

## APPENDIX I. PHYSICAL PROPERTIES – METHODS

Robert E. Boyce, Scripps Institution of Oceanography, La Jolla, California

### INTRODUCTION

Porosity-Density data, Sound Velocity data, Natural Gamma Radiation data, and Penetrometer data are discussed below with regard to their equipment, methods, errors, correction factors, presentation, and the coring disturbance relative to the validity of the data.

### POROSITY, WET-BULK DENSITY, WATER CONTENT

Porosity and density of sediments and rocks and their relationships to other physical properties of the same material have been studied many years by the petroleum industry as they are related to oil production and well logging. Correlations of porosity and wet-bulk density to other properties of sediment, such as sound velocity, encouraged Hamilton et al. (1956), Laughton (1954; 1957), Sutton et al. (1957), Shumway (1960), Schreiber (1968), Horn et al. (1969), Kermobon et al. (1969), and Hamilton et al. (1969) to collect modern marine sediment samples and analyze their porosities, densities, and other physical properties and their interrelationships. Porosity-density interrelationships have been reported with respect to soil mechanics of marine sediments (Hamilton, 1959; Moore and Shumway, 1959; Richards, 1962; Hamilton, 1969a, 1969b), heat conductivity in marine sediments (Bullard et al., 1956; Bullard and Day, 1961; Ratcliffe, 1960), and electrical conductivity in marine sediments (Boyce, 1968; Kermabon et al., 1969). In general, these were surface sediments.

Porosity and wet-bulk density relationships to consolidation have been studied by Hamilton (1956; 1960) in an investigation of the thickness, consolidation, ages, and the amounts of original sediments in the ocean basins. Actual measurements of porosity, wet-bulk density, and related properties of sediment samples, which were buried to depths of 130 meters, from the Guadalupe Mohole site, were reported on by Igelman and Hamilton (1963), Moore (1964), and Hamilton (1964; 1965).

### Methods

Aboard the *Glomar Challenger* during Leg 15, wet-bulk density and porosity were measured by two methods. One utilized small individual sediment samples, which were collected from the relatively "undisturbed" center portion of the cores. The volumes of these wet samples combined with their wet and dry weights were used to calculate their wet-bulk density and porosity. The second method required measurements of gamma-ray attenuation through the sediments and rocks, which relates to their wet-bulk density. This was done by a system called Gamma Ray Attenuation Porosity Evaluator, which will hereafter be referred to by its acronym GRAPE. The weight-volume method will be

discussed first followed by a discussion of the GRAPE method.

### Weight and Volume Density Measurements

Wet-bulk density in this report is defined as the weight in grams of the wet-saturated sediment (or rock) per cubic centimeter of the wet-saturated sediment. Porosity is defined as the volume of pore space divided by the volume of the wet-saturated sample and is expressed as a percentage. Water content is defined as the weight of water in the sediment divided by the weight of the saturated wet-sediment and is also expressed as a percentage. Salt corrections were not made.

Individual soft sediment samples were taken with a one cubic centimeter syringe with the end cut off, squared, and sharpened, so that the leading sharp edge was flush with the inside diameter of the syringe. The sampling technique is similar to that of piston coring. The syringe cylinder and the end of the plunger are placed flush with the surface of the sediment to be sampled, and then the plunger is held stationary while the cylinder is slowly pushed into the sediment. Volume measurements of hard sediments are not possible with this technique.

Volume of the soft sample is measured with the same syringe before the sample is weighed. The sample is then weighed while wet and after drying at 110°C for 24 hours and then cooling in a desiccator for at least two hours. The greatest limitation on these measurements is the size of the sample which can be weighed accurately at sea (less than one gram). Therefore, a single weighing, if the sea state permits, has an error of about  $\pm 1$  percent, and a single volume measurement on this small sample is subject to a high error of about  $\pm 4$  percent. Weight-weight water content measurements, which do not involve volume measurements, have a precision of about  $\pm 2$  percent (absolute error).

Calculations of water content, wet-bulk density, and porosity are as follows (without salt correction):

$$\text{Water Content (\%)} = 100 \times \frac{\left[ \frac{(\text{weight wet sediment}) - (\text{weight dry sediment} + \text{salts})}{(\text{weight wet sediment})} \right]}{\quad} \quad (1)$$

$$\text{Wet bulk density (g/cc)} = \frac{(\text{Weight wet sediment})}{(\text{Volume wet sediment})} \quad (2)$$

$$\text{Porosity (\%)} = (100/1.00 \text{ g/cc}) \left[ \frac{(\text{weight wet sediment}) - (\text{weight dry sediment} + \text{salts})}{(\text{Volume wet sediment})} \right] \quad (3)$$

Averaged, or estimated, grain densities are used when calculating porosity with the shore-based laboratory GRAPE computer program. Some average grain density values are approximated using the porosity, wet-bulk density, and water content measurements done on individual samples by Equation 4. This equation is not precise and has a large scatter of grain densities, especially when the sample has a high porosity, and therefore is used only to get an average value.

$$\text{Porosity} = \frac{\left(\frac{\text{wt. water}}{\text{density water}}\right) \times 100}{\left(\frac{\text{wt. water}}{\text{density water}}\right) + \left(\frac{\text{wt. dry sed. + salt}}{\text{density dry sed. + salt}}\right)}$$

Density Dry Sed. + Salt

$$= \frac{(\text{wt. dry sediment + salt})}{\left[\frac{\text{wt. evaporated (100)}}{\text{density water}} (\text{porosity})\right] - \left[\frac{\text{wt. evaporated water}}{\text{density water}}\right]} = \frac{\text{wt. dry sediment + salt}}{\left[\frac{\text{volume evaporated}}{\text{water}}\right] \left(\frac{100}{\text{porosity}}\right) - \left[\frac{\text{volume evaporated}}{\text{water}}\right]} \tag{4}$$

Salt correction may be made if desired.

**GRAPE System**

Basically, the GRAPE device consists of a drive system to move geologic material between a shielded gamma ray source (Ba<sup>133</sup>) and a shielded scintillation detector. The system also includes an analog computer which immediately calculates apparent wet-bulk density from the measured parameters. Evans (1965), Harms and Choquette (1965), Evans and Cotteral (1970), Brier et al. (1969), and Whitmarsh (1971) contain discussions of the principle; Evans (1965) and Evans and Cotteral (1970) also give a detailed equipment description.

The GRAPE works on the principle that gamma rays of a specified energy interval (0.3 to 0.359 Mev) are absorbed or scattered when they travel through a sediment or rock sample, and that this attenuation is related to the density of that material. These gamma rays are absorbed or scattered by the electrons in the minerals, and it is assumed that the ratio of the number of electrons in any given mineral to its density can be considered a constant; however, this is not true for all minerals. The variation of this "constant" is seen as a variation of the attenuation coefficient for those "anomalous" minerals. Corrections for these "anomalous" minerals may be applied in the future when the mineralogy and attenuation coefficients become accurately known. At the present, only a correction for the "anomalous" water density, or attenuation coefficient, is applied as it comprises up to 80 percent of the sample.

**Theory**

The GRAPE System provides continuous apparent wet-bulk density measurements on the basis of gamma ray attenuation in an ideal slab absorber (Evans, 1965):

$$I = I_0 e^{-\mu d \rho_B} \tag{5}$$

$$\rho_B = \frac{1}{\mu d} \ln \left[ \frac{I_0}{I} \right] \tag{6}$$

"I is the intensity of the gamma-ray beam which penetrates the absorber with no loss in energy,

I<sub>0</sub> is source intensity,

ρ<sub>B</sub> is the bulk density in g/cm<sup>3</sup>

μ is the mass attenuation coefficient in cm<sup>2</sup>/g, and

d is the thickness or diameter of the sample in cm."

In some sediments, it may be necessary to make corrections for minerals whose attenuation coefficients differ significantly (± 3%) from that of quartz. Corrections for "anomalous" attenuation coefficients of minerals, other than seawater, were not made in the Leg 15 data, but corrections may be applied in the future when the exact quantitative mineralogy and attenuation coefficient become known.

