29. ASPECTS OF PHYSICAL PROPERTIES MEASUREMENTS, LEG 47: SITES 397 AND 398

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INTRODUCTION

This chapter addresses physical properties studies other than those of more practical application to the correlation of seismic reflectors to the drilled rock column and the generation of a velocity-depth profile. Hence, these comments will apply more to those with an intrinsic interest in the physical properties themselves rather than to readers specifically attentive to the elucidation of Sites 397 and 398. The comments on sampling may provide guidance for physical properties scientists aboard *Glomar Challenger* for the first time.

SAMPLING

Physical properties measurements (sonic velocity, single sample GRAPE, water content, porosity, and density) and routine geochemical measurements (grain size, carbonate bomb, carbon-carbonate, etc.) are normally taken at least once per core. Even in relatively homogeneous sediments, however, one measurement per section is preferable. Where constantly changing lithologies are encountered, it is important that at least one measurement per core is taken on the typical dominant lithology for that core. Although analyses on minority facies certainly should be made since they may be crucial to the interpretation, these can cause some misleading average results unless care is taken to ensure that general sampling is representative of that core.

While a physical properties measurement is often of interest per se, it has increased significance if direct correlations can be made with other physical, chemical, petrologic, etc. analyses on the same sample. Since a direct relationship exists between velocity, porosity, water content, density, and calcium carbonate content, and a strong correlation is observed between these properties and seismic reflectors, it is desirable that as many of these measurements as possible should be made on the same or closely adjacent sample material. Figure 1 demonstrates two ways in which the use of the same sample material may be used optionally for both direct correlation of properties and for sample material conservation. The basic optimization principle is first to make those measurements which do not involve demolishing the sample, followed by those techniques which do.

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METHODS

This section has two purposes: (1) to familiarize the reader with the shipboard techniques for measuring physical properties, and (2) to comment on the reliability of the results. It is hoped that subsequent workers aboard *Glomar Challenger* will find these appraisals helpful.

Acoustic Velocity

All velocity measurements on Leg 47 were made aboard ship using a Hamilton Frame velocimeter (Boyce, 1973). Many of these necessarily were performed on soft sediments, where measurement through the core liner was required. Despite careful location of sonic measurements, the possibility of encountering significantly disturbed sediment was high. Acoustic coupling between the sediment and core liner is usually variable because of a slurry of sheared sediment and entrapped air along the sample-liner boundary. Furthermore, acoustic signals transmitted through these soft sediments are usually very weak, with slow rise time displayed on the oscilloscope, thus making consistently accurate readings difficult to achieve. It was observed that the amplitude of the signal could be increased considerably by increasing the downward pressure of the transducer onto the sample. In every case, this led to increasing velocities (up to 5%) with added pressure.

Acoustic anisotropy is to be expected in deeply buried sediments (Hamilton, 1970); although this has been observed in DSDP cores (for example, Tucholke et al., 1976), a consistent increase in anisotropy with increasing depth has not been found. Apparently, the degree of cementation of consolidated sediments is the singlemost significant factor controlling anisotropy, and this is often unrelated to the present depth of burial. In most cases where both values were measured on Leg 47, velocities parallel to bedding were higher than those perpendicular to bedding. But enough contrary evidence from Holes 397 and 397A leads to the conclusion that anisotropy was encountered but was not consistent.

Effect of Core Temperature Upon Velocity Measurements

Normal DSDP procedure for velocity measurements on sediment cores is to leave the cores out to equilibrate to room temperature prior to measuring their sonic velocities. The logic behind this is to achieve thermal uniformity of the sample material at the expense of taking measurements more closely related to their *in-*

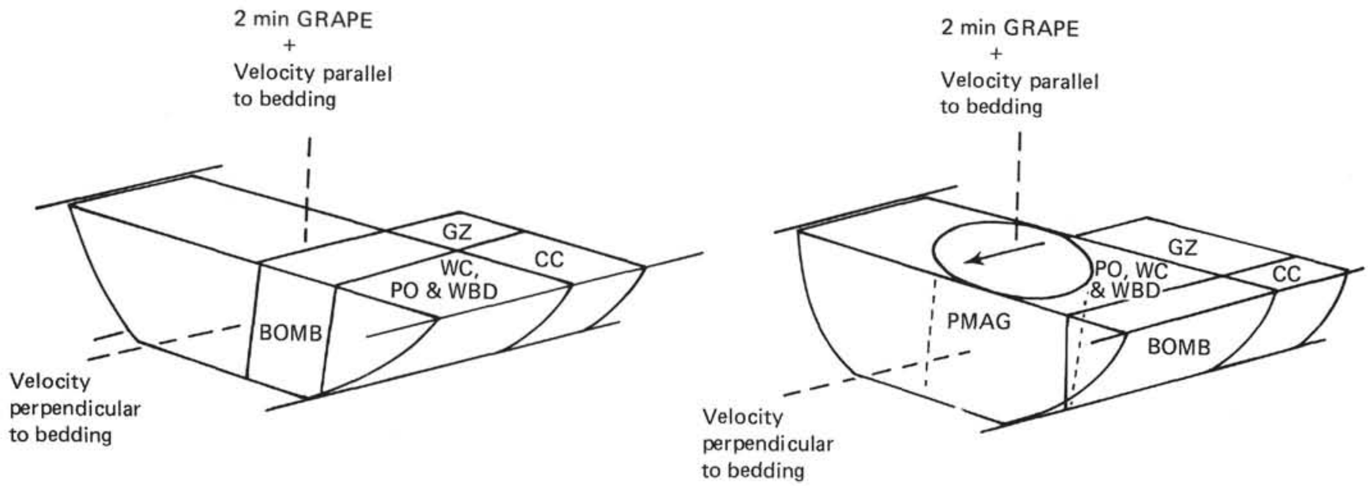

Figure 1. *Two possible methods of sampling for physical and chemical properties. The samples are labeled for the following analyses: CC, carbon-carbonate ratio; WC, water content; PO, porosity, WBD, wet bulk density (gravimetric analyses); GZ, grain size; and BOMB, carbonate bomb test for carbonate content. PMAG designates the drilled and oriented paleomagnetic sample. The velocities and 2-minute GRAPE measurements are made prior to the other samples being cut.*

situ temperatures. The *in-situ* temperature of sediments lying at 200 meters or more below the sea floor in a water depth of about 4 km will be approximately 1° to 2°C.

During Leg 47A, each core was allowed to equilibrate with a laboratory temperature of 20° to 22°C before velocity was measured. Temperatures of each core were recorded and rarely differed from the mean by more than 1.0°C. For seawater, this would account for velocity variations of ±3 m/sec (U.S. Naval Oceanographic Office, 1966).

During Leg 47B, it was observed that the fluctuation of laboratory room temperature was between 20° to 25°C. The thermal constant of the cores appears to be such that after opening, GRAPE procedures, etc., their internal temperature varied less than the room temperature and was normally between 16° to 18°C. On this basis, it was concluded that there was no loss of accuracy and that it also fit more conveniently into the laboratory routine if measurements were made on the core at this time, i.e., approximately 1 hour after recovery rather than waiting the recommended 6 hours re-equilibration time. (This applies to sediment cores soft enough to cut with a wire. When harder rocks are cut with a saw, the cut surface is frictionally heated and the above observations do not apply.)

A short experiment was conducted at Site 398 to see (1) whether the temperature effect is measurable within the accuracy of the Hamilton Frame method, and (2) to quantify the temperature effect upon velocity.

Section 398D-1-6 was cooled, then allowed to return to laboratory temperature while velocities were measured. Ignoring two spurious values, Figure 2 shows that the gradient is close to 10 m/sec per degree Centigrade. Evidently, the dependence of velocity on temperature is more critical in sediments than it is in seawater. As consolidation increases downhole, this dependence is likely to increase as well. From these considerations, it appears that a ±1°C spread in core temperatures leads to velocity changes on the order of ±5 to 10 m/sec, and perhaps larger in sediments of very low porosity. This is relatively insignificant considering the other sources of error, but it can be corrected easily. For comparison of velocities measured at different sites where equilibration temperatures were different, velocity correction to a standard temperature may be necessary. This becomes more critical with decreasing water content.

