Geotechnical Properties of Northern Bering Sea Sediment

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Abstract

The physical properties of sediments taken from the northern Bering Sea (Norton Sound area) have been determined in order to evaluate their impact on recently identified possible geologic hazards in the area. Standard identification tests (water content, Atterberg limits, grain size, specific gravity and density) as well as shear strength and compressional testing were conducterd either on board the ship or in the laboratory.

The greatest thickness of Holocene seiment occurs in Norton Sound and is located in the Yukon prodelta region. This sediment is predominantly sand-silt that appears to be highly overconsolidated. The observed overconsolidation, in view of the shallow water depths throughout the region, appears to be related to storm wave surges that severely affect the bottom.

Indications of gas-charged sediment have been found in several areas of Norton Sound. Gas-charged sediment has been responsible for failures of structures in other resource development areas and generally will tend to reduce the strength characteristics of the sediment, as a result of generation of high excess pore pressures. The overall stability of the bottom sediment could be seriously affected, particularly if excess pore pressures are generated by storm wave activity in regions of gas-charged sediment. Because of the difficulty experienced with sampling intact gas-charged sediments, in-place testing equipment is considered necessary for future work to more accurately assess the impact and extent of the gas charging.

Several cores that were taken for this study penetrated into peaty muds. The overall extent of the peaty muds and stability characteristics are not well known at this time, but should be assessed in future work with coring devices capable of greater penetration depths

Introduction

Nearsurface (<2 m) sediment from the northen Bering Sea (Fig. 1) has been investigated to determine their physical properties and geotechnical characteristics. This is part of a broader based Outer Continental Shelf Environmental Assessment Program (OCSEAP) evaluating possible geologic hazards to resource development in the area.

Widespread surface craters or pockmarks (Lewis and MacLean, 1970) indicating possible unstable gas-charged sediment are among the hazards to resource development recently identified in the study region (Nelson and Thor, 1977, Fig. 2). Acoustical anomalies from high-resolution geophysical records indicate that gas-charged sediment may be even more extensive than crater areas suggest on side-scan records. The identification of a possible thermogenic seep over a large subsurface gas accumulation south of Nome may also lead to the development of unstable potentially hazardous sediments in the area (Nelson, Kvenvolden, Clukey, in press).

Widespread active sand wave fields caused by intermittent periods of extreme storm wave loading and strong bottom currents have been identified in northeastern-southwestern Chirikov Basin (Nelson et al., 1977, Field et al., 1977). In view of the relatively shallow water depths throughout much of Norton Sound, extreme storm wave loads could cause serious problems to the bottom stability of any pipelines or gravity-seated platform installations in the region.

Grain-size analyses of the sediment from the Norton Basin indicate that it may be of the type that is highly susceptible to liquefaction potential (Fig. 4). The potential for sediment liquefaction is probably greater in the

Yukon prodelta region than in other regions, because of the thick recent deposits of coarse silt to very fine sand sizes.

The northern Bering Sea is a frontier basin for petroleum development. Consequently very little information is available on the physical properties and geotechnical characteristics of the sediments in this region. The primary objectives of this study have been to establish baseline information regarding the different types and properties of sediments in the Norton Sound region so that sediment behavior and response to the potential hazards can be assessed. Another aspect of the study has been to try to relate stratigraphic differences with corresponding changes in water content, density, plasticity, shear strength, grain size and penetration rate at different locations. Differences between recently deposited sediments and those deposited in a pre-transgressive freshwater environment were of particular interest, as they related to gas-charged sediments.

A significant part of the study addresses the coring and sub-sampling techiques used. Because of the sediment types in Norton Sound, a vibratory coring device was used to achieve 2-meter penetration. The effects of vibracoring on the physical property measurements were assessed whenever possible.

Methods of sampling and geotechnical measurements

Shipboard sampling

Sub-samples tested for this study were taken aboard the USGS R/V Sea Sounder during the early fall, 1976. The sediment samples used were a box core, Kiel vibracorer and Van Veen grab sampler. The location and station number for each sample is shown in Figure 3 . High-resolution (3.5kHz, EG&G uniboom and 90 kJ sparker) seismic records and side-scan sonar records were also obtained throughout the course of the cruise. Core lithology, radiography, sediment water content and shear strength measurements were made while on board ship.

The box corer was capable of obtaining samples, 8 inches by 12 inches in section, up to 13 inches in depth. Due to the excellent area and length ratios (and from previous experience) high quality samples were expected. A total of twenty-four box cores of varying depths was obtained.

The Soutar-Van Veen is a highly modified Van Veen grab sampler constructed by Andy Soutar of Scripps Institution of Oceanography for UCLA. The clamshell grab is driven into the sediment by a 400 lb. load, guided by vertical rails in a frame. The samples usually represented the top 12 inches of sediment. The top half was generally of good quality when there was complete closure of the clamshell halves. Samples were obtained on nearly every attempt for a total of thirty-two Soutar-Van Veen samples.

The Kiel vibracorer is a vibratory coring device utilizing a pair of counter-rotating electrically driven eccentric masses in a vibrating head. The motors, eccentric masses, and a hammer are suspended by springs on a pair of vertical rods. On each downstroke the hammer impacts an anvil at the bottom of the vibrating head driving an attached core barrel into the

sediment. The vibrating head and core barrel are guided by a frame with vertical rails. A winch extracts the sample after penetration. During sampling, performance is monitored with respect to penetration and the inclination of the sampler in the sea floor. A chart recorder was used to record depth of penetration vs. time.

The standard core barrel is a one-eighth-inch steel box by 10 cm square and 2 m in length. To improve handling and the area ratio, an adpator head was constructed for a 4.5 inches (11.43 cm) o.d. fiberglass barrel with a wall thickness of 0.125 inches (.32 cm). While the quality of sample from the Kiel vibracorer was expected to be lower than that from the box corer, particularly in non-cohesive sediment, the depth of sample taken was significantly greater. Twenty vibracore samples were obtained, mostly with fiberglass barrels.

Sub-samples were removed from each type of sediment and stored for later testing. Bulk sub-samples were obtained for determination of grain-size distribution and Atterberg limits in cohesive samples, and for grain size and direct shear in non-cohesive samples. The bulk sub-samples were sealed in plastic bags or plastic vials and stored in the ship's cooler. The bulk sub-samples were taken in each major stratigraphic horizon, at the top and bottom of homogeneous vibracores, and from the top of Soutar-Van Veen grabs. Sub-samples of known volume (approximately 100 cc) were taken and extruded into glass jars, and sealed for later determination of water content, bulk density, and specific gravity. In addition to these samples, at selected sites in cohesive box cores and Van Veen grabs, a piston sub-sampler was used to obtain 1.69 inch (4.29 cm) diameter by five-inch (12.7 cm) long undisturbed samples for uniaxial unconfined compression testing. A few 3.16 (8.03 cm) diameter sub-cores were also taken for later consolidation testing. Each triaxial or consolidation sample was capped, sealed with tape and wax, and stored upright in the ship's refrigerator.

Immediately after removal from the ship's refrigrator, water content samples were weighed to determine their wet weight. The samples and jars were dried (approximately 24 hours) and weighed. The jars were then cleaned, dried and weighed so that the water contents (salt corrected) and bulk densities (at 100% saturation) for the known volume samples could then be calculated (.1% accuracy).

According to Boyce (1975):

$$\text{Water Content} = \omega_c = \frac{\text{weight of fluid phase}}{\text{weight of solids}} = \frac{W_{\text{sea water}}}{W_{\text{solids}}}$$

or

$$\omega_c = \frac{\gamma_{sw}\,(W_{wet} - W_{dry})}{C_{sw}W_{dry} - C_{sw}W_{wet}}$$

where C_{sw} is the salt concentration of the interstial sea water, W_{dry} is the weight of the dry solids, W_{wet} is the weight of the wet sample and γ_{sw} is the unit weight of sea water corrected for salinity and temperature and

$$\text{Bulk Density} = \gamma_T = \frac{[V_T - (W_{dry} - C_{sw}W)/G]\gamma_{sw} + [W_{dry} - C_{sw}(W_w)]}{V_t}$$

where V_t is the total volume of the sample, W_w is the weight of the water evaporated from the sample, G is the specific gravity of the solid particles and the remaining symbols are the same as above. The measured bulk density (<100% saturated) of the known volume sub-samples was also determined by:

$$\gamma_T = W_{wet}/V_T$$

The salt concentration for each sample was interpolated from the closest bottom reading (approximately 4 m off bottom) taken on the R/V DISCOVERER, Cruise RP4-DI-76B-V, September 1976.

After the water contents had been calculated, all the samples were classified according to their appearance and texture in order to evaluate the

relative quality of the water content value. This classification system was used to approximate the liklihood of pore water removal, either by drainage or evaporation prior to subsampling. The categories used for the classification system were as follows:

Water Content Quality Designation

1. Poor quality sample, clean coarse sand, completely fractured.
2. Fair to poor quality, mostly sand, some cohesiveness evident, parts intact.
3. Fair quality, predominantly silty, percentage fractured.
4. Good quality, highly cohesive, silty, small percentage fractured.
5. Excellent quality sample, cohesive, clayey silt or silty clay, sample intact.

The samples classified as either 4 or 5 were then used for additional bulk density determinations by adjusting their water contents to 100% saturation (based on the average degree of saturation determined from the known volume samples, 4 or 5 classification) and inserting the adjusted water content into:

$$\gamma_T = \frac{(1 + \omega_c)\gamma_{sw}}{\omega_c + \gamma/G}$$

where ω_c is the adjusted water content value and G is the specific gravity.

The average degree of saturation for samples classified as either 4 or 5 was greater than 90%. A specific gravity value of 2.68 was used in each bulk density determination.

Actual specific gravity measurements were made on samples with an air pycnometer device. The specific volume of the solid particles was determined to .01 cc accuracy.

Atterberg limit tests were performed on samples taken at various locations. The samples for these tests came from the bulk sample bags taken aboard ship immediately after coring. Although some sample drying probably did occur prior to testing, the samples were considered to be significantly "wet" prior to the start of each test. In some instances water was added to the sample in order to obtain the appropriate value (low blow count) for the liquid limit test. Liquid limit and plastic limit tests were performed respectively as specified in ASTM D 423-66 and ASTM D424-59. None of the sediment tested contained particles coarser than 0.425 mm (No. 40 sieve) with the exception of occasional shell fragments which were removed by hand. An average of three tests was taken as the plastic limit value for each sample.

Grain size distributions were determined using three methods for different size fractions. Wet sieve splits were made at 1 mm (no. 18) and at 0.0625 mm (No. 230). The coarse fraction was sieved. A rapid sediment analyzer was used for the intermediate fraction, 1 mm to 0.0625 mm, and the mud fraction was run in a hydrophotometer giving values down to 0.0039 mm and a clay percentage finer than .0039 mm.

Shear Strength Testing Procedures

Immediately after coring, hand vane shear tests were performed onboard ship with 19 mm (.75 in) and 33 mm (1.30 in) hand vane or torvane shear devices. The torvane device (0-.2 TSF, .218 kg/cm^2 capacity) was used to determine the surficial shear strengths of the sediments. The 33 mm hand vane shear device (28 KPa, .286 kg/cm^2 capacity) was used in the softer sediments, while the 19 mm (122 KPa, 1.244 kg/cm^2) was generally used in the stiffer sediments.

Vane shear tests were conducted only on cores that appeared to exhibit at least some plasticity, i.e., not clean sand. Tests were performed at the surface and at 5 cm intervals, in both the box cores and Soutar-Van Veens and at 10-15 intervals along the vibracores. The testing intervals were usually closer in the top half of the vibracore and varied according to visual changes in sediment lithology with depth. Where stratigraphic differences were apparent readings were taken on both sides of the contact surface. Remolded as well as undisturbed tests were performed in most instances at each test location.

Hand vane tests were not performed on samples that appeared to be predominantly sandy. Since the vane test is used to get an indication of the undrained shear strength properties, tests performed on sandy sediments, where particle interlocking and grain to grain contact are significant, are not reliable.

In addition to the shipboard hand vane tests, laboratory vane (LV), unconfined compression (UC) and direct shear (DS) tests were conducted to determine sediment shear strength properties. The LV and UC tests were performed on undisturbed samples taken in 1.7" (4.32 cm) diameter plastic tubes onboard the ship immediately after coring. The DS tests were performed on remolded wet samples carefully placed into the 2.5 " (6.35 cm) diameter x 2.0" (5.08 cm) length testing ring prior to shear. The wet sediment was lightly tamped and distributed as evenly as possible as it was placed into the testing ring.

