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GEOLOGICAL SURVEY

Geotechnical Framework Study of the Kodiak Shelf, Alaska

by

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INTRODUCTION

Environmental geologic studies have been conducted on the Kodiak Shelf, Gulf of Alaska, to evaluate the potential impact and constraints that geology can impose on offshore industrial operations (Fig. 1; Hampton 1982a,b). As part of these studies, cores were taken from the diverse suite of compositionally distinct and areally restricted sedimentary deposits on the shelf and upper continental slope. Physical property measurements were made on samples from the cores, and geotechnical methods were employed in order to broadly characterize the behavior of the sedimentary deposits under conditions of static and dynamic loading. The data and conclusions are meant as a guide for detailed and site-specific studies that accompany resource regulation and development activities.

GEOLOGIC SETTING

The Kodiak Shelf consists of a series of flat banks, generally less than 100 m deep, separated by transversely trending troughs (Fig. 1). Most of the seafloor is flat to gently inclined; steep slopes are uncommon (Fig. 2).

The banks are largely covered by coarse gravelly debris, typically less than 100 m thick, although there are broad areas of bedrock outcrop at the seafloor (Fig. 3). Local thin deposits rich in shells or volcanic ash are also present. The troughs contain relatively fine-grained deposits, but sediment composition is different in each. Stevenson Trough contains terrigenous sand deposits that are molded into large sand waves, as well as deposits of terrigenous mud and volcanic ash. The floor of Chiniak Trough is covered with sediment composed predominantly of volcanic ash, with local outcrops of a terrigenous mud deposit that evidently underlies the surficial ash-rich material. Kiliuda Trough is blanketed almost entirely by a mixture of fine-grained volcanic ash, diatom tests, and minor terrigenous material. Samples from Sitkinak Trough contain terrigenous gravelly and sandy mud (Hampton, 1981).

Most of the unconsolidated sediment was originally emplaced by glacial processes. Glaciers are believed to have covered the shelf during parts of Pleistocene time, depositing a cover of till and outwash (Karlstrom, 1964; Thrasher, 1979). During the Holocene, no major input of terrigenous sediment has been made, but volcanic eruptions have spread ash across the seafloor, and biologic activity has produced carbonate and siliceous shell material (Hampton, 1981, 1982a, b). Marine currents have reworked the surficial sediment and created a segregation of sediment types. Fine-grained sediment particles have been winnowed from the banks and redeposited in the troughs. The composition of deposits in the individual troughs depends on the locally available material, with sand-size volcanic ash from the 1912 Katmai eruption being abundant near Chiniak Trough and finer ash and diatoms near Kiliuda Trough. Stevenson and Sitkinak Troughs have had essentially pure terrigenous material accessible to them.

Much reworking of shelf sediment probably was accomplished by waves during the Holocene marine transgression. The present-day shelf environment does not include strong geostrophic or tidal currents (Muench and Schumacher, 1980), and sediment reworking probably occurs only occasionally when large storm waves traverse the shelf.

Convergence of the North America and Pacific lithospheric plates a few kilometers seaward of the Kodiak Shelf causes strong compressional forces that have warped and faulted the seafloor. Strong earthquakes are frequent (Pulpan and Kienle, 1979). They range in excess of magnitude 8 and cause strong ground accelerations.

METHODS

Geotechnical measurements were made on sediment cores obtained on four cruises from 1977 to 1980. Cores could only be recovered from four physiographic areas: Chiniak Trough, Kiliuda Trough, Sitkinak Trough, and the upper continental slope (Fig. 4; Table 1). Sedimentary deposits in other areas are too stiff or coarse-grained to be collected with our coring devices.

Both gravity cores and vibracores were collected in 8.5-cm diameter plastic liners. Most cores were obtained principally for geological purposes. Upon retrieval they were cut into 1.5-m-long sections and then split lengthwise into replicate halves. Geotechnical index properties were measured on these core halves. On some, vane shear tests were made at regular intervals down-core to give measures of undrained shear strength. Subsamples were taken for determination of water content, bulk sediment density, grain specific gravity, and plasticity in the shore-based laboratory.

Several cores were taken expressly for geotechnical testing. Onboard ship, these cores were cut into 1- or 1.5-m lengths, and the ends were capped. Then each section was wrapped in cheesecloth and covered with microcrystalline wax in order to prevent moisture loss, and then stored upright in a refrigerator to retard decay of organic matter. These cores were later subjected to a suite of geotechnical tests in laboratories at the USGS and at a commercial testing company.

One-dimensional consolidation tests were run on subsamples from geotechnical cores to determine sub-failure deformational properties. Tests were run on an oedometer in a stress-controlled mode (Lambe, 1951). The consolidation tests measure change in volume with change in applied load. The results are typically expressed in plots of 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 (C_c) is the slope of the straight-line, virgin compression portion of the e-log p' curve and indicates the amount of compression produced by a particular increase in load. The maximum past pressure σ'_{vm} is the greatest effective overburden stress that the sediment has ever been exposed and is determined by a simple graphical construction (Casagrande, 1936). The ratio of σ'_{vm} to the calculated effective overburden stress at the time of sampling σ'_{vo} is the overconsolidation ratio (OCR), which can be, for example, a measure of unloading that the sediment may have experienced by erosion. A third parameter, the coefficient of consolidation (c_v), is determined for each load increment of the one-dimensional consolidation test and defines 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 on some cores, 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 and waves.

Early triaxial tests were 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 the one-dimensional 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 samples by rebounding 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'_{vm}). A premise of the NSP method is that the ratio s_u/σ'_v is constant for a particular sediment at a particular value of OCR. Moreover, a relation exists between s_u/σ'_v and OCR that allows prediction of sediment strength at confining stresses that exceed those at the level of sampling (Mayne, 1980).

RESULTS

Lithology of sediment cores is fairly uniform in each physiographic area, with a few exceptions, but major differences exist amongst the various areas (Table 1). Inspection of the geotechnical data gives consonant results; physical properties are by-and-large similar within areas, except where atypical lithology is found, and dissimilar from area to area (Figs. 5-11; Tables 1-5). Therefore, geotechnical characterization is possible for each area. That is, representative values of physical properties can be deduced, and general statements can be made about soil deformation in one area relative to others.

Index properties: Figure 5 presents index properties for sediment cores. Individual values are shown graphically at the depths they were measured. Summary values are also given, as averages for properties that are depth-independent and as linear-regression estimates at 1 m from the top of the core for those properties that vary with depth (Fig. 5, Table 2).

Water content is the weight of water relative to the weight of solids, expressed as a percent and corrected for salt content. Values in excess of 100% are possible; they indicate a greater weight of water than sediment. Water content typically decreases with depth in a uniform sedimentary deposit. This is the case for most sediment cores collected from the Kodiak Shelf, although some increases with depth occur.

Water content is highest for cores from Kiliuda Trough, followed by slightly lower values in Chiniak Trough, then by substantially lower values in Sitkinak Trough and on the upper continental slope. Water in the terrigenous sediment of the latter two areas is interparticulate; that is, it exists in the interstices between grains. But, the ash grains and diatom tests in Chiniak and Kiliuda troughs accommodate significant amounts of intraparticle water within voids and recesses in grains. The coarse ash particles abundant in Chiniak Trough include pumice shards with thin, pipe-shaped vesicles (Hampton and others, 1978). Most silt- and clay-size ash particles are flat to curved plates. Diatom tests are perforate and spherical- to basket-shaped. These nonterrigenous grains, because of their irregular morphology, would be expected to pack loosely, in addition to accommodating intraparticle water. Therefore, the high water contents in Chiniak and Kiliuda Troughs are related principally to sediment composition.

Note that anomalously low values of water content were measured in one core each from Chiniak Trough (station 582) and Kiliuda Trough (station 351). Cores from both stations are of terrigenous composition, and their water content is similar to the other terrigenous cores.

