12. SEDIMENT MASS PHYSICAL PROPERTIES — PANAMA BASIN AND NORTHEASTERN EQUATORIAL PACIFIC[1]

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ABSTRACT

Leg 16 provided a rare opportunity to conduct a detailed study of the sediment mass physical properties from depths greater than a few meters. Data presented here, with the exception of shear strength, are derived from shore-based laboratory analyses rather than the shipboard tests which have normally been reported for previous legs. This study indicates that there is no apparent relationship between variation of mass physical properties and the age of the sediment or the rate of sedimentation. The greatest single factor influencing the physical properties appears to be the depth of burial. Based on this study it is possible to delineate the characteristic physical properties of the six prominent sediment types encountered on Leg 16. In all but one test the samples were were found to be overconsolidated. It is felt that these sediments are not overconsolidated in the sense that the term is used in soil mechanics but display this characteristic as a result of some form of diagenetic bonding developed during deposition. At only one of the eight sites of Leg 16 was porosity found not to decrease appreciably with depth. This condition may, in some way, correlate with the increased content of clay-size material relative to the other sites.

INTRODUCTION

Diagenetic changes from a soft deep-sea sediment to a marine sedimentary rock have been of utmost interest for many years. In recent years, a relatively new approach, the detailed analysis of the mass physical properties of deep-sea sediment cores, has received limited use in the study of these changes (Arrhenius, 1952; Richards, 1961, 1962). These early attempts have been hindered by the relatively short sediment cores (3 to 10 m) taken from oceanographic vessels. It was not until 1961, with the experimental Mohole drilling off Guadalupe Island, that deep-sea deposits were sampled below a depth of about 25 meters. This project provided Rittenberg et al. (1963), Hamilton (1964), and Moore (1964) with the opportunity to study selected mass physical and chemical properties of the 170 meters of sediment overlying basaltic basement. With the advent of the Deep Sea Drilling Project (DSDP) in 1968, continuous sampling to depths of 700 to 800 meters below the sea floor became a reality. Although many significant data have been collected by DSDP, only gross descriptions of the samples and their mass properties have been published in the respective cruise reports.

During Leg 16 specific attention was given to the examination of sediment mass physical properties as well as to the various shipboard test procedures used in the determination of these properties. Evaluation of these procedures is the subject of a separate section in this volume (Chapter 13). In conjunction with the "standard" shipboard tests, e.g., GRAPE density and porosity, and water content, approximately 295 shear strength tests were made. In addition, 410 ten- to fifteen-gram subsamples were collected from the least disturbed sections of the cores and returned to a shore laboratory (N.O.A.A., Atlantic Oceanographic Laboratory, Miami) for bulk density, porosity, water content, and grain density determinations. An additional thirteen whole core samples (7 cm in length) were taken for later study of consolidation characteristics.

Leg 16 has provided the opportunity for making one of the most thorough studies of sediment mass physical properties of DSDP cores to date. Not only can we report on samples from depths as great as 500 meters and as old as late Cretaceous, but the study has yielded data on specific sedimentary deposits, e.g., zeolitic clays, radiolarian and diatom oozes, and chalks. These deeper samples have provided the opportunity to examine an important part of the diagenetic processes at a number of sites in the eastern Pacific.

The determination and understanding of mass physical properties of deep-sea sediments are as important to any study of diagenesis as they are in foundation engineering. As has been demonstrated by Hamilton (1959, 1964) and Moore (1964), if the depositional history of the ocean basins is to be unraveled, an understanding of sediment mass properties, particularly consolidation characteristics, must be attained.

This discussion is based on those data which have been determined in a shore laboratory, e.g., wet bulk density, water content, porosity, Atterberg limits, average grain density (specific gravity), and consolidation characteristics. The only exception is the shear strength measurements which were made aboard the *Glomar Challenger.*

[1]The original data will be compiled in a NOAA-AOML Technical Report to be published in 1973 and available through the authors.

Shipboard measurements of bulk density and porosity have been reported in the site chapters but have not been included here because of the questionable nature of some of these results (Bennett and Keller, Chapter 13).

ANALYTICAL TECHNIQUES

There is no such thing as an undisturbed sediment core, and the cores taken by the Deep Sea Drilling Project are much more disturbed than standard piston or gravity cores. A concerted effort was made to sample only those portions of the core where disturbance was observed to be minimal.

Shore-based measurements of wet bulk density, water content, porosity, and average grain density were made on 10- to 15-gram subsamples taken from the cores immediately after they were split aboard the *Glomar Challenger.* Each subsample was placed in a polyethylene vial (completely filling it) which was sealed with electrical tape and in turn was placed in a small plastic bag and sealed in a larger plastic bag containing a damp paper towel in order to maintain high humidity within the bag. The sealed bag was kept under refrigeration to further reduce any chances of moisture loss.

A brief explanation of analytical procedures used for the laboratory determination of bulk density, water content, porosity, and grain density was presented as part of the initial discussion of sediment mass physical properties of DSDP 155 (Chapter 2) and will only be touched on briefly in a few instances.

Thirteen 7-centimeter lengths of core were removed prior to splitting of the core aboard ship for later consolidation tests at the shore laboratory. These samples were primarily taken from the core catcher sleeve portion of the core barrel because of the relatively undisturbed condition of this portion. Samples were carefully packaged to insure against disturbance and moisture loss and then hand-transported to the laboratory.

All consolidation tests were made with an Anteus Back Pressure Consolidometer. A description of this apparatus, and the testing procedures employed, have been thoroughly discussed by Lowe et al (1964). The unique aspect of the back pressure technique is that as hydrostatic pressure is applied to the sample, any gas bubbles entrapped in the pore water as a result of removing the sample from its original hydrostatic pressure are redissolved. For samples taken from environments of high hydrostatic pressure, the in situ pressure cannot be attained, but a maximum back pressure of 150 psi probably insures that all gas is redissolved.

Shear strength measurements were made on board the *Glomar Challenger* using two techniques new to the Deep Sea Drilling Project, the laboratory vane shear and Swedish Fall Cone. The vane shear test consists of inserting a small four-bladed vane into the sample and applying an increasing torque until a shear occurs (Evans and Sherratt, 1948). This particular instrument and its use with submarine sediments have been more fully discussed by Richards (1961). Vane rotation for all tests was six degrees per minute. A laboratory vane shear test in clays and clayey sediment is equivalent to an undrained shear test, e.g., the unconfined compression test. In this case, vane shear strength is considered equal to the cohesion or one-half the compressive strength. A more complete discussion of the vane shear test is presented by Evans and Sherratt (1948) and The American Society for Testing and Materials (1957).

Swedish Fall Cone measurement of shear strength is widely used in Europe, where it has been adequately calibrated for the soils as well as the commonly used samplers. Although this test is not frequently used in the United States, its simplicity made it appealing for use on the Leg 16 cores. The test is basically one of dropping a weighted cone from a specific height and measuring the depth of its penetration into the sample. Penetration is then related to shear strength *(S)* by

$$S = K\,Q/h$$

where K is a constant which depends on the cone angle and the sampler design (as the latter influences sample disturbance), Q is the cone weight, and h the penetration depth of the cone (Hansbo, 1957). A K value of unity was used in determining the shear strength results presented here. In the few instances where results from the fall cone could be compared with the vane shear, the fall cone was always found to give higher values by a factor ranging from 1.1 to 3.0. It must be pointed out that the Swedish Fall Cone (Geonor model G-200) was not calibrated for the sampler used aboard the *Glomar Challenger* and caution must be excercised in the interpretation of these data. All but twenty fall cone measurements were made with the 400 g, 30° cone. The 100 g, 30° cone was used with the others. Owing to the manner in which the cores were processed aboard the *Glomar Challenger,* it was necessary to make most fall cone tests on the cores after they were split in half. All such tests were made in a plane parallel to the bedding rather than perpendicular to it as in the normal testing procedure. The effect of this procedural change is unknown and undoubtedly would vary with the degree of sample disturbance and sediment type.

The majority of the vane shear tests were made at right angles to the bedding in the lower section of each barrel between the core catcher and the steel sleeve. Not only was this usually the least disturbed section of the barrel, but it also allowed the vane to be inserted into the core and the sample tested before the sediment was removed from the barrel.

TEST RESULTS

For the purpose of this discussion, the eight sites from Leg 16 have been placed in two groups, the Panama Basin (DSDP 155, 157, and 158) and the northeastern equatorial Pacific (DSDP 159-163). Although distinct differences are seen in the mass physical properties between the sites, a certain degree of similarity exists within each grouping.

Panama Basin

The three Panama Basin sites are located on the major ridges (Coiba, Cocos, and Carnegie) which border the basin. Lithologies at the three sites are relatively similar with an upper section of nannofossil chalk ooze rich in calcareous and siliceous microfossils and vocanic glass overlying a chalk ooze which grades down to a chalk with some chert stringers at a depth of about 430 meters. Only DSDP 155 was sampled below this depth and here interbedded claystone and moderately indurated nannofossil marl and marly clay predominate to a depth of 485 meters. A nannofossil chalk, locally dolomitized and rich in altered volcanic debris, constitutes the remainder of the sedimentary section above basalt which occurs at a depth of 519 meters.