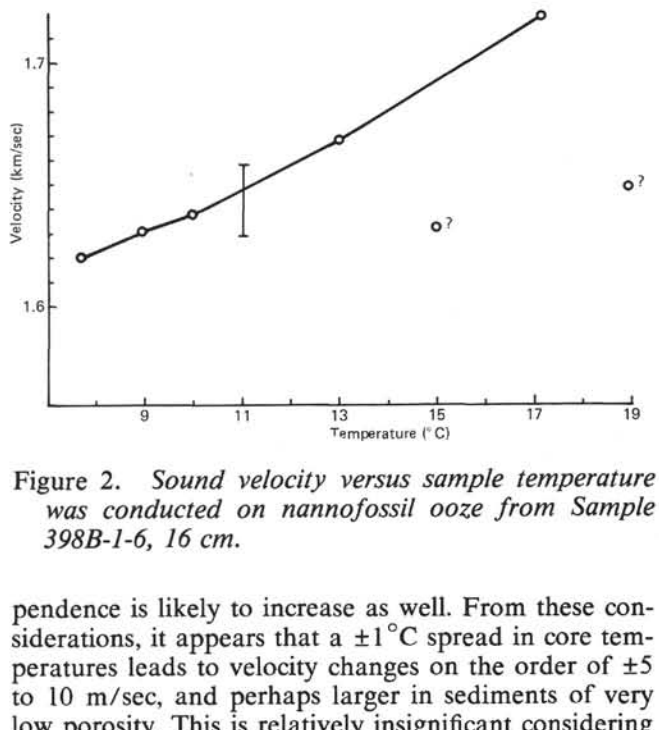

Figure 2. *Sound velocity versus sample temperature was conducted on nannofossil ooze from Sample 398B-1-6, 16 cm.*

Repeatability of Velocity Measurements

Velocity measurements were occasionally repeated to check the relative accuracy of the results. In Section 397A-16-3, five separate measurements at the same level resulted in a mean of 2.31 km/sec ±2.3 per cent. By contrast, eight repeated measurements on a standard Lucite block resulted in 2.74 km/sec ±0.8 per cent. The problems of weak signal, inaccurate thickness measurement, variable coupling between sample and transducer, etc., all contribute to the absolute error of about 2 per cent (Boyce, 1973). All shipboard velocities are likely to be considerably below *in-situ* velocities. Hydrostatic pressures at depths encountered on Leg 47 would probably raise velocities by 4 to 8 per cent. Lithostatic or tectonic pressure could raise these velocities further.

Compressional Wave Velocities as a Function of Pressure

Two silty clay and one compacted limestone samples from Site 398 were subjected to velocity measurement under increasing confining pressure to 0.50 kbar, = 50 MN/m^2 (Table 1), which corresponds to approximately 0.5 km depth of burial. The velocity curves (Figure 3) plotted at intervals of 0.05 kbar show a near-linear increase in compressional wave velocity. In the absence of any observational studies to see whether recrystallization of the sample had taken place, it is presumed that the increased velocities are due to hydrostatic compression of the sample material.

The silty clay samples demonstrated initial velocities at atmospheric pressure lower than those measured onboard *Glomar Challenger* (Table 2). Although some effort was made to keep the samples moist, the lower initial velocities could be due to some degree of desiccation. The same two samples (398D-65-4, 85 cm and 398D-121-3, 72 cm) also showed lower densities during shore-based measurement,[2] which may also be due to desiccation. These two samples have measured porosities (2-minute GRAPE) of 36.9 and 24.6 per cent, respectively. The limestone sample (398D-132-1, 8 cm) had a lower porosity of 14.8 per cent, the same density

TABLE 1
Compressional Wave Velocity Versus Hydrostatic Pressure for Selected Samples From Site 398

Pressure (kbar)	Sample (Interval in cm) 398D-65-4, 84-85 ρ=2.01 g/cm^3	398D-121-3, 72-74 ρ=2.14 g/cm^3	398D-132-1, 8-9 ρ=2.41 g/cm^3
atm	1.82	2.00	3.52
0.05	1.84	2.02	3.53
0.10	1.85	2.03	3.55
0.15	1.86	2.05	3.57
0.20	1.87	2.07	3.59
0.25	1.88	2.09	3.60
0.30	1.89	2.10	3.62
0.35	1.90	2.11	3.63
0.40	1.91	2.13	3.64
0.45	1.92	2.14	3.65
0.50	1.93	2.16	3.66

Note: Measurements made by N.I. Christensen, University of Washington, Seattle.

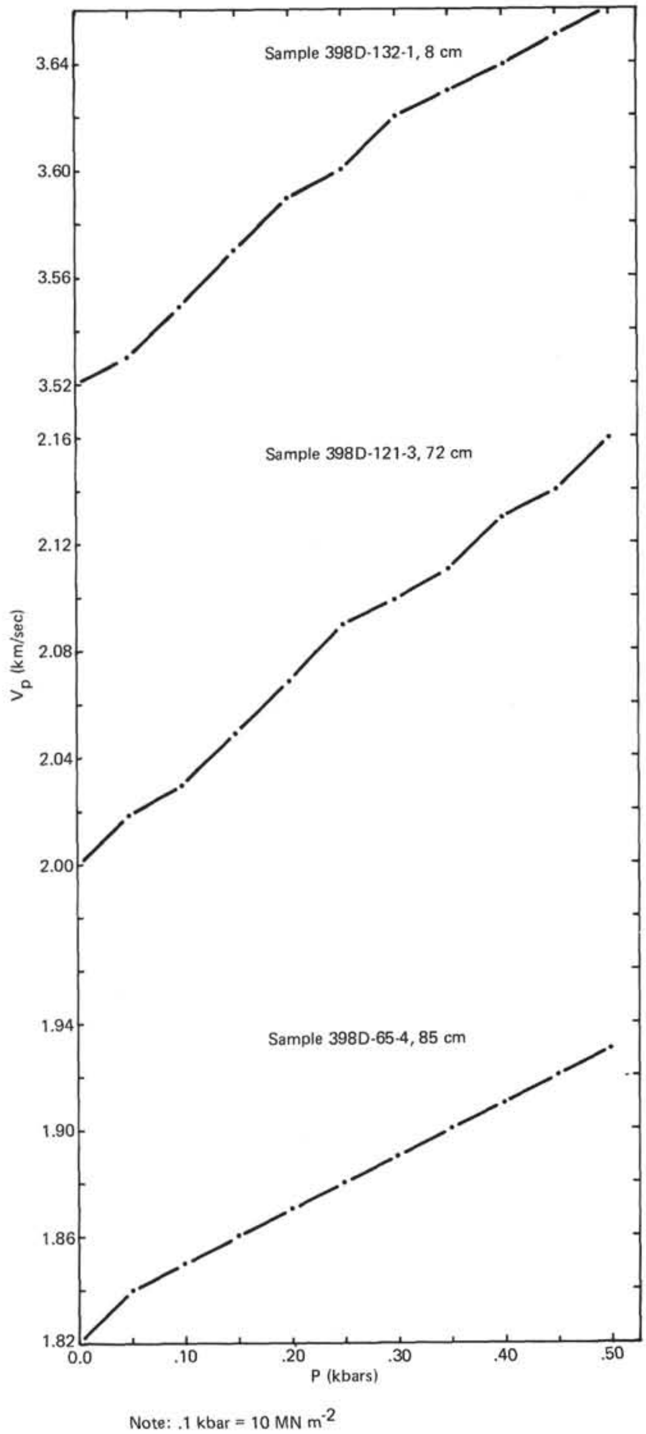

Figure 3. *Effect of increasing hydrostatic pressure on compressional wave velocity.*

as that observed onboard ship and a higher velocity at atmospheric pressure than that measured onboard ship with the Hamilton Frame. The accuracy of the Hamilton Frame apparatus was discussed earlier.

Working on the assumption that the lower velocities and densities are a result of desiccation (when the

[2] We thank Dr. N. I. Christensen for making the shore-based observations. The technique used is that described by Birch (1960).

TABLE 2
Comparison of Shipboard and Shore-Based Velocity and Density Measurements

Sample (Interval in cm)	Vp (km/sec) Shipboard	Vp (km/sec) Shore	Density (g/cm^3) Shipboard	Density (g/cm^3) Shore	% Porosity Shipboard
398D-65-4, 85	2.21	1.82	2.05	2.01	36.9
398D-121-3, 72	2.74	2.00	2.25	2.14	24.6
398D-132-1, 8	3.38	3.52	2.41	2.41	14.8

Note: Shore-based measurements made by N.I. Christensen.

seawater from the pore spaces is replaced mainly by air), using Vp seawater as 1.45 and Vp air 0.33 km/s should reduce the velocities by as much as 77 per cent × Po. This gives maxima of Δ Vp between shore and shipboard measurements for the three samples of -0.63, -0.52, and -0.39 km/sec, respectively. The difference between the measured shipboard and shore-based velocities are -0.39, -0.74, and $+0.14$ km/sec, respectively. Only sample 398D-65-4, 85 cm complies with the desiccation hypothesis; Sample 398D-121-3, 72 cm shows too high a variance; and Sample 398D-132-1, 8 cm, which shows a difference in the opposite sign, may indicate that a certain amount of recrystallization has taken place in this sample.

Gravimetric Syringe Technique

For soft sediments from Leg 47, bulk physical properties of wet density, porosity, and water content were measured by the syringe technique (Boyce, 1976). Boyce (1976) reports absolute accuracy of the water content and porosity as ±2 per cent and ±4 per cent, respectively. Relative to one another, values of wet density are accurate to ±5 per cent.

As pointed out by Mahheim et al. (1974), the syringe sample volume is so small (<1 cm^3) that large experimental errors can be expected because (1) the volume measurement is crude, and (2) a significant amount of air can become entrapped in the sample. Nonetheless, results from paired samples taken at three levels in Hole 397 show good agreement (Table 3A). As an additional check, two duplicate samples were sent to S.I.O. in sealed bottles (Table 3B). Because sample volume for the latter was considerably greater (10 cm^3), these values may be more reliable. Certainly, more comparisons are needed for an appraisal of the absolute accuracy of the shipboard syringe measurements. If considered adequate, the syringe technique affords a quick and simple method of sampling. Although volume and weight measurements are tedious, they can be done hours or days after sampling, when time or sea state permit.

