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Geotechnical Framework Study of Shelikof Strait, Alaska

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INTRODUCTION

Studies have been conducted by the U.S. Geological Survey to identify geologic conditions that might impose constraints on offshore industrial activities in Shelikof Strait, Alaska, an area designated for petroleum leasing (Fig. 1; Hampton and others, 1981; Hampton and Winters, 1981). As part of these studies sediment cores were collected throughout the strait (Fig. 2), and physical properties of sediment samples were measured by laboratory geotechnical testing methods. The geotechnical data are presented in this report and are evaluated from a regional perspective to infer the deformational response of the sedimentary deposits to static and dynamic loads.

Application of the test data to a regional analysis is restricted by the degree to which core samples are representative of the sedimentary deposits. Interpretive geologic studies indicate that the cores used for geologic testing cover the range of surficial sediment types in the Shelikof Strait lease area, but analysis of seismic-reflection profiles reveals the existence of buried stratigraphic units that were not sampled because they lie beneath the maximum core length of 3 m (Hampton and others, 1981; Hampton and Winters, 1981). Therefore, the conclusions reached in this report apply directly to the uppermost deposits in the stratigraphic section, only. Extrapolation beyond the depths of sampling is limited by the vertical uniformity of sediment type.

GEOLOGIC SETTING

Shelikof Strait is a nearly parallel-sided marine channel situated between the Kodiak Island group and the Alaska Peninsula (Fig. 1). The strait marks the location of a northeast-trending inner forearc basin that is located

near the convergent margin of the North America plate where it is being underthrust by the Pacific plate (von Huene, 1979). Large earthquakes are common to the region; at least 95 potentially destructive events (magnitude >6) have occurred since recording began in 1902. Twelve volcanoes have erupted within the last 10,000 years along the Alaska Peninsula adjacent to the strait.

The seafloor of Shelikof Strait consists of a gently southwest-sloping central platform bordered by narrow marginal channels parallel to the Kodiak islands and the Alaska Peninsula (Fig. 3). Shallow shelves trend along the adjacent landmasses, and they are connected to the marginal channels by steeply sloping seafloor. Water depth in the northeast part of the strait is generally less than 200 m, whereas in the southwest it generally exceeds 200 m and is as much as 300 m. Superimposed on the platform are some local highs and lows that have as much as 100 m relief. Along the axes of the marginal channels are several closed depressions on the order of 30 m relief.

Sedimentary deposits of presumed Pleistocene and Holocene age overlie an irregular unconformity above Tertiary and older bedrock. Thickness of the sediment above bedrock, measured from seismic-reflection profiles, is about 80 to 100 m in the northeast half of the strait and increases abruptly to more than 800 m in the southwest (Fig. 4). The thickening reflects a deepening of the unconformity.

Four seismic-stratigraphic units can be distinguished above bedrock (Fig. 5). The lowest unit (unit 1 in Fig. 5) fills the bedrock depression and reaches a thickness of 800 m. This unit is interpreted as being of glacial and glaciomarine origin (Whitney and others, 1980 a, b). The next highest unit (unit 2 in Fig. 5) is relatively thin (<60 m) and occurs mainly in the

central part of the strait. Sediment of this unit was deposited within low areas on the upper surface of bedrock and the glacial unit, and it apparently was emplaced by marine processes during the Holocene sea-level rise. The third unit (unit 3 in Fig. 5), which covers essentially all of the seafloor in the central part of the strait (platform and marginal channels), is up to 180 m thick (Fig. 6) and was deposited by the modern-day oceanic current regime of southwesterly baroclinic flow from Cook Inlet and the eastern Gulf of Alaska (Muench and Schumacher, 1980). Unit 4 in Figure 5 underlies the shallow shelves and interfingers seaward with unit 3. It is composed of sediment eroded from the adjacent landmasses. The cores subjected to geotechnical testing and discussed in this paper were taken from unit 3.

METHODS

Sediment cores were collected at 65 stations on two cruises in Shelikof Strait, in June 1980 aboard the USGS R/V S.P. LEE and in July and August 1981 aboard the NOAA ship DISCOVERER (Fig. 2). A gravity coring system with 8.5-cm diameter plastic liners in steel core barrels was used on the 1980 cruise, whereas a vibracoring system with a 10-cm square cross-section plastic liner in thin-wall stainless steel barrel was employed on the 1981 cruise. Some grab samples were taken at locations of coarse sediment where the coring devices were ineffective.

Two cores were taken at most stations. One was designated mainly for geological analysis. It was cut into 1-m or 1.5-m-long sections, then split lengthwise for geological description and vane-shear strength testing. Subsamples were taken for index property determinations.

The second core was taken expressly for geotechnical testing. It was cut into 1-m-long sections, wrapped in cheesecloth, covered with microcrystalline wax, and stored upright in a refrigerator. These cores were later subjected to a suite of geotechnical tests in laboratories at the USGS and at a commercial testing company.

Several index properties were determined for subsamples of the sediment cores. Grain size was measured by sieving and pipetting into four size classes: gravel (>2 mm), sand ($2-0.062$ mm), silt ($0.062-0.004$ mm), and clay (<0.004 mm). Water content, as a percentage of dry sediment weight, was determined from the weight of sediment samples before and after even drying at 105°C . A correction for salt content of sea water (3.5%) was made to the weighing's. Atterberg limits were determined according to standard procedures (American Society for Testing and Materials, 1976), except that samples were not sieved prior to testing. Carbon content was measured with a LECO carbon determinator with induction furnace and acid digestion. Vane shear determinations of undrained shear strength were made on split core halves with a motorized device at a vane rotation rate of $90^{\circ}/\text{min}$. The vane is $1/2$ inch diameter by $1/2$ inch high and was inserted into the sediment to a depth twice the height of the vane.

Consolidation tests were run on subsamples from geotechnical cores to determine sub-failure deformational properties. Most tests were run on an oedometer in a stress-controlled mode (Lambe, 1951). Others were run in a triaxial loading cell under constant rate of strain conditions (Wissa and others, 1971). The consolidation tests measure change in volume with change in applied load. The results are normally plotted as void ratio (e = volume of voids/volume of solids) versus the logarithm of effective (buoyant)

vertical stress (p'). Two useful parameters are derived from these curves: the compression index and the maximum past pressure. The compression index (C_c) is the slope of the straight-line portion of the e -log p' curve and indicates the amount of compression produced by a particular load increment. The maximum past pressure (σ'_{vm}) is the greatest effective overburden stress to which the sediment has ever been exposed and is determined from the e -log p' curve by a simple graphical construction (Casagrande, 1936). The ratio of σ'_{vm} to the effective overburden stress at the time of sampling (σ'_{vo}) is the overconsolidation ratio (OCR), which is a measure of unloading that the sediment may have experienced, by erosion for example. A third parameter, the coefficient of consolidation (c_v), is determined for each load increment of the one-dimensional consolidation test and is related to the rate of consolidation.

Static triaxial tests were run on cylindrical samples 3.6-cm diameter and 7.6-cm long in order to determine strength properties of the sediment. Tests were run under undrained conditions with pore pressure measurements (Bishop and Henkel, 1964). Most samples were consolidated isotropically prior to testing, but some were consolidated anisotropically.

Dynamically loaded triaxial tests were also run, with the axial stress on samples varied sinusoidally at 0.1 Hz. Both compression and tension were applied at a predetermined percentage of the static strength. These tests can be used to evaluate the failure conditions of sediment under repeated loading, such as by earthquakes.

A first set of triaxial tests was run on sediment samples that were consolidated to somewhat arbitrary stress levels. However, the later testing program followed the normalized stress parameter (NSP) approach (Ladd and

Foott, 1974), whereby consolidation stresses are chosen on the basis of maximum past pressure (σ'_{vm}), as determined from consolidation tests. Typically, the triaxial test specimen was consolidated to four times σ'_{vm} , which eliminates some of the disturbance effects associated with coring. Overconsolidation was artificially induced in some tests by rebounding the specimen to lower stress levels before applying the triaxial load. Measured values of undrained shear strength (S_u) are normalized with respect to effective overburden stress (σ'_v). A premise of the NSP method is that the ratio S_u/σ'_v is constant for a particular value of OCR. Moreover, a relation exists between S_u/σ'_v and OCR that allows prediction of sediment strength at depths below the level of sampling (Mayne, 1980).

RESULTS

Sediment description, index properties: Sediment samples could only be collected to shallow depths (<3 m) beneath the seafloor. Therefore, most are from the highest stratigraphic unit (unit 3, Fig. 5). However, judging from seismic-reflection profiles over sampling stations, a few outcrops of other units were also sampled. Seismic-reflection profiles also show that unit 3 has a typical thickness of about 80 to 100 m (Fig. 6). The appearance of acoustic reflectors within this unit indicates some lithologic variability with depth, but there is no reason to suspect radical changes in sediment type, except for possible thin beds of volcanic ash. The physical properties for the cores should therefore be representative of the terrigenous component of the unit as a whole, but drill-hole samples would be necessary to confirm this.

The texture of surficial sediment on the central platform and in the adjacent marginal channels grades from gravelly and sandy material in the northeast part of the strait to mud in the southwest (Figs. 7 and 8; Appendix A). A general fining trend from northwest to southeast across the platform also exists.

The two grab samples of coarse sediment recovered from Stevenson Entrance appear to have been taken from outcrops of unit 1. Most of the coarse clasts, which range to boulder size, are angular to subangular, and some are faceted. This supports the hypothesis that unit 1 was deposited by glacial processes.

A few grab samples of coarse material were also recovered from the shallow shelves and from the adjacent slopes. They probably are from unit 4. Coarse clasts have similar morphology to those from unit 1, perhaps reflecting glacial transport at some point in their history.

Sediment cores from the platform and marginal channels in the central portion of the strait have a fairly uniform stratigraphy with depth. Sandy sediment in the northeast end of the strait is predominantly greenish-gray, with variations from black to yellowish brown. Sand-filled burrows, pebble clasts, and whole or broken shells are common. In progressively finer-grained cores to the southwest, color remains greenish-gray but is less varied, and shells and clasts are rare.

A layer of volcanic ash occurs in many cores. Maximum thickness of the layer is nearly 20 cm. It is size-graded, with the coarsest basal fragments a few millimeters diameter. The color is from tan to white with a pink cast. The refractive index of the ash is 1.485 ± 0.002 , which in this region is unique to the outfall from the 1912 Katmai eruption (Nayudu, 1964; Pratt and others, 1973). Depth of the ash beneath the seafloor was used to calculate

values of post-1912 sediment accumulation rate (Fig. 9). Accumulation rate varies significantly throughout the strait. It is greatest near the Alaska Peninsula at the southwest end of the strait, whereas it is near zero at places in the marginal channel along the Kodiak island group.

Water content of sediment is shown in Figure 10 as interpolated values at 1-m depth in cores. It is calculated as a percentage of dry sediment weight, and therefore, values in excess of 100% are possible if the weight of water exceeds the weight of sediment grains. Water content generally decreases to the northeast, inversely correlating with grain size. Moreover, water content increases across the strait, from the Alaska peninsula to Kodiak Island. Bulk sediment density at 1-m depth, which is calculated from water content and grain specific gravity, correspondingly decreases down and across the strait (Fig. 11). Average grain specific gravity itself shows no discernible trend (Fig. 12).

Atterberg limits describe the plasticity of sediment, in terms of the liquid limit (water content that separates plastic and liquid behavior) and the plastic limit (water content that separates semi-solid and plastic behavior). Useful derivatives are the plasticity index (difference between the liquid and plastic limits), and the liquidity index (position of the natural water content relative to the liquid and plastic limits). Certain trends in plasticity are evident in Shelikof Strait. Average liquid limit, plastic limit, and plasticity index increase down the strait toward the southwest, and also generally across the strait, toward the southeast (Figs. 13, 14, and 15; Appendix A). These properties also generally increase with decrease in mean grain size (Figs. 16, 17, and 18), although the data for plastic limit are quite scattered. Plastic limit is less variable than liquid limit, which is typically the case (Mitchell, 1976; Richards, 1962).

Correlations have been made between liquid limit and compressibility (Herrmann and others, 1972; Skempton, 1944). The majority of Shelikof Strait samples fall within the medium ($30 < \text{liquid limit} < 50$) and high (liquid limit > 50) compressibility ranges.

Nearly all measured liquidity indices in Shelikof Strait are greater than 1 (Appendix A), which is usual for near-seafloor marine sediment. Sediment with a liquidity index greater than one behaves as a liquid when remolded.

A plot of liquidity index versus plasticity index - termed a plasticity chart (Casagrande, 1948) - shows a trend parallel to the A-line that divides basic soil types (Fig. 19). Most sediment samples from Shelikof Strait plot below the A-line, which is typical of inorganic silt and silty clay of high compressibility. The linear trend of data points is expected for samples taken throughout the same sedimentary deposit (Terzaghi, 1955; Richards, 1962).

Undrained shear strength of sediment samples (S_u), as measured with a laboratory miniature vane shear device, generally decreases toward the southwest end of the strait, and thus correlates with the water content trend, although there is much scatter (Figs. 20 and 21; Appendix A). The consistency of most of the near-seafloor sediment can be classified as very soft ($S_u < 12$ kilopascals), but some is soft ($12 \text{ kPa} < S_u < 24 \text{ kPa}$) to medium ($24 \text{ kPa} < S_u < 48 \text{ kPa}$) (Terzaghi and Peck, 1948). Hampton and others (1981) showed that shear strength is anisotropic in Shelikof Strait sediment cores. Values of shear strength measured with the axis of vane rotation perpendicular to the axis of core samples exceed the values of strength measured with the axis of vane rotation parallel to the core axis. The magnitude of sediment strength thereby depends on the orientation of the applied stress.

Sediment samples from Shelikof Strait are characterized by low to intermediate content of organic carbon, compared to other marine areas (Bordovskiy, 1965, 1969; Gardner and others, 1980; Lisitzin, 1972; Rashid and Brown, 1975). Most values are between 0.40% and 1.50%. Organic carbon generally increases down the strait toward the southwest, as well as across the strait toward the southeast (Fig. 22; Appendix A). Correlations with other physical properties were shown by Hampton and others (1981). Organic carbon content correlates positively with water content and plasticity index, whereas an inverse correlation is found with grain size and vane shear strength. Correlations similar to those described above have been reported by others for low organic-carbon content sediment (Bordovskiy, 1965, 1969; Bush and Keller, 1981; Keller and others, 1979; Lisitzin, 1972; Mitchell, 1976; Odell and others, 1960).

Percent calcium carbonate is typically low in Shelikof Strait sediment (Fig. 23; Appendix A). Most values are less than 3.50%. Two locations with anomalously high values, off Shuyak Island and in Stevenson Entrance, are near the boundary of the strait.

Consolidation properties: Consolidation properties as determined from laboratory tests are listed in Table 1. All tests indicate a maximum past pressure (σ'_{vm}) greater than the present overburden pressure (σ'_{vo}). The ratio $\sigma'_{vm}/\sigma'_{vo}$ is the overconsolidation ration (OCR) and is greater than 1.0 for all tests. The usual implication is that the sediment has experienced unloading as a consequence of erosion. However, there is no geological evidence for erosion; in fact, sediment is accumulating at high rates throughout most of the strait (Fig. 9). The high values of OCR probably

represent initial cementation of sediment particles or grain interlocking and are not indicative of overconsolidation in the strict sense of the term.

Compression index (C_c) is a measure of the amount of consolidation that occurs for a given increment in load. The coarse sediment at the northeast end of the strait is less compressible than the progressively finer sediment to the southwest, as indicated by a southwest trend of increasing C_c (Table 1). Richards (1962) reported a range of 0.20 to 0.87 for C_c measured on samples of marine sediment from many areas, and most values from Shelikof Strait fall within this range.

Compression index commonly shows a linear relation to liquid limit (LL). The data from Shelikof Strait, when plotted in this manner, exhibit a general trend, but with much scatter (Fig. 24). Skempton (1944) found that the relation can be expressed as

$$C_c = 0.009 (LL - 10),$$

and the regression equation for Shelikof Strait sediment is similar:

$$C_c = 0.006 (LL + 5.7).$$

The rate at which consolidation occurs in response to loading determines the coefficient of consolidation (c_v). It is directly related to permeability of a sediment and inversely related to the compressibility. The coefficient is calculated for each load increment during a laboratory consolidation test from plots of deformation versus time. As shown in Table 1, c_v commonly varies through one to two orders of magnitude for a single test. No general trend in the data is evident, although the high expected permeability and low compressibility of coarse-grained sediment would suggest a decrease of c_v to the southwest. Measurements of c_v for clay sediment from various marine locations by Richards and Hamilton (1967) are in the range $3.2 - 6.0 \times 10^{-4}$ cm²/sec, which are lower than typical values in Shelikof Strait.

Static strength properties: Sediment properties derived from static triaxial strength tests are listed in Table 2. The primary measured property is the undrained shear strength (S_u). It is the maximum sustainable shear stress within a sample subjected to a particular consolidation stress (σ_c'). S_u acts along a plane inclined at 45° to the axial load. The arcsine of S_u divided by the effective normal stress across this plane is the effective angle of internal friction (ϕ'), whose magnitude is an indication of the strength behavior of the sediment under slow (drained) loading conditions. In comparison, the ratio S_u/σ_c' gives an indication of the strength behavior during rapid (undrained) loading conditions. The difference in drained and undrained strength behavior depends on the pore water pressure generated in response to the tendency for volume change when the sediment is axially loaded. If a sediment has a high tendency for volume change, the difference in strength between rapid and slow loading can be substantial.

The effective angle of internal friction for the normally consolidated sediment samples ($OCR \approx 1$) in this study is relatively high ($35^\circ - 46^\circ$). Compare with values given by Lambe and Whitman 1969, p. 149 and 306). The higher values ($> 40^\circ$) are in the finer sediment cores from the southwest half of the strait (Table 2). Therefore, sediment from Shelikof Strait appears to be atypically strong under conditions of drained loading, with the finer sediment exhibiting higher strength. Samples tested at $OCR > 1$ tend to have ϕ' comparable to that of normally consolidated samples, except for station 649 where some overconsolidated samples have significantly higher values. The data indicate similar drained behavior of normally consolidated and overconsolidated sediment in the strait.

Lambe and Whitman (1969, p. 307, Fig. 21.4) detected a relation between ϕ' and plasticity index for normally consolidated soil. Triaxial data for which there are plasticity index values in Shelikof Strait plot within the range of Lambe and Whitman's data, except for the core at station 511, which is abnormally strong for sediment with such high plasticity (Fig. 25).

Evaluation of undrained strength, in terms of S_u/σ'_c , requires some judgement in order to detect trends. In particular, the tests run at low consolidation stress (σ'_c) seem to give erratic values of S_u/σ'_c . This was also shown to be the case for triaxial data from nearby Kodiak Shelf (Hampton, in press). Tests run at high values of consolidation stress (which corrects some of the effects of disturbance) and $OCR \approx 1$ have values of S_u/σ'_c between 0.3 and 0.6, with no areal trend (Table 2). The value of S_u/σ'_c increases with OCR for each core tested.

The static triaxial test data are plotted according to the NSP approach in Figure 26. The slope (Λ) of the line for each core is a measure of the change in undrained strength with OCR. Most cores have Λ values between 0.79 and 0.97. Mayne (1980) compiled the results of many triaxial tests and found a mean value of $\Lambda = 0.64$ with a standard deviation of 0.18. The sediment in Shelikof Strait, with its relatively high values of Λ , would tend to retain more of its strength after unloading compared to most sediment examined by Mayne (1980). The $\Lambda = 1.43$ calculated for the sediment of station 528 is greater than the theoretical limit of $\Lambda = 1.0$, and further testing is required to resolve this conflict.

Dynamic strength properties: The data from triaxial strength tests are given in Table 3. The quantity τ_{cyc}/S_u is the cyclic stress level, the average

value of shear stress (τ_{cyc}) applied sinusoidally with full stress reversal at 0.1 Hz, expressed as a percentage of the static undrained shear strength (S_u). Pore water pressure and strain accumulate with repeated application of τ_{cyc} . At some point, the pore water pressure approaches the confining stress, strain increases abruptly, and the sediment fails. In our tests, failure was chosen when 20% strain was reached.

Samples typically fail in fewer cycles at progressively higher stress levels. Figure 27 shows the number of cycles to failure versus stress level for Shelikof Strait samples. Although there is some scatter, the data fall within the range of test results on terrigenous sediment from other areas (Lee and others, 1981; Anderson and others, 1980; Hampton, in press). Moderate cyclic strength degradation is indicated; that is, after 10 cycles of loading (as might be imparted by an earthquake, for example), the samples fail at stress levels between 60% and 80% of their static strength.

DISCUSSION

The primary geotechnical concerns in Shelikof Strait include settlement of structures, bearing capacity under static and cyclic loading lateral load capacity, and anchor breakout resistance. Natural slope failures are not a serious problem because only one small sediment slide has been documented (Hampton and others, 1981). There is some evidence for gas-charged sediment, but the problem of low strength that might exist in sediment of this type was not addressed in the present study.

Quaternary sediment in Shelikof Strait covers bedrock to a thickness of from 20 m to more than 800 m (Fig. 4). The sequence consists of Pleistocene glacial and glaciomarine sediment at the base, overlain by Holocene marine

deposits. The highest stratigraphic unit, deposited by oceanic currents as exist today, has accumulated to a thickness of 80-100 m over most of the strait; the total range is about 20 m to 180 m. Geotechnical testing was performed only on samples from this uppermost unit. A geotechnical analysis based on these data probably addresses most situations of engineering concern. Deeper stratigraphic units appear from interpretive geologic studies to be relatively coarse-grained (Hampton and Winters, 1981; Whitney and others, 1980a, b), and they probably are stable, but deep drill-core samples would have to be obtained in order to confirm this by geotechnical testing.

The pattern of grain-size variation (Figs. 7 and 8) evidently reflects progressive sorting by the southwesterly flowing barotropic current that dominates circulation in the strait. The present study and the previous report by Hampton and others (1981) show that some index properties vary in relation to grain size. Properties that show a direct correlation and therefore increase to the southwest down the strait and to the southeast across the strait include water content, liquid limit, plastic limit, plasticity index, and organic carbon content (Figs. 10, 13, 14, 15, and 22). Properties that correlate inversely with grain size include bulk sediment density and undrained (vane) shear strength (Figs. 11 and 20).

Consolidation tests indicate that sediment samples are overconsolidated, but this probably is a near-seafloor diagenetic or fabric phenomenon rather than a result of erosion, because net sediment accumulation is presently occurring throughout the strait (Table 1, Fig. 9). The fine-grained sediment to the southwest has high values of compression index (C_c), which indicates that it is more compressible than the coarser material to the northeast. The rate of consolidation, as shown by the coefficient of consolidation (c_v), is

highly variable for each consolidation test and does not show an areal trend (Table 1). Intuitively, a higher value of c_v would be expected for the coarser-grained sediment because of its normally higher permeability and lower compressibility, but apparently this is not the case.

Another unexpected result is that the static drained strength, in terms of the effective angle of internal friction (ϕ), is higher for the fine-grained sediment than it is for the coarser-grained samples (Table 2). Drained strength does not vary appreciably with OCR. Undrained static strength behavior does not exhibit significant areal variation. Values of S_u/σ'_c for tests run at OCR = 1 are between 0.3 and 0.6. This parameter increases with OCR for each core that was tested. The NSP pore-pressure parameter (λ) varies from 0.79 to 0.97, which indicates significant static strength increase with OCR (Fig. 26). Again, no areal trend is apparent. But, because few data points were used to plot the lines in Figure 26 and because large scatter of data exists for some individual cores, additional strength testing at more levels of OCR would add precision to the plots and perhaps reveal some systematic variation.

Test data for most cores define similar response to cyclic loading over a broad range of number of cycles required to cause failure (e.g., cores 511, 525, 528, and 540 in Fig. 27). Dynamic strength degradation varies over a limited range at low number of cycles; for instance, it is between about 60% and 80% for 10 cycles.

Geotechnical properties of Shelikof Strait sediment can be compared with data from other studies to determine if the sediment has normal deformational behavior. However, few data exist for some properties, which makes the evaluations tentative.

Most values of compression index fall within the range of 0.20 to 0.87 reported by Richards and Hamilton (1962) for silty clay to highly colloidal clay; one test on the core from station 507 has a high value of 0.94 (Table 1). Skempton's (1944) classification of compressibility based on liquid limit indicates that Shelikof Strait samples are moderately to highly compressible (Appendix A). Substitution of the class-boundary values of liquid limit (moderate compressibility: $30 < LL < 50$; high compressibility: $LL > 50$) into the regression equation for Shelikof Strait data (Fig. 24),

$$C_c = 0.006 (LL + 5.7),$$

indicates that the range of moderate compressibility is $0.21 < C_c < 0.33$ and the high range is $C_c < 0.33$, which is consistent with classifying the sediment as moderately to highly compressible (Table 1).

Effective friction angle (ϕ') for sediment in Shelikof Strait is high ($35^\circ - 46^\circ$) compared to the range ($20^\circ - 40^\circ$) reported by Lambe and Whitman (1969, p. 149 and 306) for normally consolidated sediment. Apparently, no compilations of ϕ' exclusively for terrigenous marine sediment have been made. Hampton (in press) reports ϕ' mostly in the $30^\circ - 40^\circ$ range for terrigenous samples from the Kodiak Shelf. Shelikof Strait terrigenous sediment is relatively strong under drained loading conditions.

Lambe and Whitman (1969, p. 452, Fig. 29.19) present data on the undrained strength of normally consolidated marine clay, and values of S_u/σ'_c are between about 0.2 and 0.4. The range for normally consolidated Shelikof Strait samples is 0.3 to 0.6, so they are relatively strong under conditions of undrained loading. S_u/σ'_c for normally consolidated terrigenous

sediment from the Kodiak Shelf are also high, from 0.4 to 1.0 (Hampton, in press).

Values of the NSP factor λ are high (0.79 ~ 0.97) compared to the average value of 0.64 (standard deviation = 0.18) in the extensive compilation by Mayne (1980). The implication is that the increase of strength with overconsolidation is higher than normal.

The low to moderate cyclic strength degradation of Shelikof Strait samples is similar to the behavior of clay sediment reported in other studies (Lee and others, 1981; Anderson and others, 1980; Hampton, in press). Sediment failure in response to large earthquakes certainly is a possibility, but the potential is not as great as has been predicted for some deposits of silt in the northeast Gulf of Alaska (cyclic strength at 10 cycles as low as 40% of the static strength; Lee and Schwab, in press) and volcanic ash on the Kodiak Shelf (cyclic strength at 10 cycles is 12% of the static strength; Hampton, in press). The deposit of Katmai ash in Shelikof Strait was not subjected to geotechnical testing. However, its in situ density is so great that normal gravity coring devices could not penetrate the layer. The relative density appears to be high and therefore the liquefaction potential is low. The possibility that more deeply buried ash layers are present and might be highly susceptible to liquefaction cannot be evaluated with the information presently available.

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Table 1. Consolidation test results.

Station number	Depth in core (cm)	σ'_{vo} (kPa)	σ'_{vm} (kPa)	C_c	$c_v \times 10^{-2}$ (cm^2/sec) from to		OCR
507	39	1.1	6.0	0.94	0.17	1.10	5
	171	5.0	32.0	0.76	0.22	1.13	6
509	89	3.7	20.0	0.86	0.27	2.67	5
	94	3.7	23.0	0.88	0.12	0.81	6
511	64	2.8	15.0	0.52	0.05	2.17	5
	111	4.6	9.0	0.66	0.09	1.10	2
	191	9.8	12.0	0.45	0.18	1.38	1
649	41	2.0	56.0	0.33	0.04	1.30	28
	116	6.1	30.0	0.54	0.12	0.97	5
	167	8.9	29.0	0.60	0.08	1.40	3
525	45	3.3	26.0	0.30	0.30	1.52	8
	96	6.9	28.0	0.26	0.35	1.68	4
	165	13.8	64.0	0.26	0.54	2.23	5
528	64	4.7	43.0	0.28	0.18	1.57	9
	144	10.4	45.0	0.29	0.31	3.59	4
540	47	2.8	20.0	0.50	0.11	0.50	7
	131	6.1	48.0	0.54	0.20	0.67	8
	201	11.6	65.0	0.37	0.16	0.98	6

Table 2. Static triaxial strength test results.

Station number	Depth in core (cm)	σ'_c (kPa)	Induced OCR	S_u (kPa)	S_u/σ'_c	ϕ (degrees)
507	30	53.9	1	18.8	0.3	39
	130	140.0	1	73.5	0.5	46
509	120	172.4	1	73.4	0.4	40
	170	47.0	4.1	68.9	1.5	<42
511	17	20.7	3	25.4	1.2	39
	28	2.8	-	8.8	3.1	64
	44	1.4	-	9.6	6.3	64
	180	48.2	1	27.0	0.6	43
121	8.3	5.8	18.6	3.2	41	
649	86	24.0	5.9	57.6	2.4	<40
	86	46.7	3	52.3	1.1	<54
	109	0.3	-	13.0	43.3	<57
	109	142.3/70.7	1	58.3	0.4	39
	127	4.4	8	12.3	2.8	<69
	132	160.5	1	76.5	0.5	41
525	8	1.4	-	18.5	13.2	48
	73	19.3	6	47.5	2.5	34
	85	6.9	-	25.2	3.6	45
	152	282.5	1	121.6	0.4	37

Table 2. (continued)

Station Number	Depth in core (cm)	σ'_c (kPa)	Induced OCR	S_u (kPa)	S_u/σ'_c	ϕ (degrees)
528	37	1.4	-	18.6	12.8	50
	80	179.2	1	79.8	0.4	35
	94	6.9	-	19.0	2.8	43
	122	30.3	3.6	77.4	2.5	38
	139	178.8/89.6	1	66.7	0.3	41
540	29	15.2	6	24.2	1.6	40
	69	1.4	-	15.4	11.0	60
	120	10.3	-	16.7	1.6	47
	140	199.8	1	79.9	0.4	35
	159	114.0	1.8	82.8	0.7	40

Table 3. Dynamic triaxial strength test results.

Station number	Depth in core (cm)	σ'_c (kPa)	Induced OCR	τ_{cyc}/s_u (%)	Cycles to failure
509	137	173.6	1	49	145
	137	175.0	1	66	64
511	152	46.9	1	70	10
	167	46.9	1	47	48
649	96	153.1	1	70	22
	96	146.0	1	56	450
	140	30.2	4.4	79	17
	140	139.8	1	72	39
525	135	282.4	1	47	30
	117	282.4	1	70	7
528	23	27.5	4	32	51
	178	179.1	1	70	13
	193	179.1	1	46	110
540	152	199.8	1	71	12
	227	199.8	1	43	900+
	238	299.8	1	56	28

FIGURE CAPTIONS

1. Location map of the study area in Shelikof Strait.
2. A. Tracklines of continuous seismic-reflection profiles. Solid lines represent a regional survey contracted by the USGS Conservation Division, and dashed lines represent site surveys on cruises of the R/V S.P. Lee (1980) and NOAA ship Discoverer (1981).
B. Locations of sediment sampling stations.
3. Bathymetry of Shelikof Strait, 20-m contour interval. Depths corrected to mean lower low water.
4. Thickness of sedimentary units of probable Pleistocene and younger age. Contour interval: 50 meters except for thickness greater than 500 m where contour interval is 100 m.
5. Representative seismic-reflection profiles showing seismic-stratigraphic units.
6. Thickness of highest seismic-stratigraphic unit that covers most of the seafloor of Shelikof Strait. Contour interval: 20 m.
7. Pie-diagrams showing relative abundances of textural classes in seafloor sediment samples.
8. Mean grain size of seafloor sediment, in phi-units.

9. Sediment accumulation rates, in cm/100 yr.
10. Water content (percent dry weight) at 1-m depth in sediment cores.
11. Bulk sediment density (gm/cm^3) at 1-m depth in sediment cores.
12. Average grain specific gravity in sediment cores.
13. Average liquid limit (percent dry weight) in sediment cores.
14. Average plastic limit (percent dry weight) in sediment cores.
15. Average plasticity index in sediment cores.
16. Liquid limit versus grain size.
17. Plastic limit versus grain size.
18. Plasticity index versus grain size.
19. Plasticity chart.
20. Vane shear strength (kPa) at 1m depth in sediment cores.
21. Vane shear strength versus water content.

22. Average organic carbon content in sediment cores.
23. Average calcium carbonate content in sediment cores.
24. Graph of compression index versus liquid limit.
25. Graph of effective angle of internal friction versus plasticity index.
Solid line shows empirical relation derived by Lambe and Whitman (1969);
dashed line indicates limits of their data.
26. Graph of normalized undrained shear strength versus overconsolidation ratio.
27. Graph of cyclic stress level versus number of cycles to failure.

