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CONF-801020--5

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Geotechnical Properties of Sediments from North Pacific and Northern Bermuda Rise

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ABSTRACT

Studies of geotechnical properties for the Subseabed Disposal Program have been oriented toward sediment characterization related to effectiveness as a containment media and determination of detailed engineering behavior. Consolidation tests of the deeper samples in the North Pacific clays indicate that the sediment column is normally consolidated. The in-situ coefficient of permeability (k) within the cored depth of 25 meters is relatively constant at 10^{-7} cm/sec. Consolidated undrained (CIU) triaxial tests indicate stress-strain properties characteristic of saturated clays with effective angles of friction of 35° for smectite and 31° for illite. These results are being used in computer modelling efforts. Some general geotechnical property data from the Bermuda Rise are also discussed.

Introduction

The clay sediments which cover portions of the deep ocean basins possess physical characteristics which are favorable to the multibarrier concept of the Sub-seabed Disposal Program (SDP)-(1). In terms of geotechnical properties, these include: very low permeability which greatly inhibits the rate of water migration; continuous and slow rates of deposition such that the sediment column is completely consolidated under existing overburden conditions; shear strengths that are relatively low so that the strata are easily penetrable; and a stress-strain-time behavior typical of soft plastic clays which tend to self-heal or flow when disrupted. Under present assumptions of the SDP, the sediments are considered to be the prime barrier with canisters embedded within the unlithified layers. However, even if the canisters were to be placed in underlying sedimentary rock, the upper softer sediments would provide a significant added barrier.

The first stage of the geotechnical program is to obtain base-line data on engineering properties, coordinated with geological studies, so that a general assessment can be made of a particular area as a potential SDP study site. Initially, an area approximately 600 miles north of Hawaii (MPG-1) was chosen as a generic study site after reconnaissance studies indicated favorable conditions (2). However, a different study site on the Northern Bermuda Rise (MPG-3) was found to have unfavorable geologic conditions for consideration of the upper unlithified sediments even though the geotechnical properties in much of the area seemed to be acceptable (3). The sediment characterization studies include coring, geophysical measurements with hull-mounted acoustic systems, ship-board sampling and testing of cored sediments to determine general physical properties and a few laboratory studies of permeability, compressibility, and stress-strain properties. If these preliminary results indicate that the sediments possess favorable characteristics, then a more detailed field sampling and laboratory experimental program is implemented to provide the parameters necessary for thorough characterization of sediment strata and computer modeling studies. Since many of the geotechnical measurements require samples that are as close to the in-situ conditions as possible, considerable attention has been given to minimizing disturbance due to coring, sampling and testing and some studies are aimed at simulating the in-situ environmental conditions of pressure and temperature.

Results of analytical studies predict relatively low hydraulic gradients with very low water velocities, due to thermal effects around the canister (4,5). Special techniques have been developed to study permeability characteristics at low gradients (6) and additional experimental work is underway to study the effects of high pressure (9000 psi) and high temperature (200°c) on the rate of water migration. Other special experimental work has included detailed stress-strain tests using triaxial compression apparatus (7) and both drained and undrained creep tests. A new phase of the geotechnical program involves dynamic behavior, extension tests, and studies to determine the influence of anisotropic consolidation and of an intermediate principal stress condition. The results of all these studies will be useful in evaluating sediment response during and after canister emplacement, including possible long-term sediment and canister displacements (8).

This paper which is one of a group of nine papers discribing technical aspects of the subseabed disposal option, presents general physical properties of two SDP generic sites - one in the North Central Pacific and the other in the North Western Atlantic north of Bermuda. Also included are brief discussions relating the geotechnical properties to computer modeling studies of water migration, canister emplacement and long term displacements, and description of future needs and program.