DSDP 155

Unfortunately only the lowermost portion of the hole was cored (434-536 m); however, bulk density and porosity data are available for the upper interval from DSDP 84, 176 kilometers to the west, which is probably reasonably similar to DSDP 155. In order to present a more complete discussion of the physical properties at this site, we have taken the liberty of using the section bulk densities (average bulk density per 150-cm section) and GRAPE porosities from DSDP 84 for the interval from 0 to 250 meters. Although the reliability of these data is not believed to be as good as that of our laboratory measurements (for the section from 434-500 m at DSDP 155), it is felt that they do provide some indication of the characteristics of the overlying deposits in this area.

Wet bulk density increases gradually to a depth of about 444 meters where a noticeable offset in the density profile occurs (Figure 1). Here, in conjunction with the occurrence of a claystone-marl sequence, densities are on the order of 1.65 to 1.80 g/cc versus 1.80 to 1.92 g/cc for the immediately overlying sediment. Although prominent local variations occur, bulk density tends to increase slightly with depth within this sequence (444-480 m). These variations reflect the layered nature of the sequence, with the claystone intervals commonly displaying lower densities than the adjacent marl. The occurrence of chalk in the lower 16 meters of the section is reflected in the density profile, where values suddenly increase, ranging from 2.00 to 2.18 g/cc.

The porosity profile tends to be a mirror image of the density profile. In the uppermost part of the section, porosities are high (85 %) and slowly decrease with depth to 50 per cent at 444 meters. Here the porosity increases sharply to 65 per cent, reflecting the claystone-marl sequence. Little change in porosity occurs within the next 20 meters, but below 464 meters the marly claystone sediments display a slight decrease in porosity with depth. Locally, higher porosities are usually found to be associated with the claystone layers. The underlying chalk is quite distinct, with porosity values as low as 32 per cent. In viewing the entire sediment section (DSDP 84 and 155 data), porosities are seen to decrease on the order of 62 per cent within the 521-meter interval.

Water content at this site, defined as per cent of the sediment by dry weight, varies with depth in much the same way as does porosity. Where the claystone-marl interval is encountered, a distinct offset in the profile reflects a relative increase in water content, on the order of 70 per cent. Towards the lower part of the sequence, a gradual decline in water content occurs until the chalk zone is reached (480 m), where a pronounced decrease of about

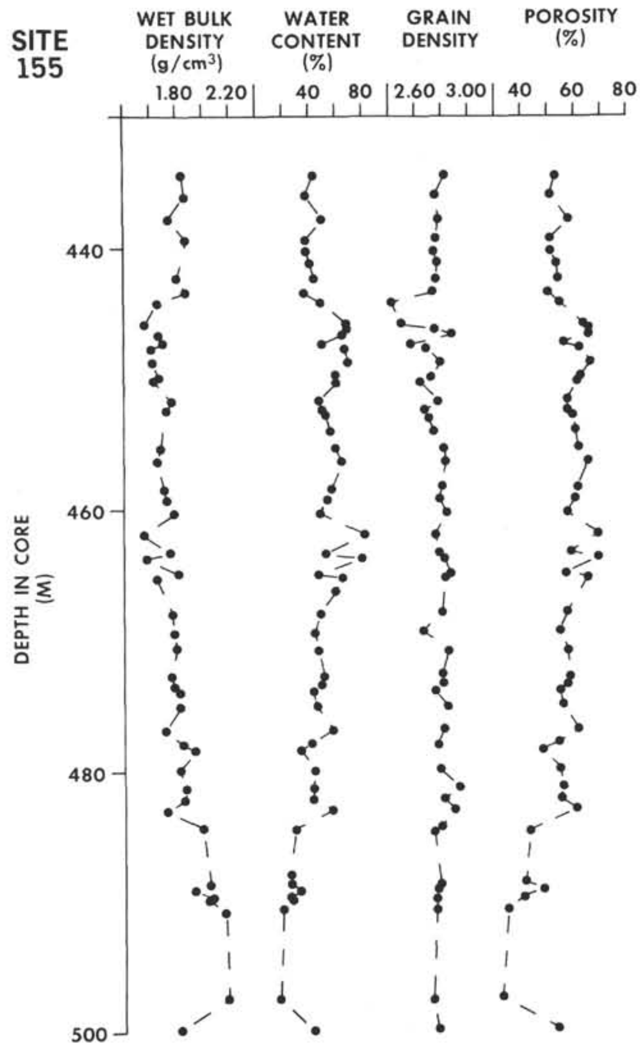

Figure 1. *Variation of physical properties with depth, DSDP 155.*

50 per cent is observed. Local anomalies between 444 and 480 meters reflect the relatively high water content associated with the claystone layers.

Grain density normally varies relatively little with depth except when major lithology changes are encountered. At DSDP 155 the overall variation is minimal, but the claystone-marl sequence can be seen to possess a slightly higher grain density (ranging from 2.76 to 2.82) than either the overlying marl or the underlying chalk. Minor variations along the profile are attributed to the claystone layers which commonly have lower grain densities (2.49 to 2.54).

The degree of symmetry and the similarity of the profiles is quite distinct and appears to be more pronounced here than at the other sites. This possibly may be attributed to the greater burial depth to which these samples have been subjected. Within the interval cored at this site, there is a gradual increase in bulk density and a decrease in porosity and water content with depth; changes in these properties over the 86-meter interval are on the order of 21 per cent, 40 per cent, and 50 per cent respectively. Although local variations in grain density occur, there is basically little change from top to bottom of the sampled section.

DSDP 157

Severe disturbance and mixing of the upper 198 meters of the core made mass physical properties analyses impractical throughout much of this interval. Only a very few measurements were possible in the upper 70 meters. Below 333 meters, core disturbance again precluded any laboratory measurements of physical properties. As a result, DSDP 157 provides relatively little data on these properties (Figure 2), and only broad generalizations are possible.

Bulk density varies only slightly (1.38 to 1.60 g/cc), increasing gradually with depth in the chalk ooze (0-240 m). Within this interval, the data indicate the occurrence of interlayering of finer grained sediment possessing lower densities. In the underlying sequence of semi-indurated chalk ooze, the distinct zone of low bulk density (252 m) probably corresponds to an interval of finer grained, less indurated sediment. Densities in the chalk (284-333m) appear to be more uniform and increase slowly with depth.

Local variations from the gradual decrease in porosity with depth are minor with only three anomalous zones of any significance evident from the profile (Figure 2). The relatively high values at 60 and 252 meters are probably associated with finer sediments as mentioned earlier, whereas the occurrence of burrows at 220 meters is believed to have resulted in the local increase in porosity and decrease in bulk density in that interval. The burrows serve to concentrate finer, less dense material.

Variations in water content with depth are usually much more pronounced than those of the other physical parameters. Thus, water content often serves as an indicator for variations in the sediment section that may not be readily apparent from other physical measurements. At DSDP 157, even with the limited data, there does not appear to be any major variation in the overall trend of decreasing water content with depth except for the anomalies at 60 and 252 meters. These two zones of relatively high water content are believed to be associated with intervals of finer grained sediment.

Except for the anomalous character of the grain density profile at 252 meters, relatively little change in density is seen throughout the sediment section. This interval of low