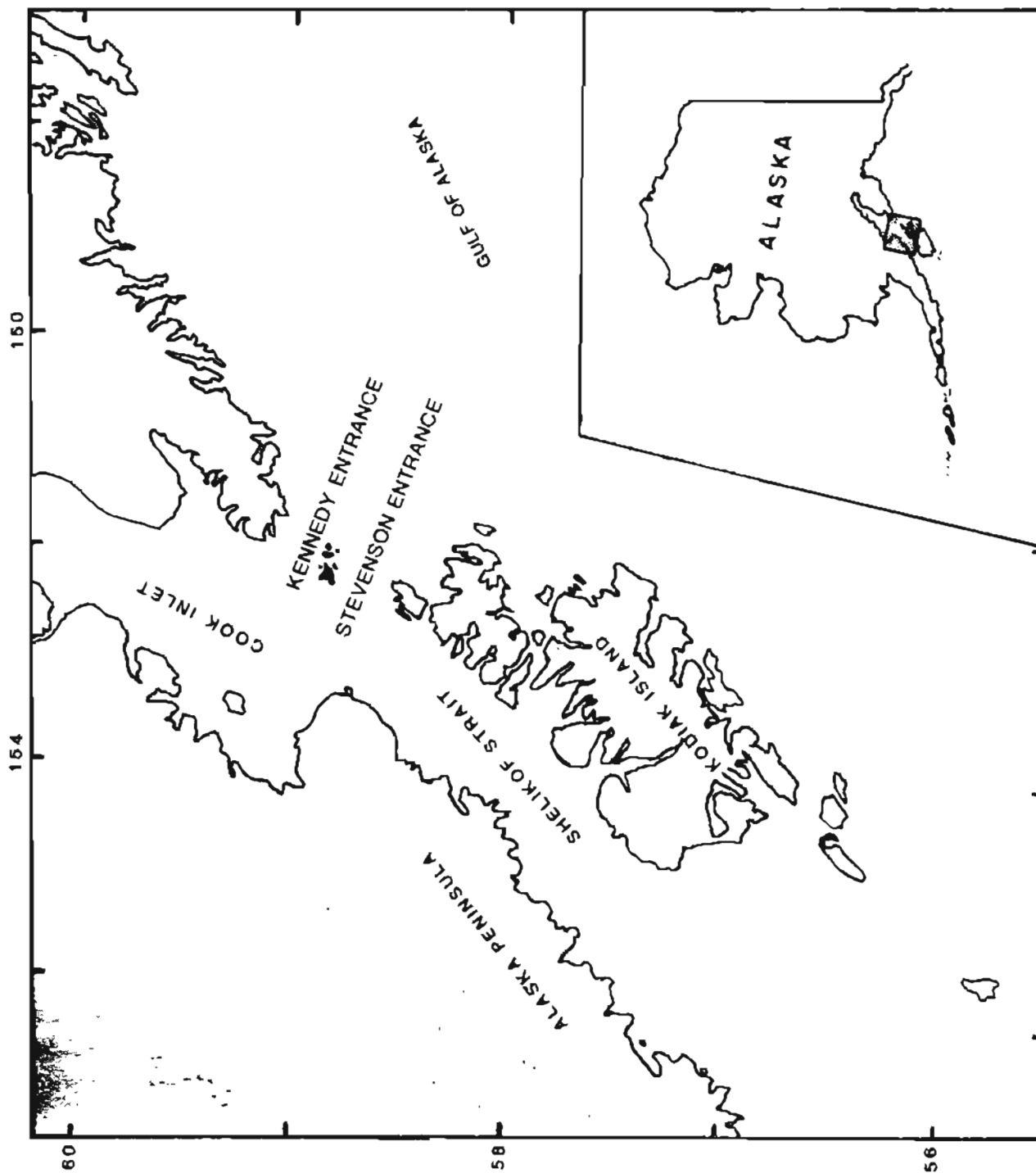


Fig. 1

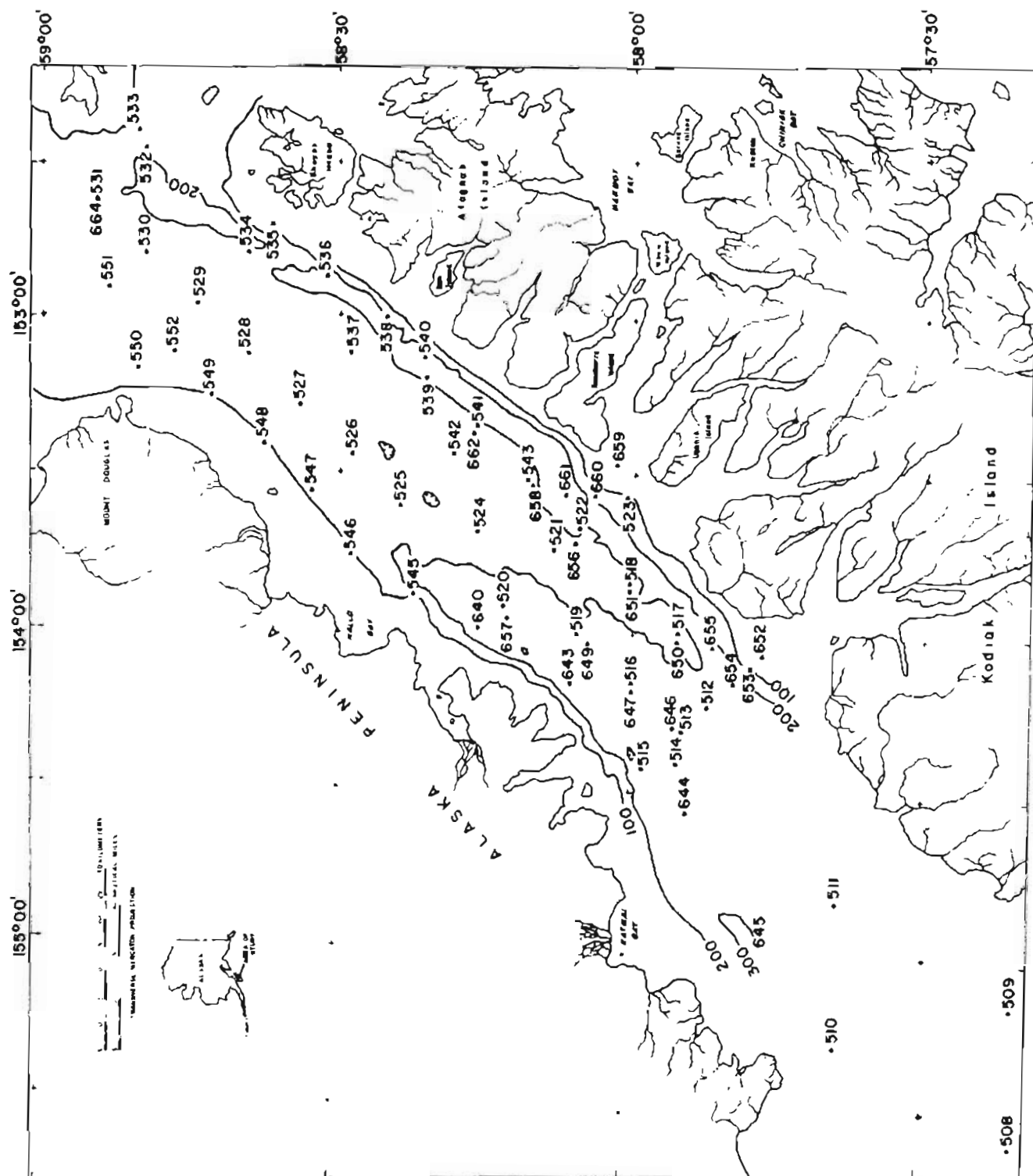


Fig. 2B

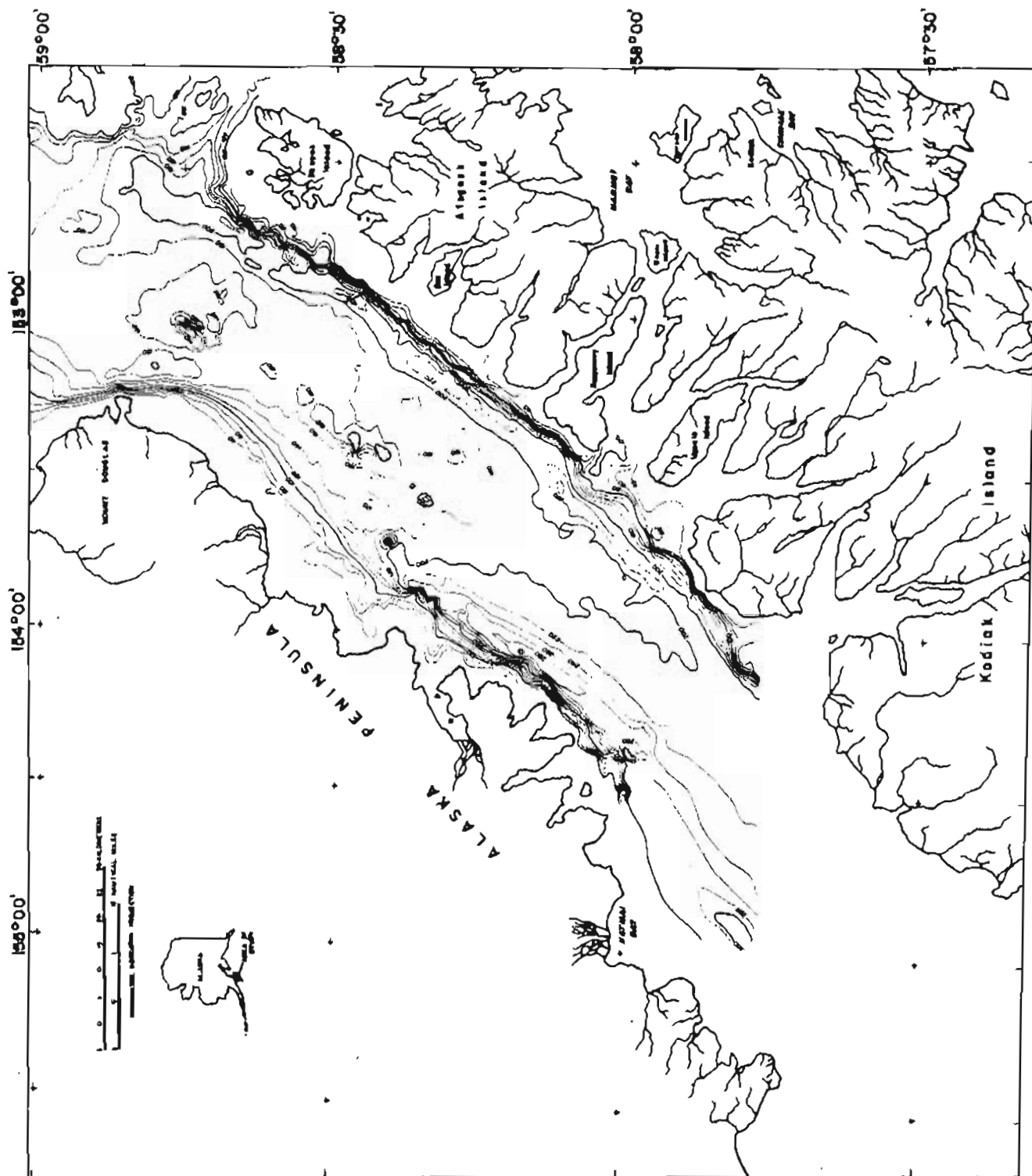


Fig. 3

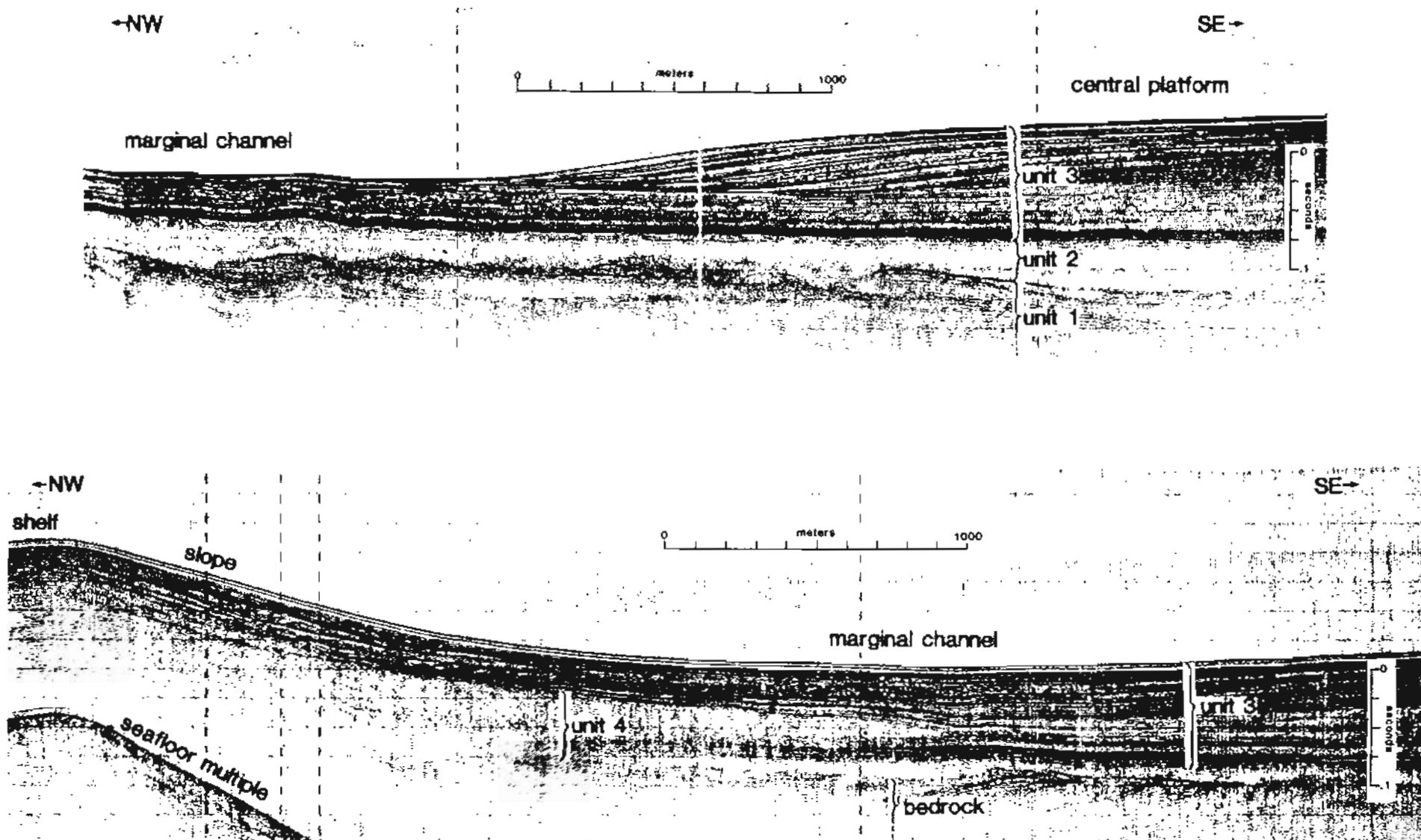


Fig. 5

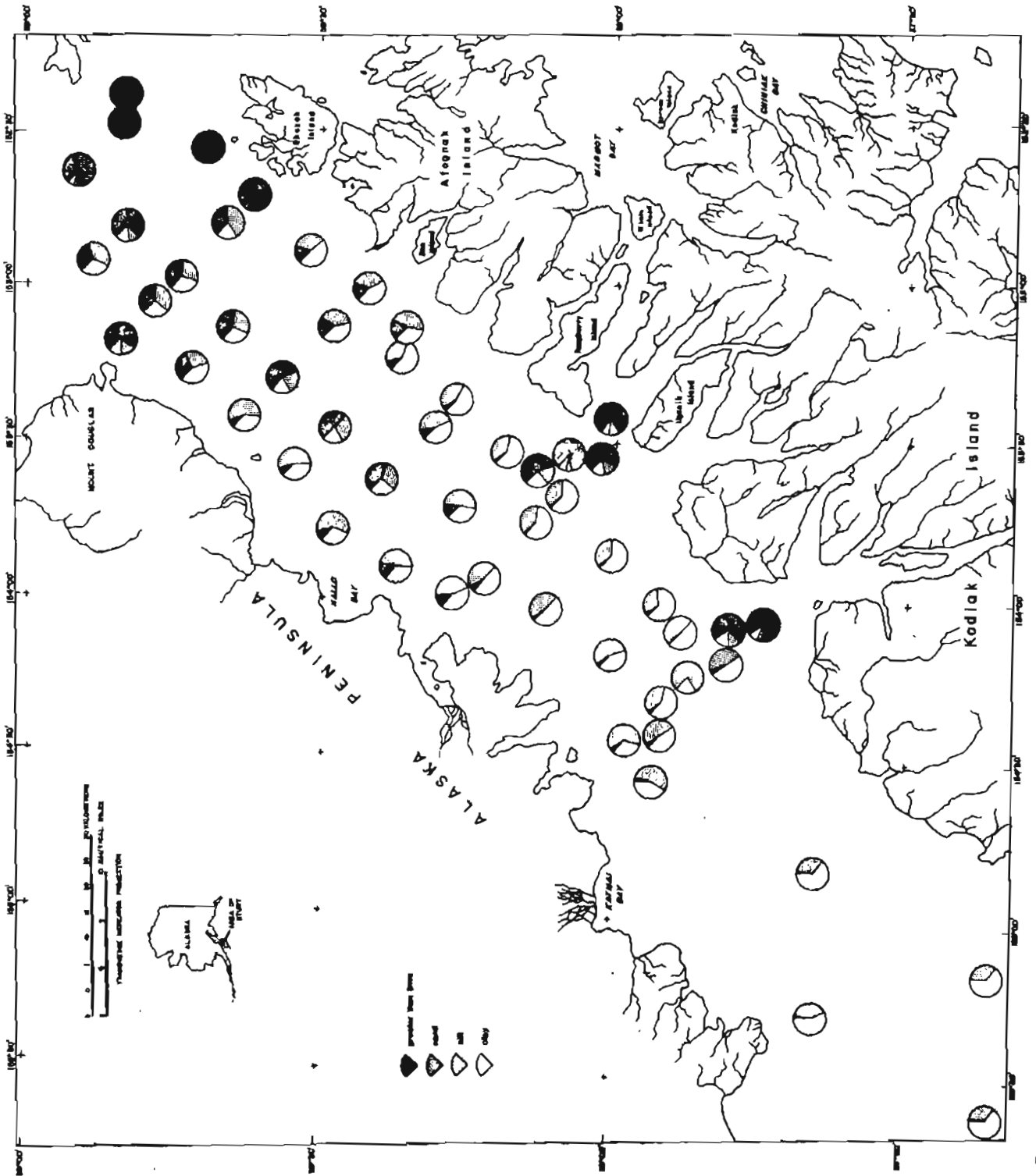


Fig. 7

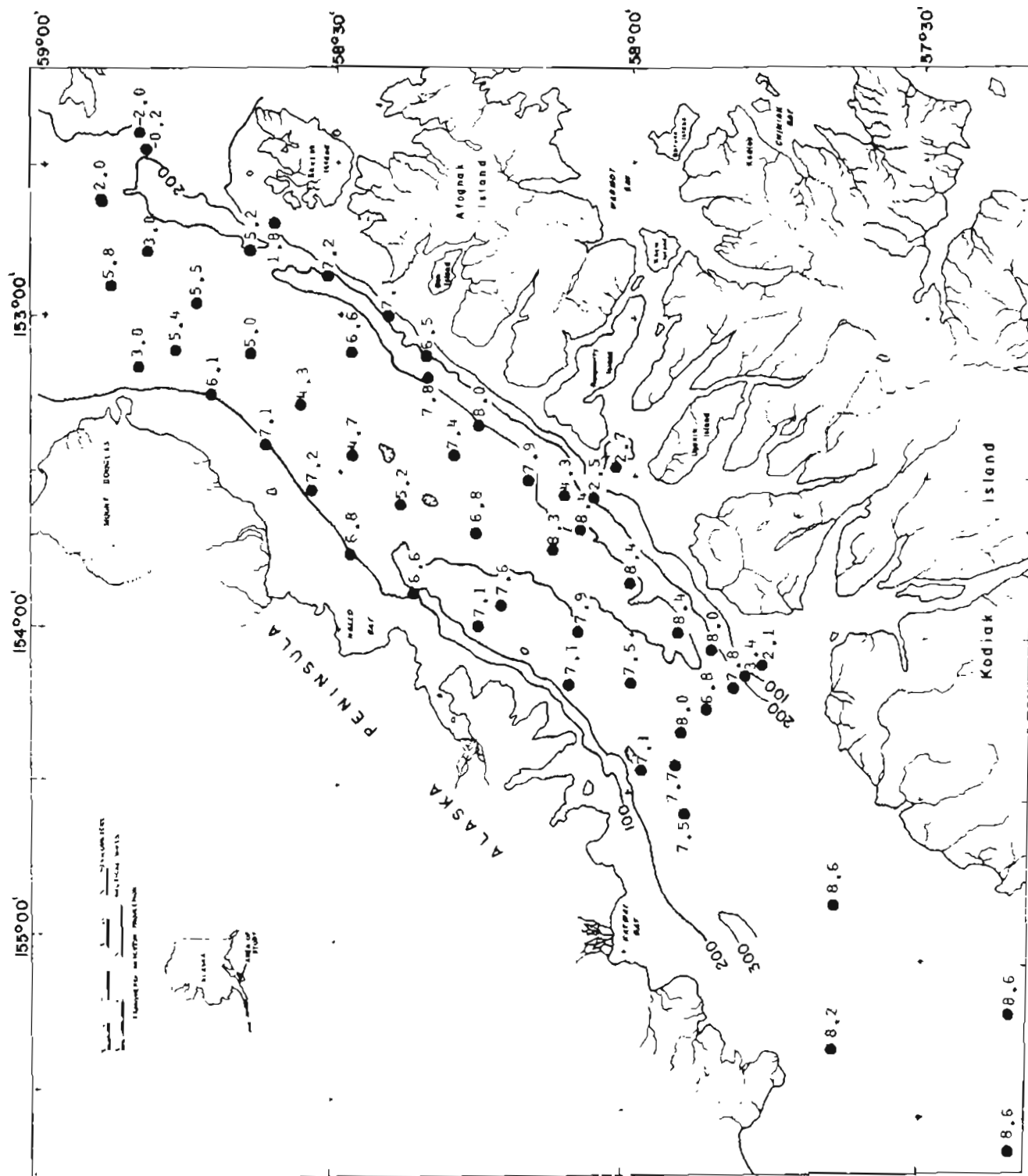
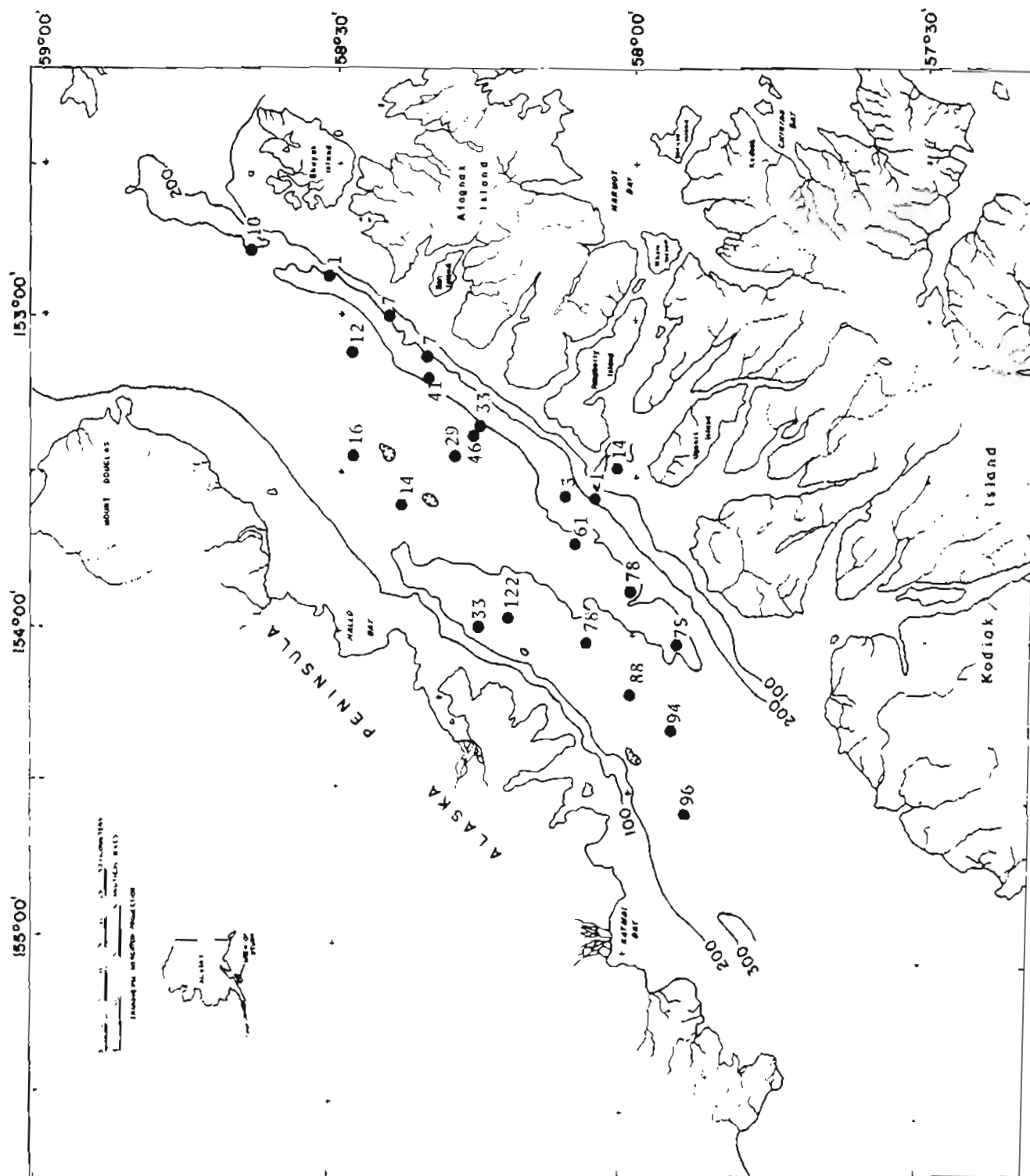