The above equation with an assumed μ of 0.100 or 0.102 cm<sup>2</sup>/g is accurate for minerals which have a similar attenuation coefficient to that of quartz or calcite, respectively, or, in other words, the equation is accurate for minerals that have a ratio of the mineral electron density (ρ<sub>e</sub>) to its bulk density (ρ<sub>B</sub>) which approximates that of quartz or calcite. According to Evans (1965) "Corrections must be provided when the electron factor (θ) varies significantly (± 3% or greater):"

$$\theta = \rho_e / \rho_B \tag{7}$$

"A convenient unit for θ is the number of electrons per cubic angstrom [ρ<sub>e</sub>] per unit density [ρ<sub>B</sub>] . . . This ratio is 0.303 for many common rocks and minerals, such as calcite, quartz, dolomite and some clays."

Evans (1965) suggests (and the method followed by Deep Sea Drilling) "In evaluating equation (. . . [Equation 6 above]) the most convenient computational procedure is to consider μ a constant, 0.100 cm<sup>2</sup>/g, and use corrected grain densities for any sample components having electron factors in the range of 0.294 ≥ θ ≥ 0.312. The corrected grain densities (ρ<sub>GC</sub>) are calculated from the following relationship:

$$\rho_{GC} = \frac{\theta_1}{\theta} \rho_{GL} \tag{8}$$

where θ<sub>1</sub> is the electron factor of the 'abnormal' component, θ is the normal electron factor 0.303, and ρ<sub>GL</sub> is the measured grain density of the component which requires correction." An example is aluminum which has an electron factor of 0.291 (Evans, 1965).

$$\rho_{GC} = \frac{0.291}{0.303} \times 2.71 \text{ g/cc} = 2.60 \text{ g/cc}$$

Electron density factors and corrected densities of some common minerals are listed in Harms and Choquette (1965, Table 1, P24C-25C) and Evans and Cotteral (1970).

Density values for seawater (1.025 g/cc) and aluminum (2.71 g/cc) are calculated by the GRAPE as approximately

1.125 g/cc and 2.60 g/cc, respectively, when calculations are based on an attenuation coefficient near that of quartz and calcite (0.100 and 0.102 cm<sup>2</sup>/g, respectively) (Schlumberger, 1966; Evans, 1965). For an approximation of "true" sediment wet-bulk density, similar density corrections for other minerals may be ignored and the GRAPE data thought of as two phases consisting of seawater and solid mineral grains of quartz. Since seawater is a major constituent, a correction factor must be applied. This is accomplished by processing the apparent density data through one of the computer programs described below.

#### GRAPE Set Up and Shorebased Computer Program

Detailed directions for the GRAPE equipment are in Evans and Cotterel (1970) and Evans (1965). The shore-based computer programs use the apparent GRAPE density data, which is internally calibrated, and therefore not affected by attenuation coefficient and diameter values dialed into the GRAPE shipboard computer, and porosity is recalculated from the corrected densities using estimated and measured average grain densities.

The GRAPE system aboard ship is set up as follows:

1) The recorder calibration is checked by setting the CALIBRATE switch to 2.25 g/cc and 0.25 g/cc, and the recorder is adjusted as necessary (assuming 0 to 2.50 g/cc scale).

2) The switch is reset to OPERATE position.

3) The I<sub>0</sub> ADJ is nulled while gamma rays are passing through air. Since the internal standards are in liners, as the cores are, it is not necessary to null I<sub>0</sub> through an empty liner, but if digital counts were being done without internal standards, it would be necessary to do this.

4) Sample drive speed is 3.83 inches/minute.

5) The DIA SET is 2.60 inches, although it is not critical so long as it is not changed between running of the internal aluminum and water standards and the cores. Diameter measurements were not made on cores in the liner by the GRAPE system.

6) The mass attenuation coefficient adjustment ( $\mu$  ADJ) is set at 0.1 cm<sup>2</sup>/g  $\times$  42.33, but this setting is not critical as long as it is not changed between running of the internal aluminum and water standards. (The density values assigned to these internal standards in the shore based computer program will determine the mass attenuation coefficient that the data is eventually calculated with.)

7) Scale: 1 to 3.5 g/cc.

8) An aluminum standard cylinder, encased in a plastic liner, and a seawater standard, also in a plastic liner, are run immediately before the core samples, also in plastic liners. These standards are run between each of the cores.

The GRAPE analog computer calculates the apparent GRAPE density (Equation 6) as gamma ray intensities are being measured. These apparent GRAPE density calculations are linearly recorded on analog chart paper, which is checked using different diameter bars of aluminum and different thicknesses of aluminum blocks.

The value of the corrected GRAPE density assigned to the aluminum standard has been checked by comparison with quartz crystals, which also calculates the corrected GRAPE density of the aluminum standard to be 2.60 g/cc

( $\pm 1\%$ ). The true density of the aluminum standard is 2.71 g/cc (alloy number is Alcoa 1100-F). Therefore, by assigning a density value to the aluminum density analog lines, the mass attenuation coefficient is assigned in the computer program and thus the mass attenuation coefficient is internally controlled. For example, 2.60 g/cc corresponds to a 0.100 cm<sup>2</sup>/g (within 1%) quartz mass attenuation coefficient, but if 3.00 g/cc were assigned to the aluminum standard, this would correspond to a 0.086 cm<sup>2</sup>/g mass attenuation coefficient. The corrected Al density of 2.60 g/cc does not agree with the mass attenuation coefficient of Al being about 0.098 cm<sup>2</sup>/g (within 1%) as cited in Evans (1965), but suggests 0.096 cm<sup>2</sup>/g ( $\pm 1\%$ ). Algebraically, an example of the mass attenuation coefficient-density relationship is as follows:

$$\frac{\text{Al Coef}}{\text{Quartz Coef}} \times \text{True Al Density} = \text{Apparent Al density calculated with a quartz attenuation coefficient}$$

$$\frac{0.096 \text{ cm}^2/\text{g}}{0.100 \text{ cm}^2/\text{g}} \times 2.71 \text{ g/cc} = 2.60 \text{ g/cc}$$

At the shore-based laboratory, only the apparent GRAPE wet-bulk density line is digitized. Since the GRAPE calculated an "anomalous" seawater density of about 1.125 g/cc using a quartz attenuation coefficient, the data have to be recalculated to "true" wet-bulk densities (disregarding other minerals which do not have the assumed attenuation coefficient similar to quartz or calcite). After the raw density data are recalculated to "true" densities, porosity is calculated from the wet-bulk density using measured or estimated grain densities.

The following program (Program 1) was used to obtain densities and porosity from the apparent GRAPE density line for Legs 3 through 11. The Leg 15 program (Program 2) is slightly different and is discussed later.

PROGRAM 1: This program was used for Legs 3 through 11.

Given:

- 1) Aluminum calibration line position on the analog graph =  $\rho_{as}$
- 2) Aluminum GRAPE density (2.60) =  $\rho_{ag}$
- 3) Seawater calibration line position on the analog graph =  $\rho_{ws}$
- 4) Seawater true density (1.025 g/cc) =  $\rho_{wt}$
- 5) Any wet-bulk density value line position on the analog graph =  $\rho_s$
- 6) Any "true" wet-bulk density value =  $\rho_t$
- 7) Grain density (estimated or independently measured) =  $\rho_{gm}$
- 8) Porosity, "true" =  $\text{Por}_t$

Find:

Derivation of "true" wet-bulk densities and "true" porosities from apparent wet-bulk densities on the GRAPE analog graph.

Solution:

To correct the density data for the "anomalous" seawater density, values of 2.60 g/cc and 1.025 g/cc (true seawater density) are assigned to the aluminum and seawater lines, respectively, on the GRAPE analog graphs. Hence, a linear interpolation is made to solve for the "true" densities of the sediment cores.

$$\frac{\rho_t - \rho_{wt}}{\rho_{ag} - \rho_{wt}} = \frac{\rho_s - \rho_{ws}}{\rho_{as} - \rho_{ws}} \text{ is proportional} \quad (9)$$

$$\rho_t = \frac{(\rho_{ag} - \rho_{wt})(\rho_s - \rho_{ws})}{\rho_{as} - \rho_{ws}} + \rho_{wt} \quad (10)$$

$$\text{Por}_t = \left[ 1 - \left( \frac{\rho_t - \rho_{wt}}{\rho_{gm} - \rho_{wt}} \right) \right] \times 100 = \% \quad (11)$$

This calculation is a good approximation for sediments which have an average grain density of 2.6 g/cc (disregarding minerals which do not have the theoretical electron density assumed by the GRAPE). However, sediments which have average grain densities as high as 3.0 g/cc or as low as 2.3 g/cc have a systemic error of plus or minus 0.8 percent (at zero percent porosity), respectively, in their density values. If the sediment is opaline silica of low density (2.0 g/cc), then the wet-bulk density error is -1.8% (at zero percent porosity). These relative errors decrease as the porosity of the sediments increase (zero error at 100% porosity), and can be corrected for, but in practice necessary corrections have not been applied.