A standard 1/2" (1.27 cm) laboratory vane and a shear rate of 10°/min (motorized unit) were used to perform the LV tests. Remolded as well as undisturbed tests were made for each test. If the sample appeared to be pre-

dominantly coarse grained with little plasticity, the LV test was not performed. As previously discussed, vane shear tests on samples of this type will not give an accurate indication of the undrained shear strength characteristics of the sediment.

After the LV test was completed, that portion of the sample which had been disturbed by the vane rotation (approximately 1x2.54 cm) was extruded and trimmed off for use as a water content sample. The rest of the sample was then extruded and used in the UC test. The length and diameter (top and bottom) of the sample were measured prior to testing. A length to diameter ratio of between 1-1/2 to 3 was used in all the tests (average $^{L}/D = 2.40$). The shear rate varied between 0.5 in/min and .16 in/min, depending on type of sample being tested. For example, higher shear rates were used with coarse grained sediment to more closely approximate undrained shear conditons. Tests were carried out to 15 to 20% strain. Subsequent to testing the samples were weighed and than dried in the laboratory oven for water content and bulk density determinations.

The DS tests were undertaken to determine the drained or effective strength characteristics of the sediment. After placement into the testing ring the normal load was applied hydraulically to the sample with a piston-diaphragm pressure system. The vertical deflection of the sample (.001 in, .0025 cm accuracy) was recorded both prior and during shear. The sample was sheared at a rate considered sufficient to allow total dissipation of pore pressures during shear (approx. .02 in/min). The samples were sheared until a definitive peak shear strength was developed or until the sample had reached 20% strain. If more than one test was performed on a sample, the bottom half of the shear ring was then manually pushed back, in the opposite direction to shear until it was approximately realigned with the top half of the shear

ring; the normal load on the sample was then increased and the test procedure repeated again. The samples were then removed from the shear box and weighed.

Sediment Compressibility Tests

A one-dimensional consolidation test was performed on a sample taken from box core 154 at 8-13 cms. The consolidation test was non back-pressured incrementally loaded with two-way drainage. Sea water was used as the surrounding pore fluid throughout the course of the test. The sample loading increment utilized throughout the course of the test was 1.0 with an initial load of 220 gms (6.94 gms/cm^2 stress) applied onto the sample (11 to 1 loading ratio). Initially the sample height was .75 in (1.90 cm) while the diameter was 2.5 in (6.35 cm). The vertical deflection of the sample was measured to .0001 in accuracy with a laboratory dial gauge. Dial gauge readings vs time were taken for all but the first two loading increments where the degree of compression was relatively small. The sample was unloaded incrementally in reverse order to the loading sequence (maximum stress = 889.19 gms/cm^2).

Extrusion of the sample from the sampling ring (3.16 in, 8.03 cm) was accomplished by extruding and simultaneously trimming the sample into the testing ring. Some difficuly was experienced with this procedure and either direct extrusion or a more sophisticated trimming device is recommended for future tests.

Geologic Background

Sedimentary History

In the late Pleistocene time of lowered sea level the eastern portion of the northern Bering Sea, including Norton Sound, was exposed. About 12,000 B.P. Sphanberg Strait was flooded by the sea level transgression allowing Yukon River fine sand and silt to be deposited (Nelson and Creager, 1977). By

about 5000 B.P. Norton Sound had been filled. The Yukon subdelta moved northward to its present location about 5000 B.P. or later. Isopachs of Holocene sediment deposited in Norton Sound since the transgression show maximum deposition has occurred northward of the present delta.

The Yukon presently carries over 90 million tons of sediment into the Bering Sea each year. Currents carry much of the sediment into the Chukchi Sea (Nelson and Creager, 1977). Areas with low current velocities in the southern and eastern Norton Sound have thicker deposits of recent sediment with grain size distributions representative of the Yukon River load. As current velocity increases, the thickness and fineness of the sediment decreases. The thin layer of recent sediment near the center of Norton Sound may be caused in part by sediment resuspension and transport resulting from storm surge and waves.

Sediment Lithology

The Holocene prodelta sediment are fine sands and silts with a small percentage of clay. The Yukon sediment typically contains a percentage of fine wood fragments and other organics. The organic carbon content in surface sediment is about 1% and decreases away from the modern subdelta. Several cores penetrated through the modern Yukon sediment into the pre-transgressive sediment (Figs. 6-13). This sediment was deposited in a fresh water environment and is typified by a finer grain size, high organic content (3 to 8% organic carbon as shown in core logs) and high gas content .

Quantitative analyses of clay mineral types within the clay fraction of surface sediment show that modern Yukon sediment contains about 40% kaolinite-chlorite and illite and about 20% montmorillonite (Fig. 5). A few analyses of pre-transgressive sediment show higher amounts of montmorillonite.

Vibracore Stratigraphy

Vibracores 70B, 72A and 103 (Figs. 6,7, and 8) are from an area of sand ridges and mud troughs off Port Clarence. The ridges are covered by sand waves and are being reworked by currents. Thin deposits of modern mud blanket troughs and ridge flanks. Beneath modern mud pre-transgressive organic-rich mud is penetrated (see vibracore 70, Fig. 6). While vibracore 72A came from a trough, the core is jumbled, possibly resulting from flow-in upon extraction. A high organic carbon content was found at the base suggesting pretransgressive freshwater peaty mud.

Vibracores 121B3 through 137B (Figs. 9 to 13) were taken in Norton Sound. Vibracore 121B3 and 131C, penetrated the modern Yukon sediment into freshwater peats, while 125E, 133B, and 137 apparently did not. The modern sediment is silts with decreasing amounts of sand and increasing amounts of clay near the eastern end of Norton Sound.

Sediment Index Properties

Specific Gravity

The specific gravity of particles was determined for a representative group of sub-samples used for water contents. The results are presented in Table 1. The values of specific gravity fell within a reasonable range (2.67 to 2.72) with the exception of the vibracore 101 sub-sample at 90 cm which had a value of 2.55. This low value can be attributed to the high organic content of the pre-transgressive sediment.

Atterberg Limits

The results from the Atterberg limit tests are tabulated in Table 2 and are shown on the plasicity chart from the standardized soils classification system (per ATM D 2487-69) in Figure 14.

Most of the Atterberg limit samples tested, with the exception of those from vibracore 133 and one sample from vibracore 40C had liquid limits less

than 50, and plasticity indices less than 20 (Table 2, Fig. 14) and would be classified as low plasticity silt (ML) or low plasticity silty clay. The very low percentages of clay (Fig. 4) would tend to favor the ML classification for these sediments. Two samples (169, 0-2 cm, and 141, 0-4 cm) plotted slightly above the A-line (Fig. 14) suggesting a classification of clays with low plasticity (CL). Both these samples however, with only slight variatons in either the liquid or plastic limits, could also be classified as ML type sediments. The sample tested from vibracore 40C (Table 2) plots just slightly below the A-line and would be classified as a high plasticity silt (MH) or as organic clay or silt-clay of medium to high plasticity (OH). Grain size analysis on this sample indicates that a significant porton of this sample is coarser than .075 mm which would favor an MH classification.

For many of these samples with either an ML or MH classification, a very large percentage of the sample fell between the sand-silt particle size break (approx. .040-.080 mm). This allowed samples that contained significant amounts of sand to exhibit plastic characteristics and therefore fit silty or clayey silt classifications.

Four of the Atterberg limit tests were performed on samples from box core 133. All these samples plotted either on or slightly above the A-line. Natural water contents for the upper three samples were all slightly greater than the corresponding liquid limit. This trend is considered typical of marine sediments with significant amounts of clay and has been reported previously by other investigators (Silva et al., 1976, Noorany, 1971). The average liquidity index (I_L) for the samples of core 133 was determined to be 1.12; this is a measure of the closenes of the in situ water content to the liquid limit. Grain-size analysis performed on these samples at 5 cm and 70 cm indicate that the clay percentage within the top meter of sediment is

probably in excess of 50% (Fig. 12). This unusually high clay content and corresponding sediment plasticity can be attributed to low velocity currents transporting very fine Yukon silts in the very sluggish counterclockwise gyre of easternmost Norton Sound.

Water Content and Bulk Density

The water content and bulk density results for the known volume water content-bulk density determinations (Table 3) exhibited widespread differences in their calculated degree of saturation values. However, the average degree of saturation for those samples categorized as either 4 or 5 (water content quality designation) was 93.4 and 97.8% respectively, indicating a relatively small loss in water content prior to sub-sampling and therefore high quality water content-bulk density determinations. Based on this, the water content-bulk density values for all the samples with either 4 or 5 water quality designatons were corrected to 100% saturation (Table 4).

The water content values generally tend to decrease with depth down to approximately .25 to .50 m and then are often constant or will occasionally increase with increasing overburden (Figs. 9 to 13). Abrupt jogs or changes in the slope of the water content profile often corresponded to changes in the sediment lithology, although such trends are also evident in some of the more homogenous material. The highest water contents (low bulk densities) were in easternmost Norton Sound (see Figs.9 to 13, and Table 4) where the highest clay percentages were found. The highest individual corrected water content corresponded to a surface sample from the Soutar Van Veen at station 137.

Unfortunately, vibrations created by the EG&G uniboom housed under the ship's sediment lab may have created pore water redistributions within the sediment prior to sub-sampling. The effects of these vibrations are difficult to assess and may have been partially responsible for some of the water

content variations present in Figures 9 to 13. Such vibrations should be eliminated by placing hard rubber pads along the core barrel in future testing procedures.

Shear Strength

Vane Shear Results

There is good agreement between the box core and vibracore vane shear tests from station 121B3 (Fig. 9) with a continuous increase in shear strength present to 25 cm. The higher value for the LV (18.7 kPa, .191 kg/cm^2) obtained at 2 cm is attributable to a loss in water content between sub-sampling and testing. The UC tests performed on the same sample were more in accord with both the shipboard vibracore and box core vane shear tests. A dramatic shift in sediment shear strength for this core is apparent at approximately 80-85 cm, where the undrained shear strength values increase from 31 kPa (.316 kg/cm^2) to 77 kPa (.785 kg/cm^2). The depth of this increase coincides with a change in sediment lithology from a sandy silt to a stiffer clayey silt. An earlier penetration record also indicates that a previous vibracore stopped at approximately the same depth as the corresponding increase in shear strength.

Because the box cores or Soutar Van Veens taken at stations 125, 131, and 137 did not penetrate to significant depths, comparisons with the vibracore vane shear results are limited, although there is at least one test at both stations 131 and 137 (Figs. 11 and 13) which would indicate that the vibracore vane shear results are partially disturbed. A reduction in the vane shear strengths for vibracore 131 at approximately 80-100 cm corresponds to a very dramatic increase in the vibracore penetraton rate and a change to soft clayey silt in the sediment stratigraphy.

The vane shear results from station 133 provide the most detailed information on the relative disturbance effects vibracoring has upon the sediment

shear strength properties. A comparison of vibracore and box core vane shear results at station 133 (Fig. 12) suggests that the vibracore shear strength value may be significantly reduced as a result of sample disturbance. The box core results show a somewhat linear increase with depth down to 50 cm where the measured shear strength value is approximately 19 kPa. The vibracore results conversely indicate a constant shear strength (approximately equal to 7 kPa, .071 kg/cm^2) down to 60 cm and then a linear increase with depth. A value of 19 kPa (.194 kg/cm^2) was not reached until a depth of greater than 1 m. The larger clay percentage (Fig. 12) may have been responsible for the apparent disturbance evident in vibracore 133B. Other investigators (Kautsoftas et al., 1976) have also found that undrained shear tests on silty clays taken with another type of vibracorer underestimated the undrained shear strength by a factor of two and severely affected the results of consolidation tests. Although more silty sediment as evidenced by the test results from station 121B3 may not be as severely affected, additional cores are considered necessary to accurately predict the amount of distrubance.