Fig. 8



Fin. 9

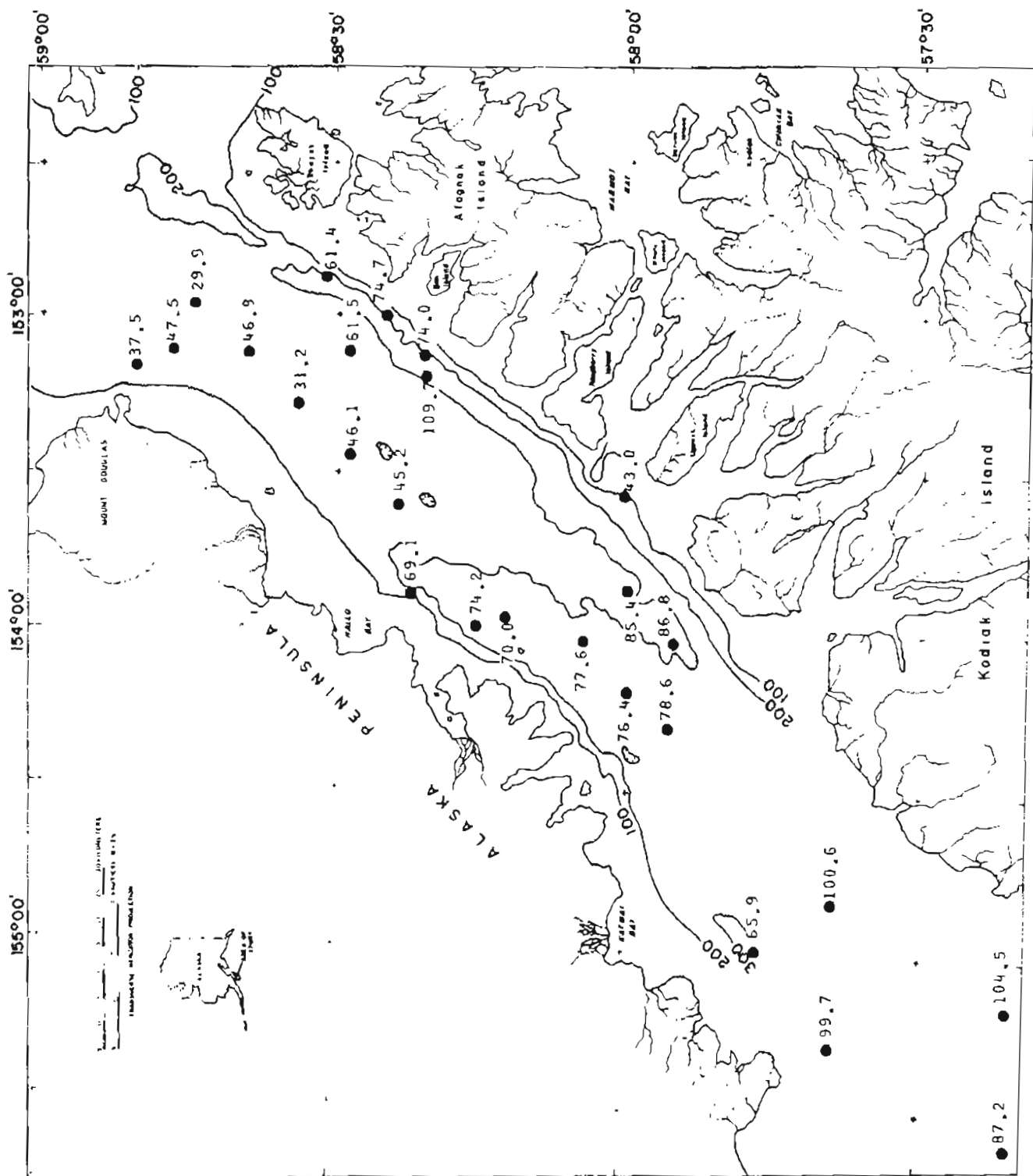


Fig. 10

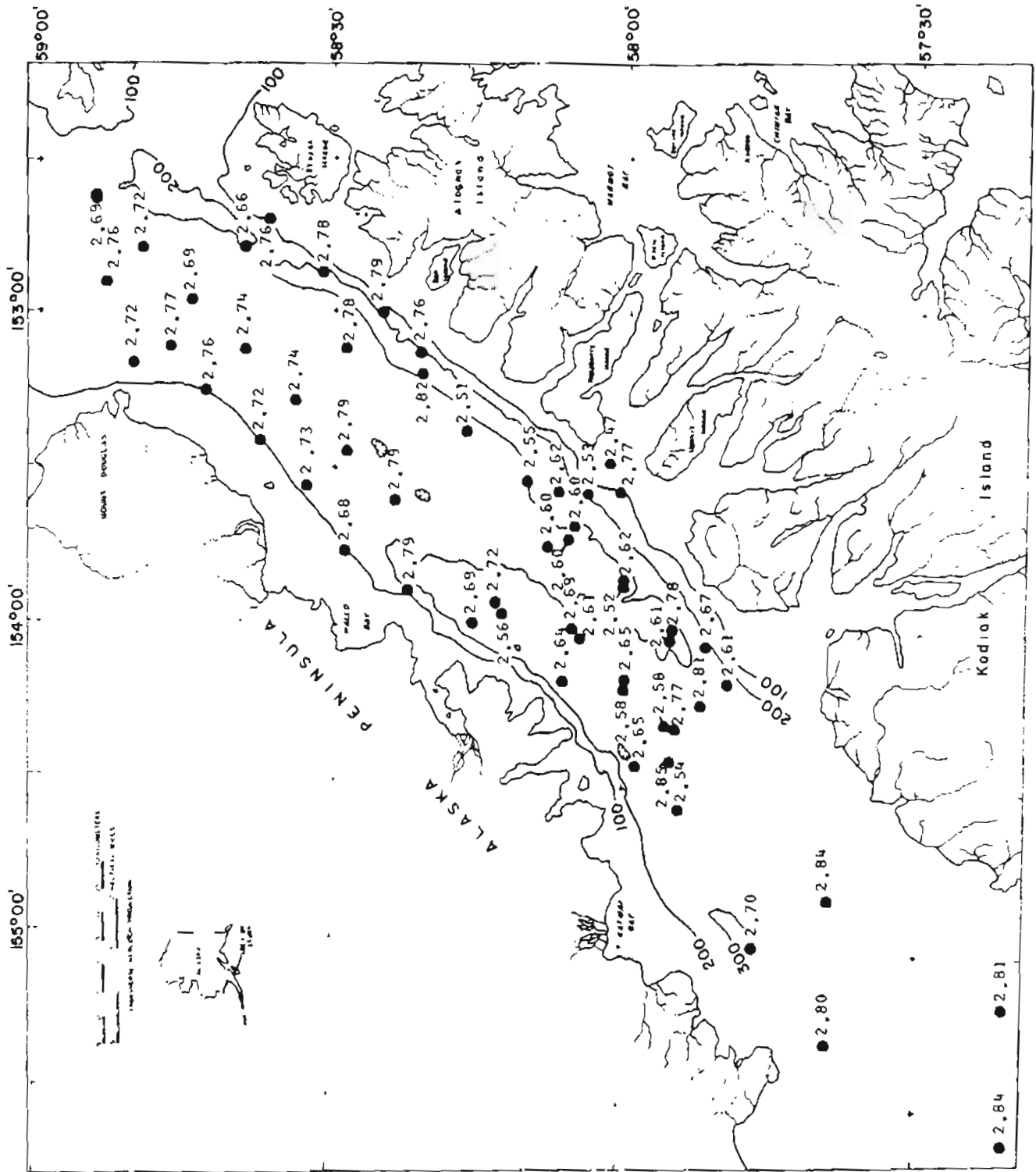


Fig 17

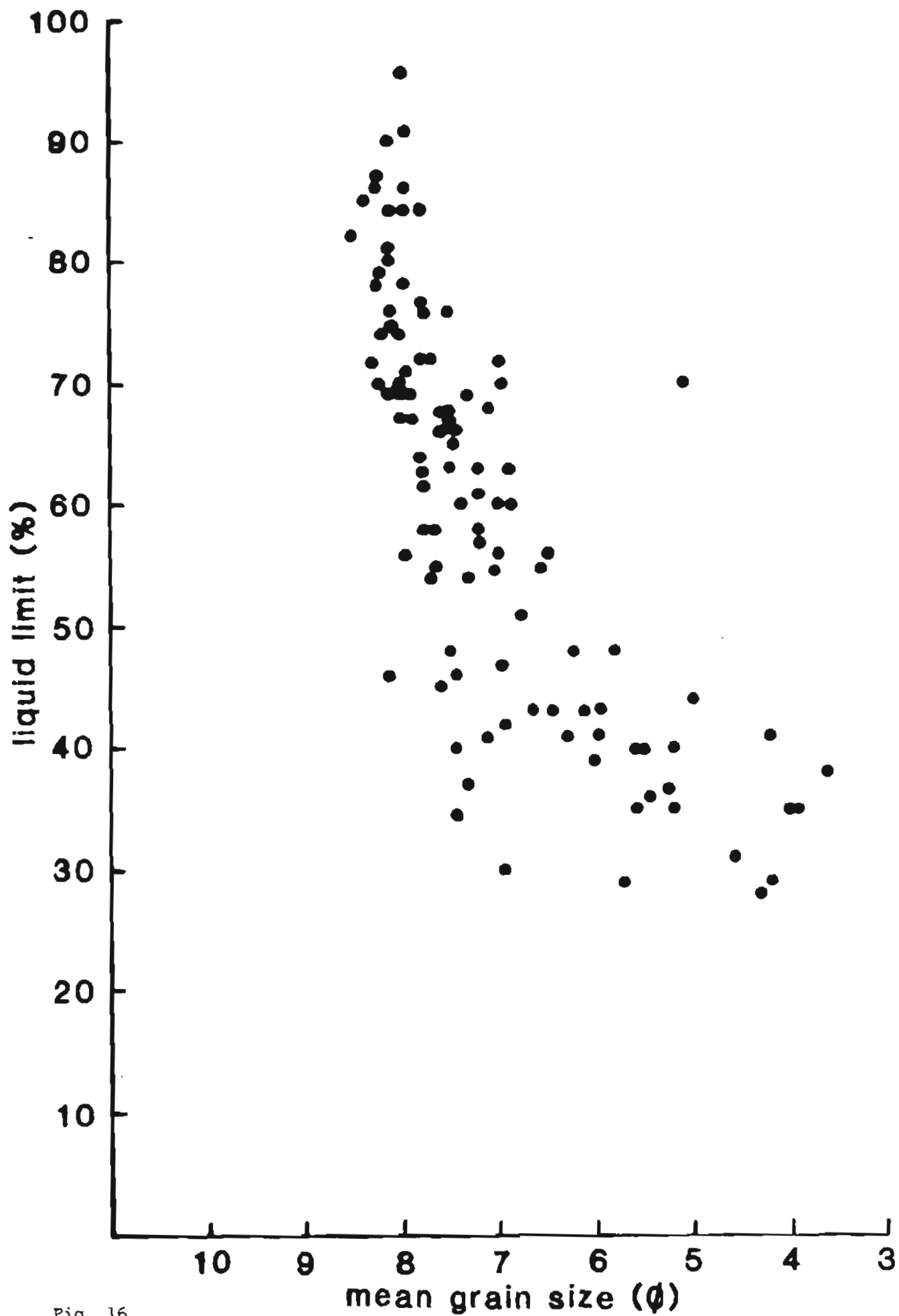


Fig. 16

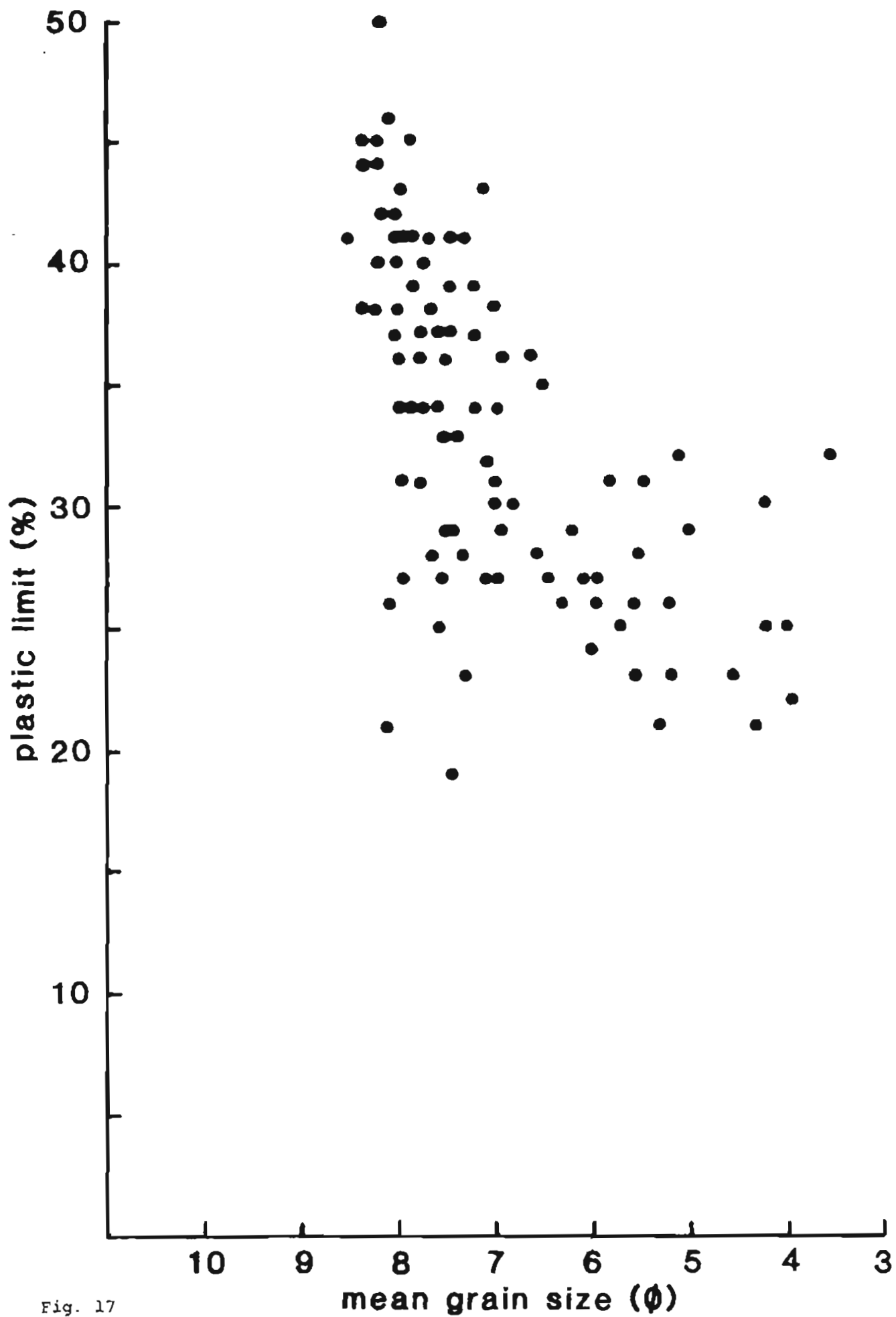


Fig. 17

Plasticity index

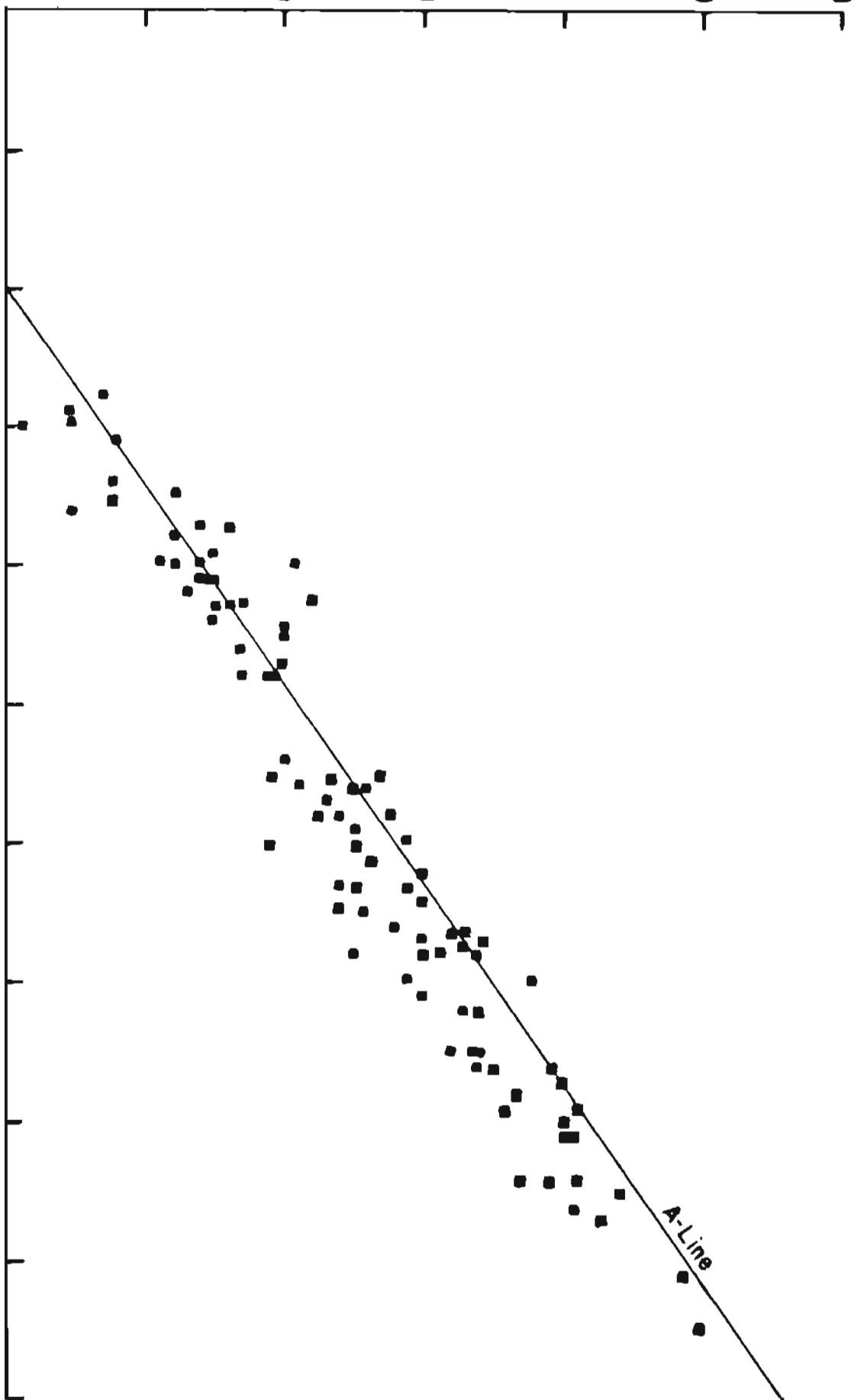
60
50
40
30
20
10

10 20 30 40 50 60 70 80 90 100

Liquid limit

A-Line

Fig. 19



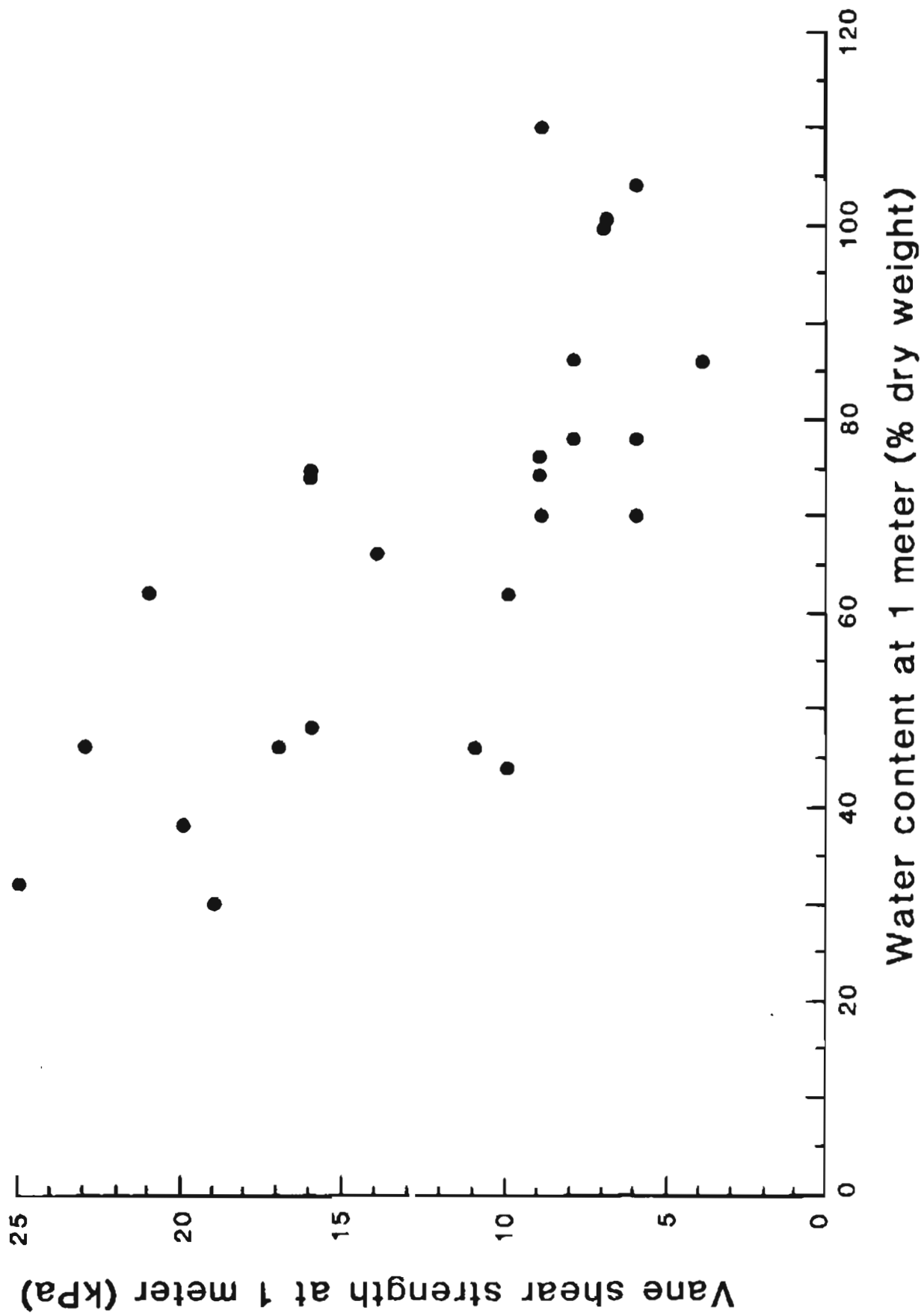


Fig. 21

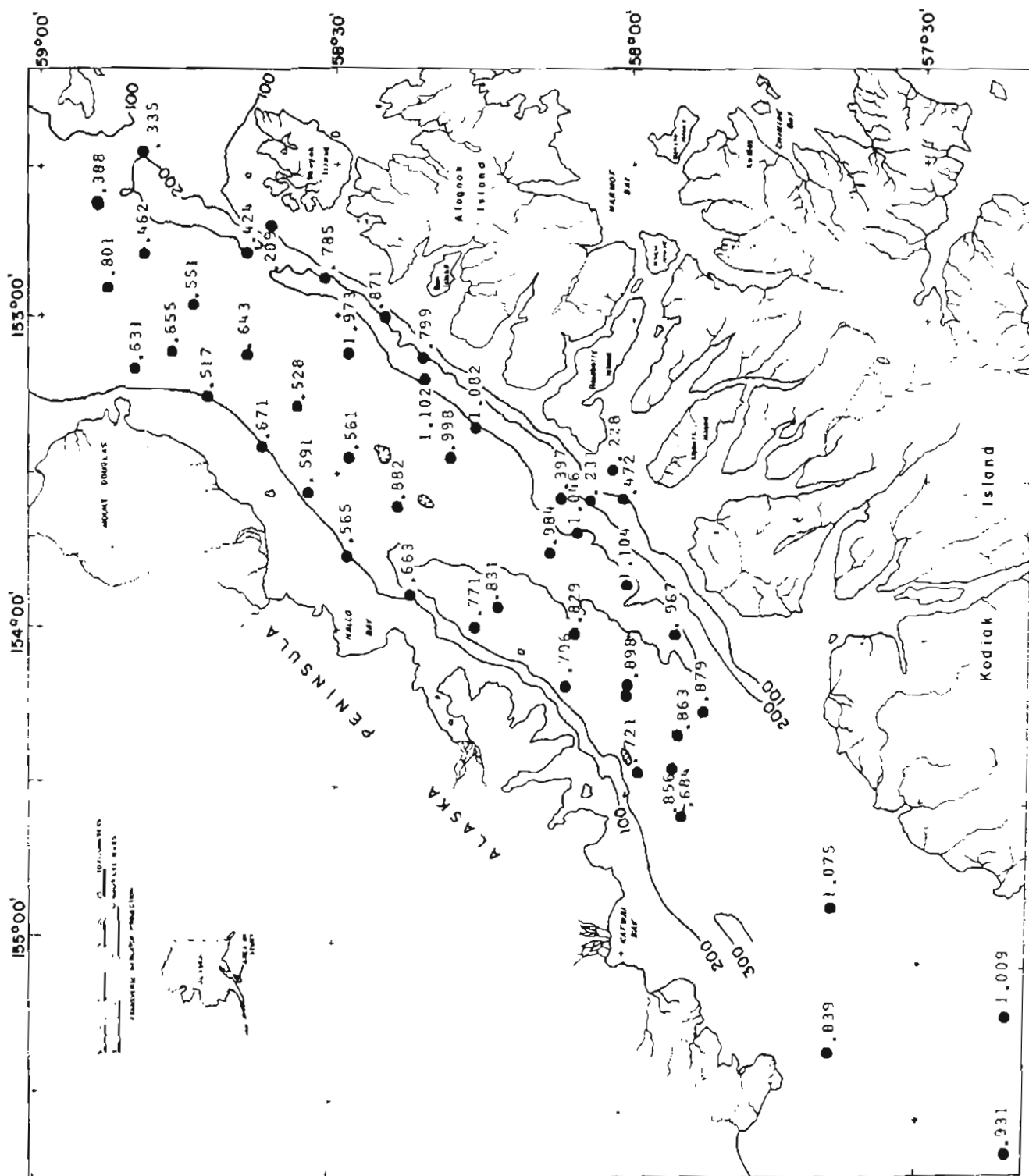


Fig. 22

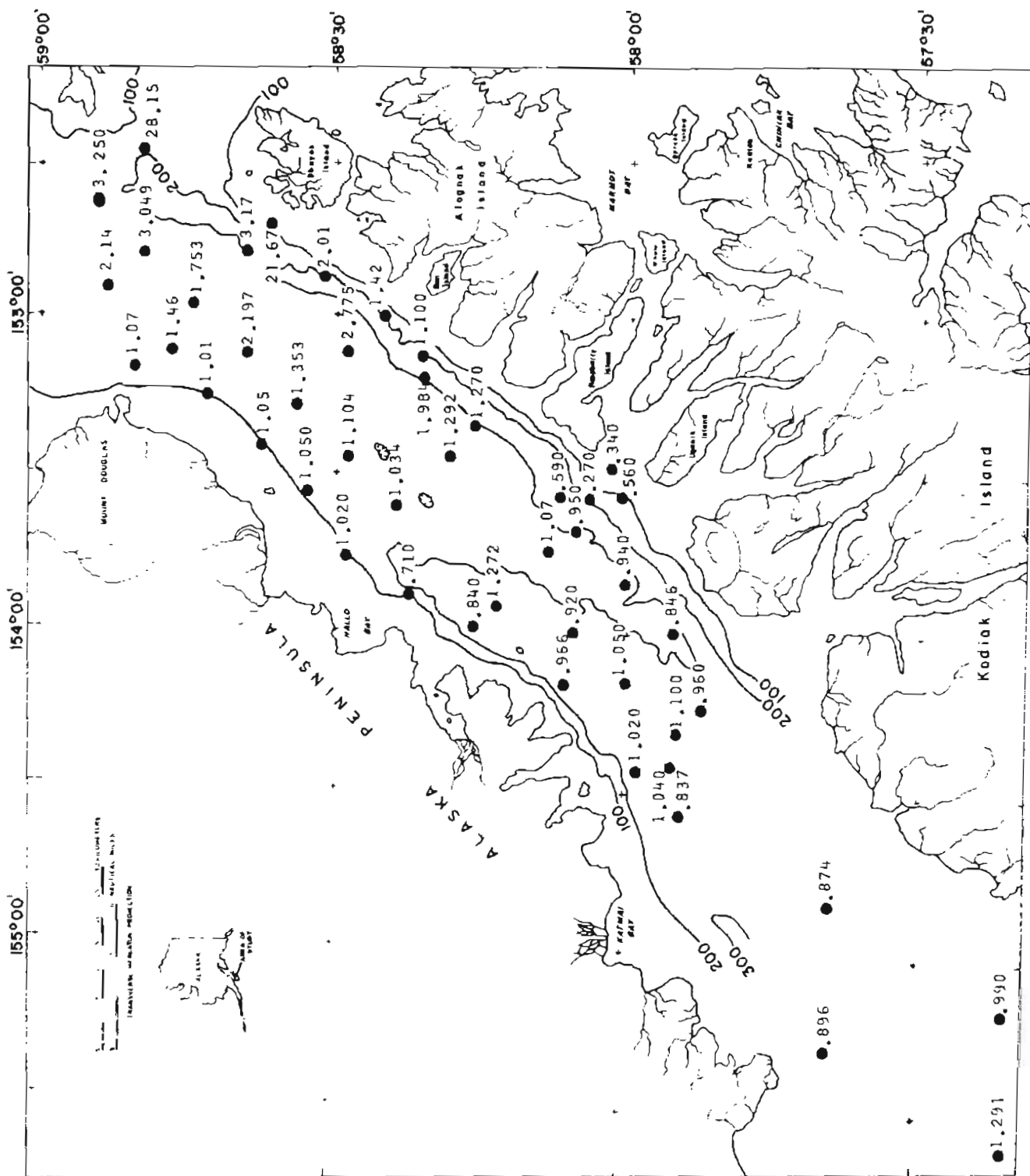


Fig. 23

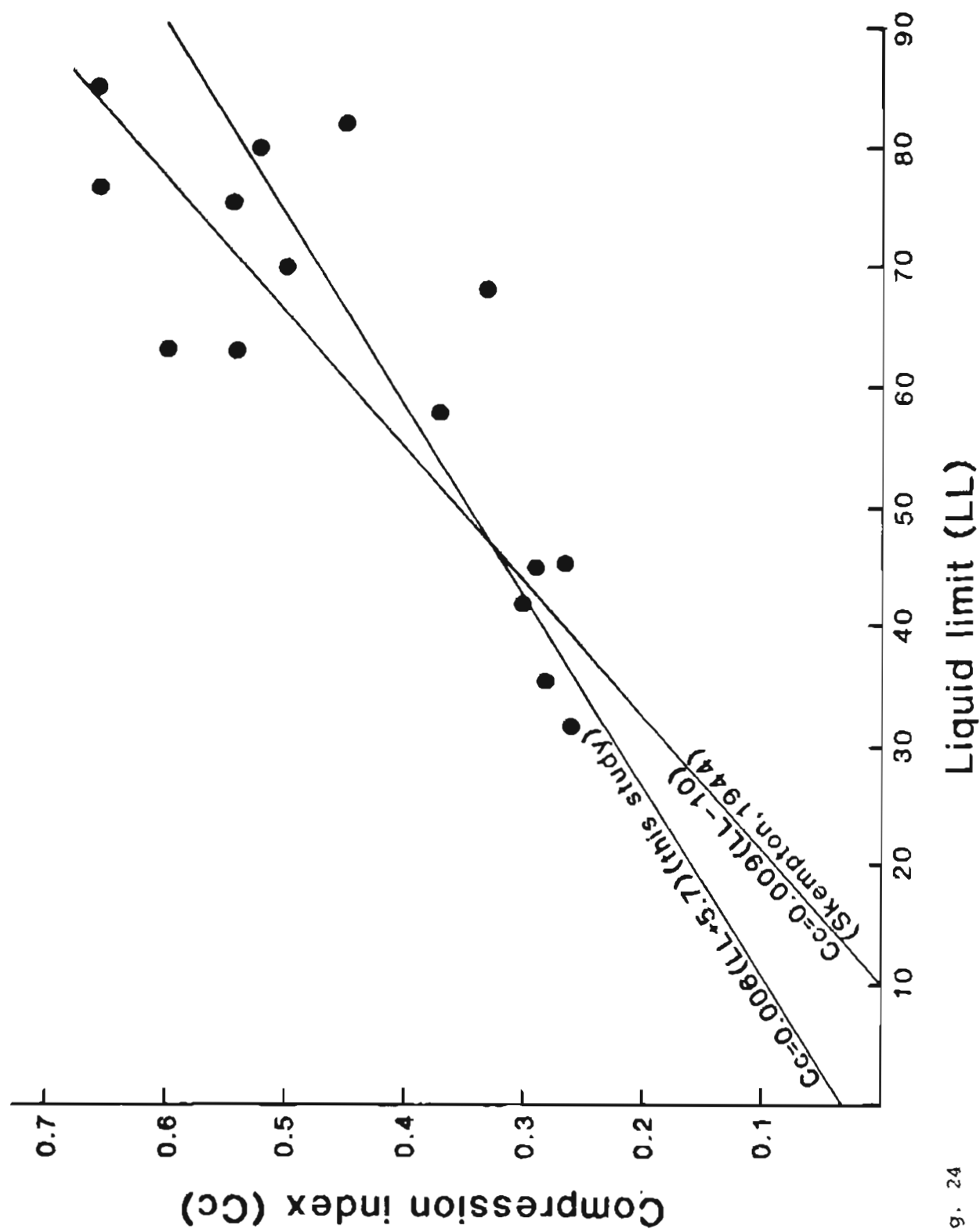


Fig. 24

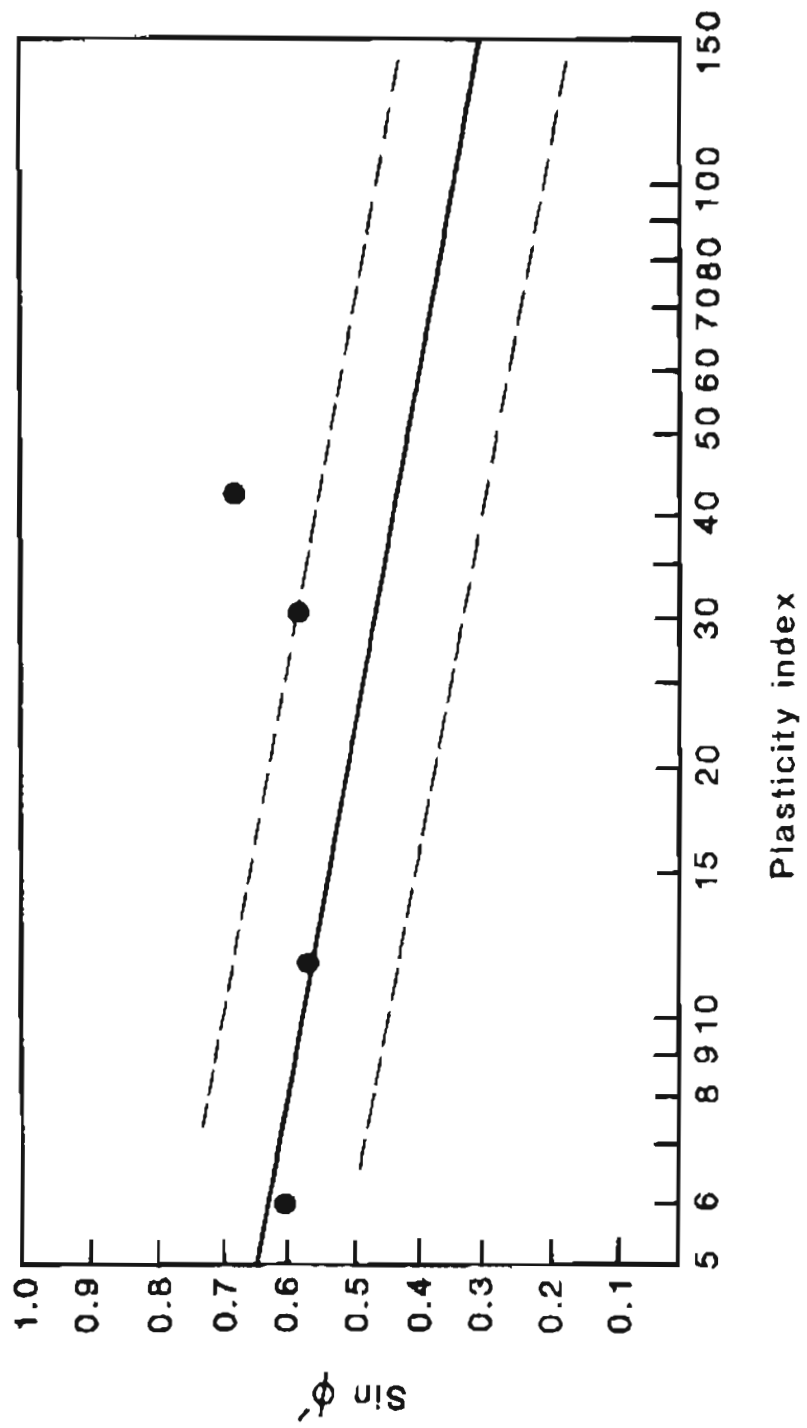


Fig. 25

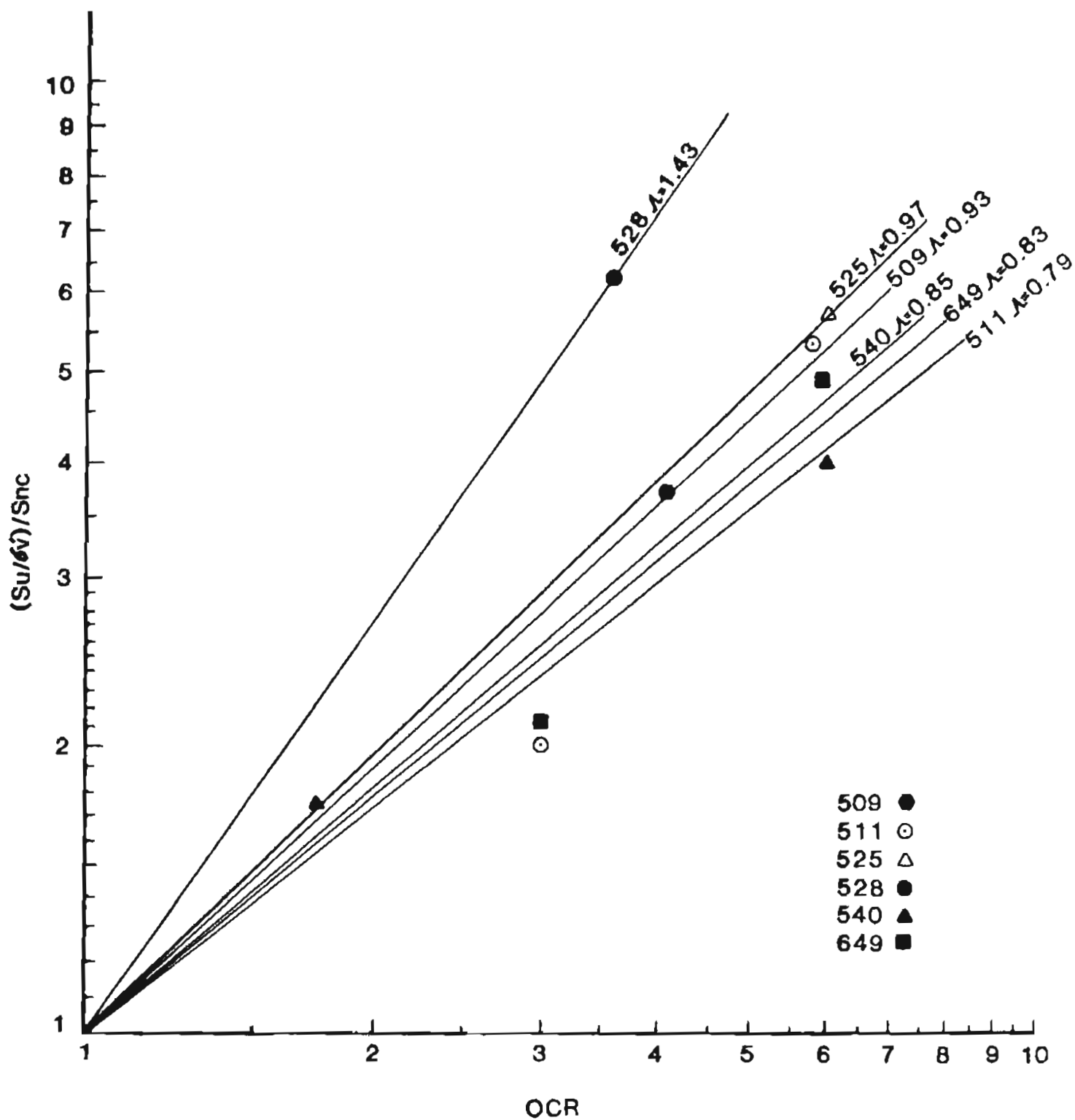


Fig. 26

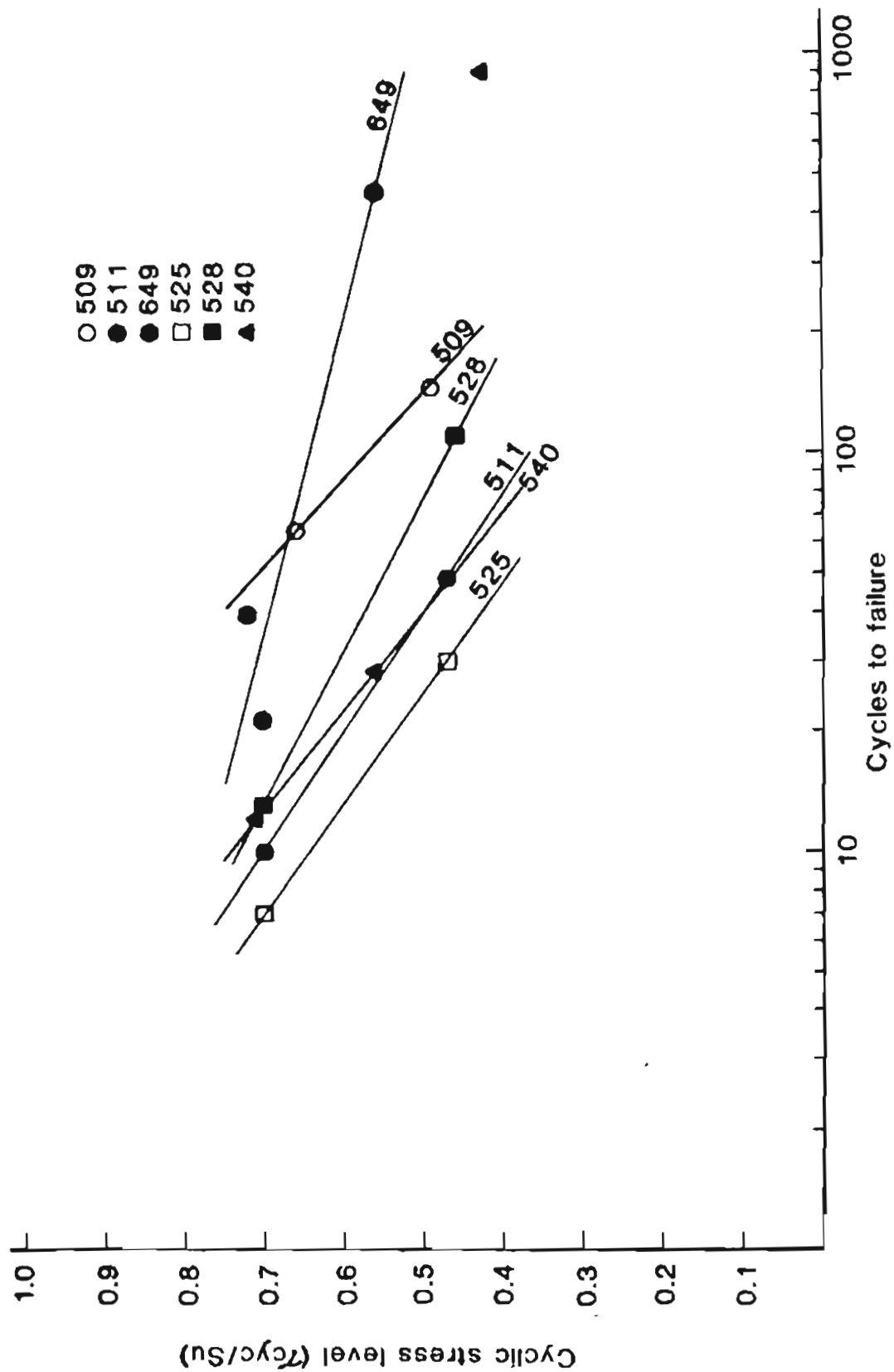
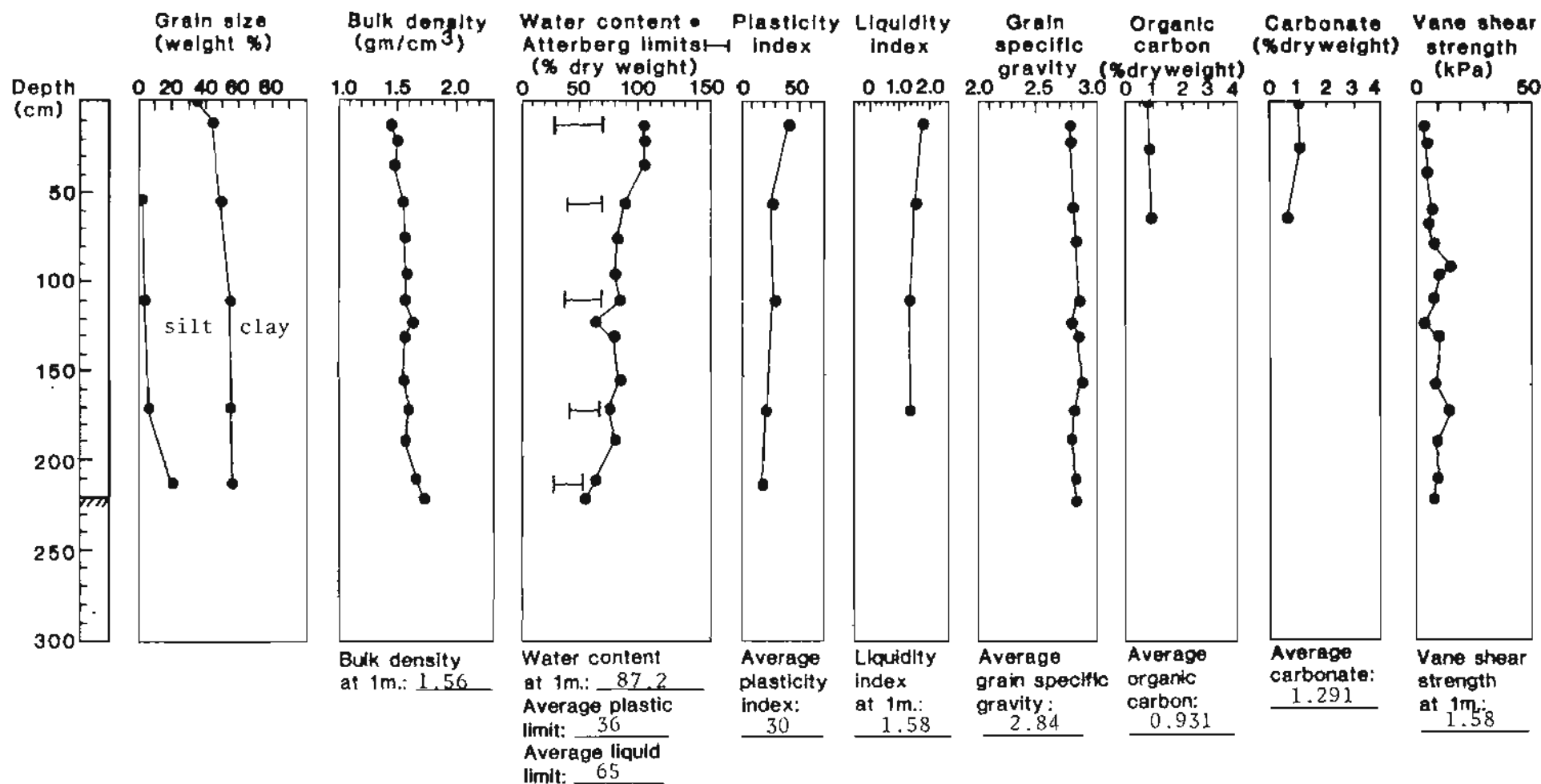


Fig. 27

Appendix A. Index property charts for sediment cores from Shelikof Strait.

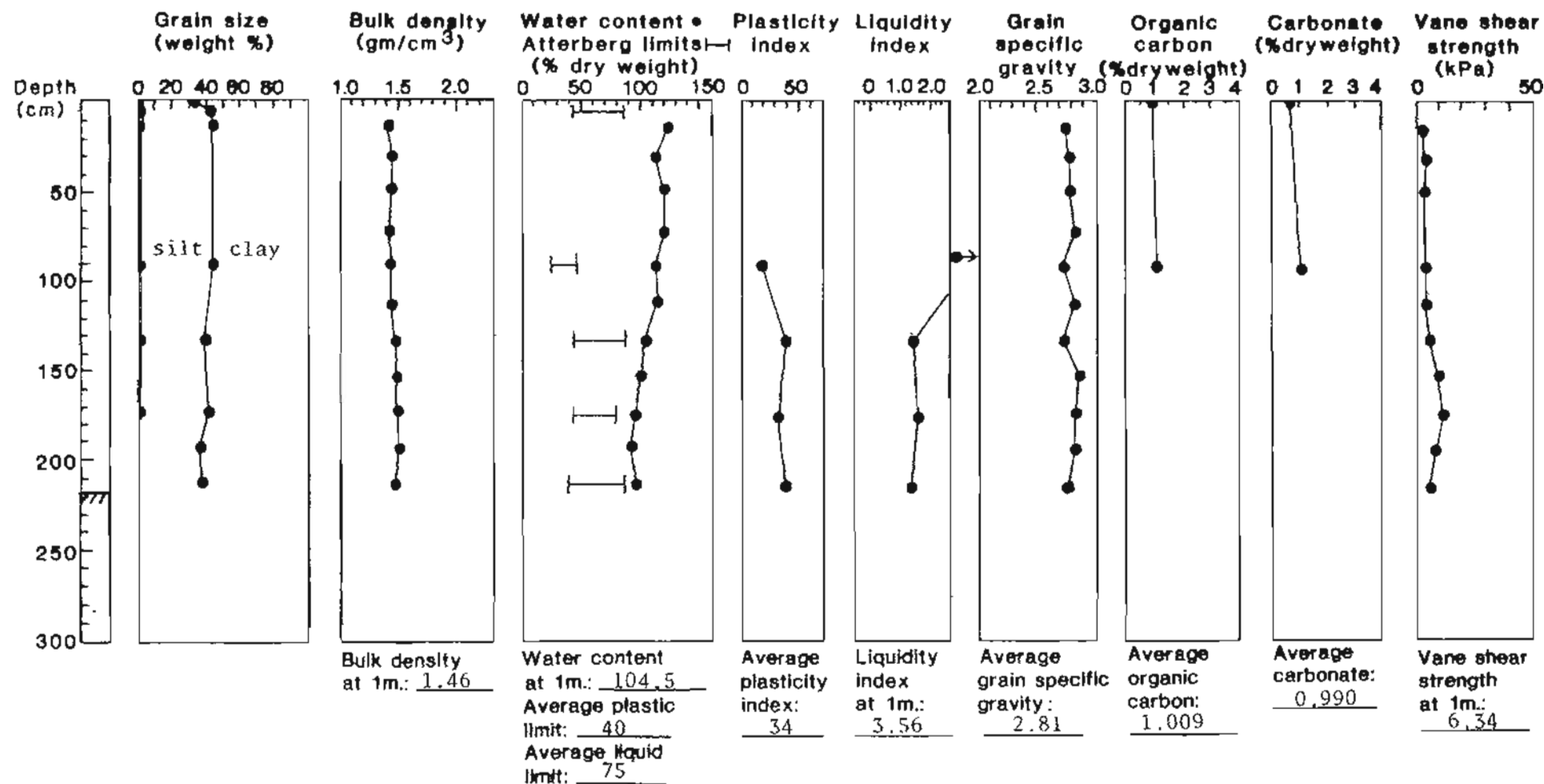
Station 508Location 57°21.01'N 155°36.41'WWater depth 270m

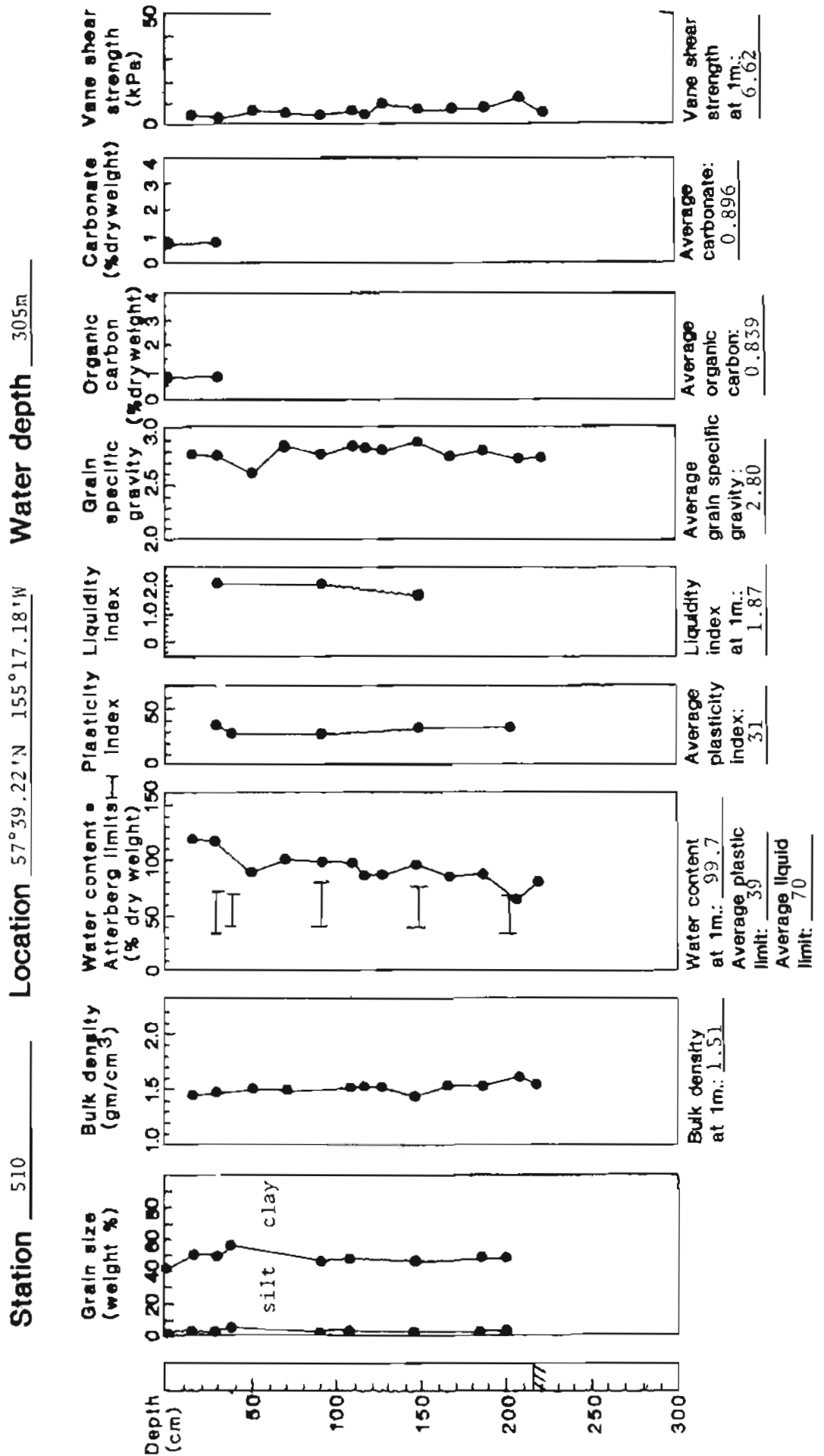
09

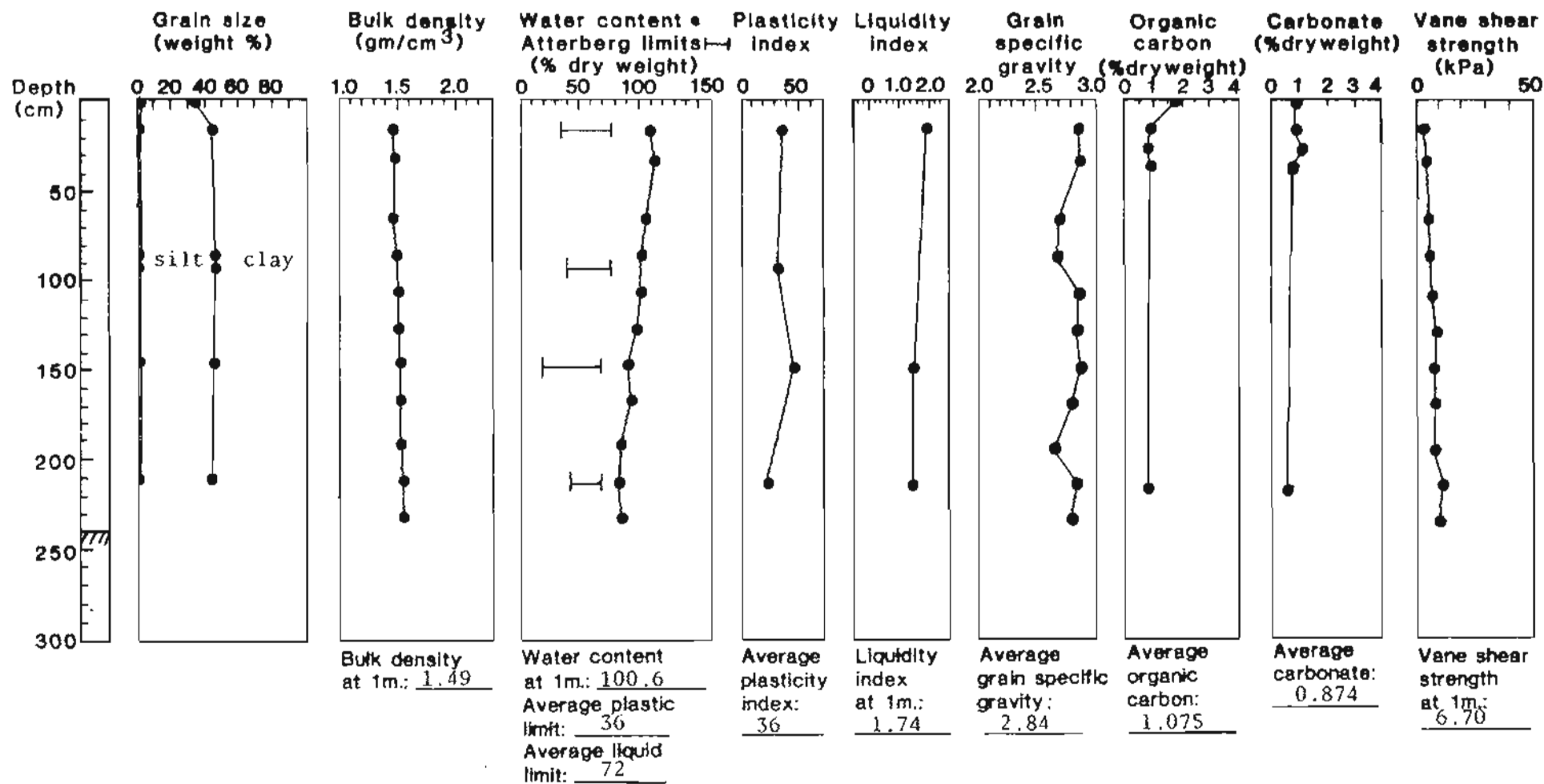


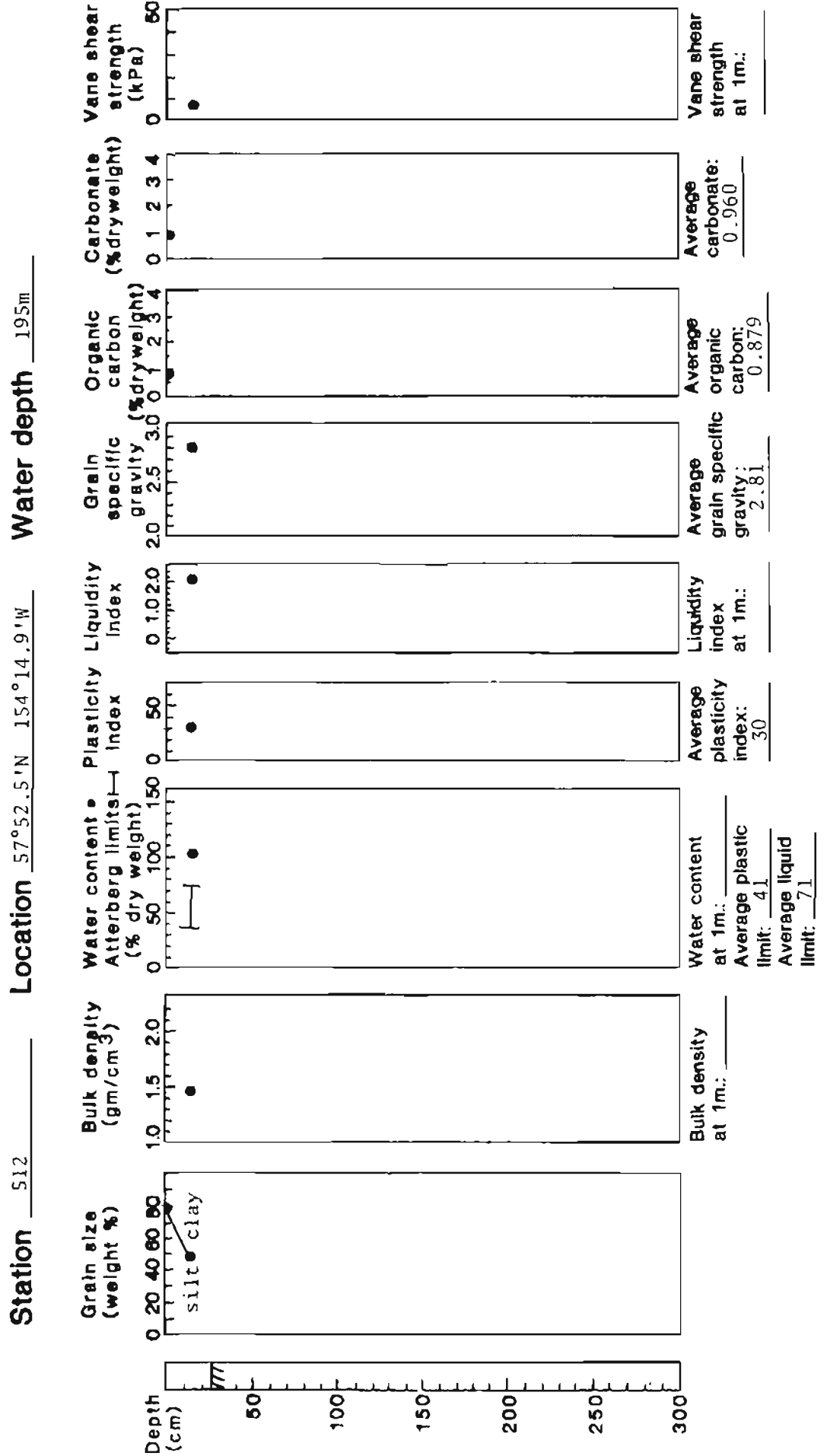
Station 509Location 57°21.29'N 155°08.66'WWater depth 225m

