PORT AND OCEAN ENGINEERING UNDER ARCTIC CONDITIONS
TECHNICAL UNIVERSITY OF NORWAY

ENGINEERING PROPERTIES OF GREENLAND AND NORWEGIAN BASIN SEDIMENTS

George H. Keller
Director,
Marine Geology and
Geophysics Laboratory

National Oceanic and
Atmospheric Administration
Atlantic Oceanographic and
Meteorological Laboratories

901 S. Miami Avenue
Miami, Florida 33130
U.S.A.

Engineering and foundational characteristics of sea-floor deposits are relatively unknown except in certain areas of the coastal zone where man has built structures such as wharves, bridges, tunnels and various pile supported platforms. Although the number of investigations pertaining to the engineering properties of the outer coastal zone and deep-sea deposits has increased significantly during the past decade, the quantity of available information is yet very limited. The scarcity of such data is even more pronounced in Arctic regions where approximately 140 to 150 sediment cores have been collected for engineering (geotechnique) studies.

Sediments of the Greenland-Norwegian basin display considerable variation of such properties as shear strength, water content, and porosity, both laterally and with depth. These deposits tend to exhibit higher average unit weight (bulk density) and shear strength, but lower water content, porosity, sensitivity, grain specific gravity, and Atterberg Limits than those sediments blanketing most of the North Atlantic basin. The Greenland-Norwegian basin sediments are characterized by inorganic clays of medium to high plasticity, sand clays, and slightly plastic inorganic silts. The process of ice-rafting, which is unique to higher latitudes, strongly influences the engineering properties of Arctic submarine deposits by transporting and later depositing coarse material, e.g., coarse sand and gravel, in oceanic areas which otherwise would only receive fine sand, silt and clay. Fine silt and clay of relatively low strength appear to blanket much of the Greenland-Norwegian basin resulting in relatively low ultimate bearing capacities of the surface deposits.

INTRODUCTION

The foundational characteristics of sea-floor deposits are yet relatively little known except in coastal areas where man has long been involved in the construction of such facilities as wharves, bridges, and breakwaters. It was only about 20 years ago, when offshore petroleum exploration began to receive serious attention, that sincere investigations began on the engineering properties of submarine sediments beyond the breaker zone.

As yet, most of the engineering studies carried out on deep-sea sediments have been by marine geologists who have utilized various aspects of soil mechanics (geotechnique) in their attempt to understand the sedimentological characteristics and depositional history of the ocean floor. One of the earliest studies was that of Arrhenius (2) who determined relative strengths on sediment cores collected during the Swedish Deep-Sea Expedition 1947-1948. Although a number of investigators were concerned with the geotechnical properties of submarine sediments prior to 1960, e.g., Hamilton (9, 10), Hamilton and Menard (11), Fisk and McClelland (8), and Moore and Shumway (30); Richards (33, 34) was the first to report on the overall engineering aspects of deep-sea deposits based on a limited number of locations in the Atlantic, Mediterranean, and Pacific basins. During the last decade an increasing number of investigators entered this field of study and have looked into such relationships as sound velocity versus certain engineering properties (5), unit weight variations with depth (17), consolidation characteristics of various deposits (4, 35), or have defined the engineering properties of some local area such as the Chesapeake Bay (13), Gulf of Bothnian (18), or the Mississippi Delta region (28, 29). The first regional study of the distribution of various geotechnical properties was presented by Keller (23) in his report on approximately 500 sediment cores from the North Atlantic and North Pacific basins. A similar study has recently been completed by Keller and Lambert (27) for the Mediterranean basin.

With the advent of the U. S. Deep Sea Drilling Project in 1968, it became possible to extend geotechnical studies to much greater depths below the sea floor. Thus far, this program has obtained sediment cores from depths as great as 1070 m below the sea floor on which tests have been made for unit weight, water content, porosity, grain size and relative strength, (31). Although these samples are disturbed, they have provided some degree of insight into the properties of sediments never before sampled in the deep sea.

To date, it is estimated that on the order of 1000 to 1300 sediment cores have been collected from all the ocean basins (beyond the continental shelf) for the purpose of geotechnical studies. In the Arctic, only about 140 deep-sea cores have been obtained for such studies. Many of these samples have been collected from icebreakers which were only equipped to handle small core samplers. As a result of this limitation, approximately 60 percent of these samples are of limited value.

This study is based on a total of 67 sediment cores, 42 of which were only suitable for Atterberg Limits, grain specific gravity, and grain size determinations. The data used herein were obtained from analyses carried out by the U. S. Naval Oceanographic Office and from project reports contracted for by the U. S. Naval Oceanographic Office (37, 39). In addition to presenting the areal distribution of selected geotechnical properties in the Greenland-Norwegian basin, the ultimate bearing capacity of surface deposits in the area is also discussed. Local variability in deep-sea deposits may not be as severe as those found in the coastal zone, nevertheless both lateral and vertical changes in these deposits are found to be significant.

Regional Setting

The regional morphology of the Greenland-Norwegian basin is not that of two simple adjacent basins but consists of a number of ridges and fracture zones which transect the area (Fig. 1). The northern extension of the mid-Atlantic ridge trends northeast from Iceland to about 72°30'N where it is intersected by the Jan Mayen fracture zone. Here the ridge has been offset to the east on the order of 200 km. The ridge then trends east-northeast, approximately midway between Greenland and Norway, to 74°N where it assumes a north-south trend as a result of its displacement by the Greenland fracture zone. A second major ridge, the Jan Mayen ridge, extends southeast from Jan Mayen Island serving as the eastern border of the Icelandic plateau. It is readily apparent from figure 1 that the continental

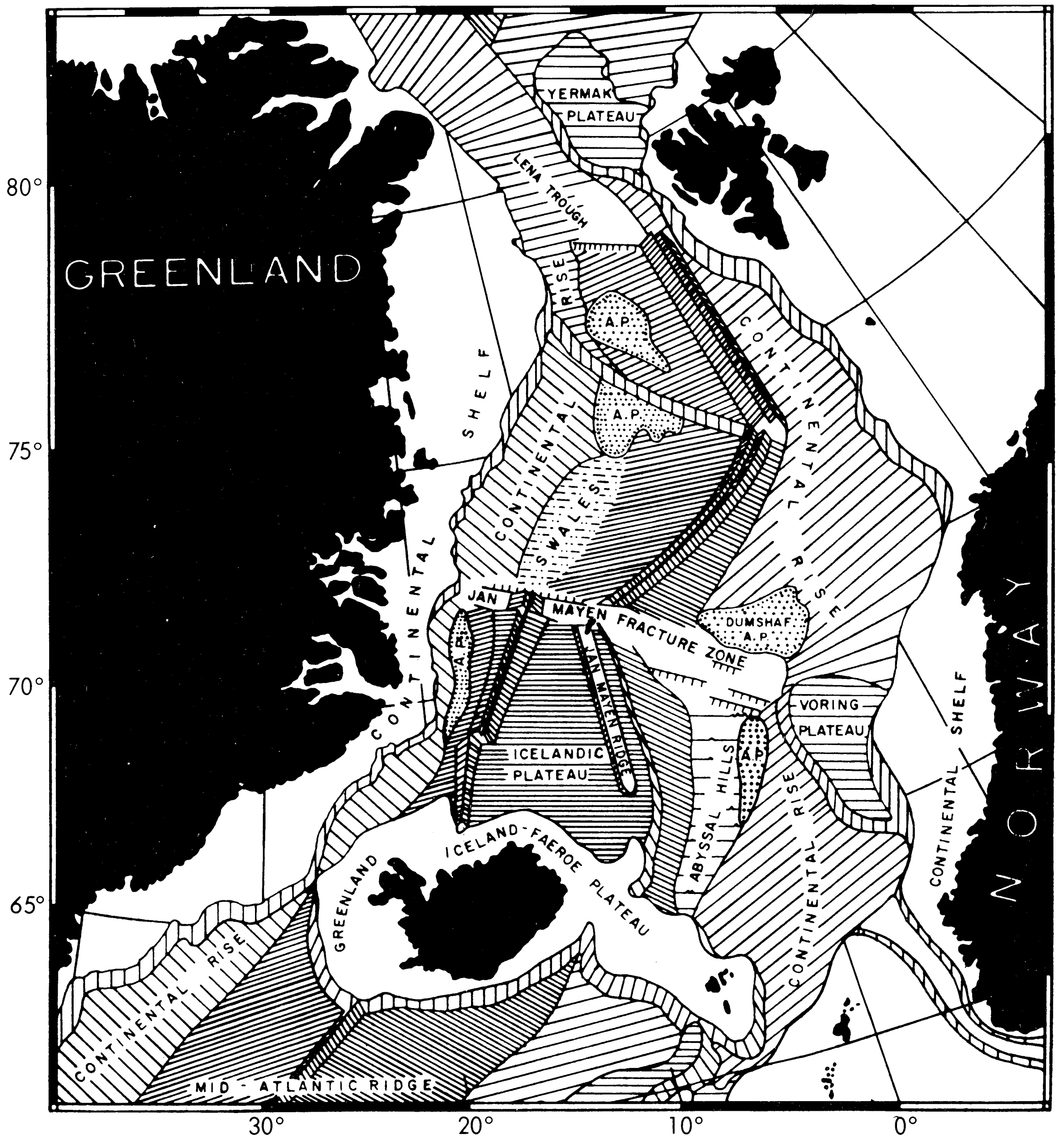

GREENLAND
NORWAY
YERMAK
PLATEAU
LENA TROUGH
CONTINENTAL RISE
CONTINENTAL SHELF
CONTINENTAL RISE
A.P.
A.P.
SWALES
CONTINENTAL
CONTINENTAL
JAN MAYEN FRACTURE ZONE
JAN MAYEN RIDGE
A.P.
DUMSHAF A.P.
ICELANDIC
PLATEAU
VORING
PLATEAU
A.P.
ABYSSAL HILLS
CONTINENTAL RISE
CONTINENTAL SHELF
GREENLAND ICELAND-FAEROE PLATEAU
CONTINENTAL RISE
MID - ATLANTIC RIDGE
80°
75°
70°
65°
30°
20°
10°
0°

FIG. 1

rise is much more extensive off Norway than along the Greenland margin. This may be attributed to a higher rate of sedimentation as geophysical observations indicate that large volumes of sediment are prograding out from the Norwegian shelf onto the continental rise (21). Tectonism and the resulting crustal features have contributed to a complex bottom topography and the absence of any large abyssal plain. For a more detailed discussion of the morphology and structural history of the Greenland-Norwegian basin, the reader is referred to the studies of Johnson and Eckhoff (19) and Johnson and Heezen (20).