Gravimetric Chunk Technique

Bulk properties of samples too indurated for the syringe were measured by the "chunk" method (Boyce, 1973). The sample volume (5 to 10 cm^3) is considerably larger than it is with the syringe technique as measured by water displacement; hence, better accuracy is expected. Table 4A is a list of paired shipboard values

TABLE 3A
Comparison of Syringe Measurements From Adjacent Samples

Sample (Interval in cm)	Wet Bulk Density (g/cm^3)	Porosity (%)	Water Content (%)
397-22-3, 121	1.74/1.75	56.3/58.4	32.4/33.4
397-45-4, 77	1.99/1.97	46.5/47.6	23.4/24.1
397-45-5, 77	1.98/1.96	46.9/46.2	23.7/23.6

TABLE 3B
Comparison of Syringe and Large-Volume Shore-Based Measurements From Adjacent Samples

Sample (Interval in cm)	Water Content (%) Shipboard/Shore Based
397-21-3, 90	35.2/39.6
397-32-3, 33	30.1/31.7

from separate samples taken at identical depths. Table 4B is a list comparing shipboard and shore-based values from samples taken at nearly identical depths. The comparisons imply that the chunk method, like the syringe, yields reasonably consistent and reliable results with a minimum amount of time spent taking and preparing the sample. The most time-consuming chore is weighing the samples, but this can be left to a time of minimum inconvenience.

GRAPE Scan Technique

For a limited portion of the time on Leg 47, one to two sections of each core were scanned by the Gamma Ray Attenuation Porosity Evaluator (GRAPE) (Boyce, 1976). He reports the accuracy of wet bulk density and porosity to be roughly ±10 to 12 per cent.

The large range of experimental error is due to many factors: (1) variations in core-liner thickness (measurements are made on unsplit core sections), (2) misaligned loose samples not filling the entire liner, (3) random variations in the gamma ray source, (4) drift

TABLE 4A
Comparison of Chunk Measurements From Adjacent Samples

Sample (Interval in cm)	Wet Bulk Density (g/cm^3)	Porosity (%)	Water Content (%)
399A-16-3, 83	2.21/2.18	27.7/30.5	12.5/14.0
397A-18-1, 10	2.06/2.10	34.4/36.2	16.7/17.2

TABLE 4B
Comparison of Shipboard and Shore-Based Chunk Measurements From Nearby Adjacent Samples

Section	Water Content (%) Shipboard (depth, cm)	Shore Based (depth, cm)
397-54-3	24.7 (88)	24.0 (117)
397-65-3	23.4 (91)	22.4 (44)
397-87-1	18.9 (100)	21.7 (100)
397A-13-1	17.3 (140)	19.3 (132)
397A-39-1	14.1 (47)	13.8 (91)

in background levels of gamma ray noise, (5) need to assume that the attenuation coefficient of the sediment is the same as that of quartz, and (6) need to assume a uniform grain density of 2.65 g/cm^3.

Corrections can be applied to minimize many of these: (1) after the core is split the true diameter of the sample can be measured, (2) standards can be run as often as necessary to detect drifts in the background level of gamma rays, (3) attenuation coefficient of the dominant mineral can be used if it is known, and (4) grain density can be measured separately.

With the advent of continuous coring in IPOD, a core is usually recovered at least every 30 minutes. Scanning an entire section requires 15 minutes, so that doing any more than two sections per core creates a backlog. It is the opinion of the authors that, considering the inordinate amount of time of the scan measurement and considering the inaccuracy of the results unless time-consuming corrections are made, other techniques of wet density and porosity measurement should be relied upon.

Static GRAPE Technique

Accuracy of the GRAPE can be improved considerably by static two-minute counts of samples removed from the liner. Because the sample is out of the liner and its thickness can be measured directly, and because of the length of time of the count, all experimental errors are minimized except for the assumed values of attenuation coefficient and grain density. Boyce (1976) reports accuracies of ±2 per cent for the two-minute count.

At Holes 397 and 397A, samples for static two-minute GRAPE measurements and gravimetric measurements were purposely taken close together to compare the results. Figure 4 shows that GRAPE densities were generally 0.1 g/cm^3 greater than those measured by gravimetric methods. Figure 5 indicates that GRAPE porosity values were consistently 5 to 10 per cent lower than corresponding gravimetric values above 40 per cent. Below this figure, discrepancies between the two techniques increased significantly.

The cause of the discrepancies between static GRAPE values and gravimetric values probably lies in part in the assumed value of the attenuation coefficient. The attenuation coefficient of water is 0.110 cm^2/g, while that of quartz is 0.100 cm^2/g (Boyce, 1974). Obviously, the proper coefficient for sediment is itself a function of porosity; it is likely to be larger for moist sediments than for consolidated sediments with lower water contents. The calculations for wet bulk density P_B and porosity F are as follows:

$$\rho_B = \frac{1}{\mu d} \ln \left(\frac{Io}{I}\right)$$

$$\Phi = \frac{\rho_g - \rho_B}{\rho_g - \rho_f}$$

where

μ = attenuation coefficient
d = sample thickness
Io = gamma ray source intensity
I = gamma ray intensity through sample
ρ_g = assumed grain density
ρ_f = density of seawater.

For all calculations on Leg 47, μ = 0.100 cm^2/g (the value of quartz) was used. As μ is inversely proportional to wet bulk density and directly proportional to porosity, it follows that for saturated sediments of high porosity the calculated GRAPE densities are too large and the porosities are too small. At Holes 397 and 397A, a value of μ = 0.108 cm^2/g for the shallowest sediments, decreasing to μ = 0.103 cm^2/g for the deepest sediments, considerably improves the agreement between GRAPE and gravimetric density values. The discrepancies in porosity values, especially for well-indurated samples, may be more a result of the assumed grain density of 2.65 g/cm^3.

Shear Strength

A Wykeman-Farrance vane shear device (Gibbs et al., 1960) was used to measure shear strength perpendicular to the bedding of split cores. A discussion of the significance of shear strength measurements in deep marine sediments is in Lee (1973). Stress and strain at Site 397 were recorded from visual observation; at Site 398, these were continuously monitored by a transducer manufactured by the Diversified Marine Corp., and displayed on a strip chart recorder. By this means, the stress build-up could be observed together with the relaxation after shearing had taken place (Figure 6). In addition to undeformed shear strength, remolded values were also measured at the latter site, although the sediments rapidly became indurated with depth such that vane shear measurements could only be made to a depth of 273.2 meters (the top seven cores).

Migliore and Lee (1971) state that for samples to drain properly, vane rotation should be no faster than 6 degrees per minute. The standard rotation rate used on Leg 47 was 89° per minute, a rate that Migliore and Lee suggest may produce values different from the slower rate by 10 per cent. As Lee (1973) and others have pointed out, drilling disturbance in unconsolidated sediments can cause more variation in measured values than that caused by real changes in sediment shear strength.

The fluctuation in the curves (in Figure 7) for both original and remolded shear strength from measurements taken on Section 398A-2-6 should not be considered significant, as it has since been deduced that the sample material for this core may not have been *in situ*. The measured shear strengths at Site 398 are shown in Table 5.

Relationship Between Compressional Wave Velocity and Clay Content (Site 398)

Horn et al. (1968) and others have pointed out a correlation between velocity and clay particle size.