Values of other index properties also can be explained in terms of composition. Grain specific gravity is low in samples from Chiniak and Kiliuda Troughs because the amorphous silica that constitutes the volcanic ash is of low density (~ 2.4 gm/cm^3) as is the hydrous silica (~ 2.1 gm/cm^3) that constitutes the diatom tests. Isolated internal vesicles within the coarse pumice shards in Chiniak Trough might explain the exceptionally low values of grain specific gravity there. The values of grain specific gravity in Sitkinak Trough and on the upper continental slope are in accord with the density of common terrigenous minerals (2.6 - 2.8 gm/cm^3).

Bulk density is calculated from porosity (water content) and grain specific gravity. In normal terrigenous marine sediment, differences in bulk density mainly reflect differences in water content, because the range of grain specific gravity is relatively small. But, the exceptionally low bulk density values in Chiniak and Kiliuda Troughs reflect not only high water content but also the unusually low values of grain specific gravity.

Atterberg limits are used in this study as a measure of the plasticity of remolded sediment. The plastic limit (PL) is the water content below which the sediment deforms as a semi-solid when remolded, whereas the liquid limit is the water content above which the sediment behaves as a liquid. The range of water content between these limits, where the sediment deforms plastically, is defined as the plasticity index (PI). The liquidity index (LI) refers to the relative position of the natural water content (w) to the plastic limit and the liquid limit. A negative value ($w < PL$) implies that the remolded sediment will act as a semi-solid, a value between 0 and 1 ($PL < w < LL$) indicates plastic behavior, and a value greater than 1 ($w > LL$) indicates liquid behavior.

Ash-rich sediment from Chiniak Trough is nonplastic; i.e., it is noncohesive and does not exhibit plastic behavior at any water content. Therefore, Atterberg limits cannot be determined for this material. The sediment in Kiliuda Trough has high values of plastic and liquid limits relative to terrigenous cores. This may be somewhat misleading, because any intraparticle water that is present probably is passive with respect to plastic behavior but is measured in plastic- and liquid-limit tests. However, the high values of plasticity index, which do not reflect intraparticle water, show that this sediment is generally more plastic than the terrigenous sediment. The high plasticity indices might be a reflection of clay mineralogy. Mitchell (1976, p. 173) presents data that indicate a higher liquid limit and plasticity index for illite than for chlorite. Hein and others (1977, 1979, and unpublished data) report that sediment from Chiniak and Kiliuda Troughs contains somewhat larger proportions of illite and less chlorite and kaolinite than sediment from Sitkinak Trough and the upper continental slope. Smectite abundance is similar in all areas. However, because the clay content in Kiliuda Trough sediment is minor and the variation in clay mineral populations is small, this mineralogy factor may not account for all the differences. Variation in organic matter, which was measured in a few seafloor sediment samples and is slightly greater than 1% in Kiliuda Trough and on the order of a few tenths of a percent in Sitkinak Trough and on the continental slope, is another possible cause.

A plot of liquid limit versus plasticity index, called a plasticity chart, can be used to categorize fine-grained sediment types according to the Unified Soil Classification System (Casagrande, 1948). Figure 6 shows that the terrigenous sediment from the upper continental slope covers a range of sediment types designated as CL to CH (low to high plasticity clay to silty or sandy clay). The two samples from Sitkinak Trough and the one terrigenous sample from Chiniak Trough plot similarly to some upper continental slope sediment, classified as CL and borderline ML (silt, very fine sand, or sandy mud). The Kiliuda Trough data plot in an entirely separate region of the chart, as MH (diatomaceous silt and volcanic ash). Comparison is favorable between the visual sediment descriptions in Table 1 and the classification according to physical properties in Figure 6. Casagrande notes that samples from the same sedimentary deposit typically fall in a linear zone parallel to the A-line (an empirical boundary between sediment types). The upper continental slope data agree well with this concept, whereas the Kiliuda Trough data are rather dispersed.

<u>Consolidation properties</u>: Table 3 is a listing of the consolidation properties as determined from laboratory tests. Most sediment from Chiniak and Kiliuda Troughs shows high maximum past pressure (σ'_{vm}) relative to the insitu overburden stress (σ'_{vo}), with consequent high values of OCR. The implication drawn from traditional theory is that substantial unloading of the sediment has occurred, by erosion perhaps, but there is no supporting geological evidence. Instead, the high OCR values might reflect initial cementation or grain interlocking. Hence, the term "false overconsolidation" might be appropriate. Terrigenous cores show lower OCR, and in fact some from

the upper continental slope have values less than 1.0, which indicates underconsolidation, a condition whereby the sediment has not compacted to an equilibrium state with the overburden load and some excess pore water pressure exists. Underconsolidation usually results from high sedimentation rates and low sediment permeability and can imply low sediment strength.

Compression index (C_c) spans a wide range of values ($0.06<C_c<1.06$), beyond the limits computed by Richards (1962) for several marine sediments ($0.20 < C_c < 0.87$). The ash-rich sandy core (station 433) from Chiniak Trough appears to be highly incompressible (low C_c), as are many of the terrigenous cores (Chiniak Trough and upper continental slope). In contrast, the fine-grained ash and diatom-rich sediment in Kiliuda Trough and the terrigenous sediment from Sitkinak Trough are moderately to highly compressible.

Skempton (1944) demonstrated a relation between compression index and liquid limit:

$$C_c = 0.009 \text{ (LL-10)}.$$

A plot of the Kodiak Shelf data shows a general agreement with this relation, but with significant scatter (Fig. 7).

The e-log p' plots for consolidation tests of sediment from station 433 in Chiniak Trough continue to curve downward at high load levels, whereas common sediment behavior yields a straight-line segment (termed the virgin compression curve) for loads greater than σ'_{vm} (Fig. 8). A likely explanation for this curvature, which indicates greater than normal settlement under high loads, is crushing of fragile, void-rich ash grains. Consolidation of most sediment types involves rearrangement of grains and expulsion of pore water, with minor grain crushing.

Coefficient of consolidation (c_v) is variable both within and between cores, but is generally high compared to reported values for other marine sediment (Richards, 1962). High c_v implies that the sediment is permeable enough to permit rapid pore water escape and fast consolidation. A value of c_v is calculated in a consolidation test at each load increment from plots of deformation versus time. The sediment at station 433 consolidated so fast immediately after loads were applied that the proper construction for calculating c_v could not be made. The obvious implication is high c_v and consequent rapid consolidation.

Static strength properties: Sediment properties derived from static triaxial strength tests are listed in Table 4. 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 terrigenous sediment samples from the upper continental slope, Sitkinak Trough, and station 582 in Chiniak Trough have values of ϕ' mostly in the 30° - 40° range, common values for marine sediment. The ash- and diatom-rich sediment in Kiliuda Trough has higher values of ϕ', 40° - 50°, whereas the ash-rich core from station 433 in Chiniak Trough has values to greater than 60°. The ash-rich sediment apparently is stronger under drained static loading conditions than the terrigenous sediment at equal confining stress.

Lambe and Whitman (1969, p. 307) present a relation between ϕ' and liquid limit for normally consolidated soil. The comparative plot of the Kodiak Shelf data in Fig. 9 shows that the terrigenous samples fall within the range of variability of Lambe and Whitman's data, whereas the ash- and diatom-rich sediment from Kiliuda Trough does not. The drained strength behavior of this sediment appears to be atypical. It is relatively strong for sediment with such high plasticity.

The values of s_u/σ_c' are highly variable and require some judgement in order to characterize the sediment types. The tests run at low levels of σ_c' seem to be the most erratic; these are the tests most likely to incorporate disturbance effects associated with coring. Other tests, except those at station 433, show fairly consistent values of S_u/σ_c' between 0.4 and 1.0 for OCR = 1, and higher values for OCR = 6. At station 433, S_u/σ_c' has significantly higher values of 3.8 (OCR = 1) and 16.1 (OCR = 5.8). Relatively high strength under conditions of undrained loading (because of low pore pressure response) is indicated for the ash-rich sandy material at this station. Somewhat surprisingly, the finer ash- and diatom-rich sediment in Kiliuda Trough exhibits undrained loading behavior similar to the terrigenous sediment.