PROGRAM 2: Program used for Legs 12 through 15 data:

A different approach (PROGRAM 2) to the calculation of "true" wet-bulk densities and porosities from the GRAPE analog graphs is that of Whitmarsh (1971), which allows a variable grain density. This program is advantageous in that the systematic errors caused by different grain densities other than 2.6 are eliminated as the varying grain matrix densities are put into the program.

Given:

- 1) Aluminum calibration line position on the GRAPE analog graph =  $\rho_{as}$
- 2) Aluminum density calculated by a quartz attenuation coefficient (0.100 cm<sup>2</sup>/g) 2.60 g/cc =  $\rho_{ag}$
- 3) Seawater calibration line position on GRAPE analog graph<sup>1</sup> =  $\rho_{ws}$
- 4) Seawater density as calculated with a quartz attenuation<sup>2</sup> coefficient (0.100 cm<sup>2</sup>/g) 1.125 g/cc =  $\rho_{wg}$
- 5) True seawater density (1.025 g/cc) =  $\rho_{wt}$

<sup>1</sup> A distilled water standard may be used in place of the seawater standard. The distilled water has a true density of about 1.00 g/cc and a corrected GRAPE density of 1.10 g/cc for quartz attenuation coefficient.

<sup>2</sup> This value will be discussed later in the text.

- 6) Grain density (estimated or measured) =  $\rho_{gm}$
- 7) Any approximate density value line position on GRAPE analog graph =  $\rho_s$
- 8) Any approximate density, and attenuation coefficient obtained recently by iteration; use  $\mu' = 0.100$  for first iteration =  $\rho'_t, \mu'$
- 9) Any "true" density =  $\rho_t$
- 10) Any "true" porosity =  $\text{Por}_t$
- 11) Water content (wt H<sub>2</sub>O/wt wet sediment) =  $w$

Find:

Derivation of "true" density and porosity data from the GRAPE analog density data.

1) The position of the seawater standard line on the GRAPE analog graph is read as 1.125 g/cc and the aluminum calibration line as 2.60 g/cc.

2) A linear interpolation is made between these two values. This step is the same as that of PROGRAM 1, except that it assigns a different density to the seawater line.

$$\rho'_t = \frac{(\rho_{ag} - \rho_{wg})(\rho_s - \rho_{ws})}{\rho_{as} - \rho_{ws}} + \rho_{wt}$$

However, these values will be in error because the GRAPE does not allow for a difference between the Compton mass attenuation coefficient of water and that of the mineral grains. This error can be overcome by the following iterative procedure.

3) An estimate of water content is calculated from the estimated density:

$$w = \frac{\rho_{gm} - \rho'_t}{\rho_{gm} - \rho_{wt}} \times \frac{\rho_{wt}}{\rho'_t}$$

4) An estimate of the Compton mass attenuation coefficient  $\mu$  of the sediment is made by:

$$\mu = W\mu_w + (1-w)\mu_q$$

$\mu_w$  = mass attenuation coefficient of seawater = 0.1099 cm<sup>2</sup>/g

$\mu_q$  = mass attenuation coefficient of quartz = 0.100 cm<sup>2</sup>/g

Hence, a better estimate of the sediment density is obtained as follows:

$$\rho_t = \frac{\rho'_t \mu'}{\mu}$$

Go to Step 3.

The iteration is continued until the density changes by less than 0.005 g/cc (only two iterations are usually required). Hence, having obtained the best estimate of density, the porosity can be calculated with a given grain density.

$$\text{Por}_t = \left[ 1 - \left( \frac{\rho - \rho_w}{\rho_{gm} - \rho_w} \right) \right] \times 100 = \%$$

In general, the Whitmarsh Program compares well with Program 1 when using a 2.6 g/cc grain density.

Method	Density g/cc			
	Whitmarsh (Program 2)	1.161	1.579	1.738
Program 1	1.162	1.580	1.740	2.017

#### Theoretical Future Program Considerations and Corrections

Persons desiring to obtain the raw GRAPE data may do so, but all expenses must be compensated by the interested party. One might rerun the program with different parameters, use his own program, or apply mineral corrections when the mineralogy becomes well known. However, until mineral corrections are made, Schlumberger (1966) has a diagram showing some density corrections for a few minerals based on a sonde calibrated in water and limestone, and some are also listed in Harms and Choquette (1965).

In the future, if one desired to correct for "abnormal" attenuation coefficients other than 0.100 cm<sup>2</sup>/gm, it would only be necessary to list the minerals by percent by weight of the dry solid phase in the sediments. These percentages would then have to be multiplied by their mass attenuation coefficients with these numbers being summed and averaged (divided by 100). This average should be the average attenuation coefficient for the mineral mixture (similar to Brier et al., 1969).

It would be necessary to recalculate the GRAPE corrected densities for the aluminum and seawater<sup>3</sup> standards so that these standards correspond to the new mass attenuation coefficient, i.e.:

True Al density = 2.71 g/cc

$$\frac{0.096 \text{ cm}^2/\text{g}}{\text{(New coefficient)}} \times 2.71 \text{ g/cc} = \text{new corrected density to assign to aluminum.}$$

The next step would be to begin Program 2 with the new corrected densities assigned to the Al and seawater<sup>3</sup> calibration lines, respectively, and insert the new mass attenuation coefficient for the solid phase in the program. These resulting densities should be fully corrected for "anomalous" mass attenuation coefficients.

#### General Discussion — Errors, Precautions and Correction Factors

Whitmarsh (1971) shows a comparison of GRAPE density averages per 1.5 meter core lengths (referred to as sections) to wet-bulk densities determined by weight and volume measurements of the entire 1.5 meter core section. These section-density averages agreed within ±0.03 g/cc, which is very good when considering the variables. The GRAPE samples a pencil size area across the diameter of the core including a disturbed portion on the sides of the liner, which is about 12 percent of the sample. However,

<sup>3</sup>For seawater standard calculated corrected density via seawater  $\mu$  and true seawater density (1.025 g/cc). It is only necessary to change seawater standard in Program 2 but no change required for seawater standard in Program 1.

that same disturbed sediment around the outer perimeter is a large volume of the core and is about 25 percent of the entire volume of the core section used in the weight-volume density calculations. In addition, minerals may be present which have a different attenuation coefficient than that of calcite.

In general, wet-bulk density data of small weighed samples agree with the GRAPE data within ±5 percent. This is fairly good when considering that the actual samples of the two methods are different. The individual porosity and wet-bulk density weighed samples are small (less than 1 cc) and from the center portion of the cores, while the GRAPE samples are of pencil size volume and extend across the entire diameter of the core. This includes the outer peripheries of the cores which are usually disturbed as a soup or heavy paste. In addition, the single GRAPE sample is a moving average of about 1 cm which is measured in a time of 2 seconds (actual movement is 2.95 mm). This short 2 second gamma ray counting period by itself has an error of ±6 percent.

The GRAPE analog records are digitized at a frequency of 800 points per a 1.5 meter core section (one point every 1.87 mm of core length). The density scale is divided into 250 scale divisions and is digitized to the nearest division (0.01 g/cc).

These data are published in this volume at the core level (9 meter core length per page) with 160 points per 1.5 meter section (one point per 0.94 cm of core length). The data points are averaged at 0.94 cm intervals and the averages are plotted in the center of these intervals.

These data plotted at the hole level in this volume, 0 to 400 or 0 to 800 meters per page, are averaged at 18.7 cm intervals (8 points per a 1.5 meter section plotted) with the data points plotted in the center of these intervals. However, significant density peaks were redrafted in the figures.