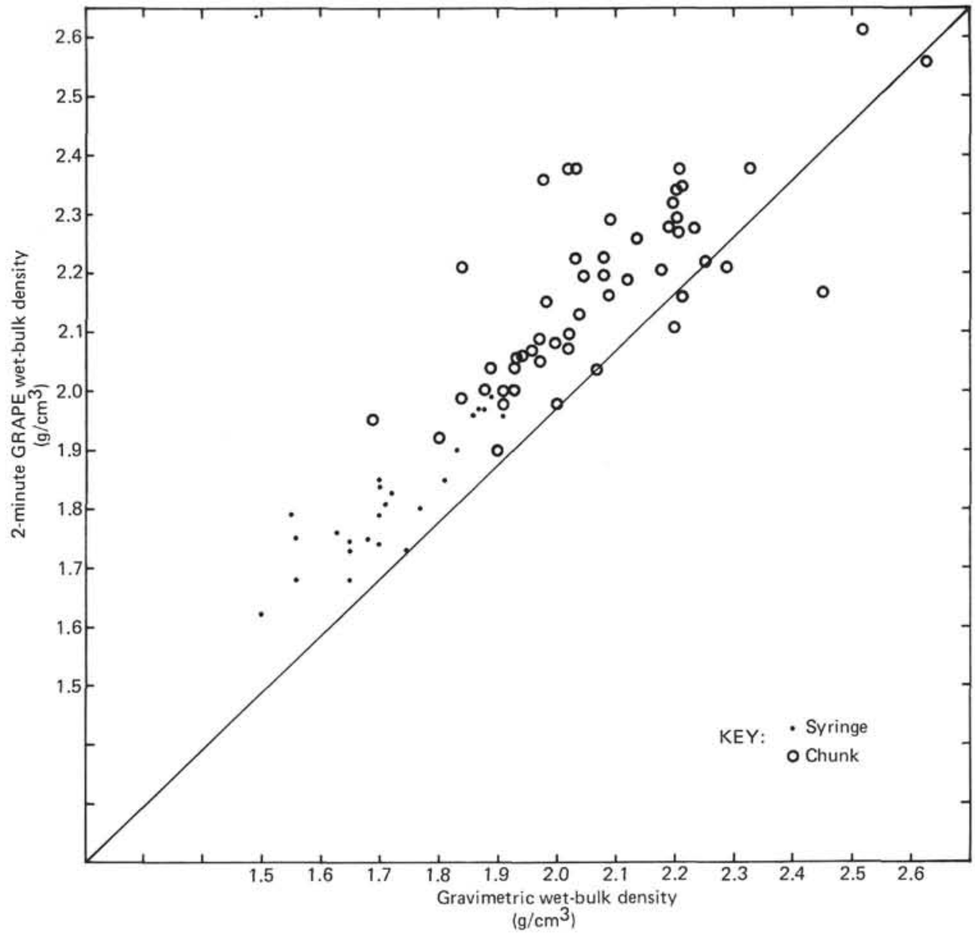

Figure 4. *Comparison of GRAPE and gravimetric wet bulk densities from duplicated samples.*

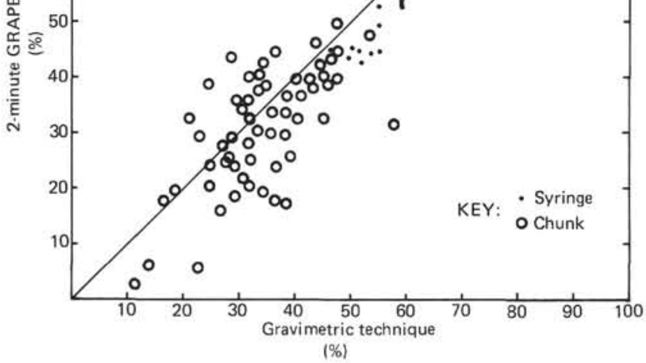

Figure 5. *Comparison of GRAPE and gravimetric porosities from duplicated samples.*

Gealy (1971), however, observed that the compressional wave velocity is dominated by wet bulk density (Figure 8) and a relationship between grain size and velocity may exist only in unconsolidated sediments. Lithification may destroy this relationship, although Figure 9A clearly shows that a relationship exists at Hole 398D between velocity and grain density (calculated at DSDP) even in higher velocity, i.e., lithified, sediments. Figure 9B demonstrates that porosity is inversely related to velocity. Vp plotted against per cent clay faction (Figure 10) shows a generalized relationship between higher sonic velocities with a lower clay content.

Laughton (1957) noted increasing acoustic anisotropy with clay content. This is observed to some extent in the softer (lower velocity) clays that show a slightly higher anisotropy than nannofossil oozes, with velocities up to 2.25 km/sec (see Site Report, this volume). In more indurated samples with velocities 2.5 km/sec, the chalks and marls have an average higher anisotropy than limestones.

Calcium Carbonate Content and Reflectors

During the drilling of Hole 398, lithologic observations provided no indication of possible reflecting lay-

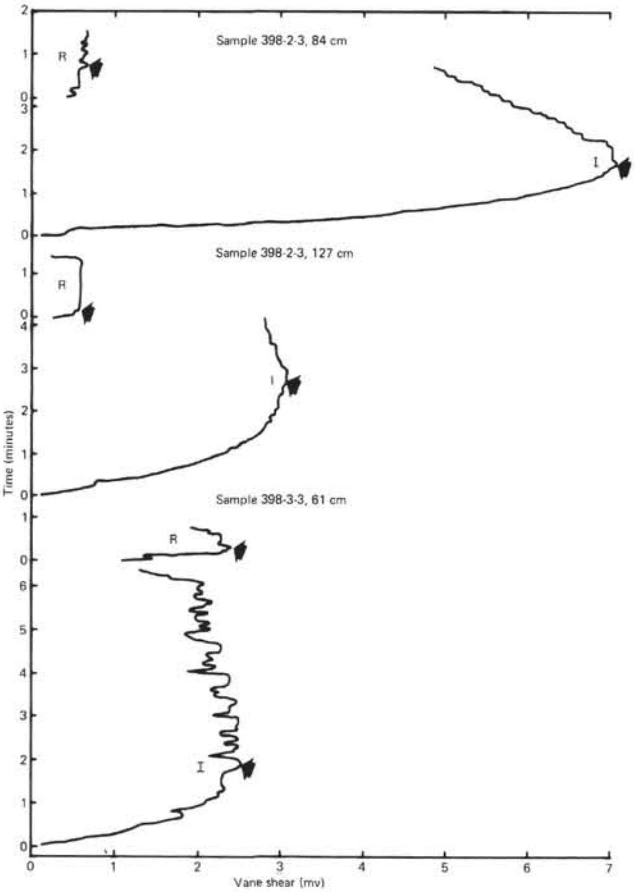

Figure 6. *Vane shear measurements on three samples using a shear transducer. The strain build up, shear point (marked by the arrow), and decline in shear strength after initial shearing has taken place. I marks initial shear curves and R indicates shear. The calibration factor is 28.812 g/cm ± mV.*

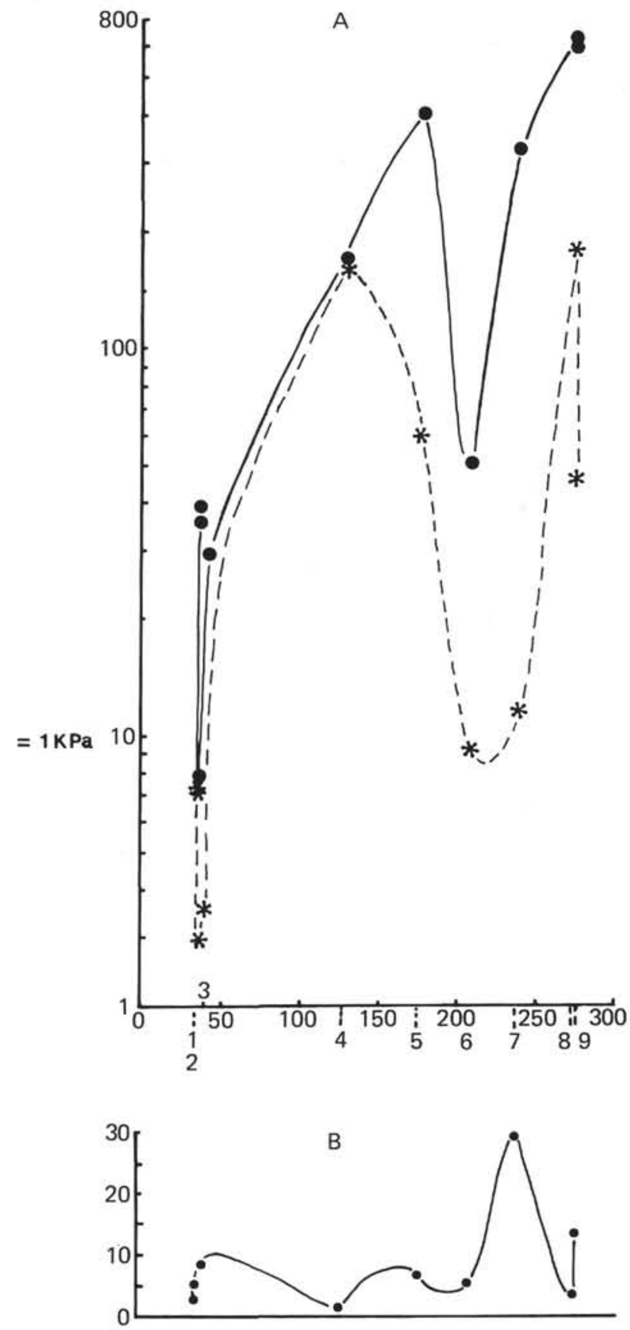

Figure 7. *Initial and remolder shear strengths (A) on the upper part of Hole 398, together with elastic sensitivity (B) of the core material. In A, solid dots mark initial shear and asterisks remolded shear strengths. Sample 6 may not have been* in situ *thus the curve may be overemphasized.*

ers, although the site survey seismic reflection profiles indicate the presence of prominent reflectors (Site Report, this volume).

Using the correlation between the reflection profile and physical properties data and lithology (Site Report, this volume), the calcium carbonate percentage was plotted relative to the depths interpreted from the reflection profile. The $CaCO_3$ content (Figure 11) is taken from the carbon-carbonate analyses made at DSDP and from onboard carbonate bomb analyses.

Given the margins of error in the seismic profile interpretation, several characteristics of the seismic profile appear related to the calcium carbonate levels.