Direct Shear Results

Direct shear tests have been performed on two remolded samples to assess the drained or effective shear strength parameters of the sediment in addition to the undrained shear strenght The effective strength envelopes for these tests are shown on Figures 15A-15B. The samples tested from Box Core 150 (0-3 cm) were predominantly sands (80%) and while no grain size analysis is available from station 147, visual inspection of the sample tested suggests that it is more fine-grained. The effects of remolding on more fine-grained sediment and the presence of some small shell fragments (most were removed by hand prior to testing) are considered to be the major factors for the differences in friction angles ϕ, observed between the two samples tested in Box

Core 147. The two samples tested from Box Core 150 are in much better accord with four of the five tests establishing an effective strength envelope of 38.4°. There is a slight downward curvature of the strength envelope at higher normal stresses, which is considered typical of sandy type samples (Lambe and Whitman, 1969).

Although a peak shear strength followed by a slight strength reduction to a residual value was observed in five of the direct shear tests, the void ratio of the samples in each test decreased steadily during shear. This indicates that even at higher normal stresses the samples were in a state above the "critical void rato," (Castro, 1956). In view of the very high percentages of fine-grained sands and coarse silts in many of the cores, samples above the critical void ratio would be considered highly susceptible to possible strength reduction resulting from liquefaction after seismic or wave induced loading. Determination of the sedimentary in-place density at depth will be necessary to properly evaluate the liquefaction potential of the sediments.

Vibracore Penetration Results

The depth vs. time chart records from the Kiel vibracore were differentiated to get penetration rate vs. depth plots. The chart recorder used had many functional problems and in several cases poor records or no records were obtained. The results are presented with the core logs (Figs. 6 to 13). Once the sampling frame reached bottom and the cable tension relaxed, a small amount of immediate penetration occurred due to the weight of the vibrating head. The vibrator was started and the core penetrated until a thermal sensor in the vibrating head automatically stopped vibration. Cycles of cooling and vibration were made until the core was full or no further penetration was accomplished. The maximum amount of penetration and the amount of recovery

are shown on the penetration rate graphs. Often in clean sand either a portion of the core or the total core would flow out when the vibracore was brought on deck.

In clean sand the vibracore penetrated rapidly to between 25 cm and 75 cm and then continue at a steady rate of about .5 m/min. Where more than one attempt was made at a station as at station 70, the penetration rates seemed to have good agreement. Peaty mud layers seem to cause an oscillation and decrease in penetration rate.

In the cohesive sediments in Norton Sound (vibracores 121B3 to 137; Figs. 9 to 13) the fiberglass barrels were unable to penetrate some sediment. The metal box barrels usually penetrated to full depth with numerous vibrating cycles required. Measurements in the metal box vibracores indicate the fiberglass barrels stopped when the shear strength exceeded about 30 kPa. The material properties of the fiberglass barrels appear to dissipate the vibrational energy in cohesive sediments, thereby reducing the effective penetration of the corer. In sands however, the vibrations apparently liquefied the sediments along the barrel, thereby reducing the amount of skin friction and increasing the total penetration.

The general variations in the penetration rates correlated with changes in sediment types and strengths. Too little information however, is available at this time to quantitatively correlate actual shear strength values with penetration rates.

Consolidation

The consolidation test results (Fig. 16) from the test performed on box core sample 154 at 8-13 cm, suggest that the surficial sediment in this area is highly overconsolidated (OCR = 9.11). About 8 m of recent Yukon sediments have been accumulated in the inner prodelta area during the past 10,000 years

which tends to eliminate large-scale removal of sediment by erosion as the primary cause for the observed overconsolidation. Nelson and Creager, 1977 have suggested that intermittent storm activity is responsible for sediment resuspension of as much as 40% of the sediment in the area. Bottom wave induced storm loading is therefore considered to be a primary contributing factor to the observed overconsolidation. Cementation also could affect the nearsurface freshwater sediment and may be partially responsible for the overconsolidation. Additional studies are necessary in order to more properly assess both the effects of storm loading and cementaton on these overconsolidated sediment.

The coefficients of consolidation c_v for the test were determined by the square root of time curve fitting technique (Taylor, 1948). Because the first three points on the square root of time vs. void ratio plots were generally non-linear, some amount of interpretation was required in order to determine c_v. Consequently the calculated average value of c_v may have been slightly lower than the actual values. A high speed recorder capable of recording the compression in the first few seconds after each loading increment is recommended for future consolidation tests on very silty samples. Both the average coefficient of consolidation (c_v) and coefficient of permeability (k) were typically in the range of values found for silty type sediments (Lambe and Williams, 1969). The corrected compression index (C_c) whch is a measure of the rate at which the sediment will consolidate with increasing stress overburden was low (.153) and also typical of silty, coarser-grained sediments.

Conclusions

The sediment index properties were found to vary appreciably in the upper few meters of sediment for different locations in the Northern Bering Sea.

Water contents were higher (lower bulk densities) for the clayey silt in eastern Norton Sound; values typically were greater than 70% in the upper 1 m whereas values on the prodelta sandy silt typically were 30 to 60%. Atterberg limits showed highly plastic clay in eastern Norton Sound while samples taken from the Yukon prodelta or central and western Norton Sound areas exhibited no plasticity or were low plasticity silts. The specific gravity of the sediment did not vary appreciably except in one instance (2.55) for a freshwater sample with a high organic carbon content.

The undrained shear strengths (S_u) were generally found to increase with depth although in several cases the increase was not significant through the first meter of sediment. Below the first meter a dramatic increase in the undrained shear strengths (over a relatively short distance) was often observed. This increase is clearly evident in vibracores 121B3 and 131C where the undrained shear strength shifted from approximately equal to 10 - 15 kPa to over 30 kPa at the interface between recently deposited Holocene sediment and the underlying, pre-transgressive freshwater mud. In many instances, changes in the vibracore penetration records corresponded well with changes in core stratigraphy and undrained shear strength values. Numerous vibrates were necessary in order to penetrate pretransgressive sediments in Vibracore 121B3 while a significant shift in slope of the penetration rate vs depth can be observed in 131C.

Direct shear tests of remolded sands produced an effective friction angle of 38.4^{o} while tests on remolded Yukon silt were not as consistent and may have been partially influenced by drainage problems with the testing equipment. A consolidation test performed on a sample from the Yukon prodelta area indicated a significant amount of overconsolidation (OCR=9.11). This is believed to be related to storm wave activity which is particularly influ-

ential in the study region in view of the relatively shallow water depths (typically <25 m) in Norton sound. The densification of the sediment by storm waves may actually make them less susceptible to liquefaction from any subsequent seismic activity. This would be equivalent in seismic engineering to stabilizaton of a sedimentary deposit by a prior earthquake or series of earthquakes.

The presence of gas-charged sediment within the region could make the nearsurface sediment potentially unstable and present a serious problem to bottom pipeline or gravity structure installations. A gas seep occurs in northwest Norton Sound surrounded by possible thermogenic gas-charged sediment (Cline and Holmes, 1977 and Nelson, et al., 1978); a thin layer of recent Holocene sediment overlies biogenic gas-charged freshwater peaty mud in east central Norton Sound (Nelson and Thor, 1977). Relative geotechnical differences between gas-chargedand non gas-charged areas were difficult to determine because of the lack of cohesiveness and resulting dissipation of gases during coring and sampling of much of the sediment. Relative penetrability appears to be significantly greater in gas-charged sediment (Nelson et al., 1978) and tests will be used in future work to assess differences in bottom penetration at various sites throughout Norton Sound.

The cores that were taken with the vibracorer undoubtedly underwent some disturbance during sampling. The amount or degree of disturbance is believed to be related to the sensitivity of the sediment sampled. Silty type sediment taken with the vibracorer exhibited less reduction in undrained shear strength values (as compared with box core samples) than more sensitive clay-type sediment. Because of the difficulty of penetrating most of the sediment with either gravity or piston core devices and the disturbance effects inflicted by vibracoring, the use of in-situ penetrometer devices is recommended in future work.

Acknowledgments

We thank James Hein for completing clay mineral analyses and Jeff Patry and Ronald Williams for assisting with geotechnical and textural analyses. Devin Thor, Jeff Patry and Ronald Williams assisted with figure compilation and drafting.

We appreciate the considerable efforts of officers and scientific staff of the R.V. Sea Sounder in helping with the collection of data at sea.

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TABLE 1

SPECIFIC GRAVITY SEA-76-BS

Sample Designation	Depth (cm)	Specific Gravity	% Organic* Carbon
SUTR 47B	surface	2.69	0.91
VIBR 94C	40	2.71	0.66
VIBR 101	60	2.55	5.27
VIBR 102	25	2.70	0.37
VIBR 102	70	2.67	0.37
VIBR 102	138	2.70	0.96
VIBR 133	39	2.70	0.96
VIBR 133	36	2.73	0.96

*Taken from closest sample location

TABLE 2

ATTERBERG LIMITS SEA5-76-BS

Sample Designation	Depth (cm)	Liquid Limit	Plastic Limit W_p	Plasticity Index I_p
SUTR 40C	surface	53	31	22
BOX 121	18-22	40	26	14
SUTR 125	0-5	25	17	8
BOX 133	0-5	76	29	47
BOX 133	13-17	68	35	33
BOX 133	22-24	71	29	42
BOX 133	35-40	71	30	41
BOX 141	0-4	42	24	18
BOX 141	15-18	41	30	11
BOX 145	16-19	33	27	6
BOX 147	2-9	29	25	4
BOX 152	0-4	27	23	4
BOX 154	0-3	44	30	14
BOX 154	26-29	40	33	7
BOX 161	surface	41	31	10

TABLE 3

Sample Designation	Depth (cm)	Water Cont.% Salt Corr. (weighed)	Water Cont.% Salt Corr. (calculated)	Bulk Density (weighed) gm/cm^2	Bulk Density (calculated) gm/cm^2	Water Cont. Qual. Des.	% Sat.
VIBR 94	40	12.4	30.7	1.67	1.94	1	40.3
	140	24.1	33.4	1.78	1.91	1	72.2
	168	28.4	29.1	1.95	1.96	3	97.2
SUTR 40C	3-8	70.7	80.2	1.47	1.56	4	88.2
SUTR 47B	surface	95.1	114.4	1.31	1.44	4	83.1
SUTR 49	surface	79.2	106.1	1.27	1.46	3	74.6
VIBR 101	15	21.6	22.2	2.06	2.07	5	97.3
	90	69.3	65.3	1.68	1.64	5	106.1
	142	19.4	27.3	1.71	1.99	2	71.1
VIBR 102	25	5.5	27.3	1.65	1.99	1	20.1
	70	10.1	28.8	1.68	1.97	1	35.1
	138	22.3	22.5	1.91	2.06	1	99.1
VIBR 103	8	21.1	26.4	1.92	2.00	1	79.9
	85	21.0	21.7	2.07	2.08	3	96.8
	140	20.3	23.9	1.99	2.04	3	84.9
VIBR 106A	110	27.9	33.2	1.84	1.91	1	84.0
VIBR 121B	22-24	40.6	43.7	1.76	1.70	4	92.9
	82-85	56.4	56.3	1.70	1.69	4	100.0
	140-144	29.5	29.1	1.98	1.96	5	101.4
BOX 121	3-15	31.5	31.5	1.93	1.93	4	100.0
SUTR 131	2-8	53.3	54.8	1.69	1.70	4	97.3
BOX 133	3-15	71.2	75.9	1.54	1.58	5	93.8
BOX 141	0-5	49.8	49.8	1.75	1.74	5	100.0
BOX 149	3-14	25.3	27.0	1.97	1.99	3	93.7
BOX 150	3-12	21.0	22.8	2.03	2.06	2	92.1
BOX 154	10-18	43.0	46.6	1.73	1.77	4	92.3
BOX 161	2-12	48.5	51.8	1.69	1.73	3	93.6
SUTR 174	2-7	25.3	33.5	1.97	2.10	3	75.5

TABLE 4 WATER CONTENTS -BULK DENSITIES
(4 and 5 Quality Designation)

