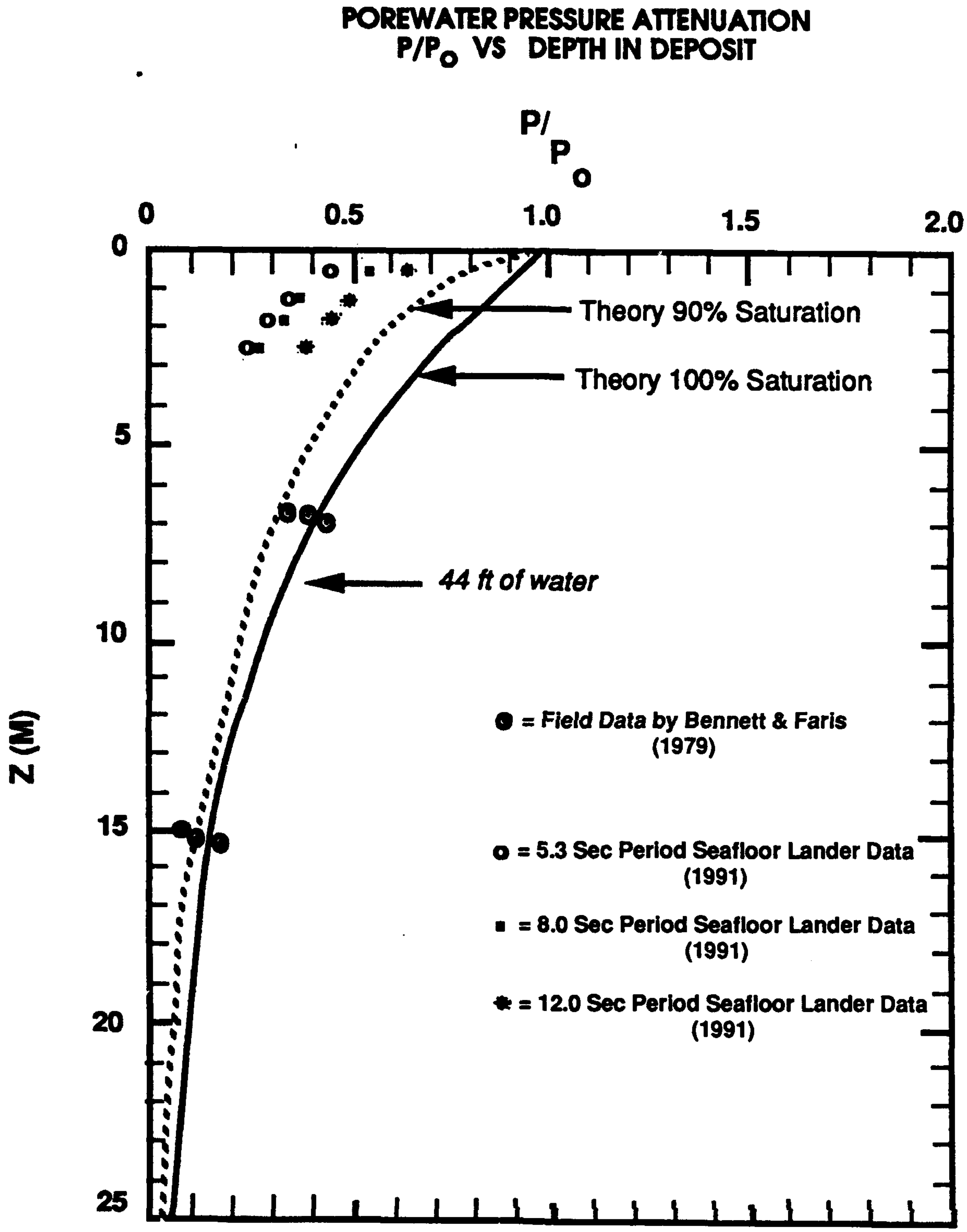


Figure 16 Ratio of Pore Water Pressure (P) to Bottom Pressure (P_o) Versus Subbottom Depth. Theory for Mississippi Delta Sediment and Data from Bennett and Faris (1979). Seafloor Lander Data (1991) Plotted for Selected Waves of 5.3 Sec, 8.0 Sec, and 12.0 Sec Periods (see Table 13). Figure Drafted from Yamamoto, 1981.