The strong variation in $CaCO_3$ content in the upper part of the core (Figure 11) may be due to disturbance, although it could relate to the strong Pleistocene reflectors. The carbonate level then remains moderately stable at approximately 60 per cent down to approximately 360 meters, which is a region of the mainly weak Reflectors 1Aa to 1Ad. Reflector Green at 373 meters is associated with a local, 80 per cent, peak in $CaCO_3$ which occurs below it, but has a similar increase between Reflector 1Bf and 1Bg. Between these two reflectors is another local carbonate peak which suggests a strong reflector should exist between Green and 1Bf at approximately 420 meters. This is observed west of Site 398 on profile GP-19; a minor difference in location between this site survey profile and the actual location of Site 398 could explain this. Below Re-

TABLE 5
Site 398 Vane Shear Strengths

Reference No.	Sample (Interval in cm)	Depth (m)	Initial Shear Strength	Remolded Shear Strength	Sensitivity	Comment
1	398-2-3, 127	29.27	35.84	7.14	5.02	chart
	398-2-3, 127	29.27	39.84	7.34	5.43	manual
2	398-2-3, 139	29.39	7.65	2.94	2.61	manual
3	398-3-3, 61	38.11	30.0	3.57	8.40	chart
4	398-4-3, 92	125.42	172.03	162.73	1.06	manual
5	398A-1-5, 82	179.32	418.46	60.44	6.92	manual
6	398A-2-3, 105	205.05	51.145	9.299	5.50	manual
7	398B-1-3, 38	232.88	339.42	11.62	29.20	manual
8	398D-2-2, 37	272.87	660.24	185.98	3.55	manual
9	398D-2-2, 81	273.31	623.04	46.956	13.269	manual

Note: Good agreement is seen between the transducer (chart) and manual values of Sample 1. All values are plotted in Figure 7 although the disparity between closely located Samples 1 and 2 and 8 and 9 may suggest some spurious data.

flector 1Bg, the calcium carbonate curve generally decreases but with several distinct departure from a smooth curve. These departures may relate to the series of Reflectors 1Bg to 2c between approximately 600 and 900 meters.

The almost total absence of $CaCO_3$ throughout Velocity Group 6 and the sharp increase to approximately 30 per cent at Reflector Yellow is clearly related. Another fairly constant level of calcium carbonate is associated with the region of ill-defined reflectors between Yellow and 3a. There are moderately large fluctuations across Velocity Group 7a. The majority of the region of further ill-defined reflectors between 3a and Orange is mainly related to the region of very low carbonate content. Reflector Orange consists of massive indurated limestones and limestone breccias and is clearly related to the major peak in $CaCO_3$ just below 1400 meters. A moderate calcium carbonate content is observed below Orange, with small peaks down to 1600 meters. Below 1600 meters, more violent digressions are found which presumably are related to the divers and often strong, dipping reflectors between Orange and acoustic basement.

Any correlation between calcium carbonate content and evidence of reflectors is probably not due to the reflectance of $CaCO_3$ itself, but to calcite cementation of the particles, producing increased density and velocity in these strata. Detailed studies of the degree of cementation of these beds remains to be done and will be the subject of a later publication. Unfortunately, only during the later part of Leg 47B was it realized that a relationship between velocity and calcium carbonate content existed. Only at the bottom of the hole were carbonate samples taken from part of the velocity sample material; there were too few to plot. It is recommended that these parameters be measured on the same sample during future legs.

In places which have remained above the CCD and which record a complete noneroded sequence of carbonate sediments, calcium carbonate curves may prove to be a useful tool. These offer a good opportunity for the correlation of reflectors, lithologies, etc. on an oceanwide scale, assuming that changes in carbonate cycles are related to ocean circulation and are thus oceanwide if not globally synchronous phenomena.

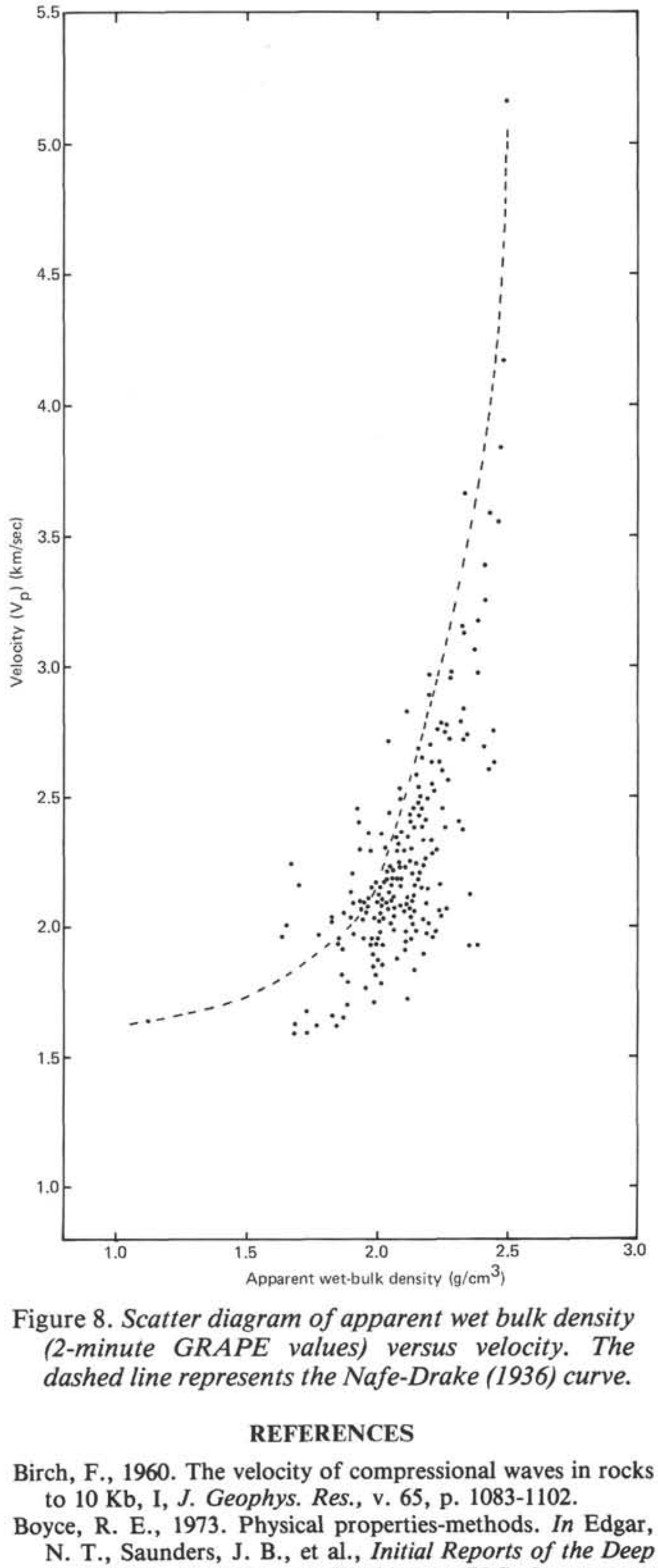

Figure 8. *Scatter diagram of apparent wet bulk density (2-minute GRAPE values) versus velocity. The dashed line represents the Nafe-Drake (1936) curve.*

REFERENCES

Birch, F., 1960. The velocity of compressional waves in rocks to 10 Kb, I, *J. Geophys. Res.*, v. 65, p. 1083-1102.

Boyce, R. E., 1973. Physical properties-methods. *In* Edgar, N. T., Saunders, J. B., et al., *Initial Reports of the Deep Sea Drilling Project*, v. 15: Washington (U.S. Government Printing Office), p. 1115-1128.

________, 1974. Instruction for grain density, wet-bulk density, water content, and porosity determinations by individual samples and Gamma Ray Attenuation Porosity Evaluation, Handbook, Scripps Institution of Oceanography.