Regional Aspects of Geotechnical Properties

Surface Sediment Types.-Sediments found in the Greenland-Norwegian basin are largely the product of glacial activity, with varying amounts of material contributed by ice-rafting as well as slumping from nearby submarine ridges. Aside from the 67 sediment samples discussed here (Fig. 2), the majority of the samples collected in this area date back to the Norwgian Vöringen cruise (36), the Danish Ingolf-Expedition (3) and the studies of Holtedahl (14, 15, 16). Only a very general distribution of surface deposits in the Greenland-Norwegian basin can be presented from the available data. Excluding those areas of considerable topographic relief, the basin is primarily blanketed with fine silts and clays which probably have been derived from the streams and rivers of Norway and Greenland. Seismic reflection observations (39) indicate that most of the sediment east of the mid-Oceanic ridge has been derived from Norway. Local areas of coarser grained material result from slumping and small scale turbidity currents associated with seismic ridges such as Jan Mayen ridge (39). West of the mid-Oceanic ridge fine pelagic sediments cover much of the area with local variations in sediment type owing to slump and turbidity current activity from the steep flanks of the adjacent ridge (39). Bottom photographs from various parts of the Norwegian Sea (continental slope, abyssal plain, abyssal hills, and Icelandic plateau) all revealed a bottom composed of silty and sandy clay and occasional ice-rafted pebbles (39). None of the photographs showed any indication of active bottom currents.

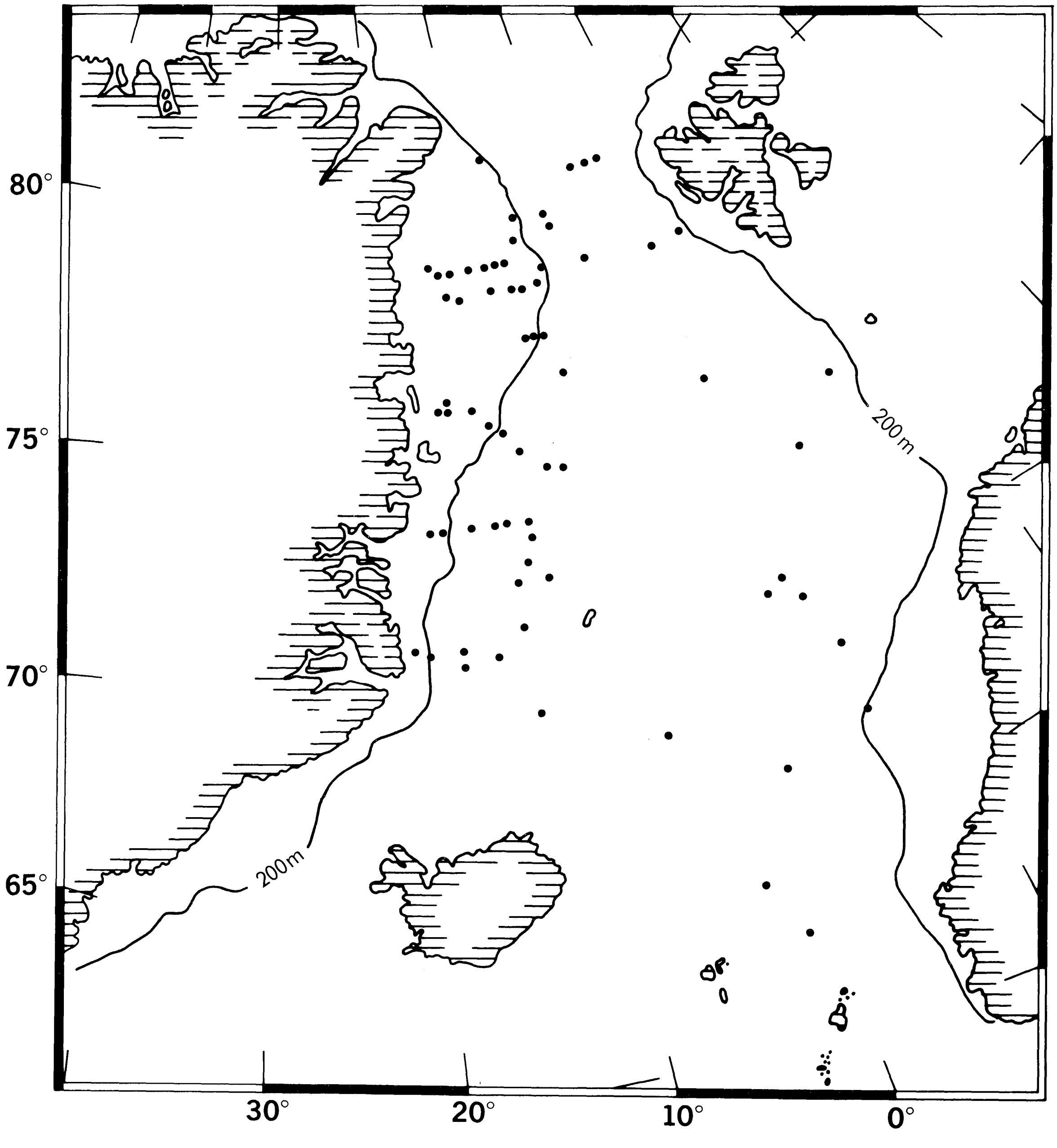


FIG. 2

As a generalization, it appears that surface deposits on the margins of the basins consist of relatively coarse grained (sandy silt) glacial-fluvial-sediments grading seaward into silty clay and finally at the greater depths to a calcareous ooze (23). In his study of the southeastern part of the Norwegian Sea, Holtedahl (16) described a series of sediment cores from the continental slope out onto the continental rise. He reported surface deposits of gray sandy clay to water depths of approximately 800 m and gray silty clay from depths of 800 m to at least 1000 m. Beyond depths of 1500 m he found a brown sandy clay with a very high concentraion of Foraminifera. For this deep-water surface deposit, which is on the order of 15 cm thick, Holtedahl reported a calcium carbonate content of 45 percent. The detailed work of Holtedahl tends to substantiate the generalization made above.

In contrast to the mid-Oceanic ridge which has little or no sediment cover, the Jan Mayen ridge is blanketed by 100 to 300 m of sediment (20). Sedimentation in the Greenland-Norwegian basin is typical of the Arctic area, but atypical of most deep-sea basins in that ice-rafting plays a significant role in Arctic deposition. The occurrence of coarse material (pebbles and cobbles) has been frequently noted both on the Arctic sea-floor and in cored samples (Fig. 3). Such ice-rafted material obviously influences the engineering properties of basin deposits to a considerable degree, especially if the debris should comprise a sizeable proportion of the deposits. Engineering tests performed on the cored samples avoided zones of ice-rafted material and, therefore, provided biased results which only approximate the general characteristics of these particular sediments.

Shear Strength.-Shear strength measurements were made on samples comprised primarily of fine grained cohesive sediment (silty clay) with minor occurrences of fine sand stringers. Zones with pebbles were not tested. Shear strength of cohesive material is dependent on the cohesion (c), angle of internal friction (ϕ) of the sediment, and the effective stress normal to the shear plane ($\bar{\sigma}$) simply expressed as:

$$\tau_f = c + \bar{\sigma} \tan \phi$$

Saturated, silty clays, stressed without drainage (loss of pore water) respond with respect to the applied load as if they have no angle of internal friction (ϕ=o). Under these conditions, shear strength then is equal to the cohesion (τ_f=c).

