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XIV. GEOTECHNICAL PROPERTIES OF DEEP-SEA SEDIMENTS AND MANGANESE NODULES IN THE PENRHYN BASIN, SOUTH PACIFIC (GH83-3 AREA)

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Introduction

Some geotechnical properties of deep-sea sediments and manganese nodules were measured on board during the GH83-3 research cruise to collect fundamental data for mining technology of deep-sea manganese nodule. The geotechnical properties measured were: (i) vane shear strength, cone penetrating resistance, and water content of deep-sea sediments; (ii) adhesiveness between each manganese nodule and sediment; and (iii) dimension and weight of each manganese nodule according to our previous works (Tsurusaki and Hirota, 1977; Handa, 1979; Tsurusaki and Handa, 1981a & b; Handa and Tsurusaki, 1981; Tsurusaki and Saito, 1982; Saito and Tsurusaki, 1982; Tsurusaki, 1984; Handa and Yamazaki, 1986). A sub-core sample was taken from each box core for a shore-based analyses for the same purposes.

The purposes of shipboard measurement and laboratory testing are: (i)to determine the geotechnical properties of deep-sea sediments in the Central Pacific which includes the areas of abundant manganese nodules; (ii) to determine the relationship between geotechnical properties and sediment type; (iii) to determine the degradation of the sample due to sub-coring, handling, and storage; (iv) to determine the quantitative relationship between nodule dimension and its weight; and (v) to obtain basic data to estimate nodule abundance from deep-sea photographs.

These works were performed by the National Institute for Resources and Environment as a part of the National Research and Development Program, "Manganese Nodule Mining System."

Geotechnical properties of deep-sea sediments

Procedure and equipment

Shipboard vane shear testing was carried out by a hand-operated vane shear tester. It consisted of calibrated torsional spring torque meter (capacity: 2 cm•kg) attached to a 40 cm long stainless steel shaft and terminating with a 2-cm wide, 4-cm high, and 90-degree four-blade vane. Strength was measured at 6 cm down-core intervals from

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the surface of box core. Each measurement consisted of original and remolded strength measurements. The original strength value reported is maximum shearing resistance developed by sediments when the vane was rotated at constant increasing rate of torque (about 0.12 cm•kg/sec). The remolded strength is the resistance to shear the sediments shortly after vane had been rotated several times quickly by hand. The torque was converted to shear strength by a following equation.

Vane shear strength (g/cm^2) = 34.1 × Maximum torque (cm•kg)

The vertical interval of vane measurement was 50 cm for homogeneous sediment cores and several measurements were added optionally in the case of laminated samples from piston cores. The vane was penetrated only 1 or 2 cm into the half-split surfaces of piston cores and was rotated vertically to the core axis. The equations to convert torque to shear strength for piston cores are:

Vane shear strength (g/cm^2) = 119 × Maximum torque (cm•kg) for 1 cm penetration

= 68.2 × Maximum torque (cm•kg) for 2 cm penetration

Cone penetrating testing was carried out by a hand-operated electrical load cell type cone tester. It consists of a 60-degree tip cone with 3.5 cm in diameter, a load cell, a 60-cm long outer tube, an amplifier, a recorder, and a penetration depth marking unit. Penetrating resistance was measured at the center of the box core with the penetrating rate of about 1 cm/sec. and penetrating resistance force was divided by the area of cone.

Water content was determined from the weight of sample before and after drying for 24 hours at 105°C. The weight lost after drying divided by that of dried samples is expressed as percentage. A 6 cm I.D. PVC pipe was inserted into each box core and disc samples were taken at 6 cm vertical intervals from the sub-core. For piston cores, one-fourth column samples of 10-cm long were taken at 50-cm vertical interval. The weight of wet and dry samples was measured by using a shipboard electrical balance in order to avoid the influence of ship's heaving and waving.

Adhesiveness between manganese nodule and sediment was measured on several selected nodules on undisturbed box core surface using tweezers and a small electrical load cell. Adhesiveness per unit area was determined from the picking up force divided by the area where manganese nodule had contacted to the sediments. The area was measured from the projection figure which was taken by a still camera.

Sampling for laboratory geotechnical testing was done on each box core. A 10-cm I.D. and 50 cm long clear plastic tube was inserted into the box core using a vacuum pump. Sub-core was sealed with a plastic lid and rubber stoppers on the top and bottom of sediment column and kept vertical in a refrigerator (about 4°C). Bulk samples were taken from box cores after subcoring and kept in a large plastic bag for shore-based model test.

Results of onboard measurements

Vane shear strength, core penetrating resistance, and water content measurement were performed on 7 box cores and 16 piston cores. The profiles of strength and water content versus test depth for each core are shown in Figures XIV-1 and XIV-2.