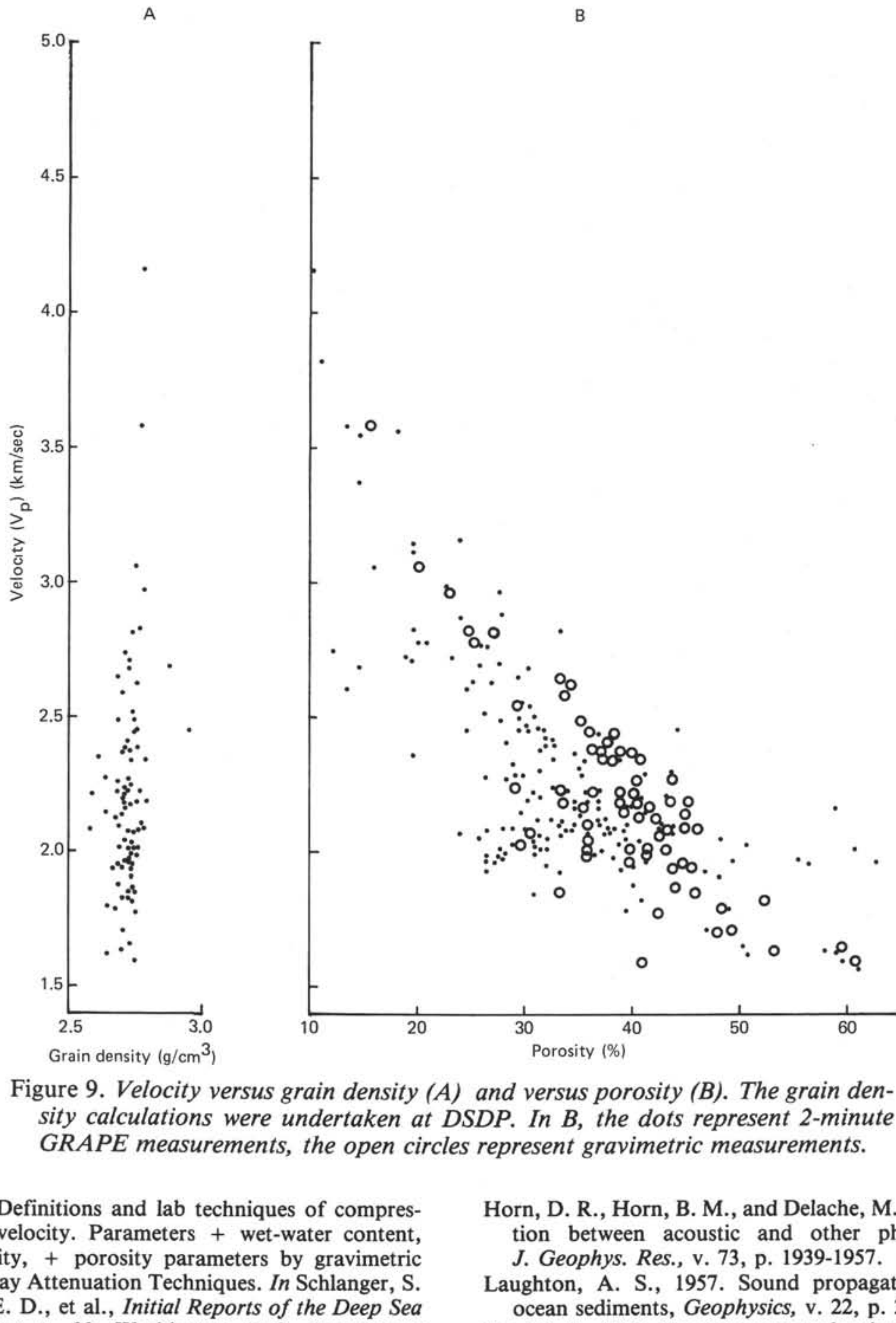

Figure 9. *Velocity versus grain density (A) and versus porosity (B). The grain density calculations were undertaken at DSDP. In B, the dots represent 2-minute GRAPE measurements, the open circles represent gravimetric measurements.*

________, 1976. Definitions and lab techniques of compressional sound velocity. Parameters + wet-water content, wet-bulk density, + porosity parameters by gravimetric and Gamma Ray Attenuation Techniques. *In* Schlanger, S. O., Jackson, E. D., et al., *Initial Reports of the Deep Sea Drilling Project,* v. 33: Washington (U.S. Government Printing Office), p. 931-958.

Gealy, E. L., 1971. Sound velocity, elastic constants and related properties of marine sediments in the western equatorial Pacific: Leg 7, *Glomar Challenger. In* Winterer, E. L., Riedel, W. R., et al., *Initial Reports of the Deep Sea Drilling Project,* v. 7, Part 2: Washington (U.S. Government Printing Office), p. 1105.

Gibbs, H. J., et al., 1960. Shear strength of cohesive soils, *Am. Soc. Civil Engineers Research Conference of Shear-Strength of Cohesive Soils,* p. 33-162.

Hamilton, E. L., 1970. Sound velocity and related properties of marine sediments, North Pacific, *J. Geophys. Res.,* v. 75, p. 4423-4447.

Horn, D. R., Horn, B. M., and Delache, M. N., 1968. Correlation between acoustic and other physical properties, *J. Geophys. Res.,* v. 73, p. 1939-1957.

Laughton, A. S., 1957. Sound propagation in compacted ocean sediments, *Geophysics,* v. 22, p. 223.

Lee, H. J., 1973. Measurements and estimates of engineering and other physical properties, Leg 19. *In* Creager, J. S., Scholl, D. W., et al., *Initial Reports of the Deep Sea Drilling Project,* v. 19: Washington (U.S. Government Printing Office), p. 701-720.

Manheim, F. T., Dwight, L., and Belastock, R. A., 1974. Porosity, density, grain density, and related physical properties of sediments from the Red Sea drill cores. *In* Whitmarsh, R. B., Ross, D. A., et al., *Initial Reports of the Deep Sea Drilling Project,* v. 23: Washington (U.S. Government Printing Office), p. 887-908.

Milgliore, H. J. and Lee, H. J., 1971. Seafloor penetration tests: presentation + analysis of results, *U.S. Naval Civil Engineering Lab. Tech. Note N-1178.*

Nafe, J. E. and Drake, C. L., 1963. Physical properties of marine sediments. *In* Hill, M. N. (Ed.), *The sea:* New York (Interscience), v. 3, p. 749.

Tucholke, B. E., Edgar, N. T., and Boyce, R. E., 1976. Physical properties of sediments and correlations with acoustic stratigraphy: Leg 35, Deep Sea Drilling Project. *In* Hollister, C. D., Craddock, C., et al., *Initial Reports of the Deep Sea Drilling Project,* v. 35: Washington (U.S. Government Printing Office), p. 229-250.

U.S. Naval Oceanographic Office, 1966. *Handbook of oceanographic tables,* SP-18, Washington, D.C.

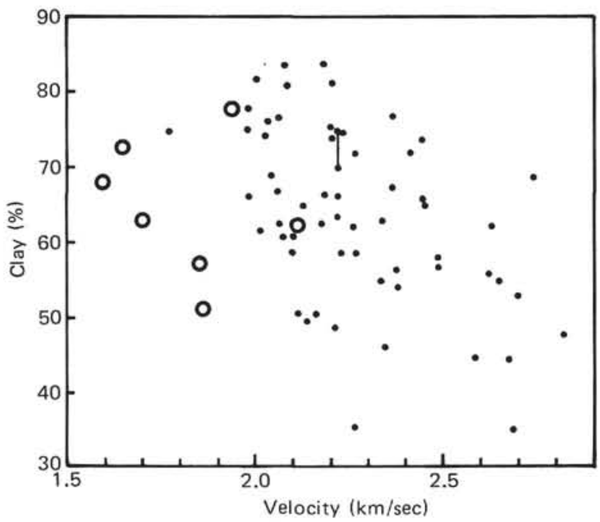

Figure 10. *Velocity versus clay content. Circled readings indicate velocities perpendicular to the bedding. The clay content analyses were undertaken by DSDP.*

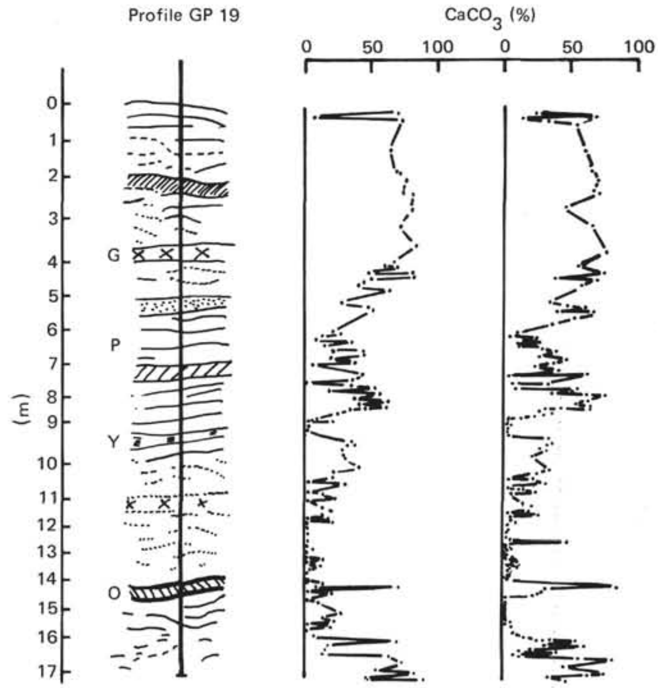

Figure 11. *Correlation between reflectors from profile GP-19 (unprocessed record) and calcium carbonate content. The depths to reflectors is in M × 100. The letters refer to those reflectors annotated by color. The close comparison between carbonate analyses is also shown. The left-hand curve is from carbon-carbonate analyses by DSDP and the right-hand curve from onboard carbonate bomb measurements (with thanks to Anne Gilbert).*

APPENDIX I

Listed Velocity, Wet Bulk Density, Porosity, Impedance, Water Content, Grain Density, and Percentage Calcium Carbonate Data From Hole 398. These do not represnet the total measurements of these parameters, but are selected where < 1 parameter has been made on the same sample material.