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North Pacific Study Site: MPG-1

Site MPG-1 lies between latitudes 30° and 31° 30' N, and longitudes 157° and 159° W, some 1000 Kilometers north of the Hawaiian Islands. The typical abyssal hills of the site give way to the Musicians Seamounts some 150 km to the west, and to the rough, northeast-trending Murray Fracture Zone some 100 km to the south. The abyssal hills typically have relief of 100 to 200 m, and dimensions of 20 to 50 km north-south versus 5 to 25 km east-west. This topography is believed to be primary, that is, it formed by faulting parallel to the crest of the East Pacific Rise when the oceanic crust formed some 100 million years ago. Scattered through the region are eight small seamounts with relief of 300 to 900 m. The age of formation of these features is unknown.

The thickness of sediment above basalt basement is highly variable, ranging from essentially zero to a maximum of about 60 m. In general, the sediment blanket thins from south to north, from an average of about 40 m for the southern third of the area to 25-30 m for the northern third.

The sediments recovered by piston cores show consistent vertical variations in lithology throughout the site. Topographic depressions receive up to twice the sediment of topographic highs. This pattern of fractionation has not changed for at least the past several million years (9).

The surface sediments are fine grained quartz-illite-rich clays. These clays are of terrestrial origin, and have been carried from the glaciated and adjacent regions of Eurasia and North America by stratospheric winds. They have accumulated at one to three meters per million years for the past three million years. The quartz-illite clays are underlain by even finer clays that are rich in smectite, ferromanganese oxyhydroxides, and the zeolite, phillipsite. These clays are enriched in components formed in the ocean basins; iron hydroxide from mid-ocean ridge hydrothermal systems and authigenic manganese oxhydroxides, smectite and zeolite. Such deposits accumulated at rates of a few tenths of a meter per one million years (10,11). Finally at depths in excess of 16 m, the clays again became richer in quartz and illite, reflecting deposition of eolian material beneath the northeast trades some 45 to 70 million years ago when the site lay far southeast of its present location (11).

The locations of all samples used for geotechnical purposes are shown in Fig. 1. Four different sampling tools have been used: the standard piston corer with an inside diameter (I.D.) of 6.3 cm, the Giant Piston Corer (GPC) with an ID of 11.4 cm (12), a large diamter (10.2 cm) gravity corer (13) and a dredge to obtain bulk samples of the surficial materials. Of these, the gravity corer is considered to obtain the least disturbed sample but the depth of penetration is limited to approximately 3.0 m. The standard piston corer generally produces considerable distortion to the sample because of the small diameter and relatively large traction stresses. In addition, because of weight and handling limitations the depth of penetration in these fairly stiff sediments has been limited to less than 10 m. Only one GPC sample has been recovered from the MPG-1 site; however this core (LL-44, GPC-3) yielded a very high quality continuous sample to a depth of 24.4 meters in the sediment column (14,15). The bulk samples obtained with a dredge bucket are useful for laboratory experiments requiring large volumes of material which is usually reconstituted and reconsolidated to approximate in-situ conditions.

In general, great care has been taken to minimize distrubance to samples. In the case of the GPC, special ship-board sampling and testing techniques were employed such that all the sampling and much of the testing was done immediately after recovery of the core. The core was extensively subsampled and the sealed specimens were stored in sea water at 2 to 4° C. The usual procedure for the shorter gravity cores is to seal and transport them to a shore based laboratory as quickly as possible.

As indicated in Figure 1, many sediment samples have been recovered from MPG-1 and a large amount of geotechnical data has been obtained. For the purpose of this paper, attention is focused on data from the longest piston core and on a few typical gravity cores, although some results from other cores are included. The vertical variability of geotechnical properties in LL-44-GPC-3 is illustrated in Figure 2. The most important feature is the dramatic increase in water content, with concurrent decrease in density, that occurs between six and nine meters where there is a change of almost 100% in water content from 110 to 200%. The maximum water content is approximately 250% at a depth of 11 meters. This increase is of course directly related to compositional changes, described by Heath (2) but nevertheless required careful study of other geotechnical properties important to the multi-barrier concept. The miniature-vane shear and unconfined compression data were obtained onboard the ship within one day of recovery and the curve representing undrained shear strength was obtained from triaxial compression tests conducted on sub-samples many months later. The vane shear trend is approximated by a logarithimic function of depth:

$$S_u(z) = 0.2 \ln(1+0.1149z)$$

where z is the depth in meters and $S_u(z)$ is the undrained strength in kg/cm^2. Except for a few measurements of over 400 gm/cm^2, the undrained shear strength at the bottom of the core is slightly over 300 gm/cm^2. Some of the variability in the lower few meters is probably the result of disruption of sedimentary layers due to incremental coring caused by high traction stresses and piston motion. Closer inspection of the upper several meters of strength profile reveals a change from an almost constant value of 50 gm/cm^2 in the upper 4 meters (the lower values in the upper one meter are attributed to disturbance) to a relatively rapid increase to 100 gm/cm^2 between 4.5 and 6.0 meters; corresponding to the changes in composition and water content/porosity/density for the upper illites and deeper smectites. Grain size analyses using the pipette method (16) indicate mean grain size of slightly less than one micron throughout the core. The plot of Activity index clearly reflects the combined effects of compositional and related factors on sediment characteristics. The compression index, C_c, (slope of the void ratio vs log of stress curve) is about 1.0 for the upper 5 meters of illite and increases quite rapidly to a value of 2.7 for the deeper smectite layers (Fig. 2).

Water content and vane shear data for three typical gravity cores are shown in Fig. 3. Except for a few localized excursions, all the cores show approximately the same magnitudes and trends in water content but there are some differences in undrained shear strengths. The average water content for the upper 1.0 meters is almost constant at about 114 percent and then decreases in an approximately linear fashion to 100% at 2.2 meter depth. Comparison of water content data for all cores within MPG-1 generally indicates a high degree of lateral homogenuity although the depth to the smectite zones was less than two meters in one core. (MA-2, GC-8).

The vane shear data (Fig. 3) is not as consistent as water content results but the same trends are evident in all cores. Most gravity cores showed a relatively constant value of shear strength within the upper two meters. The average shear strength within this zone varies from 3.4 kPa to 6.3 kPa with an average for all gravity cores of 4.8 KPa.

A comparison of undrained shear strength for the MPG-1 cores and data for some other marine clays published by Meyerhoff (17) is shown in Fig. 4 (18). Included are some data from remolded-reconsolidated samples. The normalized strength values for smectite plot below the proposed correlation line at high plasticity index whereas the illites plot above the line at low plasticity index. The anomalous point (point number 1 for the upper 3 meters) reflects the effects of apparent overconsolidation and almost constant shear strength mentioned earlier. Although there is some deviation from the correlation line proposed by Skempton and Bjerrum, the general trend remains the same.

The presence of apparent overconsolidation in the upper few meters is further illustrated in Fig. 5. The overconsolidation Ratio (OCR) is the ratio of the maximum preconsolidation stress determined from tests conducted on subsamples from gravity or box cores to the calculated overburden stress at the sample depth. The OCR is in excess of 10 at very shallow depth and does not approach unity (normally consolidated) until a depth of 4 to 6 meters is reached. This behavior is attributed to high interparticle bond forces and/or cementation which can develop in these highly flocculated, fine-grained sediments with a very slow rate of accumulation. The relatively invariant water content and shear strength of these surficial layers is the result of these effects since the normal process of consolidation due to increasing overburden stress is inhibited by the presence of intrinsic strength or bonds. The OCR for the deeper smectite layers is still slightly greater than unity (average value below 4 meters for LL-44, GPC-3 is 1.3). Within the accuracy of the sampling, experiments, and calculations it is concluded that the sediment column is normally consolidated.

The results of many permeability tests are summarized in Fig. 6. These tests were conducted in a special back-pressure apparatus with the capability of directly measuring rate of water flow with hydraulic gradients as low as 2.0 (6). Included are results of tests on other types of deep sea sediments which were conducted for comparative purposes. The wide range of void ratios produced in the experimental program allow for extrapolations to deeper zones and detailed analysis of permeability behavior. One interesting result is that, even though the in-situ void ratio changes drastically from less than 3.0 for the upper illites to greater than 5.0 for the lower smectites, the coefficient of permeability at in-situ void ratios is relatively constant at a value between 2×10^{-7} to 1×10^{-6} cm/sec with an average value of 5×10^{-7} cm/sec to a depth of 20 meters. Of all the sediments compared, the smectites and illites have lower coefficients of permeability and hence present a more efficient barrier to movement of radionuclides by mass transport within the interstitial water.