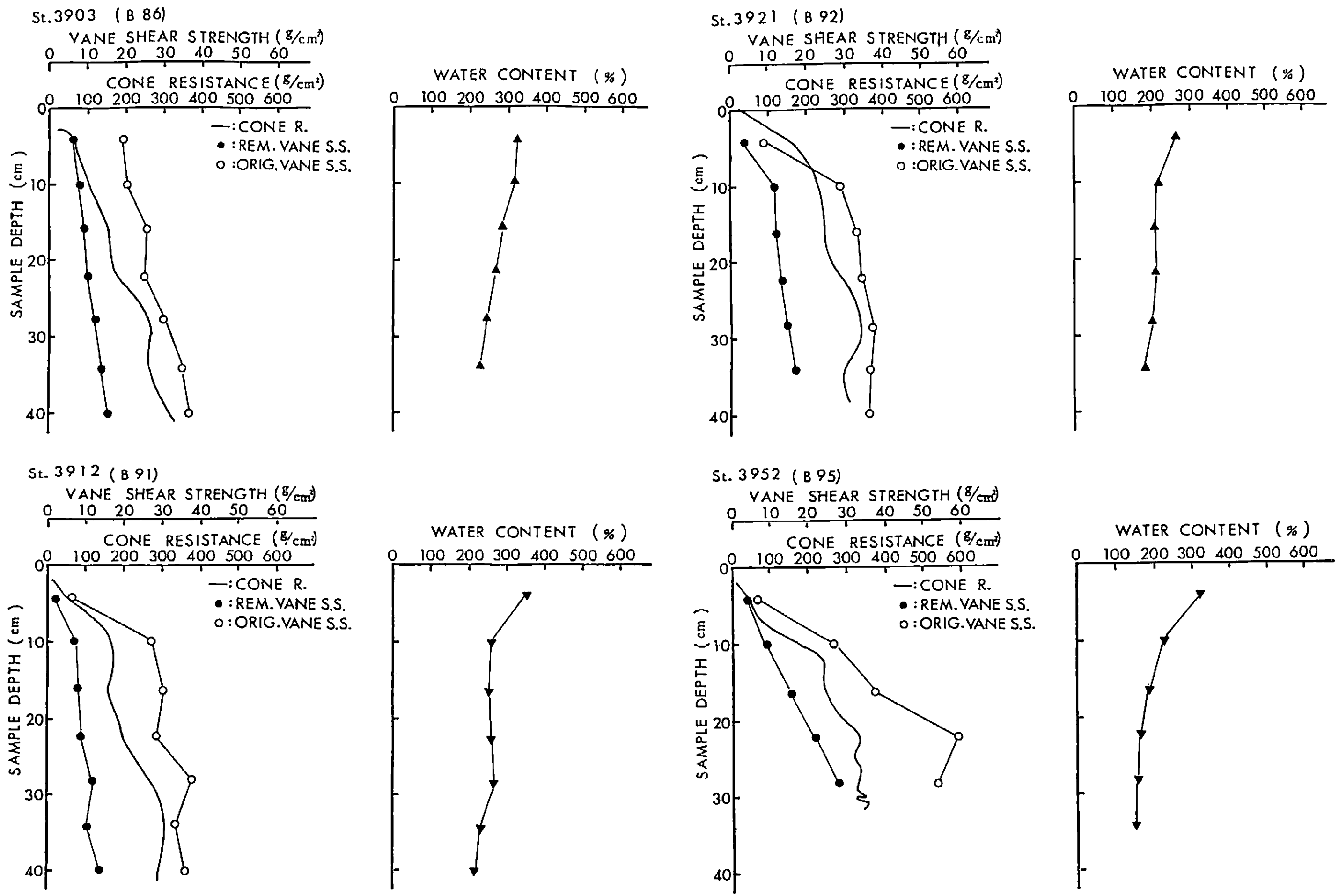


Fig. XIV-1 Geotechnical properties versus sample depth in box cores (B86–B100).

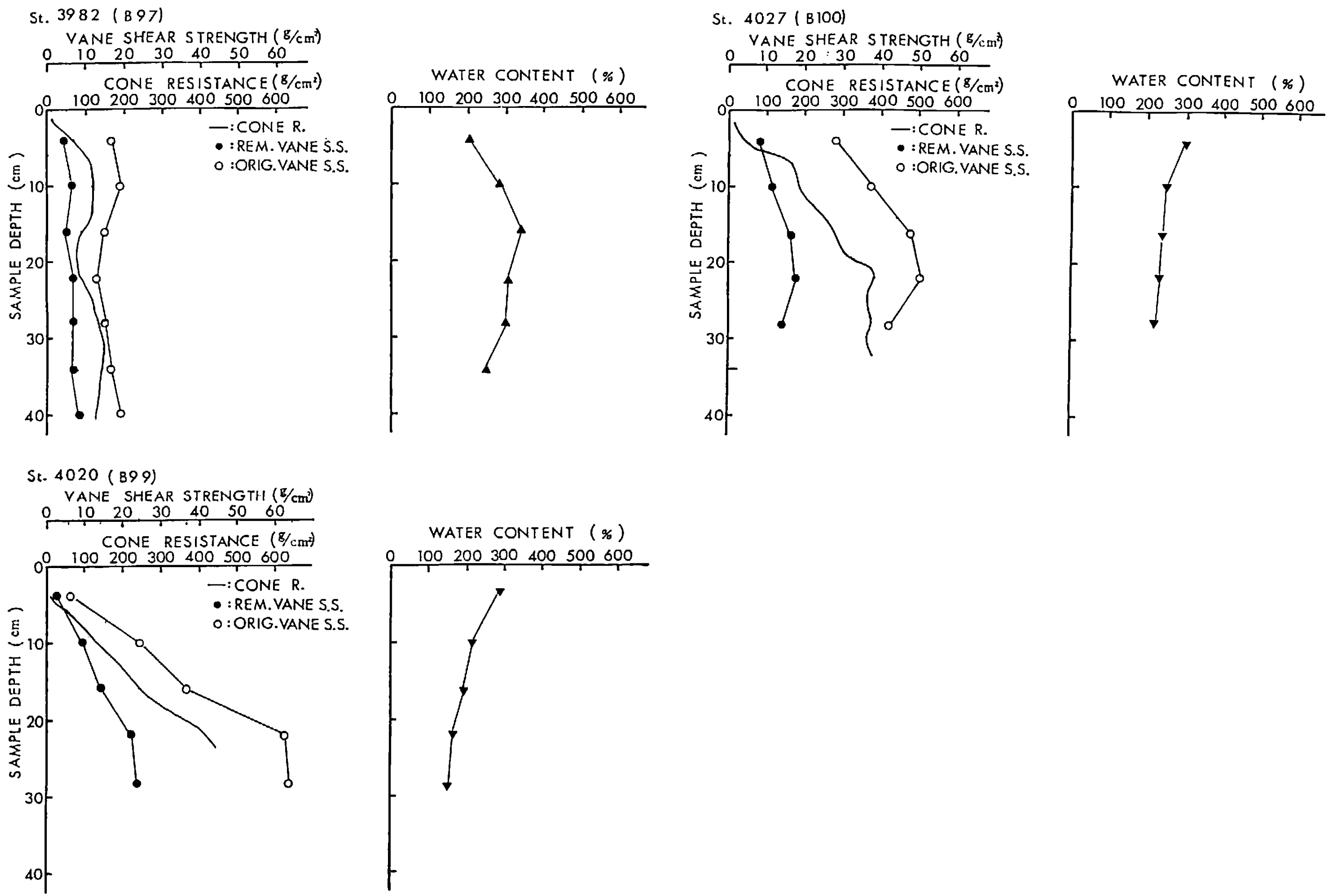


Fig. XIV-1 (continued)