When comparing any wet-bulk density sample data to the GRAPE densities, it is imperative to pick a core that is "undisturbed" and of uniform lithology so that the GRAPE density and the individual sample densities are both looking at the same sample. Recovery from the top of the hole, the first 200 meters, is usually disturbed sediment with "soupy" sediment strewn down the sides of the core. This latter is included in the GRAPE sample, but the individual wet-bulk density samples are taken at the center of the core and do not include "soup". Therefore, the GRAPE density data at the top of holes tend to be lower than the individual samples. This also applies to the individual cores. The top of individual cores tend to be more disturbed than the lower sections. Thus, individual sample densities taken in the lower core sections tend to match the GRAPE data better than the data from the top core sections.

The GRAPE data should be viewed with caution as it is the result of continuous diameter-scanning along the entire length of an unopened core which includes undisturbed sediment, disturbed sediment, and drilling slurries. Because of the nature of the GRAPE sample, only the maximum wet-bulk density values, and corresponding minimum porosity values (to a lesser extent), are probably valid. The minimum wet-bulk density values and maximum porosity values are always suspect of being disturbed sediment and drilling slurries.

In the upper part of some holes, a smaller diameter extended core barrel (2.25 inches) was used rather than the normal 2.60-inch diameter core barrel. Correction for this anomalous diameter was calculated by the following formula:

$$\begin{aligned} \text{Corrected Density} &= A + A \frac{(2.60 - 2.25)}{2.25} \\ &= 1.155 A \end{aligned}$$

where  $A$  is the apparent GRAPE DENSITY.

When the sediments being drilled are firm, coring sometimes recovers lumps of firm sediment alternating with soft sediment or a drilling slurry. This is observed in the GRAPE data as alternating high and low densities or just a sequence of high density peaks. The inverse is seen in the porosity data. Caution should be used when observing this pattern, as it is probable that only the maximum density (minimum porosity) values are valid (having this porosity or less; or having this density or greater).

Some stiff sediments or rocks are cored without plastic flowage and since the drill bit has a smaller diameter than the core liner (6.61 cm internal diameter), the hard sediment sample also has that small diameter with the remaining space being filled with a drilling slurry or highly disturbed sediment (in some cases air). A problem arises here because a 6.61-cm diameter is assumed in the density calculation. Correction for anomalous diameters have been done by hand for some cores at a few sites.

Where possible, the GRAPE data were adjusted (dotted density and porosity lines in core and hole plots) for incorrect diameters of the core. Diameters of the true hard rock were generally smaller than 6.61 cm and their diameters were measured from the core photographs. Since the larger of the two split halves was normally photographed, there should be no error because of not splitting the core exactly through the center. This was checked in many cases where the cores were photographed both split and whole (at Site 146).

The assumption that the cores were split through the center and the diameter of the core could be obtained from the photographs of the split core would have errors as explained below if in actuality they were not split through the center. Assume the hard rock diameter is about 5.8 cm because of the drill bit. If the rock was cut 0.5 cm off center, the smaller width of the two halves would be 5.7 cm, thus introducing a 2% systematic decrease in the diameter measurement (increase in density value). If the core was 1.0 cm off center, the smaller width would be 5.4 cm, thus causing a systematic decrease of 7% in the diameter measurement (increase in density value). However, the cores were cut within 0.5 cm of the center in most cases.

An additional source of systematic error related to the diameter is that the 5.8 cm diameter rock core may have been lying on the side rather than in the center of the core liner, thus allowing the gamma beam to pass 4 mm off center. This would cause a systematic decrease of density of 2% or less if a 5.8 cm diameter is assumed in the calculation and only air surrounded the rock core (of 2.6 g/cc density). If water surrounded a 2.6 g/cc dense rock core, the error would be 1.1% or less (decrease in density value), and as the

rock density decreases, this error also decreases, eventually to zero when the theoretical core density reaches 1.0 g/cc.

Density adjustments for varying diameters were made by determining the typical density of the disturbed sediment or drilling slurries (about 1.2 g/cc; ranged from 1.0 to 1.35 g/cc). However, 1.2 g/cc is primarily an assumption and the reader may wish to recalculate the data using air or some other density which he feels is appropriate. The maximum wet-bulk density values (minimum porosity) were recalculated using the following formula.

$$100A = D(100 - x) - Sx$$

$$D = \frac{100A - Sx}{100 - x}$$

where,

$A$  = apparent wet-bulk density measured by the GRAPE without diameter correction

$D$  = wet-bulk density after diameter correction of density of central hard sediment or rock

$S$  = drilling slurry density (1.2 g/cc) (or other values if appropriate)

$x$  = the percentage that the diameter of the hard sediment or rock is smaller than internal diameter of the liner.

Porosity was recalculated using the new densities.

Only the maximum density and minimum porosity trends were recalculated as lesser densities and greater porosities are suspect of being drill-disturbed sediments, smaller diameter cores, or rock fragments. These adjusted data are very rough approximations.

Where the sediments were soft and unconsolidated, they were probably disturbed and, thus, the density data do not represent precise in situ conditions. However, they may represent overall approximate conditions if water is not added or subtracted and the disturbance is mainly plastic flowage. Maximum porosities and water contents and minimum wet-bulk densities are always suspect of being highly disturbed sediments. All data, unless from extremely disturbed sediment, are reported since they can be used as a control for the natural gamma-ray data, which is related to porosity.

Porosities are calculated from the GRAPE wet-bulk densities via approximated grain densities for cores or sections. However, core sections may have within them layers of sediment with high or low grain densities. The reader interested in specific individual porosities of these layers may easily recalculate the porosity via the wet-bulk density by using his own grain density value.

#### SOUND VELOCITY MEASUREMENTS

Knowledge of the velocity of sound through marine sediments is obviously important for its use in the interpretation of reflection profiles, refraction data, and future well log correlations. Velocities of marine sediments have previously been measured under laboratory condi-

tions, and, in some cases, in situ, by Hamilton (1956; 1963), Hamilton et al. (1956), Laughton (1954; 1957), Sutton et al. (1957), Shumway (1960), Schreiber (1968), Horn et al. (1968), Hamilton et al. (1969), and others. These investigations, and those of Nafe and Drake (1957; 1963), related sound velocities to other mass physical properties of surface sediment. Subsurface sediment sound velocities have been analyzed by Hamilton (1965) with samples retrieved from the experimental Mohole (Guadalupe Site).

### Sampling Philosophy

Sound velocity measurements were taken in each major lithology on undisturbed samples. From some high quality hand-sized samples it is possible to detect anisotropy. Samples of stiff sediment or isolated chunks of hard rocks are lifted from the core and cleaned of disturbed material. The surfaces of the sample that have contact with the transducers are carefully (so as not to disturb the sample) squared off with a knife or saw and smoothed. The acoustical contact with the transducers is made with a few drops of seawater.

In a few instances, the velocities of weak sediments were measured through the core liner when the sediments were too soft to be handled without destroying their integrity. In these measurements, the typical liner travel time and liner thickness, as measured with the transducers, were subtracted in the calculation. These measurements were used to get a "ball park" answer for a particular sediment type, or for drilling predictions; these data are discussed as generalities in the text and labeled in the tables as approximate data.

When samples contained abundant gas it was not possible to measure velocities, because of sound pulse attenuation. Even if the pulse were not completely attenuated, the data would not be representative of in situ conditions, despite pressure and temperature corrections because of gas expansion and loss factors.

### Sound Velocity Method and Equipment for the Hamilton Frame System

Leg 15 was the first leg using the Hamilton-Frame system to measure sound velocities aboard the *Glomar Challenger*. A generalized summary of this technique is given below.

Sound velocity is essentially the distance that sound waves travel at a given temperature and pressure. To effectively assess the sound velocity of rocks or sediments we must measure the distance the sound wave travels, the time required to travel this distance, and the temperature and pressure at which this occurs. In this case, it is the compressional velocity at 400 kHz.

In the Hamilton-Frame system, the travel distance is measured simply by attaching a Dial Micrometer to a transducer that moves a vertical distance equal to the sample thickness (Figure 1). When the sending and receiving transducers are touching each other, there is zero distance between them. A distance reading  $D_1$  is recorded from the Dial Micrometer. When a sample is placed between the transducers, a second Dial Micrometer reading  $D_2$  is recorded, and the travel distance is calculated as  $D_1 - D_2$ .