Isotropically consolidated undrained ($\overline{CIU}$) triaxial tests were conducted on "undisturbed" and reconstituted-reconsolidated specimens (remolded samples of the MPG-1 sediments). The Mohr-Coulomb parameters of effective cohesion ($\bar{c}$) and effective friction angle ($\bar{\phi}$) determined from these tests are listed in Table 1. Also listed are friction angles for similar sediments reported by other investigators. The undisturbed smectite series (LL-44 GPD-3 1800 cm) had a slightly higher friction angle than the two undistrubed illite series (MA-02 GC-04 100 and 200 cm). These values compare favorably with friction angles reported by H. J. Lee and E. L. Hamilton (19) from samples of pelagic clay (illite) and amorphous iron oxide (smectite) obtained from sites east of MPG-1. Silva and Clukey (20) report friction angles of 34 and 35.8 degrees for illite sediments from the central North Pacific.

Comparing friction angles of the undisturbed and remolded samples, the remolded illite samples exhibited a 30% reduction in friction angle due to the remolding-reconsolidation process used in the test program. The higher friction angles of the undisturbed samples can be attributed to differences in sediment structure and physio-chemical factors. It is generally accepted that undisturbed samples have an inherent structure which upon remolding is irreversibly lost. The friction angles of the smectite samples were apparently not significantly affected by the remolding process. Sensitivity measurements from miniature vane shear tests show similar changes of decreasing sensitivity with increasing smectite content. Thus, the strength properties of the illites appear to be influenced strongly by the degree of disturbance and remolding while the smectite sediment is apparently less sensitive to these processes.

Also presented in Table 1 are the average normalized undrained strengths for each sample series. This ratio, referred to in soil mechanics texts as the c/p ratio or the ratio of undrained strength to effective overburden pressure ($S_u/\bar{\sigma}_{vo}$), is a basic relationsip used to compare strengths of different materials or the same material under different physical conditions. The values of undrained shear strength calculated from the triaxial results have also been superimposed on the shear strength profile of LL-44, GPC-3 in Figure 2. The comparison with the vane shear strengths is excellent for the entire depth. These results show that the vane shear strengths are a very good indicator of undrained shear strength and that the large diameter Giant Piston Corer recovers high quality samples with little disturbance to sediment stress-strain properties.

In addition to triaxial strength tests, a study has been initiated to determine long term stress-strain properties - or creep behavior - of these sediments. A typical drained creep curve for an undisturbed illite sample maintained at a constant stress level equal to approximately 45% of its failure strength for 80 days is given in Fig. 7. These and other data show an initially high, but decreasing strain rate for the primary stage of creep (first 40 days) followed by a low and essentially constant strain rate (secondary stage) to the end of test. Other tests indicate that the material will fail in creep rupture at stress levels of about 60% of the strength determined with standard triaxial procedures. In general, the creep strains for these sediments are significantly higher than those reported for terrestrial soils. The data from the creep experiements is being utilized in computer modeling studies of hole closure behavior following penetration and possible canister migration caused by temperature gradients (8).

<u>Northern Bermuda Rise MPG-3</u>

The northern Bermuda Rise generic study area comprises those portions of the Rise between 32° to 36° N latitude and 56° to 64° W longitude which lie at least 200 miles distant from Bermuda (Fig. 8). The New England Seamount Chain cuts the northeastern corner of this area and the Sohm Abyssal Plain lies immediately to the east.

Deposits of hemi-pelagic clay cover most of the area to a thickness exceeding 1000 m (21) thereby effectively smoothing most basement topography (22, 23). These sediments are deposited primarily by bottom currents (24,25). The uppermost 200-300 m of these sediments are highly stratified in airgun and 3.5 kHz seismic profiles (22). These sediments have deposited at rates up to an average 40 cm/1000 years for the last 1.0-1.8 MY (22,24).