Sample Designation	Water Content Quality	WaterContent % (weighed)	WaterContent % Corrected (100% sat.)	Bulk Density Corrected (gm/cm^2)
VIBR 121B				
0-2 cm	4	47.0	50.3	1.76
6-7	5	35.0	35.8	1.90
42.44	5	47.0	48.1	1.76
66-88	4	38.0	40.7	1.85
104-106	4	31.0	33.2	1.92
128-120	4	31.1	33.3	1.92
159-163	4	32.8	35.1	1.91
BOX 121				
9-13 cm	4	33.1	35.4	1.91
VIBR 125B				
8-11 cm	4	33.1	36.1	1.90
38-42	5	21.0	21.5	2.12
63-66	4	21.7	23.2	2.09
123-125	4	32.8	35.1	1.91
VIBR 131				
20-22 cm	4	59.7	63.9	1.66
39-41	4	94.5	101.2	1.49
99-100	4	58.9	63.1	1.66
173-175	4	40.3	43.1	1.82
SUTR 131D				
0-5 cm	4	76.3	81.7	1.56
VIBR 133				
7-9 cm	5	99.2	101.4	1.51
22-24	5	99.2	75.5	1.59
35-37	5	45.7	46.7	1.79
52-55	5	66.6	68.1	1.63
68-71	5	59.8	64.1	1.66
86-89	5	43.3	44.3	1.81
116-119	5	47.4	48.5	1.77
128-121	5	47.4	48.5	1.77
145-148	5	53.9	55.1	1.72
161-164	5	49.1	50.2	1.76
VIBR 137				
25-27 cm	5	87.6	89.6	1.53
62-64	5	128.0	130.9	1.41
82-84	5	75.2	77.0	1.59
92-94	5	85.1	87.0	1.54
111-113	5	74.2	75.9	1.59
127-129	5	50.5	51.6	1.75
SUTR 137				
0-5 cm	4	128.8	137.9	1.39
BOX 141				
8-12 cm	5	44.6	45.6	1.80
15-18	4	34.9	37.3	1.88
BOX 147				
2-6 cm	5	30.2	30.9	1.97
BOX 154				
4-5 cm	4	66.5	43.0	1.62
13-14	4	52.4	56.1	1.71
26-29	4	42.0	45.0	1.81
BOX 156				
33-35 cm	4	76.3	81.7	1.56

TABLE 5

UNDRAINED SHEAR STRENGTHS S_u SEA5-76-BS

Sample Designation	Depth (cm)	Undrained Shear Strength (S_u) gm/cm^2	Remolded Shear Strength (S_r) gm/cm^2	Sensitivity (S_u/S_r)
SUTR 40C	0-3	37.0	9.3	4.0
	8-10	46.3	18.5	2.5
SUTR 47B	0-4	20.4	10.2	2.0
SUTR 49A	0-4	10.2	5.1	2.0
	5-9	20.4	10.4	2.0
	12-16	51.0	25.5	2.0
VIBR 49	49-50	150.0	--	--
BOX 141	surface	0.0	--	--
	9-10	54.0	--	--
	14-15	153.0	--	--
BOX 145	3-14	159.0	--	--
	3-14	149.0	--	--
BOX 149	2-14	99.5	--	--
BOX 150*	surface	64.3	--	--
	0-3	836.5	--	--
	6-7	120.4	--	--
	3-12	44.8	--	--
BOX 154	surface	0.0	--	--
	0-3	259.6	91.4	2.8
	4-5	23.5	0.0	--
	10-11	51.0	2.0	25.0
	15-16	78.5	20.4	3.8
	3-13	124.4	--	--
	20-21	105.1	9.0	2.1
	24-25	263.2	58.1	4.5
	29-30	189.1	43.9	4.3
BOX 159	3-14	358.0	--	--
	19-20	90.0	--	--
BOX 161	0-10	74.6	--	--
SUTR 163	surface	36.0	--	--
SUTR 170	surface	23.5	--	--

Fig. 1. Map of Bering and Chukchi Seas with delineation of study area.

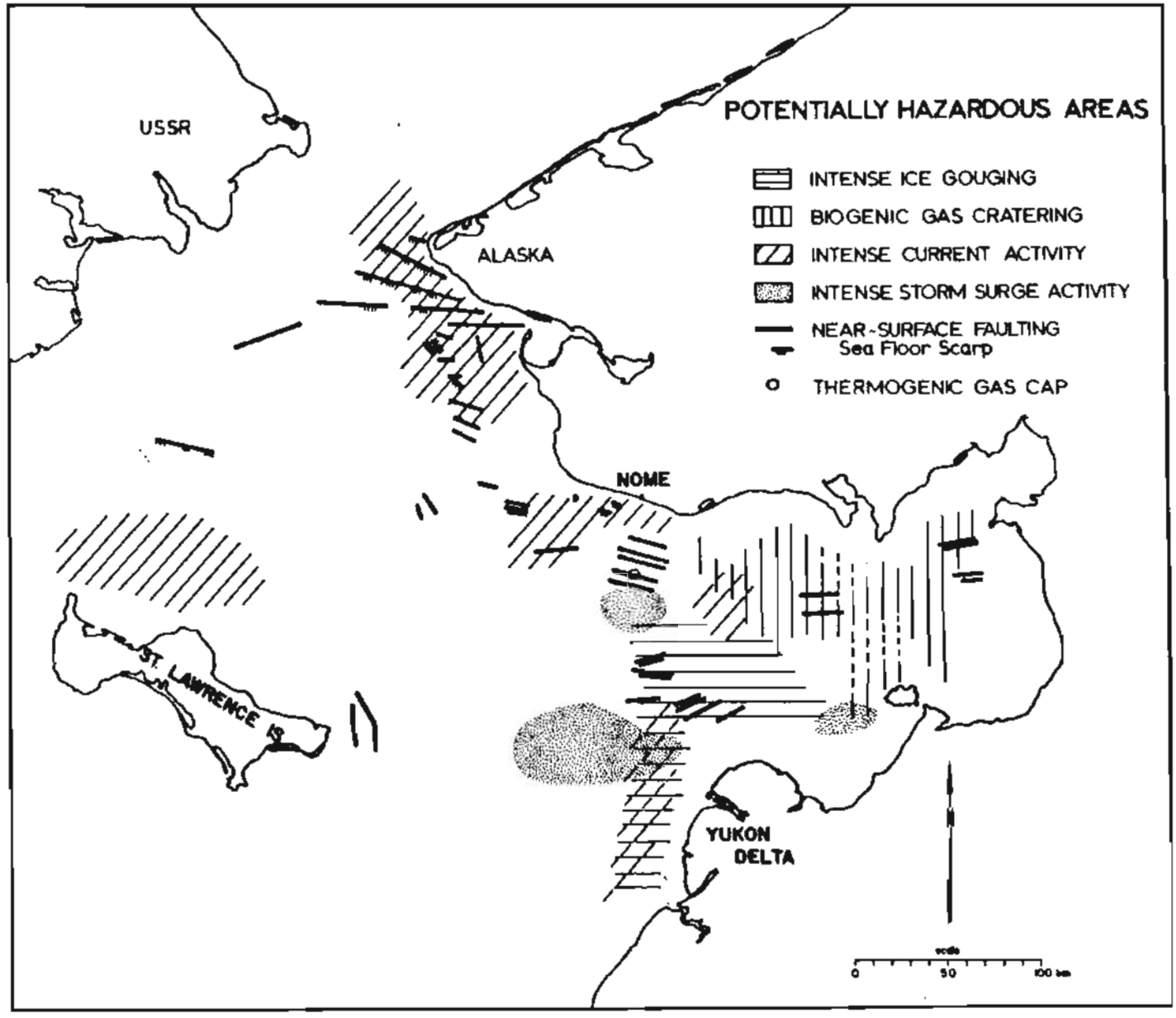


Fig. 2. Potential geohazards in Norton Sound (after Nelson, 1977).

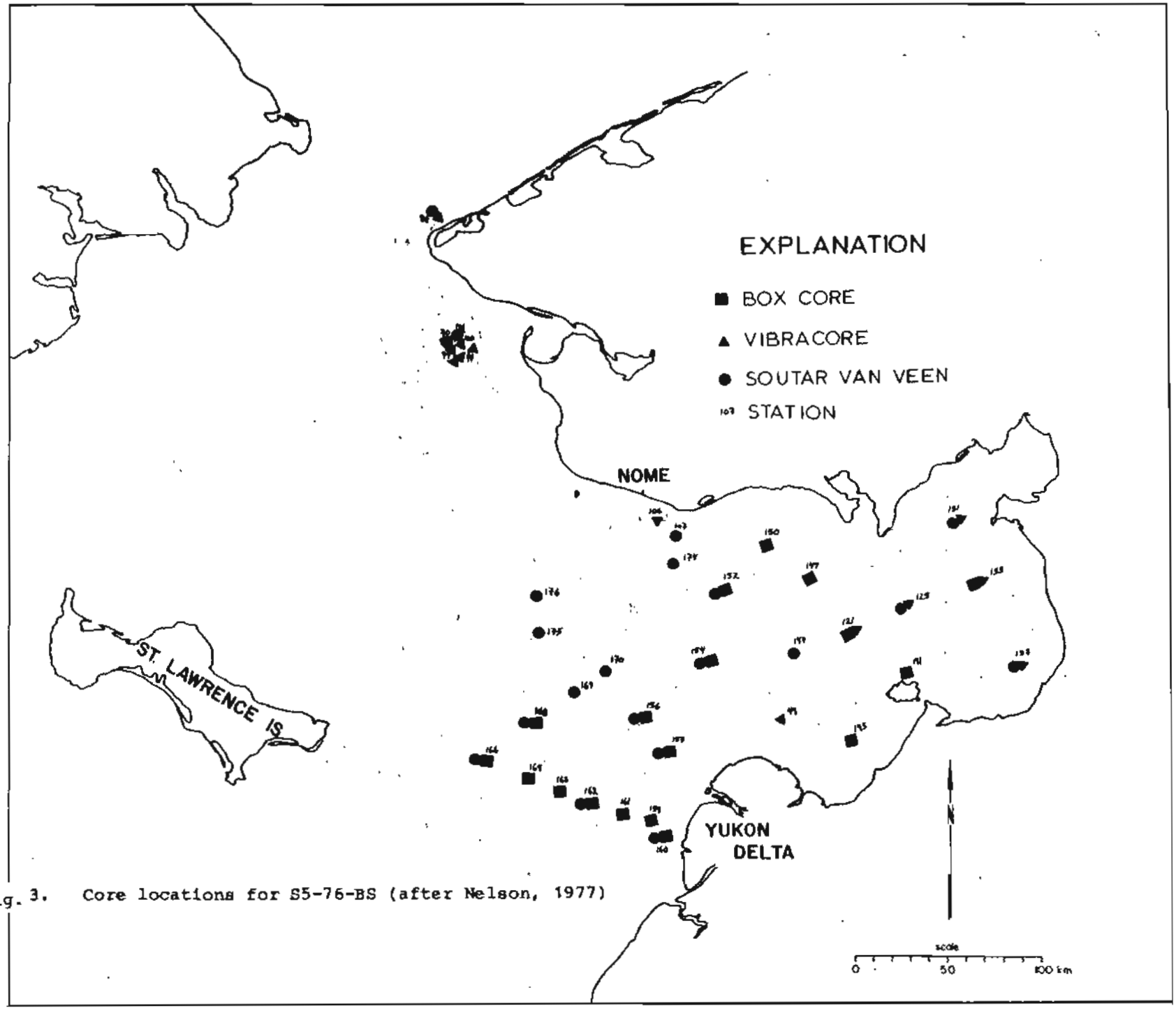
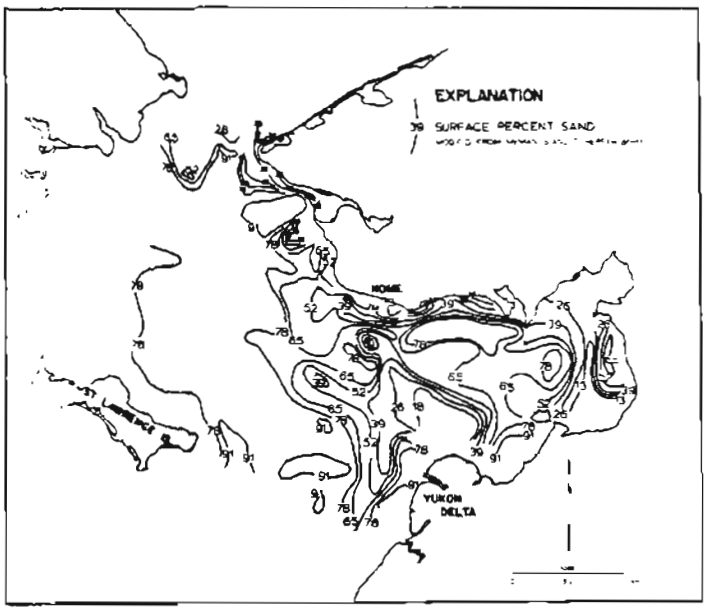
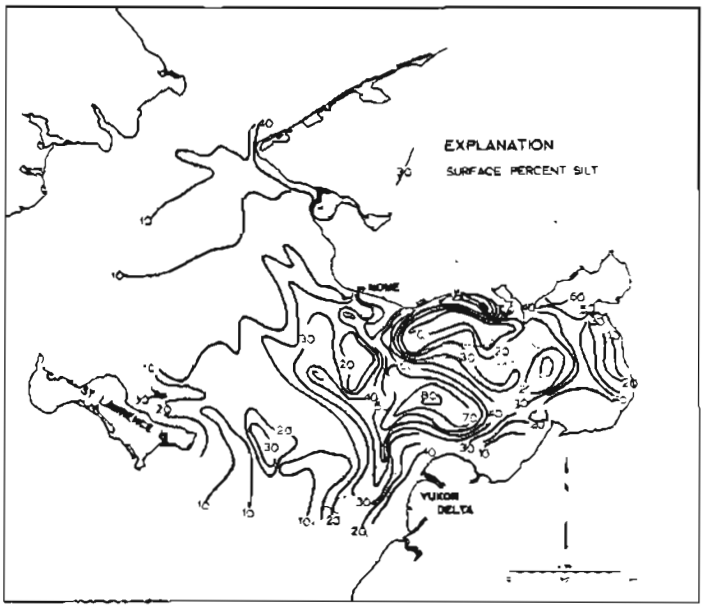