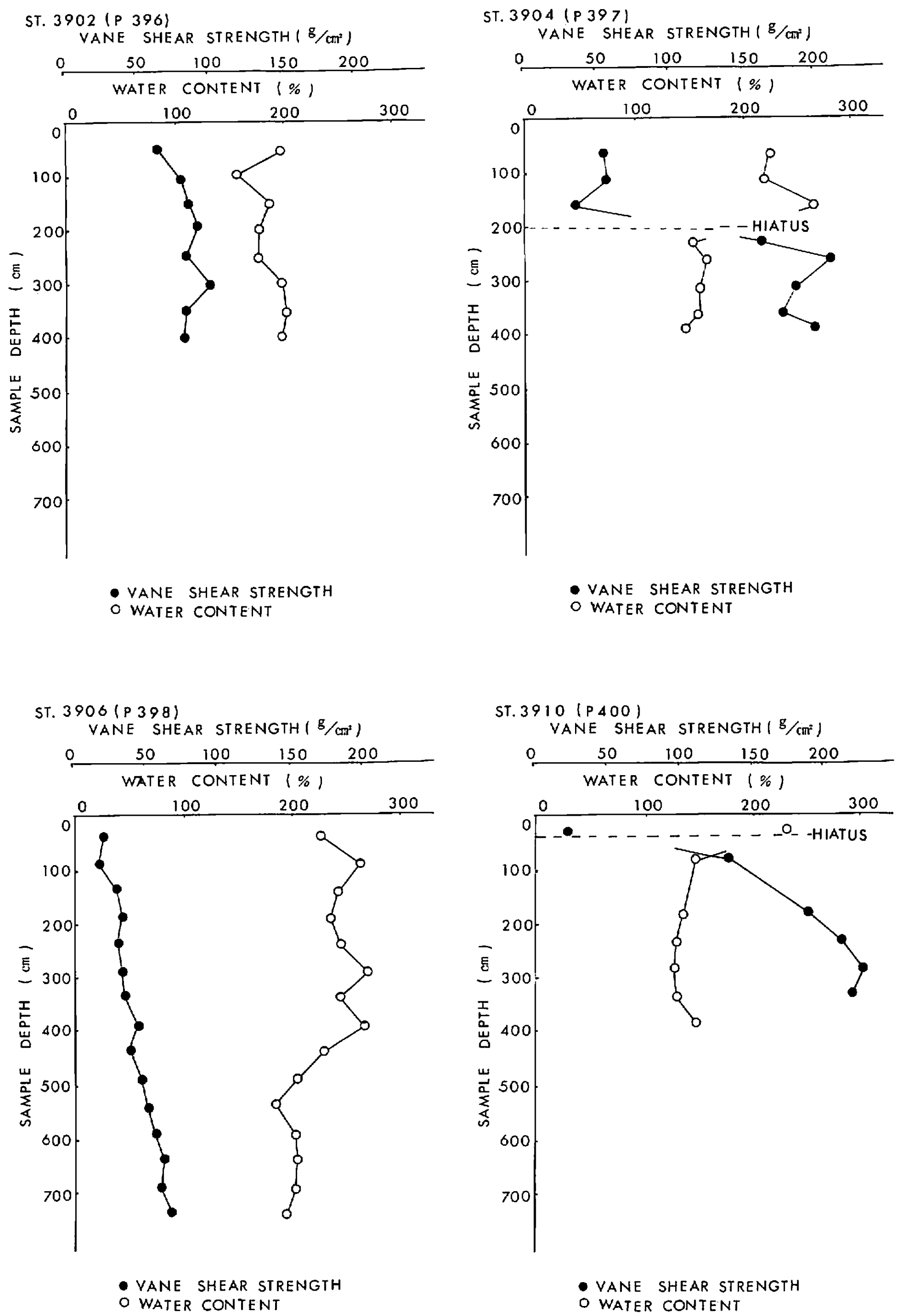


Fig. XIV-2 Geotechnical properties versus sample depth in piston cores (P396-P412).