Figure 10 is a plot of the static triaxial data according to the NSP approach. The slope Λ of the line for each sample is an indication of the change in strength with OCR. The ash-rich cores from both Chiniak and Kiliuda Troughs have similar values of Λ, 0.80-0.84. The terrigenous sediment from station 445 in Sitkinak Trough has a value of $\Lambda = 0.68$, which is near the average of $\Lambda = 0.64$ for numerous triaxial data compiled by Mayne (1980). An implication of the data in Figure 10 is that the ash-rich sediment would retain a larger portion of its strength after unloading compared to the terrigenous sediment.

S_u/σ_v' values were calculated from the vane shear data (Table 2). The magnitude of strength increase with effective overburden pressure is greater for the ash-rich sediment from Kiliuda Trough than for the terrigenous sediment from Sitkinak Trough. This may be related to higher OCR and Λ for the ash-rich sediment compared to the terrigenous sediment (Table 3, Fig. 10) and does not necessarily conflict with the S_u/σ_v' values derived from the triaxial data (Table 4).

Dynamic strength properties: The data from cyclic triaxial strength tests are given in Table 5. The quantity τ_{cyc}/S_u is the cyclic stress level: the average value of shear stress (τ_{cyc}) applied sinusoidally at 0.1 Hz 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 not a discrete event, and was arbitrarily defined at 20% strain.

Samples typically fail in fewer cycles at progressively higher stress levels. Figure 11 shows the number of cycles to failure versus stress level for Kodiak Shelf samples. All except the sandy ash deposit from Chiniak

Trough (station 433) fall in a range that shows low to moderate dynamic strength degredation. For example, after 10 cycles of loading (as might be imparted by an earthquake), these sediments will not fail unless the applied stress level is at least from 70% to nearly 100% of their static strength. Tests on terrigenous sediment from other geographic areas have shown similar results (Lee and others, 1981; Anderson and others, 1980).

In contrast, the ash-rich sediment from Chiniak Trough is highly suseptible to failure under cyclic loading. Its dynamic strength at 10 cycles is only about 12% of its static strength. Recall that the static undrained strength of this material is relatively high, but under repeated loading it becomes highly suseptible to liquefaction-type failure.

DISCUSSION

Three sediment types have been tested in this study: 1) muddy terrigenous sediment collected throughout Sitkinak Trough, along the upper continental slope, and at one station each in Chiniak and Kiliuda Troughs, 2) muddy ash- and diatom-rich sediment with minor amount of terrigenous minerals from Kiliuda Trough, and 3) ash-rich sandy mud with a minor amount of terrigenous minerals from Chiniak Trough. Each has a distinctive set of physical properties, and some differences in deformational behavior can be expected.

The terrigenous sediment cores have physical properties that by and large are within normal ranges measured on terrigenous sediment elsewhere, except that several samples exhibit low compressibility. This implies relatively small settlement when subjected to sub-failure loads. The reason for this behavior is not evident.

Steep seafloor slopes exist in Sitkinak Trough and along the upper continental slope, so, given the geotechnical properties and the tectonic activity, slumping of the terrigenous sediment is possible. Large slumps have in fact been observed in seismic-reflection profiles along the upper continental slope, and a geotechnical analysis by Hampton and others (1978) indicates that earthquakes and removal of support by faulting are the likely triggering mechanisms. Seismic profiles in Sitkinak Trough have not revealed large slumps, but the existence of steep slopes warrants concern. Static stability can be crudely evaluated by performing a simple factor of safety calculation:

$F=(S_u/\sigma_v^{'}) / (\sin\gamma \cdot \cos\gamma)$ where F is the factor of safety and γ is the slope angle of the seafloor. F= 1.0 indicates incipient instability, whereas higher values indicate stability.

The steepest slopes in Sitkinak Trough are on the order of 50% (27°) (Fig. 2). From Table 4, a minimum value of $S_u/\sigma_v^{'}$ is about 0.4, which will give F=1 at a slope of 18.4°. This implies that steep slopes are statically unstable under conditions of undrained loading if underlain by the weakest sediment. Under conditions of drained loading, the critical slope angle is equal to ϕ', which is 26° - 37° and greater than slope angles likely to be encountered in the trough.

The effects of earthquake loading can be evaluated for a simplified two-dimensional model by the method developed by Lee and others (1981):

$$k=(\gamma^{'}/\gamma)\ (A_C A_D S_u/\sigma_v^{'}-\sin\gamma \cdot \cos\gamma)/\cos^2\gamma$$

where k is the pseudo-static horizontal acceleration (expressed as a percent of gravity) required to cause failure, A_C is a correction factor for the strength difference between isotropic (laboratory) versus anisotropic (field) confining pressure, A_D is a correction factor for cyclic strength degredation, and $\gamma'/_\gamma$ is the ratio of buoyant total to bulk densities.

The core from station 445 has enough data for analysis. An anisotropically consolidated triaxial test was run at a horizontal to vertical stress ratio of 2, which models the field confining-stress conditions. The ratio of static strength (51.8 kPa) determined in this test to the static strength (58.4 kPa) determined for a sample consolidated isotropically to the same stress level, gives a value of 0.89 for A_C. From Figure 11, the cyclic strength degredation is seen to be slight; it is about 0.98 of the static strength at 10 cycles (a reasonable number of load applications by an earthquake). Using the bulk density at 1-m depth from Table 2,.
$\gamma'/_\gamma$= 0.45. Determination of k for several values of seafloor slope are given in

Table 6. Using the data from Seed and others (1975), the distances ($d_{6.5}$) from an earthquake of magnitude 6.5 that would experience accelerations equal to k can be estimated (Table 6).

The above analysis of dynamic loading involves many simplifications and works best where k values can be calculated for an area of known instability and compared to k values from a nearby area of potential instability (Lee and others, 1981; Winters and Lee, 1982). Moreover, a state of overconsolidation was measured in oedometer tests at station 445 (Table 3). If this condition continues with depth, greater stability than calculated above would exist. On the other hand, the cyclic strength degredation is exceedingly small, and values of 0.60 to 0.80 are more typical for terrigenous sediment. Stability would be reduced as a consequence of greater cyclic degredation.

Both static and dynamic analysis indicate potential instability in the steepest areas of Sitkinak Trough. The fact that no large sediment slides have been observed points to the need for further study.

The fine-grained sediment in Kiliuda Trough, which is composed of volcanic ash, siliceous diatom tests, and a minor quantity of terrigenous minerals, plots with sediment of similar composition on a plasticity chart (Fig. 6; Casagrande, 1948). It has high water content and, because of the low grain specific gravity, a low bulk sediment density. This indicates a low increase of overburden stress with depth and a consequent low increase of dependent properties such as consolidation state and shear strength. However, values of compression index (C_c) are the highest measured on the Kodiak Shelf (Table 3), which implies relatively large amounts of settlement under a given load.

The sediment is highly plastic (Fig. 5) and, compared to other sediment of similarly high plasticity, it is relatively strong under conditions of drained loading. Its undrained static loading behavior is similar to the terrigenous samples that were tested (Table 4). In dynamic, undrained triaxial tests, the Kiliuda Trough sediment has somewhat more strength degredation at low numbers of cycles than terrigenous samples, but is by no means unusually suseptible to repeated loading.

The sandy, ash-rich sediment from Chiniak Trough (station 433) is different in most respects from the other sediment types. Clay content is low, so the sediment classifies as noncohesive according to plasticity tests. Its water content is lower than that of the sediment from Kiliuda Trough, but due to low grain specific gravity, the bulk density is comparable (Table 2). In contrast to the samples from Kiliuda Trough, station 433 material is highly incompressible, similar to the underlying terrigenous material sampled at station 582 (Table 3). But, the downward concavity of the virgin compression curve (Fig. 8) suggests that excessive settlement (perhaps due to grain crushing) occurs under high loads. Rapid consolidation also is indicated by oedometer tests.