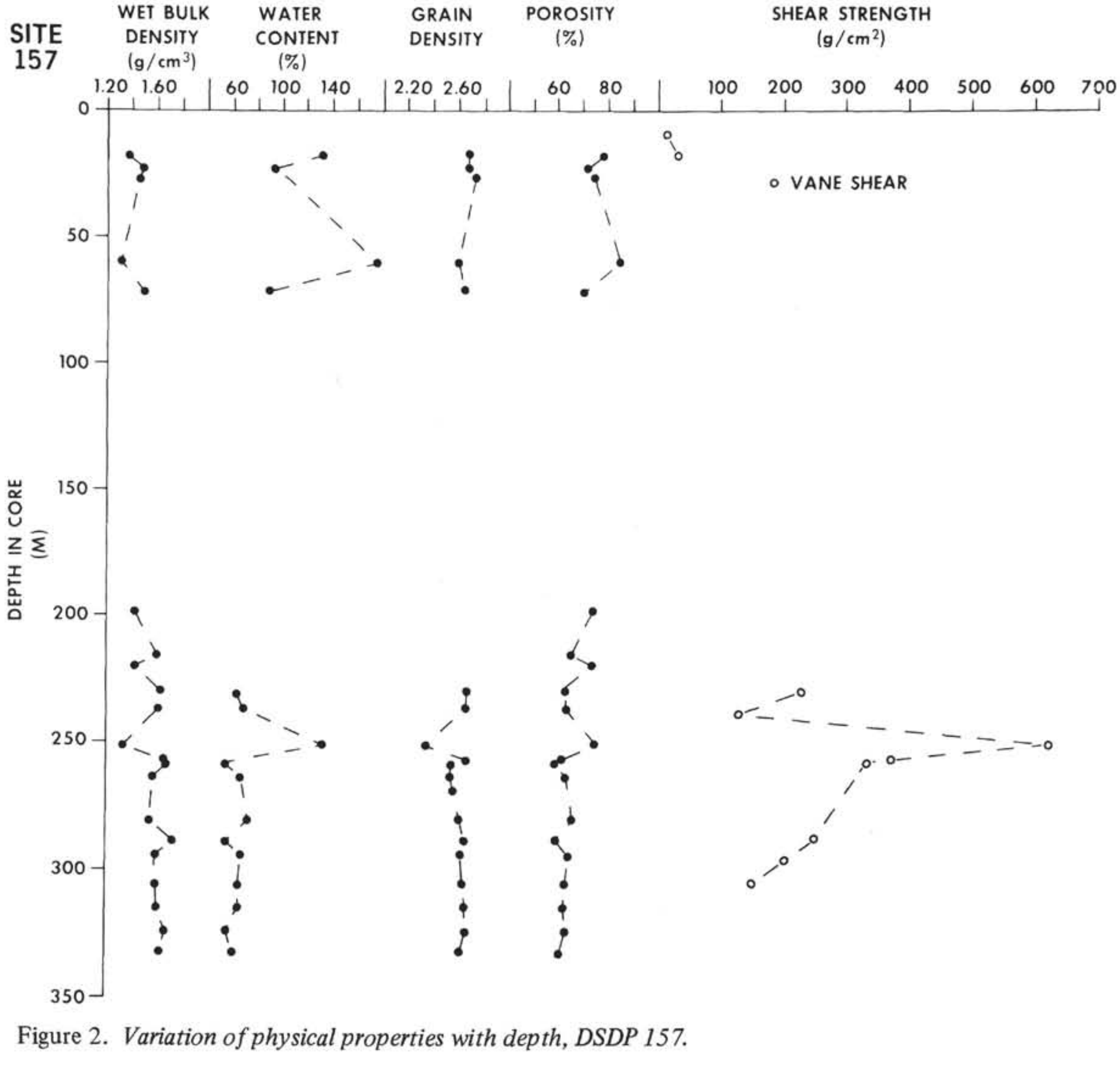

Figure 2. *Variation of physical properties with depth, DSDP 157.*

grain density may possibly be due to a relative increase in the occurrence of microfossils, but without a detailed examination of the sediment composition, an explanation is not readily available.

Unfortunately, core disturbance severely limited the number of vane shear tests that could be made at this site. Shear strengths in the lower section (230-300 m) were commonly on the order of 200 g/cm^2 except in the interval of 240 to 255 meters where values of 350 and 620 g/cm^2 were recorded. The anomalous nature of this 15-meter interval is clearly reflected in all the physical properties. The high shear strength observed in this zone is unusual in that relatively low strengths are commonly found in association with sediments of low density and high water content. An explanation for this higher strength is not apparent, but it possibly could be explained if a concentration of microfossils were found in this interval along with some degree of cementation.

The mass physical properties observed at this site indicate a gross uniformity of the sedimentary sequence sampled. The recorded variations are basically attributable to depth of burial. Wet bulk density is seen to increase while porosity decreases 18 and 22 per cent respectively from the top to the bottom of the sampled section. The absence of any sharp changes in bulk density and porosity with depth indicates that induration of the chalk sequence (240-335 m) is apparently a gradual process.

DSDP 158

The largest change in the mass physical properties with depth occurs within the upper 64 meters of the cored section. Here porosity and water content decrease on the order of 21 and 59 per cent respectively, while bulk density increases approximately 28 per cent. Overall, these same properties tend to be more or less uniform throughout the remainder of the section. Exceptions to this are three sections which display distinct changes in lithology. A sharp decrease in bulk density, with a correspondingly rapid increase in porosity and water content, occurs at 141 to 168 meters in association with a nannofossil ooze rich in Radiolaria, as well as large numbers of diatoms and foraminifera. Such a concentration of microfossils could explain the anomaly displayed by the respective profiles. These microfossils often contain a relatively large internal cavity which in turn is water-filled. These forms generally possess a much larger volume per unit of weight than rock particles of comparable size. Such unique properties could account for the low bulk density and the higher water content and porosity. However, a similar behavior of these properties would also be seen if a concentration of clay-size material occupied this interval. A more definitive explanation for these rapid changes is not feasible without closer examination of the sediment composition.

The marked increase in density and decrease of water content and porosity in the underlying interval (170-182 m) appear to reflect the occurrence of an increased concentration of volcanic ash. The associated increase in grain size would result in the higher densities and relatively low water content.

The most distinct offset of the respective profiles occurs at 209 meters where the lowest bulk density and some of the highest water content and porosity values were recorded. Although the reason for this severe change in the properties must await further analysis, indications are that these values reflect the presence of a great abundance of Radiolaria and diatoms. The extremely low grain densities recorded for this interval lend support to this assumption. Grain densities of 2.30 reflect the concentration of low specific gravity material such as Radiolaria and diatoms, which are primarily composed of opaline silica with a specific gravity of 2.10.

Grain density varies relatively little with depth and only at 160 and 208 meters are any significant changes recorded. These relatively low values undoubtedly reflect the increased abundance of a low specific gravity mineral such as opaline silica, as noted above.

Vane shear measurements reveal a rapid increase in shear strength to a depth of about 60 meters. Below this horizon the increase is gradual until the anomalous interval at 141 to 158 meters, where a sharp increase in strength is recorded. This increase, in a zone of relatively low bulk density and high water content, presents a problem similar to that noted for DSDP 157. No apparent explanation is available for this association, unless there was a possible concentration of microfossils, as suggested earlier, which would cause these increased strengths.

Although the Panama Basin sites are some distance apart, generalizations about the mass physical properties appear possible. Indications are that the physical properties undergo their most rapid change with depth within the uppermost sedimentary sequence (0-70 m). Below depths of about 70 to 100 meters, changes in bulk density, porosity, and water content tend to be rather gradual except in zones associated with local variations in lithology. In some cases it appears there may be large intervals of the section where there are no changes in these properties, such as in the lowermost parts of the cores from DSDP 157 and 158 (Figures 2 and 3). Examining the deeper section cored at DSDP 155, it can be seen that the respective parameters are gradually changing with depth.

Porosities are seen to decline from about 80 to 64 per cent in the upper 300 meters. If this were extrapolated to 500 meters based on DSDP 155 data, porosity is found to reach a low of 32 per cent, or an overall decrease of 63 per cent through the 500-meter interval. This is in considerable contrast to the very small (5 %) decrease Hamilton (1964) found in the 136-meter interval sampled by the experimental Mohole at the Guadalupe site.

Similarly, using the recorded values from the three sites, water contents are found to decrease on the order of 86 per cent through the 500-meter interval, whereas bulk density increases about 61 per cent. Viewing the mass physical properties, the transition from nannoplankton chalk ooze to chalk is quite gradual, as might be anticipated.

Northeastern Equatorial Pacific

The stratigraphic section sampled at the five sites in the northeastern equatorial Pacific is basically similar. A relatively thin layer (10-30 m) of zeolitic brown clay blankets the area. Underlying this clay, a gradation is seen from a calcareous clay to a nannofossil chalk ooze down to the