The acoustically stratified sediments are found in three large deposits (26) totaling an area of 2×10^5 km. These sediments are primarily illite-rich clays containing a variable calcium carbonate component which fluctuates between 5-37% (22,27).

As will be seen in this report, the barrier properties of the well-stratified sediments pose no major problems to the SDP. However, a geological analysis (26) of these sediments suggests that they are too strongly effected by bottom currents to guarantee the long-term integrity of a shallow repository located within them. This suggests that western North Atlantic hemi-pelagic clay environments should be downgraded in favor of simpler clay environments such as red clays or perhaps the fine-grained portions of abyssal plains.

A total of four Large-diameter (11.4) Piston Cores (a lighter version of the GPC) and sixteen Large-diameter Gravity Cores were taken on the plateau region of the northern Bermuda Rise. As discussed above, the current feeling is that this region is not a suitable study site for "shallow" burial because of geological considerations. Therefore we have not undertaken a detailed experimental program to determine the important parameters necessary to fully assess these sediments from the point of view of the barrier concept, and only general geotechnical information has been assembled to characterize the area. Water content and vane shear profiles for two piston cores taken in the acoustically laminated sediments are shown in Fig. 9. Both cores show very extreme variations in water content (and therefore density) which accounts for the presence of many subbottom acoustic reflectors on the 3.5 kHz records.

The dramatic increase in water content starting at about one meter depth is especially well defined in EN23, LPC-1 with a change from 85% to 200% occurring within a few centimeters. This zone of high water content has been observed in earlier cores 300 miles to the east (28) as well as in most cores taken on EN-24. There is another very well defined peak at 6.7 meters with a similar change from 100% to 190%. The peak in water content at shallow depth is also present in EN-24, LPC-3 but is interrupted by intermittent thin layers of low water content material. The variability shown by these thin lower water content sections could be the result of erosional events indicated by dating techniques mentioned earlier and concurrent changes in sediment type.

Except for a relatively high strength in the upper meter, the vane shear strength in the upper six meters of EN-23, LPC-1 is very low with an average value of about 2 kPa. This data also agrees very well with previously reported data (28). The shear strength within the same zone of EN-24, LPC-3 is somewhat higher at about 3 kPa, but still quite low, considering the depth of burial.

From a geotechnical property point of view, the laminated sediments of the northern Bermuda Rise appear to have many of the necessary qualifications for a study site - i.e., they are fine-grained clays with low permeability (29) and have low shear strength. However, even if the site were suitable from an overall geological perspective, there are some important remaining questions which would have to be studied. Some earlier work (28) indicates that the sediment column may not be completely consolidated due to present overburden conditions. This may be the result of a combination of low permeability, intermittent episodes of high accumulation rates, and the presence of an upper zone of "apparent" overconsolidation which tends to restrict the compaction process by providing a long drainage path to the sediment-water interface. Any remaining excess pore pressures in the sediment column due to underconsolidation would mean that water is migrating upward. Although this in itself does not mean there is a breach mechanism for transport of radionuclides to the surface, it certainly would have to be factored into the analyses of water migration.

Future Plans and Needs

Selection of a repository site will be based on data derived from geophysical and geotechnical surveys. In order to establish the geotechnical characteristics of such sites with confidence it will be necessary to recover samples of clay from horizons which are representative of the projected location of the waste canisters. However, it has been shown that these sites have a high degree of lateral uniformity, it is thus not necessary to do extensive coring in order to fulfill this geotechnical characterization requirement. Rather, the principal challenge is in achieving the required coring depth. A Long Coring Facility (LCF) is being developed for these purposes in a joint program between the University of Rhode Island and Sandia National Laboratories (30). This device is conceived as a 0.12 m inside diameter 50 m long piston coring system capable of recovering high-quality cores which will be used for laboratory geotechnical measurements. The performance characteristics of the LCF have been modeled mathematically, and the results of parameter studies using these models are reported by Karnes et al. (31). It is anticipated that the LCF will be fielded in 1983.