Fig. 3. Core locations for S5-76-BS (after Nelson, 1977)





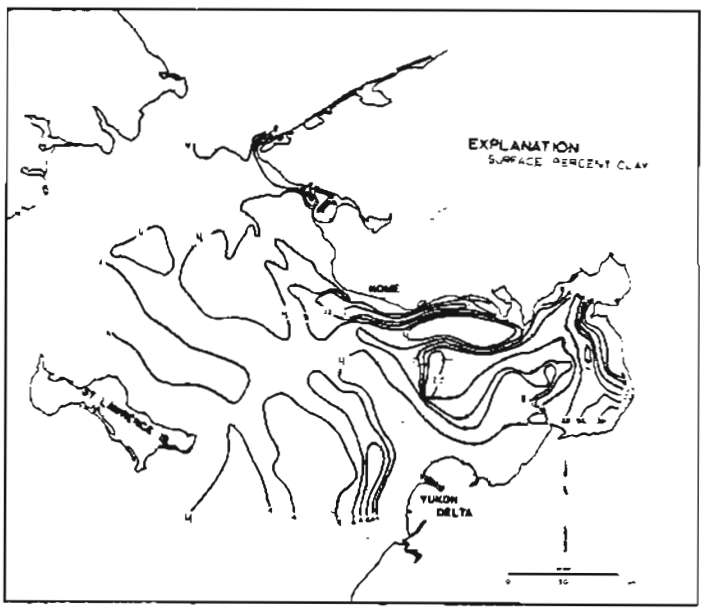


Fig. 4. Grain size distribution in Norton Sound area

(modified after McManus et al., 1976

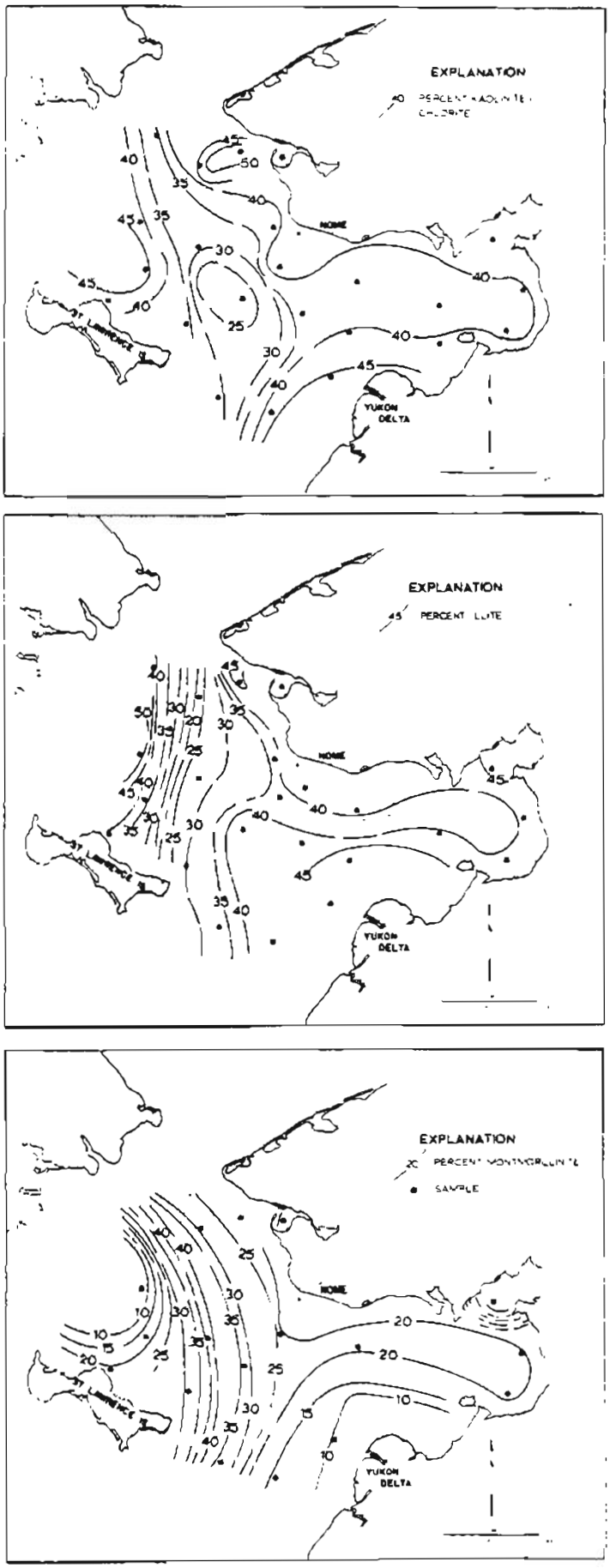


Fig. 5. Clay mineralogy in Norton Sound area

(data from James Hein, U.S. Geological Survey, Menlo Park, California).

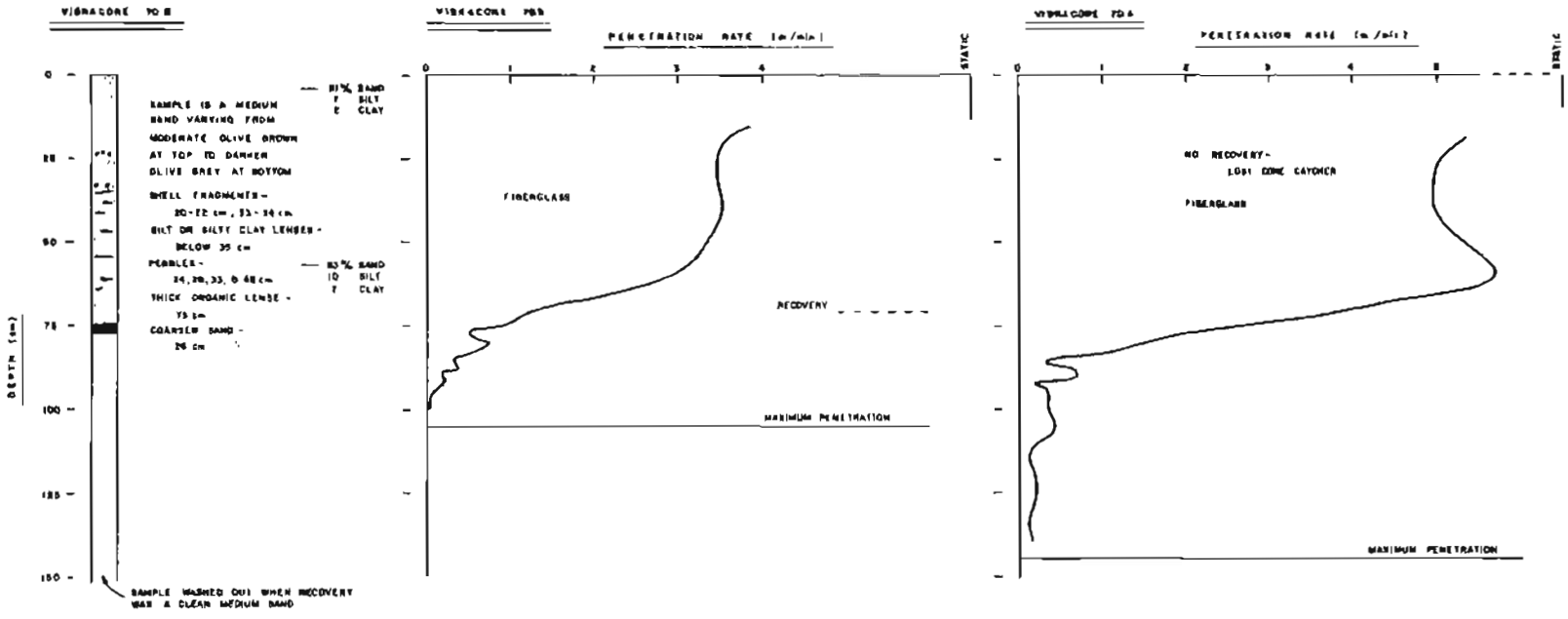


Fig. 6. Vibracore log from sandwave field near Bering Strait.

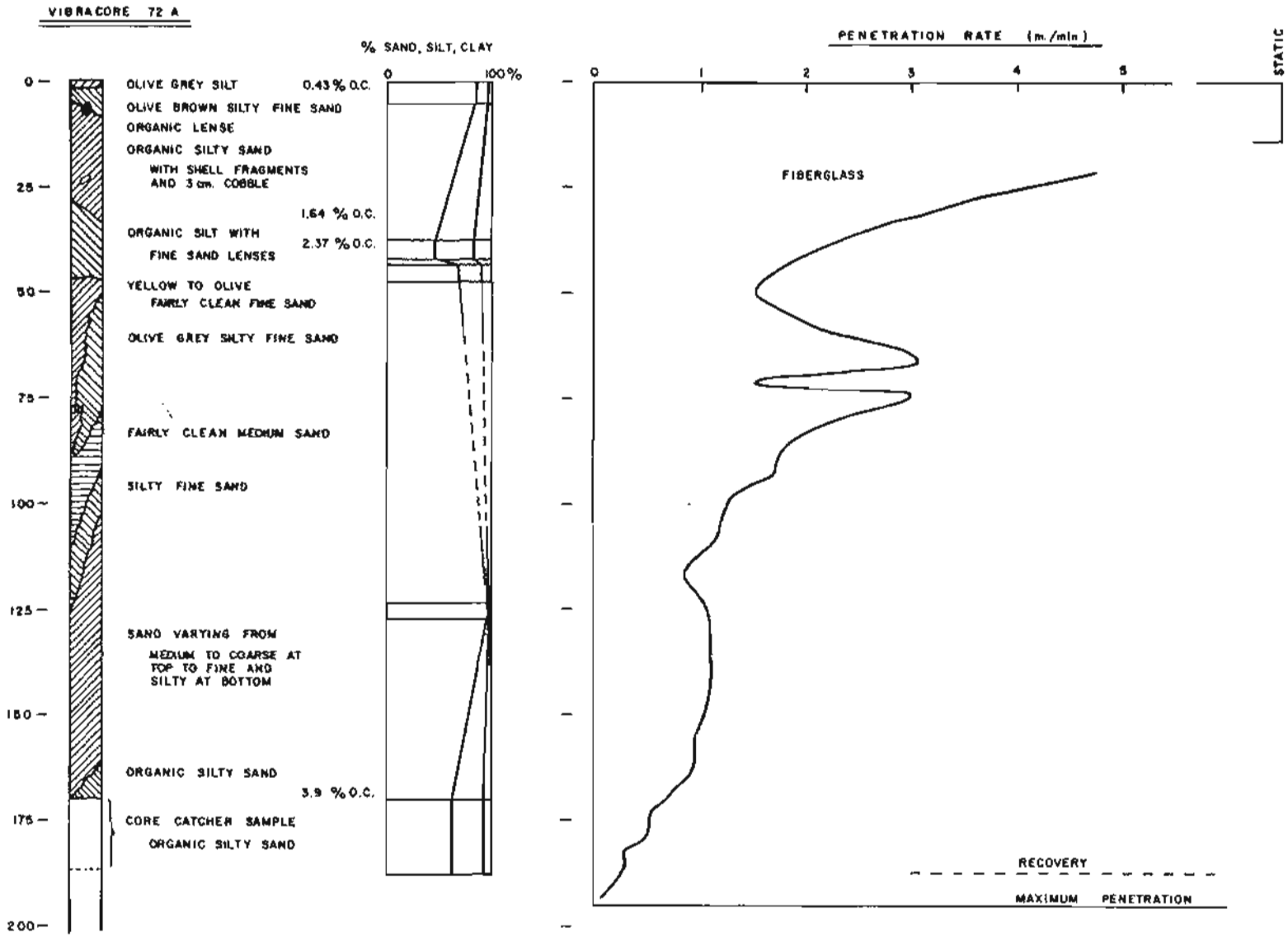


Fig. 7. Vibracore log of core from sandwave field in Bering Straits.

