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MEASUREMENT OF RESIDUAL/REMOLDED VANE SHEAR STRENGTH OF MARINE SEDIMENTS

by

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and

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Introduction

Laboratories typically perform two vane shear tests at each location, one to obtain the undisturbed undrained vane shear strength (Su) and another to obtain an undrained shear strength (Sur) on the same material after destruction of the structure along the surface of sliding. A sensitivity of the soil (S_t), is defined as Su/Sur. The term sensitivity indicates the effect of remolding on the consistency of a clay, regardless of the physical nature of the causes of the change, (Terzaghi and Peck, 1). The vane shear strength test on the disturbed material is performed in the same manner as the original test. Between the two tests the sample's original structure is destroyed, either by physically removing the sample and mixing it either

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by hand with a spatula (Keller et al., 2) or with a mechanical mixer or by rapidly rotating the vane within the solid through several revolutions (Calius and Richards, 3). Few comparisons of the two techniques are available, although Richards (4) indicated that soil remolding by hand, with subsequent retesting by laboratory vane, yields a somewhat lower value of shearing strength on the disturbed material. Higher sensitivity values thereby result.

The resulting vane shear strength after destruction of the soil structure has been variously called the remolded strength, residual strength or ultimate strength. The actual term to be used is dependent upon how the soil structure was destroyed. The process of kneading or working a clay is commonly referred to as remolding. Soils that have had their natural structure modified by manipulation in this manner are called remolded soils (ASTM, 6). The softening effect is probably due to two different causes: destruction of the orderly arrangement of the molecules in the adsorbed layers, and injury to the structure that the clay acquired during the process of sedimentation. In contrast, the residual or ultimate shear strength was defined by Skempton (7) as the ultimate shearing resistance after large displacements under fully drained conditions. After a surface of sliding forms and extensive slip occurs, the bonds between the soil particles are destroyed and the particles along the surface of sliding assume an orientation favorable to a low resistance to shear along the surface.

In the following sections the variation of shear strength as effected by (1) remolded or residual vane strength as compared to the undistrubed vane shear strength, (2) effect of anisotropy on the variation of the measured vane shear strength values, (3) effect of the number of revolutions of the vane on the determination of vane remolded shear strength, and (4) the effect of the liquidity index on the remolded shear strength. This will be followed by case studies from the North Pacific and the Gulf of Mexico.

Vane shear strength results presented in this paper were performed using a Wykham/Farrance device with torsional springs. Tests were conducted normally at 9 degrees per minute unless noted otherwise. A test series was conducted using various rates of vane rotation on a pelagic clay material from the North Pacific as shown in Fig. 2. A review of Fig. 2 shows that for the test conditions and material being tested there was no effect of rotation rate on the resulting vane shear strength. A similar test program showed the same effect for the other materials used in this study.

Remolded/Residual Vane Shear Strength

An idealized schematic of the various shear strengths determined using the vane shear apparatus is presented in Fig. 1. A review of Fig. 1 shows the residual strength also called the ultimate strength as defined by Skempton (7) is the strength after a large deformation. For the purposes of this study the residual shear strength (S_R) will be defined as the vane strength after a rotation of 180 degrees (0.5 revolutions of the vane). In contrast, the determination of the remolded vane shear strength depends on whether the test was conducted using an in situ vane (S_{FVR}) or in the laboratory. In the labortory, remolded vane shear strength will be shown to depend on whether the soil was remolded using either a vane (S_{LVR}) or by hand manipulation (S_{RM}). For the purposes of this paper, vane remolding will be considered an approximation of the more thorough hand or mechanical remolding.

A comparison of relative remolded vane shear strengths as determined by these three methods is $S_{FVR} > S_{LVR}$ or S_{RM}. The reason for the observed variation between field and laboratory remolded vane shear strengths is believed due to the reduction in applied stress, Arman et al. (8) and Fenske (9). Law (10) has shown that the vane shear strength increases with increasing horizontal stress and to a much lessor degree on the vertical stress. In contrast, the variation between the vane shear strengths as determined from the laboratory miniature vane remolded test (S_{LVR}) and the hand remolded vane test (S_{RM}) is small as shown in Figs. 3 through 6. Whether S_{RM} or S_{LVR} is largest, based on very limited data, appears to depend on the Liquidity Index of the soil, see Fig. 7.

Effect of Anisotropy

The effect of anisotropy on the determination of vane remolded and hand remolded vane shear strengths was investigated using box cores from the Eel River Fan. The box cores were taken from a water depth of appoximately 500 m. The soil recovered in the box core was a silty clay. Vane tests were performed in both the vertical (Fig. 4) and the horizontal (Figs. 5 and 6) directions. The horizontal tests were conducted at depths of 6 cm and 33 cm in the box core. A comparison between the vertical and horizontal tests indicate that the hand remolded vane tests at the top of the box core are equal (2.5 kPa). The hand remolded vane test at a depth of 33 cm is increased to a value of approximately 3.5 kPa. This behavior would be expected with increasing depth and decreasing water content.

In comparison, the shear strength as determined in the vane remolded test is dependent on the direction in which the test is performed. A review of Fig. 4 for the vertical test indicates a vane remolded shear strength of approximately 6 kPa, while in Fig. 5 for the horizontal test a remolded shear strength of approximately 3.3 kPa is determined. The undistrubed vane shear strengths presented in Figs. 4 through 6 exhibit this same behavior.

Effect of the Number of Revolutions On the Determination of the Residual Vane Shear Strength

The effect of the number of revolutions of the vane on the determination of the remolded vane shear strength for a marine clay is shown in Fig. 8. A review of Fig. 8 shows that for a case shown the shear strength decreses rapidly during the first three vane revolutions. After the first three revolutions the shear strength is relatively constant over the interval from 3 to 10 vane revolutions. A summary of selected recommendations for the number of vane revolutions to determine remolded vane shear strengths is presented in Table 1. Based on the above limited information the vane remolded shear strength should be determined only after a minimum of between 3 to 5 revolutions of the vane.