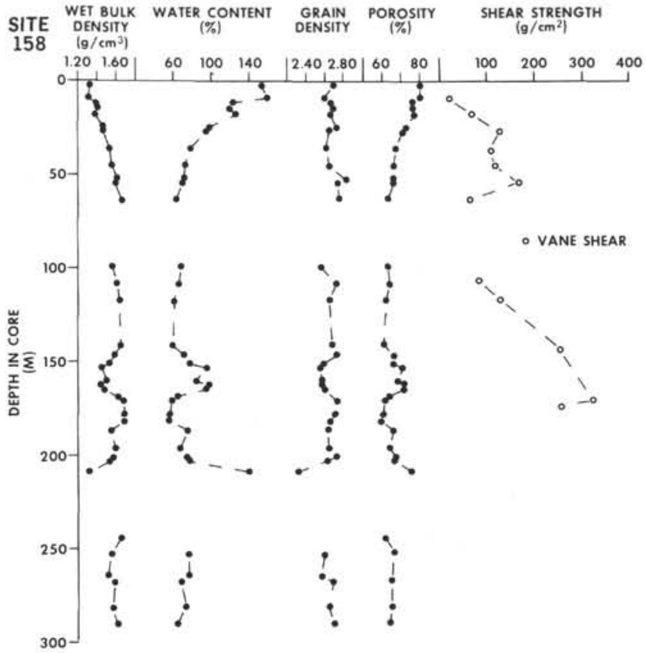

Figure 3. *Variation of physical properties with depth, DSDP 158.*

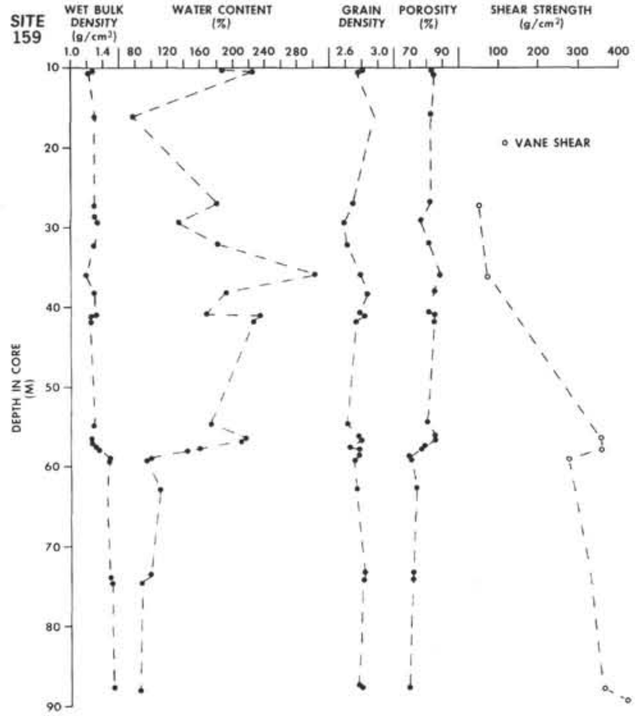

Figure 4. *Variation of physical properties with depth, DSDP 159.*

top of the basalt. Alternating sequences of clay and marl are common as are thin chert stringers in the lower part of the cored interval. Local zones of ferruginous clay rich in Radiolaria occur at various depths throughout the section. Of particular note at a number of the sites is the occurrence of ferruginous microaggregates in a clay matrix in a relatively thin zone just above the basalt.

DSDP 159

Sediments at DSDP 159 consist of Radiolarian clay overlying a sequence of alternating layers of calcareous clay and marl which grades to a nannofossil chalk ooze in the lowermost section.

Bulk densities are relatively low throughout the sampled interval, ranging from 1.29 g/cc at 10 meters to 1.54 g/cc at 88 meters. Little change in density is observed in the upper 30 meters of the section. A somewhat anomalous profile is seen for the interval of 30 to 58 meters, where densities are lower than those of the overlying material. Commonly, bulk density increases with depth owing to the effect of overburden; however, in this instance it appears that the abundance of clay in this sequence has strongly influenced the observed density profile. At 58 meters bulk density increases markedly and continues to increase gradually to the base of the section at 88 meters (Figure 4). This pronounced change clearly reflects the combined effects of less clay-size material and the increasing degree of consolidation found at depth.

As shown at this site, water content seems to amplify the lithologic changes. The high peaks (water contents of 180 % or higher) clearly reflect the presence of clay layers, whereas the lower values are indicative of the interlayered marls. A similar relationship is displayed by porosity, but to a lesser degree.

Remarkably little variation is seen in both wet bulk density and porosity throughout the sampled interval. An overall density increase of 16 per cent and a 6 per cent decrease in porosity are relatively minor. Hamilton (1964), in reporting a similar observation, attributed these small changes to low rates of deposition, the great age of the sediment, and interparticle bonds behaving as a chemical cement. Similar porosity characteristics with depth are found at other sites and are mentioned later.

Owing to the high overall degree of disturbance at this site, the shear strengths (Figure 4) have only a limited value and caution must be excercised in the use of these data. Strengths increase gradually with depth to about 59 meters where the base of the interlayering clay-marl sequence occurs. Below this interval the section consists primarily of a marl ooze which appears, based on the bulk density and water content profiles (Figure 4), to be increasing in degree of consolidation with depth.

Vane shear strengths recorded at 59 and 88 meters are questionable due to the development of cracks around the sample during the shear test. The low vane value at 59 meters is particularly suspect since in the same interval bulk density and water content markedly increase and decrease respectively; shear strength would normally be expected to increase in this case. Fall cone measurements in the same interval give considerably higher strengths than the vane value and appear to more adequately reflect the relative properties of the denser marl sequence. The vane value at 88 meters, although probably a bit low, agrees reasonably well with the fall cone measurements at 89.5 meters. However, both of these values appear much lower than might be anticipated considering that bulk density and water content are essentially at their highest and lowest respective limits in the sampled section. At best, the data presented here can only serve as a crude generalization of the anticipated shear strengths at this site.

DSDP 160

Variation with depth of lithology and physical properties is relatively minor at this site in comparison to the others from Leg 16. The sediment column consists primarily of 27 meters of zeolitic clay overlying 81 meters of nannofossil chalk ooze, with a thin (1 m) layer of calcareous clay, rich in ferruginous aggregate, above the basalt in which the site bottomed.

As shown in the respective profiles (Figure 5), the zeolitic clay and the underlying nannofossil chalk ooze display distinctly different mass physical properties. The zeolitic clay possesses relatively low bulk densities (1.30 to 1.33 g/cc and distinctly high water contents (170 to 290 %) and porosities (82 to 89 %). Grain densities are also found to be relatively higher (2.70 to 2.84) in the clay.

Aside from two slightly anomalous zones in the chalk ooze sequence, the section appears to be homogenous. Within this sequence (27-106 m), bulk densities increase gradually with depth from 1.47 g/cc at 35 meters to 1.64 g/cc at 106 meters. Similarly, water content and porosity display an overall decrease with depth through the same interval. These overall trends are considered characteristic of a relatively homogenous sequence which is undergoing increasing consolidation with depth of burial.

The explanation for the anomalous behavior of the bulk density, water content, and porosity profiles at a depth of 58 meters is not entirely clear. However, the increased abundance of ferruginous micronodules and a slightly higher calcium carbonate content may have been responsible for the observed properties. The slightly smaller offset in the profiles at 87.5 meters may reflect the higher degree of consolidation of the chalk ooze as reported in the lithologic log.

The slight decrease in bulk density and grain density with the corresponding increase in water content and porosity at the base of the hole reflects the presence of the thin calcareous clay zone overlying the basalt.

A look at the respective profiles (Figure 5) indicates that over the entire interval (106 m) of the sampled section, bulk densities increase approximately 26 per cent, whereas porosity decreases about 23 per cent. Water content on the other hand displays a much more pronounced decrease (66 %) over the same interval. Examining only