High static strength was measured in triaxial tests on samples from station 433 for both drained and undrained conditions (Table 4). However, dynamic loading causes severe strength degredation, to 12% of the static undrained strength at 10 cycles (Fig. 11). Earthquake-induced sediment slides are not likely, because the seafloor is generally horizontal where the ash-rich sediment occurs. However, loss of bearing capacity due to liquefaction is possible, which could cause sinking and failure of pipelines.

Ash-rich material covers most of the floor of Chiniak Trough (Table 1; Hampton, 1981), but the deposit pinches out near the trough margins and may only be several meters thick. Seismic-reflection profiles show that the terrigenous core at station 582 is near the lateral edge of the trough sediment fill and probably represents a sedimentary deposit that underlies the surficial ash deposit and extends a few tens of meters to deeper, presumably strong and stable glacial material. The ash was erupted in 1912 from Mt. Katmai on the Alaska peninsula (Hampton and others, 1979), and the fine-grained terrigenous section as sampled at station 582 may represent the normal Holocene sedimentary environment in Chiniak Trough. Buried ash deposits from earlier volcanic eruptions may be present.

The ash-rich sediment from both Chiniak and Kiliuda Troughs has similar values of the normalized strength parameter Λ (0.80 to 0.84) (Fig. 10). The one terrigenous sample for which determination could be made has a more normal value of $\Lambda = 0.68$. Overconsolidated ash-rich sediment would strengthen more than the terrigenous sediment would. Oedometer tests indicate various levels of overconsolidation for ash-rich sediment, but there is no geologic evidence that unloading has occurred. Perhaps the overconsolidation is only present at shallow depths, or it may reflect a physical phenomenon other than unloading.

It is evident from the geotechnical framework study of Kodiak Shelf that a variety of fine-grained sediment types with different physical properties exists. The deposits cover a minor area of the shelf when compared to the extent of coarse-grained glacial deposits and sedimentary bedrock that probably have favorable geotechnical properties. But, where the fine-grained sediment is encountered, it can present special engineering concern.

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Table 1. Locations of sampling stations and descriptions of sediment types.

Physiographic area	Station number	North latitude	West longitude	Sediment type
Chiniak Trough	329	57° 38.95'	151° 58.03'	sandy mud with ash and terrigenous minerals
	432	57° 25.50'	151° 23.43'	sandy mud with ash and terrigenous minerals
	434	57° 26.71'	151° 25.26'	muddy sand with ash and terrigenous minerals
	582	57° 29.7'	151° 38.6'	sandy mud with terrigenous minerals; ash-rich only at top of core.
Kiliuda Trough	343	56° 39.37'	153° 04.72'	mud with ash and terrigenous minerals
	344	56° 39.47'	153° 05.63'	mud with terrigenous minerals and ash
	347	56° 36.76'	153° 17.92'	mud with terrigenous minerals and ash
	348	56° 37.66'	153° 18.89'	mud with terrigenous minerals and ash
	349	56° 38.24'	153° 19.80'	mud with ash and terrigenous minerals
	351	56° 46.86'	153° 11.02'	gravelly sandy mud with terrigenous minerals and mud
	439	56° 08.13'	154° 17.33'	mud with ash and terrigenous minerals
	440	56° 39.15'	153° 06.36'	mud with ash and terrigenous minerals
	441	56° 39.50'	153° 04.62'	mud with ash and terrigenous minerals
	578	56° 39.5'	153° 05.2'	mud with ash and terrigenous minerals

Table 1 (continued)

Physiographic area	Station number	North latitude	West longitude	Sediment type
Kiliuda Trough (continued)	579	56° 54.9'	152° 32.6'	mud with terrigenous minerals and ash
Sitkinak Trough	355	56° 08.53'	153° 29.41'	gravelly sandy mud with terrigenous minerals
	356	56° 05.55'	153° 31.28'	gravelly muddy sand with terrigenous minerals
	357	56° 07.56'	153° 38.46'	muddy sand with terrigenous minerals
	445	56° 11.17'	153° 17.28'	sandy mud with terrigenous minerals
	455	56° 12.44'	152° 58.36'	mud with terrigenous minerals
Upper Continental Slope	224	56° 46.3'	151° 34.5'	mud with terrigenous minerals
	225	56° 47.5'	151° 37.5'	mud with terrigenous minerals
	226	56° 48.3'	151° 40.9'	mud with terrigenous minerals
	239	57° 50.7'	149° 07.4'	mud with terrigenous minerals
	240	57° 48.3'	149° 05.4'	mud with terrigenous minerals
	336	57° 46.60'	149° 02.08'	mud with terrigenous minerals
	340	57° 17.48'	150° 24.92'	sandy mud with terrigenous minerals

Table 1 (continued)

Physiographic area	Station number	North latitude	West longitude	Sediment type
Upper Continental Slope (continued)	450	55° 56.06'	154° 14.13'	sandy mud with terrigenous minerals

Table 2. Summary values of index physical properties. (Replicate cores taken at some stations.)

Physiographic area	Station number	Water Content at 1 m (% dry weight)	Bulk density at 1 m (gm/cm^3)	Average plastic limit	Average liquid limit	Average plasticity index	Liquidity index at 1 m	Average grain specific gravity	Vane shear strength at 1 m (kPa)	s_u/σ'_v
Chiniak Trough	329	93	1.39	np	np			2.26		
	432	81/86	1.47/1.45					2.32/2.30		
	433	67	1.52					2.30		
	582	32	1.95	18	30	13		2.74		
Kiliuda Trough	343	105	1.43					2.56	19.69	4.67
	344	123	1.37	68	118	50		2.53	16.71	4.61
	347	99	1.44					2.59	14.10	3.27
	348	122	1.34	56	114			2.59	12.00	3.60
	349	132	1.38	52	104	52		2.63	3.50	0.94
	351	37	1.89					2.75	30.27	3.47
	439	133/99	1.37/-	67/-	110/-	43/-	1.31/-	2.57/2.52	10.12/-	
	440	100						2.52		
	441	97						2.60		
	578	122		60	102	42	1.47		15.90	

Table 2. Cont'd

Physiographic area	Station number	Water Content at 1 m (% dry weight)	Bulk density at 1 m (gm/cm^3)	Average plastic limit	Average liquid limit	Average plasticity index	Liquidity index at 1 m	Average grain specific gravity	Vane shear strength at 1 m (kPa)	S_u/σ_v'
	579	91/100	1.48/-	54/-	87/-	33/-		2.64/-	-/13.63	
Sitkinak Trough	355	35	1.88					2.75	5.11	0.59
	356	36	1.86					2.70		
	357	36	1.86					2.65	7.44	0.88
	445	40	1.83	22	31	10	1.82	2.71	19.80	2.43
	455	45	1.77	23	36	12	1.24	2.69	15.23	2.02
Upper Continental Slope	224	45	1.76	24	53	29	1.19	2.75		
	225	33	1.92	18	30	12	1.17	2.72		
	226	38	1.85	17	32	15	1.30	2.74		
	239	32	1.91	17	32	15		2.72		
	240	36	1.87	20	48	27	1.17	2.79		
	336	48	1.74	29	60	29		2.69		
	340		1.91					2.71	11.29	1.27
	450	21		19	20	4				

Table 3. Consolidation test results.