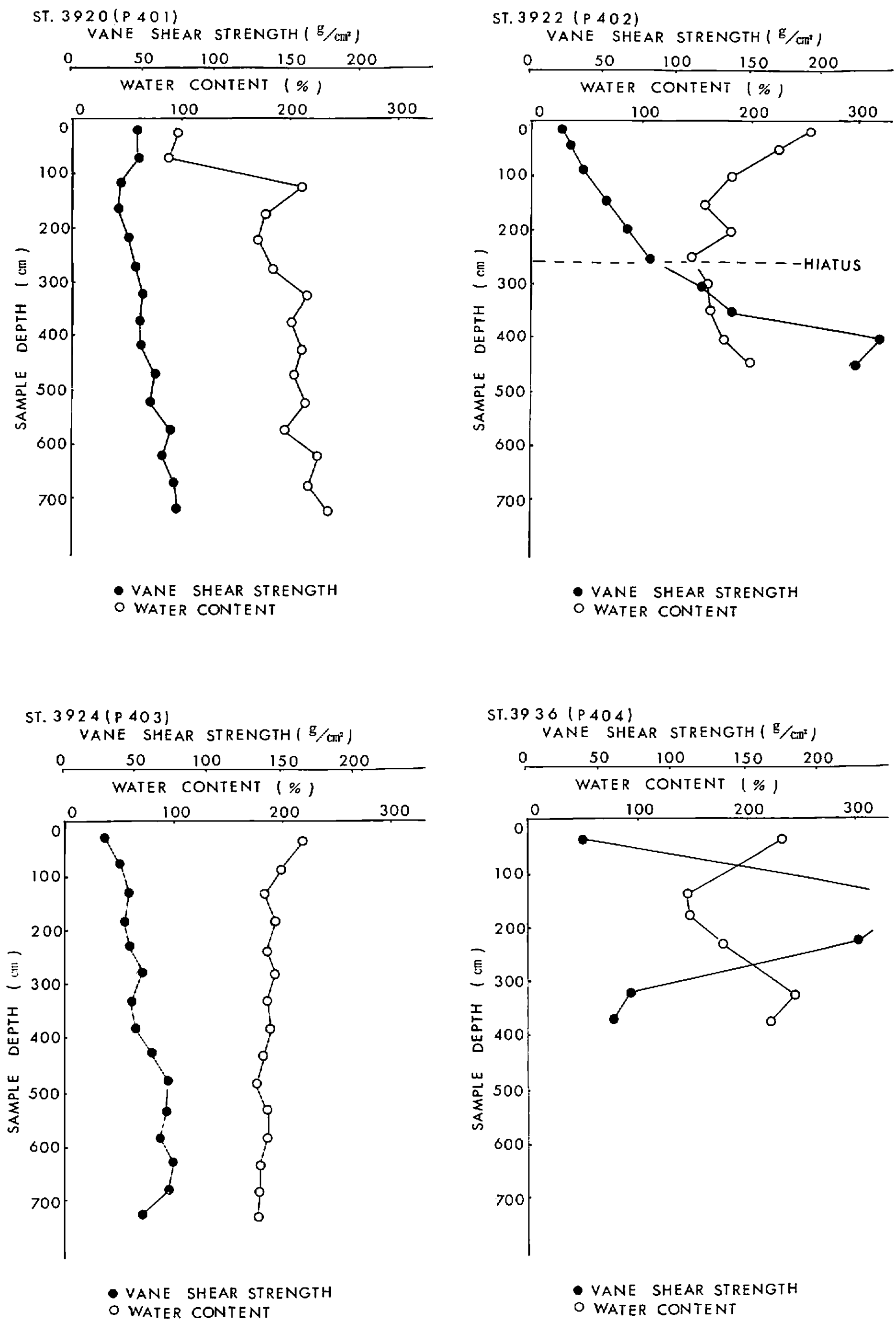
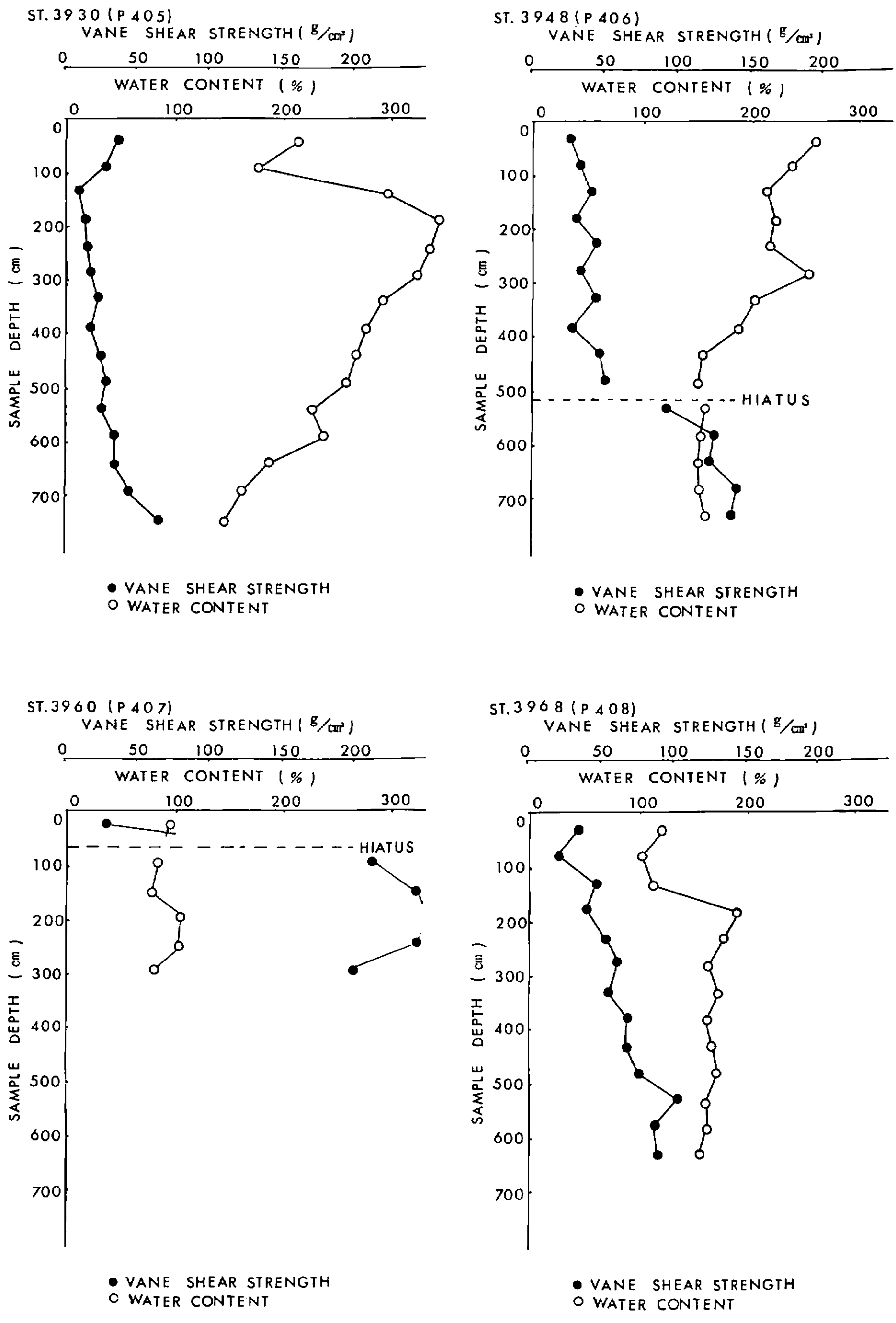