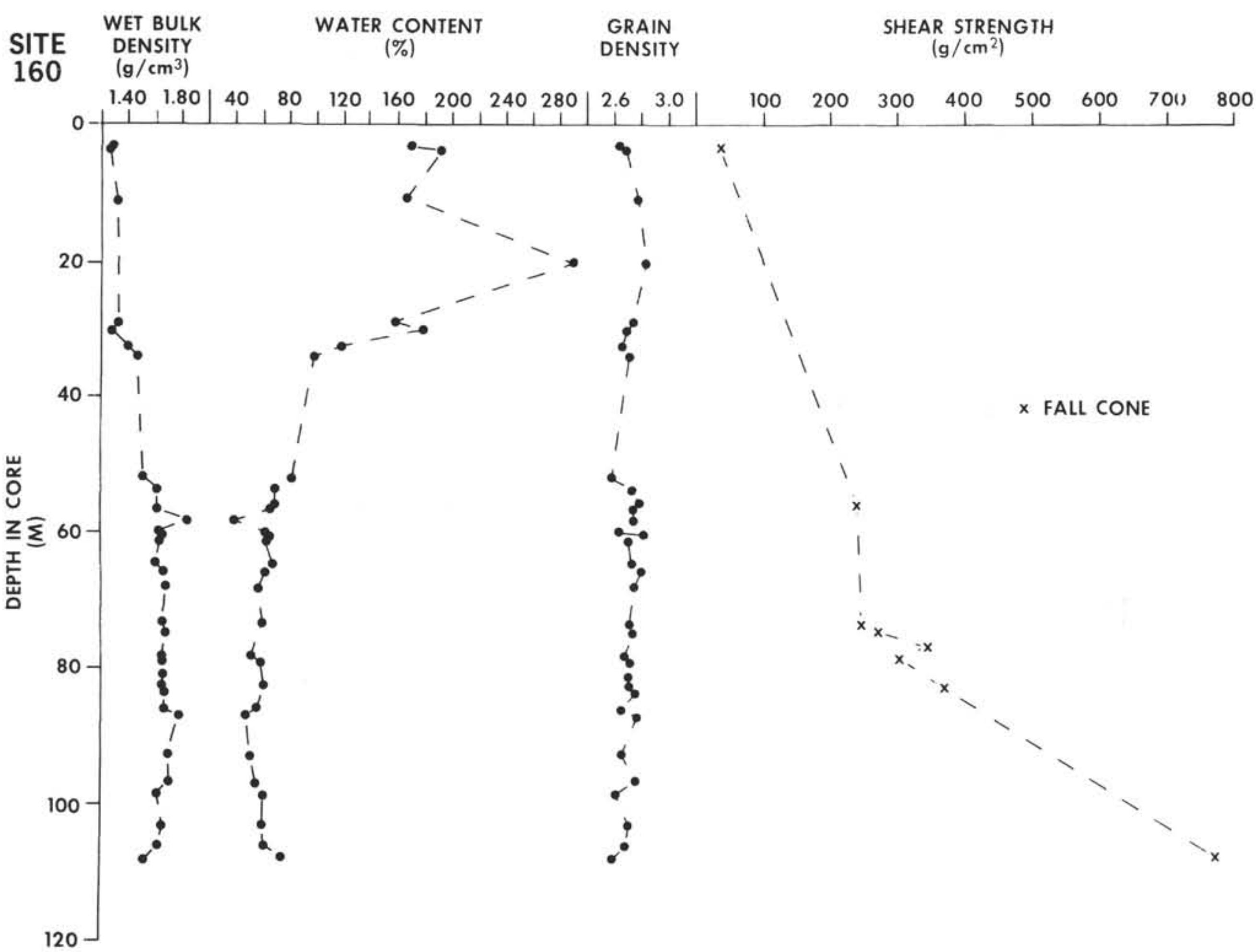

Figure 5. *Variation of physical properties with depth, DSDP 160.*

the interval from 27 to 106 meters (the chalk ooze), bulk densities are seen to increase 12 per cent as porosities and water contents decrease 15 and 38 per cent respectively.

Unfortunately, only limited shear strength data are available for this site. It is equally unfortunate that the available data are not from intervals which would provide a valid comparison between the strength characteristics of the zeolitic clay and the underlying chalk ooze. Based on the other physical properties, it could be expected that a noticeable contrast would exist between the shear strengths of these two distinct units. Although the strength of zeolitic clay can be quite high as reported at DSDP 163, it would probably be lower than that of the denser and drier chalk ooze. The few observations reveal only that the overall profile is indicative of the anticipated increase in shear strength with depth in a relatively homogenous unit (Figure 5).

DSDP 161

Four major lithologic units comprise the stratigraphic section at DSDP 161. The uppermost is a thin veneer (2 m) of zeolitic clay which blankets a 155-meter section of relatively homogenous nannofossil marl-chalk ooze. Below this unit a nannofossil chalk with less marl occupies the 155- to 200-meter interval. The lowermost sedimentary unit (200-245 m) is a clayey radiolarian ooze with an abundance of ferruginous microaggregates.

Of the eight sites studied on Leg 16, DSDP 161 provided the best series of subsamples for the measurement of mass physical properties. Although sample disturbance was still a problem, there were fewer zones of severely disturbed material than usual.

Except for minor local variations, bulk densities increase gradually from 1.47 g/cc in the zeolitic clay to 1.67 g/cc at a depth of 140 meters in the nannofossil chalk ooze. A corresponding decrease in water content and porosity occurs in this same interval. A reversal in these general trends is noted in the 140- to 155-meter interval, although no major change in lithology was recorded. Here bulk density actually decreases about 11 per cent relative to that of the overlying material. A somewhat comparable increase in water content and porosity is associated with this section.

The change from a chalk ooze to a chalk at 155 meters is clearly reflected in the physical properties (Figure 6). At this contact, bulk density increases sharply and, although it tends to decrease with depth to 200 meters, it is relatively higher than that of the immediately overlying material. The general slope of the water content, porosity, and bulk density profiles associated with the chalk are somewhat anomalous in that just the opposite slopes would be anticipated because of the increasing degree of consolidation with depth.

The radiolarite in the lower 45 meters of the core is distinctly characterized by its mass physical properties. Bulk densities are the lowest (1.36 g/cc, recorded throughout the sampled interval, whereas water contents and porosities are the highest measured in the core. These extreme values are not readily explained by the available data; however, the combination of intense burrowing and the abundance of ferruginous aggregates, clay, Radiolaria, and diatoms may well account for the observed properties.

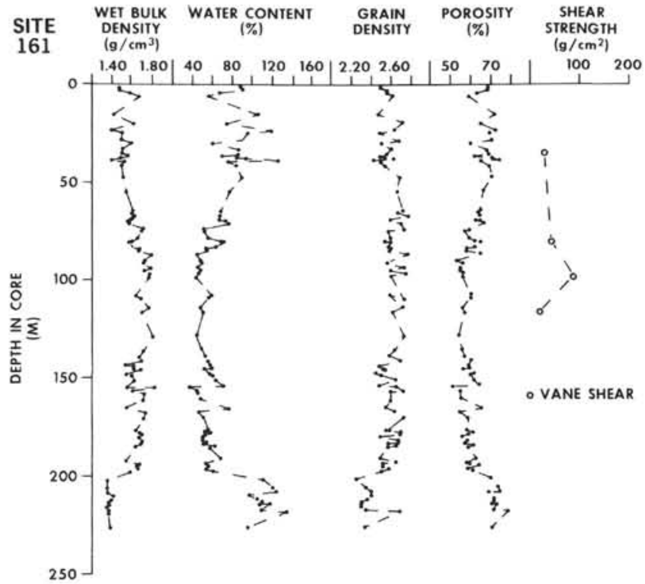

Figure 6. *Variation of physical properties with depth, DSDP 161.*

The radiolarite is also distinguished by very low grain densities, owing to the high opaline silica content of the Radiolaria.

Although a limited number of shear strength measurements were made at this site, it was determined that sample disturbance in these intervals was so great that the measured values were essentially that of the remolded strength. These remolded strengths for the chalk ooze were on the order of 20 to 40 g/cm².

Despite the distinct lithologic changes encountered in the cored section, the variation of physical properties with depth appeared to be somewhat unusual. Although distinct changes are expected to reflect different lithologies, an overall trend of increasing bulk density and decreasing water content and porosity would normally be anticipated with increasing depth. No such trend is observed at this site; in fact, higher water contents and porosities occur in the lower part of the section than in the upper few meters of the core. The lower portion of the core did not appear to be excessively disturbed, certainly not more than other intervals.

DSDP 162

The sedimentary section consists of about 26 meters of interlayered chalk ooze, clayey radiolarian marl ooze, and ferruginous radiolarian clay overlying a 37-meter thickness of relatively homogenous clayey radiolarian ooze. The remainder of the 150-meter section is primarily a clayey radiolarian marl ooze with some ferruginous clayey radiolarian ooze and an occasional chert layer. Only the lowermost 6 meters of this section differs in that it is a ferruginous zeolitic clay.

The clay intervals within the interlayering sequence (0-26 m) display considerably higher water contents (100 % higher) and porosities (24 % higher) than the adjacent chalk ooze. Similarly, the wet bulk densities of the clay are approximately 21 per cent lower than those of the chalk ooze. Bulk density and porosity are remarkably uniform within the clayey radiolarian ooze sequence (26-63 m), varying little from 1.20 g/cc and 85 per cent respectively. An examination of grain densities indicates that the section is not quite as homogenous as bulk density and porosity values might suggest. Although there is some variation in water content, it is relatively minor, and the entire sequence is found to possess a water content on the order of 245 per cent.

Insofar as bulk density and porosity are concerned, the remainder of the section (63-140 m) is similar to that of the overlying clayey radiolarian ooze. Variations in either parameter are only on the order of 5 to 6 per cent throughout the 87-meter interval. Water contents and grain densities appear to vary slightly more.