REFERENCE	NUMBER OF VANE REVOLUTIONS	
	LAB	FIELD
Arman et al. (8)	6	10
Skempton (11)	-	6 or more
Eden and Hamilton (5)	4	-
Pyles (12)	3	3

Table 1 - Summary of Selected Recommendations For The Number of Revolutions to Determine the Vane Remolded Shear Strength

Effect of the Liquidity Index On Remolded Vane Shear Strength

A number of investigators have studied the relationship between remolded shear strength and the liquidity index (LI). Pyles (12) showed that the ratio of vane remolded shear strength (S_{LVR}) to the undisturbed peak vane shear strength (S_u) is constant for all values of liquidity index (LI), but was dependent on whether vane strengths were determined in the field or laboratory. The vane remolded shear strength in Pyles study was determined after 3 revolutions. A linear relationship between LI and the logarithm of Sensitivity (S_t) has been shown by Bjerrum (13) and later expanded by Eden and Hamilton (13). In this work Bjerrum showed that as the liquidity index increases the sensitivity also increases. A form of this relationship can be presented as the liquidity index (LI) versus the logarithm of the remolded shear strength as shown in Fig. 9. This graph is a modified form of one previously presented by Sullivan et al. (16). The data presented in Fig. 9 was developed using different testing techniques (CU triaxial, vane, unconfined compression tests) on remolded soil. A review of Fig. 9 shows that a uniquie relationship exists between the liquidity index and the remolded strength independent of the manner in which the shear strength is determined. Various equations describing this relationship have been presented by various authors but are generally limited to the ranges in liquidity index or shear strength over which they are applicable (Wroth and Wood, 14; Sullivan et al., 16).

Case Studies

Test results from three sites are presented in Figs. 10 to 14. In each case, laboratory miniature vane tests were peformed to determine both the undisturbed and vane remolded shear strengths. In addition, the variation of bulk density, water content, plastic limit, and liquid limit are also presented as a function of depth.

A. North Pacific, Deep Sea Drilling Project Site 576A

The site was located near the Shatsky Rise in the Northern Pacific as shown in Fig. 10. The site consisted of two units. The upper unit was subsequently divided into two subunits (1A and 1B). Subunit 1A (0-28 m) consisted of a yellowish brown to brown pelagic clay of Pliocene and Quaternary age. Shipboard scientists estimated that this unit is largely of eloian origin. Subunit 1B (28-55 m) consisted of a dark brown pelagic clay which is very fine grained. Unit II extended from a depth of 55 m to the bottom of the hole and consisted of interbedded dark brown pelagic clay similar to subunit 1B and pale brown nannofossil ooze. A summary of the bulk density, water content, liquid and plastic limits as well as the average and remolded vane shear strengths are summarized in Fig. 11. A review of Fig. 11 shows that the undisturbed vane shear strength is greater at all depths than the remolded vane shear strength and that the S_t is variable over depth ranging from approximately 3 at a depth of 10 m to 1.4 at a depth of 42 m.

B. Mississippi Fan, Deep Sea Drilling Project Site 616B

The site was located in the lower part of the Mississippi Fan alongside the fan channel as shown in Fig. 12. The site consisted of two units. The upper unit consisted of a thin (25 cm) layer of yellow brown marly foraminiferal ooze. Unit II extended below this layer to the bottom of the hole (0.25 - 370 m). This unit was subsequently divided into four sequences. Sequence 1 (0.25 - 65 m) consisted of silt laminated muds and fine grained turbidites with highly inclined laminae. Sequence 2 (65 - 146 m) consisted of homogeneous very fine grained mud and clay with fewer thin silt laminae. Sequence 3 (146 - 250 m) consisted of interbedded medium to fine grained sands, silty sands, lignite bearing muds and fine grained silt mud turbidites. Sequence 4 (250 - 370 m) consisted of homogeneous muds. A summary of the bulk density, water content, liquid and plastic limits as well as the average and remolded vane shear strengths are summarized in Fig. 13. A review of Fig. 13 shows that the undisturbed vane shear strength is greater at all depths than the remolded vane shear strength and that the S_t varies from 3.5 at a depth of 70 m to 6.5 at a depth of 200 m.

C. Mississippi Fan, Deep Sea Drilling Project Site 617A

The site was located near the upper portion of the Mississippi Fan in the toe area of the Massingale Slide as shown in Fig. 12. The site consisted of two units. The upper unit is thin (25 cm) consisting of an olive brown foraminifer mud. Thnis unit overlays Unit II which is made up of terrigenous muds and silts. The Unit II is subsequently broken up into three sequences. Sequence 1 (0.25 - 46 m) consists of homogenous muds and muds with silt laminations. Sequence 2 (46 - 84 m) is composed of silt laminated mud. Sequence 3 (84 - 192 m) consists of mud with silt laminations. A summary of the bulk density, water content, liquid and plastic limits as well as the average and remolded vane shear strengths are summarized in Fig. 14. A review of Fig. 14 shows that the undisturbed vane shear strength is greater at all depths than the remolded vane shear strength and that the S_t varies from 10 at 2 m to 14 at a depth of 50 m.

A comparison of these case studies with previously published sites is presented in Table 1. A review of this table shows that for the cases presented the range of sensitivity of marine sediments varies between 2 to 14. In addition, the sensitivity is shown to increase with depth.

Summary

In summary the following observations can be made.

(1) Hand remolded vane shear strengths do not depend on vane orientation.

(2) Vane remolded shear strengths vary with the orientation of the vane.

(3) Vane remolded shear strengths should be determined only after a minimum of between 3 to 5 revolutions of the vane.

(4) Field vane remolded tests give higher shear strengths than either laboratory vane remolded tests or hand remolded vane shear strength tests.

(5) Whether the hand remolded or vane remolded shear strength test is largest, based on very limited data, appears to be based on the Liquidity Index (LI) of the soil.

(6) A linear relationship exists between the Liquidity Index (LI) and the logarithm of remolded shear strength. This relationship appears to be independent of the manner in which the shear strength is determined or the soil remolded.

(7) Sensitivities for DSDP site 576A in the Northern Pacific vary from 3 at a depth of 10 m to 1.4 at a depth of 42 m.

(8) Sensitivities for DSDP site 616B in the Gulf of Mexico on the Mississippi Fan vary from 3.5 at a depth of 70 m to 6.5 at a depth of 200 m.

(9) Sensitivities for DSDP site 617A in the Gulf of Mexico on the Mississippi Fan vary from 10 at the surface to 14 at a depth of 50 m.