Table 13 **Sediment Pore Water Pressure Attenuation P/P_0 with Depth Below the Sea Floor for 5 Different Wave Periods. Selected Seafloor Lander Data (1991).**

POREWATER PRESSURE ATTENUATION
P/P_0 VS DEPTH IN DEPOSIT

PIEZOMETER SENSOR DEPTH →	0.54 ft	1.25 ft	1.96 ft	2.66 ft
WAVE PERIOD ↓		P/P_0 VALUES ↓		
5.3 sec	0.44	0.32	0.29	0.24
7.5 sec	0.53	0.38	0.35	0.28
8.0 sec	0.53	0.38	0.36	0.31
8.2 sec	0.55	0.42	0.40	0.32
12.0 sec	0.64	0.49	0.46	0.39

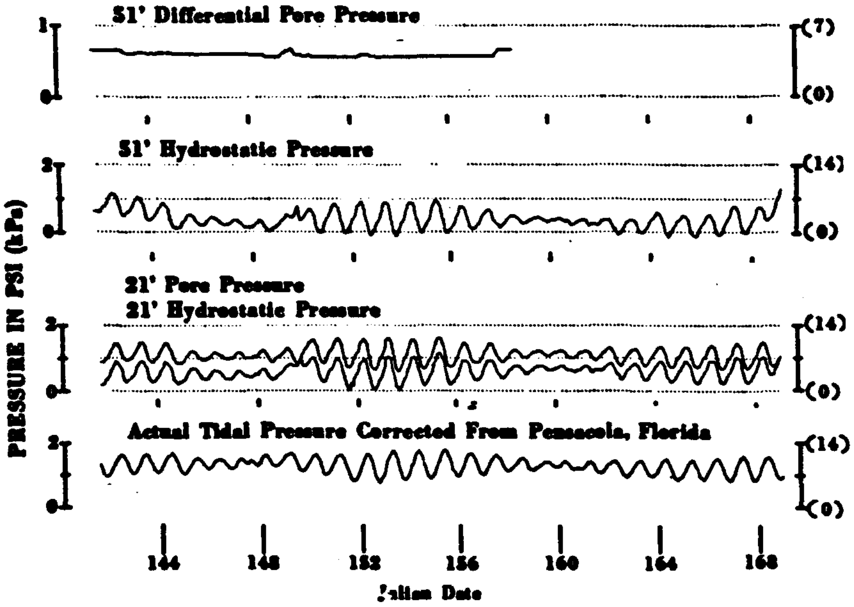


Figure 17 Comparison of Absolute and Differential Pressures in Response to Tidal Activity in Block 28, East Bay Area. Note "Flat" Response of Differential Sensor due to Equivalent Pressure Response Through Sediment and Water Column. Pressure Fluctuation Induced by Tides in 13.5m of Water. Data Shows that Pressure Response from Tidal Waves are "Felt" to Depths of at Least 51 Feet below the Seafloor in Mississippi Delta Sediments (from: Bennett et al, 1982).

SUMMARY AND RECOMMENDATIONS

Initial investigations of pressure attenuation and marine sediment properties in the Gulf of Mexico continental shelf sediments have revealed significant pore pressure attenuation generated by surface waves. Preliminary data suggest that attenuation is not only largely a function of the degree of saturation and presence of free gas in the sediment, but also a function of wave period. Other important factors contributing to subbottom sediment pressure attenuation, as revealed by theory, (Yamamoto, 1981, and Yamamoto, et al., 1978) include permeability, shear modulus, and porosity. Examination of the geotechnical properties determined from the 5 cores collected at the Lander site reveals that core 1 is somewhat anomalous compared with data from cores 2-5. Input parameters for modeling should be taken, therefore, from the cores closest to the Lander (cores 3, 4, 5).

Given the limited field data presently available for "ground truthing" existing theory, additional field testing in sand, silt, and clay deposits under different wave climates (different wave periods) is crucial in establishing reliable input parameters and model verification and/or modification if necessary. Because marine sediments are very variable, laterally and vertically, and they are often stratified (multi-layers of different sediment types), it is crucial that a milti-layer model be developed to approximate real world sedimentary deposits. The multi-layer model should be able to accommodate variable sediment properties with depth below the sea floor and perhaps at a later time be extended to a three dimensional model. Tests of pressure signals generated by passing vessels and the wave pressure attenuation through the various sediment types should be carried out during the Lander field tests in selected geological environments.

REFERENCES

Bennett, R. H. and D. N. Lambert. "Rapid and Reliable Technique for Determining Unit Weight and Porosity or Deep-Sea Sediments." Marine Geol., v. 11, pp. 201-207, (1971).