Physiographic area	Station number	Depth in core (cm)	σ'_{vo} (kPa)	σ'_{vm} (kPa)	C_c	$c_v \times 10^{-2}$ (cm^2/sec) from	$c_v \times 10^{-2}$ (cm^2/sec) to	OCR
Chiniak Trough	433	42	2.2	190.0	0.12	*	*	8
		92	5.2	150.0	0.07	*	*	29
	582	103	9.5	21.0	0.10	0.13	0.68	2.2
		194	21.5	40.0	0.06	0.52	2.27	1.9
Kiliuda Trough	439	66	2.3	24.0	1.06	0.33	1.65	10.4
	578	82	3.2	60.0	0.50	0.35	2.19	18.8
		180	7.2	118.0	0.48	1.24	3.51	16.4
		244	9.8	100.0	0.42	0.76	2.09	10.2
	579	51	2.0	110.0	0.43	0.21	2.27	55.0
		119	6.0	67.0	0.43	0.47	3.99	11.2
	579	176	9.6	80.0	0.37	0.71	4.54	8.3

Table 3 (continued)

Physiographic area	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
Sitkinak Trough	445	12	0.6	3.4	0.73	0.10	1.06	5.7
	455	18	3.9	14.8	0.32	0.11	1.60	3.8
		102	8.4	89.0	0.30	0.11	0.31	10.6
Upper Continental Slope	224	25	1.3	3.8	0.55	0.01	0.29	2.9
		155	13.2	65.0	0.18	0.21	1.10	4.9
		395	47.0		0.16	0.07	0.50	
	225	135	13.0	9.0	0.10	0.10	2.05	0.7
	226	25	2.4	8.3	0.12	0.09	1.12	3.5
	239	165	15.2	9.2	0.16	0.05	2.27	0.6
		287	29.0	22.0	0.12	0.02	0.26	0.8

Table 3 (continued)

Physiographic area	Station number	Depth in core (cm)	σ'_{vo} (kPa)	σ'_{vm} (kPa)	C_c	$c_v \times 10^{-2}$ (cm^2/sec) from	$c_v \times 10^{-2}$ (cm^2/sec) to	OCR
	240	45	7.2	6.3	0.38	0.02	0.32	0.9
	450	53	5.3	96.0	0.15	0.18	1.74	18.1

*c_v could not be determined from the data, but consolidation was extremely fast.

Table 4. Static triaxial strength test results.

Physiographic area	Station number	Depth in core (cm)	σ_c' (kPa)	Induced OCR	S_u (kPa)	s_u/σ_c'	ϕ' (degrees)
Chiniak Trough	433	100	0.7	-	1.9	2.9	<62
		114	353.3	1	1325.3	3.8	46
		124	60.4	5.8	974.4	16.1	<53
	582	41	1.4	-	9.4	6.7	33
		63	6.9	-	17.8	2.6	43
		113	48.2	1	52.4	1.1	34
		142	8.0	6	30.7	3.8	31
		155	165.4	1	56.2	0.3	47
		183	35.8	-	45.9	1.3	36
Kiliuda Trough	439	94	291.2	1	256.9	0.9	43
		118	194.2	1	110.8	0.6	45
	578	49	244.8/62.0	1	98.2	0.4	45
		148	241.2	1	109.4	0.4	41

Table 4 (continued)

Physiographic area	Station number	Depth in core (cm)	σ'_c (kPa)	Induced OCR	S_u (kPa)	s_u/σ'_c	ø' (degrees)
Kiliuda Trough	578	190	75.8	6	122.3	1.6	44
(continued)		205	130.9	3	157.7	1.2	44
		219	1.0	-	22.9	22.9	50
		233	11.7	-	32.9	2.8	50
	579	61	68.9	6	151.0	2.2	45
		103	248.1	1	122.6	0.5	43
		151	1.0	-	22.3	22.3	54
		165	910	-	2.3	0.3	45
Sitkinak Trough	445	37	141.2	1	58.4	0.4	35
		37	141.0/68.4	1	51.8	0.4	36
		46	30.7	5.9	42.9	1.4	<34
		46	60.4	3	42.6	0.7	<30
		95	294.2	1	180.4	0.6	37
		107	194.0	1	128.5	0.7	30

Table 4 (continued)

Physiographic area	Station number	Depth in core (cm)	σ_c' (kPa)	Induced OCR	S_u (kPa)	s_u/σ_c'	ϕ' (degrees)
Sitkinak Trough (con't)	445	119	97.1	1	73.6	0.8	26
	455	110	103.0	1	105.9	1.0	32
		122	199.1	1	155.9	0.8	37
Upper Continental Slope	224						35
	225						35
	226						37
	239						30
	450	62	289.3	1	294.1	1.0	40
		74	103.9	1	207.9	2.0	38

Table 5. Dynamic triaxial strength test results.

Physiographic area	Station number	Depth in core (cm)	σ_c' (kPa)	Induced OCR	τ_{cyc}/S_u (%)	Cycles to failure
Chiniak Trough	433	76	347.2	1	12	12
		85	344.2	1	6	230
	582	77	165.3	1	74	14
		92	165.3	1	53	58
Kiliuda Trough	578	55	241.0	1	77	1
		68	75.8	6	60	21
		84	75.8	6	41	520
		135	241.0	1	50	35
	579	75	248.1	1	75	9
		89	248.1	1	45	242
Sitkinak Trough	445	60	137.8	1	93	16
		60	134.1	1	51	410

Table 6. Values of variables in dynamic slope stability analysis.

α	k	$d_{6.5}$ (km)
1°	0.15	28
5°	0.12	34
10°	0.08	51
15°	0.05	80
20°	0.014	240

FIGURE CAPTIONS

1. Location map of the Kodiak Shelf, Alaska, showing physiographic features and bathymetry.

2. Map of seafloor slopes. Coverage extends from 3-mile limit to 100 m water depth. Contours in percent.

3. Generalized thickness map of unconsolidated sedimentary deposits. Contours in meters.

4. Locations of sediment sample stations. (See Table 1.)

5. Index physical properties of sediment samples.

6. Plasticity chart and sediment classification according to the Unified Soil Classification System. (See Casagrande, 1948.)

7. Compression index versus liquid limit for Kodiak Shelf sediment samples. Empirical relation derived by Skempton (1944) is shown for reference.

8. Oedometer consolidation test results, plotted as logarithm of the effective consolidation stress versus void ratio: (Note that unload-reload cycle was performed once during each oedometer test.) A) Station 433, showing continuous downward curvature of loading curve. B) Normal loading curve, showing straight-line relation between void ratio and effective consolidation stress at loads exceeding approximately 100 kPa.

9. Effective angle of internal friction versus placticity index. Center line is the empirical relation derived by Lambe and Whitman (1969), and upper and lower lines show range of variation of their data.