DSDP 162 displays a rather unusual variation of physical properties with depth. Not only are the bulk densities and porosities remarkably uniform throughout the lower 123 meters of section, but lower densities as well as higher porosities and water contents are found at depth than in the uppermost portion of the section (Figure 7). Bulk density decreases about 20 per cent, whereas water content and porosity increase 116 per cent and 12 per cent respectively within the cored interval. These variations are anomalous in that they are just opposite to those commonly reported in a depth profile. Exceptions have been reported, however, such as Hamilton's (1964) finding of relatively little change in porosity (5 %) through a 136-meter interval of deep-sea deposits off Guadalupe Island and Meade's (1963) reporting of an increase in porosity with depth in fine-grained sediments in the San Joaquin Valley of California. Meade attributed the anomalous condition to variations in grain size, high diatom content, and the type of exchangeable cation adsorbed on the clay minerals. A detailed analysis of the DSDP 162 core has not been completed, so a definite explanation for the observed variation cannot be given. There is good reason to believe,

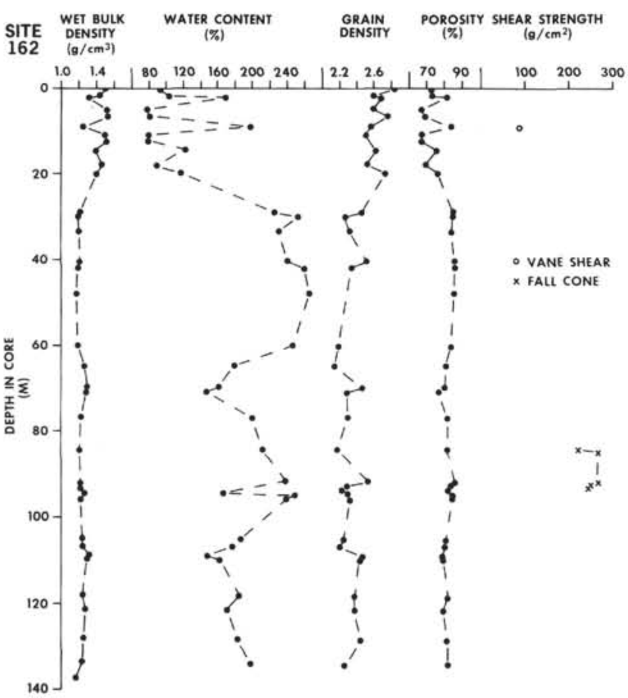

Figure 7. *Variation of physical properties with depth, DSDP 162.*

however, that the very high concentration of Radiolaria at this site may have strongly influenced these physical properties. Evidence for this is suggested by the findings of other studies where it has been shown that a similar relationship of these three properties often occurs in zones relatively rich in the skeletal remains of microorganisms (A.F. Richards, 1962, personal communication). This relationship is attributed to the unique shape and internal structure of these forms.

Unfortunately, only a small number of shear strength measurements were made at this site. In one of the upper clay zones, a shear strength of 88 g/cm² was recorded at a depth of 9 meters. Lower in the section (84-95 m) a series of fall cone tests showed strengths from 224 to 264 g/cm² for the clayey radiolarian marl ooze and the ferruginous clayey radiolarian ooze sequence. Because of so few measurements, little more than a presentation of the observed values is feasible (Figure 7).

DSDP 163

Lithologically, the sample sequence at this site can be divided into four major units. The uppermost consists of 28 meters of ferruginous radiolarian zeolitic clay which, in turn, overlies 112 meters of clayey radiolarian ooze with thin porcelanous chert beds scattered throughout the section. Underlying this interval is a relatively thin zone (22 m) of ferruginous zeolitic clay with a few chert beds. The lowermost part of the sedimentary section (162-276 m) is a nannofossil chalk with some flinty cherts.

Both the zeolitic clay and the clayey radiolarian ooze are characterized by very low bulk densities as well as high water contents and porosities. Although the wet bulk densities are basically similar (1.22 g/cc), there is a decided contrast among the other physical properties of these two units (Figure 8). Water contents, grain densities, and porosities are notably greater in the zeolitic clay than in the radiolarian ooze. Water contents of 200 to 260 per cent and porosities of 85 to 90 per cent as are found at this site characterize the zeolitic clays blanketing much of the Pacific basin (Keller and Bennett, 1968). The underlying clayey radiolarian ooze displays a remarkably low grain density of 2.00, which undoubtedly reflects the high concentration of Radiolaria and diatoms found in this section.

The overall trend with depth of the various properties is interrupted by a zone of ferruginous zeolitic clay (140-162 m). Here, in respect to the established trend, the zeolitic clay displays a slight decrease in bulk density along with increases in water content and porosity. Such a relationship is indicative of zeolitic clays, just as it is in the surface deposits, but in this instance the water contents and porosities are slightly lower and the bulk densities higher owing to the effective overburden pressure.

The nannofossil chalk, which comprises the lowermost sedimentary unit, contrasts sharply with the overlying material. Bulk densities are much higher, ranging from 1.72 to 1.90 g/cc, while water contents and porosities are considerably lower, varying from 54 to 35 per cent and 60 to 49 per cent respectively.

At DSDP 163 the "normal" trend of increasing bulk density and decreasing water content and porosity with depth is clearly displayed. Within the sampled section,

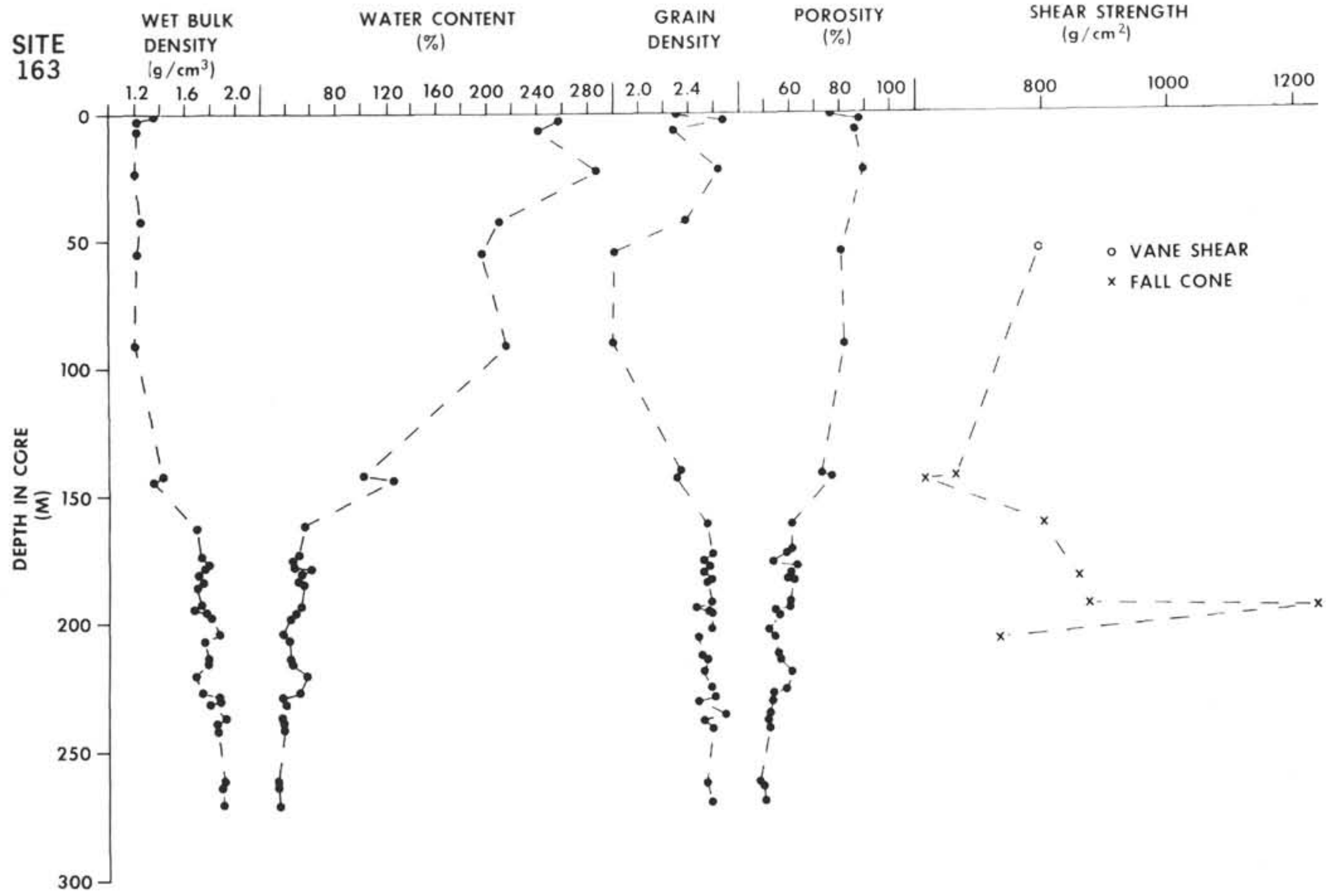

Figure 8. *Variation of physical properties with depth, DSDP 163.*

density is found to increase from 1.36 to 1.90 g/cc (41 %), whereas water content decreases about 73 per cent and porosity by about 36 per cent.

Shear strength measurements were made in all the lithologic units except the uppermost zeolitic clay. Based on only a few measurements, a broad generalization can be made in regard to the overall strength characteristics of the sediment section. The clayey radiolarian ooze sequence appears to have a relatively high shear strength, on the order of 800 g/cm², whereas the ferruginous zeolitic clay (140-162 m) possesses a notably lower strength (610-660 g/cm²). As might be anticipated, the underlying denser chalk displays much higher values. The sharp decrease in shear strength at 208 meters is associated with a zone of mottling and may possibly reflect the slight increase in water content and decrease in bulk density.

Consolidation Characteristics

Consolidation is used here in the soil mechanics sense, meaning the reduction of volume due to an imposed load. The consolidation test is commonly employed by the foundation engineer to determine the rate and amount of settlement of a structure, but here it is used basically to assist in understanding the depositional behavior of deep-sea sediments.