Fig. XIV-2 (continued)



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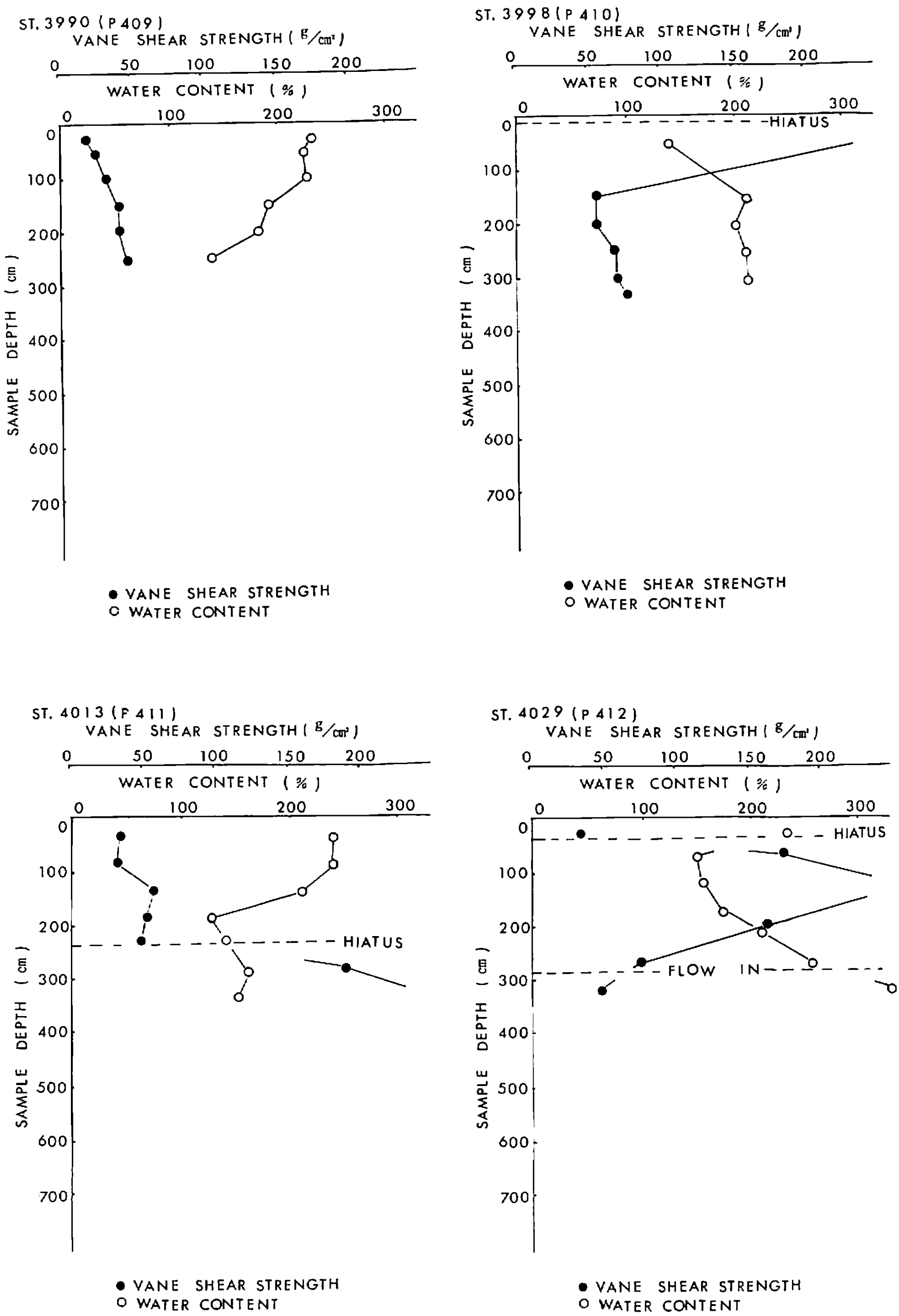

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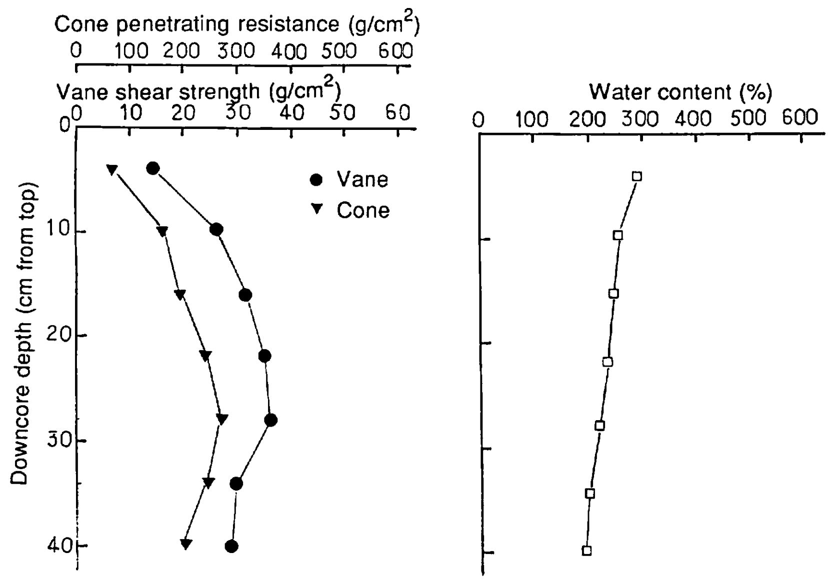


Fig. XIV-3 Geotechnical properties versus sample depth in box cores covered with abundant nodules (averages for 6 stations).

Adhesiveness between manganese nodule and sediment was measured on 24 nodules from 5 box cores (B86, B91, B92, B97, B100). Lithology and locations of cores are described by Nishimura and Saito (Chapter IV, this volume).