10. Normalized strength versus overconsolidation ratio. (See Mayne, 1980.)

11. Stress level versus number of cycles to failure.

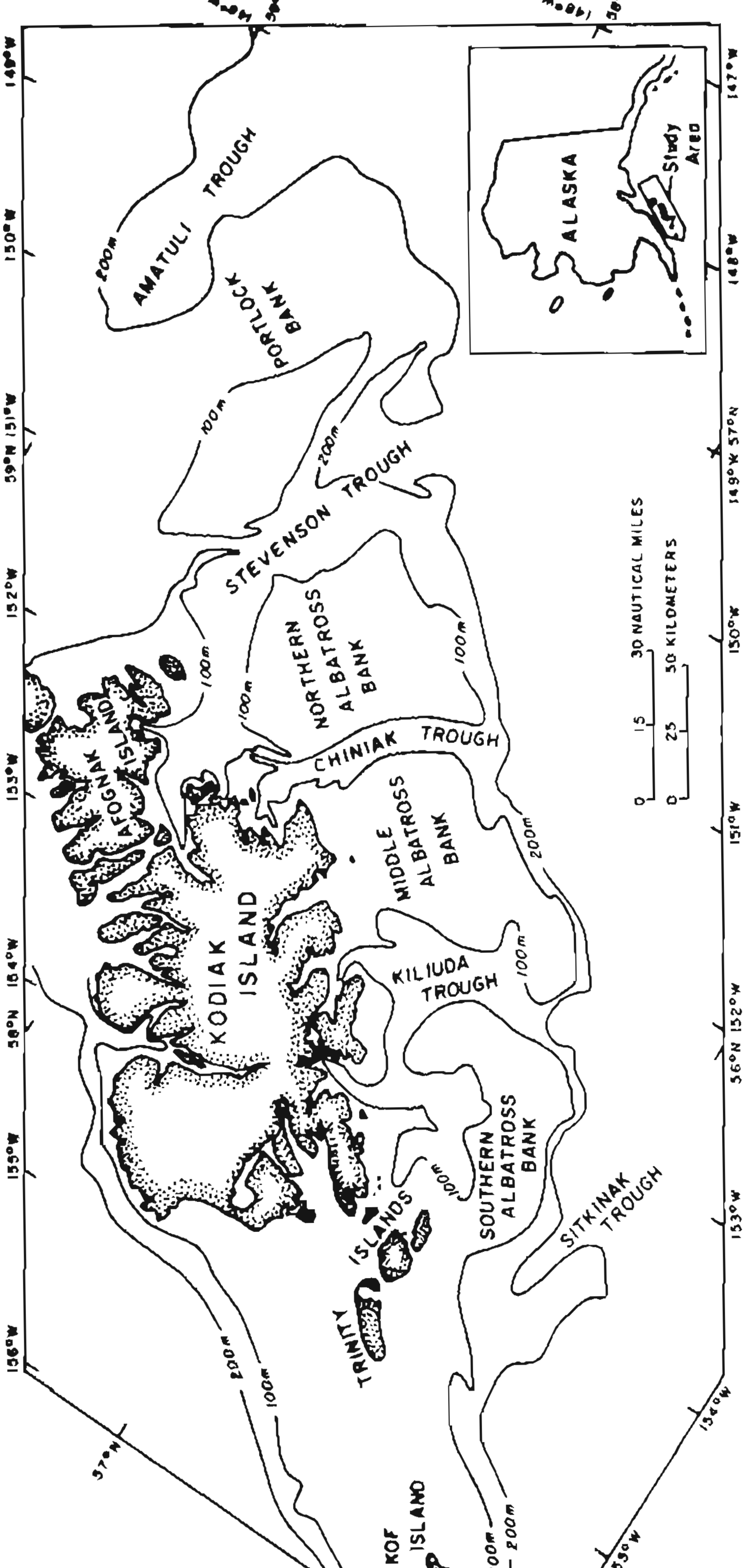

KODIAK ISLAND
AFOGNAK ISLAND
TRINITY ISLANDS
CHIRIKOF ISLAND
AMATULI TROUGH
PORTLOCK BANK
STEVENSON TROUGH
NORTHERN ALBATROSS BANK
CHINIAK TROUGH
MIDDLE ALBATROSS BANK
KILIUDA TROUGH
SOUTHERN ALBATROSS BANK
SITKINAK TROUGH
ALASKA
Study Area
0 15 30 NAUTICAL MILES
0 25 50 KILOMETERS
100m
200m

Fig. 1


KODIAK ISLAND
AFOGNAK ISLAND
TRINITY ISLANDS
CHIRIKOF ISLAND
0 10 20 30 NAUTICAL MILES
0 10 20 30 40 50 KILOMETERS
156°W
155°W
154°W
153°W
152°W
151°W
150°W
149°W
148°W
147°W
57°N
56°N
58°N
59°N

Fig. 2

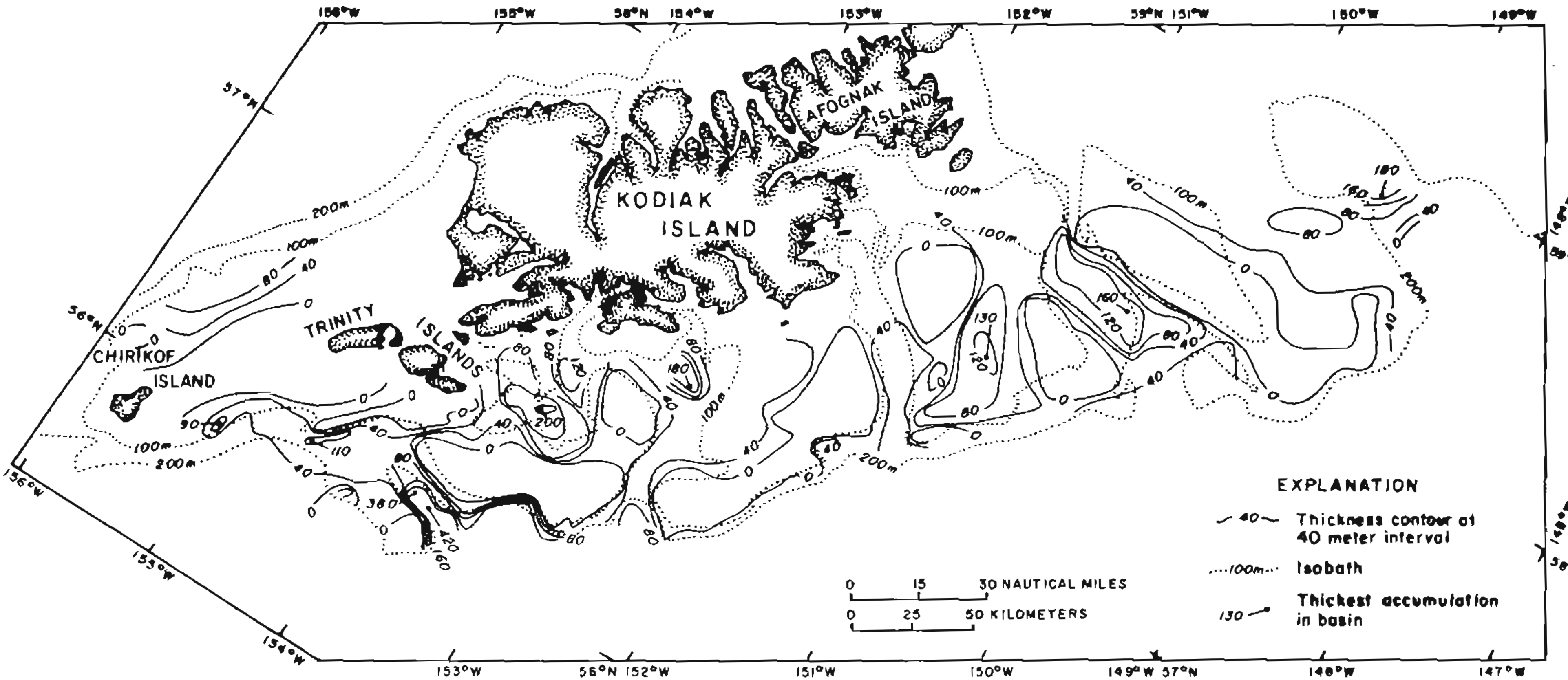
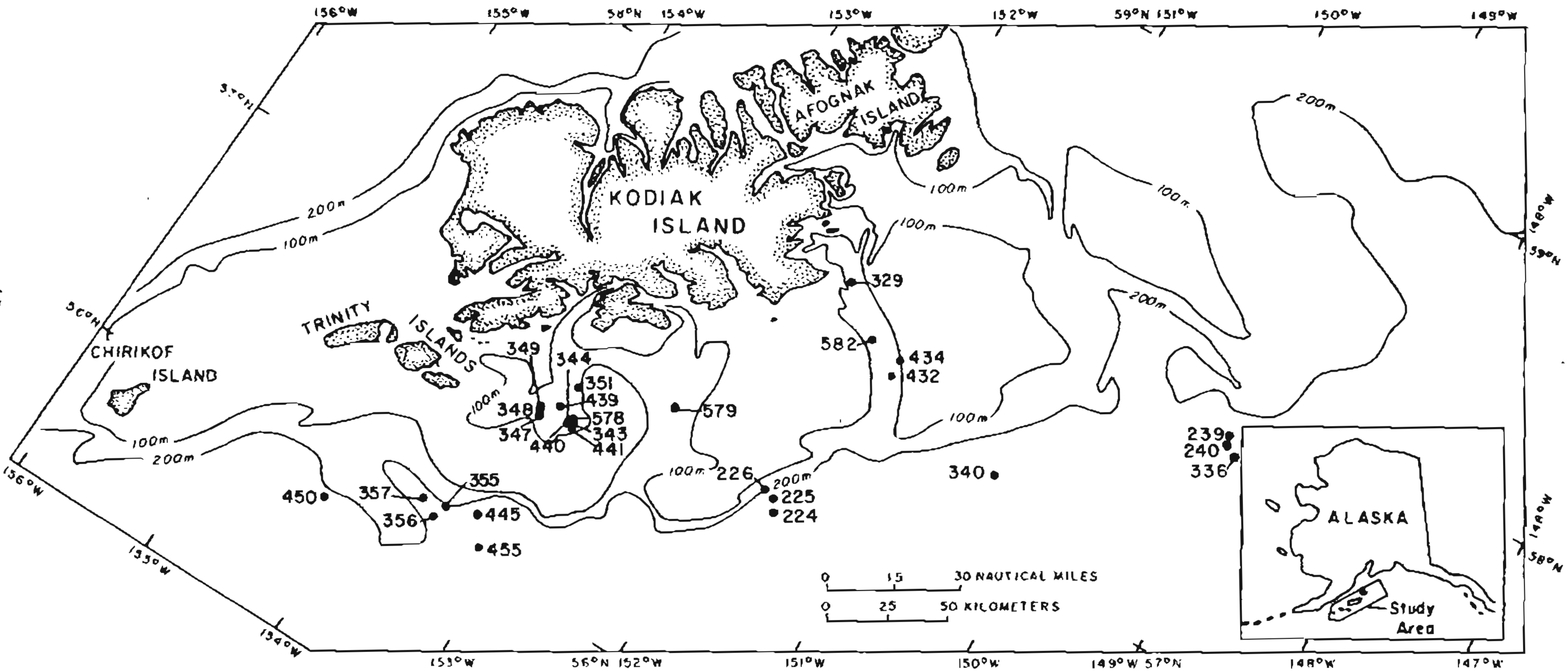