The environmental conditions existing in a subseabed nuclear waste repository are substantially different from those that would be employed in routine laboratory geotechnical measurements. Ambient pressure is on the order of 70 MPa at 6 km water depth, and temperatures of the sediment in the immediate vicinity of the canister will reach $473^{\circ}K$ several years after emplacement and then slowly decrease as the heat-producing radioisotopes in the waste decay (32).

This decay also effectively superposes a radiation field on the sediment near the canister. It is evident that a realistic simulation of these in-situ conditions for laboratory measurements of sediment shear strength, creep deformation characteristics and permeability is desirable in order to guarantee a complete understanding of how a nuclear waste canister will interact with the surrounding sediment. Efforts are currently underway to determine the geotechnical properties of the sediment under simulated repository conditions. Initially, pressure and temperature conditions will be simulated, and ultimately, radiation environments will be coupled with these. It is also anticipated that a number of in-situ field measurements of geotechnical properties will be employed to make direct comparisons with data obtained from these laboratory measurements. The in-situ measurements will include sophisticated versions of a vane shear apparatus, a dynamic soil penetrometer, an in-situ pore pressure measuring probe as well as a direct measurement of sediment bearing strength.

Accurate numerical modeling of the sediment requires material response descriptions over a wide range of loading conditions (8). Specialized laboratory techniques are being used to obtain such response descriptions. These techniques include dynamic triaxial and compressibility tests in which loading times are in the range of 5 to 10×10^{-3}s. Such data is required to support modeling of dynamic penetration of the canister into the sediment, where impact velocities could be as high as 100m/s. In addition, quasi-static measurements are underway to determine the failure characteristics of the sediment under triaxial extension and true triaxial loading conditions. Data from both types of tests are required to describe hole closure following dynamic penetration. Finally, investigations of the anisotropic properties of the sediment are also necessary to complete the description of the failure characteristics of this material.

ACKNOWLEDGEMENT

This work is supported by the U.S. Department of Energy, through Sandia National Laboratories under contract # 13-9927.

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TABLE I

Strength Properties of HPG-1 Sediments

	$\bar{c}$ kPa	$\bar{\phi}$ degrees	$q_{fu}/\bar{\sigma}_c$
Smectite			
LL-44 GPC-3, 1800 cm	1.6	35.5	0.437
PS-9 Vertical (Remolded)	1.1	37.3	0.440
PS-18 Vertical (Remolded)	0.9	36.3	0.468
Illite			
MA-02 GC-04 200 cm	0.0	34.8	0.374
MA-02 GC-04 100 cm	3.0	33.0	
PI-18 Vertical (Remolded)	9.9	30.4	0.449
PI-2 Vertical (Remolded)	1.3	24.6	0.362
Lee and Hamilton (1974)			
Illite (depth: upper 10 meters)	1.8-3.3	35.0-36.0	
Smectite (depth: upper 10 meters)	3.4-4.1	37.0-38.0	
Silva and Clukey (1975)			
Illite (depth: upper meter)			

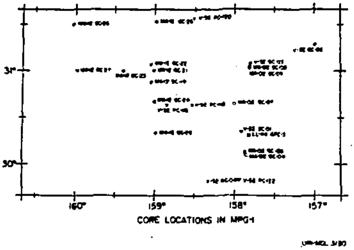

Figure 1. Locations of cores sampled for geotechnical testing in MPG-I Giant Piston Core (GPC); Standard Piston Cores (PC) and a Gravity Core (GC) were utilized. Core number and type is prefixed by a cruise designation number (i.e., V-32).

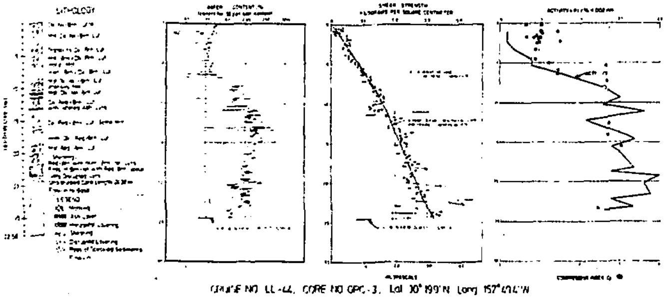

Figure 2.. Summary of geotechnical properties: LL-44, GPC. Note the agreement between vane shear strength data obtained shipboard with data calculated from laboratory triaxial tests. Additionally, observe the similar changes in water content, activity and compression with depth.