Geotechnical properties of box cores

The average value of vane shear strength, core penetrating resistance, and water content versus test depth for six box cores which contained abundant nodules (more than 10 kg/m^2) are shown in Figures XIV-3 and Table XIV-1. The figure shows that

Table XIV-1 Geotechnical properties of deep sea sediments collected by box corers (with more than 10 kg/m^2 of manganese nodule abundance).

sample depth (cm)	vane shear strength (g/cm²)									cone penetrating resistance (g/cm²)				water content (%)			
	original				remolded				sensitivity								
	ave.	sta. dev.	max.	min.	ave.	sta. dev.	max.	min.	ave.	ave.	sta. dev.	max.	min.	ave.	sta. dev.	max.	min.
4	14.3	8.6	28.3	6.1	4.8	2.2	8.5	2.7	3.0	68.3	43.9	156	40	293	52	353	200
10	26.0	7.1	38.2	18.4	8.5	2.5	11.9	5.1	3.1	165.3	51.5	227	100	257	32	304	221
16	31.1	11.2	47.7	14.3	10.5	4.6	16.0	4.8	3.0	194.0	71.4	245	97	250	54	335	191
22	34.5	17.5	58.7	11.9	12.4	6.5	22.5	5.1	2.8	243.0	109.6	332	90	239	45	300	176
28	35.4	13.2	52.9	14.3	13.9	6.6	25.9	6.5	2.6	277.0	88.6	330	120	231	44	291	168
34	30.0	9.6	36.5	15.7	11.6	4.0	16.4	6.8	2.6	245.8	81.0	298	130	212	41	254	150
40	30.2	10.9	36.5	17.7	11.2	3.0	13.3	7.8	2.7	204.5	112.4	313	125	211			

the water content is about 300% at the surface and decreases linearly with depth to about 200% below 30 cm depth of sediments. Vane shear strength versus test depth shows that the largest increase with depth occurs in the upper 16 cm layer of sediments from 10 g/cm^2 at 4 cm to 30 g/cm^2 in the average value. Below this depth it increases very slightly to about 40 g/cm^2 until the depth reaches to 30 cm. Then, it remains almost constant at deepter parts.

Sensitivity is calculated from ratios between original and remolded vane strength ranging from 2.5 to 3.5. This means the strength of the sediments after remolding decreases down to 30 to 40% of the original strength.

Cone penetrating resistance also increases with depth from 70 g/cm^2 at 4 cm depth to 150 to 200 g/cm^2 at 10 cm and shows the tendency of increment to 300 to 400 g/cm^2 below 30 cm depth.

Considering all results of measurements of the box cores, at the surface portion of deep-sea sediment (0 to 20 cm depth) the water content tends to decrease and the shear strength tends to increase with depth, and they change very little below the depth until about 40 cm deep layer. The water content shows a negative correlation with vane shear strength and cone penetrating resistance. Vane strength shows a positive correlation with cone resistance in the uppermost sediments.

Box cores B95 (St. 3952) and B99 (St. 4020) show different trends from others. The vane shear strength and the cone penetrating resistance increase much at the lower portion of the cores and do not reach a constant value. The water content tends to decrease with depth from surface.

The water content of B97 (St. 3982) core is very low (200%) and the surface vane shear strength is very high at the surface. These may be caused by the difference of particle size from other cores. Lower part of this core shows a very low vane shear strength and a higher water content than those at the surface. In the case of operation of this core, the corer might have overpenetrated into the sea-floor sediments and collected excess sediments. After recovery of the box core onto the deck, the lowest part of the sample was dug out from the bottom mouth of the corer. So, the sample might be disturbed much by this procedure and/or the strength might be very low originally. Both of these can result in low strength and high water content of sediments.

Geotechnical properties of piston cores

The relationship between water content and vane shear strength and sample depth on each piston core is profiled in Figure XIV-2. The lateral dotted line on each profile means clearly visible lithological change such as hiatus.

In most cases of homogeneous sediment throughout whole core column except very surface portion, water content decreases and vane shear strength increases monotonically with sample depth from the surface. For example, the core P408 (St. 3968) consists of apparent homogeneous brown sediments over the core. The water content decreases from 200% to 150% and the vane shear strength increases from 20 g/cm^2 to 100 g/cm^2 monotonically with sample depth.

Some other homogeneous cores P398 (St. 3906) and P405 (St. 3930) show very soft nature. The vane shear strength is less than 50 g/cm^2 and the water content is more than 200% throughout whole core column.

The core P401 (St. 3920) shows unusual properties. The water content is very low (less than 100%) at the surface and tends to increase with the core depth throughout the sample column. The vane shear strength is relatively high (50 g/cm²) at the surface and decreases once (25 g/cm²). Then, it tends again to increase monotonically with sample depth. This is caused by that the surface sediment consists of zeolitic sand. Lithological components of sediments must be taken into account to understand the increment of water content with sample depth.

Many core samples include several lithological changes within the sample column as shown in figures and those lithological changes have affected more or less on geotechnical properties. Just under the hiatus the vane shear strength ranges extremely high (150 to 200 g/cm²) and the water content is less than 150%, for instance in cores P397, P400, P402, and P411. With the increment of sample depth the vane strength increases and the water content decreases under the hiatus similar to the upper portion of hiatus.

At the portion of flow-in of core sample the water content is very high (more than 300%). Generally, the water content of piston cores down to about seven meters depth ranges from 250% to 150% and the vane shear strength ranges from 20 g/cm² to 100 g/cm².

Adhesiveness between nodule and sediments

Adhesiveness per unit area between the manganese nodule and surface sediments varies very widely from 5 g/cm² to 15 g/cm² as shown in Table XIV-2.

The table shows that the adhesiveness measured in the same box core sample varies very little, but it scatters much among the different box core samples. Since there must be some relationships between adhesiveness and surface vane shear strength of the sediments, the adhesive properties should be discussed together with the results of the previous measurements.