Bennett, R. H., J. T. Burns, T. L. Clarke, J. R. Faris, E. B. Forde, and A. F. Richards. "Piezometer Probes for Assessing Effective Stress and Stability in Submarine Sediments." Marine Slides and Other Mass Movements. Plenum Publishing Corp., New York, pp. 129-161, (1982).

Bennett, R. H., and J. R. Faris. "Ambient and Dynamic Pore Pressures in Fine-grained Submarine Sediments: Mississippi Delta". Appl. Ocn. Res., 1, pp. 115-123, (1979).

Bennett, R. H., H. Li, P.J. Valent, J. Lipkin, and M. I. Esrig. "In-Situ Undrained Shear Strengths and Permeabilities Derived from Piezometer Measurements." Strength Testing of Marine Sediments: Laboratory and In-Situ Measurements, ASTM STP 883, R. C. Chaney and K. R. Demars, Ed., American Society for Testing and Materials, Philadelphia, pp. 83-100, (1985).

Yamamoto, T., H. L. Koning, H. Sellmeijer, and E. van Hijum. "On the Response of a Poro-elastic Bed to Water Waves." J. Fluid Mech., 87, p. 193-206, (1978).

Yamamoto, T. "Wave-induced Pore Pressures and Effective Stresses in Inhomogeneous Seabed Foundations." Ocean Engineering, V. 8, pp. 1-16, (1981).

ACKNOWLEDGMENTS

This work was supported by the Naval Surface Warfare Center (NSWC) White Oak, program manager, Gregory Page, under work request number N6092191WRW0247. We appreciate the encouragement by Dr. Herbert Eppert and Dr. Michael Richardson during the project. Dr. William R. Bryant critically reviewed an earlier version of this report. Anne Rutledge kindly ran the consolidation and permeability tests at Texas A&M University. Dr. Wayne A. Dunlap provided the geotechnical laboratory instrumentation for the consolidation and permeability tests. We appreciate the helpful discussions with Dr. Wayne Dunlap and Armand Silva concerning various aspects of the design of the Lander pads and bearing capacity formulations. Dave Young did considerable design and machinery of the piezometer probe and other equipment. Carl Jackson, John Love, and the late Dr. Charles Rien NRL, Code 250 provided considerable engineering support during the lander design and construction period. The Mississippi National Guard kindly provided the core data used in the design of the lander pads. NOARL's (NRL) 6.1 basic research program provided funds for the lander construction and supported this research. The authors appreciate the efforts of Lee Nastav in the preparation of several figures and the assistance of Mary Simmons and Keith Kingrey in the preparation of figures, tables, data reduction, and extensive laboratory analyses. The professional assistance of the captain and crew of the R/V Kit Jones, University of Mississippi, is greatly appreciated.

Distribution List

Mr. Gregory Page (5)
Naval Surface Warfare Center
Attn: Code U-42
White Oak
Silver Spring MD 20910

Dr. Joseph Kravitz
Marine Geology & Geophysics
Office of Naval Research
Attn: Code 1125GG
800 North Quincy St., BCT #1
Arlington, VA 22217-5000

Ms. Dianne Farence (2)
Naval Surface Warfare Center
Electronic and Instrumentation Branch
Attn: Code U-42, White Oak
Silver Spring, MD 20910

Norma Holland (1)
Naval Surface Warfare Center
Attn: Code R-14, White Oak
Silver Spring, MD 20910

Dr. Michael Richardson (2)
Naval Research Laboratory
Attn: Code 361
Stennis Space Center, MS 39529

Dr. Herbert Eppert, Jr. (2)
Naval Research Laboratory
Ocean Sciences Directorate
Attn: Code 300
Stennis Space Center, MS 39529

Mr. Sam Tooma (2)
Naval Research Laboratory
Attn: Code 360
Stennis Space Center, MS 39529

Dr. Philip Valent (2)
Naval Research Laboratory
Attn: Code 300
Stennis Space Center, MS 39529

Dr. William R. Bryant (1)
Department of Oceanography
Texas A&M University
College Station, TX 77843

Dr. Wayne A. Dunlap (1)
Offshore Technology Research Center
1200 Mariner Drive
Texas A&M University
College Station, TX 77845

Dr. Tokuo Yamamoto (1)
Geoacoustics Laboratory
Rosentiel School of Marine & Atmospheric Science
University of Miami
4600 Rickenbacker CSWY Virginia Way
Miami, FL 33149