The travel time across the sample is measured in a similar manner as the distance and is made simultaneously with the distance measurements. The lower transducer sends the sound wave and the upper one receives it. When the two transducers are together, the received wave is observed in an oscilloscope and a relative time reading,  $t_1$ , is recorded. There is some relative time across the transducers at zero separation. A sample is placed between the transducers and a second reading,  $t_2$ , of the received wave is recorded. This is essentially the relative time the sound takes to cross the transducers plus the sample. Thus, the time that the sound traveled through the sample is  $t_2 - t_1$ . Velocity is calculated by  $Vp = (D_1 - D_2) / (t_2 - t_1) = \text{km/sec}$ . The temperature of the sample is recorded at the time of measurement.

### Temperature

The velocity measurements were done after the samples were brought to room temperature. This allows for a good comparison of data and eliminated samples with a temperature gradient. The temperatures of the soft sediments could be obtained by simply inserting a thermometer into, or near the sample. Where the rocks were without a soft matrix in which to insert a thermometer, the room temperature was recorded after sufficient time was allowed for the rock to come to room temperature.

### Velocity Measurement Procedures

1. The microsecond/cm dial is set on 1, 2, 5, or 10, the lowest multiple of which will allow the entire use of the cm-delay dial range. (An estimate of the travel time is made in order to use the full measurement scale.) If a multiple greater than 1 is used, then the error of the dial reading will also be increased by that factor; for example, if 5 is selected, the error in reading the cm-delay dial is multiplied by 5.

2. The two transducers are placed together and the dial micrometer ( $D_1$ ) value (cm) is recorded. A few drops of seawater are placed between the transducers to obtain a good acoustical contact.

3. The cm-delay dial is adjusted to slightly greater than zero.

4. The delay sweep (channel 2) is adjusted by the horizontal position knob, to the left or approximate zero position, so that the beginning of the wave train (where it first deviates from the horizontal) is aligned with the center vertical grid line on the scope face.

5. The focus, intensity, and amplitude (volts per division) are adjusted so that the break from the horizontal is easy to read.

6. A recheck is made to see if the vertical line on the scope face is aligned exactly with the position where the sound wave first deviates from the horizontal.

7. The cm-delay dial reading ( $T_1$ ) and the microsecond/cm dial reading are recorded.

8. A sample, with carefully squared off ends, is placed between the transducers after the contacts have been moistened with a few drops of seawater. A distance reading  $D_2$  is recorded.

9. The cm-delay dial is adjusted until the area where the signal first deviates from the horizontal is again aligned with the center vertical grid line on the face of the scope.

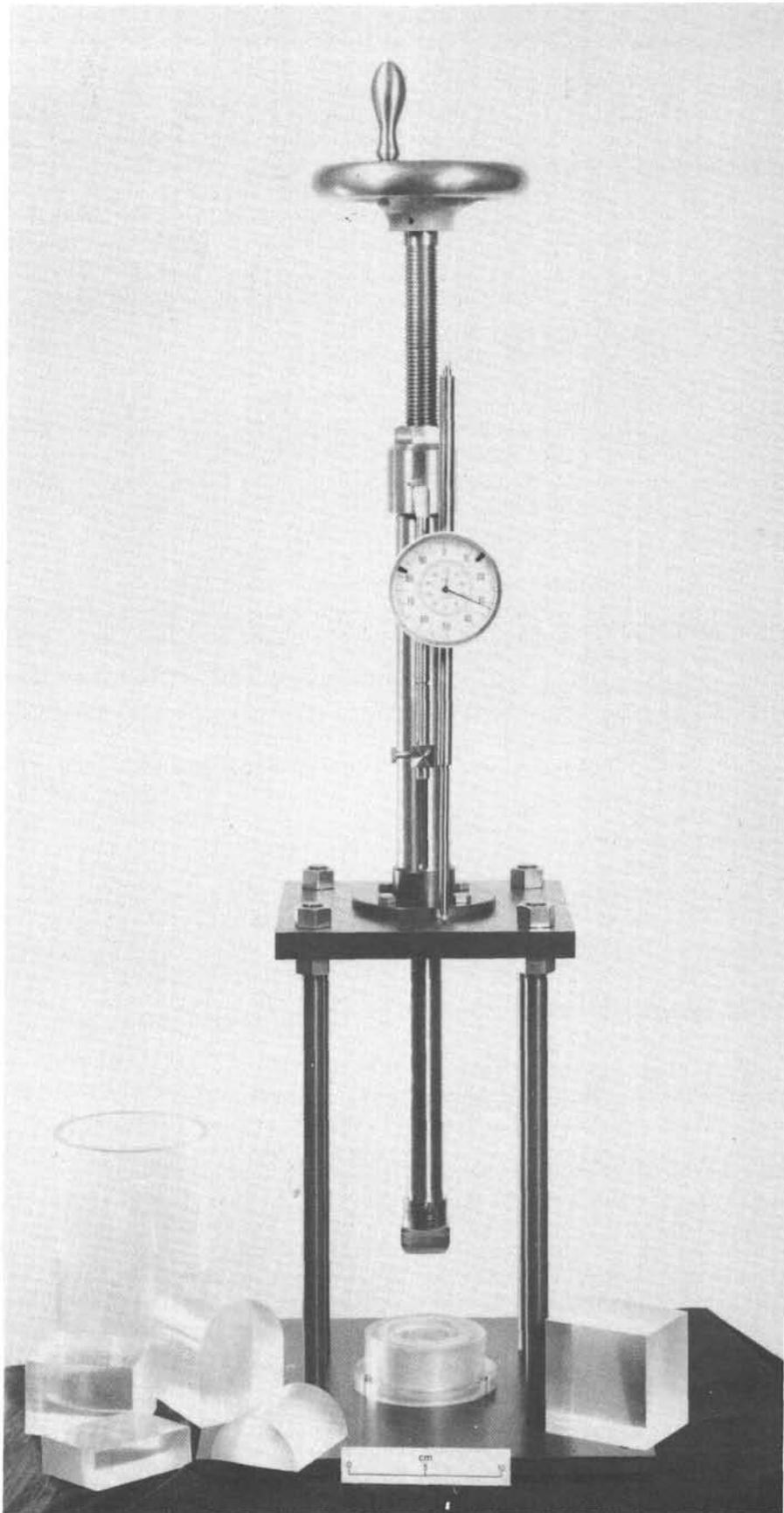


Figure 1. *Hamilton-Frame, dial micrometer, Deep Sea Drilling rectangular transducers, and lucite accessory blocks. The "D" shaped block was used in determining the thickness and travel time through the plastic liners when samples were too soft to be properly removed from the core liner.*

10. Focus, intensity and amplitude (volts per division) is adjusted again so that the break from the horizontal is easily read.

11. Again, the vertical line on the scope face is aligned exactly with the position where the sound wave first deviates from the horizontal.

12. The cm-delay reading  $T_2$  is recorded.

13.  $V_p = (D_1 - D_2) / [(T_2 - T_1) \times \text{microsecond/cm}] = \text{km/sec}$

14. Sample temperature is measured and recorded.

#### Measurements through Liner

If the samples were too weak to be handled without being destroyed, it was possible to measure the velocity through the longitudinal split core liner. An average liner thickness and travel time was obtained by first measuring the travel time and diameter of the "D" shaped block, and then the travel time and distance of the combined liner and "D" shaped block. The time and distance differences in these two measurements are the thickness of the liner and the travel time through the liner. An average liner thickness and an average travel time were subtracted in the sound velocity calculation of the samples whose velocities were measured through the plastic liner.

#### Electronics

"The barium titanate transducers are excited to emit ultrasonic pulses in the compressional mode. A General Radio 1217C pulse generator, followed by an Underwater System, Inc., pulse amplifier, is used to excite the transmitting crystals at their resonant frequency of approximately 400 kHz. A 250 volt pulse of about 0.5 microsecond duration is used to obtain the sonic ring. The transmitted pulse is also used to trigger the sweep of a dual trace. . ." (DSDP Core Manual Pt. 5, p. V 7/1) Hewlett-Packard 180A oscilloscope (temporarily used while the dual trace tektronix 561A oscilloscope was being repaired) with three 1821A and 1801A plug-in units. These are used to display the received signals (Figure 2).