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Sample	Water Depth, m	Location	Water Content, %	Average S_u, kPa	Sensitivity
CRUX 3	unknown	Pacific	232	12	10
CRUX 201			224	8	10
STYX 9-1C	5398	15°40'S, 172°00'W	133	13	2
STYX 9-2	5060	11°55'S, 169°32'W	284	5	4
STYX 9-3	4300	8°01'S, 166°35'W	148	6	3
STYX 9-5A	5069	8°36'N, 154°37'W	247	7	4
STYX 9-5B	5032	8°36'N, 154°18'W	388	9	4
STYX 10-1	5517	23°50'N, 143°58'W	123	4	2
STYX 10-1C	5508	23°25'N, 144°05'W	118	4	3
DSDP 576A	6217	Northern Pacific	98 to 216	Upper 10m: S_u = 0.6	2-10
				10 to 25 m: S_u = 0.28	
		32° 0' N, 164°30'W		Below 25 m: S_u = 0.22	
DSDP 616B	2983	Mississippi Fan Gulf of Mexico	50	70m: 20	3.5
			25	200m: 130	6.5
		26°24'N, 86°36'W			
DSDP 617A	2467	Mississippi Fan Gulf of Mexico	75	2m: 10	10
			42	50m: 72	14
		26°24'N, 88°24'W			

TABLE 1 - Location and Undrained Strength Properties of Selected Marine Sediments.
(Expanded From Noorany, 1985)

LIST OF FIGURES

Fig. 8 - Vane Remolded Laboratory Miniature Vane Strengths Versus Number of Vane Rotations, Mississippi Fan, DSDP Leg 96, Site 617A, Core 1-2, Vertical Vane Orientation.

Fig. 9 - Remolded Shear Strength Versus Liquidity Index.

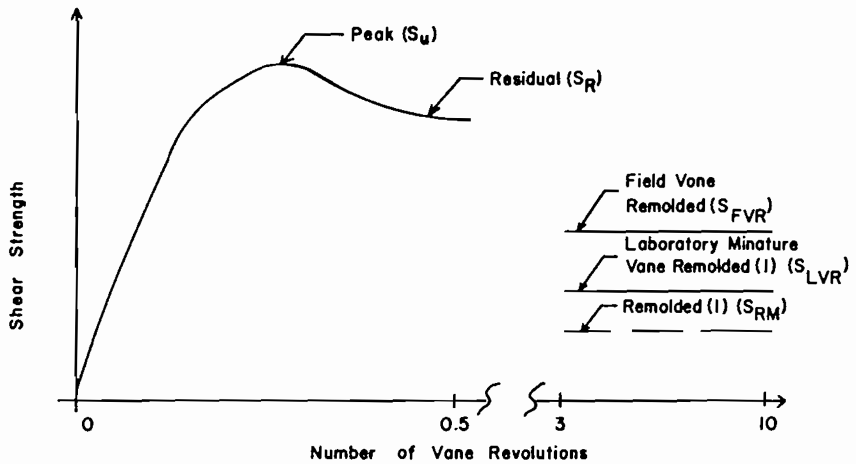
Fig. 10 - Location Map of DSDP Site 576A In The Northwest Pacific.

Fig. 11 - Geotechnical Properties of Northwest Pacific Pelagic Clays: DSDP, Leg 86, Site 576 A.
(Data expanded from Geotechnical Consortium, 1984.)

Fig. 12 - Location Map of Mississippi Fan In The Gulf of Mexico showing Sites Studied, DSDP Leg 96.

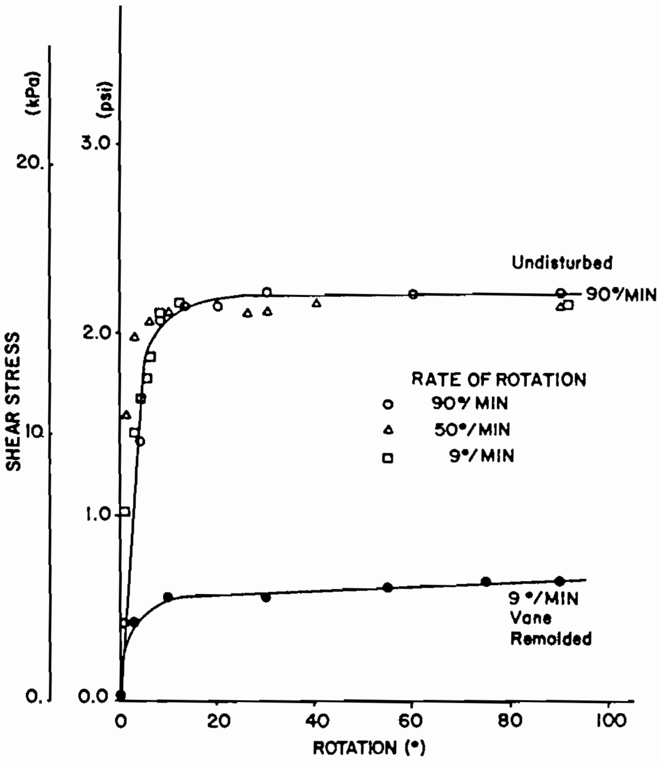
Fig. 13 - Geotechnical Properties of Mississippi Fan Sediments: Deep Sea Drilling Project, Leg. 96, Site 616B.
(Data expanded from shipboard Scientists Report.)

Fig. 14 - Geotechnical Properties of Mississippi Fan Sediments, DSDP), Leg 96, Site 617A.
(Data expanded from shipboard Scientists Report.)



Note: (1) Shear strength determined from either Laboratory Minature Vane Remolded or Remolded may be reversed due apparently to soils plasticity characteristics.

Fig. 1



SHEAR STRESS
(kPa)
(psi)
20.
10.
0.
3.0
2.0
1.0
0.0
0
20
40
60
80
100
ROTATION (°)
Undisturbed
90°/MIN
RATE OF ROTATION
○ 90°/ MIN
△ 50°/MIN
□ 9°/MIN
9 °/MIN
Vane
Remolded