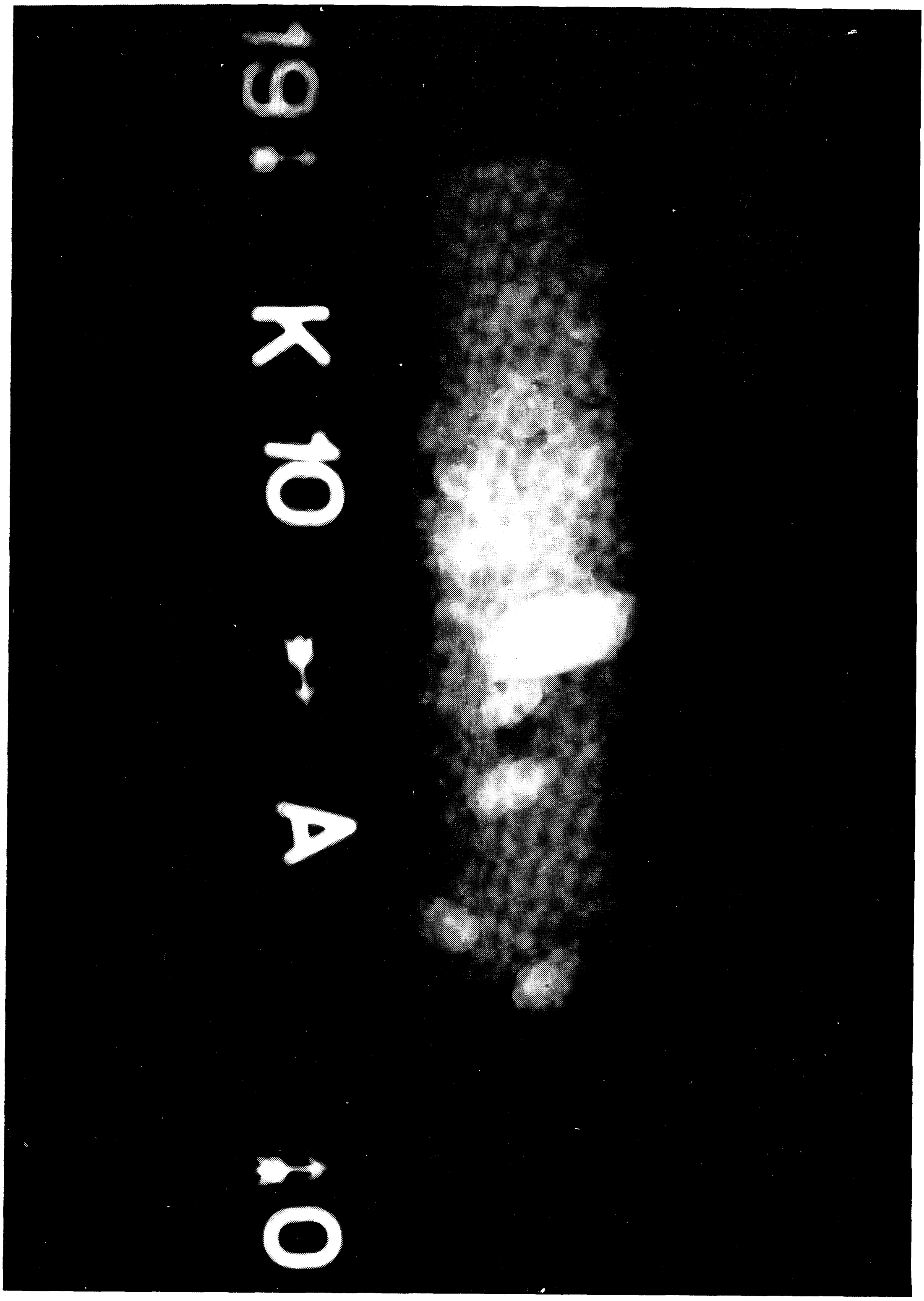


FIG. 3

A more detailed discussion of shear strength can be found in a basic soil mechanics text book.

Measurements of shear strength were made by either a laboratory vane shear apparatus or the fall cone. Both methods provide a simple yet suitable test for these relatively soft submarine sediments. All fall cone measurements were taken from Texas Instruments, Inc. (39) and were based on the conversion graphs of Hansbo (12). The vane shear method follows that described by Evans and Sherratt (7) and more specifically as applied to deep-sea deposits using the procedure outlined by Richards (33).

Both piston and gravity corers were used during the sampling program of this area. The cores varied from 2.6 to 6.0 cm in diameter and from 0.35 to 10 m in length. An average length for the 67 cores studies is on the order of 2.0 m. The smaller diameter cores were only used for grain size, Atterberg Limits and grain specific gravity measurements. Considering the areal extent of the Greenland-Norwegian basin and the relatively shallow depths to which sampling was possible it was decided, for the purpose of displaying the areal distribution of the geotechnical properties, to average the measured values of the respective parameters over the entire length of each core. This averaged value is that which is displayed at each core location noted in later figures. It is realized that the limited number of sediment cores available for this study precludes any detail discussion of the engineering properties of the deposits occurring in the Greenland-Norwegian basin, however, these data do provide an insight into the general sedimentological characteristics of the basin. Sediments blanketing the sea floor underlying the Greenland Sea appear to possess distinctly lower shear strengths than those of the Norwegian Sea (Fig. 4). A general boundary between the two areas appears to approximate the location of the Jan Mayen fracture zone. To the north, average shear strengths in the upper meter or two of the sea floor seldom reach 60 g/cm^2 (0.8 psi), and more commonly range from 30 to 40 g/cm^2 (0.4 to 0.6 psi). South of the Jan Mayen fracture zone shear strengths are much higher and vary from 74 to 142 g/cm^2 (1.2 to 2.0 psi). A distinct area of relatively high strength material is noted along the Jan Mayen ridge. Studies elsewhere have also observed higher shear strengths associated with topographic "highs" (24). This

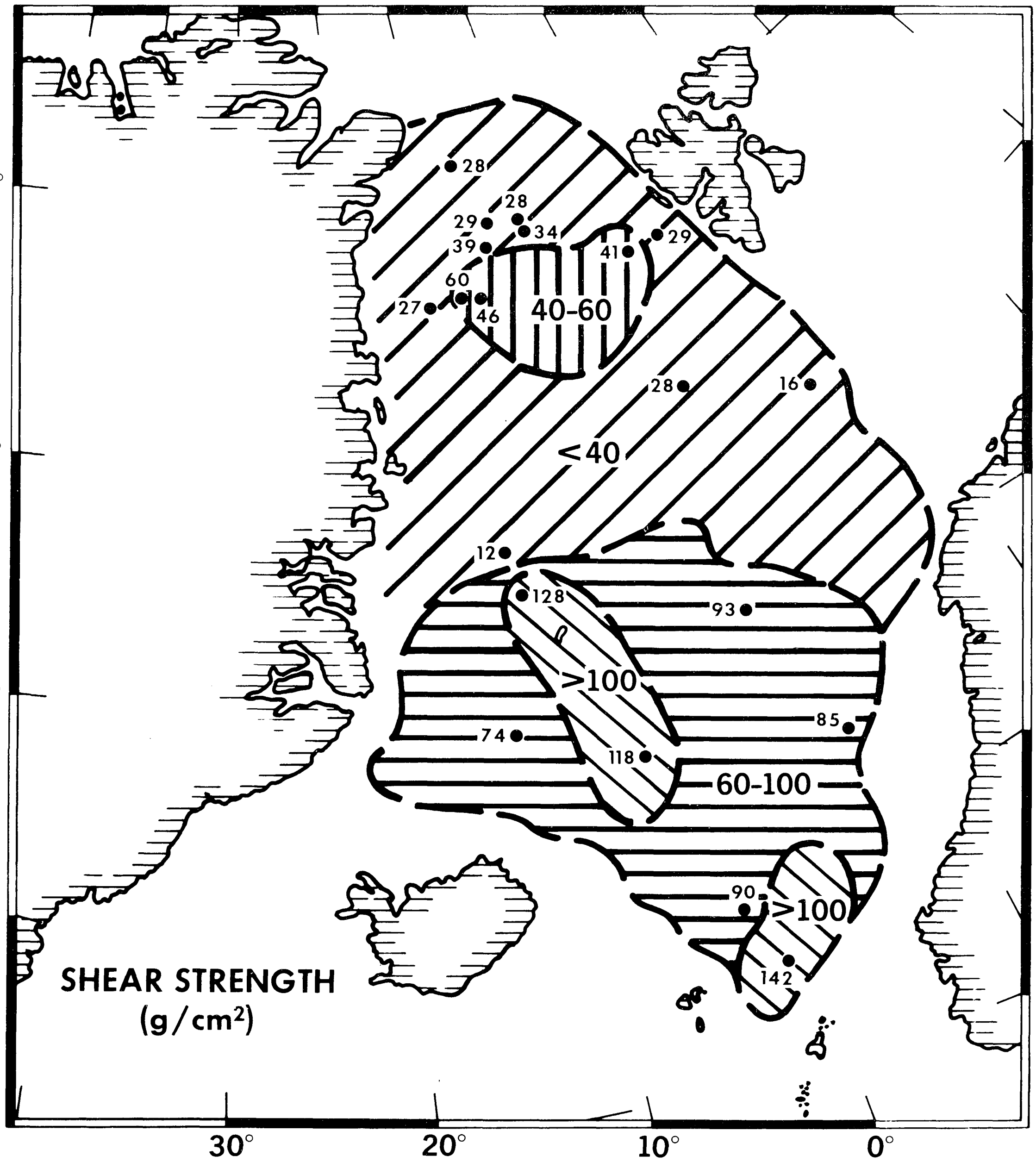

80°
75°
70°
65°
30°
20°
10°
0°
SHEAR STRENGTH
(g/cm²)
40-60
<40
60-100
>100
>100
28
29
28
34
39
41
29
60
27
46
28
16
12
128
93
85
74
118
90
142