Sample (Interval in cm)	Velocity (km/sec)		Wet Bulk Density (g/cm^3)			Impedance	Porosity (%)			Water Content (%)		Shear Strength (g/cm^2)	Grain Size			
	Parallel Bedding	Perpen-dicular Bedding	Chunk Gravimetric	2-Min GRAPE	Shore-Based		Gravimetric	2-Min GRAPE	Shore-Based	Gravimetric	Shore-Based		$CaCO_3$ (%)	Sand	Silt	Clay
2-3, 139-143	1.59		1.73	1.57		2.50	40.75	56.49			25.91	1.97	13			
3-3, 68-81	1.60		1.69	1.69	1.69	2.70	60.6	59.08	60.6	35.8	35.82	2.76				
4-3, 91-103	1.63		1.73	1.69		2.82	59.2	59.26		34.3			68/76			
A1-5, 89-109	1.66			1.84		3.05		50.15								
A2-3, 118-131	1.65		1.77	1.87	1.77	2.92	41.6	48.0	41.1	23.3	23.25	2.30				
B1-3 40-66					1.72				54.5		31.63	2.59	74			
D2-. , 34-38	1.67			1.73	1.76	4.31		56.63	58.25		33.12	2.82				
D3-5, 142-165	1.62		1.82	1.84	1.82	4.88	50.6	50.56		27.8	27.81	2.65				
D4-3, 58-79	1.65				1.71			59.28			34.72	2.74	83			
D5-3, 33-68	1.67												60			
D5-5, 23-40	1.71				1.908			46.87			24.56	2.71				
6-3, 42-45	1.81															
6-4, 2	1.696	1.72											49			
6-6, 39-58	1.82		1.98	2.03		3.60	42.75	38.15		21.64		2.71				
7-3, 50-58	1.85		1.94	1.99		3.60	45.71	40.62		23.52		2.74				
7-4, 108	2.07	2.06														
8-3, 5-6	1.95	1.99	2.05	2.13		4.15	39.1	32.0		19.0		2.74				
9-2, 93-101			2.01				41.13			20.42		2.73	58-64			
9-5, 3-5	1.82	1.79	1.99	1.99		3.62	42.98	40.62		21.65		2.73				
12-3, 83-92	1.86	1.79	2.05	1.23?		3.81	39.88	87.4?		19.45		2.75	27			
13-1, 106-117			1.93				32.4			16.78		2.38	49			
13-5, 20-21	1.97	1.89	2.099	2.74		5.4	36.4	55.4		17.34		2.73				
14-1, 71-73	1.93		2.03			3.92	40.79			20.08		2.74				
15-4, 82-84	2.24	2.07				4.995	2.23									
19-4, 86-87	1.96	1.86	2.04	1.79		3.51	39.72	56.72		19.46		2.73				
20-3, 71	1.196	1.77	1.95	1.64		3.21	44.57	62.5		22.8		2.72	28			
21-3, 106-107	1.70	1.82	1.90	1.89		3.37?	47.6	46.77		25.01		2.72				
22-3, 73-4	1.90	1.79	1.96	1.99		3.78	44.86	40.62		22.89		2.74				
23-3, 70-71	1.87	1.78	1.95	2.0		3.74	43.88	40.0		22.52		2.69				
24-6, 36-37	1.93	1.73	1.88	1.89		3.38	47.28	46.77		25.19		2.67				
25-6, 53-54	1.79	1.65	1.88	1.85		3.59	47.6	49.23		25.3		2.68				
27-1, 77	1.94	1.74	1.96	2.11		3.8	43.55	33.23		22.25		2.7				
28-3, 110	1.95	1.76		2.0		3.90		40.0								
29-3, 104-105	2.18	2.02	2.14	2.13		4.64	33.37	32.0		15.58		2.71				
30-1, 103-104	1.99	1.89	2.02	2.06		4.1	41.17	36.31		20.35		2.73				
30-3, 22	2.25	2.09		2.12		4.73		32.62								
30-5, 58	2.29	2.13		2.22		5.08		26.46								
31-1, 14	2.19	2.06		2.16		4.73		30.15								
31-3, 34	1.93			2.02		3.9		38.77								
31-4, 39	2.15	2.05		2.17		4.67		29.54								
31-1, 102-104	2.03			2.18		4.43		28.92								
33-3, 97	1.95		1.95			3.80	43.55			22.31		2.69				
34-3, 5	2.1		2.089	2.08		4.37	35.74	34.68		17.11		2.7				
34-4, 5-6	2.01		2.11	2.14		4.3	35.7	31.35		16.89		2.73				
35-1, 128	2.16	2.0		2.08		4.62		35.08								
35-2, 141	2.16	1.88	2.1			4.54	35.26			16.73		2.71				
35-5, 146	2.20			2.14		4.71		31.39								
36-1, 74	2.12	2.03	2.14	2.14		4.54	33.23	31.39		15.56		2.70				
36-3, 3	2.07	1.82		1.94		4.02		43.69								
36-5, 147	2.11	1.94		2.05		4.33		36.92								
36-6, 4	2.07	1.92		2.04		4.22		37.54								
38-2, 14	1.93			2.22				26.46		23.9						
38-5, 79			1.92				45.92					2.71				
39-1, 2	1.81		1.83	1.87?		3.38	52.15	48.0?		28.47		2.74				
39-3, 47	1.98			2.22		4.4		26.46					56			
39-4, 59	1.96			2.22		4.35		26.46								
40-1, 138	1.98	1.83		2.01		3.98		39.39								
40-3, 17	2.01		2.06	2.13		4.28	39.34	32.0		19.15		2.74				
41-1, 44	2.03	1.9		1.98		4.02		41.23								
41-3, 51	1.96			2.21		4.33		27.08								
41-4, 19	1.95	1.85	2.17			4.01	33.2			15.29		2.75				
41-5, 8	1.99	1.91		2.19		4.36		28.31								
41-6, 17	1.93			2.34		4.52		19.08								
42-1, 94	2.07	2.0	2.2	2.26		4.68	30.44	24.0		13.81		2.73				
42-3, 71	2.06			2.23		4.59		25.85								
44-3, 170	2.01	1.90		2.2		4.42		27.69								
45-1, 23	2.08			2.22		4.62		26.46								
45-3, 79	2.09			2.18		4.56		28.92								
46-1, 37	2.04		2.14	2.15		4.37	36.02	30.77		16.86						
46-3, 24	2.09			2.195		4.47		28.00								
46-4, 77	2.06			2.11		4.36		33.23								
47-1, 9	2.05			2.13		4.37		32.0								
48-2, 74	1.98	1.85	2.13			4.22	35.58			16.68		2.76	22			
50-1, 71	1.84			2.15		3.96		30.8								
50-4, 13	1.77		2.01				42.16			20.97		2.75				
50-5, 39	1.78			2.01		3.58		39.4								
54-2, 58	1.91			1.87		3.57		48.0								
55-2, 2			1.91				47.95			25.05		2.76				
56-2, 12	2.03			1.83		3.72	50.5									
56-4, 19	2.08	1.91	1.96	1.96		4.08	39.5	42.5		20.19						
57-2, 29	2.1			2.11		4.43		33.2								