Table XIV-2 Adhesiveness between the nodule and sediments.

sample no.	no. of measurement	adhesiveness (g/cm^2)		surficial vane strength (g/cm^2)
		ave.	sta.dev.	
B 86	4	14.0	3.9	19.1
B 91	6	6.5	1.3	6.8
B 92	6	11.7	1.1	9.2
B 97	4	15.3	2.9	16.4
B 100	4	4.9	2.1	11.3

Dimensions of manganese nodules

Procedures

Collected nodules by box corers and free-fall grabs were rinsed by sea water to avoid attached muds, and were provided for the following shipboard descriptions: (i) to determine their morphological types; (ii) to classify them into size fractions; (iii) to weigh them in wet state, to check numbers in respective size fractions, and to calculate nodule abundance; (iv) to measure long axis and short axis, and thickness of individual nodules using a slide caliper; (v) to weigh individual nodules; (vii) to observe their internal structure on cut section; and (vii) to take pictures of whole nodules and cut section.

Our study aims at the shipboard descriptions (iv) and (v). Measurement were performed on 48 grab samples out of 146 grabs (FG563 through FG708). Other descriptions (i) through (iii) and (vi) through (vii) are summarized in chapters VIII (Usui) and IX (Usui and Mita) of this cruise report.

Results and discussion of shipboard measurement

Table XIV-3 shows some statistics calculated from data obtained during the cruise. Figure XIV-4 shows the size and weight distribution of nodules sampled from this area. The highest size fraction of nodules is 1-2cm diameter with a relative frequency of 36%. In a cumulative weight curve, the nodule long axis which represents 50% of total weight is approximately 4.2 cm.

The relationships between the long axis and short axis, between the long axis and vertical thickness, and between the long axis and weight of nodules are shown in Figure XIV-5 (A), (B) and (C), respectively. In these scatter diagrams, number of observations at each fraction was plotted as shown in the legend. The regression lines, which were obtained by the weighted regression analysis. were also drawn. The equation for these lines are as follows:

$S = 0.81 \times L$ ....(1)

$T = 0.71 \times L$ ....(2)

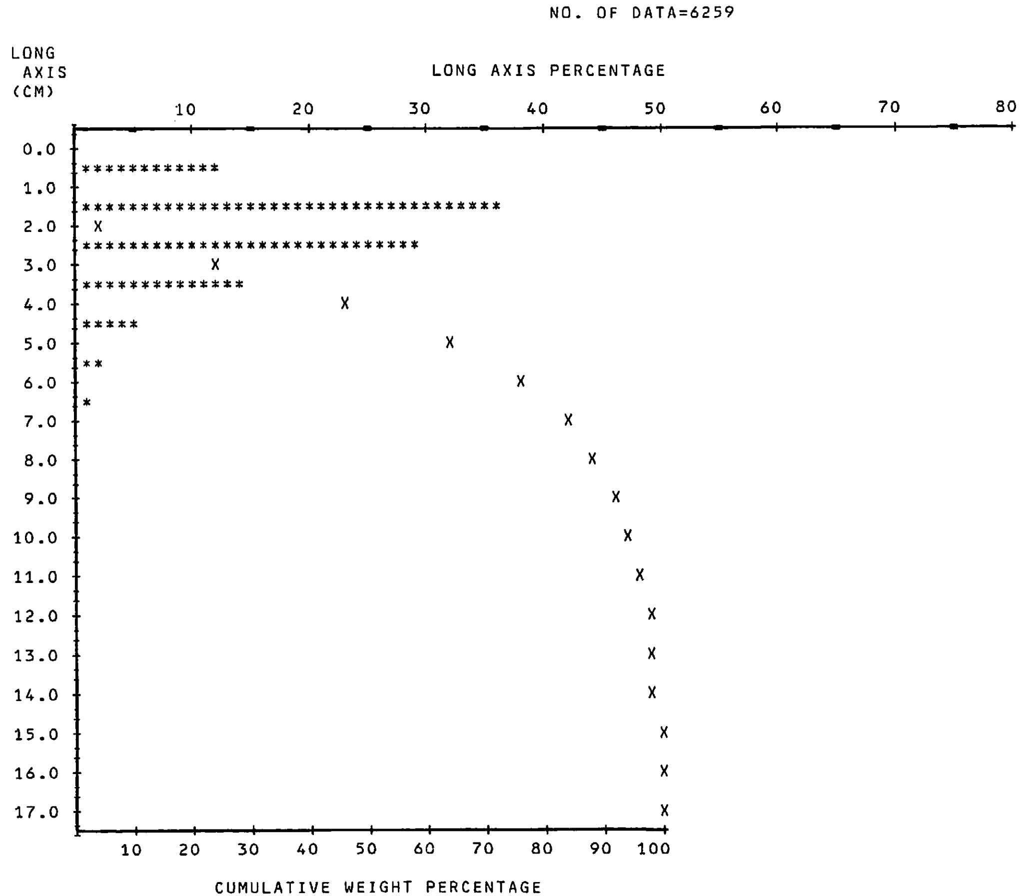
$W = 0.37 \times L^3$ ....(3)

where L : nodule long axis (cm)
S : nodule short axis (cm)
T : nodule thickness (cm)
W : nodule weight (g)

Table XIV-3 Statistics of dimensions of manganese nodules.

	DATA	MEAN	VARIANCE	STD DIV.	STD ERR. OF MEAN	MINIMUN VALUE	MAXIMUN VALUE
Long axis	6259	2.4	1.97	1.40	0.02	0.5	17.0
short axis	5381	2.0	1.09	1.04	0.01	0.6	9.4
thickness	5381	1.8	0.97	0.98	0.01	0.2	9.5
weight	5381	16.	1207.64	34.75	0.47	0.	762.

NOTE : weight "0." = less than 1 g



LONG AXIS (CM)	LONG AXIS FREQ	LONG AXIS PERCENT	WEIGHT CUM. PERCENT
0.0			
	733	11.71	
1.0			0.26
	2259	36.09	
2.0			5.23
	1813	28.97	
3.0			24.08
	875	13.98	
4.0			46.95
	334	5.34	
5.0			64.91
	131	2.09	
6.0			77.39
	50	0.80	
7.0			84.67
	27	0.43	
8.0			89.36
	13	0.21	
9.0			92.04
	8	0.13	
10.0			94.48
	7	0.11	
11.0			96.96
	2	0.03	
12.0			97.55
	2	0.03	
13.0			97.87
	2	0.03	
14.0			99.11
	1	0.02	
15.0			99.71
	0	0.0	
16.0			99.71
	2	0.03	
17.0			100.00

Fig. XIV-4 Size and weight distribution of nodules.