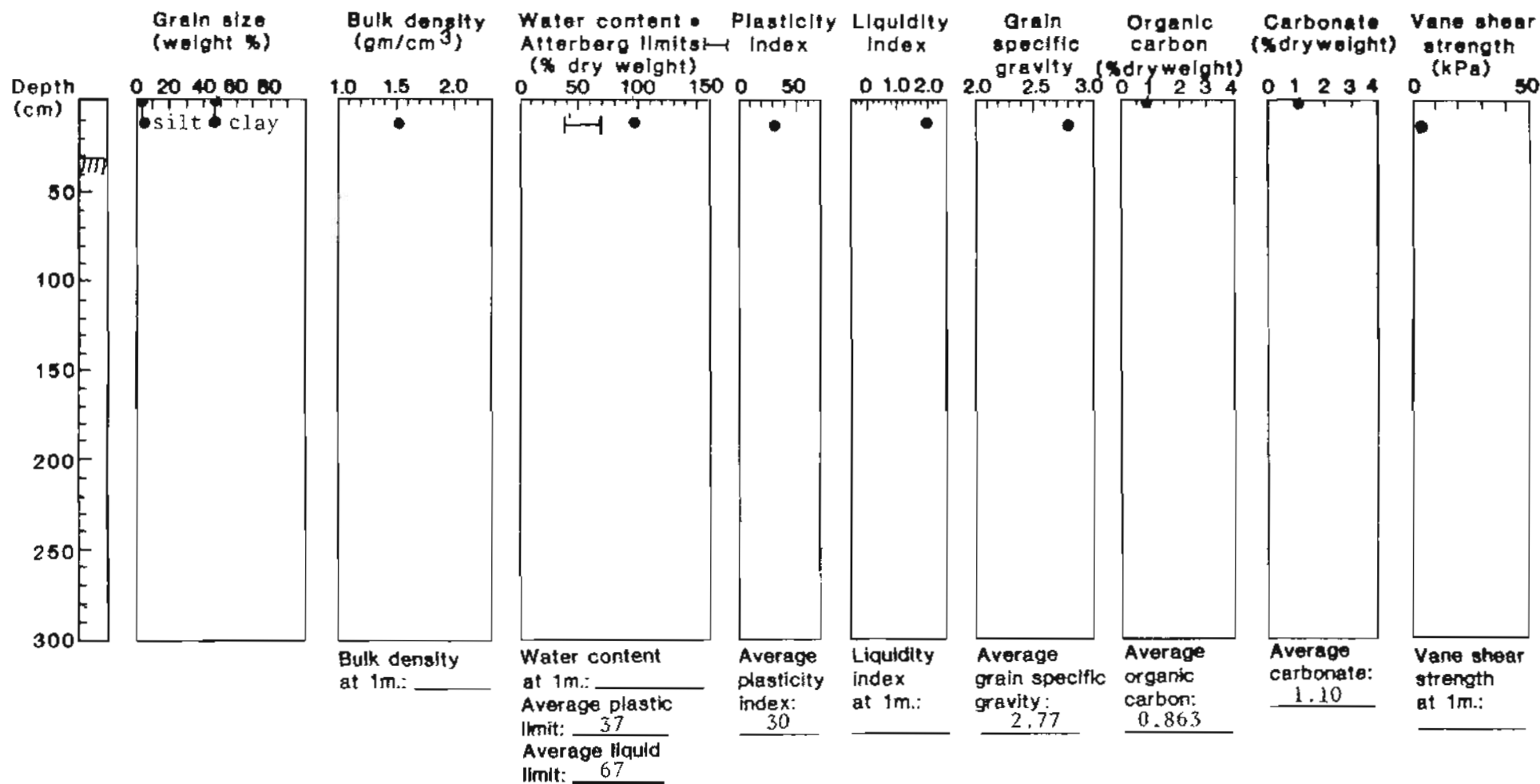
19

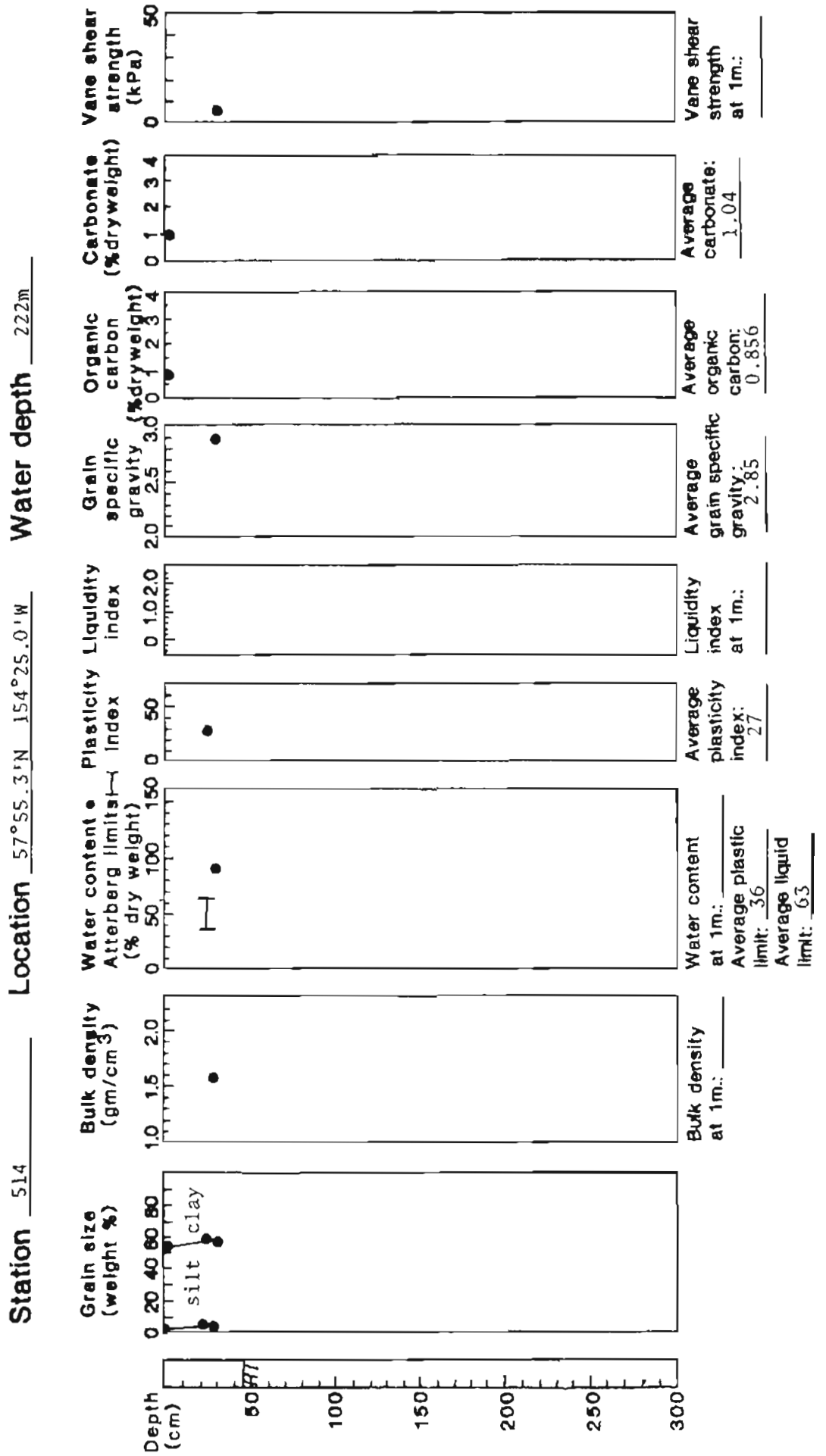


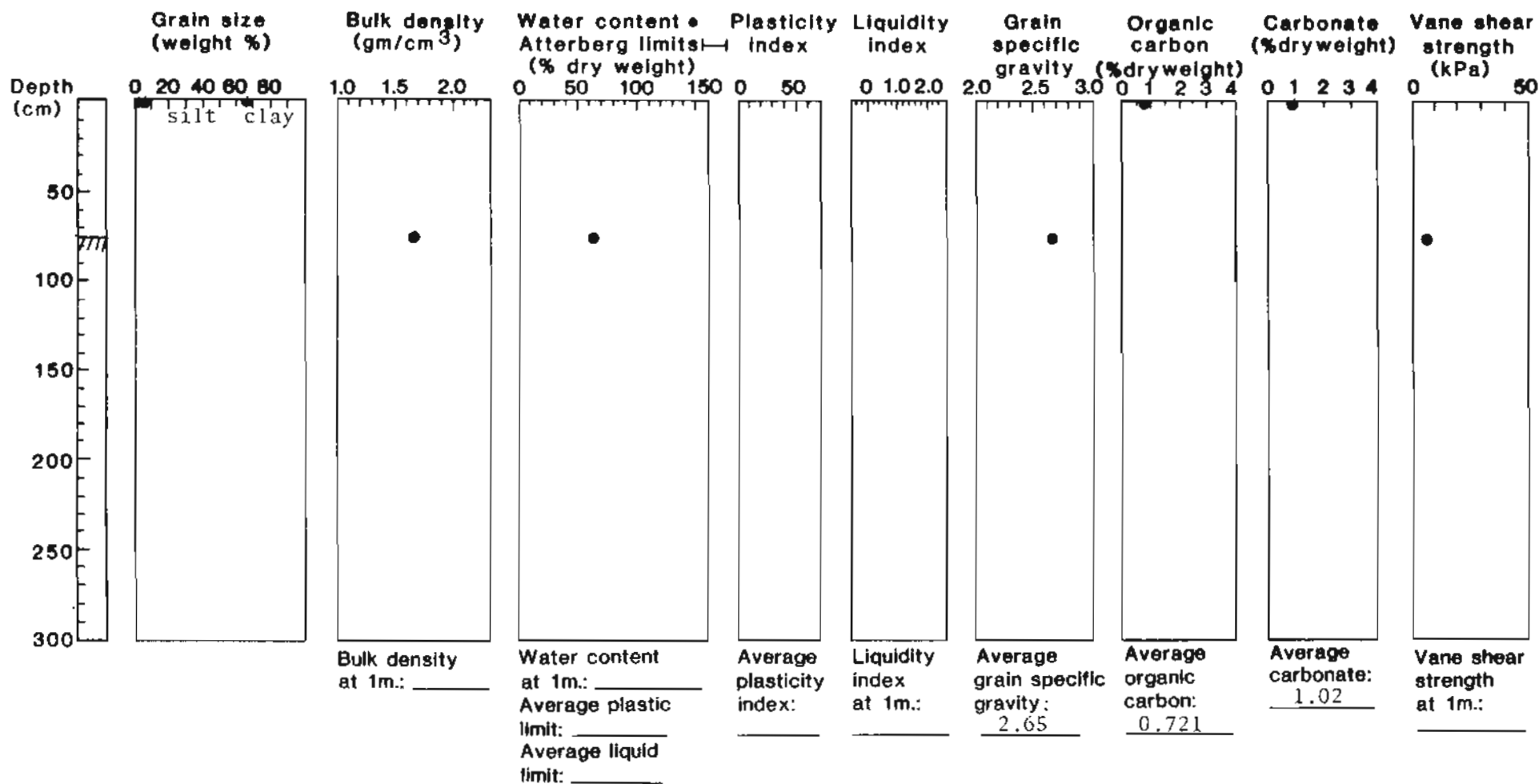


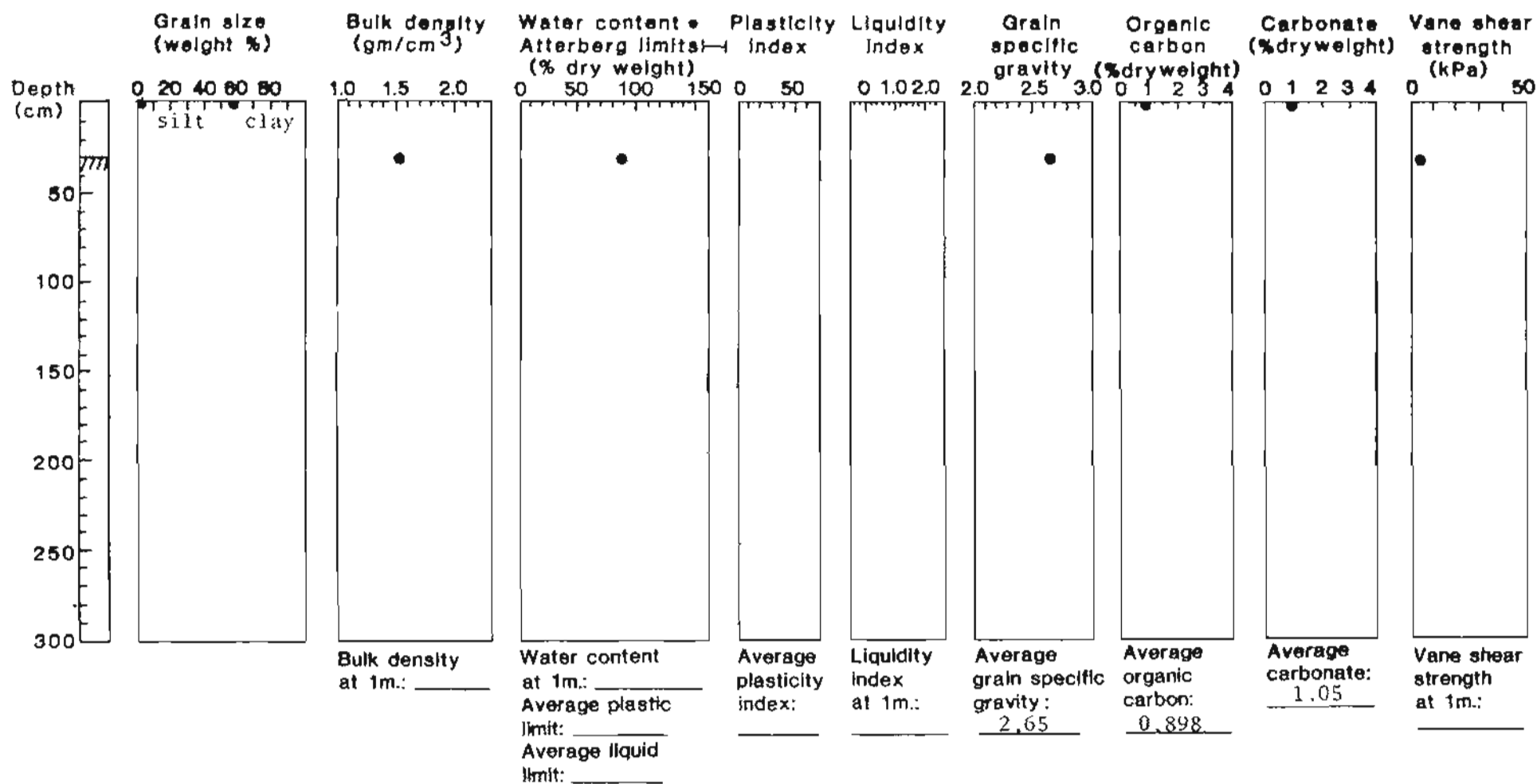
Station 511Location 57°39.08'N 154°50.14'WWater depth 214m

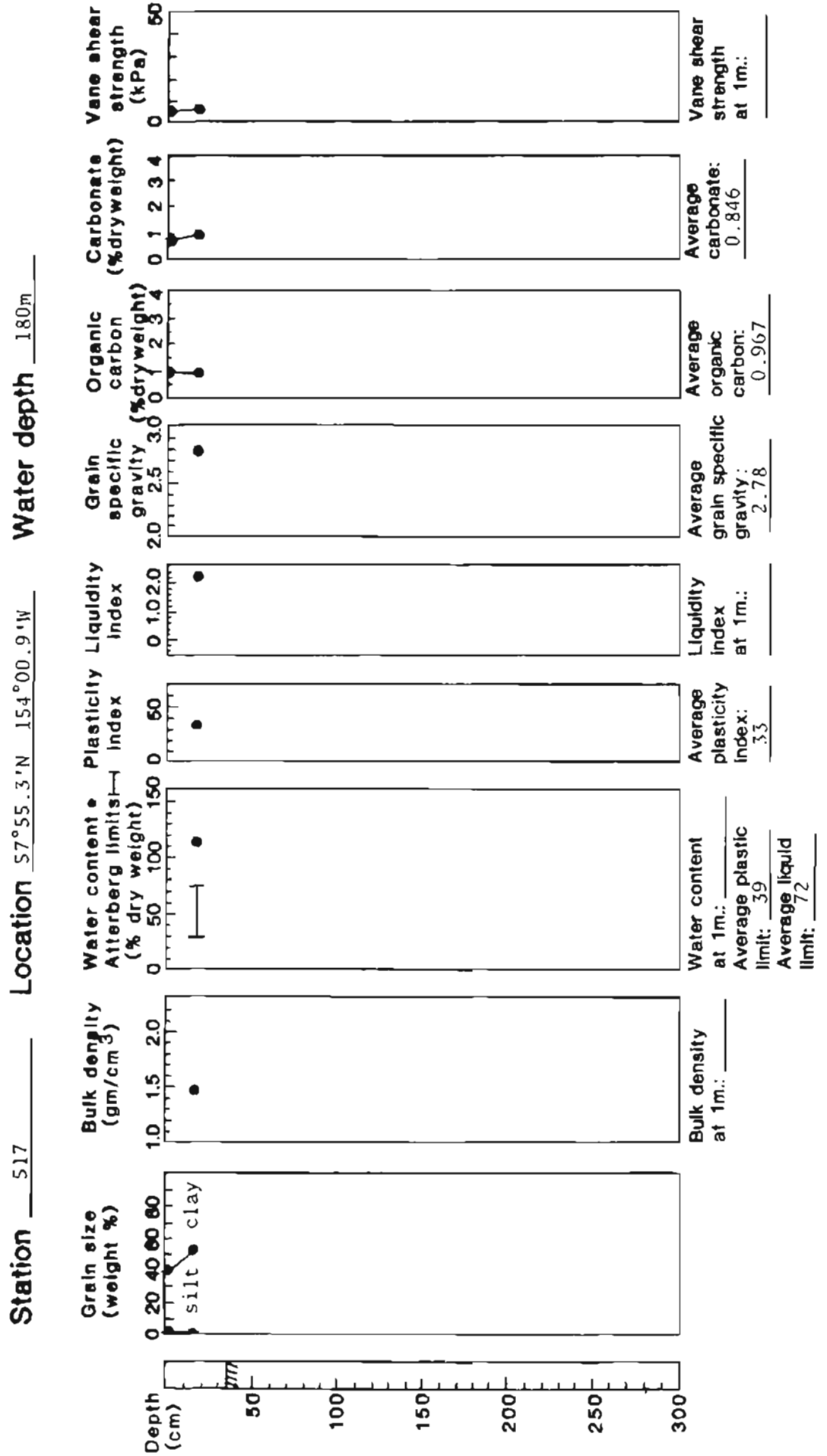


Station 513Location 57°54.8'N 154°19.8'WWater depth 205m



Station S15Location 57°59.0'N 154°27.3'WWater depth 238m

Station 516Location 58°00.3'N 154°10.6'WWater depth 205

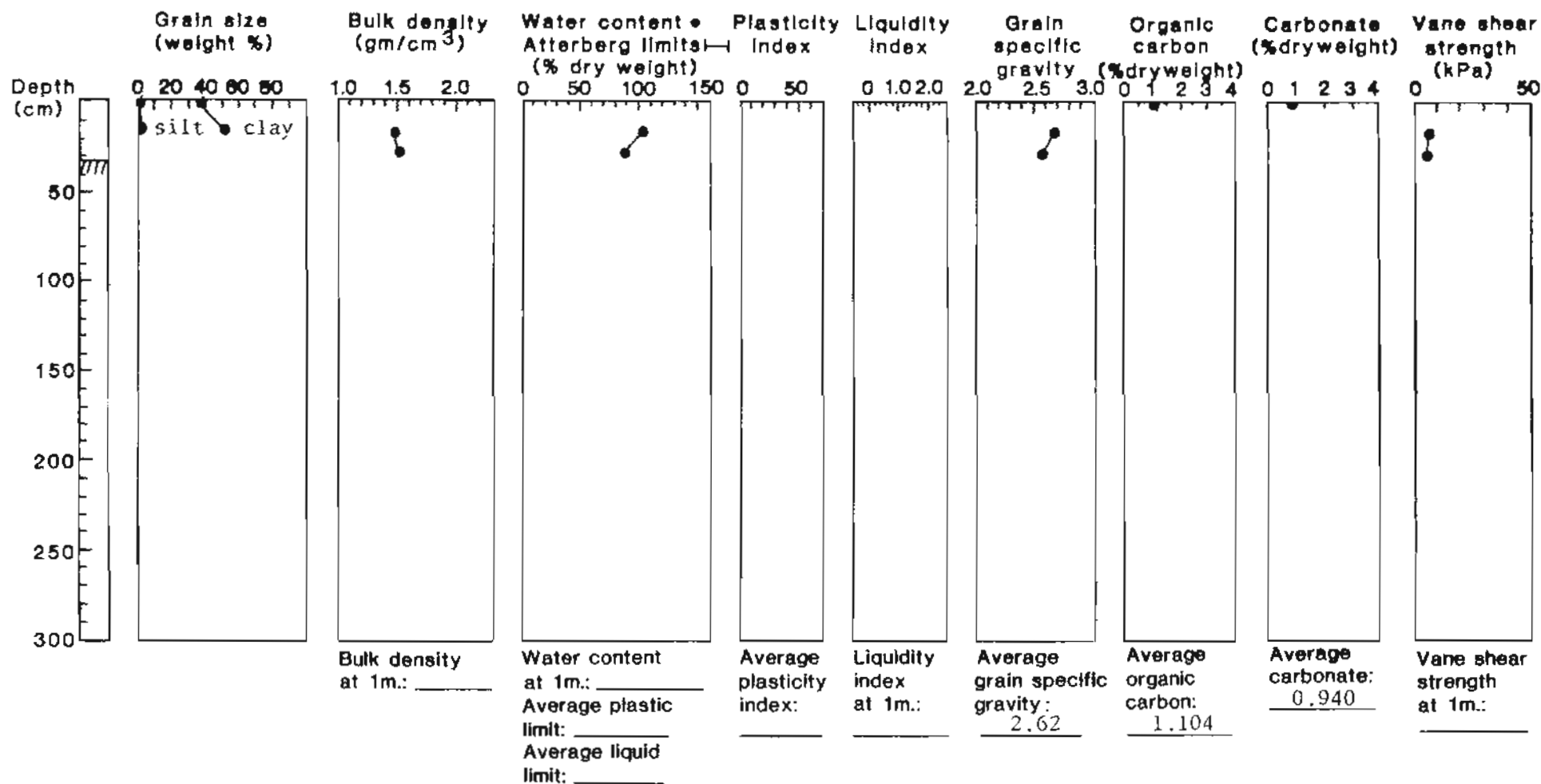


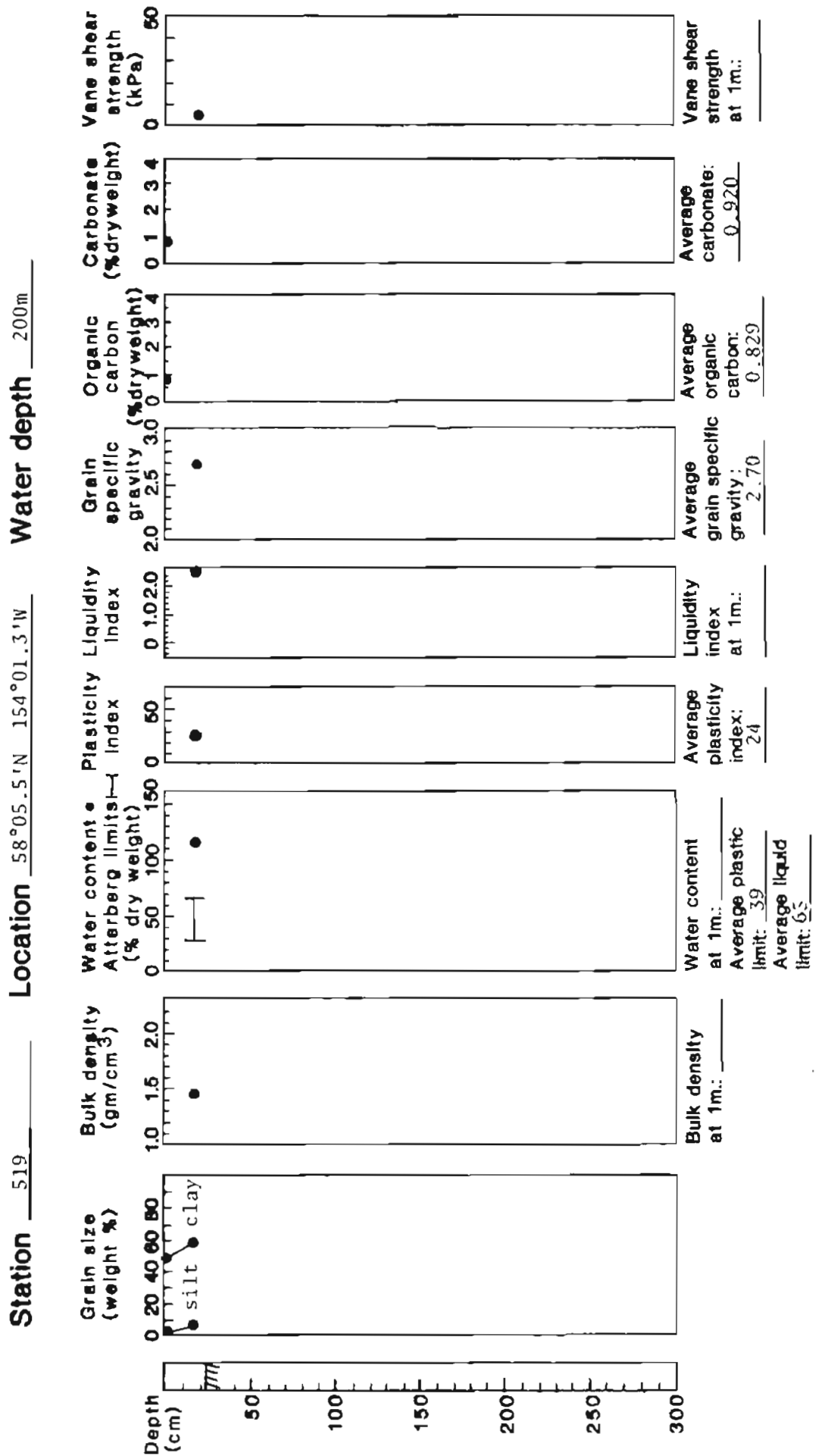
Station 518

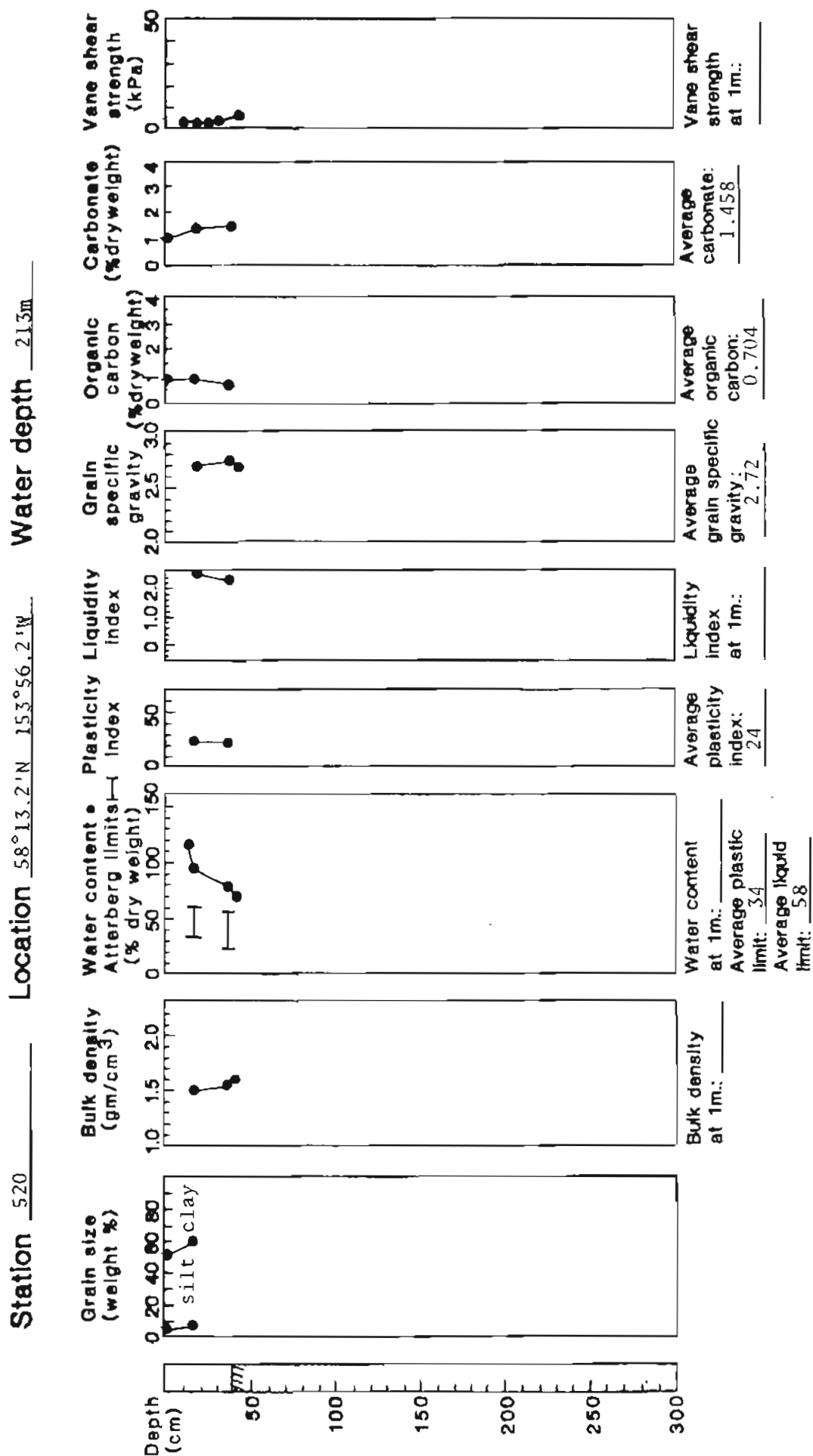
Location 58°00.3'N 153°51.6'W

Water depth 180m

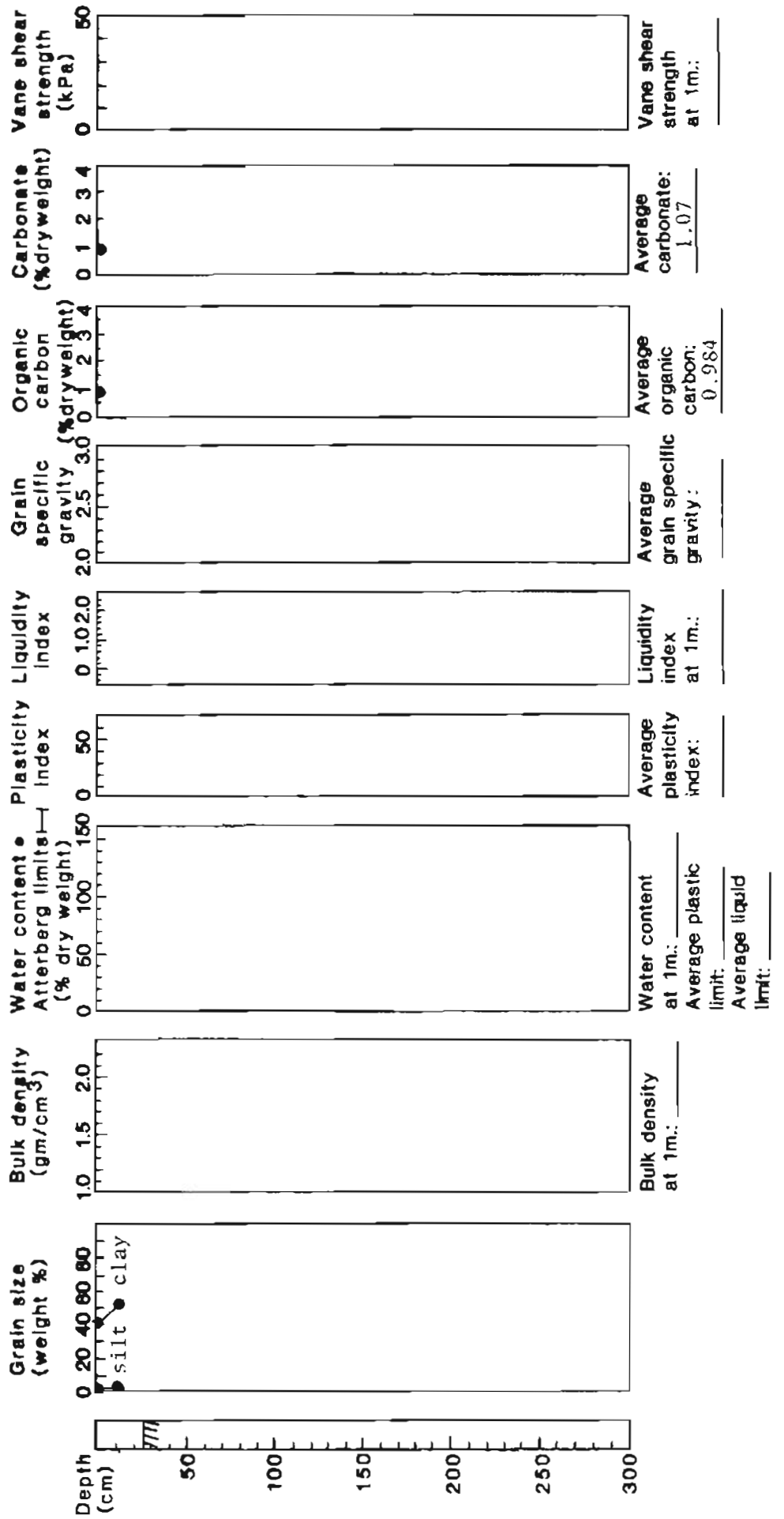
70



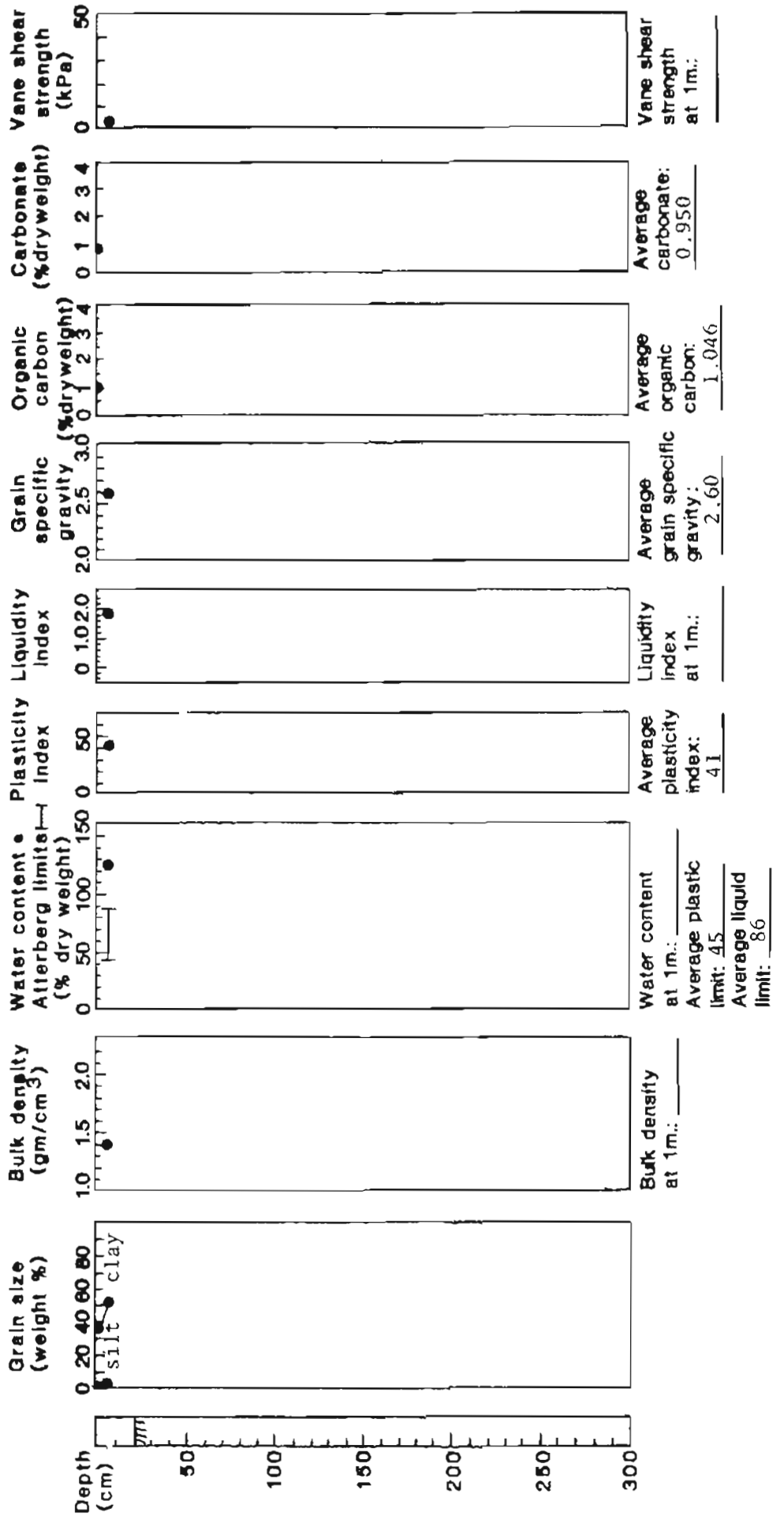


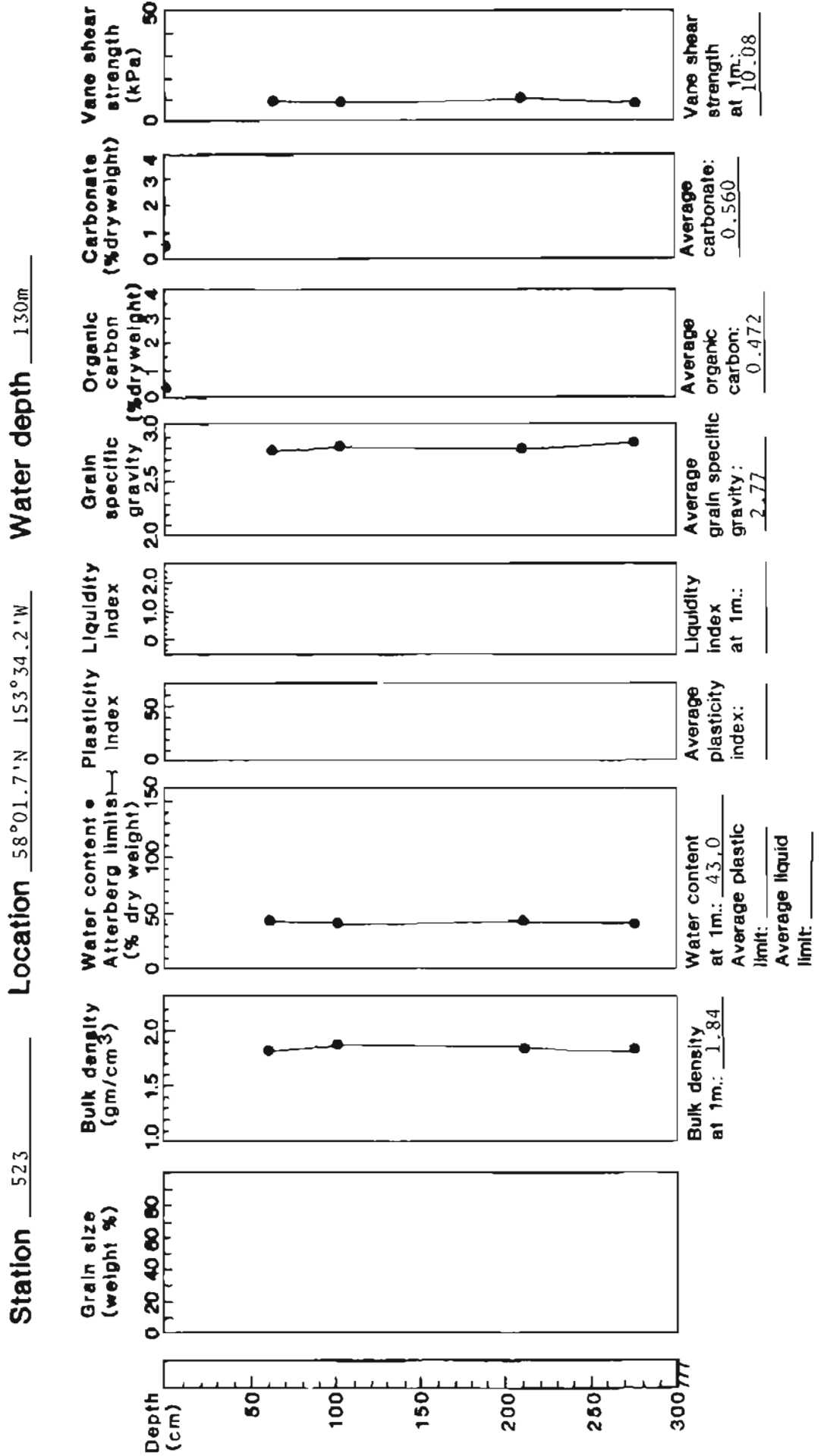


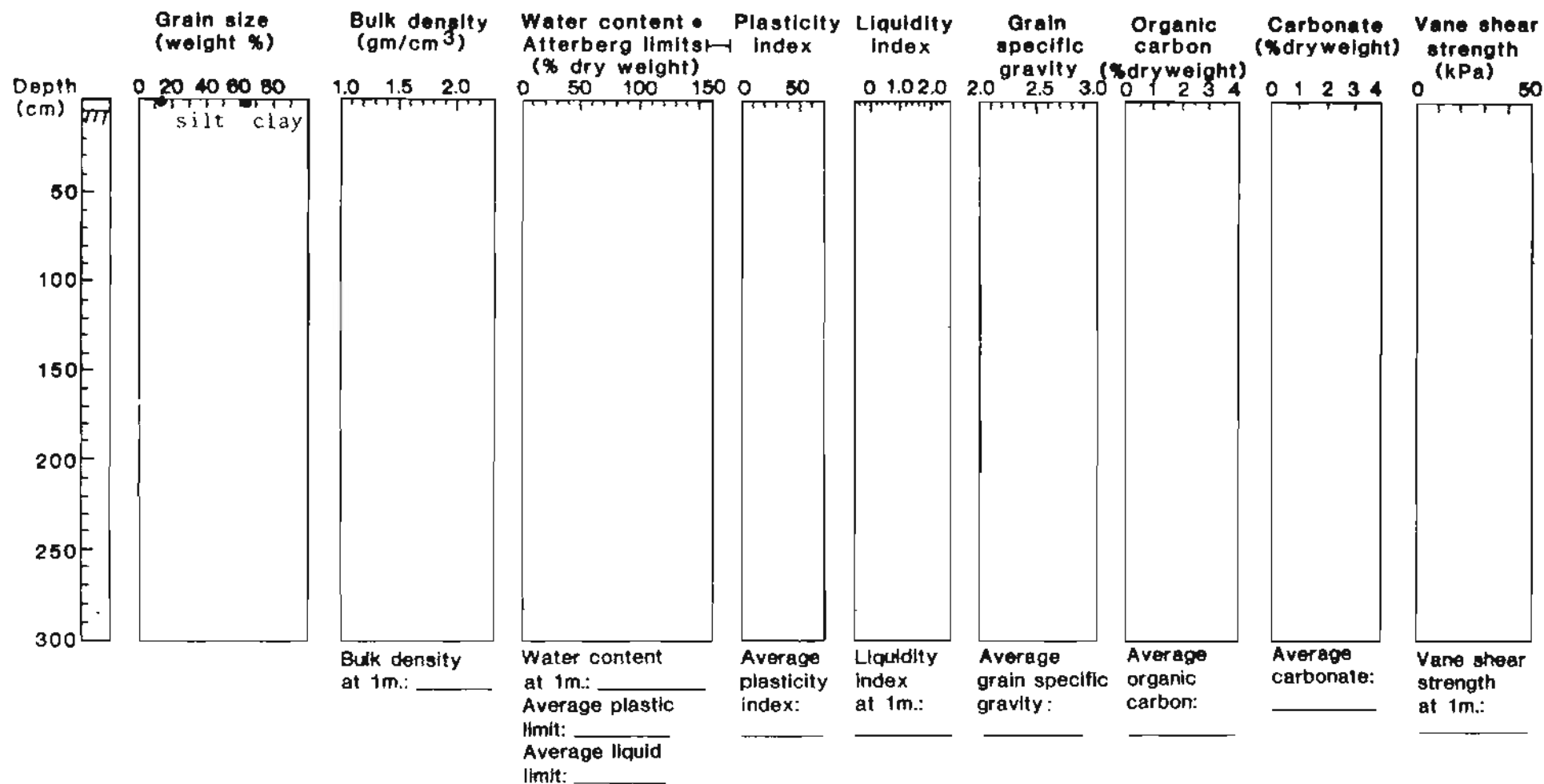
Station 521 Location 58°07.93'N 153°45.4'W Water depth 185m