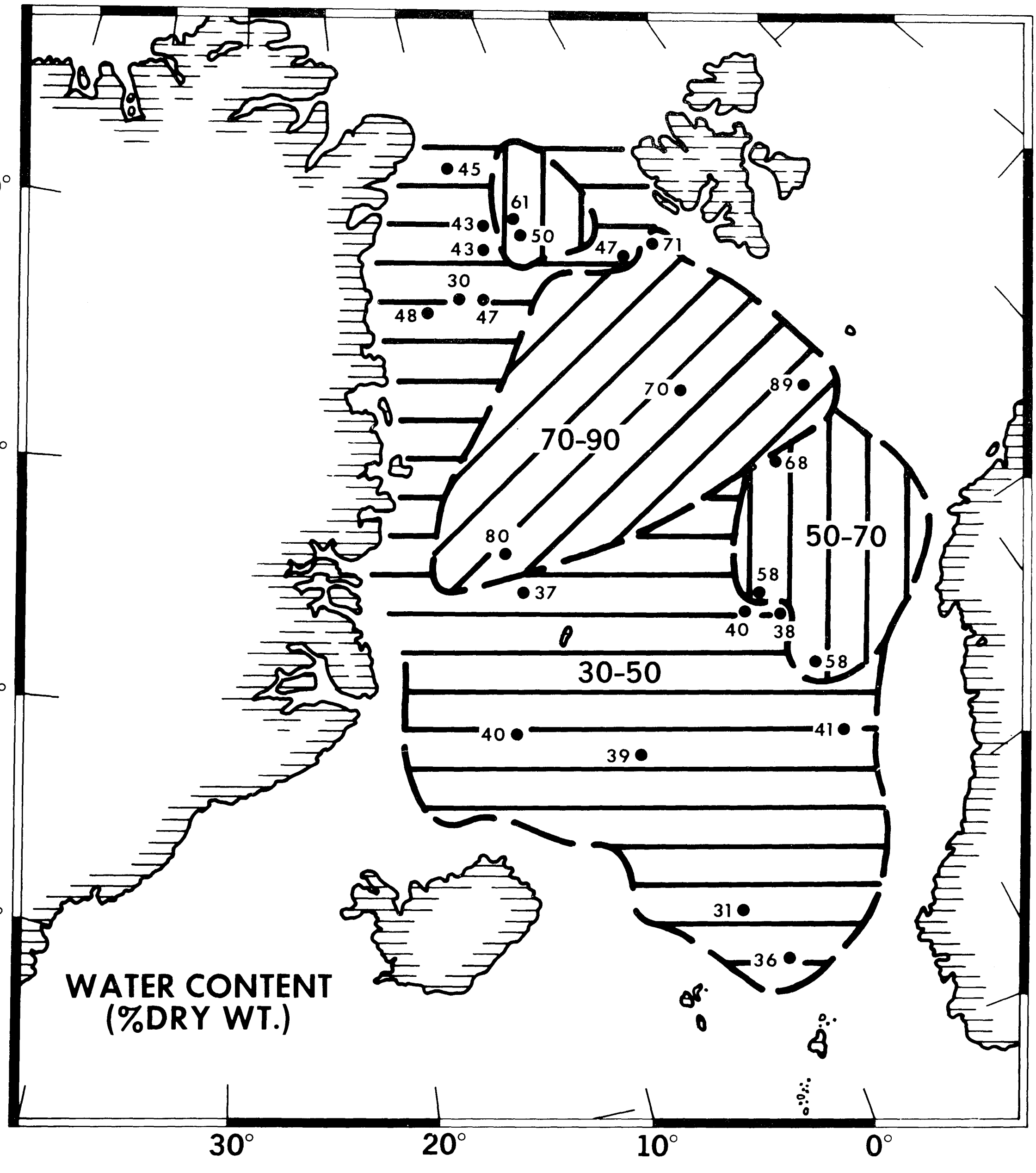
FIG. 4

phenomenon may be possibly attributed to the winnowing action of water movement over "highs" which then results in a slightly denser, stronger sediment occurring in such areas. This cannot, however, be taken as a generalization since this relationship is not always found to be true. Another area of high average shear strength is located just northeast of the Shetland Islands at the foot of the continental slope.

The higher shear strengths found south of the Jan Mayen fracture zone may be, in part, attributed to the influx of slightly coarser material from nearby submarine ridges, the Faeroe and Shetland Islands, the margin of Iceland, as well as from Greenland and Norway. On the other hand, source areas for the northern portion of the basin are few and more distant. As an overall comparison, shear strengths are commonly found to be lower than those reported for the North Atlantic basin (23). Based on the limited data presented here, it is not possible to characterize the various physiographic provinces of the study area by their strength properties. For example, little distinction can be found between the shear strength values reported for the Dumshaf abyssal plain, Voring plateau, or Icelandic plateau.

<u>Water Content</u>.-Water content (w) is used here as a ratio, expressed as a percent, of the weight of water to the weight of oven-dried solids in a specific sediment mass. Laboratory determination of water content is based on the standard procedure outlined by the American Society for Testing Materials (1).

Average water contents for the Greenland-Norwegian basin range from 30 to 89 percent, but more frequently vary between 40 and 60 percent (Fig. 5). The Jan Mayen fracture zone appears to separate the relatively higher water content sediments to the north from the slightly lower water content deposits south of this prominent feature. In comparing figures 1 and 5, little correlation can be seen between the water content distribution and the presence of major bottom features. Continental shelf sediments off the northeast coast of Greenland display water contents of 40 to 50 percent reflecting the relative increase in sediment grain size found in that area. Similar low values in the southern portion of the basin may also be influenced by the presence of coarse sediments eroded from topographic



80°
75°
70°
65°
30°
20°
10°
0°
45
61
43
50
43
47
71
30
48
47
70
89
70-90
68
50-70
80
58
37
40
38
58
30-50
40
41
39
31
36
WATER CONTENT
(%DRY WT.)

FIG. 5

1296

features in the general area. Most of the Greenland-Norwegian Sea basin deposits possess water contents well below those commonly found in the North Atlantic and North Pacific basins (23).

Unit Weight.-Unit weight or bulk density (γ) is the weight per unit of total volume of a given sediment mass. Deep-sea sediments are sufficiently close to being 100 percent saturated that the term saturated unit weight can also be applied here.

Variation in the areal distribution of average unit weights in the Greenland-Norwegian basin is remarkably small. Values range from 1.51 to 1.97 g/cm^3 (94.2 to 122.9 pcf), but more commonly vary between 1.60 and 1.75 g/cm^3 (99.8 and 109.2 pcf) (Fig. 6). A zone of relatively high unit weights [1.72 to 1.97 g/cm^3 (107.3 to 122.9 pcf)] extends across the northern part of the study area between Greenland and Vestspitsbergen. This band of high density sediment may be a phenomenon resulting from a combination of relatively nearby sources of heavy minerals (Greenland and Vestspitsbergen) and the general current pattern in this portion of the Greenland Sea. The presence of similar high density sediment in the southeast sector of the basin could possibly be attributed to bottom topography and bottom currents. Indications are that bottom water flows out of the Norwegian Sea between the Faeroe and Shetland Islands (22). It has also been found that considerable sediment has been deposited on the north slope of the Faeroe-Iceland ridge indicating a relatively quiet bottom energy condition just prior to the passage of the water mass out of the basin and over the ridge. Such a current regimé might tend to selectively deposit heavier grains and result in the distribution pattern shown in figure 6.

Average unit weights throughout the Greenland-Norwegian basin are generally somewhat higher than those reported for much of the North Pacific and North Atlantic basins (23).

Porosity.-Porosity (n) as used here, is the ratio of the volume of voids in a given sediment mass to the total volume of the mass and is calculated based on the measured water content, unit weight and grain specific gravity. A more detailed discussion of porosity determination or that of any of the other engineering properties discussed above is commonly found in texts dealing with soil mechanics.