The consolidation test, in the very simplest of terms, consists of loading a small free-draining, confined, cylindrical sample of sediment with increasingly larger normal loads, while recording the rate and amount of volume decrease under each load. Results of this test are usually displayed in a plot of void ratio (volume of voids divided by the volume of solids) versus the log of normal pressure, commonly referred to as an *e*-log *p* curve. It is this curve that serves as the basis for settlement calculations as well as determining the preconsolidation pressure (the greatest load to which a sediment sample has been subjected). A thorough discussion of the consolidation theory as well as testing procedures can be found in most soil mechanics texts and only a limited discussion is presented here.

Consolidation tests normally provide a means whereby the depositional history of a deposit can be determined. In soil mechanics terminology a deposit is said to be *normally consolidated* if the effective overburden pressure is equal to the preconsolidation pressure. The effective overburden pressure acting on the sample in place is the combined wet bulk density of the overlying sediment minus the bulk density of water, which, in this case, is an assumed average of 1.026 g/cc. If the overburden pressure is greater than the preconsolidation pressure, the sediment is said to be *underconsolidated* (the sediment has not yet consolidated under its present load), and, if the overburden pressure is less than the preconsolidated pressure, the deposit is considered to be *overconsolidated.* Underconsolidated sediments commonly occur in areas of rapid deposition such as deltas, owing to insufficient time for the drainage of pore water (Moore, 1961). On the other hand, overconsolidated sediments are found where considerable erosion has removed much of the overburden or in deposits which have been desiccated to some degree.

As noted earlier, the degree of sample disturbance of the *Glomer Challenger* cores is considerable and subsampling had to be done very selectively. Unfortunately, even with the great care in subsample selection and later transport to the laboratory, only four of the thirteen samples collected provided usable results from the consolidation tests.

To date, consolidation tests have been made on approximately twenty-five deep-sea samples from depths greater than 9 meters below the sea floor. The first such tests were those by Hamilton (1964) on the Mohole (Guadalupe site) samples and more recently by W. Bryant (1972, personal communication) on samples collected in the Gulf of Mexico during Leg 10 of the Deep Sea Drilling Project.

The four samples discussed here are from the northeastern equatorial Pacific (DSDP 160, 161, and 163) and represent depth intervals of 9, 63, 81, and 142 meters respectively. At DSDP 160 two subsamples from depths of 9 and 63 meters were tested and found to possess a considerable degree of overconsolidation (Figures 9 and 10). Although sample disturbance pressure from the *e*-log *p* curves to within more than 20 or 25 per cent based on the graphical method of Casagrande (1936), the overconsolidated nature of these sediments is clearly evident by the contrasting low overburden pressures. The zeolitic clay at 9 meters (DSDP 160) appears to be considerably more overconsolidated than the nannofossil chalk ooze sampled at 63 meters. In a chalk ooze at a depth of 81 meters (DSDP 161) a similar, but less pronounced overconsolidated condition is observed (Figure 11). At a depth of 142 meters (DSDP 163A), a zeolitic clay displays an essentially normally consolidated characteristic (Figure 12).

The predominant overconsolidated characteristics found here were also reported by Hamilton (1964) in his study of Mohole (Guadalupe site) cores to a depth of 136 meters. It is obvious that these deep-sea sediments have not been stripped of a significant amount of overburden by erosion nor have they been subjected to desiccation, the two usual causes of overconsolidation. Although not yet

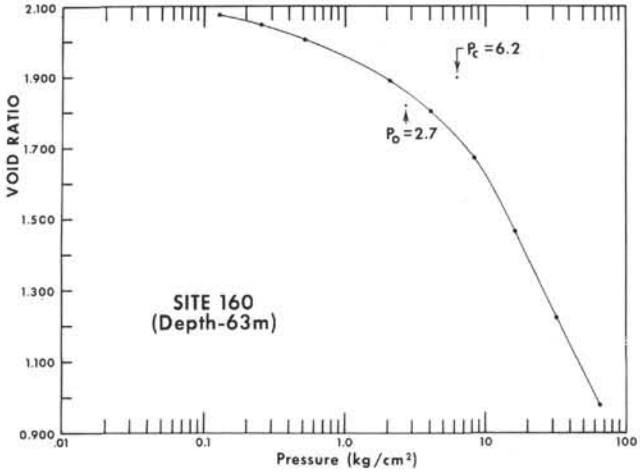

Figure 10. *Void ratio versus log pressure curve.* Pc = *preconsolidation pressure,* Po = *overburden pressure. DSDP 160, 63 meter depth.*

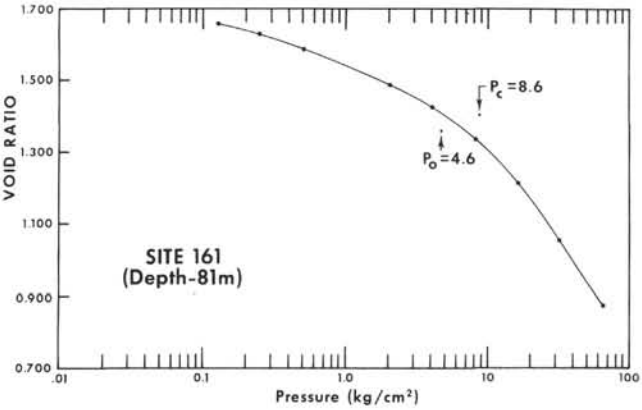

Figure 11. *Void ratio versus log pressure curve.* Pc = *preconsolidation pressure,* Po = *overburden pressure. DSDP 161, 81 meter depth.*

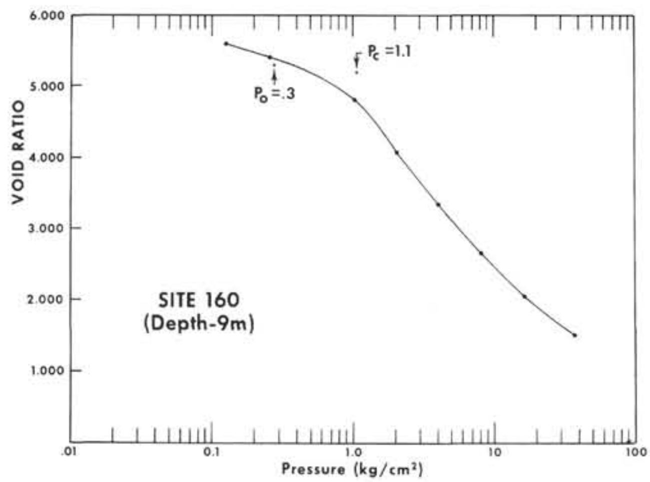

Figure 9. *Void ratio versus log pressure curve.* Pc = *preconsolidation pressure,* Po = *overburden pressure. DSDP 160, 9 meter depth.*

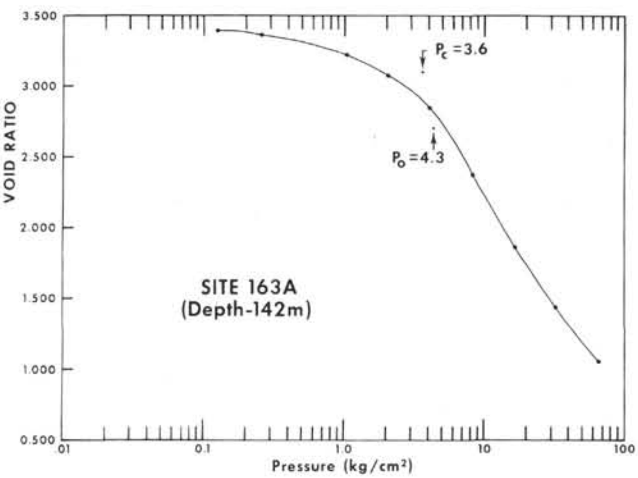

Figure 12. *Void ratio versus log pressure curve.* Pc = *preconsolidation pressure,* Po = *overburden pressure. DSDP 163, 142 meter depth.*

proven, it appears that the extremely slow rate of deposition and the great age of deep-sea sediments may be responsible for this apparent overconsolidated state. Earlier investigators have postulated that the slow deposition rate is responsible for the development of "rigid bonds" as the result of adsorbed water around clay particles or intergrain bonds attributed to incipient lithification from the solution and redeposition of various minerals (Terzaghi, 1941; Hamilton, 1964). Bjerrum (1967) attributes this phenomenon to diagenetic bonds and goes further to say that, where diagenesis has affected a clay, the preconsolidation pressure cannot be determined from a consolidation test. If this assumption is followed, then none of the preconsolidation pressures reported here are valid and the degree of overconsolidation cannot be accurately determined. It can only be stated that these samples display consolidation characteristics similar to that of an overconsolidated sediment.

The 142-meter sample from DSDP 163A differs in that it is the only sample not found to be overconsolidated. Unfortunately, this was the only sample from this site, and the overall consolidation characteristics with depth for this site are not known. It is unusual that the deepest sample tested should be normally consolidated. Owing to the limited data available, and explanation for this phenomena has not been attempted.