KODIAK ISLAND
AFOGNAK ISLAND
TRINITY ISLANDS
CHIRIKOF ISLAND
EXPLANATION
Thickness contour at 40 meter interval
Isobath
Thickest accumulation in basin
0 15 30 NAUTICAL MILES
0 25 50 KILOMETERS

Fig. 3


KODIAK ISLAND
AFOGNAK ISLAND
TRINITY ISLANDS
CHIRIKOF ISLAND
ALASKA
Study Area
200m
100m
0 15 30 NAUTICAL MILES
0 25 50 KILOMETERS
329
582
434
432
349
344
351
439
578
343
441
348
347
440
579
226
225
224
340
239
240
336
355
357
356
450
445
455
156°W
155°W
154°W
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147°W
58°N
59°N
57°N
56°N

Fig. 4

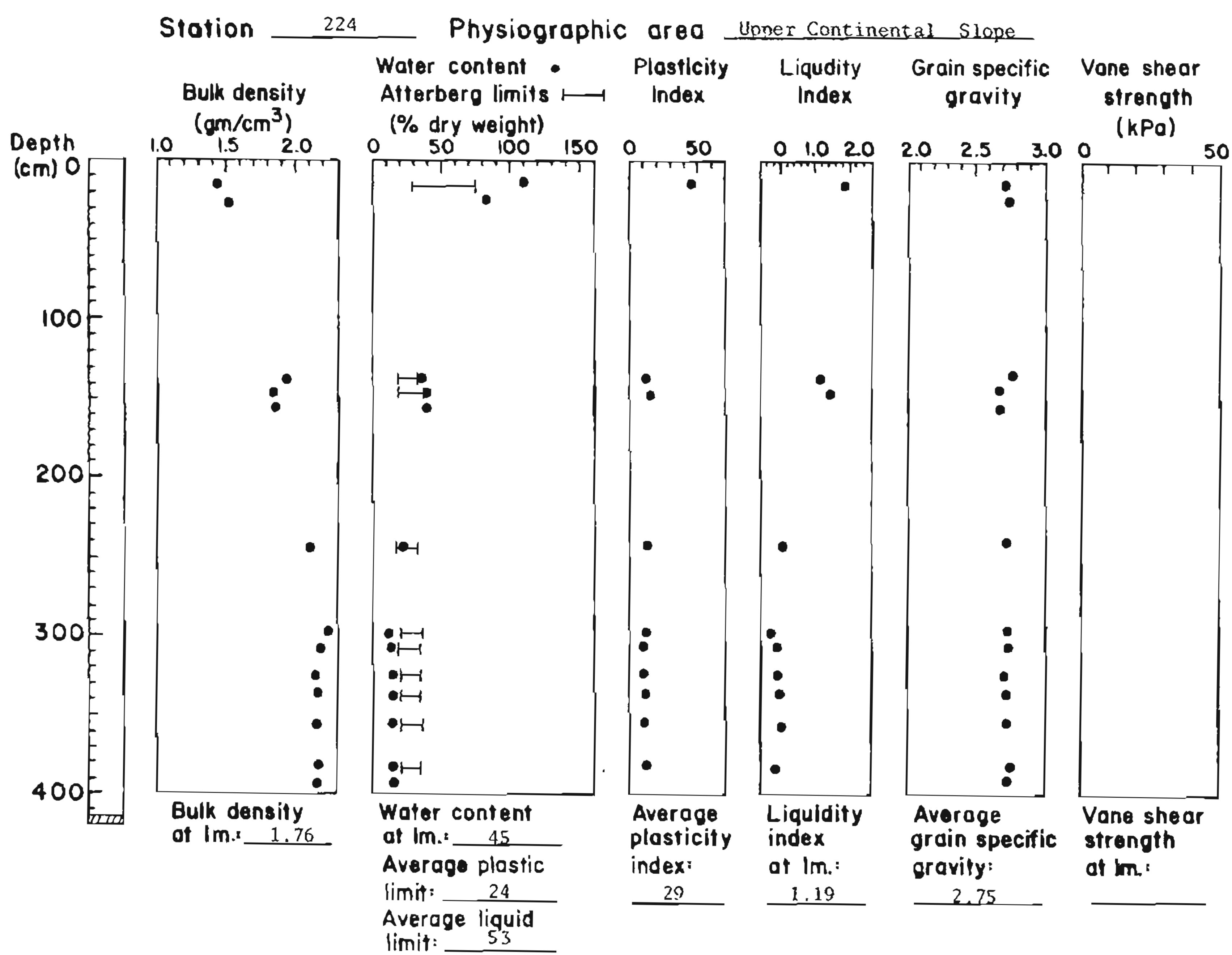
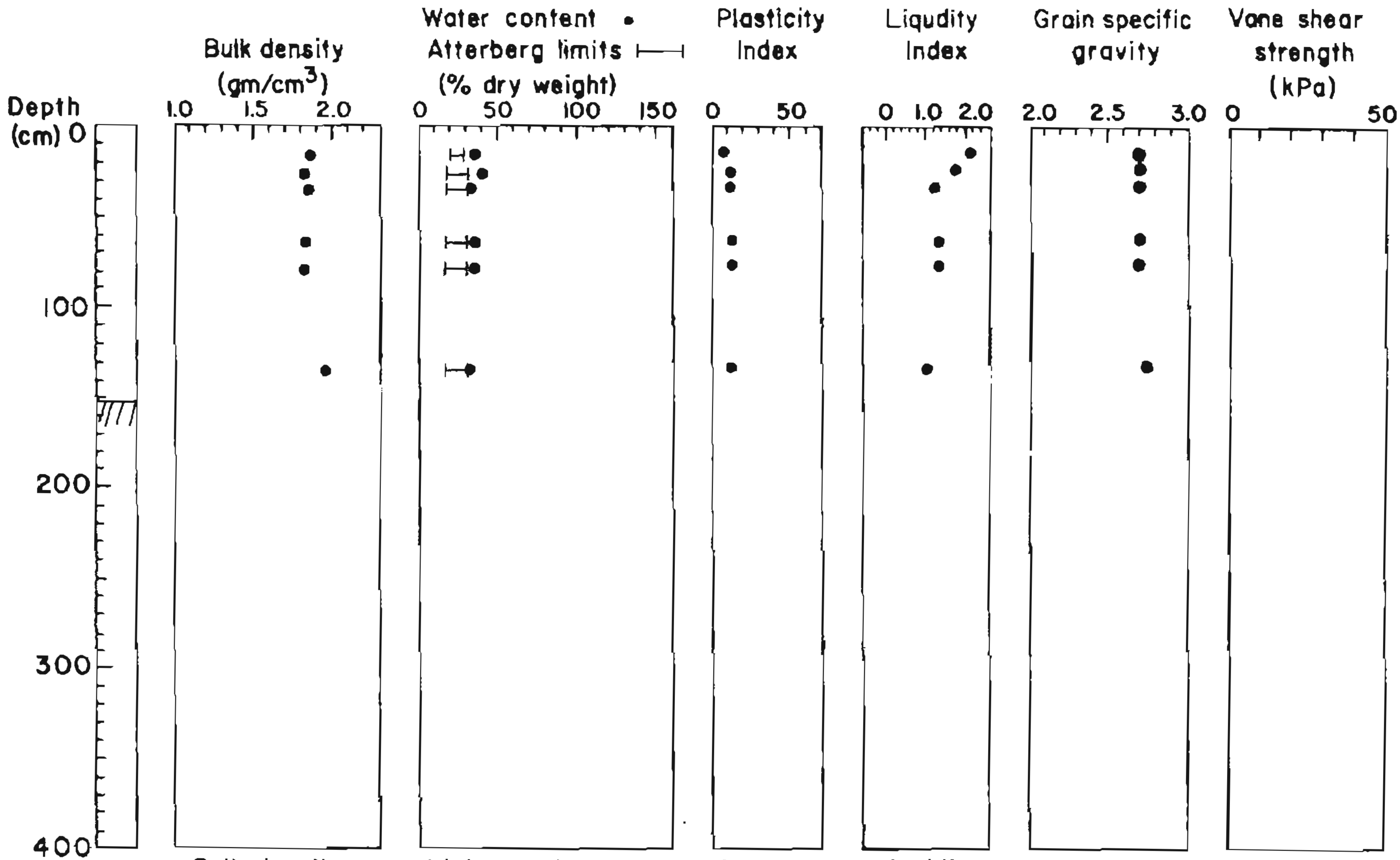