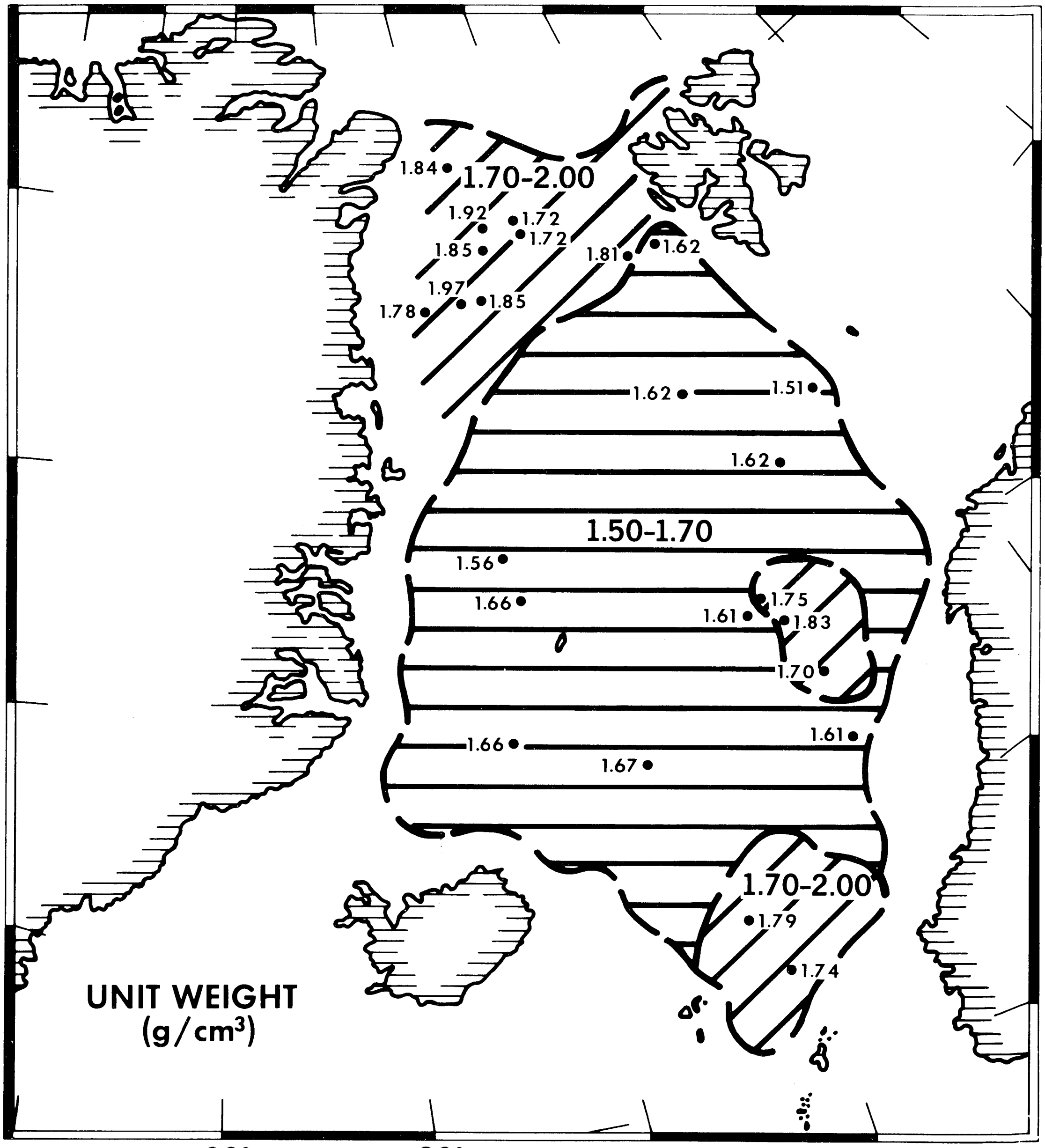

80°
75°
70°
65°
30°
20°
10°
0°
1.70-2.00
1.84
1.92
1.72
1.72
1.85
1.81
1.62
1.97
1.85
1.78
1.62
1.51
1.62
1.50-1.70
1.56
1.66
1.75
1.61
1.83
1.70
1.61
1.66
1.67
1.70-2.00
1.79
1.74
UNIT WEIGHT
(g/cm³)

FIG. 6

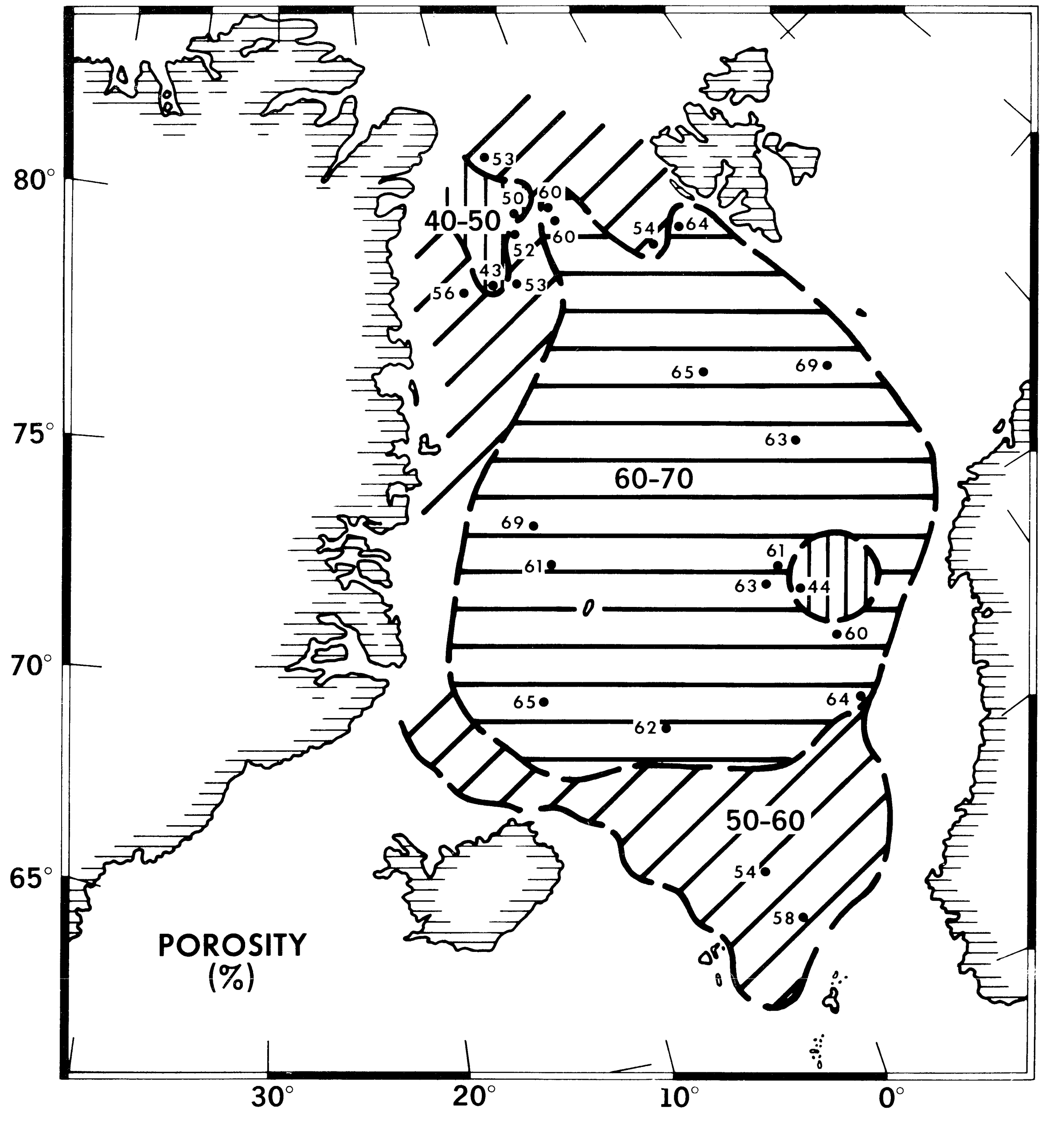
Some of the lowest porosities yet observed in submarine sediments (43 to 50 percent) occur on the northeast continental shelf of Greenland. Porosities in the study area vary from 43 to 69 percent, but more frequently are in the range of 55 to 65 percent (Fig. 7). As might be anticipated, the areal distribution of porosity in the basin has taken on much the same pattern as that noted for unit weight. In comparison, porosities for the Greenland-Norwegian basin appear to be only slightly lower than those commonly found over much of the North Atlantic (25).

Ultimate Bearing Capacity.—Most installations on the deep-sea floor to date, have been relatively light weight (e.g., pipelines, cables, and various pieces of mining equipment). For the engineer concerned with the placement of such structures or hardware on the sea floor, bearing capacity of the bottom material must be ascertained in order to determine the depth to which such an installation will penetrate the sediment during its initial placement. Because bearing capacity rather than consolidation characteristics of deep-sea sediments is of greater significance to the engineer in such a situation, a short discussion of the ultimate bearing capacity of surficial deposits in the Greenland-Norwegian basin has been included here.

Ultimate bearing capacity is the average load per unit of area needed to produce failure by rupture of a supporting sediment mass. This property is a function of the product of the shear strength and one or more factors, which depend on the size and shape of the load as well as the depth of loading. For the purpose of this discussion, a strip load at the sediment surface serves as the basis for ultimate bearing capacity determinations shown in figure 8. The commonly used bearing capacity equation for a shallow strip footing developed by Prandtl (32) and modified by Terzaghi (38) is:

$$Qc = cNc + \gamma D N_q + \frac{\gamma B}{2} N\gamma \qquad (1)$$

Where Qc is the ultimate bearing capacity, c the cohesion, γ sediment unit weight, D the depth of the load below the surface, B width of the footing, and Nc, N_q, and $N\gamma$ are bearing capacity factors which are dependent on the angle of internal friction, depth and shape of the footing and roughness of its base. In the case of a surface loading and assumed zero angle of internal friction, the factors Nq



80°
75°
70°
65°
30°
20°
10°
0°
40-50
60-70
50-60
53
50
60
60
52
43
53
56
54
64
65
69
63
69
61
61
63
44
60
65
62
64
54
58
POROSITY
(%)

FIG. 7

and $N\gamma$ become unity and zero respectively and equation (1) is reduced to:

$$Qc=cNc \quad (2)$$

Although several values have been suggested and used for Nc, 5.14 has been selected for the purpose of this discussion. Based on equation (2) and a few selected surface (0 to 5 cm) shear strength values, ultimate bearing capacity was determined for the study area (Fig. 8). Bearing capacity values range from a low of 31 g/cm^2 (0.4 psi) to a high of 350 g/cm^2 (4.9 psi), but within the few samples in which surface shear strength data exist values of 100 to 200 g/cm^2 (1.4 to 2.9 psi) are more common.