Fig. 2

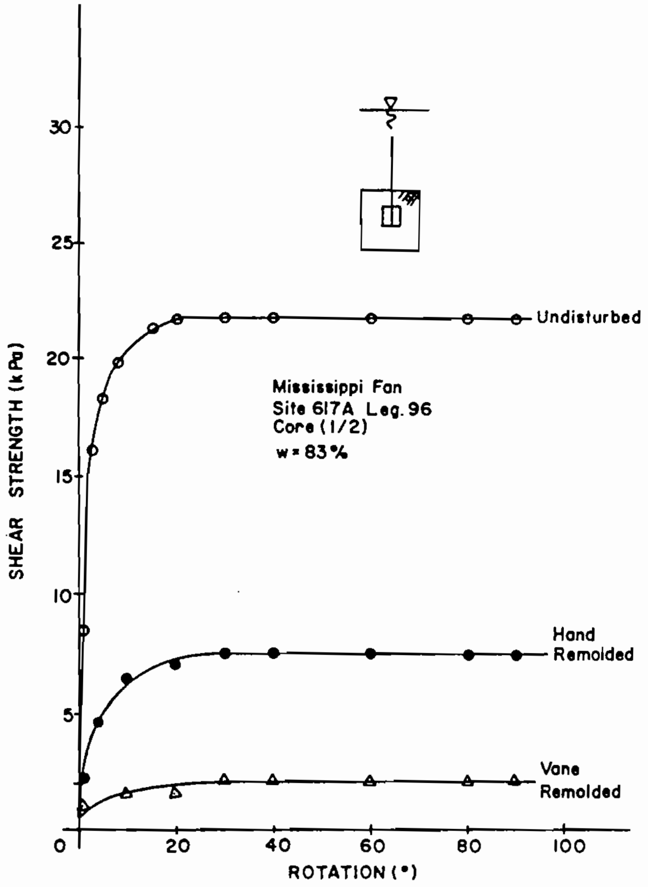
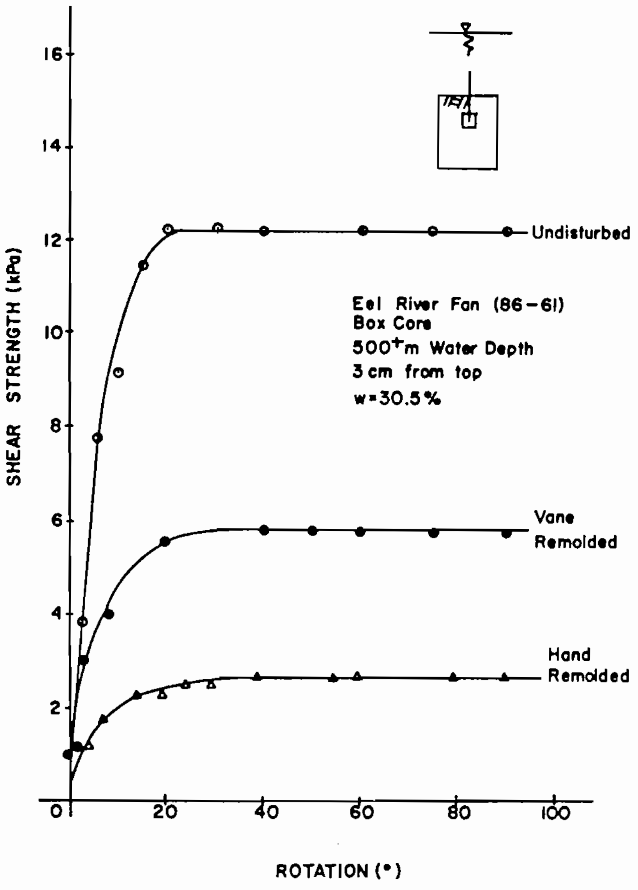

30
25
20
15
10
5
0
SHEAR STRENGTH (kPa)
Undisturbed
Mississippi Fan
Site 617A Leg. 96
Core (1/2)
w = 83%
Hand
Remolded
Vane
Remolded
20
40
60
80
100
ROTATION (°)

Fig - 3



16
14
12
10
8
6
4
2
0
20
40
60
80
100
SHEAR STRENGTH (kPa)
ROTATION (°)
Undisturbed
Vane Remolded
Hand Remolded
Eel River Fan (86-61)
Box Core
500+m Water Depth
3 cm from top
w=30.5%

Fig. 4

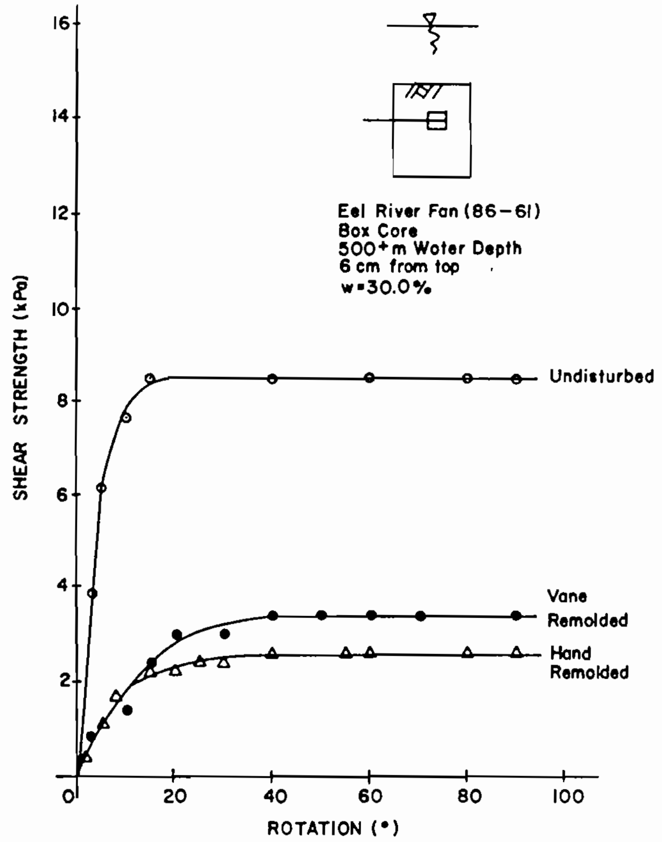
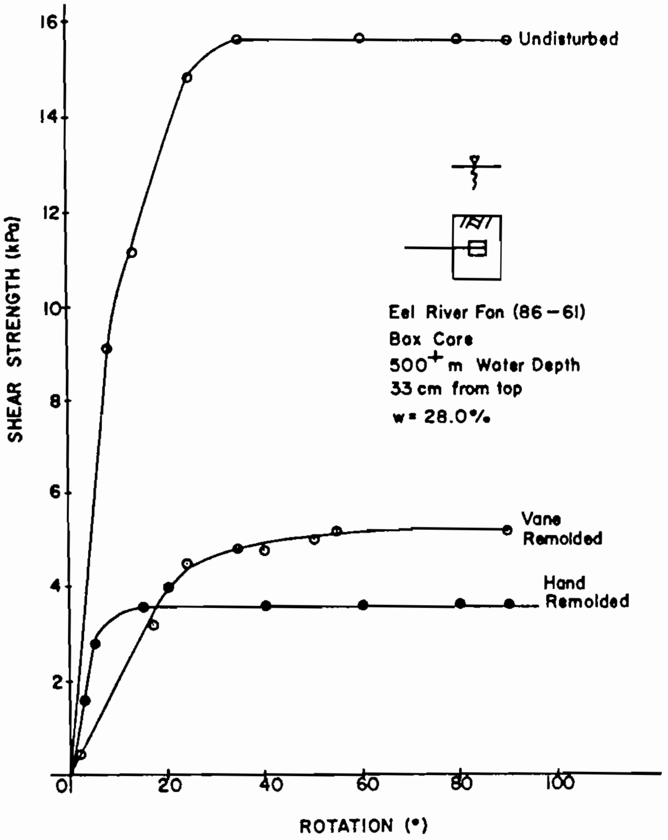