The received sound wave signal in the oscilloscope was adjusted until the position where it first deviates from the horizontal was aligned with the center vertical grid line on the scope face (Figure 3). Time is (cm-delay)  $\times$  (microsecond/cm). It was stressed that the lowest multiple on the microsecond/cm dial be selected so that the entire range of the cm-delay dial is used. This maintains a high degree of precision. Also, the higher the multiple the greater the absolute error in final time. For example, if the microsecond/cm dial is on 2, then the error in reading the cm-delay dial is multiplied by two.

The two transducers are electronically identical and either may be used as the driver or receiver. However, the best acoustical contact is made by driving the signal with the lower transducer. The transducers are moistened with a few drops of seawater to ensure a good acoustical coupling.

The transducers are 1"  $\times$  1/2" Barium Titanate crystals with a thickness resonant frequency of approximately 400 kHz. The brass crystal holders are machined to accommodate an epoxy cradle that houses the crystals in acoustic and electrical isolation (Figure 4). Standard BNC connectors are provided for connecting the electronic driver-

amplifier and the monitoring oscilloscope to the transducers. A special conducting epoxy is used on the crystal surface for the electrical grounding of the crystal to the holder. The entire crystal holder is nickel-plated for appearance and to increase surface hardness.

#### Electrical Set-up

- 1) Unit power supply, General Radio Co., Type 1203-8; Turn on.
- 2) Unit pulse Generator, General Radio Co., Type No. 1212-C:
  - a) Pulse duration 0.5 microsecond.
  - b) PRF of 300 cycles; 100 cycles may be necessary in hard rocks or with metal semistandards.
  - c) 250 volt pulse.
  - d) Amplitude: 9-10.
- 3) Hewlett-Packard 1801A dual trace amplifier, plug in:
  - a) Oscilloscope input: Channel B
  - b) Display: Channel B
  - c) Coupling AC/DC = AC
- 4) Hewlett-Packard, plug in 1821A time base and delay generator:
  - a) Sweep mode: DLY'D SWP
  - b) AC/DC coupling: DC
  - c) Slope +
  - d) Microsecond/cm: This should be set on 1, 2, 5, or 10, the lowest multiple (adjusted for each sample) which will allow the use of the entire range of the cm-delay dial. Thus usage should retain high precision.
- 5) Hewlett-Packard Oscilloscope:
  - a) Intensity: adjust for eye
  - b) Focus: adjust for eye
  - c) Scale Illuminator: on or off as is preferred.
  - d) Adjust the cm-delay dial to approximately zero and also adjust the delay sweep (by the Horizontal Position Knob) to an approximate zero position.
  - e) Coupling AC/DC = DC.
  - f) Volts/division: adjust amplitude until the wave is easily read.

#### Geometric Checks on the Frame

Geometric checks on the assembly of the transducer frame were conducted as follows:

- 1) That all plates and bolt stands were squared.
- 2) That the upper and lower transducers were mounted so that the long axes were parallel to the core's long axis. It was recognized that if they are not, then when sending the sound pulse through low velocity sediment, resting in a liner, part of the sound path would be "refracted" through the plastic liner.
- 3) That the transducers were squared when they were in contact as well as when they were separated.
- 4) That the Dial Micrometer was mounted completely square with the transducer rod and the upper plate on which the toe of the Dial Indicator rod rests. Dial Micrometer reading techniques and checks were conducted as follows:
  - a) When cranking the upper transducer downward onto solid objects, the contact was identified when the Dial Micrometer needle hesitated. At this point the

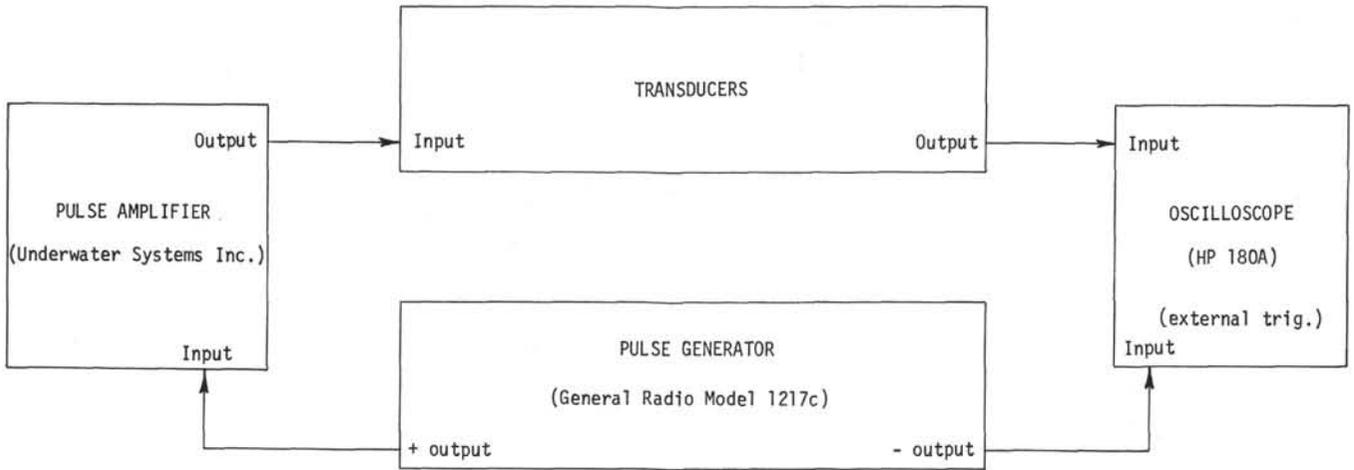


Figure 2. Block Diagram of velocimeter.

lower transducer or solid rock supported the weight of the upper transducer bar, but there was a slight amount of "play" in the transducer bar bearing so the transducers were not crushed. In soft sediment, however, where the transducer bar could not be supported, the needle hesitation could not always be seen, but when it was, the transducer bearing play was removed by backing off with the turn screw. This was done so that the upper transducer would not slowly sink into the sediment.

- b) Semi-standard machined blocks were available whose length, width, and breadth could be independently measured with a micrometer. These blocks were placed together to check the total throw of the Dial Micrometer.

**Electronics Empirical Time Delay Check**

After confirmation (or correction) of the Dial Micrometer, it was possible to empirically check and calibrate, when necessary, the time delay electronics.

1) By using the Semistandard machined blocks of different thicknesses the time delay of the electronics system could be directly related to the thickness of the block that the sound travels through. Thus, this was a check on its linearity.

2) For a rough check on the method, and for training purposes, the plastic, lead, brass, and aluminum blocks were used. These have velocities of 2.74, 2.22, 4.52, and 6.29 km/sec, respectively; which, however, may change some with varying temperature. Velocities are not measured through the edges of the 1" standards as this will not give good data because of a geometric bar velocity (Abernathy, 1965).

The absolute accuracy of the time delay electronics is tested with distilled water at known temperatures and compared with tables of sound speed of distilled water at different temperatures.

**Sound Velocity Tests and Comparisons**

The following were measurements used to test the precision and accuracy of the device.

- 1) Distilled water at a known temperature:

Measured	Theoretical	Percent Error
1.503	1.489	+0.93
1.490	1.489	+0.07
1.486	1.490	-0.27

- 2) Semistandard lucite, brass and aluminum blocks:

	LUCITE	BRASS	ALUMINUM
Boyce, Leg 15	2.741 km/sec (± 0.84%)	4.506 km/sec (± 0.45%)	6.293 km/sec (±1.29%)
Schrieber <sup>3</sup>	2.745 km/sec (± 0.006 km/sec)	4.529 km/sec (± 0.004 km/sec)	6.295 km/sec (± 0.008 km/sec)

**NATURAL GAMMA RADIATION**

These natural gamma radiation measurements permit the location of radionuclide concentrations, which in some cases are not obvious to the naked eye, in addition to allowing these cores to be correlated with well logs. In general, natural gamma measurements distinguish argillaceous from nonargillaceous formations (Lynch, 1962). In fine grained sediments, clay and zeolite minerals have ion exchange capacities which may hold gamma-ray emitting isotopes in addition to isotopes which may be contained in the original mineral structures or organic carbon. Gamma radiation from sand tends to be low unless potassium feldspars are abundant (Lynch, 1962). Silica and calcium carbonate from organisms usually have low radiation, although radionuclides can be concentrated by some organisms (Koczy, 1963), and dolomites are likely to contain radioactive elements.