Plasticity

Atterberg limits provide the basis for a very simple yet effective classification system. These limits, liquid and plastic, are basically the water contents at which a sediment changes from the liquid to the plastic state. A detailed discussion of these limits can be found in almost any soil mechanics text. Owing to the relatively large amount of sediment needed for the Atterberg limit determinations, only nine of the Leg 16 samples were classified by this test.

Studies of short sediment cores by Richards (1962) and Keller (1970) indicated that the majority of deep-sea sediments can be classified as inorganic clays of medium to high plasticity using the classification of Casagrande (1948). The samples from Leg 16, which are from greater depths below the sea floor, appear to be slightly more organic clays of high compressibility (Figures 12 and 13). As shown in Figure 13, chalk and chalk oozes commonly display much lower liquid limits and degrees of plasticity than the zeolitic clays which have exceptionally high liquid limits and plasticity indices.

Sensitivity

Sensitivity determinations (the ratio of undisturbed strength to remolded strength) were made on only nine samples at DSDP 157, 158, and 159 owing to the lack of time needed to make additional shear strength tests. These nannofossil chalk oozes, with varying concentrations of Radiolaria, diatoms, and foraminifera, ranged in sensitivity from 2 to 7, slightly insensitive to very sensitive based on the classification of Rosenquist (1953). These values agree with those reported by Keller and Bennett (1970) for a large number of short cores from the Pacific. Within the depth ranges of the Leg 16 samples tested (9-117 m), no apparent correlation was found between sensitivity and depth of burial.

SUMMARY

As has been shown in the depth profiles of the various physical properties, not only is there considerable variation with depth, but from site to site as well. Even between the two closest sites (DSDP 161 and 162), a distance of 450 km, a major difference exists among the physical properties. However, making the assumption that the samples collected during Leg 16 represent the 0- to 300-meter interval, a number of generalizations can be made concerning the sediments from the sampled area.

There is no apparent relationship between variation of mass physical properties and the age of the sediment or the rate of sedimentation for the respective stratigraphic sequences. It has been reported elsewhere, however, that, in the areas of extreme rates of sedimentation, such as in deltaic deposits, the physical properties are influenced by the deposition rates (Moore, 1961). In the case of the abyssal plain deposits encountered on this leg, the greatest single factor influencing the physical properties appears to be the depth of burial. Lithologic changes are also major factors responsible for many of the variations noted here.

Excluding DSDP 155, since the samples were only taken from below 300 meters, it is possible to delineate the characteristic mass physical properties of a number of the sediment types encountered during Leg 16 (Table 1). Table 1 presents average values for the various parameters based on the laboratory rather than the shipboard analyses. Of particular interest is the radiolarite found at 200 meters at DSDP 161. This material displays a remarkably low wet bulk density yet high water content and porosity for its depth of burial. This can probably be attributed to the unique packing of the individual Radiolaria.

A number of the samples display properties similar to that of an overconcolidated sediment as determined from a consolidation test. This characteristic is not truly due to overconsolidation as the term is employed in soil mechanics, but appears to be a diagenetic property of deep-sea sediments. Hamilton (1964) and others have postulated that this property results from a bonding of the grains such that the fabric of the sediment is altered little by an

TABLE 1
Sediment Types and Selected Physical Properties

	Wet Bulk Density (g/cc)	Water Content (% dry wt.)	(%) Porosity	Grain Density
Radiolarian brown clay	1.25	200	85	2.30
Brown zeolitic clay with Radiolaria	1.25	250	85	2.67
Nannofossil chalk ooze	1.53	83	72	2.61
Nannofossil chalk	1.67	53	58	2.65
Brown clay with Radiolaria and ferruginous aggregate	1.60	65	65	2.60
Radiolarite	1.38	105	73	2.40

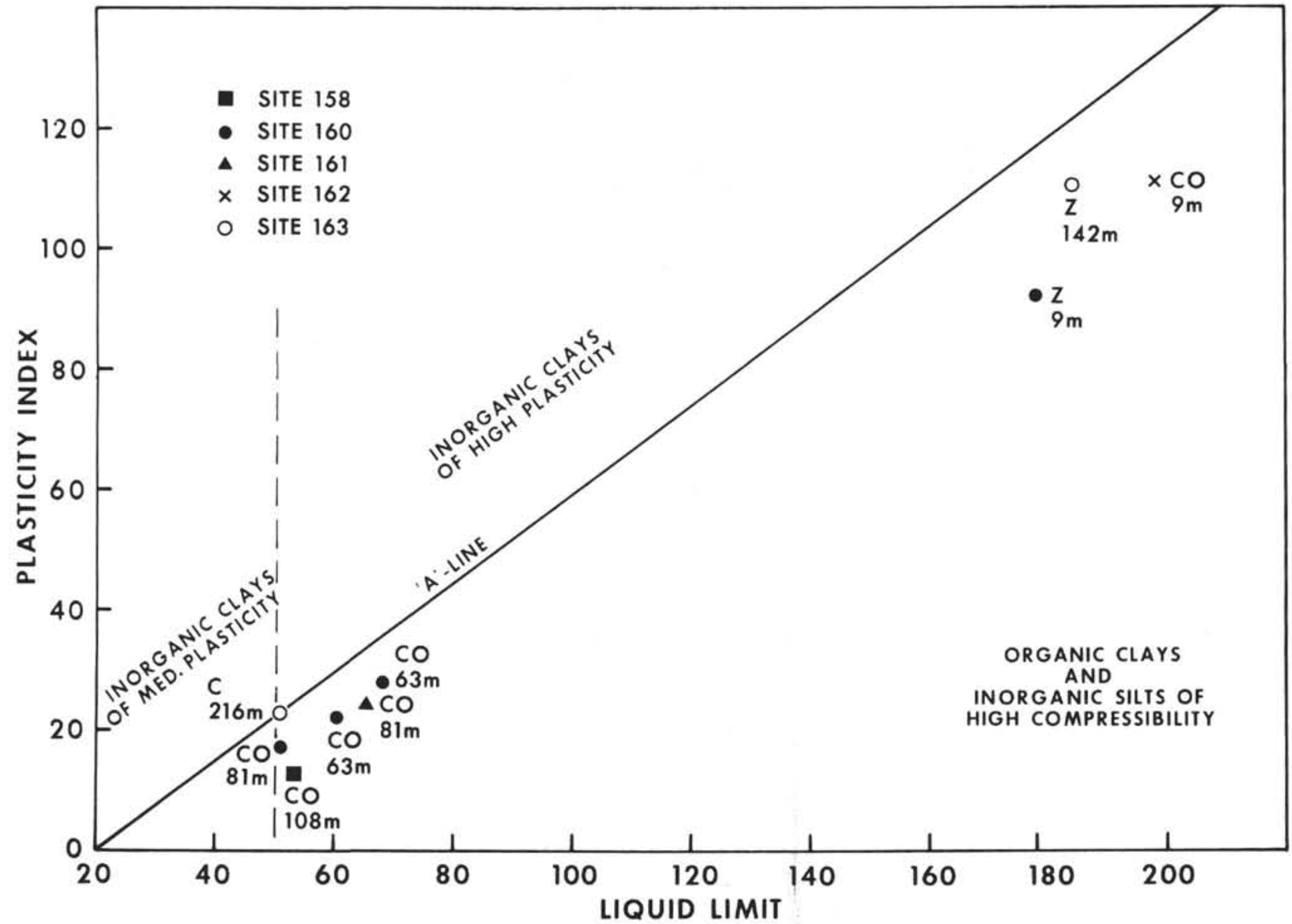

Figure 13. *Plasticity chart; letters indicate sediment type* C = *chalk,* CO = *chalk ooze,* Z = *zeolite clay; numbers are the depth in hole of the subsample.*

overburden pressure. In his study of the Mohole core (Guadalupe site), Hamilton (1964) found little change in porosity with depth and attributed this to the bonding and stabilization of the sediment fabric. This appears to be a logical finding in view of the assumptions made above. Leg 16 data, however, present a slightly different finding. Although most of the samples tested give the appearance of an overconsolidated sediment, porosities are found to decrease considerably with depth at all but one site. This would appear to be an anomalous situation if the sediments are indeed overconsolidated as the tests indicate. There may be, however, an explanation for this phenomenon in the fact that these porosity decreases occur primarily in sediments consisting largely of chalks abundant in Radiolaria, diatoms, and coccoliths. These may, in turn, contribute significantly to resolution and the reduction of voids. If this is the case, evidence should readily be seen from a close examination of these microfossils. DSDP 162, which displays little or no change in porosity with depth, possesses much more clay throughout its section. There is an indication from sections of the various cores that, in clay sequences, the porosity change with depth is minor. The clay at DSDP 162 may therefore serve to balance out the effect of the chalk ooze.

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