16
14
12
10
8
6
4
2
0
20
40
60
80
100
ROTATION (°)
SHEAR STRENGTH (kPa)
Eel River Fan (86-61)
Box Core
500+m Water Depth
6 cm from top
w=30.0%
Undisturbed
Vane
Remolded
Hand
Remolded

Fig. 5



16
14
12
10
8
6
4
2
0
SHEAR STRENGTH (kPa)
0
20
40
60
80
100
ROTATION (°)
Undisturbed
Vane
Remolded
Hand
Remolded
Eel River Fan (86 – 61)
Box Core
500^{+} m Water Depth
33 cm from top
w = 28.0%

Fig. 6

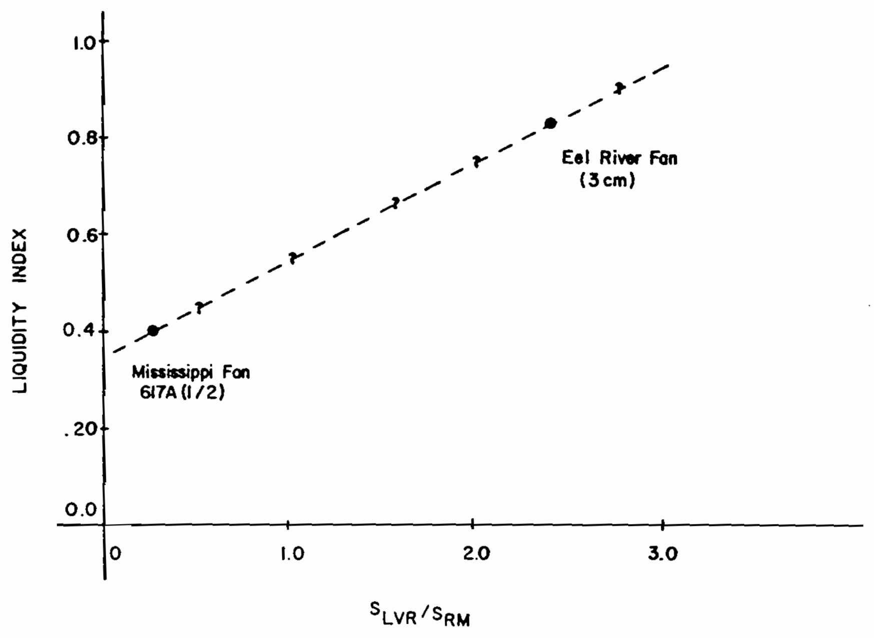

1.0
0.8
0.6
0.4
.20
0.0
LIQUIDITY INDEX
0
1.0
2.0
3.0
S_{LVR}/S_{RM}
Eel River Fan
(3 cm)
Mississippi Fan
617A (1/2)