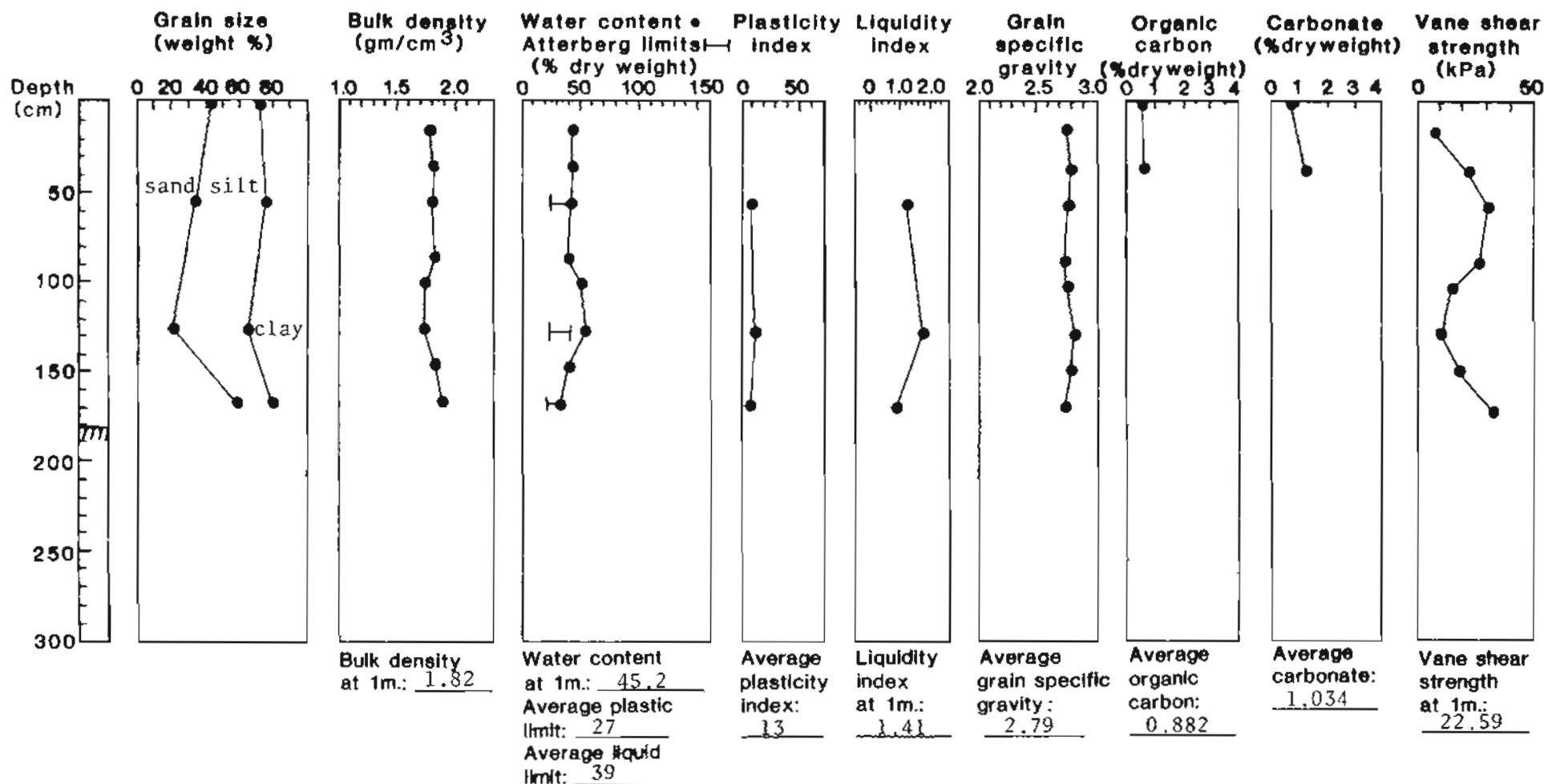
Station 522 Location 58°05.5'N 153°41.1'W Water depth 185m