As a result of the sampling procedure, the upper few centimeters of a sediment core are frequently disturbed to a greater degree than the lower portion of the sample. This then would lead to lower shear strengths and thus to lower bearing capacities than would be found had the shear tests been made in situ. The values shown in figure 8 are, therefore, conservative, but just how conservative cannot be determined from the available data. A study in the Gulf of Maine dealing with the variation between in place versus laboratory tests found shear strength in surficial sediments to vary from as little as 1 or 2 percent to as much as 85 percent. Such variations are dependent on the design of the sampling device, sediment type, and handling of the samples prior to laboratory testing.

Sediment Plasticity.—Based on sediment plasticity properties, Casagrande (6) developed a rather simple method for classifying fine-grained deposits. This classification utilizes a plasticity chart, the ordinate being the plasticity index and the abscissa the liquid limit. An A-line drawn across the chart serves as an empirical boundary between inorganic clays above with organic clays and inorganic silts falling below. Based on relatively simple liquid and plastic limit determinations, sediments can be roughtly classed as to their textural and organic characteristics. In some instances it has been found that the plasticity chart also serves to indicate similar and dissimilar source areas of the deposits as was reported by Keller and Lambert (27) in their study of the Mediterranean Sea. The samples studied here do not reveal any such distinction between the deposits of the Norwegian and Greenland Seas (Fig. 9).

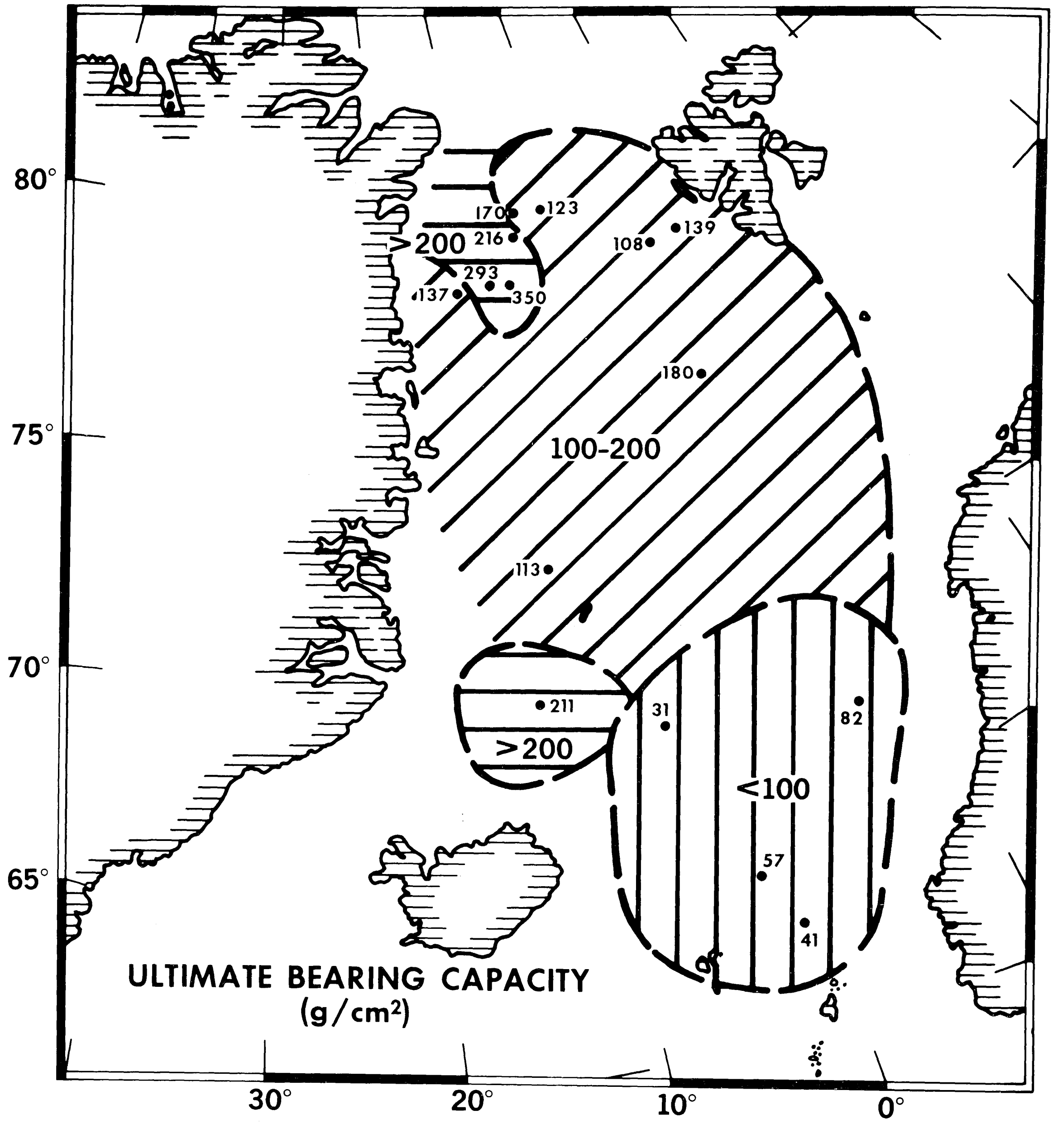

80°
75°
70°
65°
30°
20°
10°
0°
>200
170
123
216
293
137
350
108
139
180
100-200
113
211
>200
31
82
<100
57
41
ULTIMATE BEARING CAPACITY
(g/cm²)

FIG. 8

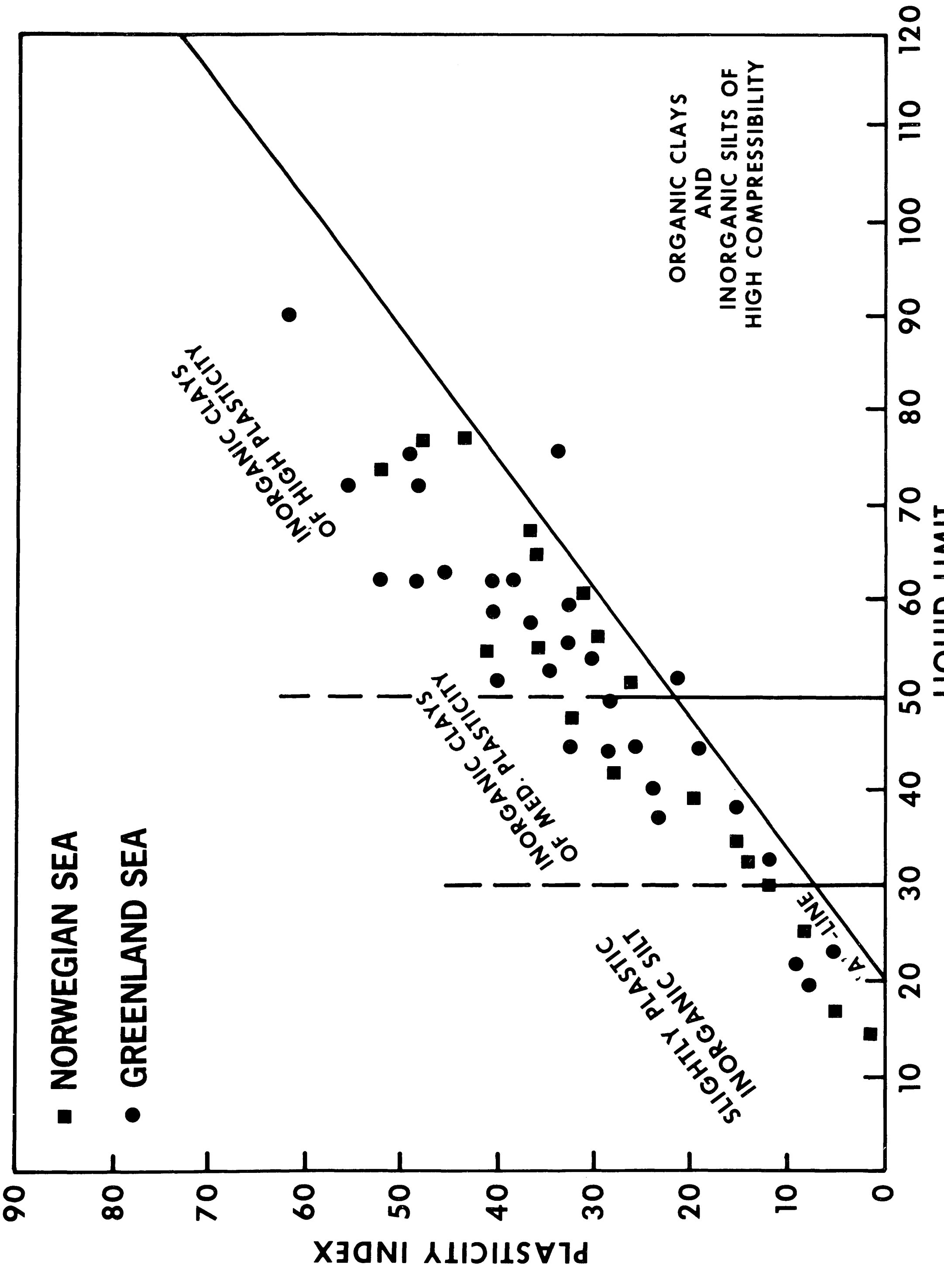

NORWEGIAN SEA
GREENLAND SEA
PLASTICITY INDEX
LIQUID LIMIT
ORGANIC CLAYS
AND
INORGANIC SILTS OF
HIGH COMPRESSIBILITY
INORGANIC CLAYS
OF HIGH PLASTICITY
INORGANIC CLAYS
OF MED. PLASTICITY
SLIGHTLY PLASTIC
INORGANIC SILT
'A'-LINE
0
10
20
30
40
50
60
70
80
90
100
110
120

FIG. 9

As has been found in the case of all the engineering properties discussed above, the plasticity charactistics of the Greenland-Norwegian basin sediments are also noticably distinct from those of the North Atlantic basin. The Greenland-Norwegian basin deposits are found to be largely inorganic clays of medium to high plasticity, sandy clays, and slightly plastic inorganic silts (Fig. 9). Inorganic clays of high to medium plasticity predominate in the North Atlantic basin (34), but are considerably less significant in the area of this study.