Fig. 7

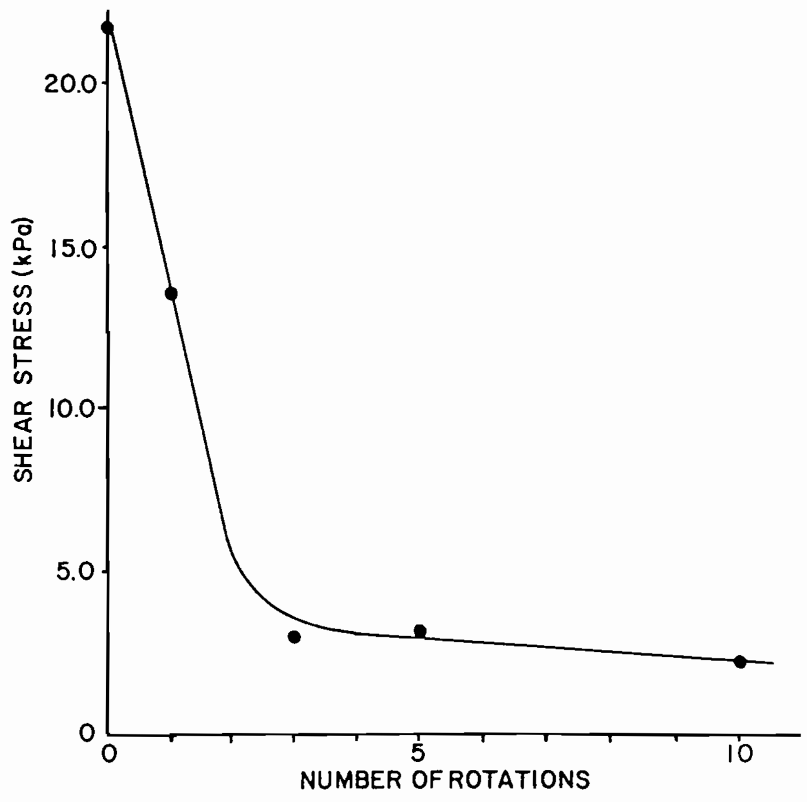


Fig- 8

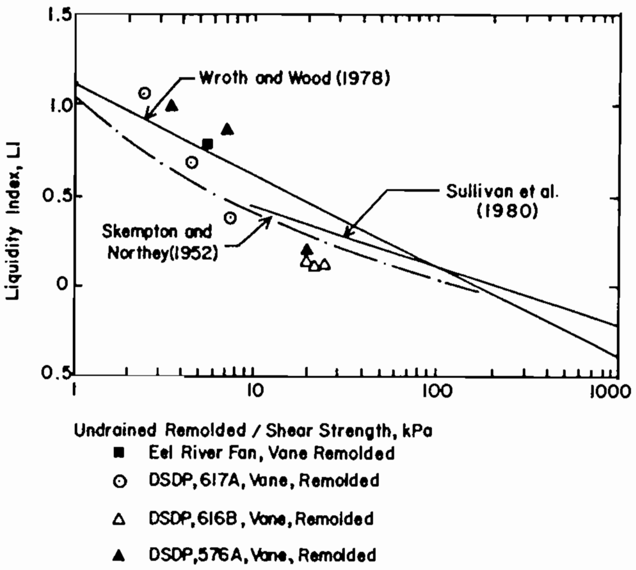
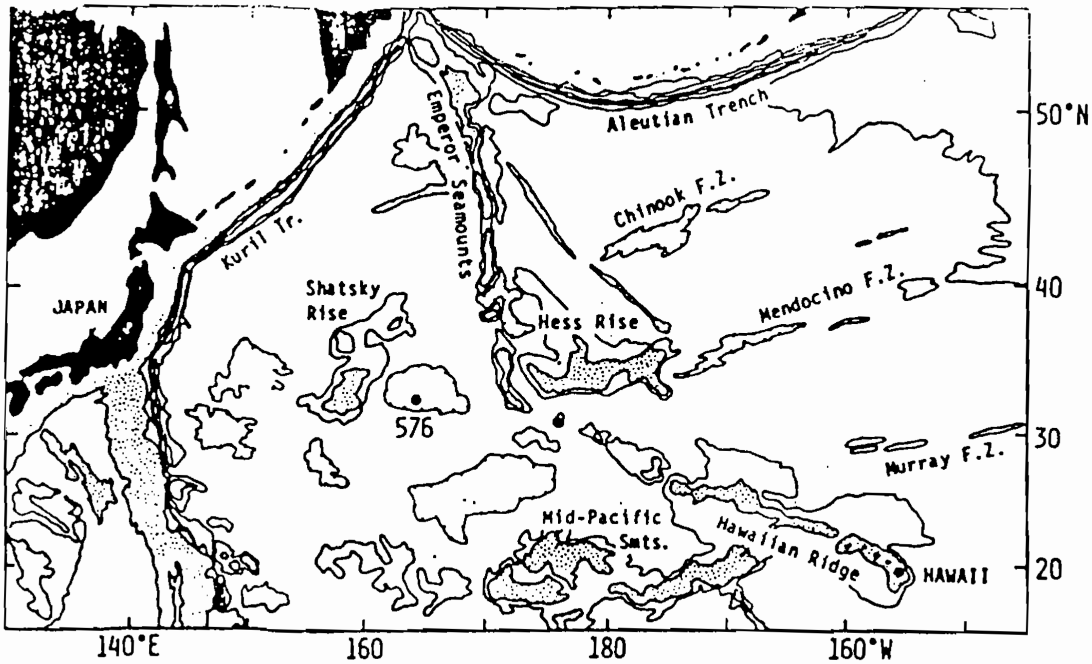
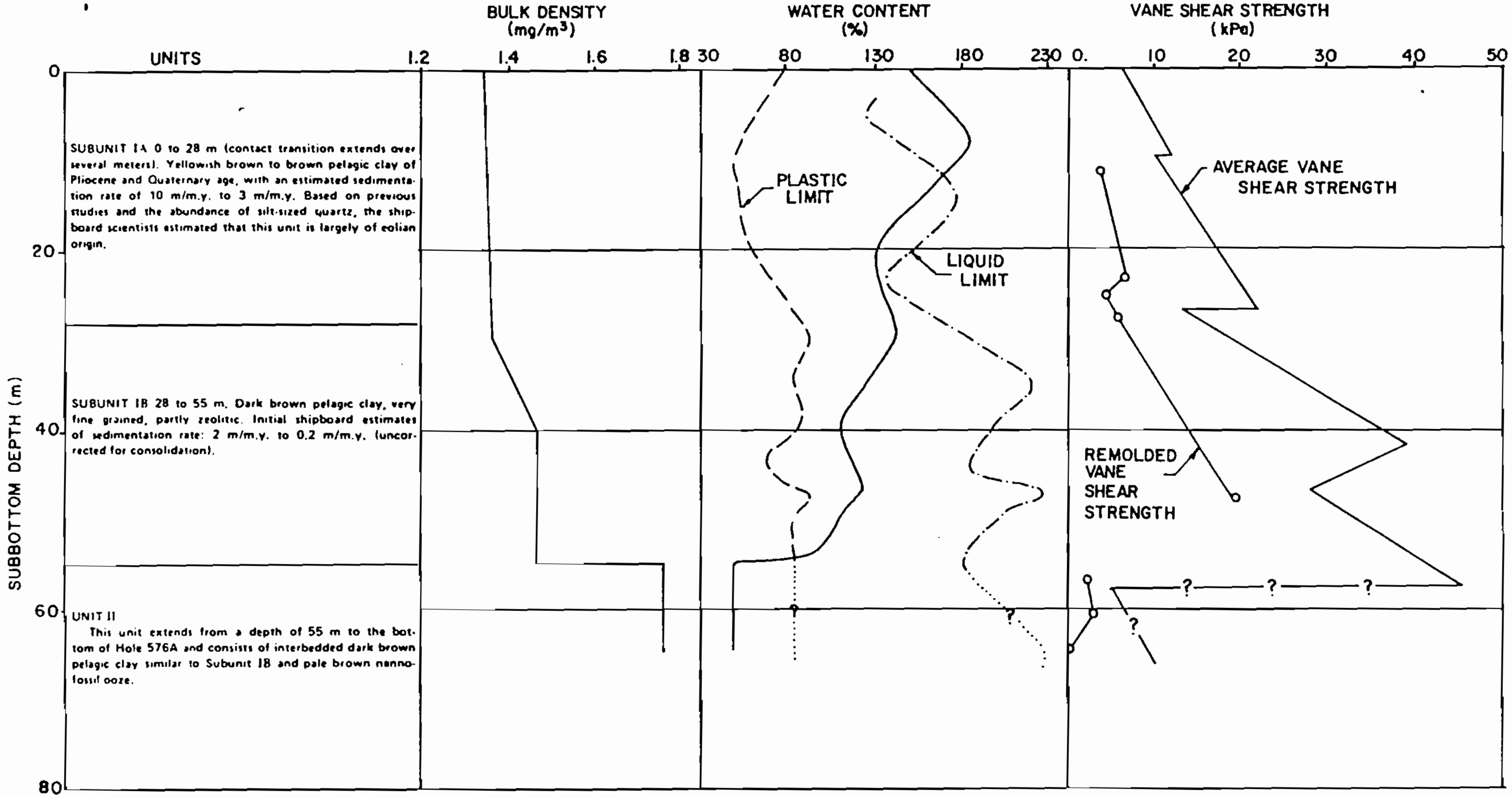