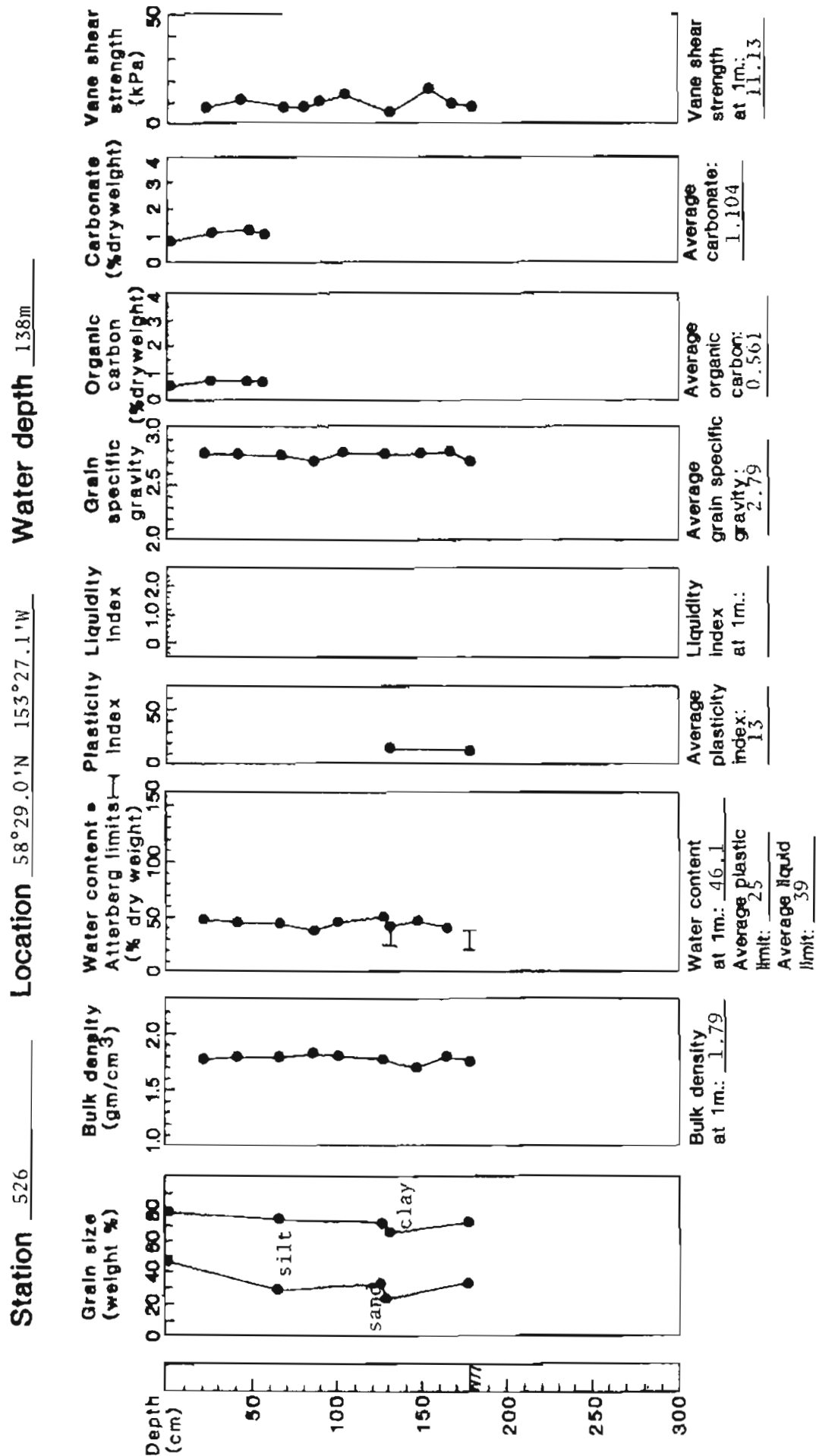




Station 524Location 58°15.94'N 153°41.87'WWater depth 175m

Water depth 158m

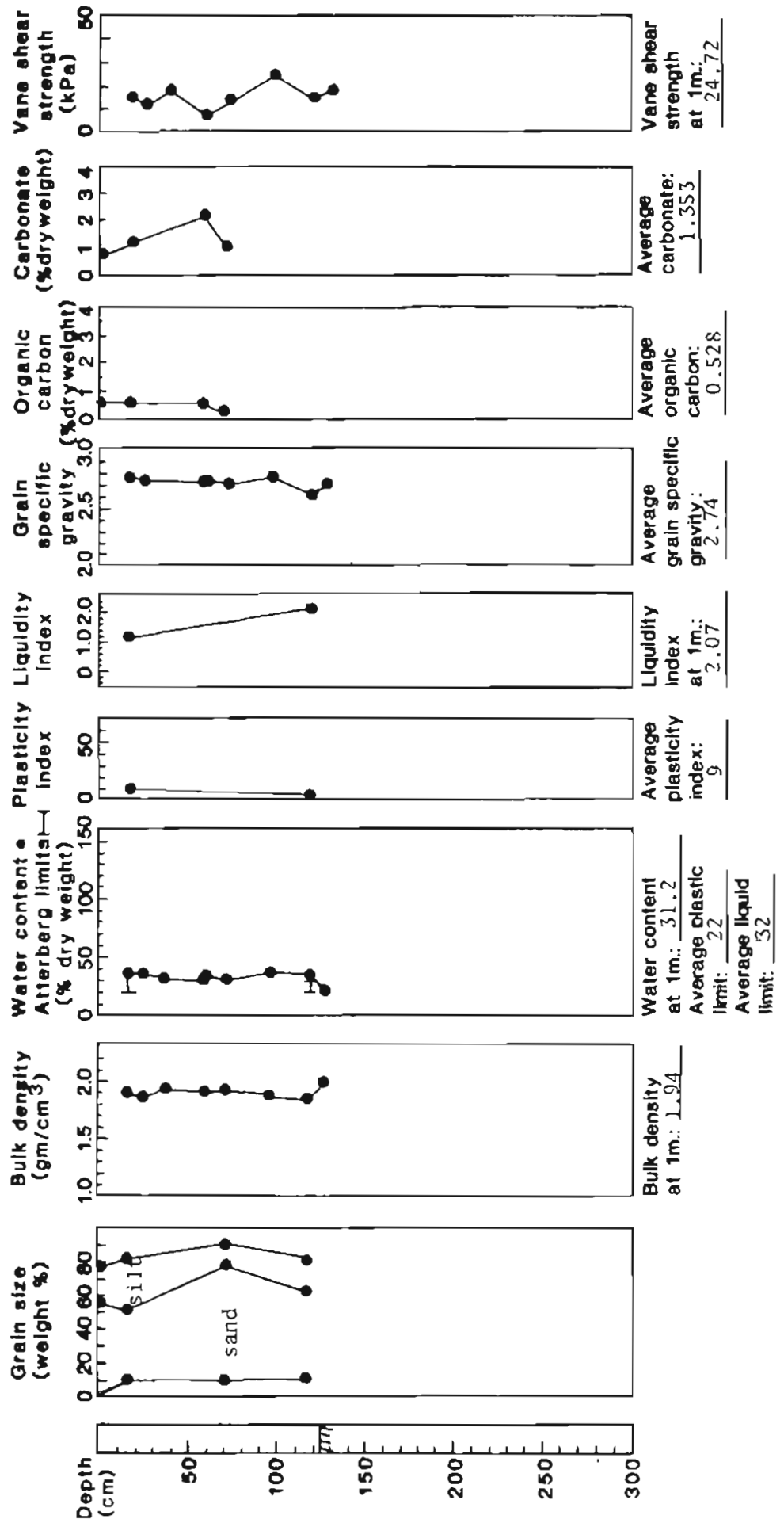




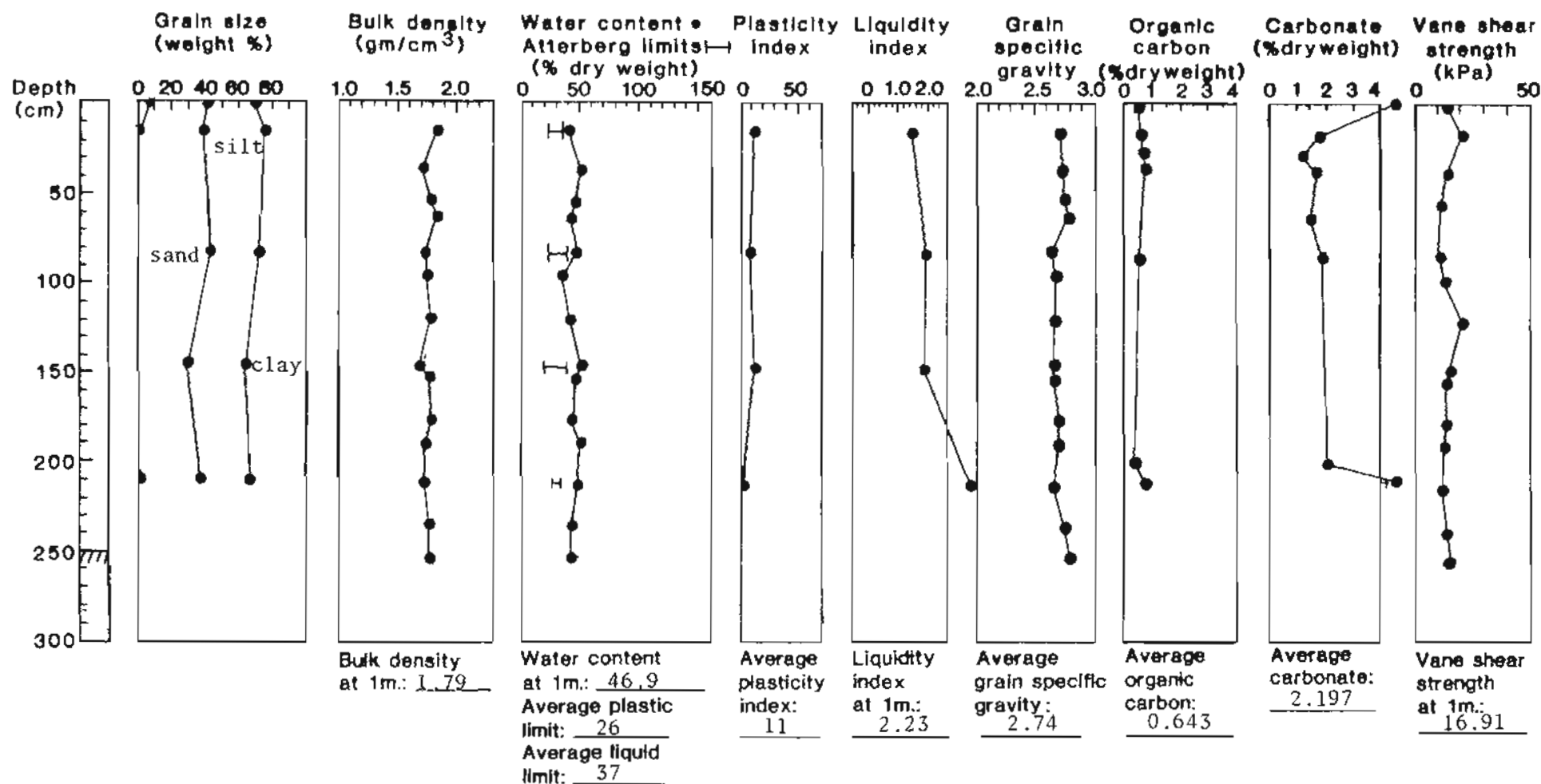
Station 527

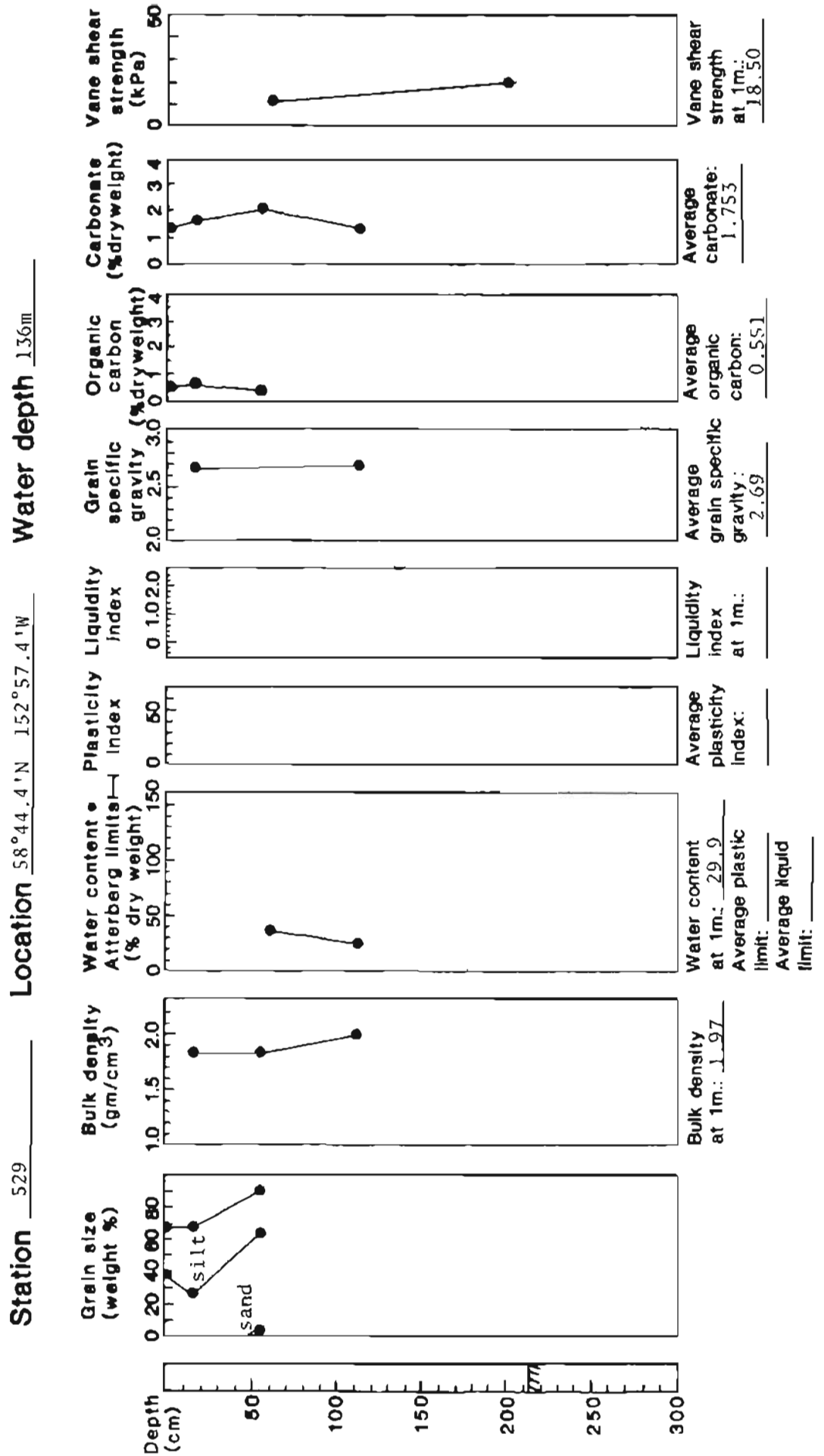
Location 58°34.2'N 153°17.6'W

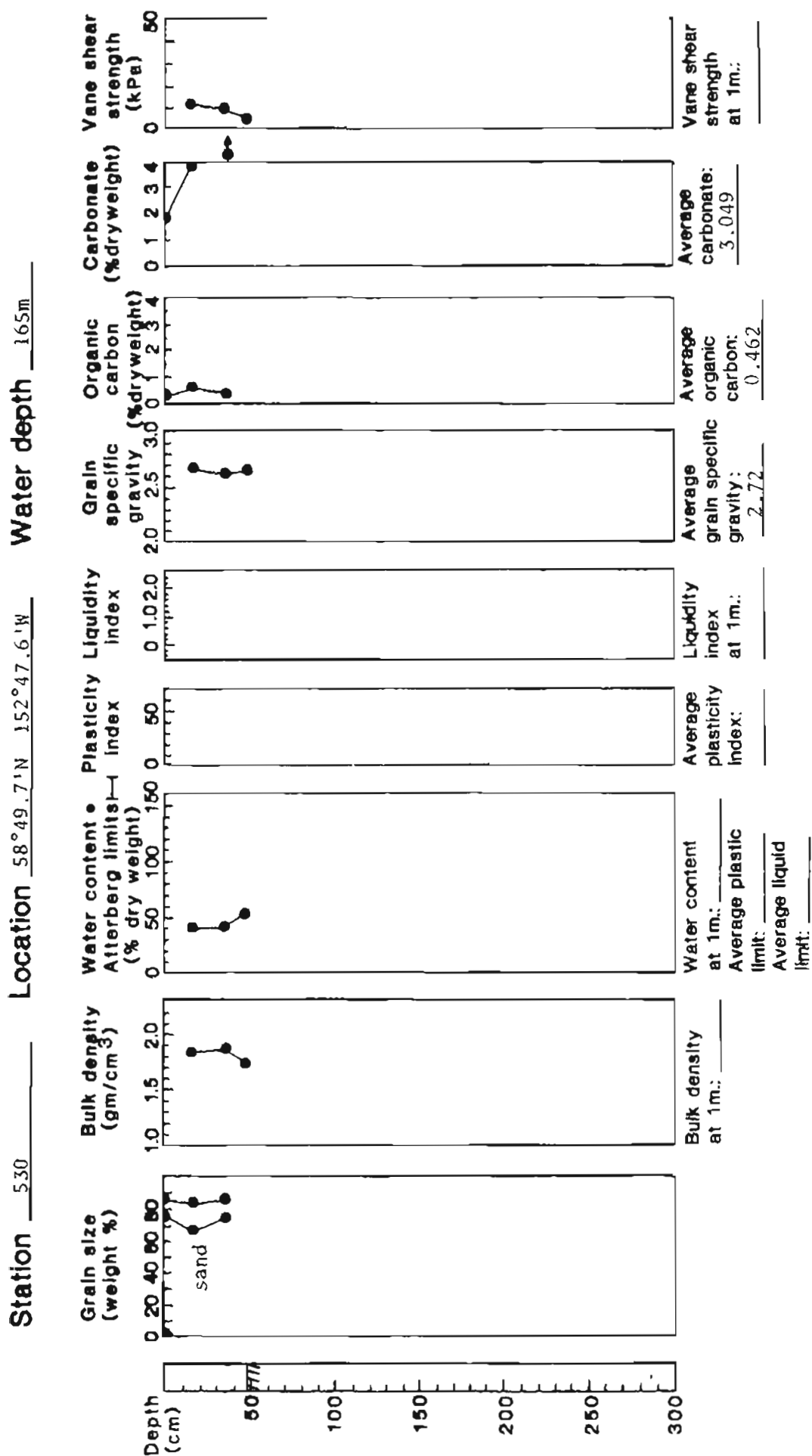
Water depth 153m



Water depth 159m



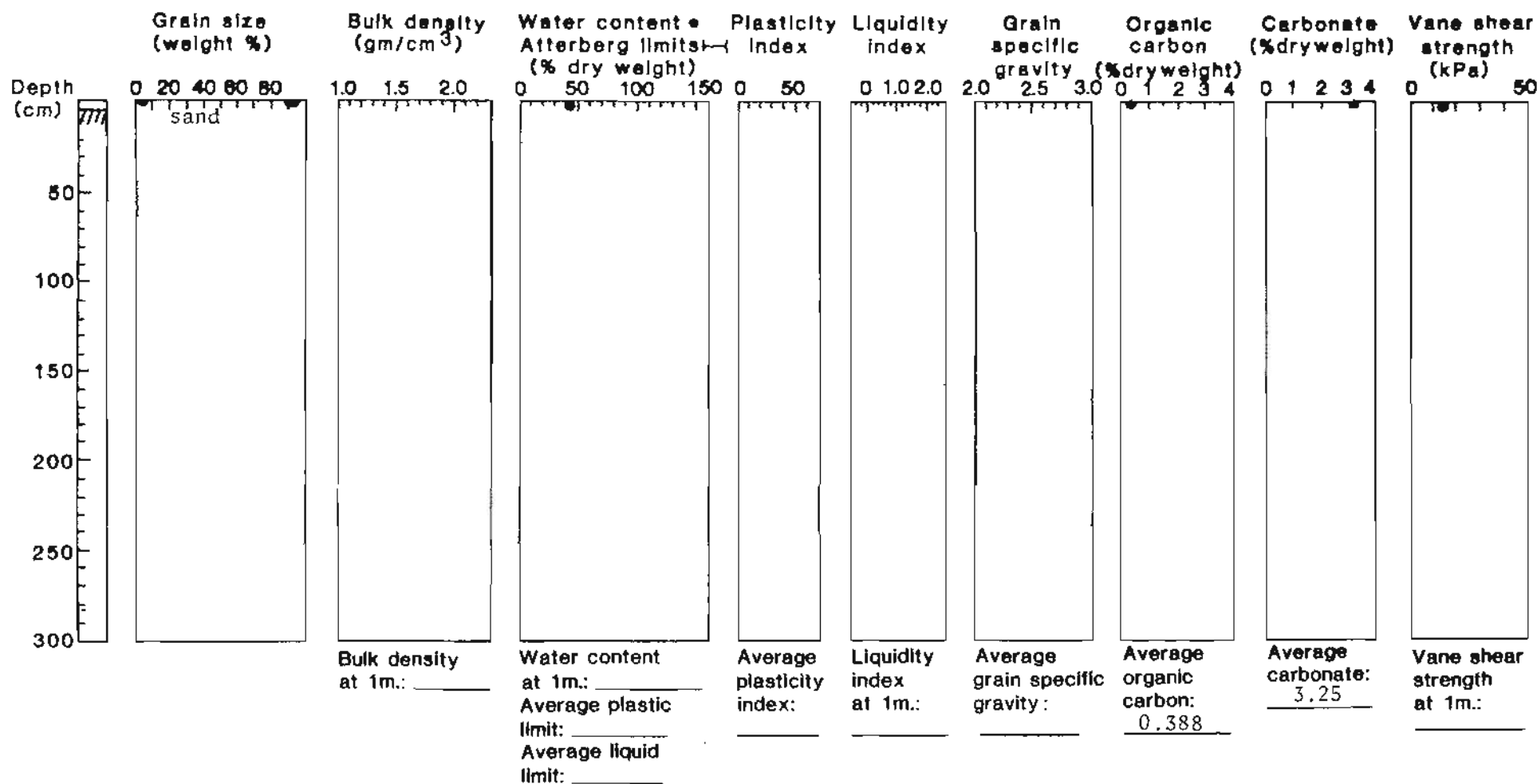


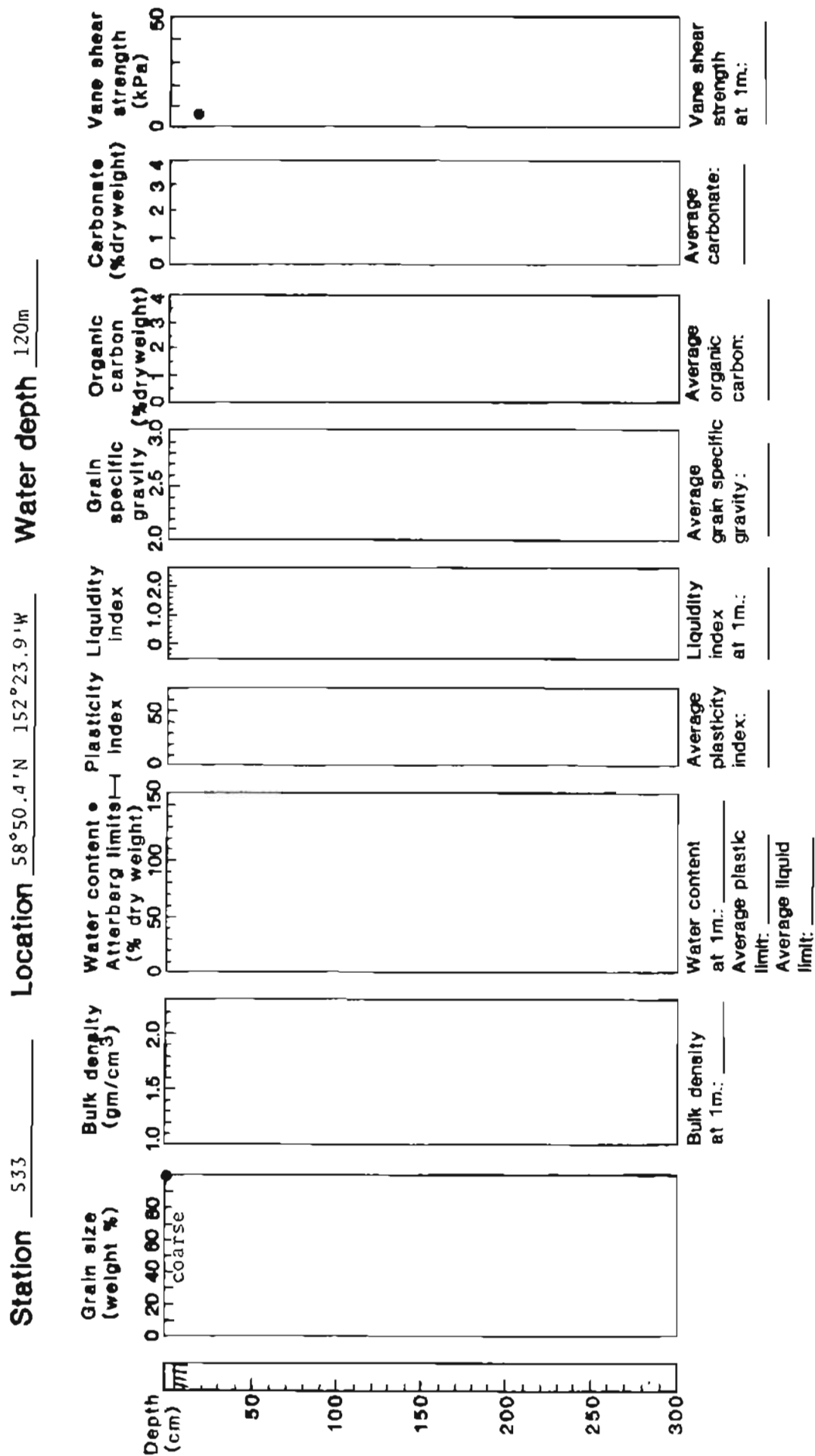


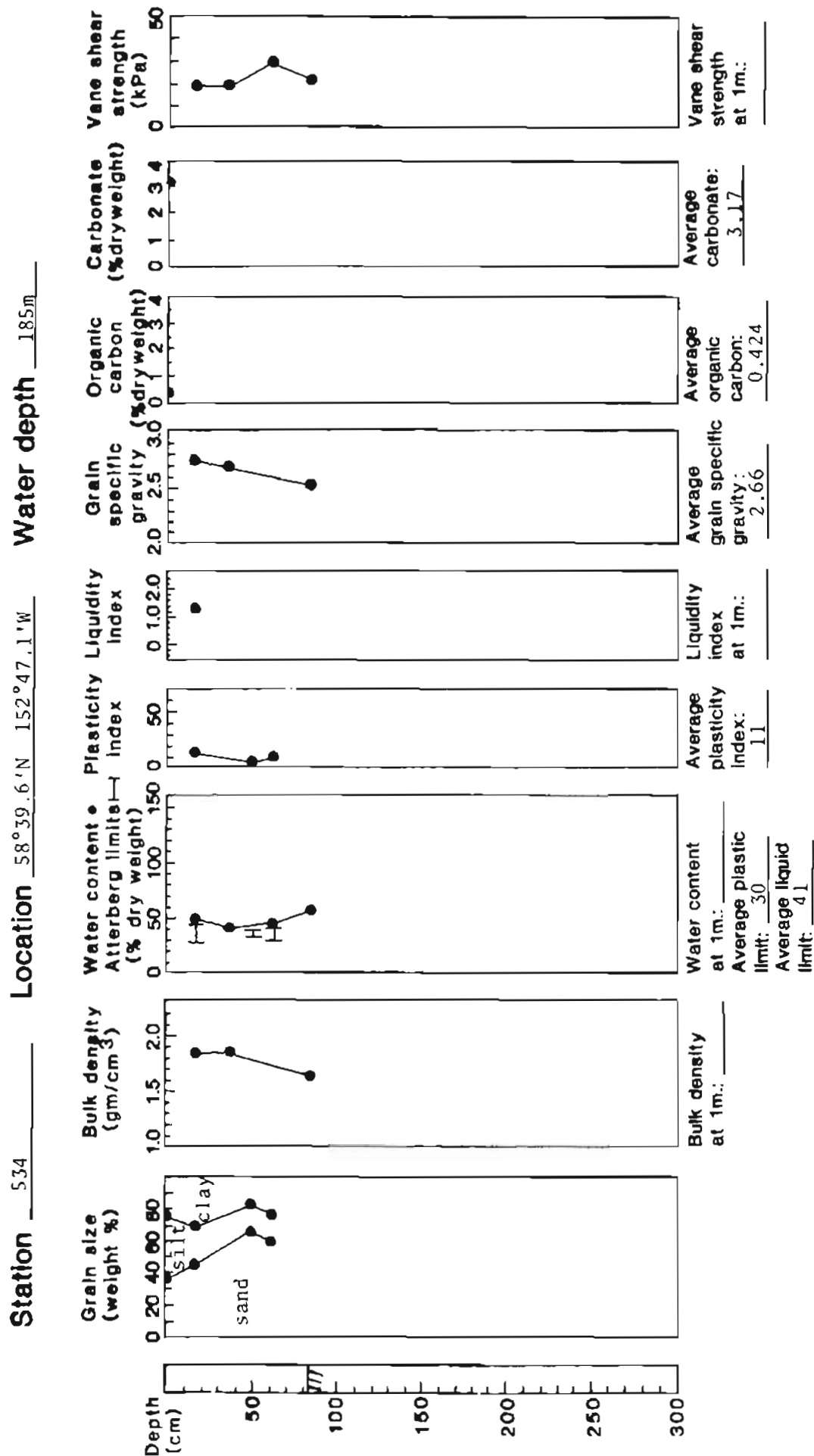
Station 531

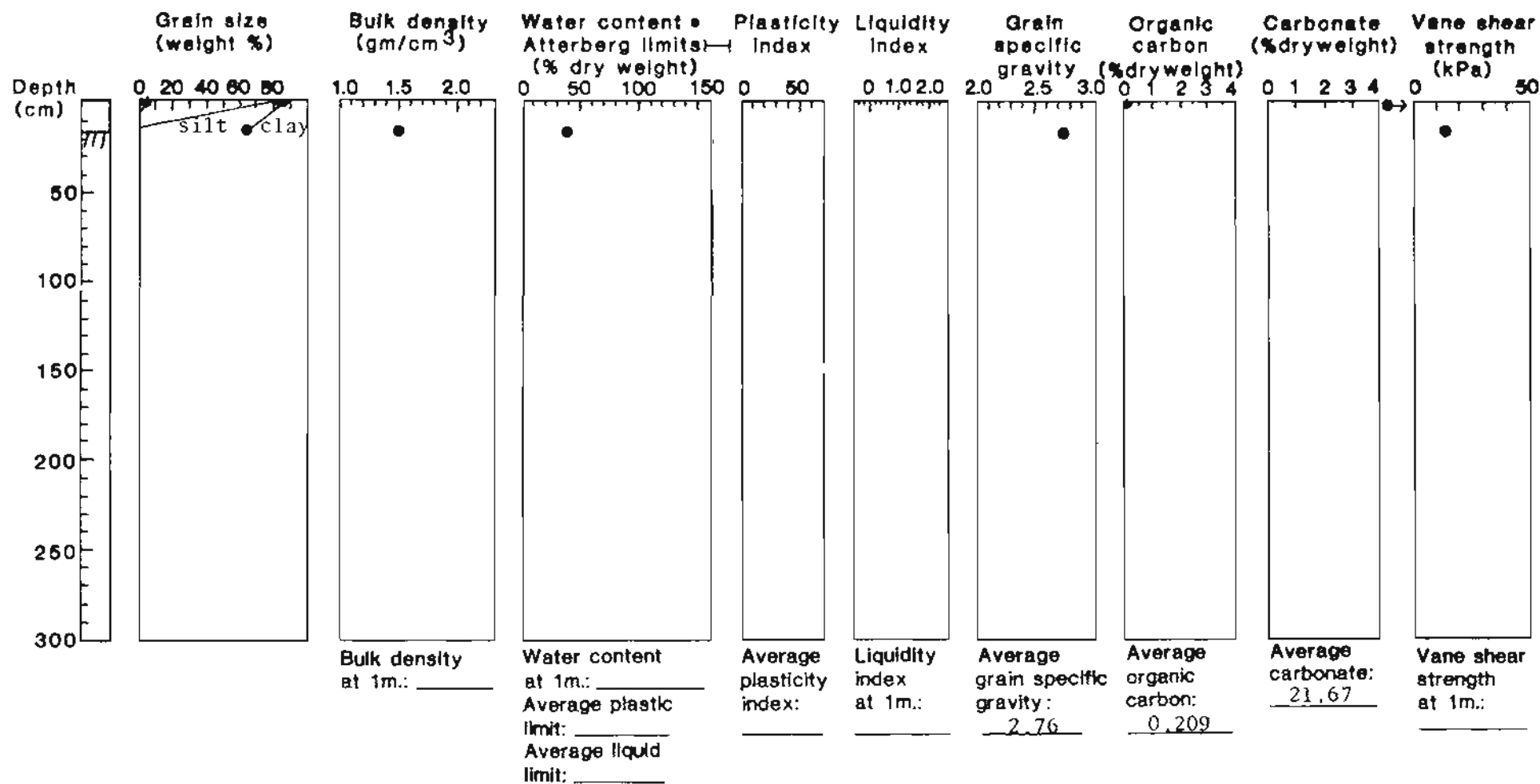
Location 58°54.9'N 152°37.3'W

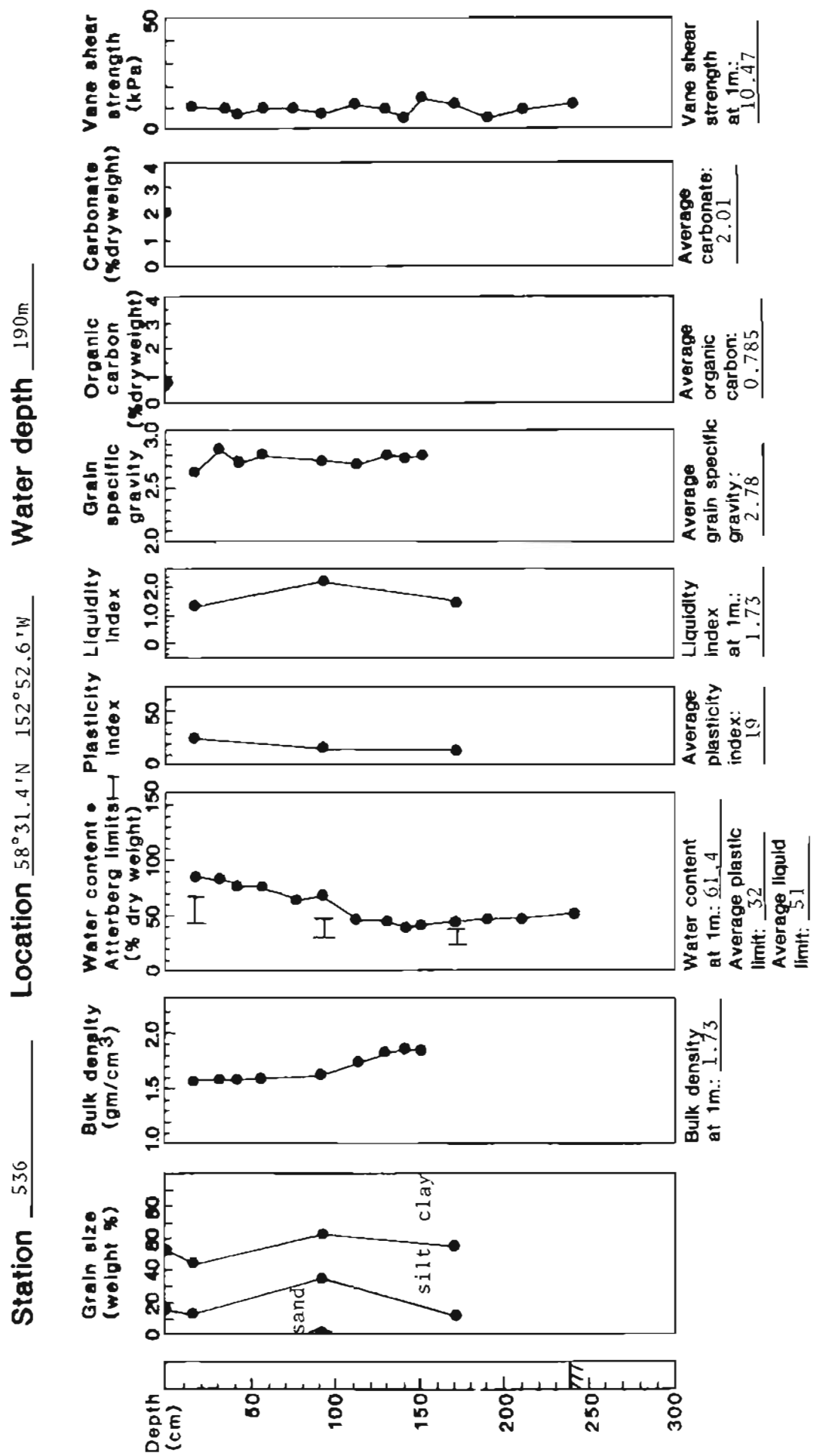
Water depth 161m

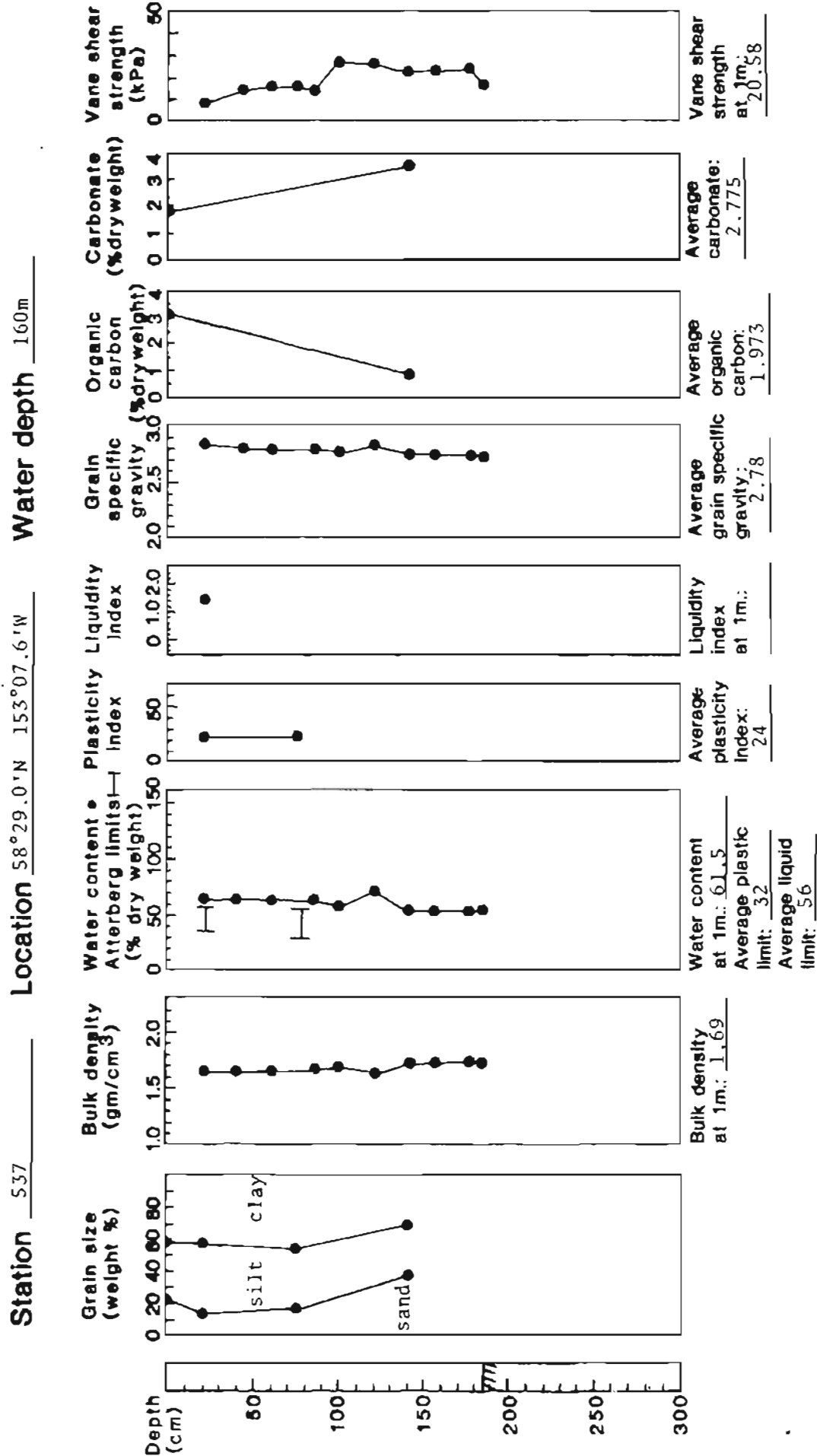






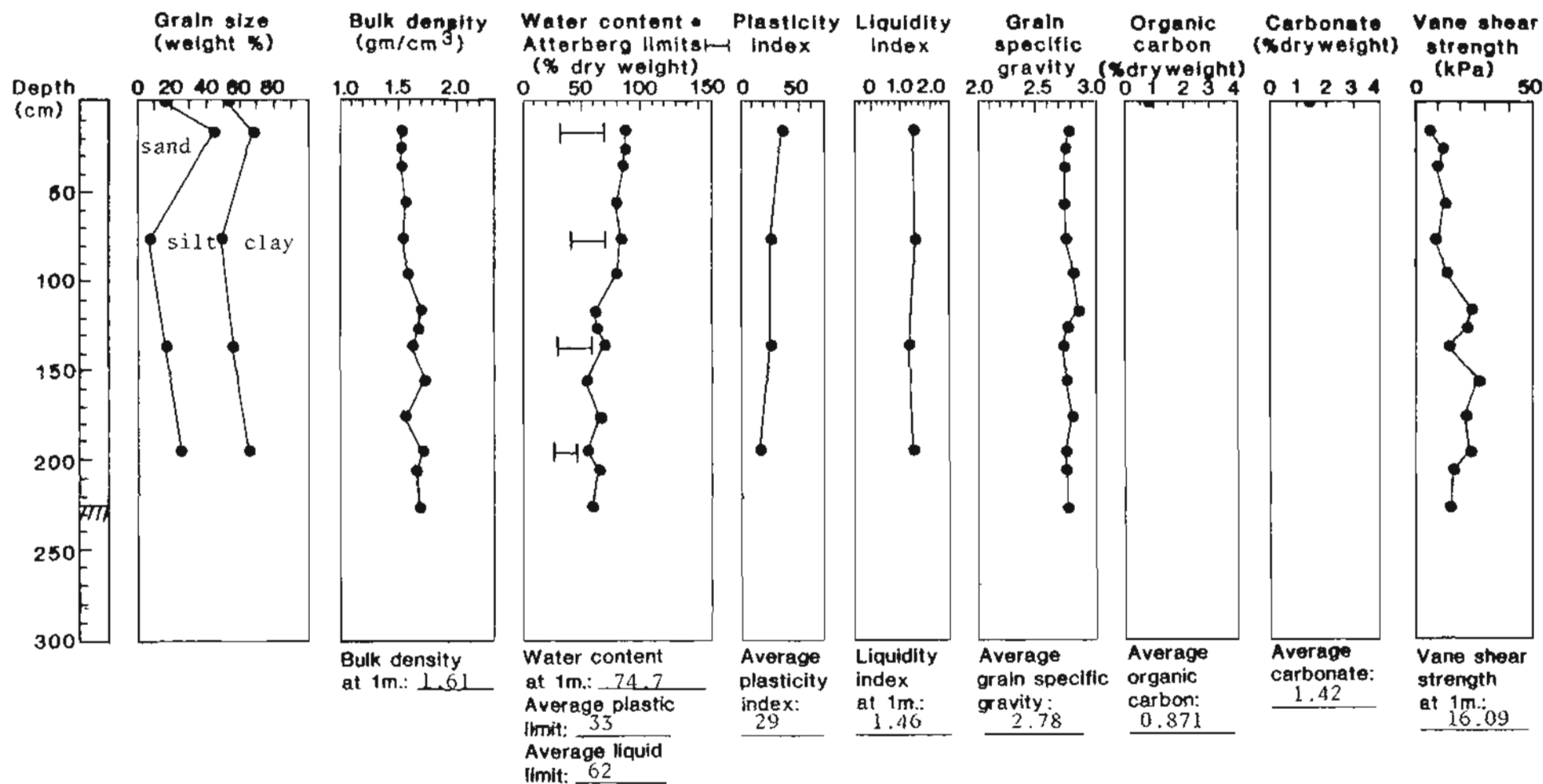
Station 535Location 58°37.0'N 152°42.0'WWater depth 98m



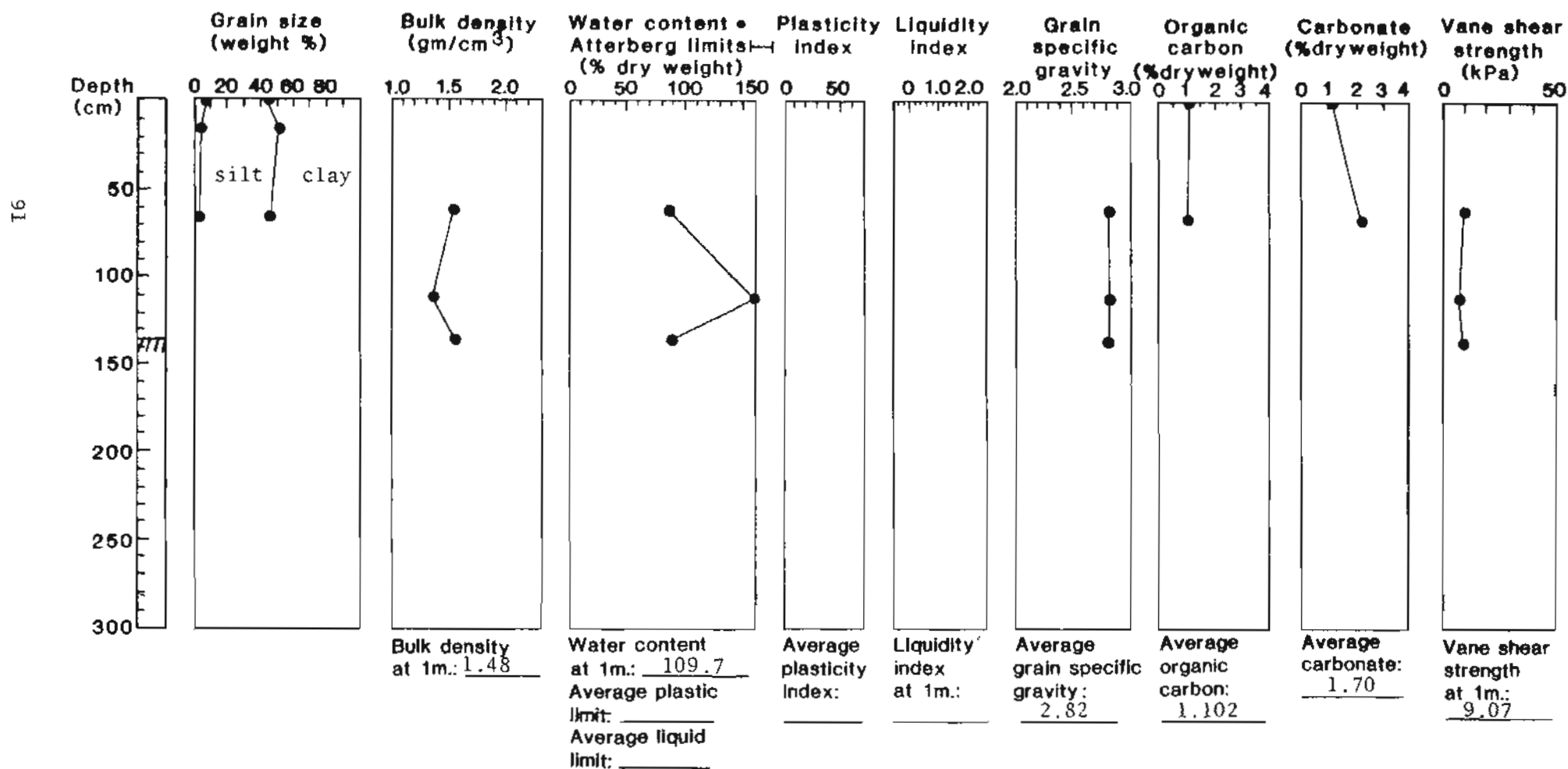


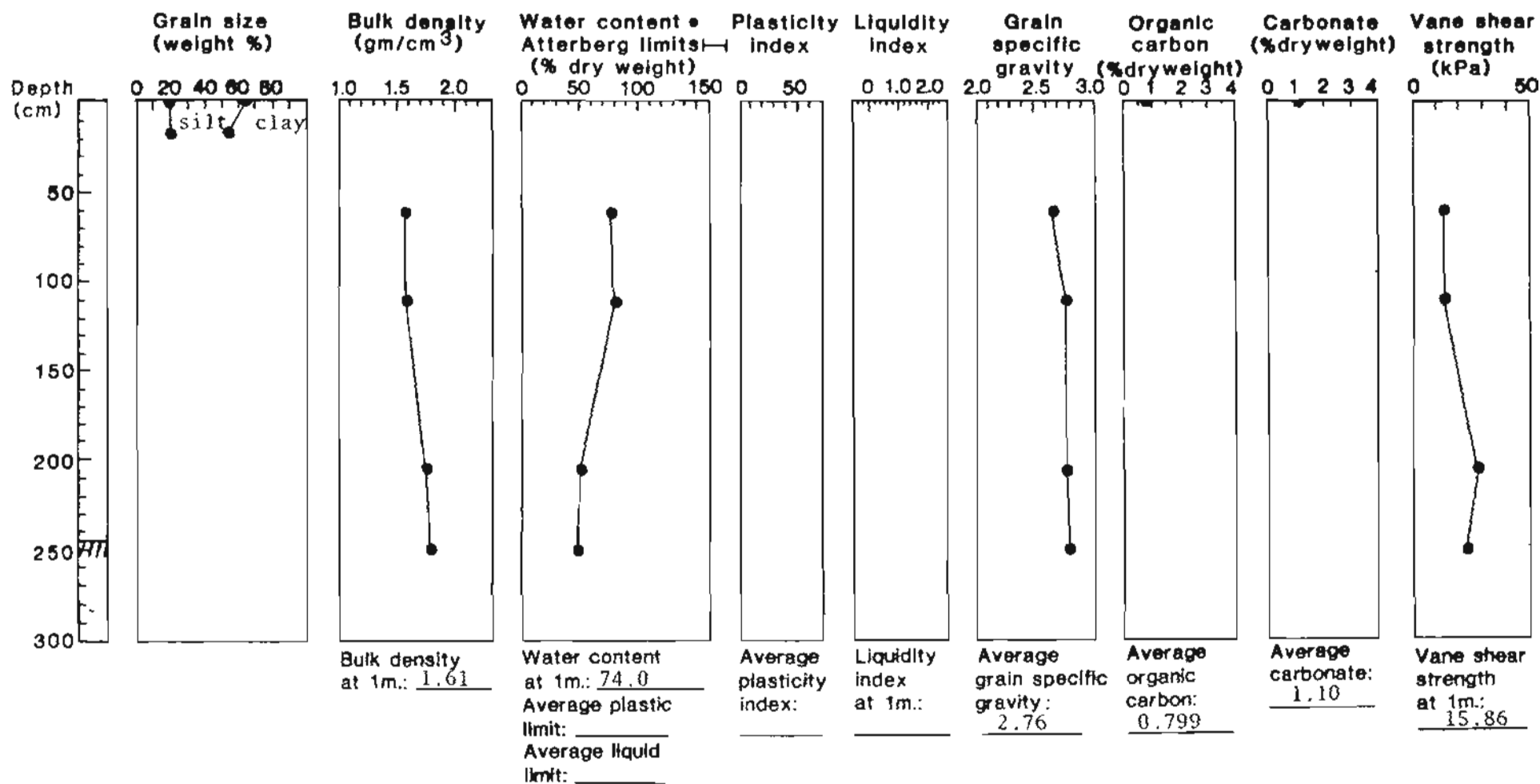
Station 538Location 58°25.2'N 153°00.2'WWater depth 190m

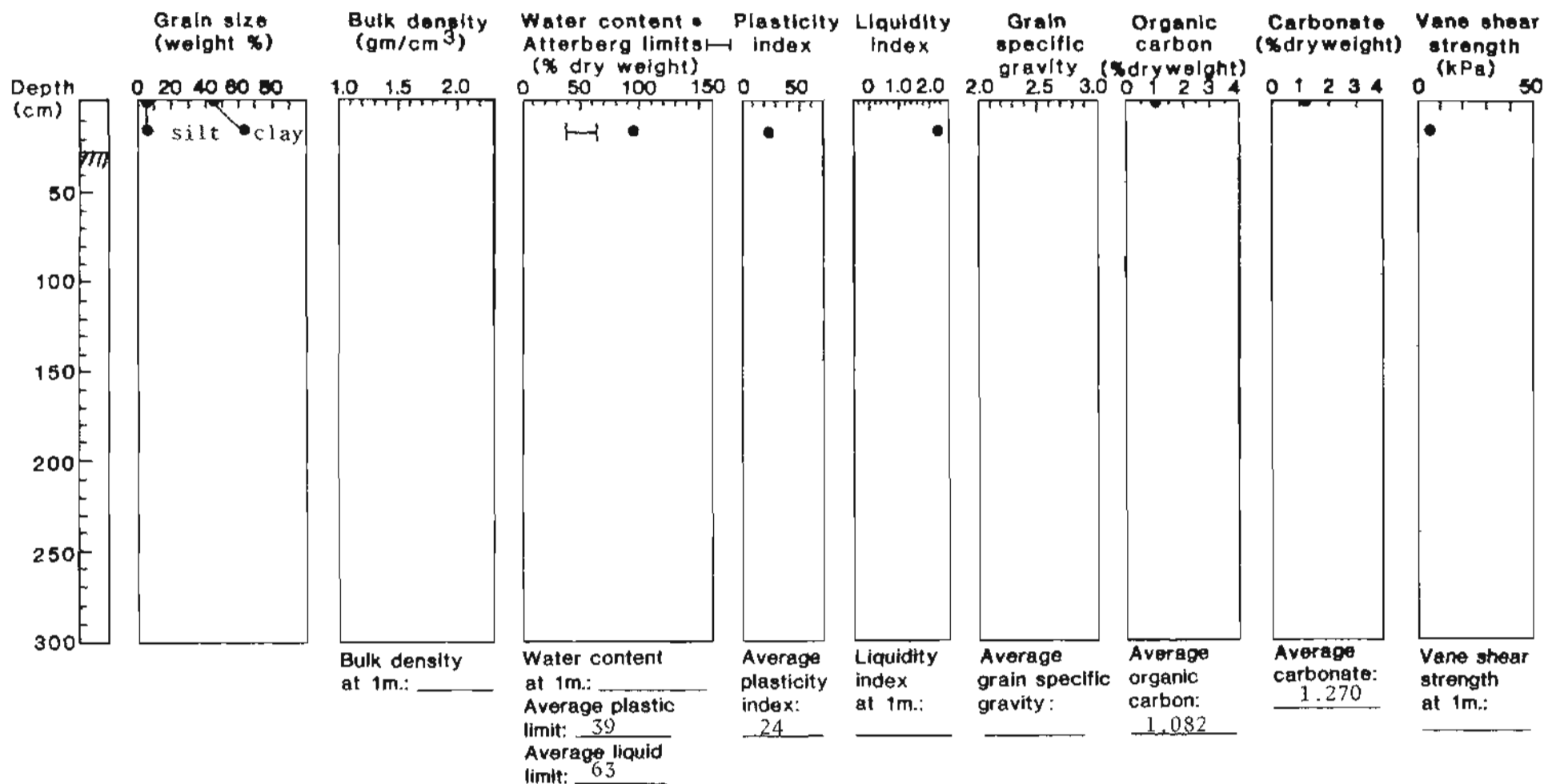
06

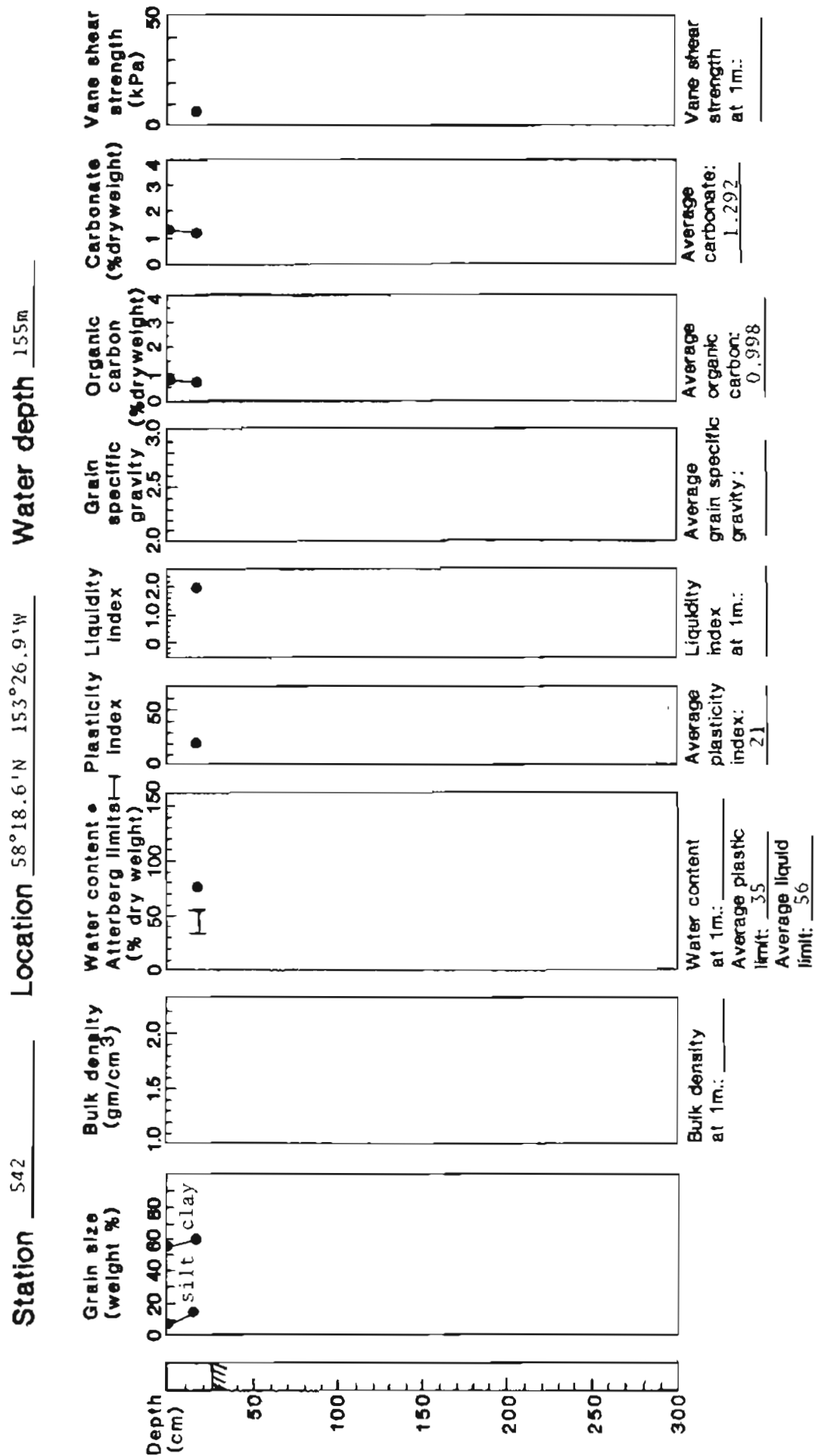


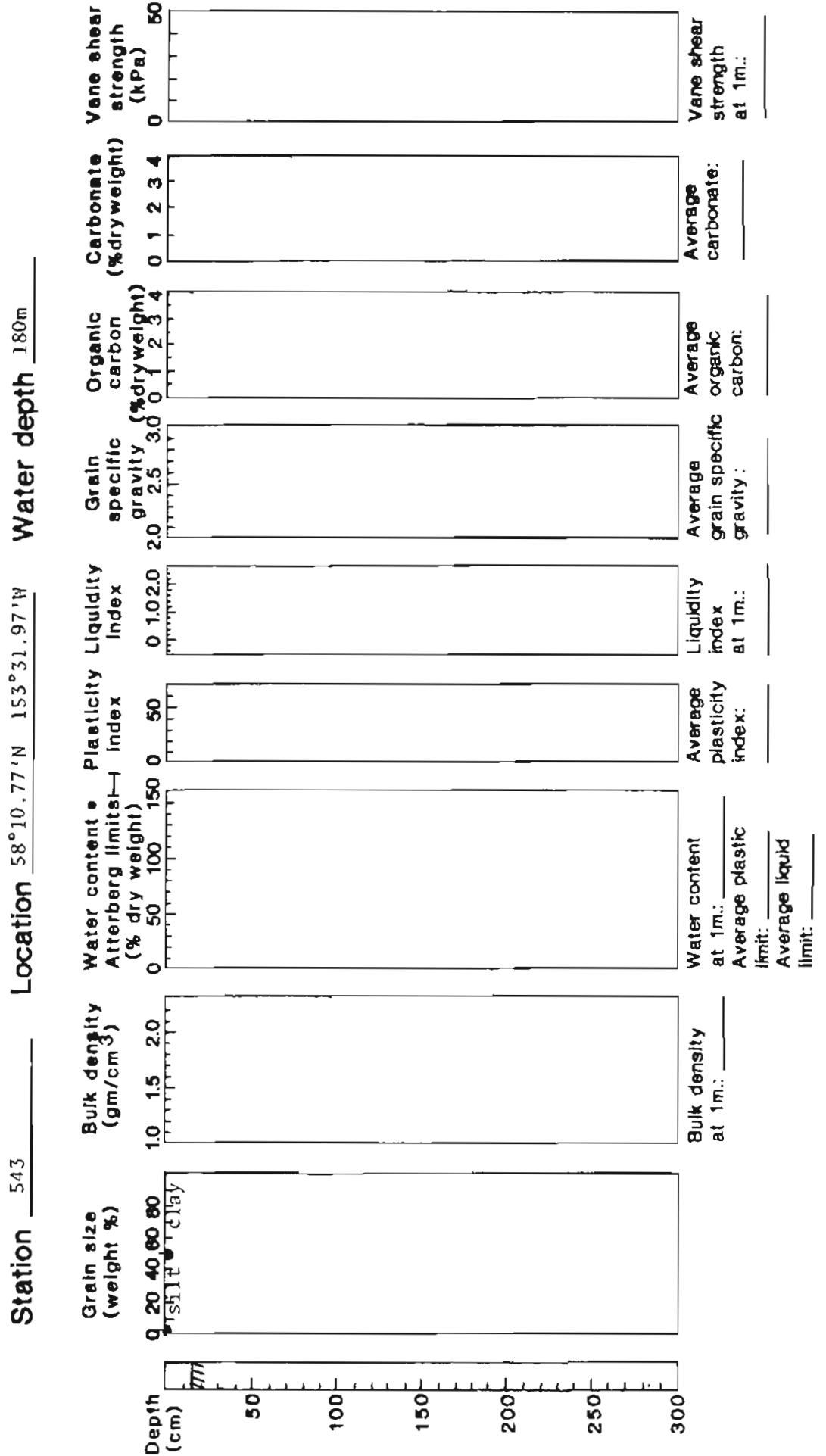
Water depth 175m



Station 540Location 58°21.5'N 153°07.6'WWater depth 210m

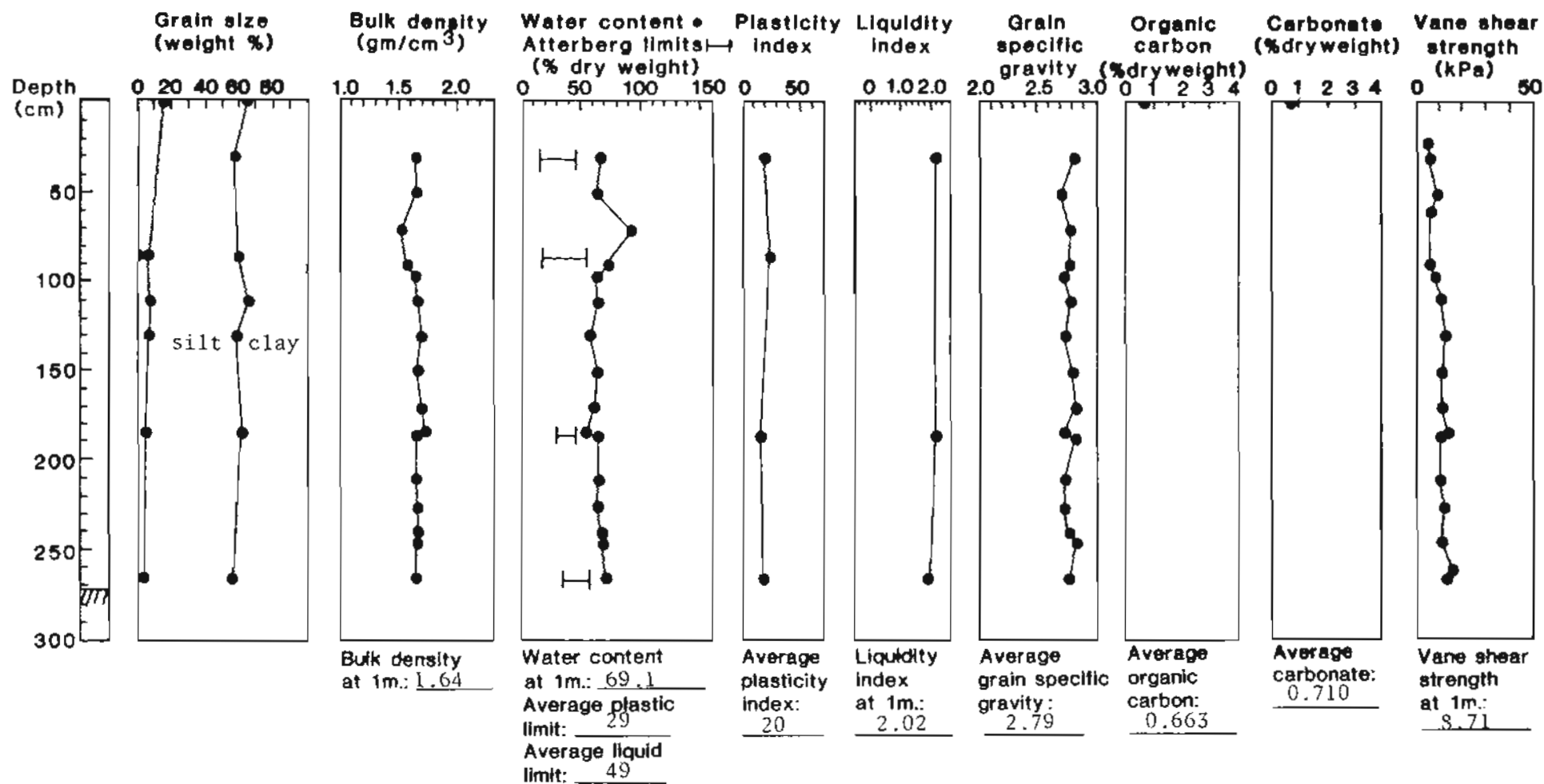
Station S41Location 58°15.8'N 153°22.0'WWater depth 167m

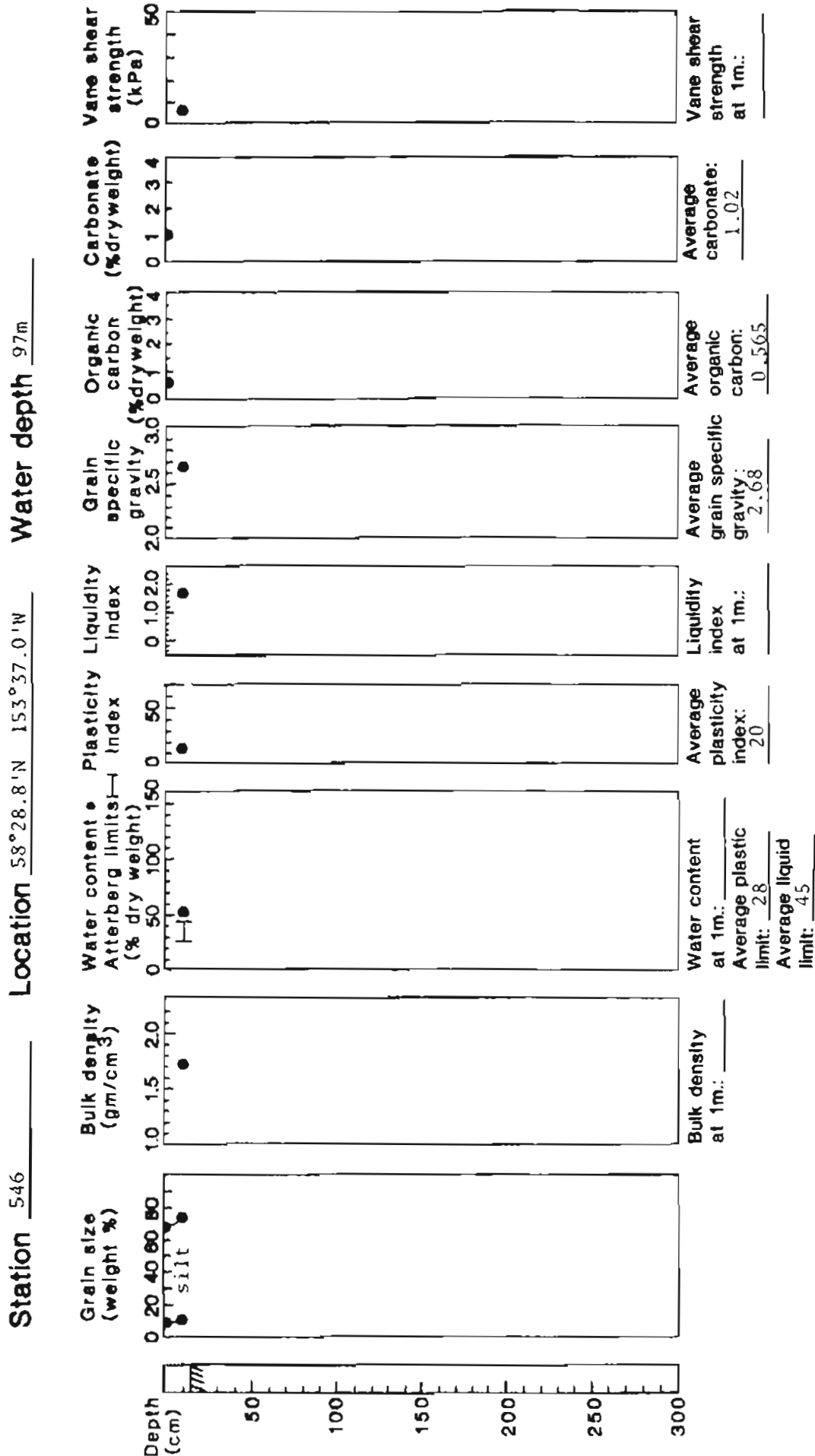




Station 545Location 58°22.5'N 153°53.5'WWater depth 175m

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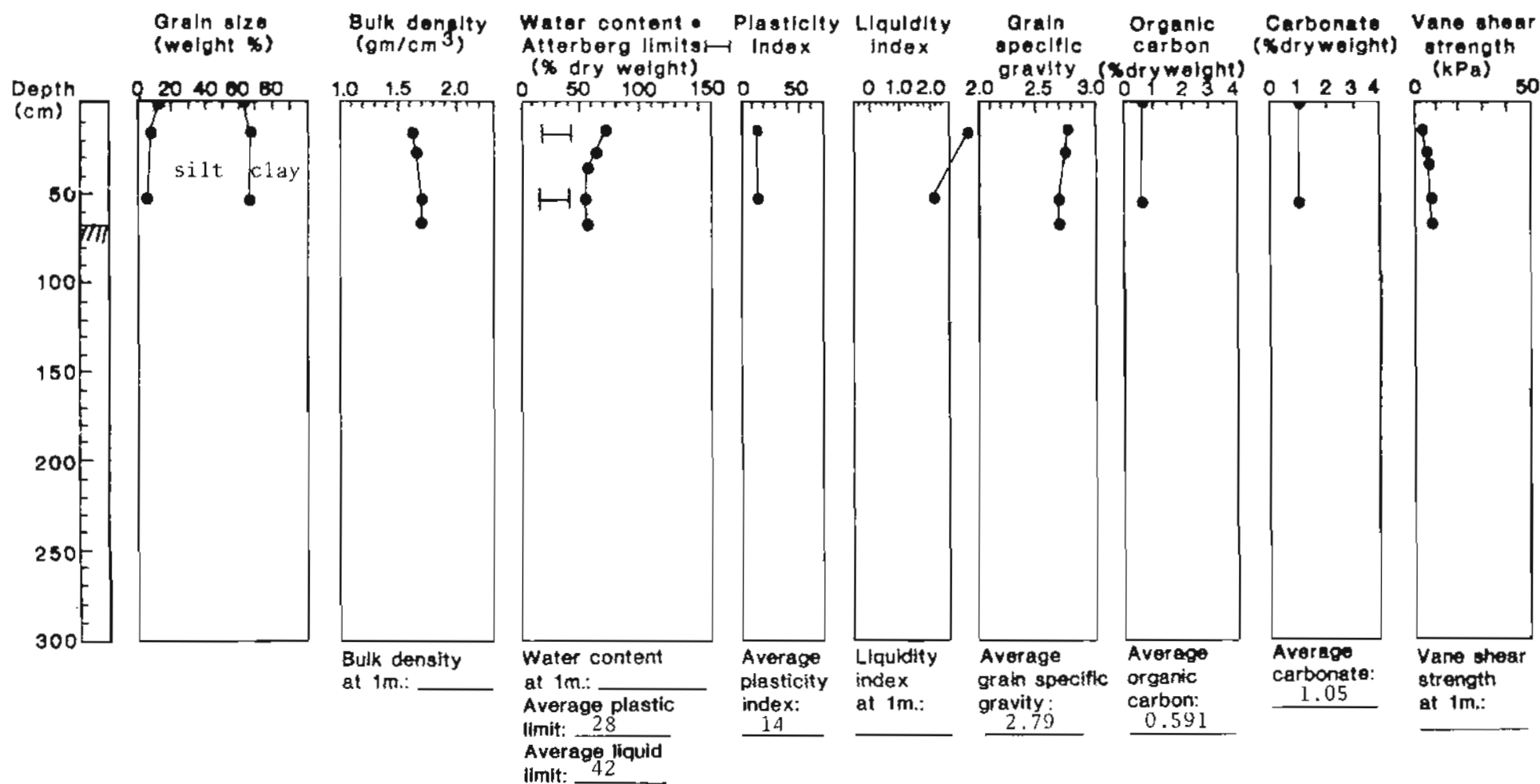