Variation of Engineering Properties with Depth.-The previous discussion has dealt with averaged values of various geotechnical parameters which is a practical way in which to display the areal distribution of such properties over a large area. There is, however, obviously considerable variation of these properties with depth owing to a number of different environmental conditions influencing deposition in the basin, e.g., turbidity currents, ice-rafting, and "normal" sedimentation. As shown in Table 1, the "extremes" observed in the Greenland-Norwegian basin are substantial in many instances.

The occurrence of ice-rafted material throughout the basin can be significant and may well prove to be very deceiving when attempting to determine the engineering properties of a deposit to a relatively shallow depth. The significance of turbidity currents and their influence on a depositional environment may not be quite so obvious. Turbidity current deposits (turbidites), which occur in the study area, are decidedly distinct when observed in a cored sample and greatly influence the overall engineering properties of the sedimentary deposit (Fig. 10).

SUMMARY

Sixty-seven sediment cores from throughout the Greenland-Norwegian basin were examined for their engineering properties. Although these relatively few cores cannot be considered as representive of the entire basin, some generalizations are feasible regarding the regional distribution of certain engineering properties and the range of the respective parameters for the surficial layers within the basin deposits.

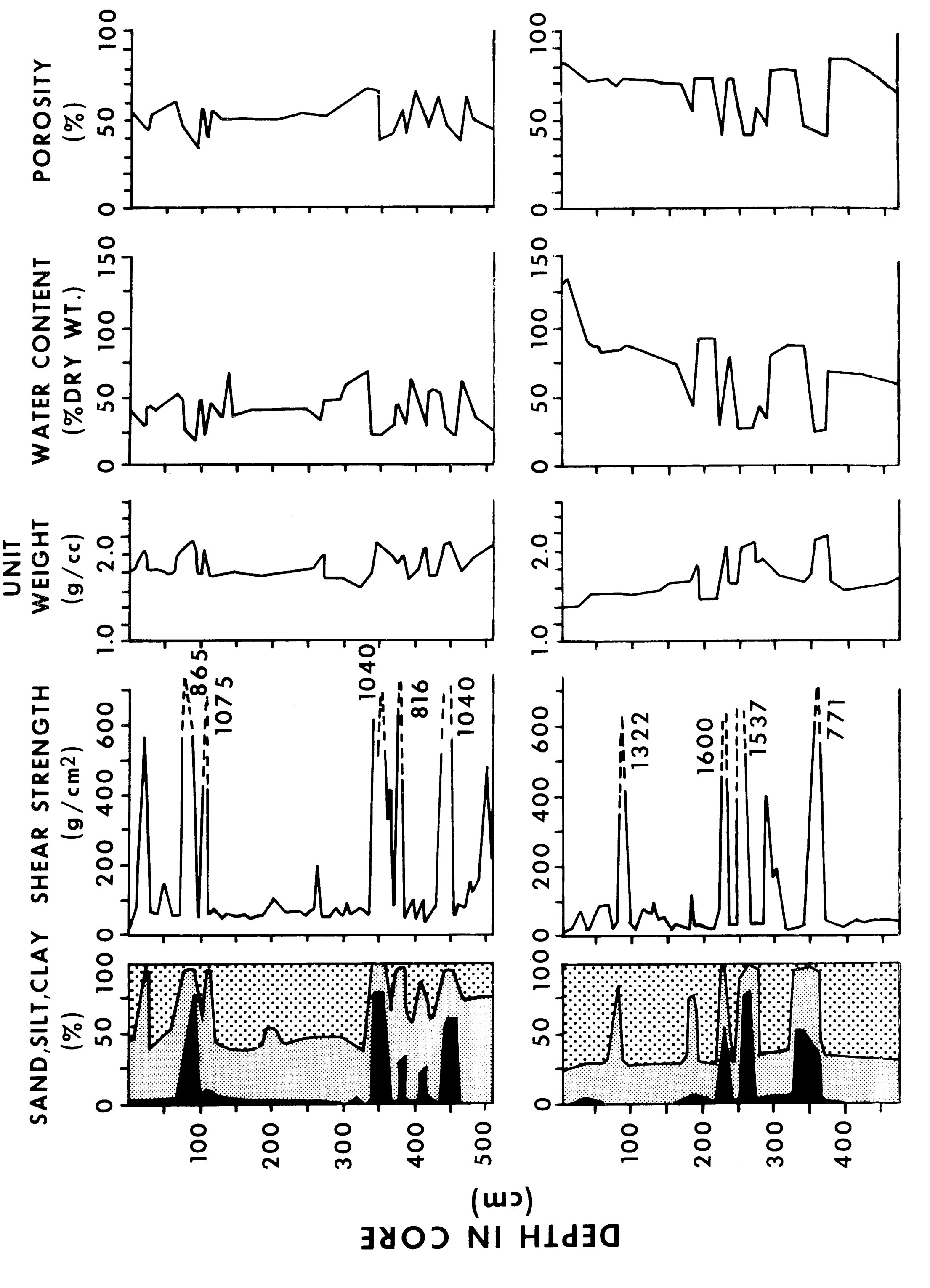

POROSITY (%)
WATER CONTENT (%DRY WT.)
UNIT WEIGHT (g/cc)
SHEAR STRENGTH (g/cm²)
SAND,SILT,CLAY (%)
DEPTH IN CORE (cm)
865
1075
1040
816
1040
1322
1600
1537
771

FIG. 10

1305

Sediments blanketing the Greenland-Norwegian basin are primarily of glacial-fluvial origin, entering the basin from nearby land masses. The deposits consist mainly of silty and sandy clays interlayered with silt and fine sand turbidite sequences. Pelagic clays comprise a large portion of the deposits occurring in the southwest sector of the basin, whereas a foraminiferal ooze constitutes much of the surface deposit in the center of the basin. Ice-rafted pebbles and cobbles occur randomly both laterally and vertically throughout the area.

Average shear strengths range from 27 to 142 g/cm^2 (0.4 to 2.0 psi), with the higher values commonly found in association with the sediments overlying the Jan Mayen ridge. As a general observation it is noted that the sediments south of the Jan Mayen fracture zone possess a higher shear strength than those to the north.

Water content within the basin deposits varies from 31 to 89 percent, but is normally within the range of 40 to 70 percent over much of the area. Water contents are generally lower in the southern part of the basin increasing northward beyond the Jan Mayen fracture zone. In the northern sector of the basin low water contents are also encountered on the northeast continental shelf of Greenland.

Average unit weights are relatively high in comparison to other deep-sea deposits and are found to range from 1.51 to 1.97 g/cm^3 (94.2 to 122.9 pcf) in the Greenland-Norwegian basin. Much of the basin, however, is found to be covered with sediments possessing unit weights between 1.60 and 1.75 g/cm^3 (99.8 to 109.2 pcf). Areas of relatively high density material are found in the northern and southern most parts of the basin. This distribution may reflect the influence of bottom current transport.

Porosity of the Greenland-Norwegian basin deposits varies from 43 to 69 percent, but more commonly ranges from 55 to 65 percent over much of the area. Relatively low porosities occur in the northern and southern parts of the study area.

Using the classification system developed by Casagrande (6) which is based on the plastic characteristics of a sediment, it is found that the Greenland-Norwegian basin deposits are largely classed as inorganic clays of medium to high plasticity, sand clays, and slightly plastic inorganic silts. Based on plasticity indices no basic distinction can be made among the sediments found in various parts of the basin as to their source.

An overall examination of the distribution of engineering properties in the Greenland-Norwegian basin indicates that those deposits underlying the Greenland Sea possess relatively higher unit weight and water content, but lower porosity and shear strength than those sediments of the Norwegian Sea. In comparison to the North Atlantic, the Greenland-Norwegian basin sediments display distinctly different engineering properties (Table 1). Unit weights are considerably higher than those in the Atlantic as are shear strengths and grain specific gravities, but to a somewhat lesser extent. Such properties as water content, porosity, sensitivity, liquid limit, and plastic limit are all lower than those reported by Keller and Bennett (26) for the North Atlantic basin.