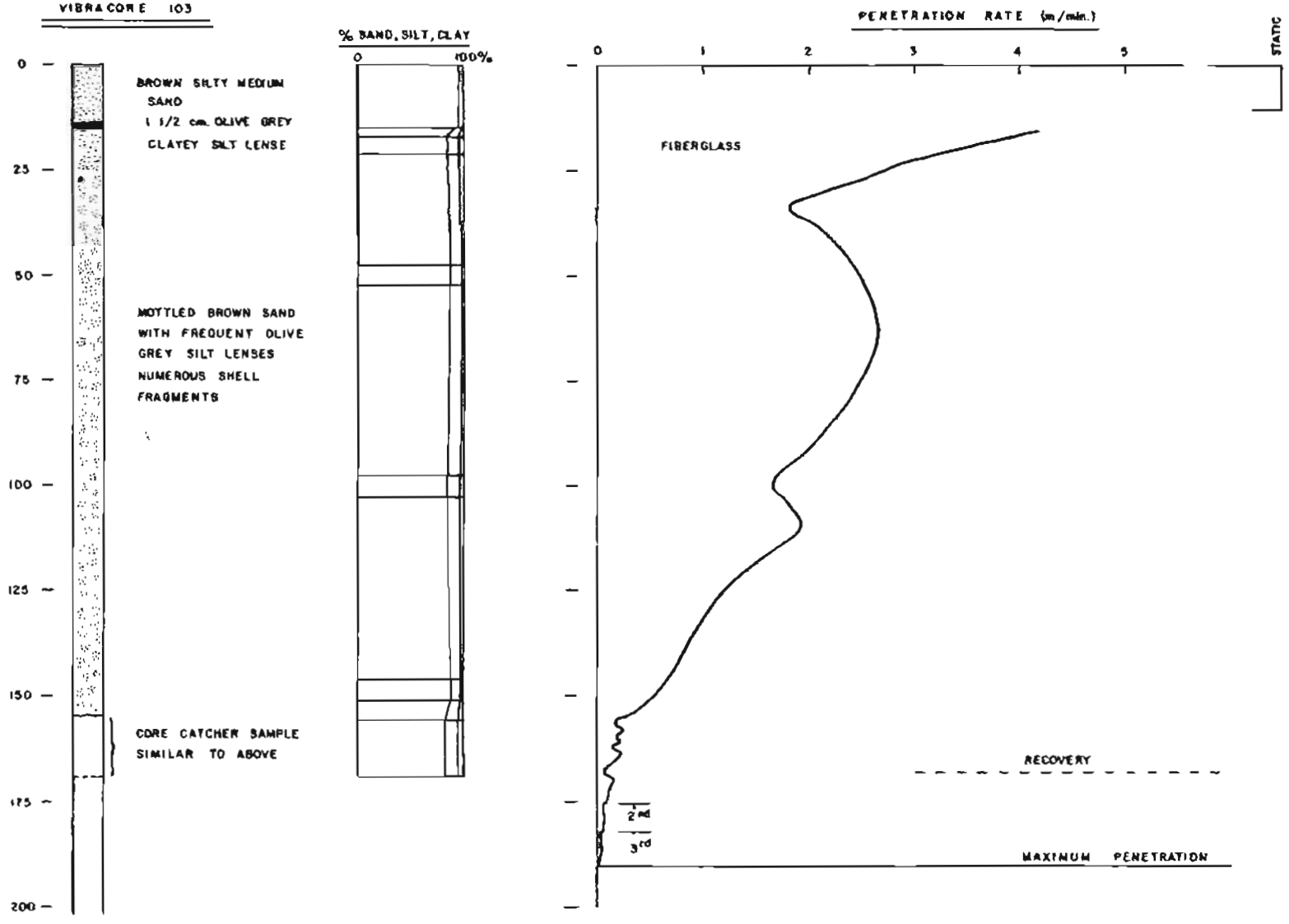


Fig. 8. Vibracore log in Norton Sound.

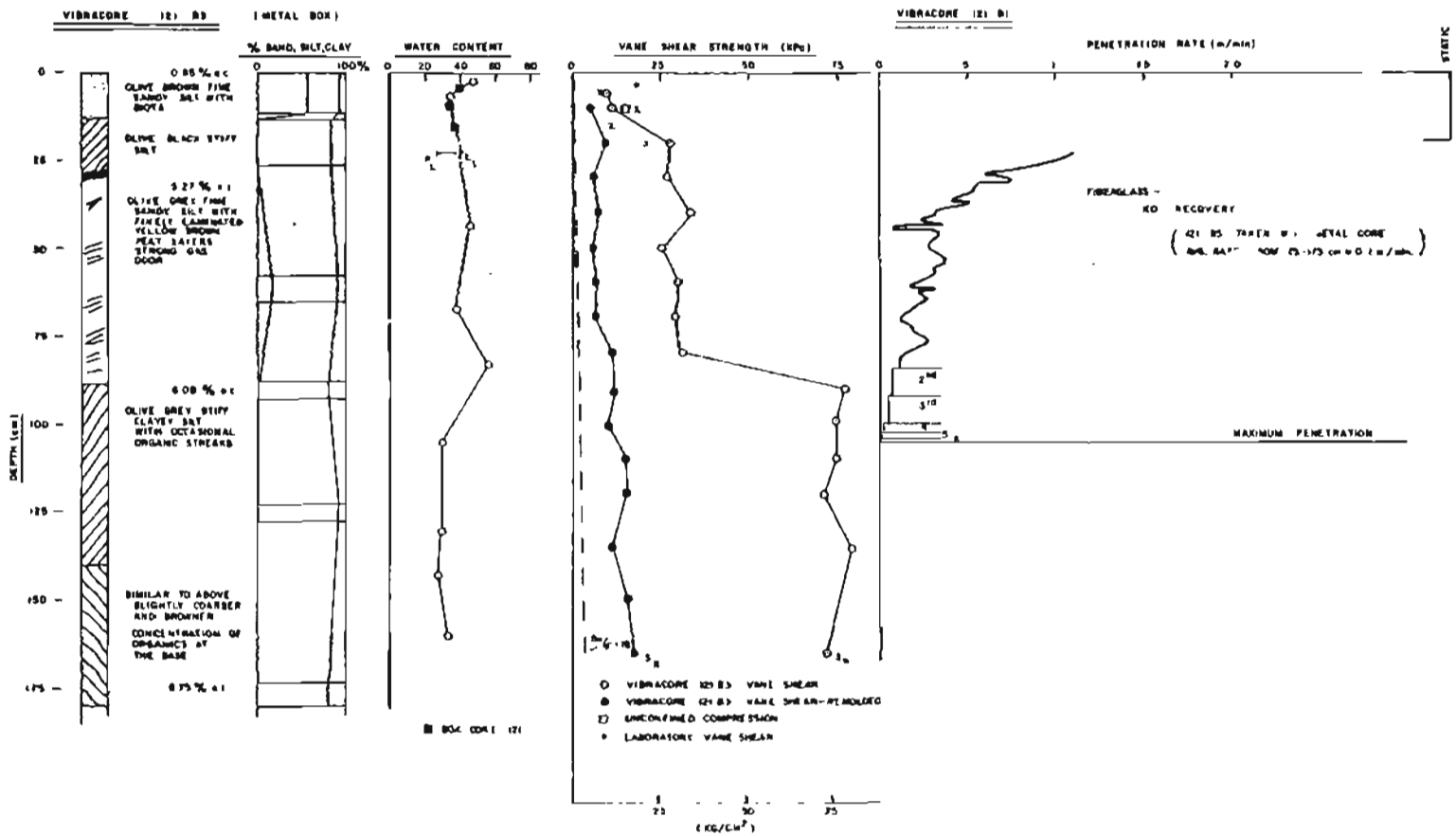


Fig. 9. Vibracore log of core taken in gas crater area in Norton Sound.