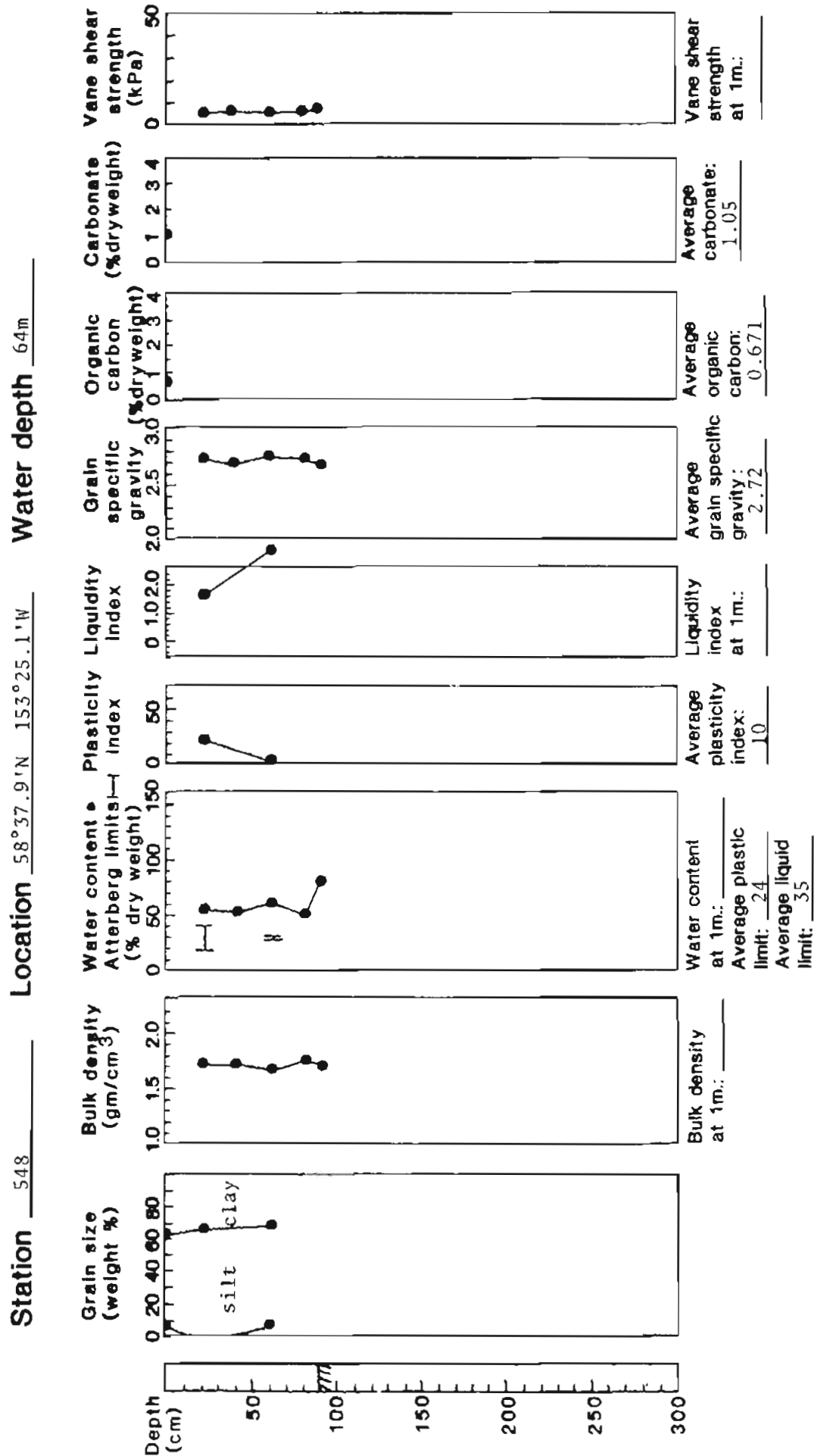


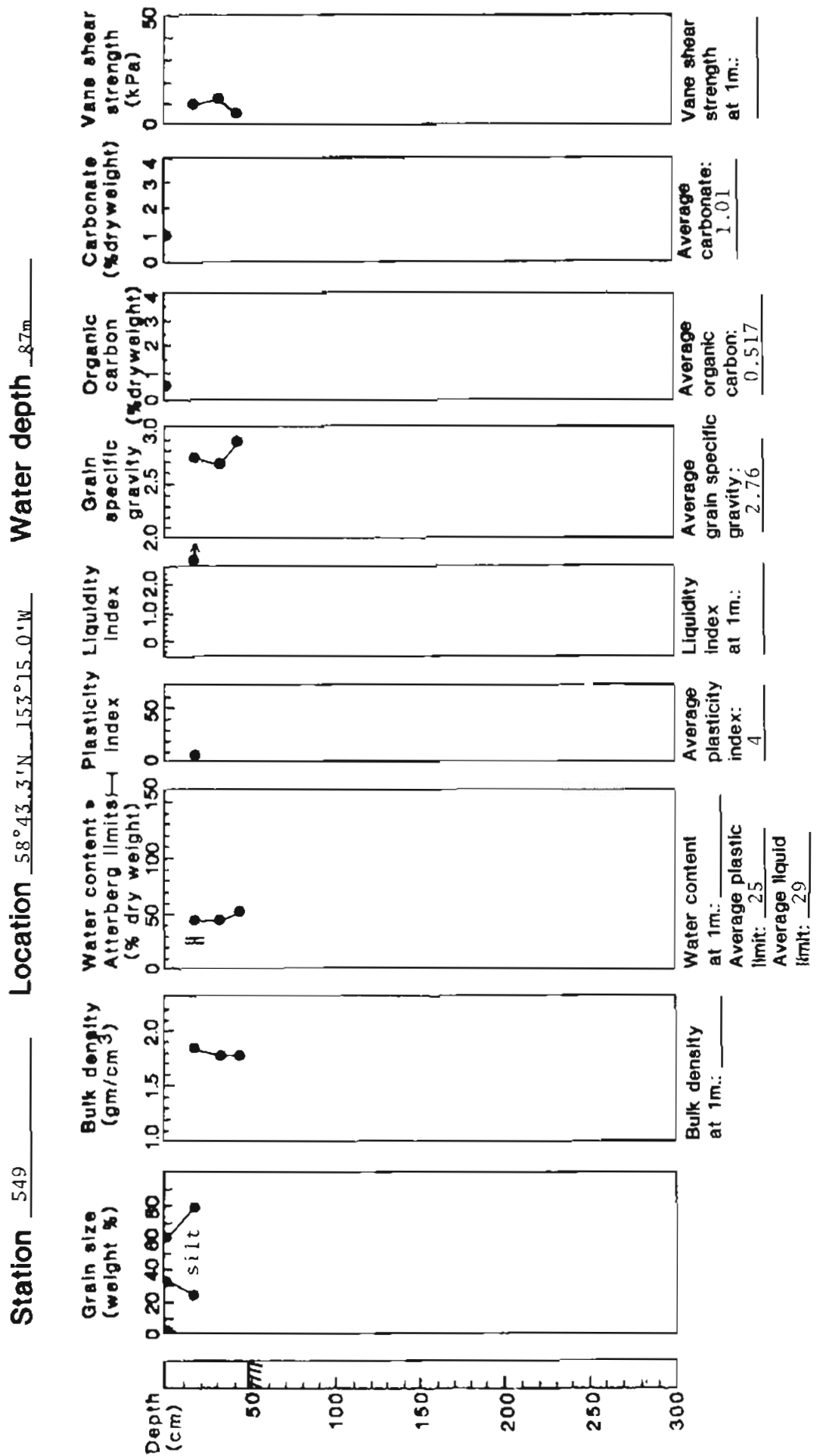
Station 547

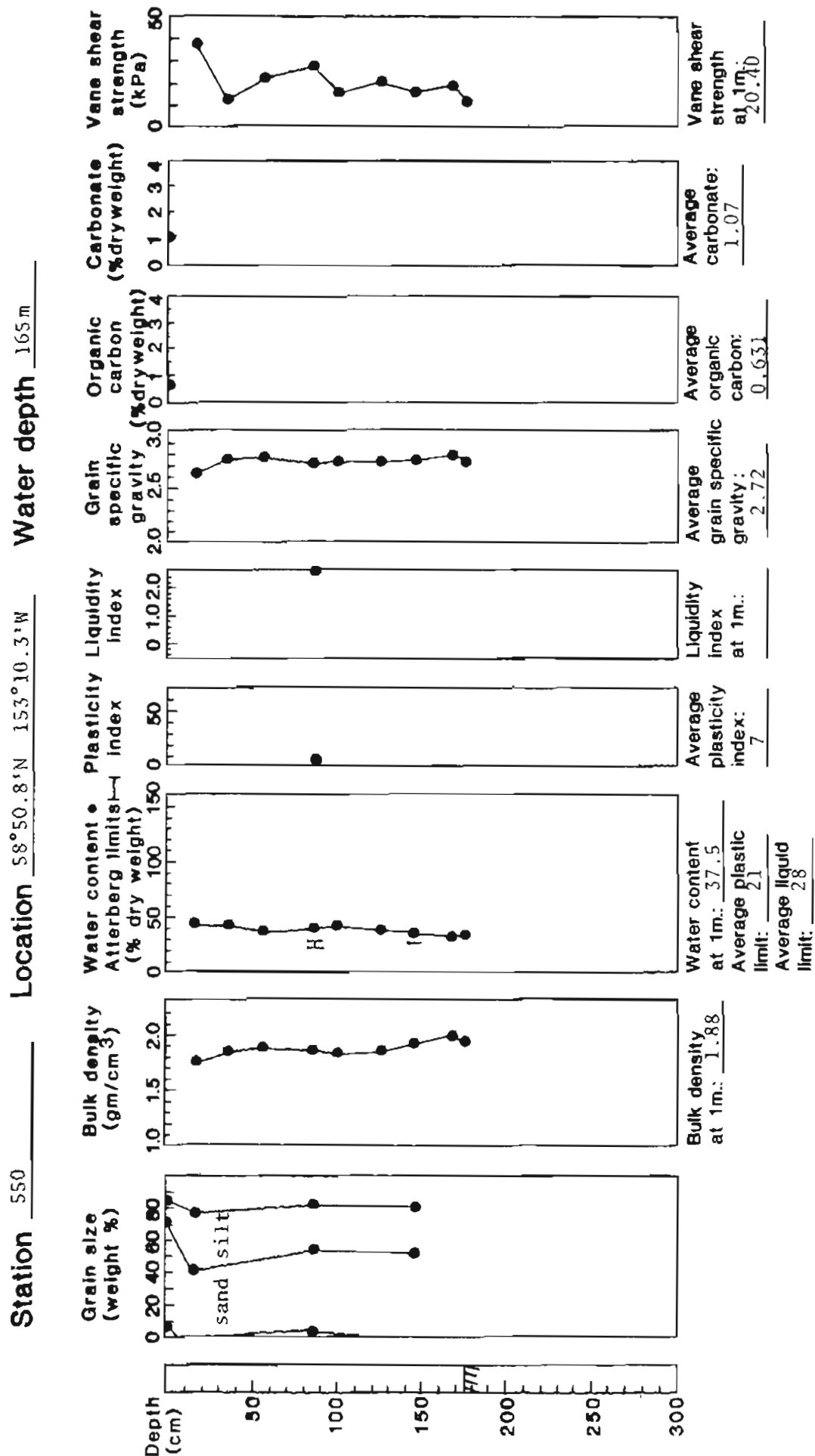
Location 58°33.0'N 153°34.4'W

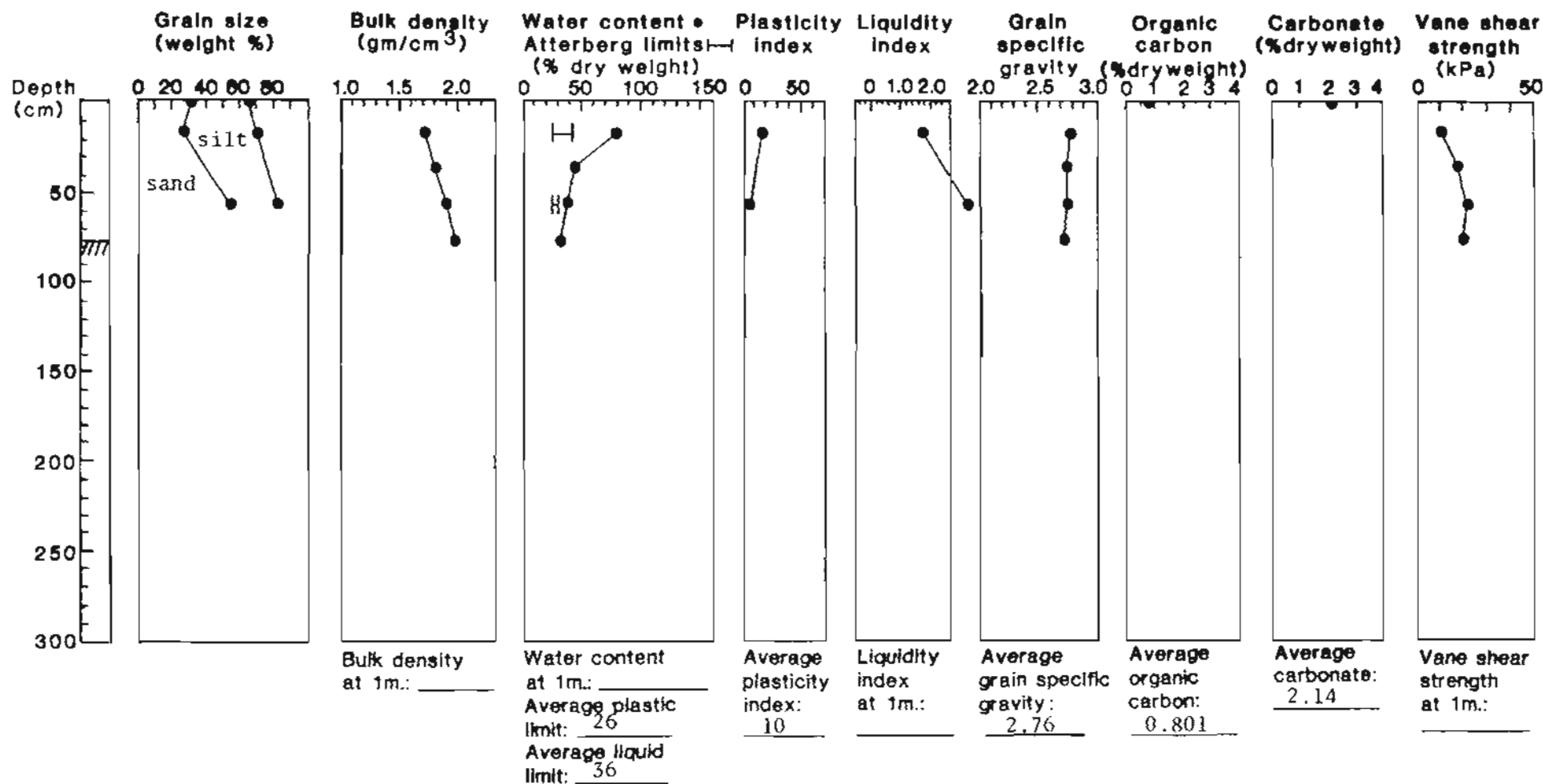
Water depth 89m

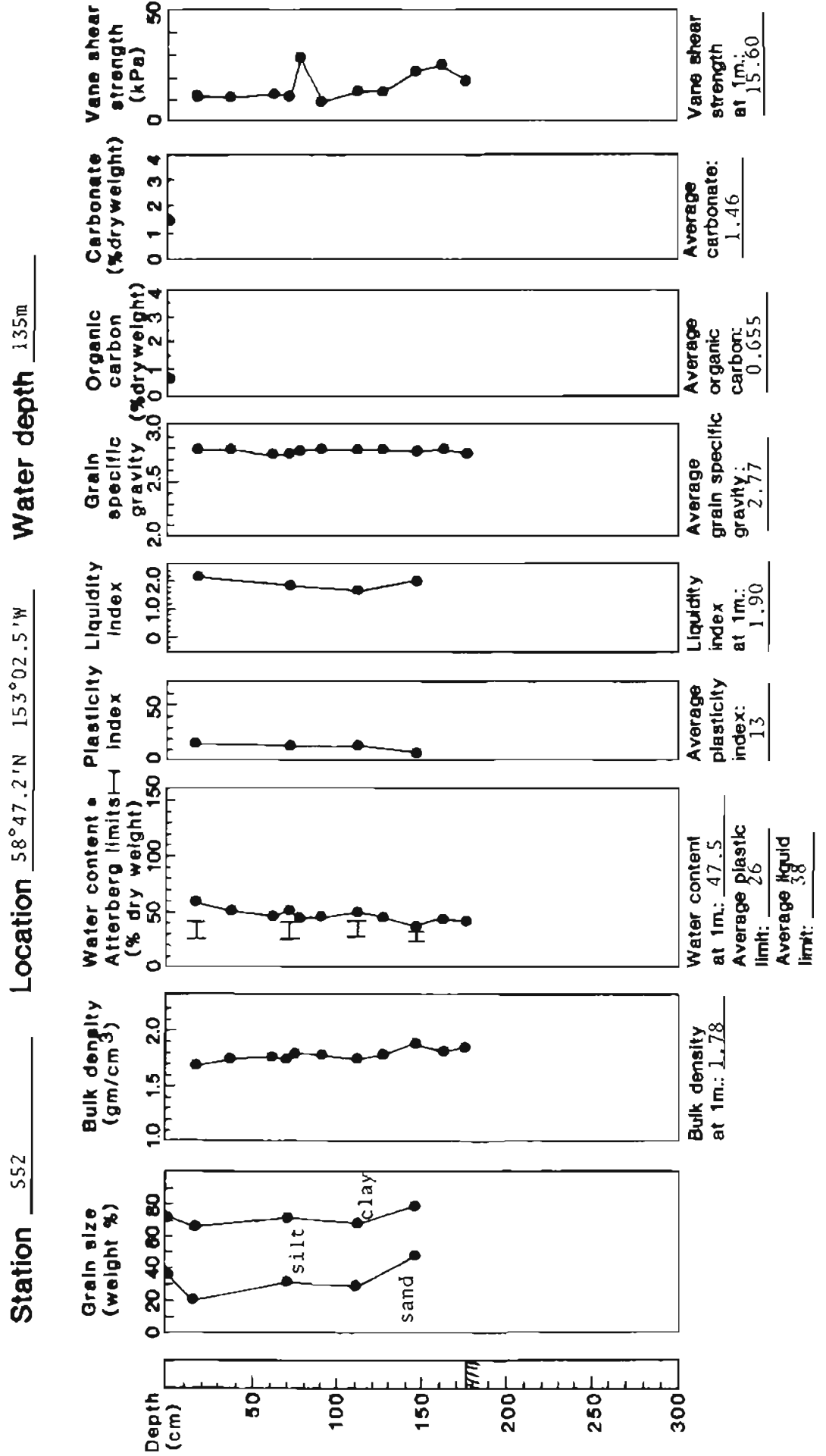


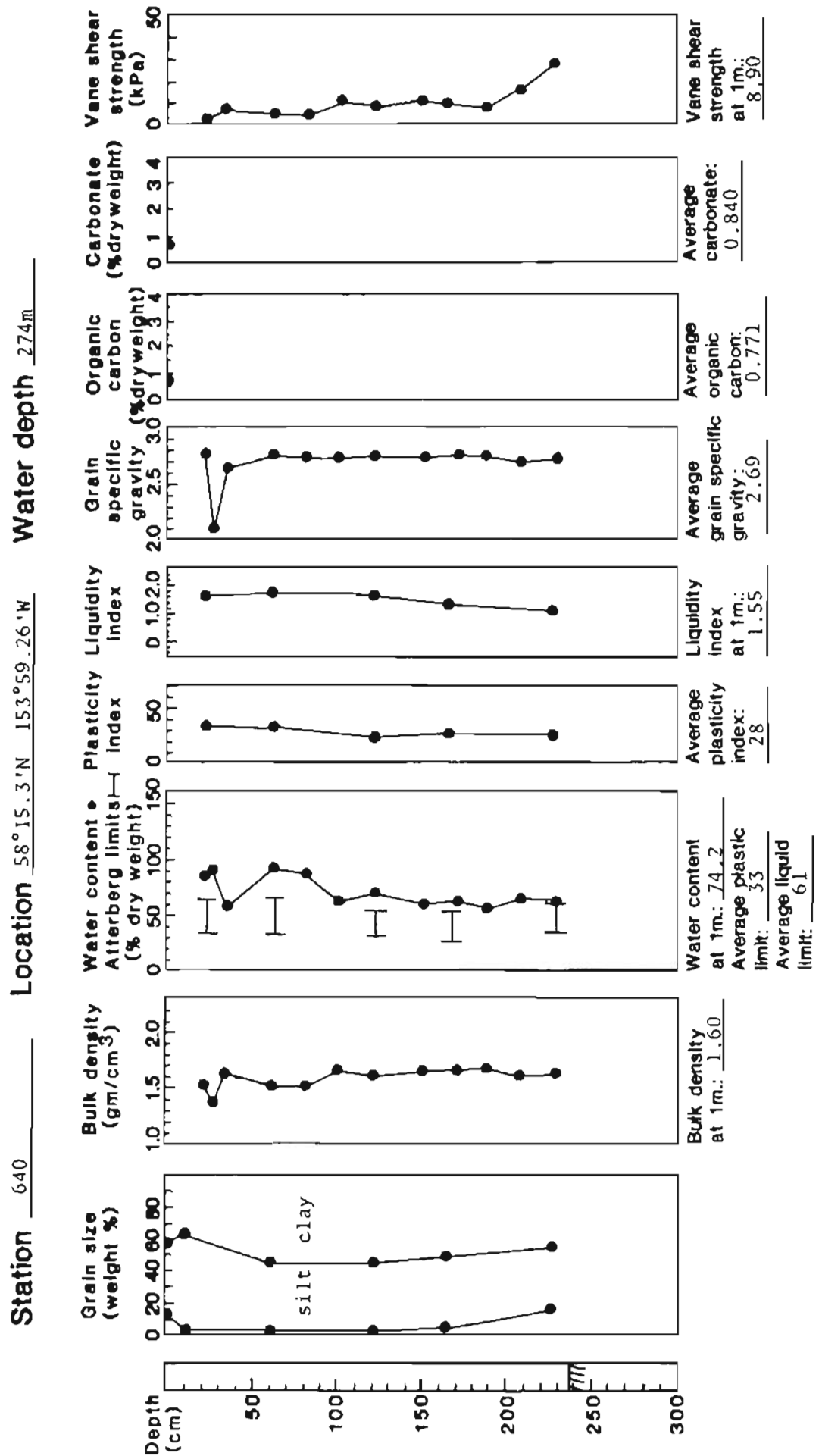




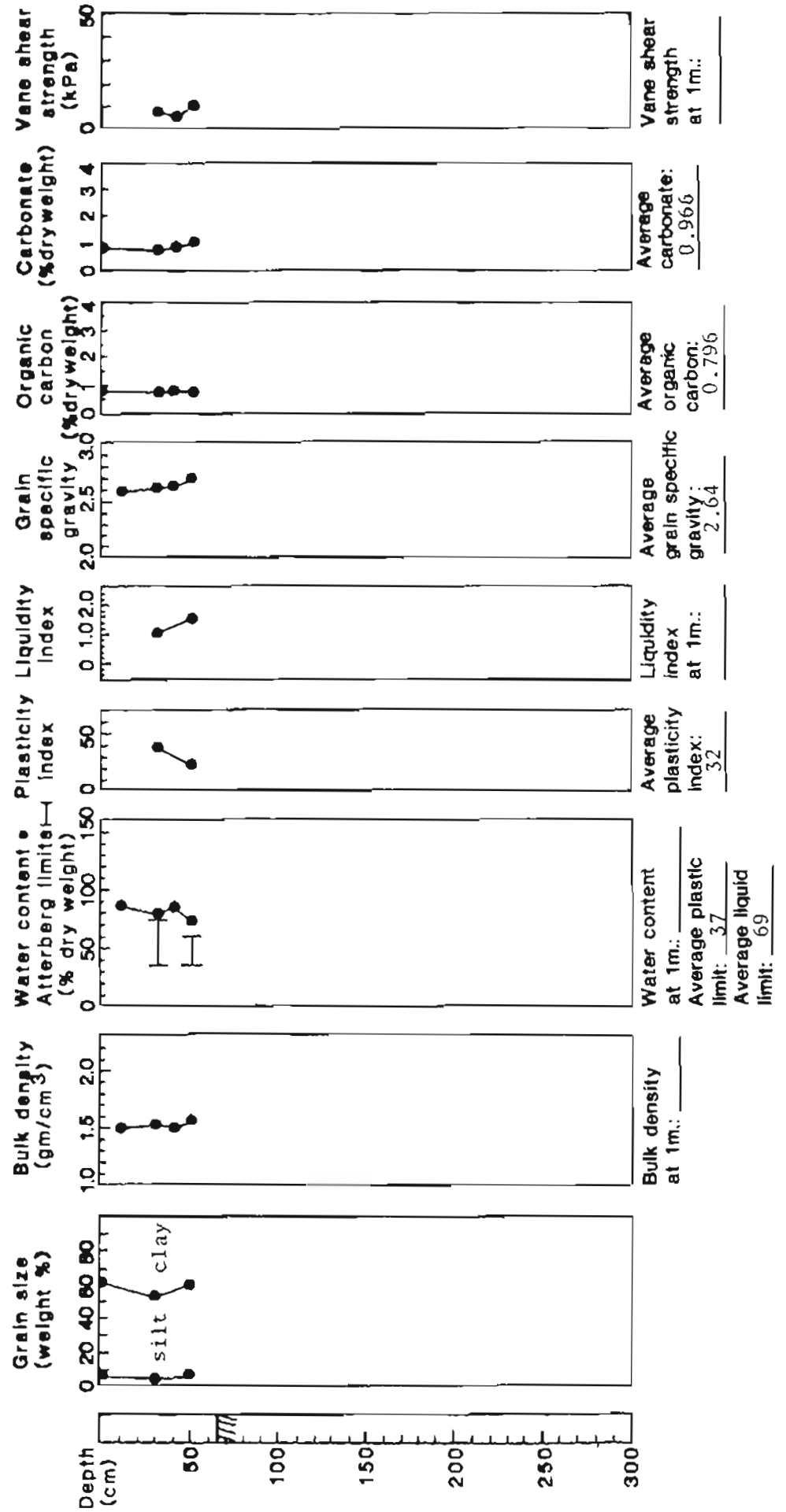


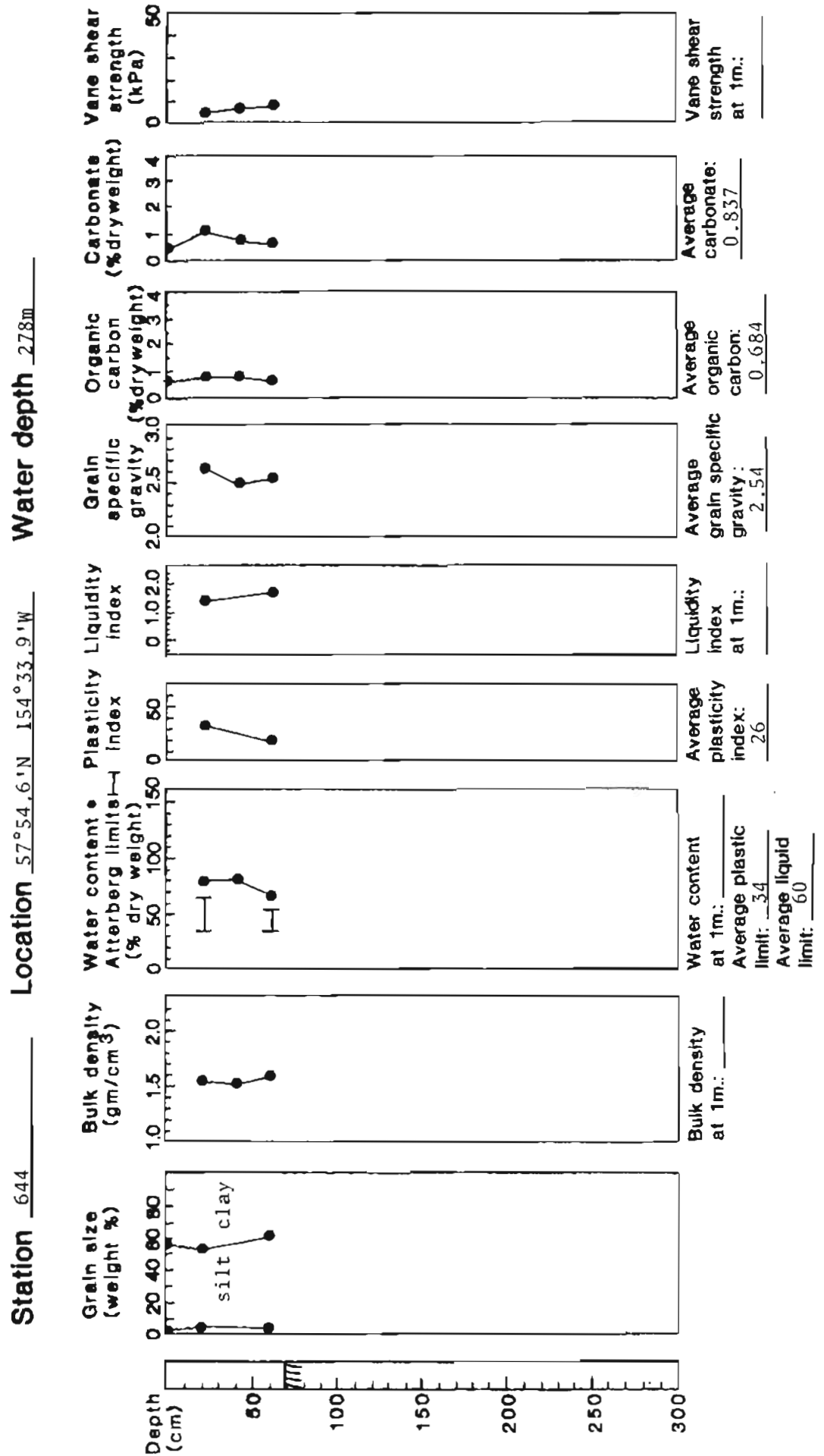
Station 551Location 58°53.6'N 152°54.4'WWater depth 155m