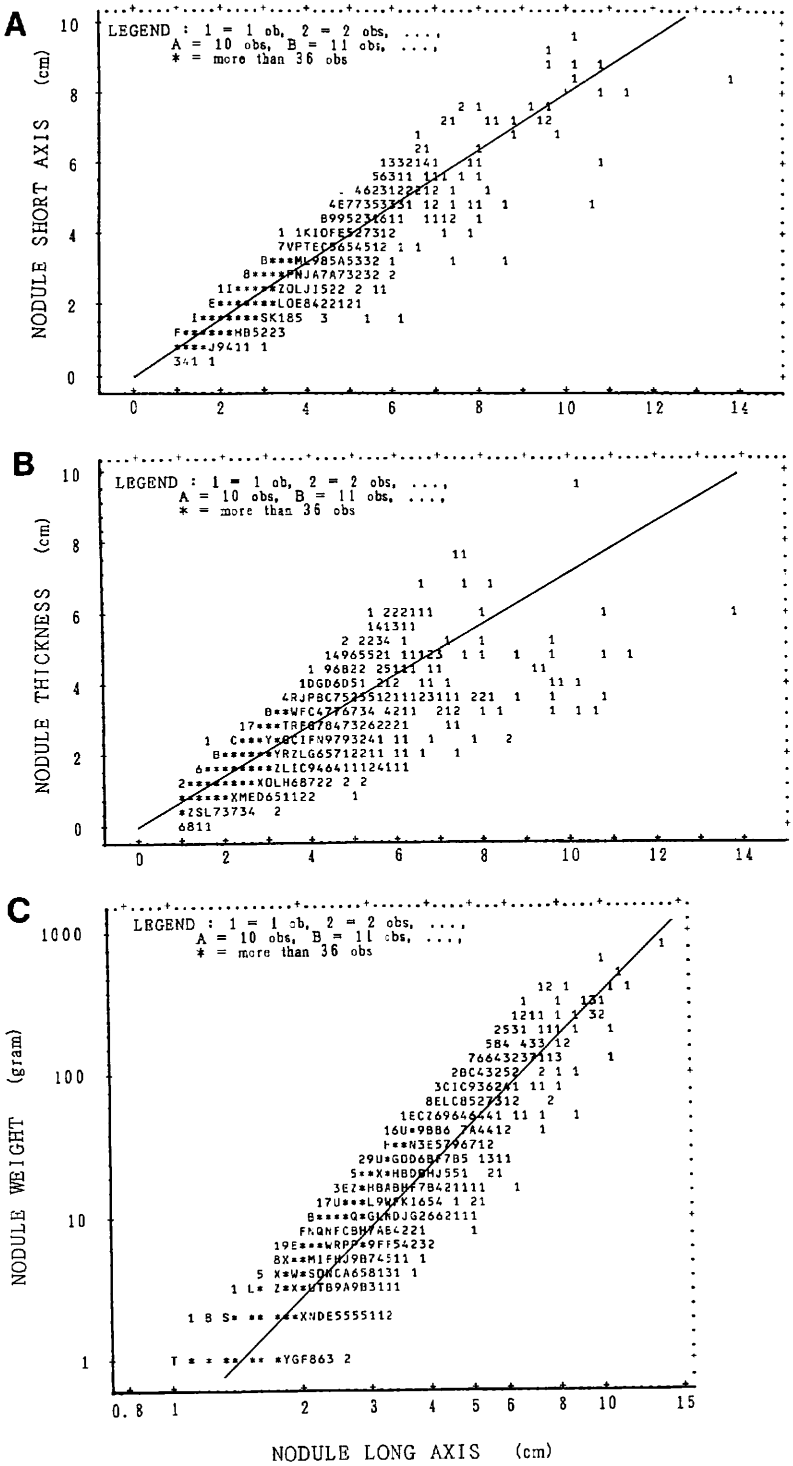


Fig. XIV-5 (A) Relationship between long axis and short axis of nodules. (B) Relationship between long axis and thickness of nodules. (C) Relationship between long axis and weight of nodules.

Total number of data is 5381 for equations (1) and (2), and is 5042 for equation (3) respectively. The standard error of above equations are 0.42, 0.59, and 19.1 respectively. The correlation coefficient for variables of these relationships are 0.92, 0.81, and 0.86 respectively.

Summary

The geotechnical properties of deep-sea sediments and manganese nodules measured on board the cruise R/V Hakurei-maru GH83-3 in the Penrhyn Basin of the South Pacific are summarized as follows:

(1) The average water content for box core sediments decreases linearly from 300% at the surface to 200% at 40 cm depth.

(2) The average vane shear strength for box core sediments increases with sample depth from 10 g/cm^2 at the surface to 30 g/cm^2 at 20 cm depth, but increases very slightly below 20 cm until 30 cm depth of sample. Below this depth, it remains almost constant.

(3) The average cone penetrating resistance for box core samples increases from 70 g/cm^2 at the surface to 150 to 200 g/cm^2 at 10 cm depth and keeps increasing to 300 to 400 g/cm^2 below 30 cm depth of sample.

(4) The geotechnical properties of piston core sediments are influenced much by the lithology of sediments.

(5) The average of adhesiveness per unit area between the nodule and surface sediments ranges from 5 g/cm^2 to 15 g/cm^2. Further discussion of relationship between adhesive properties and sediment strength will be needed together with more additional data.

(6) The modal class for nodule long axis is from 1 to 2 cm with a relative frequency of 36% by considering the data of 6259 in total.

(7) The average nodules long axis is 2.4 cm with a standard deviation of 1.4 cm.

(8) The relationship between nodule long axis and nodule short axis, and between the nodule long axis and nodule thickness could be expressed by linear equations, while the relationship between nodule long axis and nodule weight could be expressed by a third power equation.

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