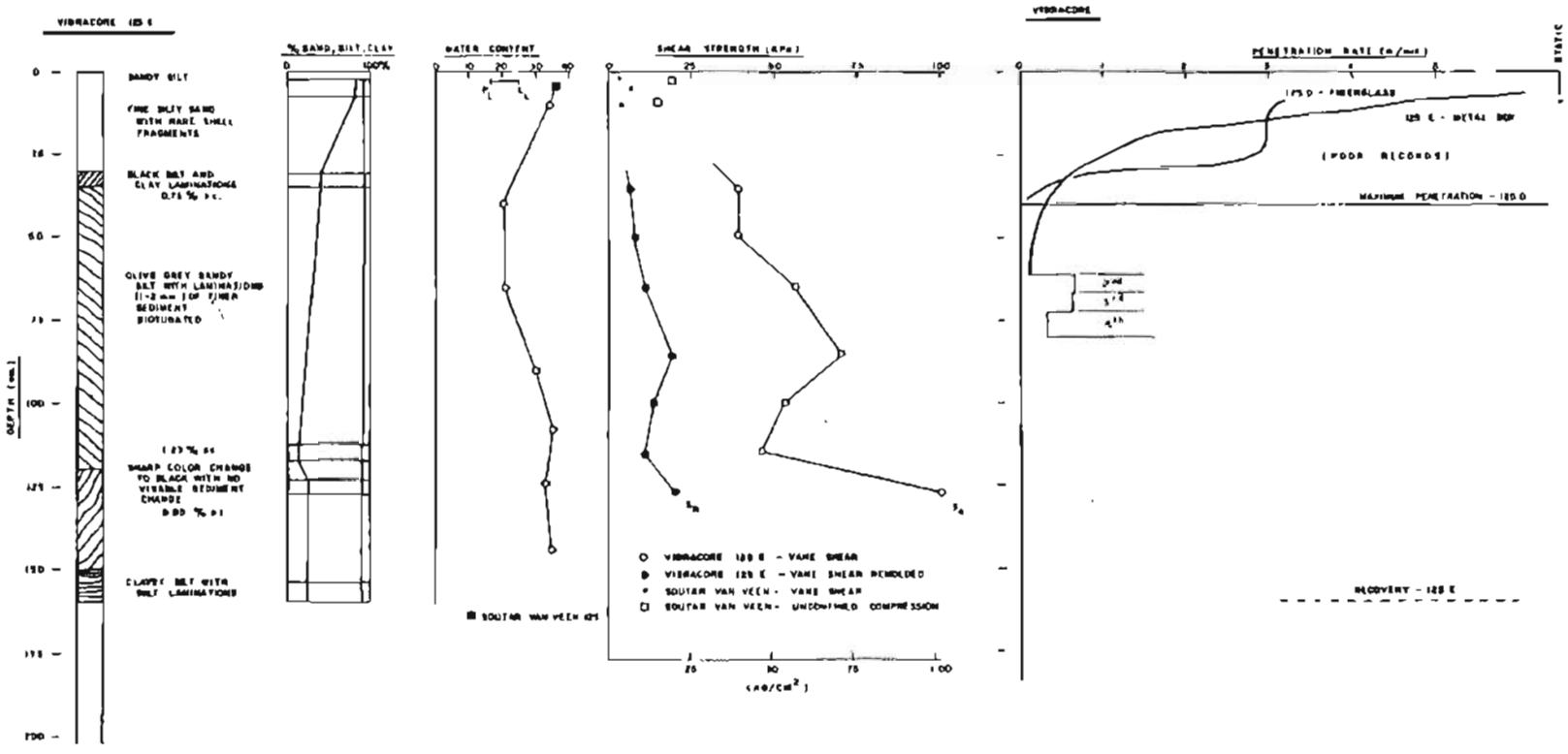
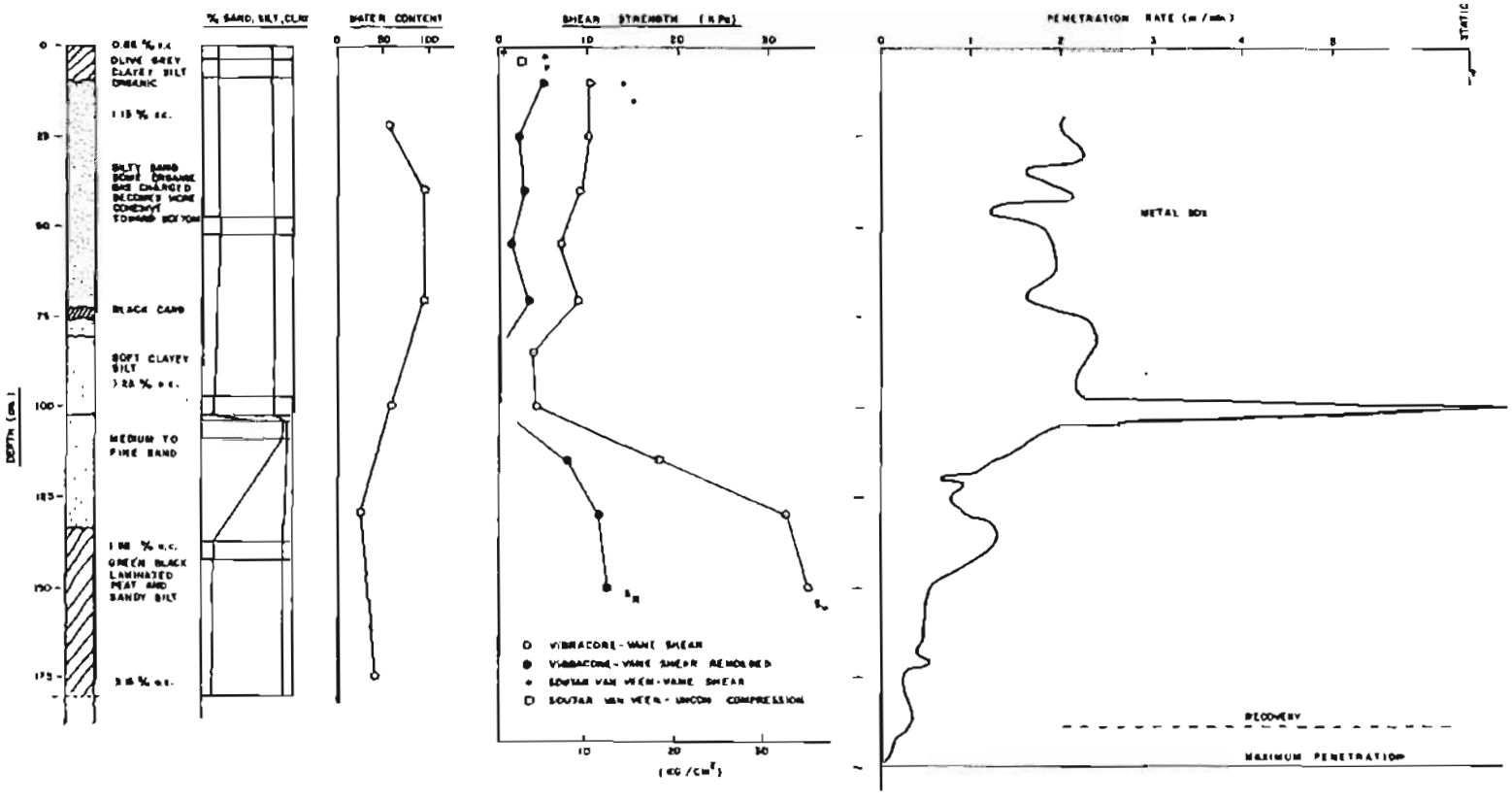


Fig. 10. Vibracore log of core taken in gas crater area in Norton Sound.



11. Vibracore log of core taken in fine-grained sediments in eastern Norton Sound.

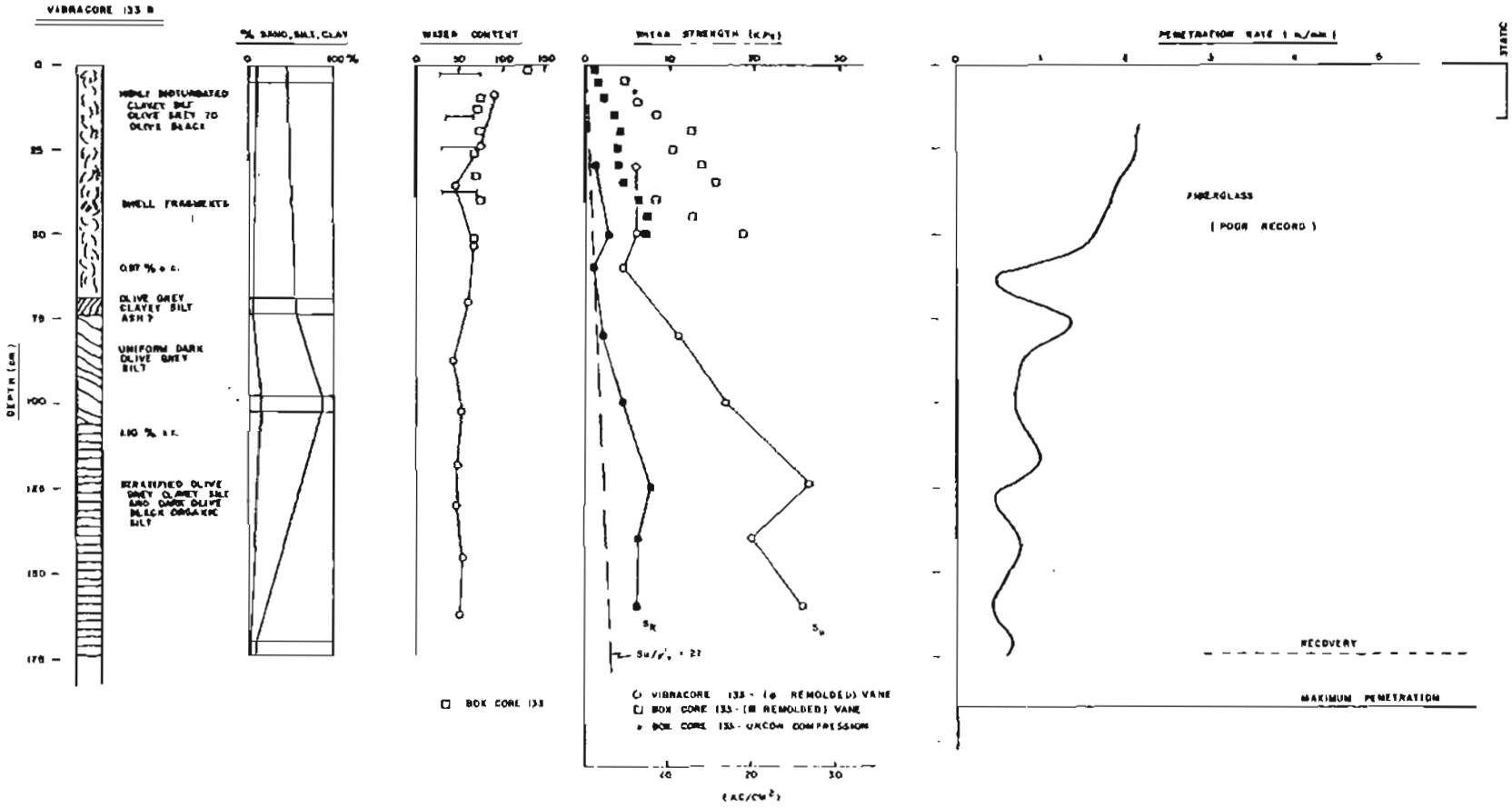


Fig. 12. Vibracore log of core taken in fine-grained sediment in eastern Norton Sound.

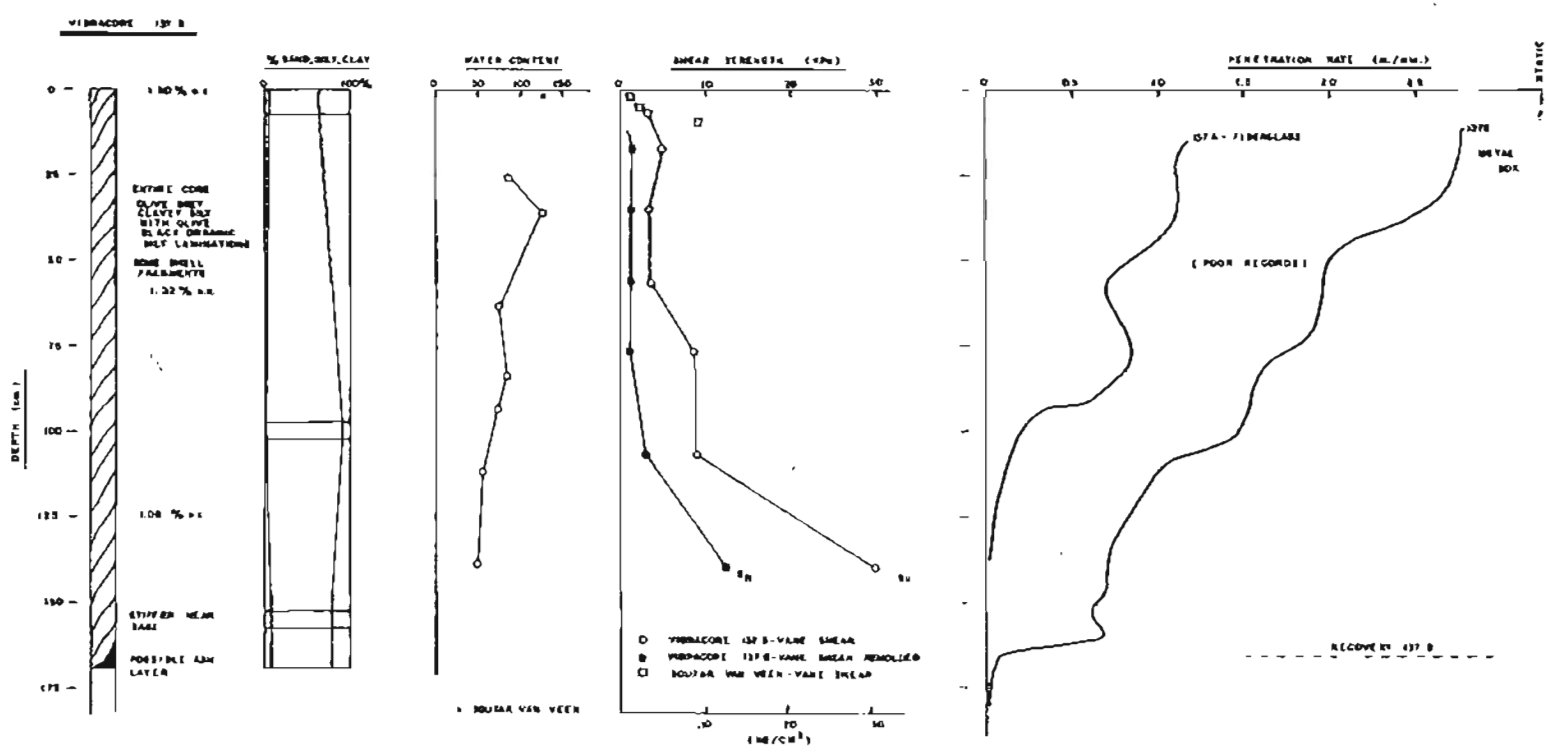
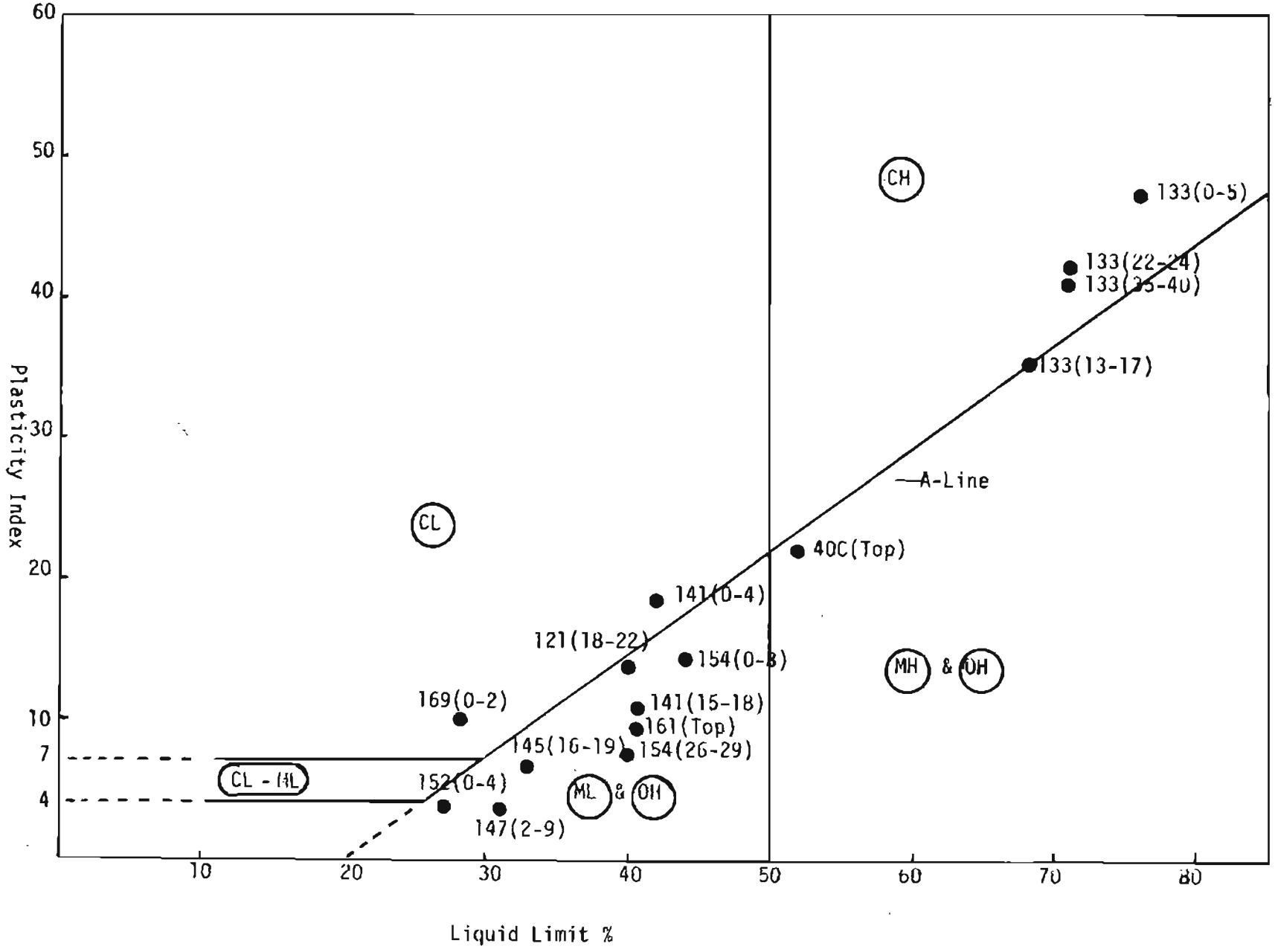