1.5
1.0
0.5
0
0.5
1
10
100
1000
Liquidity Index, LI
Wroth and Wood (1978)
Sullivan et al. (1980)
Skempton and Northey(1952)
Undrained Remolded / Shear Strength, kPa
■ Eel River Fan, Vane Remolded
⊙ DSDP, 617A, Vane, Remolded
△ DSDP, 616B, Vane, Remolded
▲ DSDP, 576A, Vane, Remolded

Fig. 9



Aleutian Trench
50°N
Emperor Seamounts
Chinook F.Z.
Kuril Tr.
Shatsky Rise
JAPAN
Hess Rise
Mendocino F.Z.
40
576
30
Murray F.Z.
Mid-Pacific Smts.
Hawaiian Ridge
HAWAII
20
140°E
160
180
160°W

Fig. 10



SUBUNIT IA 0 to 28 m (contact transition extends over several meters). Yellowish brown to brown pelagic clay of Pliocene and Quaternary age, with an estimated sedimentation rate of 10 m/m.y. to 3 m/m.y. Based on previous studies and the abundance of silt-sized quartz, the shipboard scientists estimated that this unit is largely of eolian origin.

SUBUNIT IB 28 to 55 m. Dark brown pelagic clay, very fine grained, partly zeolitic. Initial shipboard estimates of sedimentation rate: 2 m/m.y. to 0.2 m/m.y. (uncorrected for consolidation).

UNIT II
This unit extends from a depth of 55 m to the bottom of Hole 576A and consists of interbedded dark brown pelagic clay similar to Subunit IB and pale brown nannofossil ooze.

Fig. -Geotechnical Properties of Northwest Pacific Pelagic Clays: Deep Sea Drilling Project Leg 86, Site 576A

Fig. 11

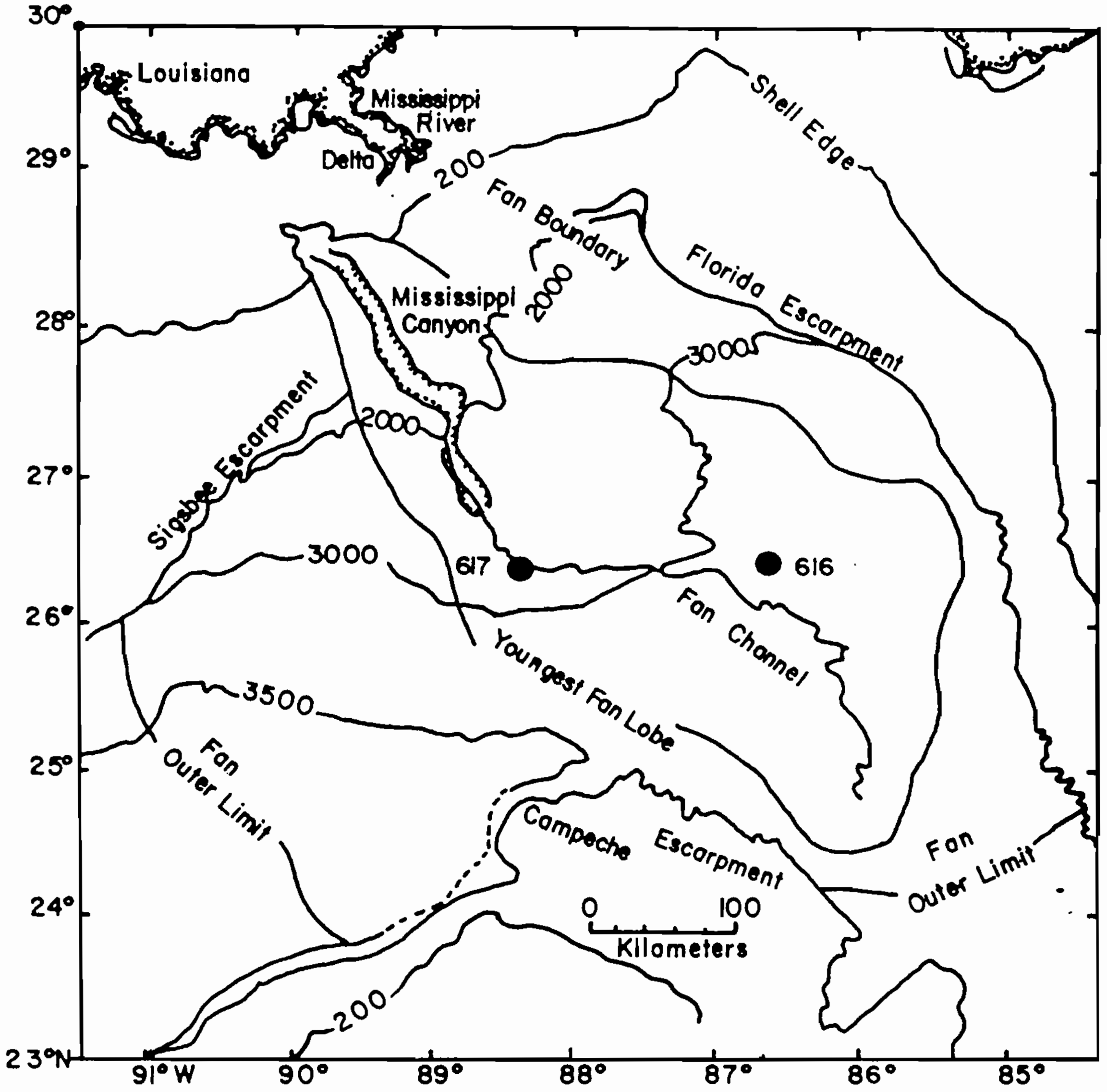


Figure LOCATION MAP SHOWING SITES STUDIED, DSDP LEG 96.

Fig. 12 Chaney / Richardson.