These gamma measurements do not distinguish between any particular isotopes. In sediments, the potassium isotope series typically contributes most of the total natural gamma

<sup>3</sup>Lamont-Doherty Geological Observatory, Personal Communication, 1971.

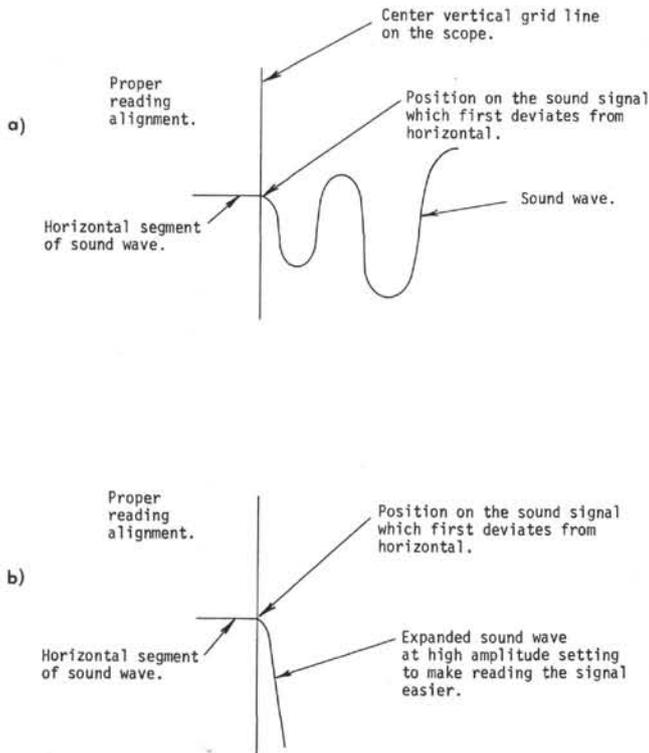


Figure 3. The sound signal in the scope is read where it first deviates from horizontal. (a) This is the sound wave before the amplitude (volts per division) is increased, and (b) This is after the amplitude is increased to facilitate easier reading.

radiation, with the remainder usually being emitted from the uranium and thorium isotopes (Evans and Lucia, 1970). Natural radiation in the form of gamma rays can be emitted from isotopes like  $U^{235}$ ,  $Ra^{226}$ ,  $Pb^{212}$ ,  $P^{214}$ ,  $K^{40}$ ,  $Th^{208}$ ,  $Bi^{214}$ ,  $P^{36}$  and other isotopes. Radioactive particles in marine sediments are discussed by Koczy and Rosholt (1962), Koczy (1963), Mauchline and Templeton (1964), Prospero and Koczy (1966), and Lal and Peters (1967). These works contain comprehensive reviews and references.

#### Methods

Aboard the *Glomar Challenger*, natural gamma radiation is recorded at intervals of 7.62 cm (3 inches) along the core (6.62 cm I.D.) during a 1.25 minute period. The volume of core segment scanned, however, is greater than the 7.6 cm core segment. Radiation counts at the ends of the cores are low because the volume of the sediment being scanned is reduced. Radiation counts are reproducible within  $\pm 100$  and the data are reported with the atmospheric background count (counts with equipment empty) subtracted, but reported at the bottom of the core plots as a footnote. Detailed equipment descriptions are in the DSDP manual and in Evans and Lucia (1970).

A few cores were recovered in the extended core barrel which has a 2.25 inch liner I.D. compared to the normal 2.60 inch liner I.D. The volumetric differences per unit length, between the two core sizes, relative to the smaller

core is 33.7%, therefore the natural gamma counts of the 2.25 inch I.D. cores were increased by this percentage. A notation is made in the individual site chapters where this correction has been applied.

#### Discussion

These natural gamma radiation data have been measured, in part, from disturbed sediment samples, thus they do not accurately represent in situ values. For most unconsolidated sediments these values may represent the relative differences at in situ conditions. This is especially true when high radiation is typically emitted from very porous samples, because if the sediments were more consolidated, the radiation emitted per unit volume would be even higher.

The density and porosity of these cores has been continuously measured, therefore, the reader may estimate the amount of solid material being scanned and the gamma values for any given porosity. For example, if the sediment is homogeneously disturbed and has an apparent porosity of 90%, then a 10% decrease in porosity to 80% would essentially double the amount of particulate matter, which here is assumed to be emitting the natural gamma radiation. Precautions must be taken, however, when trying to correct for porosity in a nonhomogeneous core in which porosity varies across the diameter of the cores, such as a small diameter hard rock surrounded by a soupy paste. Other problems which may be encountered would be a high gamma emitting sediment with disturbed material along the liner being a different sediment type.

#### PENETROMETER

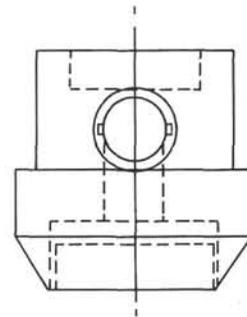
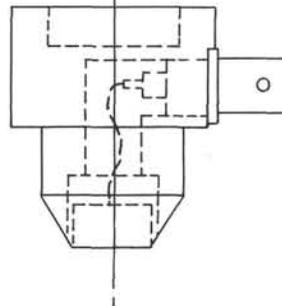
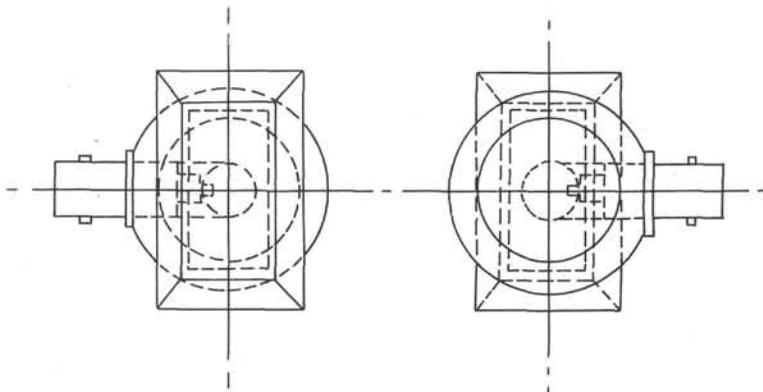
The purpose of the penetration measurements is to indicate relative differences of the sediment stiffness for purposes of lithologic description. Penetrometer values are in units of millimeters that a standard needle will penetrate under a fixed load of  $50 \text{ g} \pm .1 \text{ g}$ . The standard needle is about 5 cm in length and 1.00 to 1.02 mm in diameter. This equipment is described in detail in American Society of Testing and Materials (1965). These measurements are not designed to be a calculated specific unit of strength such as shear strength.

**Discussion:** Because the surface sediments are normally disturbed during coring operations, these values are not necessarily representative of in situ conditions.

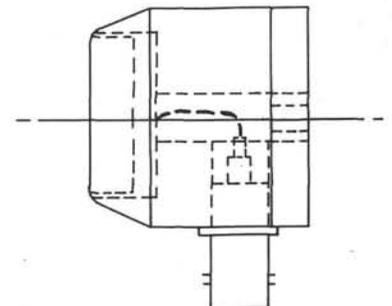
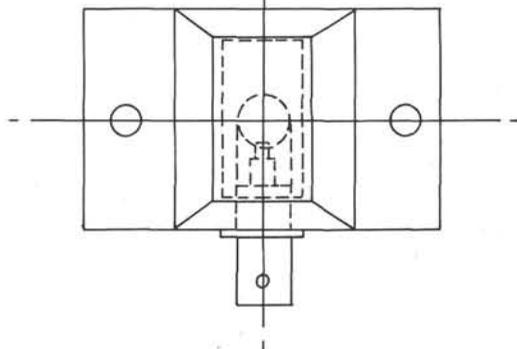
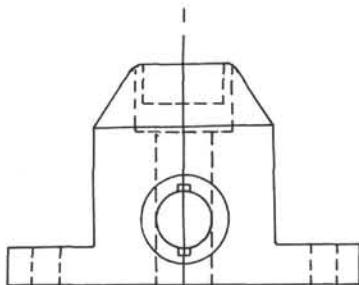
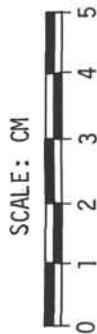
#### REFERENCES

- Abernethy, S. H., 1965. Improved equipment for a pulse method of sound velocity measurement in water, rock, and sediment: U. S. Navy Electronics Lab., San Diego, Calif. Tech. Memo. No. 824.
- ASTM, 1965. Standard method of test for penetration of bituminous materials: Am. Soc. Test. Mat. D-5-65, p. 1007.
- Boyce, R. E., 1968. Electrical resistivity of modern marine sediments from the Bering Sea: J. Geophys. Res., V.73, p.4759.
- Brier, Chester, Bennin, Robert and Rona, P. A., 1969. Preliminary evaluation of a core scintillation counter for bulk density measurement in marine sediment cores: J. Sediment. Petrol., V.39, (4), p.1509-1519.