APPENDIX I – *Continued*

Sample (Interval in cm)	Velocity (km/sec) Parallel Bedding	Velocity (km/sec) Perpendicular Bedding	Wet Bulk Density (g/cm³) Chunk Gravimetric	Wet Bulk Density (g/cm³) 2-Min GRAPE	Wet Bulk Density (g/cm³) Shore-Based	Impedance	Porosity (%) Gravimetric	Porosity (%) 2-Min GRAPE	Porosity (%) Shore-Based	Water Content (%) Gravimetric	Water Content (%) Shore-Based	Shear Strength (g/cm²)	$CaCO_3$ (%)	Grain Size Sand	Grain Size Silt	Grain Size Clay
57-3, 7	2.19		1.99	2.07		4.53	45.11	35.7		22.67		2.8				
58-1, 40	2.16			1.70		3.67		58.5					32			
58-2, 3	2.08		2.02	2.1		4.37	42.96	33.8		21.3		2.78				
59-1, 100	2.09		1.93	1.91		3.99	44.98	45.5		23.33		2.69				
59-3, 147	2.12			2.04		4.32		37.5								
60-1, 38	2.09			2.03		4.24		38.2								
61-2, 42	2.04		2.005	2.06		4.20	41.39	36.3		20.64		2.71				
62-2, 146	2.07			2.07		4.28		35.7								
63-2, 13	2.1			2.05		4.31		36.9								
63-5, 69	2.21		1.94	2.0		4.42	40.63	40.		20.9		2.59				
65-2, 119	2.12		1.96	2.04		4.28	42.71	37.5		21.77		2.68				
66-1, 4	1.93			1.98		3.82		41.2								
67-1, 114	2.18		1.96			4.27	45.44			23.16		2.76				
68-1, 22	2.20		1.88	1.91		4.2	48.4	45.5		25.69		2.71				
69-2, 20	2.13	1.86		2.02		3.76		38.8								
69-3, 26	2.03			2.02		4.1		38.8								
70-3, 50	1.94			2.		3.88		40.								
71-1, 101	2.1		1.97	1.94		4.06	44.94	43.7		22.76		2.77				
72-3, 68				1.95				47.27		22.42		2.8				
72-5, 82	2.0			1.66		3.32		60.9								
73-2, 36	2.03			1.98		4.02		41.2								
73-3, 96	2.07		1.998	2.04		4.22	42.56	37.5		21.3		2.74				
74-2, 5	2.02			2.0		4.04		40.								
74-3, 69	2.12		1.93	2.0		4.05	45.2	40.		23.39		2.7				
75-3, 33	2.06			1.95		4.02		43.1								
76-3, 72	2.27		1.97			4.26				20.92		2.64				
77-1, 36	2.21	1.77		1.95				43.1								
77-4, 56	2.08		1.96	1.92		3.99	45.93	44.9		23.48		2.77				
78-4, 60	2.17		2.01	2.02		4.38	41.53	38.8		20.65		2.73				
79-1, 10	2.05			1.87		3.83		48.								
79-3, 10	2.14		1.90			4.07	44.96			23.62		2.64				
80-3, 102	2.27		1.97			4.47	43.7			22.15		2.73				
80-4, 81	2.098		1.96			4.12	42.5									
81-2, 19	2.01		2.01	2.05		4.12	42.45	37.		21.13		2.75				
82-3, 149	2.0		1.93				42.45			23.51		2.69				
84-1, 105	2.10	2.17		2.05		4.31		37.								
85-2, 43	2.06	1.88		2.14		4.41		31.4								
85-2, 84	2.13		1.98				43.34			21.87		2.73				
86-3, 133	2.13		2.01	2.04		4.35	40.53	37.5		20.14		2.70				
87-1, 120	2.16			2.05		4.43		36.9								
87-5, 81	2.34		2.06	2.07		4.84	40.65	35.7		19.7		2.79				
89-2, 16	2.08	1.88		2.09		4.35		34.5								
89-5, 18	2.37		2.02	2.10		4.98	39.76	34.8		19.64		2.7				
90-1, 15	2.29	1.99		2.1		4.81		33.8								
90-1, 64	2.33		2.18			5.08	28.9									
90-3, 20	2.34		2.09	2.12		4.96	32.6	37.09		17.76		2.73				
92-3, 102	2.24	1.89		2.12		4.75		32.6								
93-1, 23	2.18		2.07	2.09		4.56	38.73	34.5		18.7		2.75				
93-3, 23-29	2.22	1.92		2.11		4.05		33.2								
93-6, 69	2.08	1.82		2.01				39.4								
95-1, 114	2.36			1.98		4.67		41.2								
95-2, 77	2.38		2.08	2.14		5.09	36.94	31.4		17.76		2.71				
96-2, 12	2.4			2.13		5.11		32.0								
96-3, 69	2.18		2.04	2.03		4.43	40.11	38.15		19.71		2.73				
96-4, 88	2.17			2.0		4.34		40.								
97-4, 26	2.22	1.89	2.003	2.06		4.57	40.05	36.3		20.0		2.67				
99-1, 105	2.46			2.14		5.26		31.4								
99-5, 33-7	2.24		2.05	2.08		4.66	39.15	35.1		19.15		2.72	1			
100-2, 105	2.35	2.06	2.0	2.02		4.75	37.71	38.8		18.86		2.61				
100-4, 87	2.22			2.15		4.77		30.8								
101-2, 3	2.19		2.01			4.40	43.42			21.57		2.79				
101-5, 117	2.43	2.08		1.57		?2.43		66.5?								
102-3, 50	2.49		2.13	2.20		5.48	35.14	27.7		16.46		2.75				
102-4, 138	2.50			2.15				30.8								
103-5, 84	2.45		2.25	2.25		5.51	35.9	24.6		15.95		2.95				
104-1, 58	4.18		2.09	2.48		8.72	38.93	10.46		18.66		2.78				
105-1, 145	2.83		2.32	2.33		6.59	24.71	19.7		10.65		2.76				
105-3, 11	2.89			2.20		6.36		27.7								
106-3, 8			2.09				38.28			18.36		2.76				
106-5, 49	2.50			2.17		5.43		29.5								
107-1, 71	2.30			2.14		4.92		31.4								
107-3, 34	2.37	2.38	2.07	2.33		5.52	38.06	19.7		18.38		2.73				
108-2, 112	2.31	2.36		2.08		4.80		35.1								
108-6, 115	2.22		2.08	2.07		4.60	38.75	35.69		18.59		2.77	21			
109-1, 108	2.41			2.19		5.28		28.3								
111-2, 111	2.38	2.45	2.13	2.27		5.40	35.93	23.4		16.87		2.76	0			
112-3, 91	2.38		2.12				36.29			17.13		2.76				
112-5, 104	2.41	2.05		1.58		3.81		65.9								
113-1, 85	2.45	2.17		2.16				30.2								
113-2, 16	2.44		2.13	2.05		5.00	35.75	36.9		16.81		2.75				
113-4, 52	2.29			2.08		4.76		35.1								
114-3, 19	2.23		2.126				36.26			17.06		2.77				

APPENDIX I – *Continued*

Sample (Interval in cm)	Velocity (km/sec) Parallel Bedding	Velocity (km/sec) Perpendicular Bedding	Wet Bulk Density (g/cm^3) Chunk Gravimetric	Wet Bulk Density (g/cm^3) 2-Min GRAPE	Wet Bulk Density (g/cm^3) Shore-Based	Impedance	Porosity (%) Gravimetric	Porosity (%) 2-Min GRAPE	Porosity (%) Shore-Based	Water Content (%) Gravimetric	Water Content (%) Shore-Based	Shear Strength (g/cm^2)	Grain Size $CaCO_3$ (%)	Grain Size Sand	Grain Size Silt	Grain Size Clay
115-1, 15	2.49	3.01		2.09		5.29		34.5								
115-3, 64	2.26		2.01			4.54	40.33			20.05		2.69				
116-1, 4	2.30			1.94		4.46		43.7								
117-1, 114	2.26			2.19		4.95		28.3		15.58						
117-4, 125	2.46			1.93		4.75		44.3								
118-4, 34	2.41		2.09	2.12		5.11	37.17	32.6		17.82		2.73				
118-6, 54	3.57			2.95		10.53		18.5								
119-2, 10	2.63		2.16	2.21		5.81	34.27	27.1		15.88		2.76				
119-5, 110	2.59		2.13				33.74			15.81		2.71				
120-2, 16-19	2.69		2.39	2.41		6.48	25.98	14.8		10.85		2.88				
121-1, 77	2.7		2.23	2.2		5.94	28.84	27.7		12.94		2.73				
121-3, 77	2.74			2.25		6.17		24.62								
121-5, 125	2.75			2.45		6.74		12.3								
122-1, 38	2.76			2.22		6.13		26.5								
122-4, 88	2.74	1.46?	2.21			6.06	29.49			13.33		2.72				
122-6, 77	2.45			2.17		5.32		29.54								
123-1, 102	2.55	1.36	2.16	2.22		5.59	33.04	26.5		15.28		2.74				
123-3, 97	2.78			2.32		6.45		20.3								
124-1, 85	2.60			2.25		5.85		24.62								
124-4, 46	2.71	2.21	2.26	2.04		5.53	27.91	37.5		12.35		2.75				
125-2, 56	2.63	2.28	2.19	2.45		6.44	31.52	12.31		14.4		2.74				
125-5, 50	2.77			2.26		6.26		24.0								
127-4, 18	2.22	2.01	2.16			4.79	32.25			14.91		2.72				
128-1, 78	2.38	2.08		2.17		5.16		29.5					11			
128-3, 65	2.49	2.13	2.18	2.09		5.20	30.14	34.5		13.86		2.68	39			
129-3, 70	2.68		2.18	2.16		5.79	31.77	30.15		14.59		2.73	6			
129-4, 32	2.72	2.47		2.27		6.17		23.4								
129-5, 127	2.77	2.40		2.23		6.18		25.9								
130-1, 63	2.73	2.35		2.34		6.39		19.1								
130-3, 14	2.72	2.36		2.33		6.34		19.7								
130-3, 37			2.26				26.19			11.60		2.70	10			
132-1, 8	3.38	3.06		2.41		8.15		14.8								
132-3, 90	2.82	2.36	2.27	2.11		5.95	27.02	33.2		11.92		2.74	35			
133-2, 70	3.58	3.37	2.49	2.43		8.70	15.68	13.54		6.29		2.77	81			
133-5, 75	2.78	2.20		2.24		6.23		25.23								
134-1, 89	2.54	2.21	2.21	2.16		5.49	29.14	30.2		13.16		2.71	43			
134-2, 40	3.38	3.18		2.41		8.15		14.77								
134-3, 51	2.78	2.31		2.27		6.71		23.4								
135-1, 123	2.95	2.48		2.28		6.73		22.8								
135-3, 119	3.06	2.83	2.398	2.38		7.28	20.22	16.62		8.43		2.75	74			
136-2, 3	2.97	2.58	2.37	2.20		6.53	23.10	27.69		9.77		2.78	64			
137-1, 25	3.25			2.41		7.88		14.8								
137-2, 90	3.12	2.60		2.33		7.27		19.7								
138-1, 24	3.55	3.39		2.46		8.73		11.7								
138-2, 116	2.97		2.37	2.39		7.10	23.46	16.0		9.9		2.79	45			