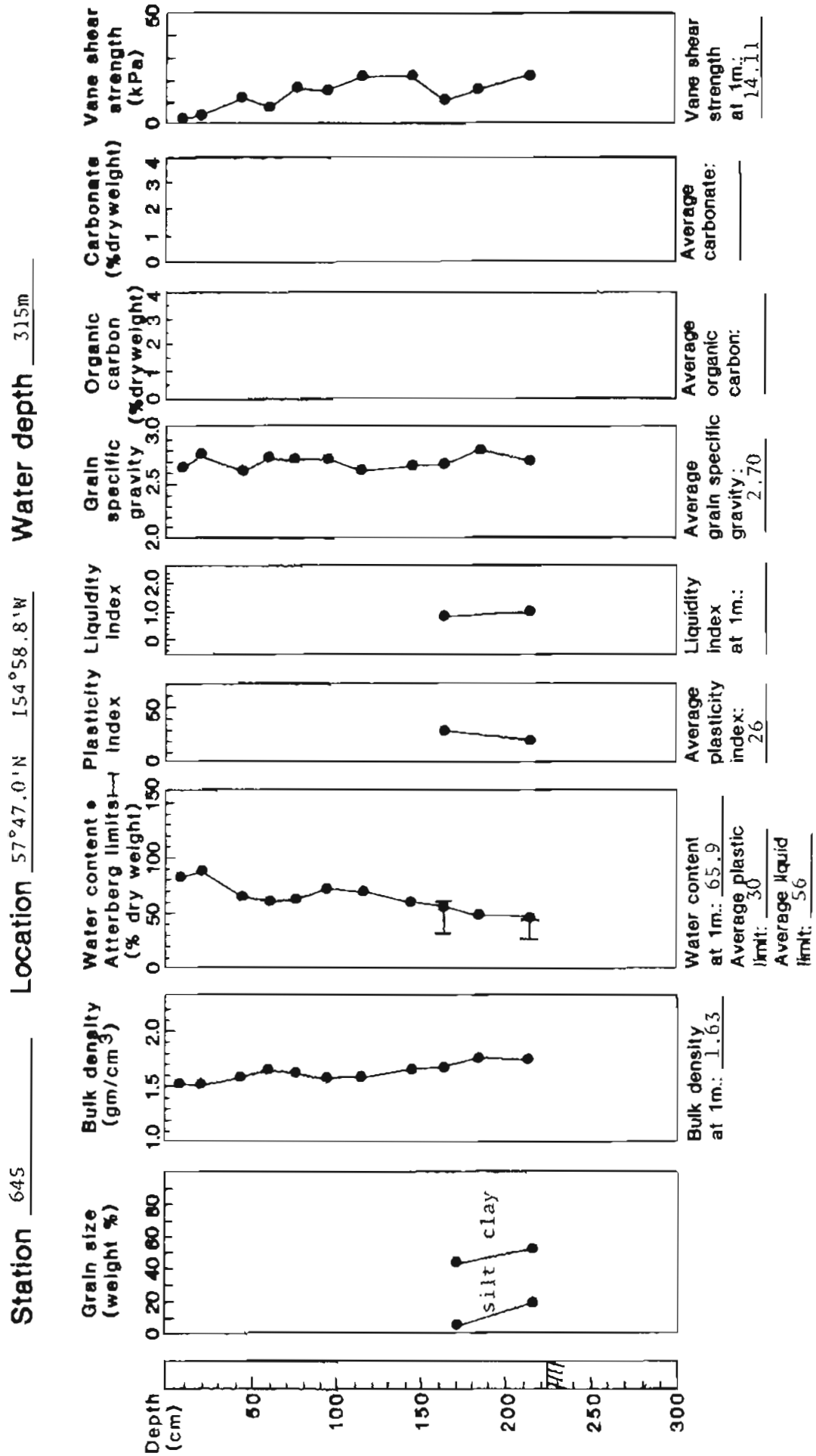


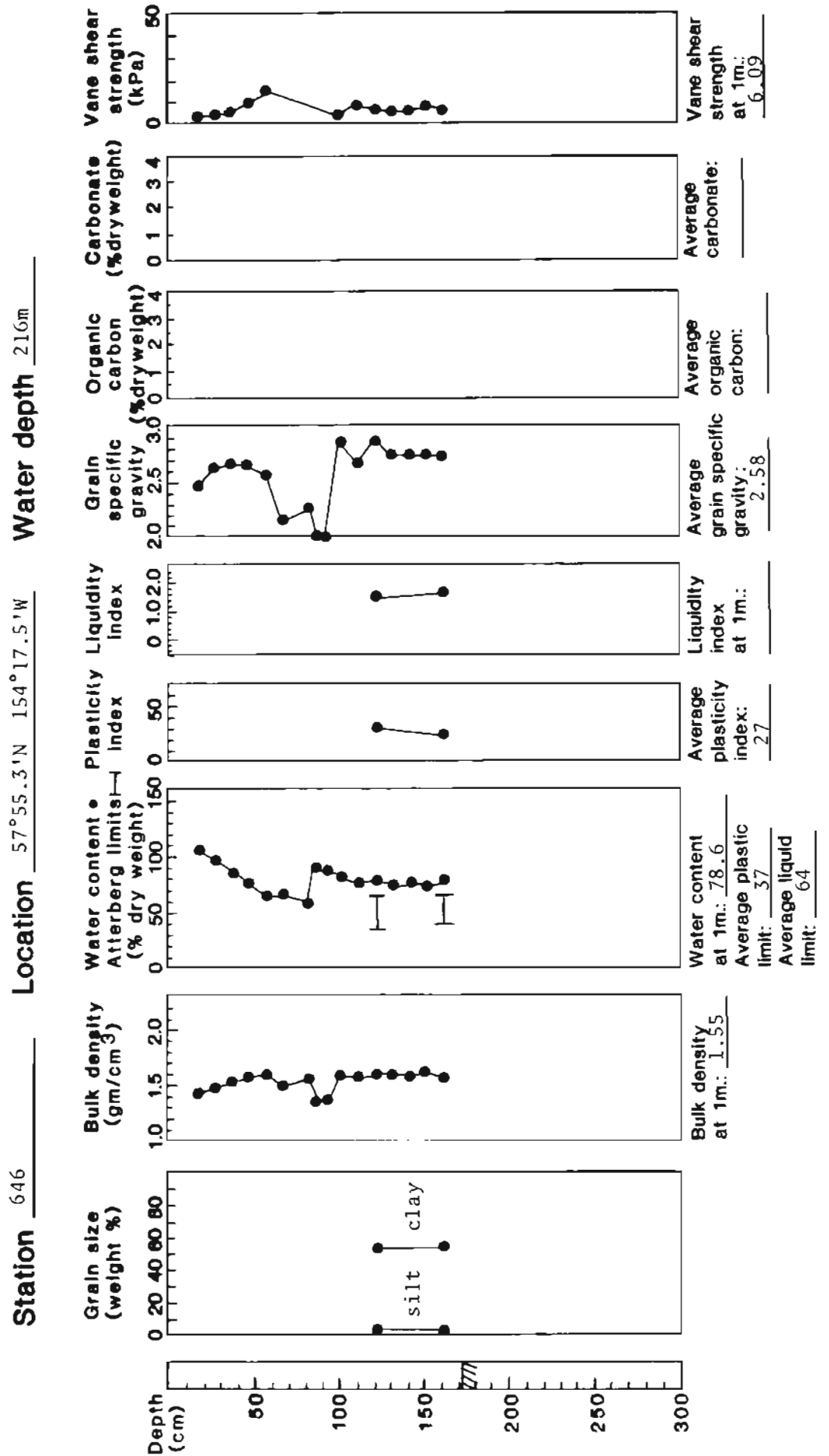


Station 643 Location 58°05.7'N 154°09.1'W Water depth 288m



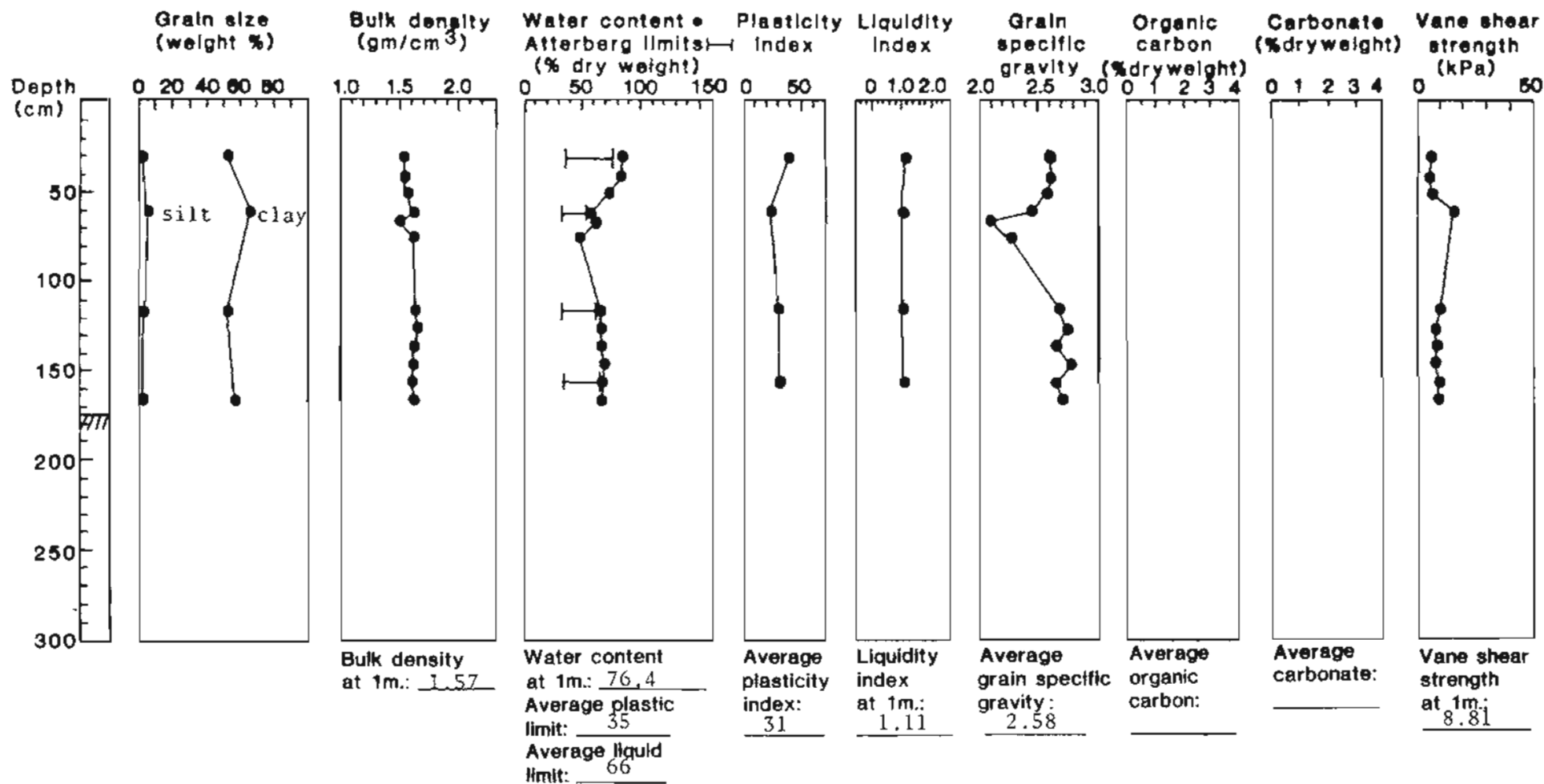


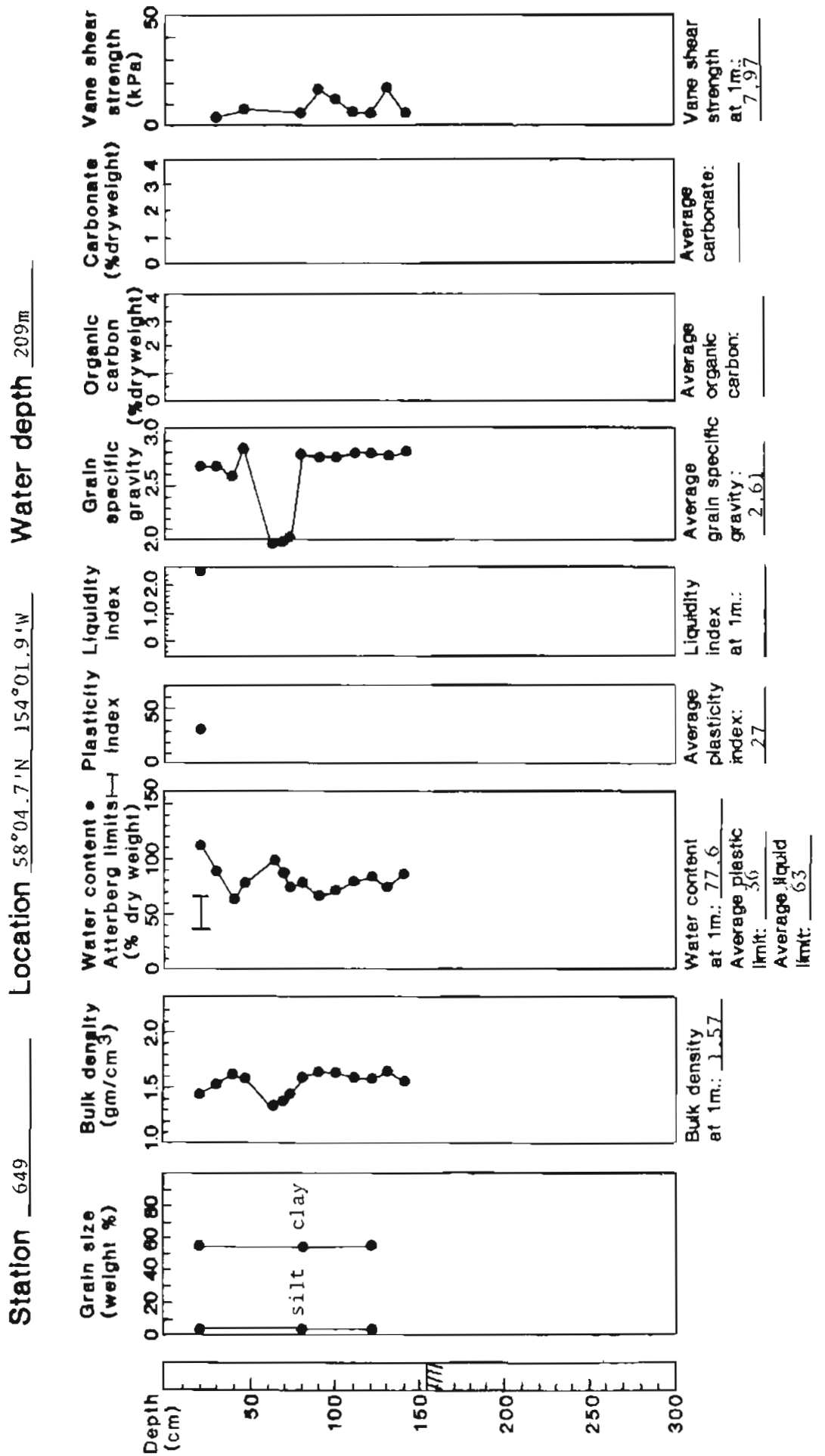


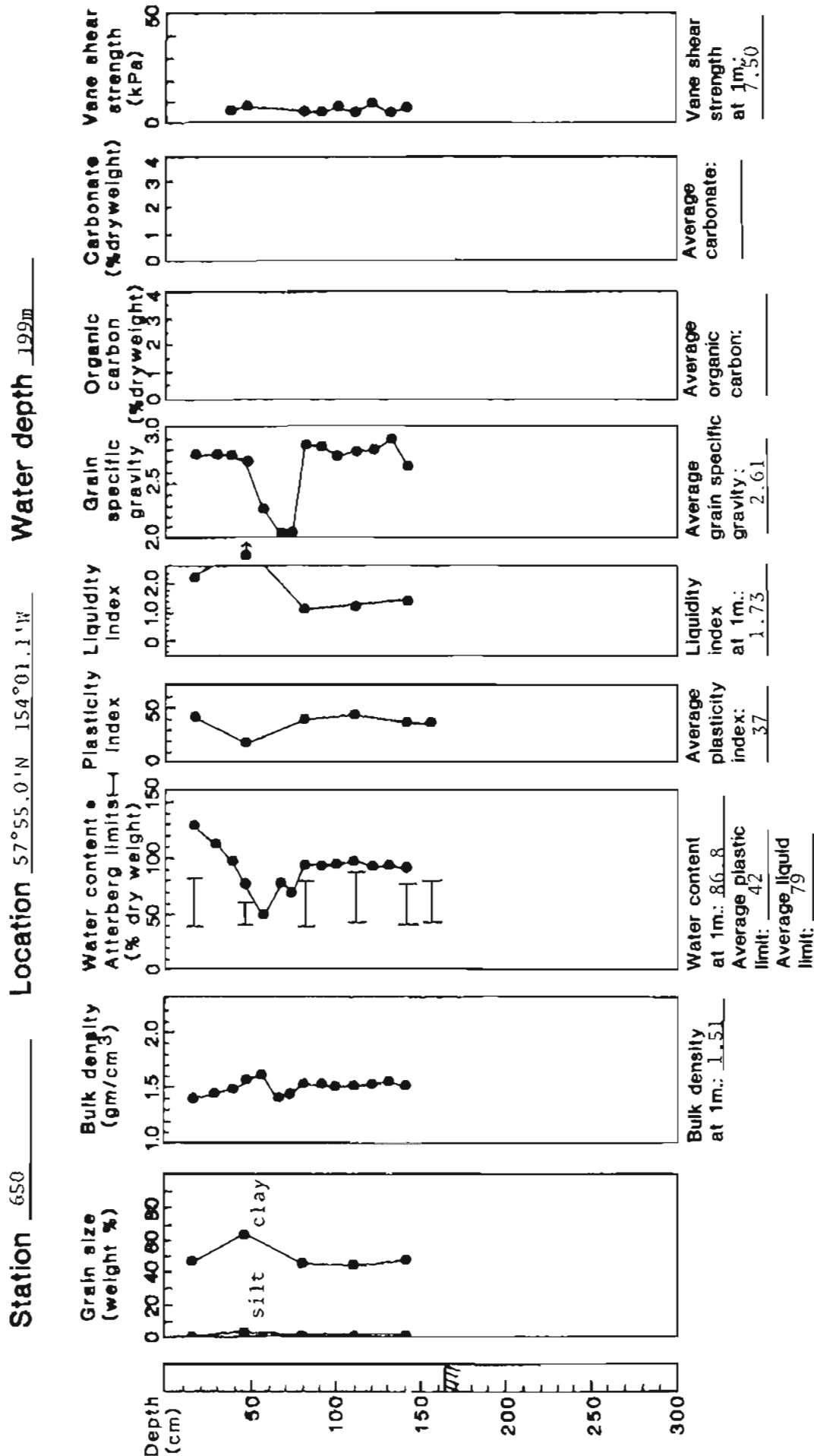


Station 647Location 57°59.8'N 154°10.7'WWater depth 220m

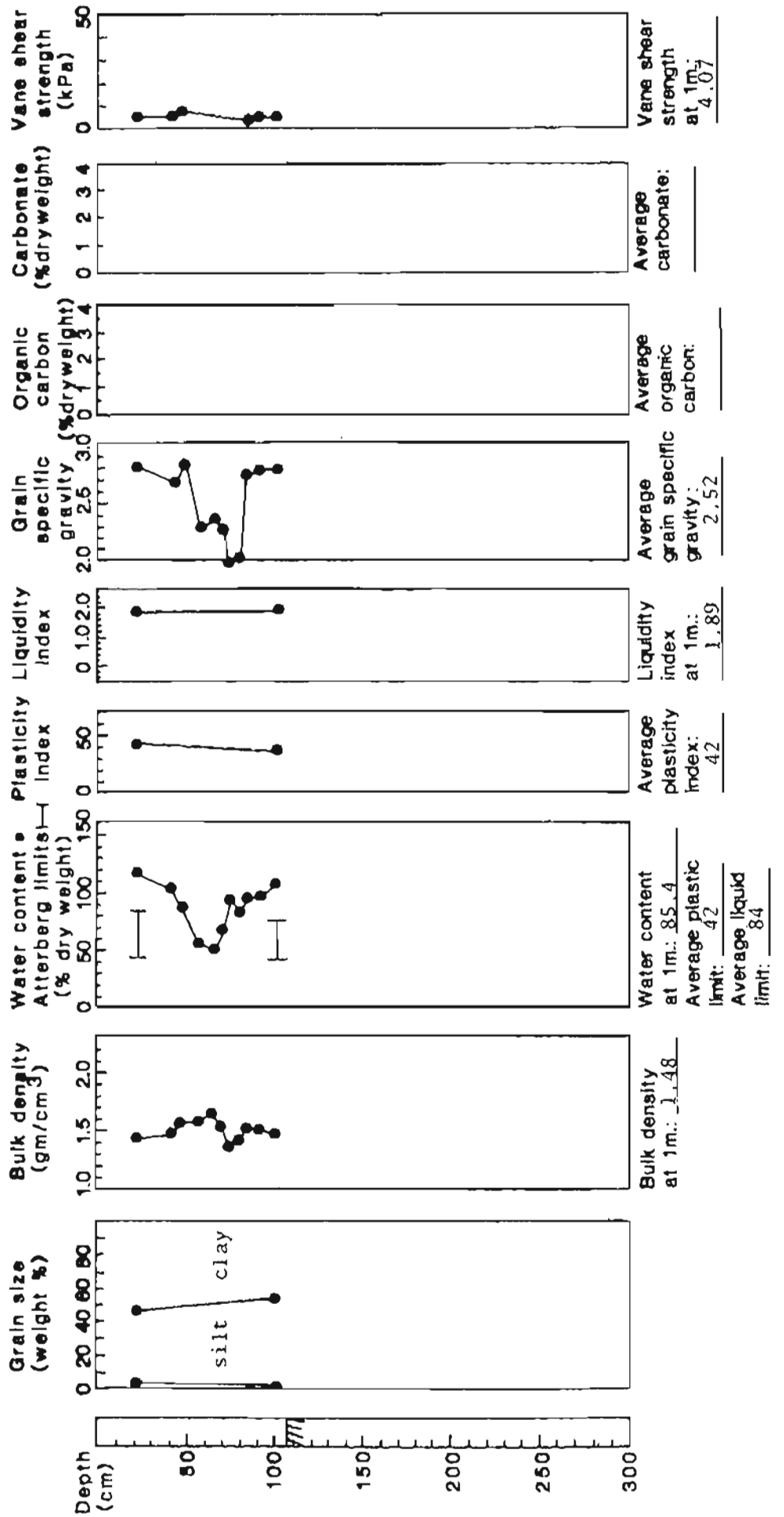
601







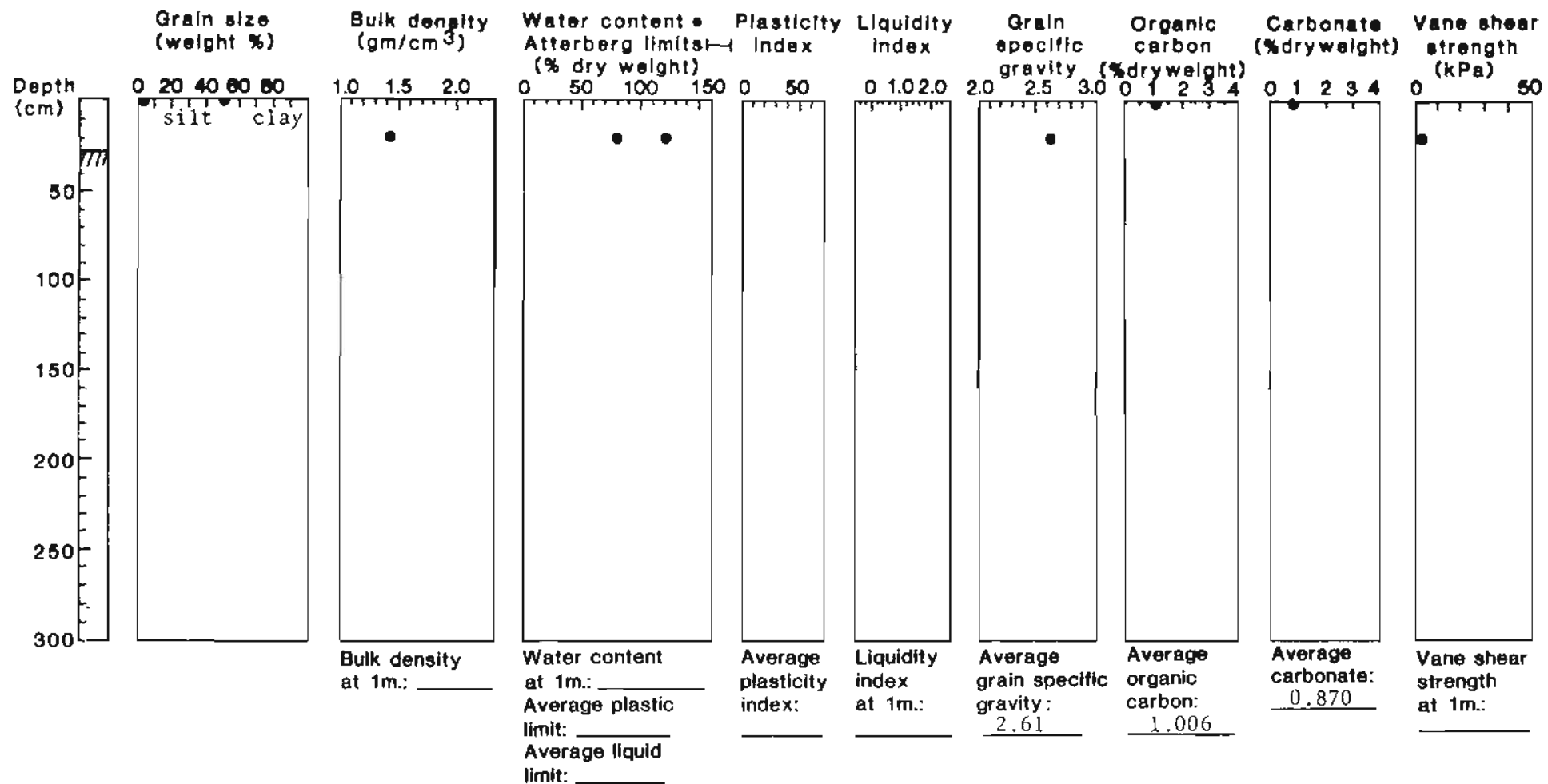
Station 651 Location 58°00.1'N 153°52.6'W Water depth 194m

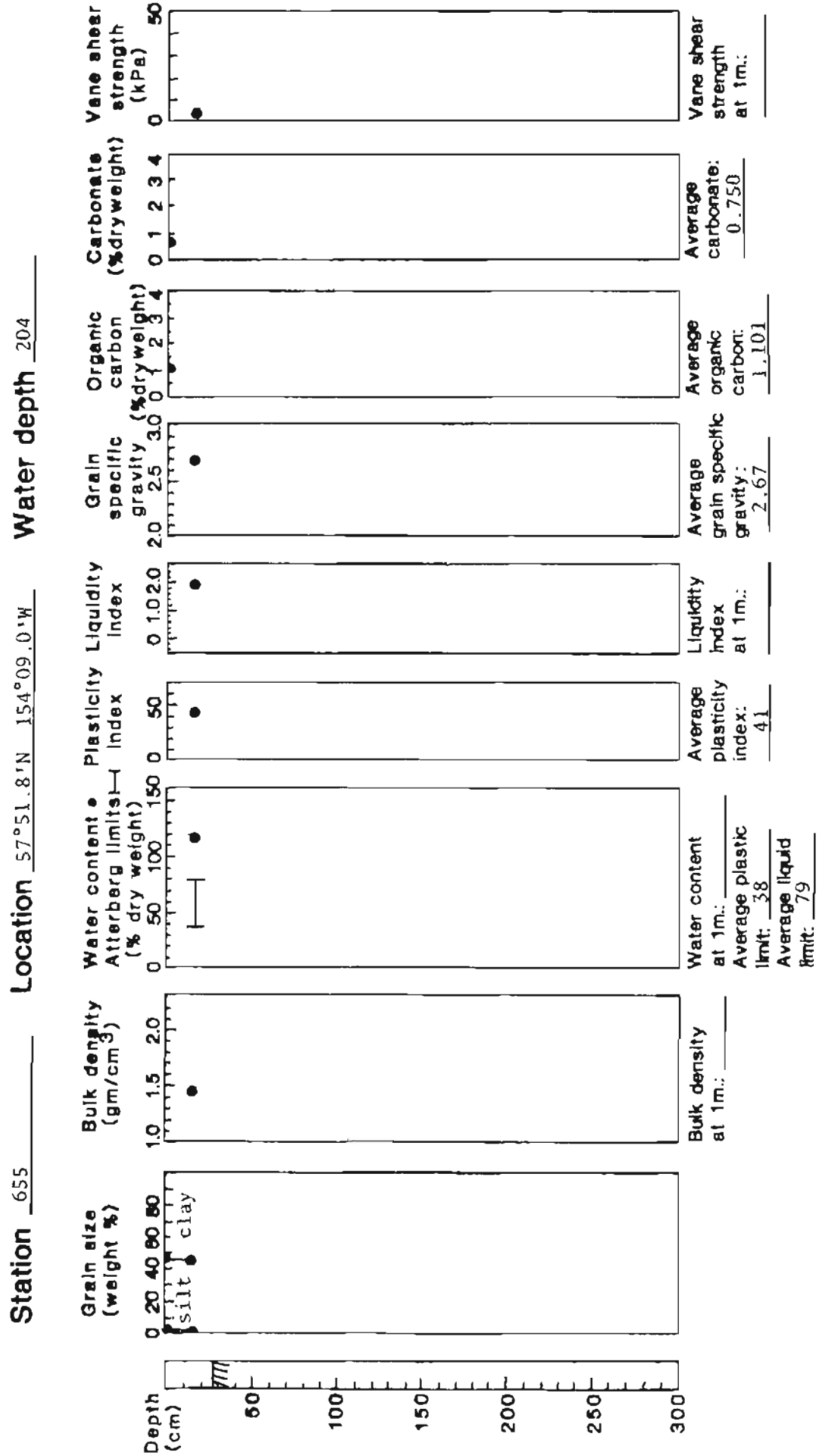


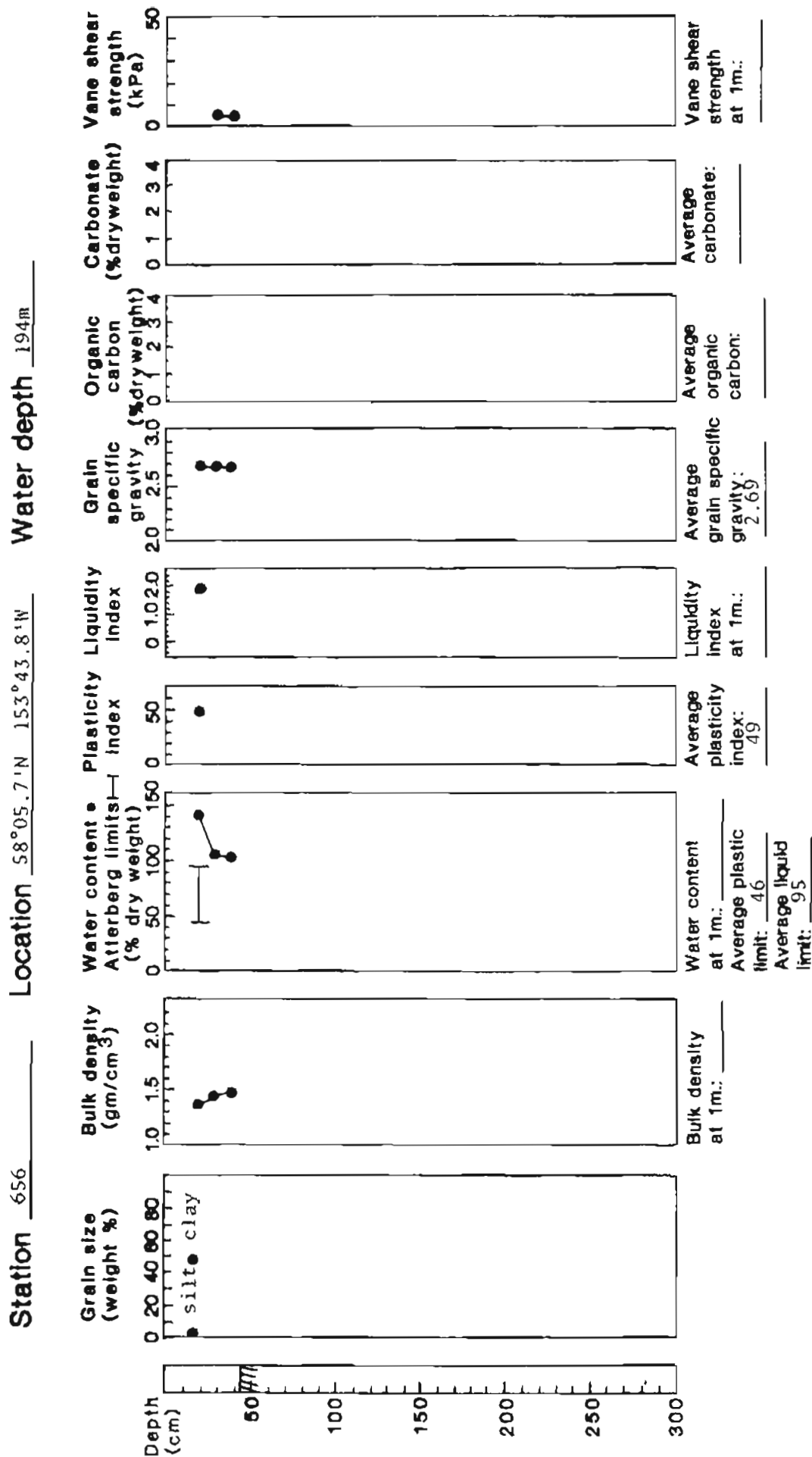
Station 654

Location 57°07.4'N 154°09.0'W

Water depth 232m



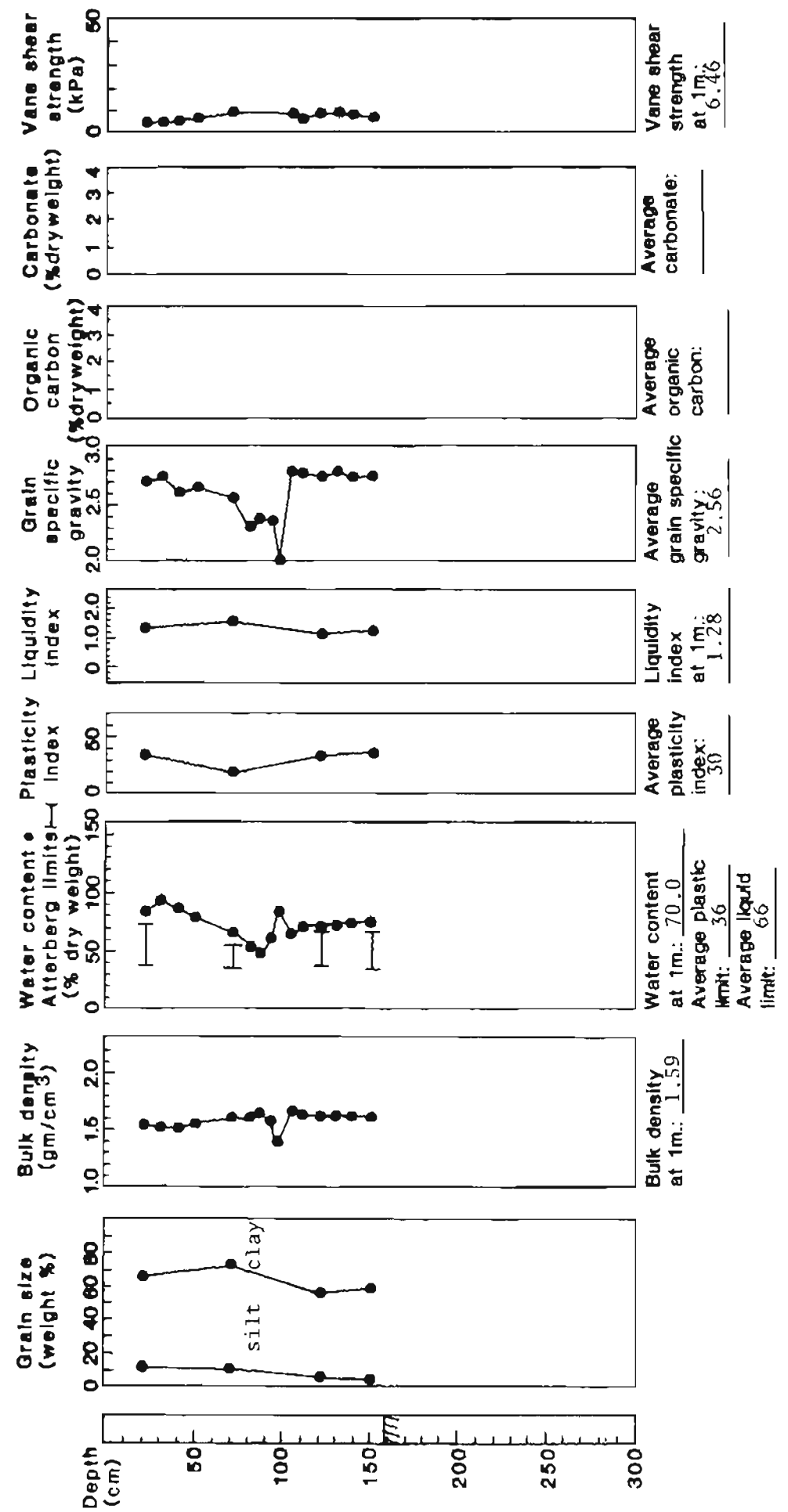




Station 657

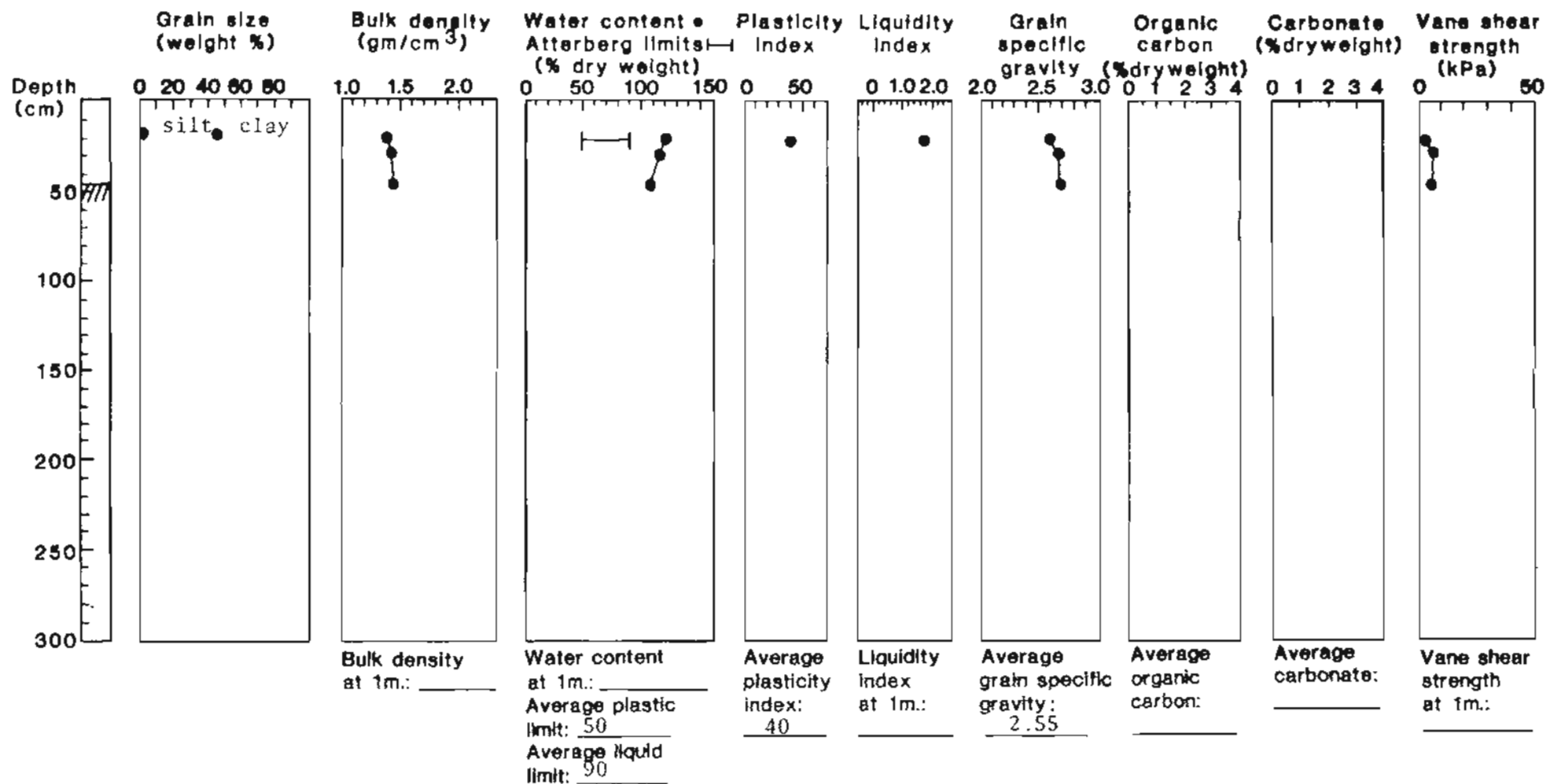
Location 58°12.9'N 153°57.4'W

Water depth 232m



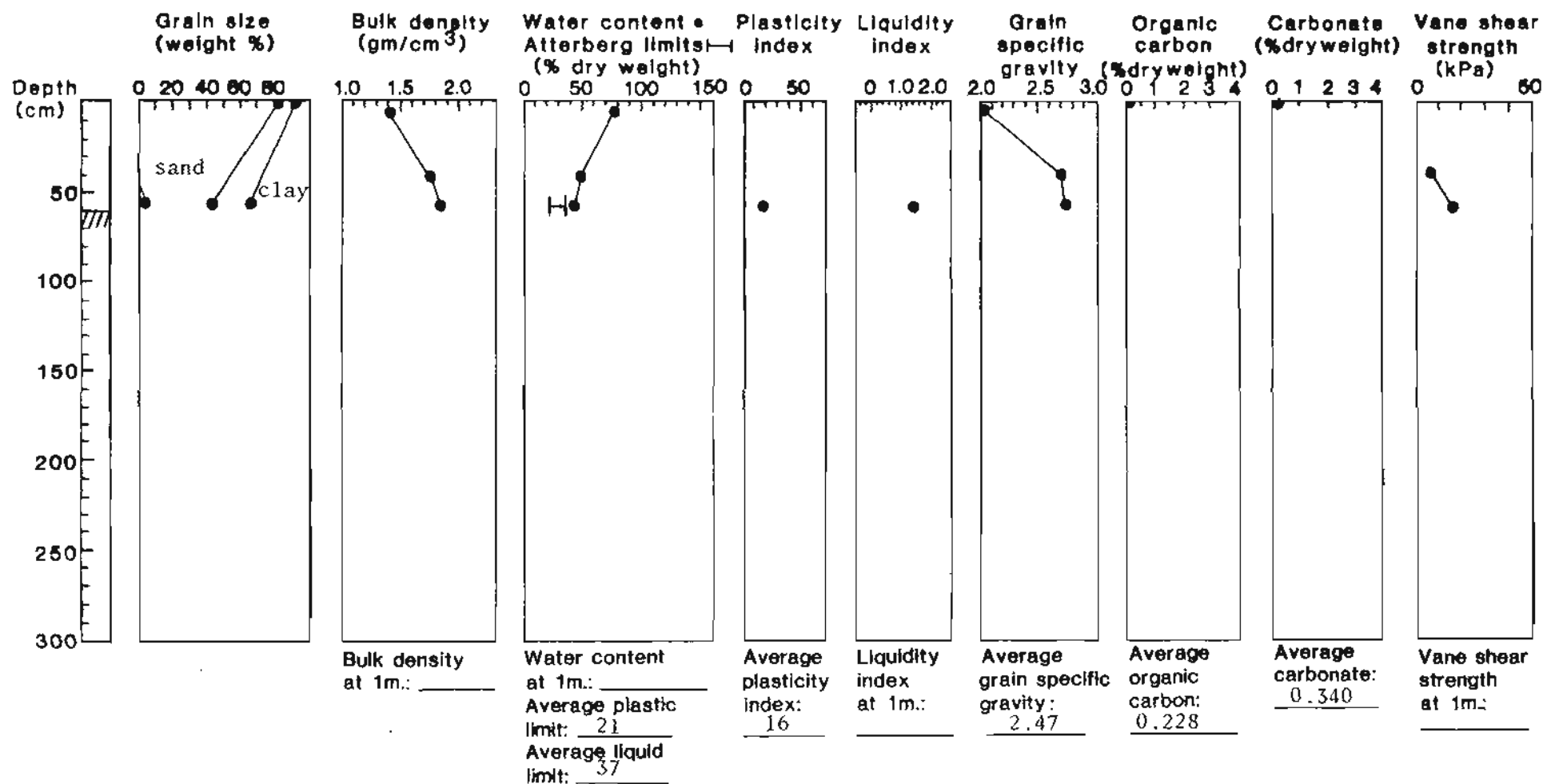
Station 658Location 58°10.6'N 153°32.6'WWater depth 190m

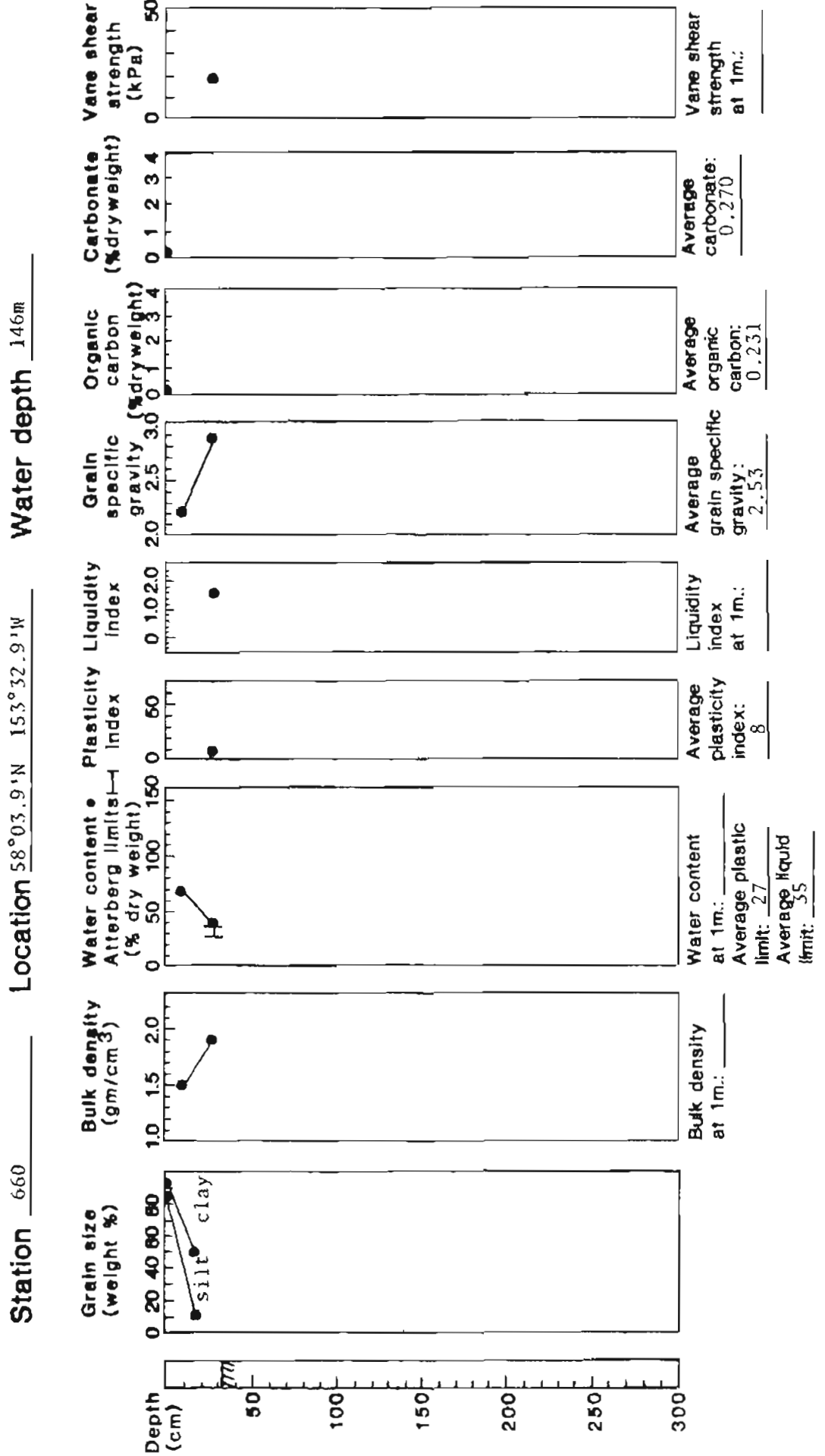
117

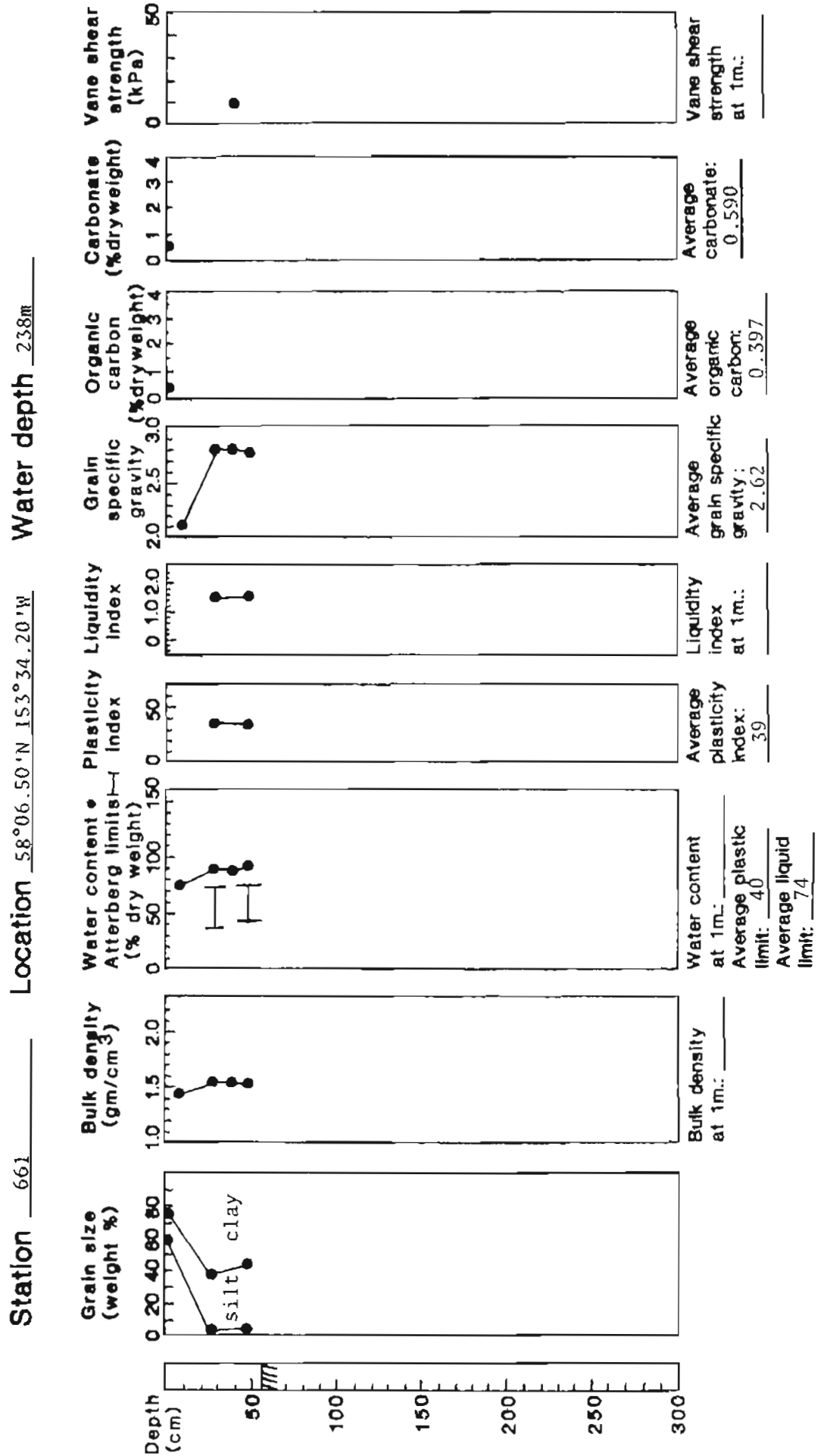


Station 659Location 58°01.8'N 153°28.5'WWater depth 112m

118







176m

Station 664

Location 58°55.00N 153°36.90W

Water depth 174m