Fig. 13. Vibracore log of core taken in fine-grained sediment in eastern Norton Sound.

Fig. 14. Plasticity chart showing distribution of fine-grained sediment in Norton Sound.



PLASTICITY CHART

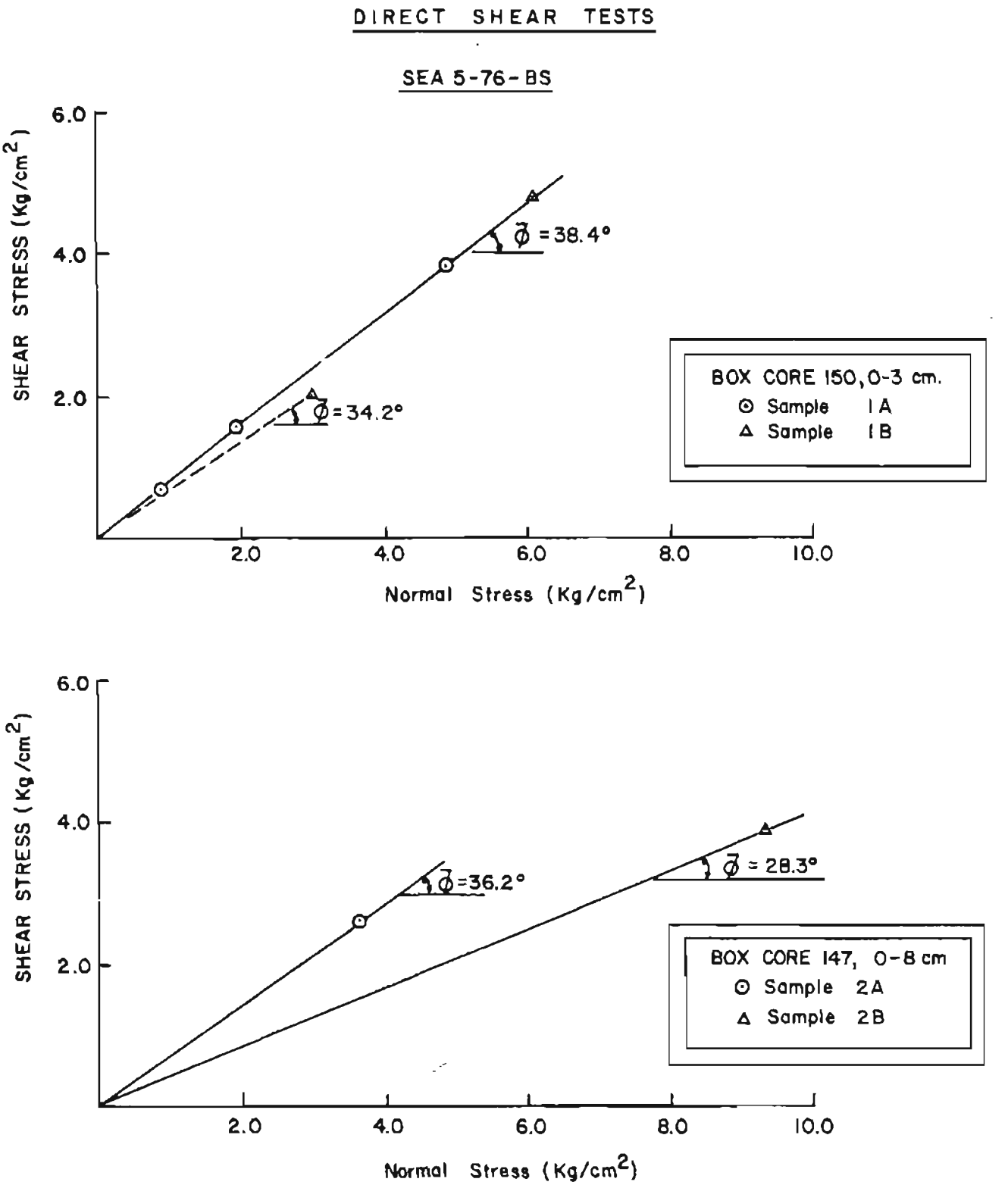
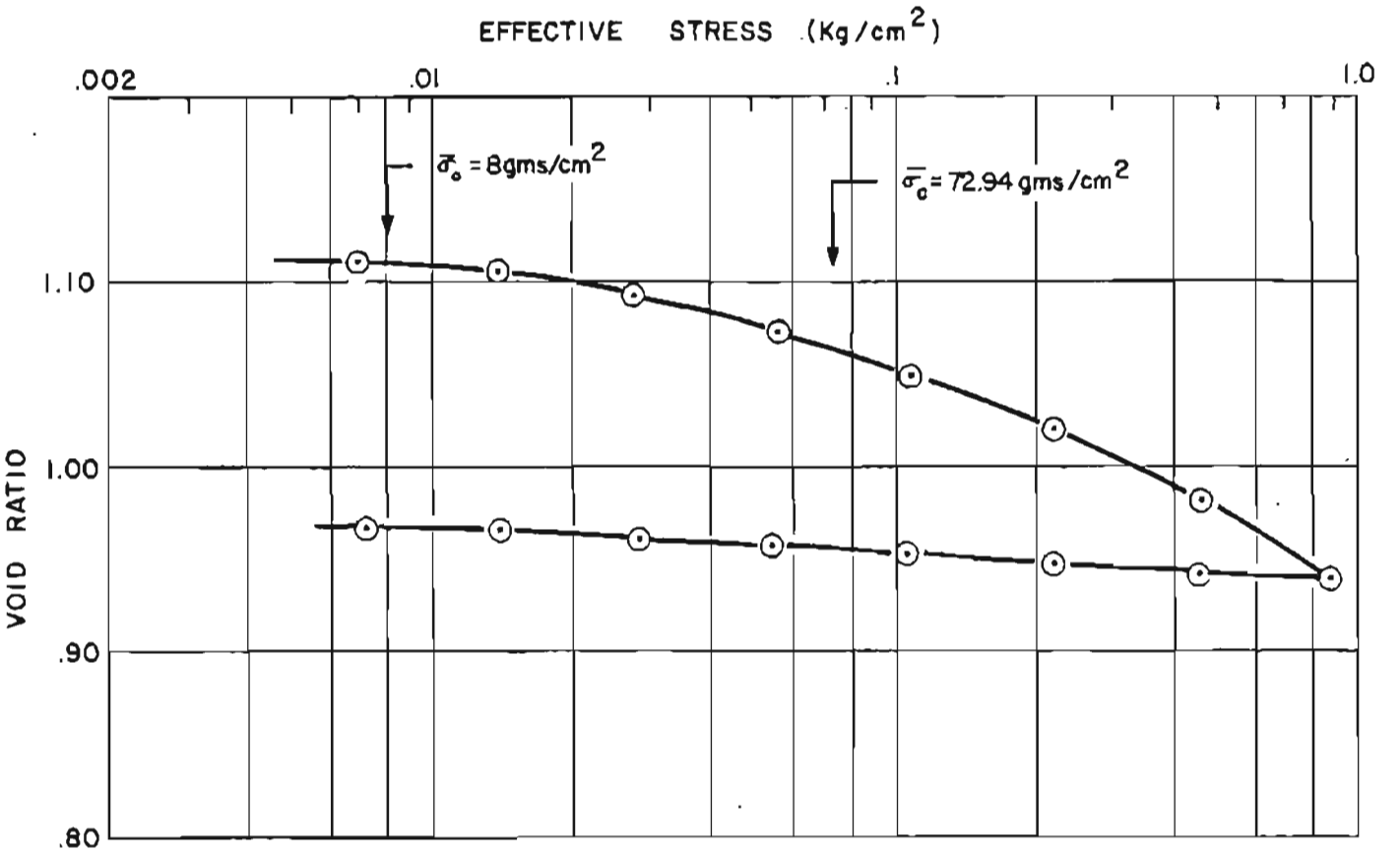


Fig. 15. Direct shear tests of samples from central Norton Sound.



CONSOLIDATION TEST - SEA5-76-BS

BOX CORE 154, 8-13 cms.

OVERBURDEN STRESS ($\bar{\sigma}_o$ = 8.0 gms/cm^2)
PRECONSOLIDATION STRESS ($\bar{\sigma}_c$ = 72.9 gms/cm^2)
OVERCONSOLIDATION RATIO ($\bar{\sigma}_c / \bar{\sigma}_o$ = 9.11)
AVERAGE COEFF. OF CONSOL (cv = 3.58 x 10^{-3} cm^2/sec)
AVERAGE COEFF. OF PERMEABILITY (k = 1.20 x 10^{-6} cm/sec)
COMPRESSION INDEX (CORRECTED) = .153

Fig. 16. Consolidation test performed on silty sample of Yukon sediment.