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Figure 4. *Deep Sea Drilling rectangular transducers used with the Hamilton-Frame system.*

- Bullard, E. C. and Day, A. A., 1961. The flow of heat through the floor of the Atlantic Ocean: *Geophys. J.*, V. 4, p. 282.
- Bullard, E. C., Maxwell, A. E. and Revelle, R., 1956. Heat flow through the deep sea floor: *Advan. Geophys.*, V. 3, p. 153.
- Evans, H. B., 1965. GRAPE—A device for continuous determination of material density and porosity: SPWIA Logging Sym., 6th Annual, Dallas, Texas, 1965. Trans. V. 2, p. B1-B25.
- Evans, H. B. and Cotterell, C. H., 1970. Gamma-Ray Attenuation Density Scanner: Initial Reports of the Deep Sea Drilling Project, Volume II, Washington (U. S. Government Printing Office), 442-454.
- Evans, H. B. and Lucia, J. A., 1970. Natural Gamma Radiation Scanner: Initial Reports of the Deep Sea Drilling Project, Volume II, Washington (U. S. Government Printing Office), 440-442.
- Hamilton, E. L., 1956. Low sound velocities in high porosity sediments: *J. Acoust. Soc. Am.* V. 28, p. 16.
- , 1959. Thickness and consolidation of deep sea sediments: *Geol. Soc. Am. Bull.*, V. 70, p. 1399.
- , 1960. Ocean basin ages and amounts of original sediments: *J. Sediment. Petrol.*, V. 30, p. 370.
- , 1963. Sediment sound velocity measurements made in situ from bathyscaph TRIESTE: *J. Geophys. Res.*, V. 68, p. 5991.
- , 1964. Consolidation characteristics and related properties of sediments from Experimental Mohole (Guadalupe Site): *J. Geophys. Res.*, V. 69, (20), p. 4257.
- , 1965. Sound speed and related physical properties of sediments from experimental Mohole (Guadalupe Site): *Geophysics*, V. 30, (2), p. 257.
- , 1969a. Sound velocity, elasticity, and related properties of marine sediments, north Pacific: II. Elasticity and elastic constants: *Naval Undersea Res. Devel. Center, San Diego, Calif.*, T. P. 144.
- , 1969b. Sound velocity, elasticity, and related properties of marine sediments, north Pacific, II Prediction of in situ properties: *Naval Undersea Res. Devel. Center, San Diego, Calif.* T. P. 145.
- Hamilton, E. L., Bucker, H. P., Keir, D. L. and Whitney, J. A., 1969. In situ determinations of the velocities of compressional and shear waves in marine sediments from a research submersible: *Naval Undersea Res. Devel. Center, San Diego, Calif.*, T. P. 163.
- Hamilton, E. L., Shumway, G., Menard, H. W. and Shippek, C. J., 1956. Acoustic and other physical properties of shallow-water sediments off San Diego: *Acoust. Soc. Am. J.*, V. 28, p. 1.
- Harms, J. C. and Choquette, P. W., 1965. Geologic evaluation of a gamma-ray porosity device: SPWLA Logging Sym., 6th Annual Trans., Dallas, Texas 1965. VII, p. C1-C37.
- Horn, D. R., Horn, B. M. and Delach, M. N., 1968. Sonic properties of deep-sea cores from the north Pacific basin and their bearing on the acoustic provinces of the north Pacific: *Tech. Rept. No. 10, CU-10-68 NAVSHIPS N00024-67-C-1186*.
- Igelman, K. R. and Hamilton, E. L., 1963. Bulk Densities of mineral grains from Mohole samples (Guadalupe Site): *J. Sediment. Petrol.*, V. 33, p. 474.
- JOIDES (Joint Oceanographic Institutions' Deep Earth Sampling Program), 1965. Ocean drilling on the continental margin: *Science*, V. 150, p. 709.
- Kermabon, A., Gehin, C., Blavier, P. and Tonarelli, B., 1969. Acoustic and other physical properties of deep-sea sediments in the Tyrrhenian Abyssal Plain: *Marine Geol.* V. 7, (2), p. 129-146.
- Koczy, F. F., 1963. Age determination in sediments by natural radioactivity: *The Sea*, M. N. Hill (Ed.), New York. (Interscience Publishers), V. 3, p. 816-831.
- Koczy, F. F. and Rosholt, J. N., 1962. Radioactivity in oceanography. *In Nuclear Radiation in Geophysics*, Israel, H. and Krebs, A. (Eds.): Berlin. (Springer-Verlag), p. 18-46.
- Lal, D. and Peters, B. 1967. Cosmic ray produced radioactivity on the earth. *In Cosmic Rays II: Encyclopedia of Physics*, S. Flugge and K. Sitte (Eds.), New York. (Springer-Verlag), V. 46, p. 551-612.
- Laughton, A. S., 1954. Laboratory measurements of seismic velocities in ocean sediments: *Roy. Soc. (London) Proc.*, Ser. A 222, 336.
- Laughton, A. S., 1957. Sound propagation in compacted ocean sediments: *Geophysics*, V. 22, p. 233.
- Lynch, E. J., 1962. Formation evaluation: New York (Harper and Row), p. 422.
- Mauchline, J. and Templeton, W. L., 1964. Artificial and natural radioisotopes in the marine environment. *In Oceanography and Marine Biology, An Annual Review*, H. Barns (ed.): London (George Allen & Unwin Ltd), p. 229-279.
- Moore, D. G., 1964. Shear strength and related properties of sediments from experimental Mohole (Guadalupe Site): *J. Geophys. Res.*, V. 69, p. 4271.
- Moore, D. G. and Shumway, G., 1959. Sediment thickness and physical properties: Pigeon Point Shelf, California: *J. Geophys. Res.*, V. 64 (3), p. 367.
- Nafe, J. E. and Drake, C. L., 1957. Variation with depth in shallow and deep water marine sediments of porosity, density and the velocities of compressional and shear waves: *Geophysics*, V. 22, p. 523.
- Nafe, J. E. and Drake, C. L., 1963. Physical properties of marine sediments: *The Sea*, M. N. Hill (Ed.), New York (Interscience), V. 3, p. 794-815.
- Prospero, J. M. and Koczy, F. F., 1966. Radionuclides in oceans and sediments. *In Encyclopedia of Oceanography*, R. R. Fairbridge (Ed.): New York (Reinhold Publishing Corp.), p. 730.
- Ratcliffe, E. H., 1960. The thermal conductivity of ocean sediments: *J. Geophys. Res.*, V. 65, p. 1535.
- Richards, A. F., 1962. Investigations of Deep-Sea Sediment Cores, Part II, Mass Physical Properties: U. S. Navy Hydrographic Office, Washington D. C., Tech. Rept. 106, p. 146.
- Schlumberger, 1966. The formation Density Log. *In Schlumberger Log Interpretation Principles: Paris (Kecran-Servant [23827])*, p. 47-49.
- Schreiber, B. C., 1968. Sound velocity in deep sea sediments: *J. Geophys. Res.*, V. 73, p. 1259.
- Shumway, G., 1958. Sound velocity vs. temperature in water-saturated sediments: *Geophysics*, V. 23, p. 494.
- , 1960. Sound speed and absorption studies of marine sediments by a resonance method, Part I, Part II: *Geophysics*, V. 25, p. 451, 659.
- Sutton, G. H., Berckheimer, H., and Nave, J. E., 1957. Physical analysis of deep sea sediments: *Geophysics*, V. 22, p. 779.
- Whitmarsh, R. B., 1971. Precise sediment density determination by gamma-ray attenuation alone: *Sediment. Petrol.* V. 41, No. 3, p. 882-883.