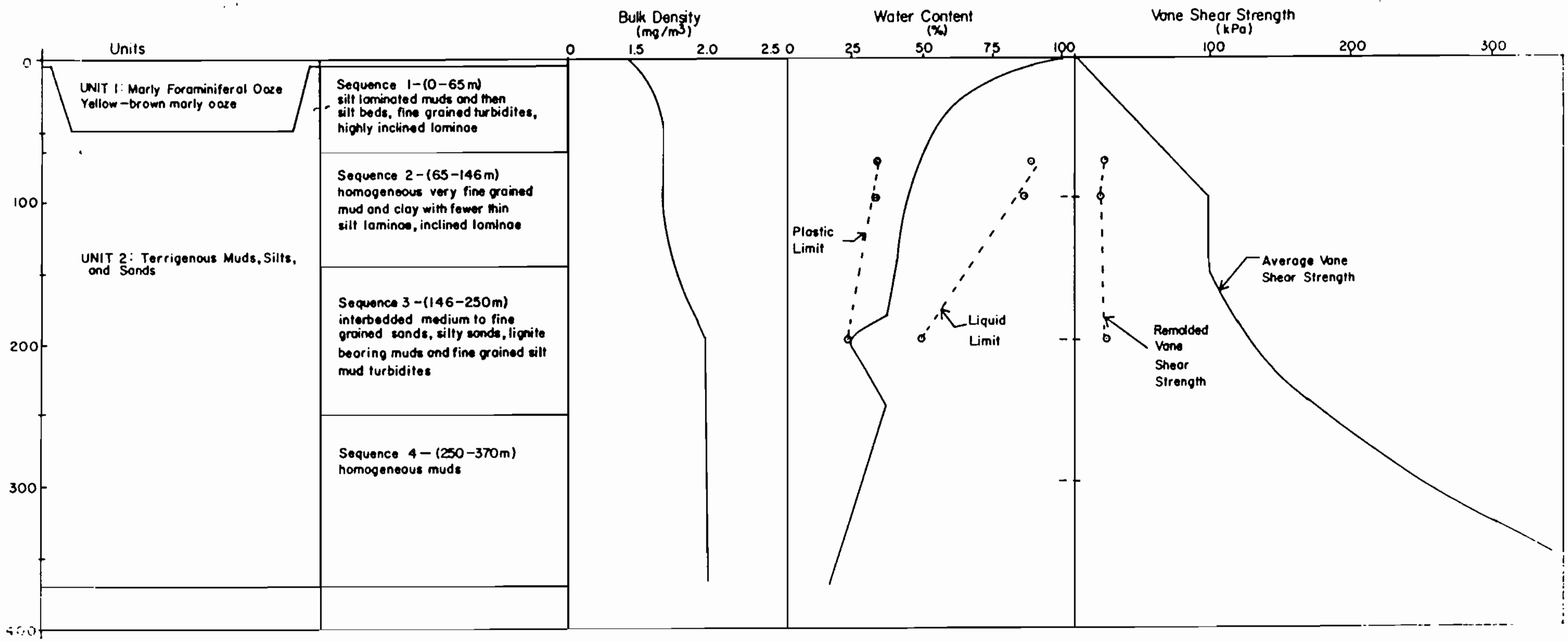


Fig. — Geotechnical Properties of Mississippi Fan Sediments: Deep Sea Drilling Project, Leg. 96, Site 616B

Fig. 13

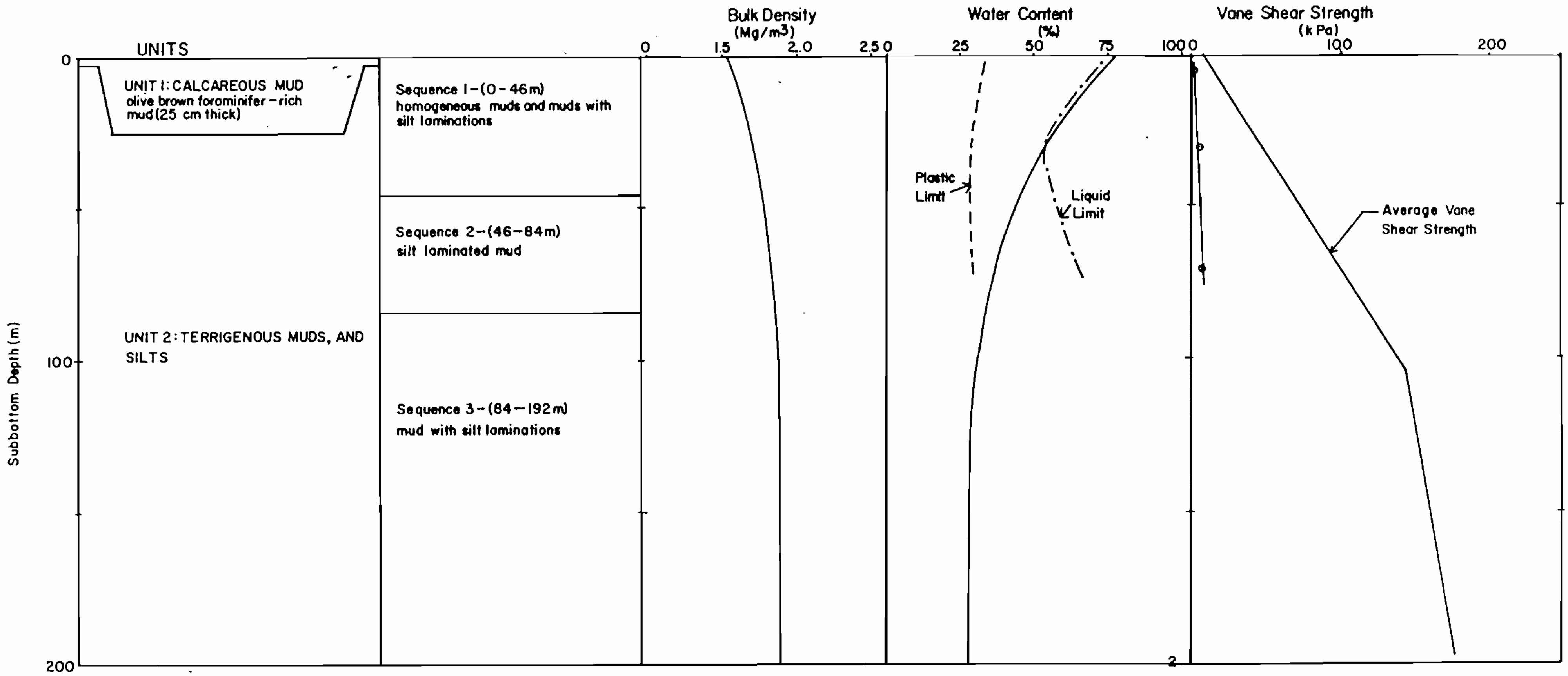


Fig. — Geotechnical Properties of Mississippi Fan Sediments:
Deep Sea Drilling Project, Leg 96, Site 617A

Fig. 14