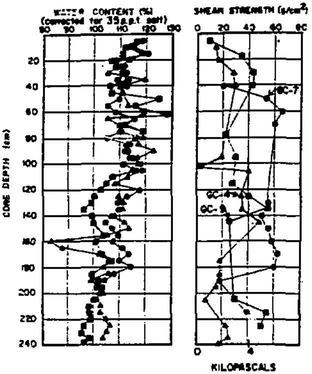

Figure 3. Water content and shear strength profiles for three gravity cores from MPG-1. These show consistent qualitative properties over a fairly wide area. See Figure 1.

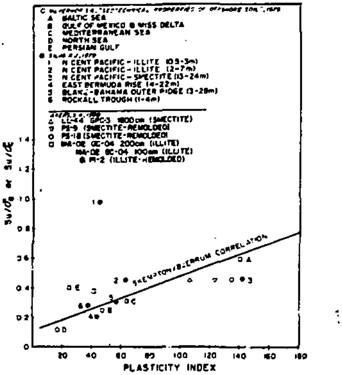

Figure 4. A comparison of normalized strength data versus plasticity index of various marine clays with a correlation developed by Skempton and Bjerrum. With the exception of one set surficial sediments in MPG-1, good agreement exists.

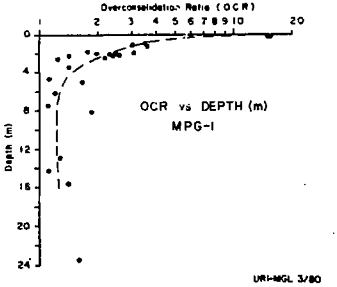

Figure 5. Over-consolidation ratio versus depth, MPG-1. This semi-log plot indicates that surficial sediments probably have high interparticle forces which are overcome by overburden stresses.

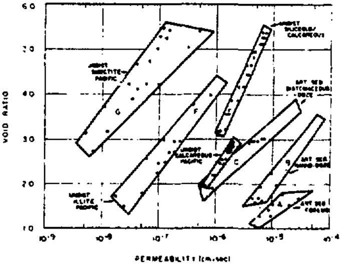

Figure 6. Comparison of permeability versus void ratio for various deep-sea clays. Groups F & G are results from samples obtained in MPG-1.

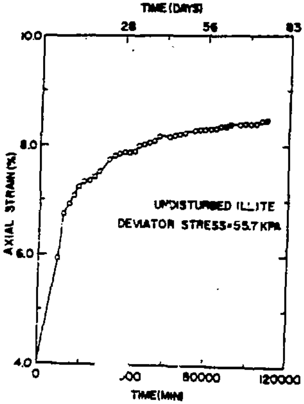

Figure 7. Typical plot of time versus axial strain for a drained creep test performed on a sample from MPG-1. This sample was isotropically consolidated and then strained for 80 days at a constant stress level of 45%.

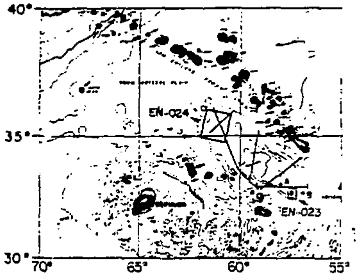

Figure 8. Locations of MPG-1 study areas on the Northern Bermuda Rise. Piston cores, gravity cores and acoustic profiling transects have been conducted in detail in these areas.

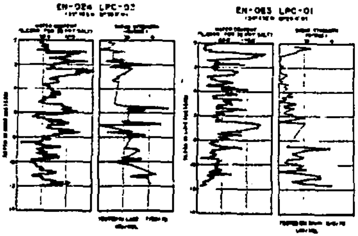

Figure 9. Water content and vane shear strength profiles, Northern Bermuda Rise. The many dramatic changes in these values correlate well with the laminated character of the 3.5 kHz acoustic record.