ACKNOWLEDGMENTS

I gratefully acknowledge the assistance of Joseph Kravitz of the U. S. Naval Oceanographic Office for providing the photograph shown in figure 3 and of G. Leonard Johnson from the same office for permission to use his physiographic diagram.

TABLE I

VARIATION OF ENGINEERING PROPERTIES

	γ (g/cm^3)	w (%)	n (%)	τ_f (g/cm^2)	S_t	G	w_L	w_p
GREENLAND-NORWEGIAN BASIN								
MAX.	2.21	187	84	300	9	2.98	96	40
MIN.	1.32	20	35	5	1	2.56	17	12
AVE.	1.72	51	59	57	3	2.74	51	23
NORTH ATLANTIC BASIN								
MAX.	2.56	207	85	925	88	2.86	104	38
MIN.	1.25	15	32	1	1	2.45	47	20
AVE.	1.52	86	66	52	4	2.73	65	27

S_t = Sensitivity
G = Grain specific gravity
w_L = Liquid limit
w_p = Plastic limit
see text for other symbols

REFERENCES

(1) American Society for Testing Materials (1958): 1958 Book of ASTM Standards including tentatives, Part 4. Philadelphia, Pa., 1426 p.

(2) Arrhenius, G. (1952): Sediment cores from the East Pacific: Reports of the Swedish Deep-Sea Expedition, 1947-1948, v. 5, no. 1, 277 p.

(3) Böggild, O. B. (1899): Habvundens afleiringer: Den Danske Ingolf-Expedition, v. 1, no. 3.

(4) Bryant, W. R., P. Cernock, and J. Morelock, Jr. (1967): Shear Strength and consolidation characteristics of marine sediments from the western Gulf of Mexico. pp. 41-62, in Richards, A. F., (ed.) Marine Geotechnique, Univ. Ill. Press, Urbana, Ill., 327 p.

(5) Buchan, S., F. C. D. Dewes, D. M. McCann and D. Taylor Smith (1967): Measurements of the acoustic and geotechnical properties of marine sediment cores. pp. 67-92, in Richards, A. F., (ed.) Marine Geotechnique, Univ. Ill. Press, Urbana, Ill., 327 p.

(6) Casagrande, A. (1948): Classification and identification of soils. American Society Civil Engineers, Trans. v. 113, pp. 901-931.

(7) Evans, I., and G. G. Sherratt (1948): A simple and convenient instrument for measuring the shear resistance of clay soils. Jour. Scientific Instruments and Physics in Industry, v. 25, pp. 411-414.

(8) Fisk, H. N., and B. McClelland (1959): Geology of continental shelf off Louisiana: its influence on offshore foundation design. Geological Society America, Bulletin, v. 70, pp. 1369-1394.

(9) Hamilton, E. L. (1956): Low sound velocities in high porosity sediments. Jour. Acoustical Society America, v. 28, pp. 16-19.

(10) Hamilton, E. L. (1959): Thickness and consolidation of deep-sea sediments. Geological Society America, Bulletin, v. 70, pp. 1399-1424.

(11) Hamilton, E. L., and H. W. Menard (1956): Density and porosity of sea-floor surface sediments off San Diego, California. American Association Petroleum Geologists, v. 40, pp. 754-761.

(12) Hansbo, S. (1957): A new approach to the determination of the shear strength of clay by the fall-cone test. Royal Swedish Geotechnical Institute Proc., No. 14, 47 p.

(13) Harrison, W., M. P. Lynch, and A. G. Altschaeffl (1964): Sediments of lower Chesapeake Bay, with emphasis on mass properties. Jour. Sedimentary Petrology, v. 34, pp. 727-755.

(14) Holtedahl, H. (1950): A study of the topography and the sediments of the continental slope west of Möre, W. Norway. Univ. Bergen Årbok, Naturv. r. 5.

(15) Holtedahl, H. (1955): On the Norwegian continental terrace, primarily outside Möre-Romsdal, its geomorphology and sediments. With contributions on the Quaternary geology of the adjacent land and on the bottom deposits of the Norwegian sea. Univ. Bergen Årbok, Naturv. r. 14.

(16) Holtedahl, H (1959): Geology and paleontology of Norwegian Sea bottom cores. Jour. Sedimentary Petrology, v. 29, pp. 16-29.

(17) Igelman, K. R., and E. L. Hamilton (1963): Bulk densities of mineral grains from Mohole samples (Guadalupe site). Jour. Sedimentary Petrology, v. 33, pp. 474-478.

(18) Jerbo, A. (1967): Geochemical and strength aspects of Bothnian clay sediments. pp. 177-186, in Richards, A. F. (ed.) Marine Geotechnique, Univ. Ill. Press, Urbana, Ill., 327 p.

(19) Johnson, G. L., and O. B. Eckhoff (1966): Bathymetry of the North Greenland sea. Deep-Sea Research, v. 13, pp. 1161-1173.

(20) Johnson, G. L., and B. C. Heezen (1967): Morphology and evolution of the Norwegian-Greenland Sea. Deep-Sea Research, v. 14, pp. 755-771.

(21) Johnson, G. L., J. A. Ballard, and J. A. Watson (1968): Seismic studies of the Norwegian continental margin. Norsk Polarinstitut-Årbok 1966, pp. 112-119.

(22) Jones, E. J. W., M. Ewing, J. I. Ewing, and S. L. Eittreim (1970): Influences of Norwegian Sea overflow water on sedimentation in the northern North Atlantic and Labrador Sea. Jour. Geophysical Research, v. 75, pp. 1655-1680.

(23) Keller, G. H. (1968): Shear strength and other physical properties of sediments from some ocean basins. pp. 391-417, in Proc. Civil Engineering in the Oceans. American Society of Civil Engineers, 926 p.

(24) Keller, G. H. (1969): Mass properties of the sea floor in a selected depositional environment. pp. 857-877, in Proc. Civil Engineering in the Oceans - II. American Society of Civil Engineers, 1265 p.

(25) Keller, G. H., and R. H. Bennett (1968): Mass physical properties of submarine sediments in the Atlantic and Pacific basins. pp. 33-50, in Proc. XXIII International Geological Congress, Section 8, 321 p.

(26) Keller, G. H., and R. H. Bennett (1970): Variations in the mass physical properties of selected submarine sediments. Marine Geology, v. 9, pp. 215-223.

(27) Keller, G. H., and D. Lambert (1971): Geotechnical properties of submarine sediments, Mediterranean Sea. in Proc. Mediterranean Symposium, VIII International Sedimentological Congress (in press).

(28) Kolb, C. R., and R. I. Kaufman (1967): Prodelta clays of southeast Louisiana. pp. 3-21, in Richards, A. F., (ed.) Marine Geotechnique, Univ. Ill. Press, Urbana, Ill., 327 p.

(29) McClelland, B. (1967): Progress of consolidation in delta front and prodelta clays of the Mississippi River. pp. 22-40, in Richards, A. F. (ed.) Marine Geotechnique, Univ. Ill. Press, Urbana, Ill., 327 p.

(30) Moore, D. G., and G. Shumway (1959): Sediment thickness and physical properties: Pigeon Point Shelf, California. Jour. Geophysical Research, v. 64, pp. 367-374.

(31) Peterson, M. N. A., N. T. Edgar, M. Cita, S. Gartner, Jr., R. Goll, C. Nigrini, C. von der Borch (1970): Initial reports of the Deep-Sea Drilling Project, v. II, Washington, D. C., 501 p.

(32) Prandtl, L. (1920): Über die Härte plastischer Körper. Koniglichen Gesellschaft der Wissenschaften zu Göttingen, Matematisch - physikalische Klasse, p. 74-85.

(33) Richards, A. F. (1961): Investigations of deep-sea sediment cores, I. Shear strength, bearing capacity, and consolidation. U. S. Navy Hydrographic Office, Tech. Rept. 63, 70 p.

(34) Richards, A. F. (1962): Investigation of deep-sea sediment cores, II. Mass physical properties. U. S. Navy Hydrographic Office, Tech. Rept. 106, 146 p.

(35) Richards, A. F., and E. L. Hamilton (1967): Investigations of deep-sea sediment cores, III. Consolidation. pp. 93-117, in Richards, A. F., (ed.) Marine Geotechnique, Univ. Ill. Press, Urbana, Ill., 327 p.

(36) Schmelck, L. (1882): On oceanic deposits: The Norwegian North-Atlantic expedition 1876-1878, v. 9, no. 2.

(37) Schreiber, B. C. (1967): Marine Geophysical Survey Program 65-67, Western North Atlantic and Eastern and Central North Pacific Oceans - core, sound velocometer, hydrographic and bottom photographic stations. Alpine Geophysical Associates, Inc., SP-96-SF-8, Area SF, v. 8, 19 p. 26 fig.

(38) Terzaghi, K. (1943): Theoretical soil mechanics. John Wiley & Sons, Inc., New York, 510 p.

(39) Texas Instruments, Inc. (1967): U. S. Naval Oceanographic Office Marine Geophysical Survey Program 1965-1967, North Atlantic Ocean, Norwegian Sea and Mediterranean Sea. Area 1, v. 5, Geology and Geophysics, 39 p.

FIGURE CAPTIONS