Station 224 Physiographic area Upper Continental Slope
Depth (cm)
0
100
200
300
400
Bulk density (gm/cm³)
1.0 1.5 2.0
Water content •
Atterberg limits ⊢⊣
(% dry weight)
0 50 100 150
Plasticity Index
0 50
Liquidity Index
0 1.0 2.0
Grain specific gravity
2.0 2.5 3.0
Vane shear strength (kPa)
0 50
Bulk density at lm.: 1.76
Water content at lm.: 45
Average plastic limit: 24
Average liquid limit: 53
Average plasticity index: 29
Liquidity index at lm.: 1.19
Average grain specific gravity: 2.75
Vane shear strength at lm.:

Fig. 5 (p. 42-30)

Station 225 Physiographic area Upper Continental Slope



Bulk density at lm.: 1.92

Water content at lm.: 33

Average plastic limit: 18

Average liquid limit: 30

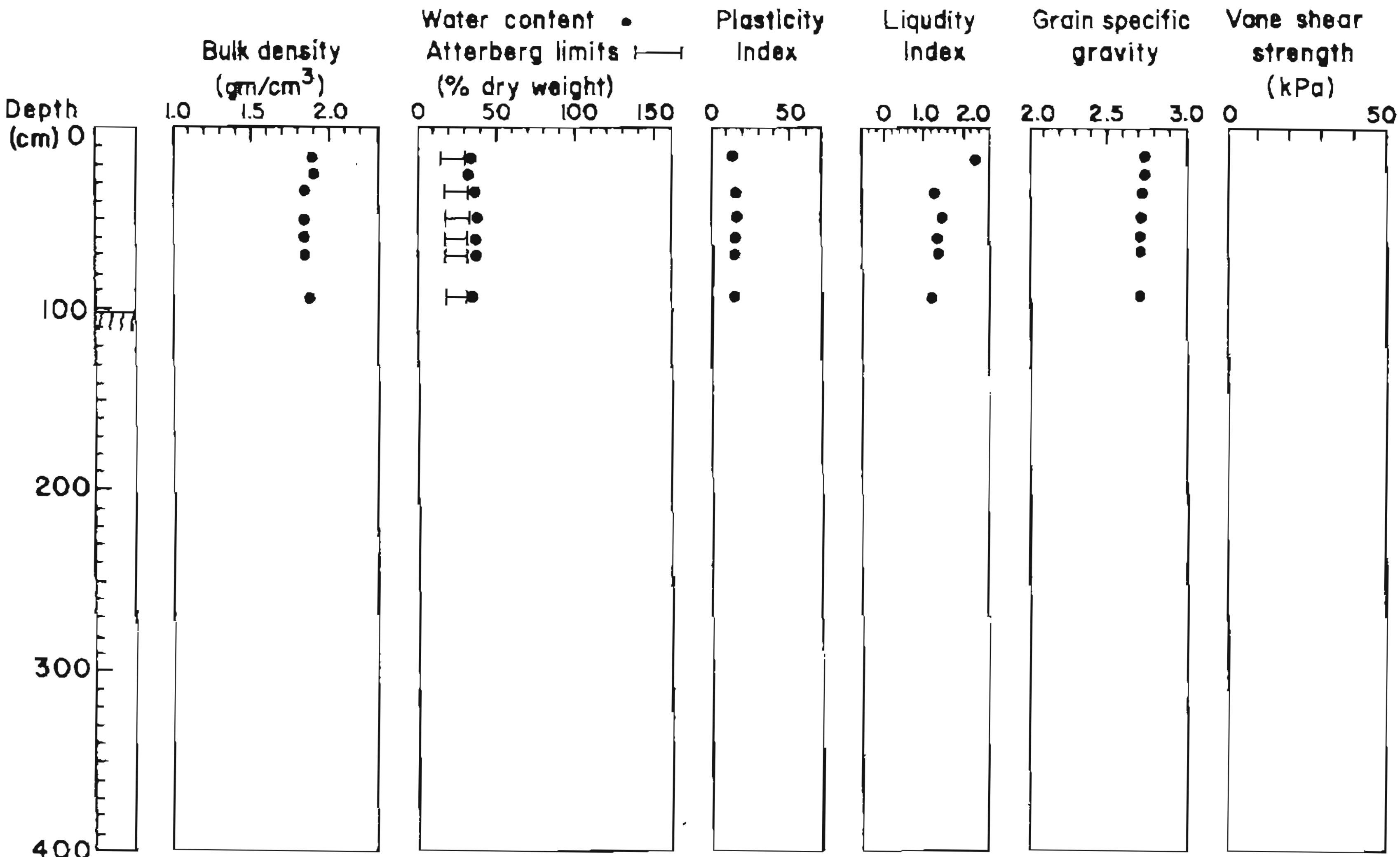
Average plasticity index: 12

Liquidity index at lm.: 1.17

Average grain specific gravity: 2.72

Vane shear strength at lm.: ______

Station 226 Physiographic area Upper Continental Slope



Bulk density at lm.: 1.85

Water content at lm.: 38
Average plastic limit: 17
Average liquid limit: 32

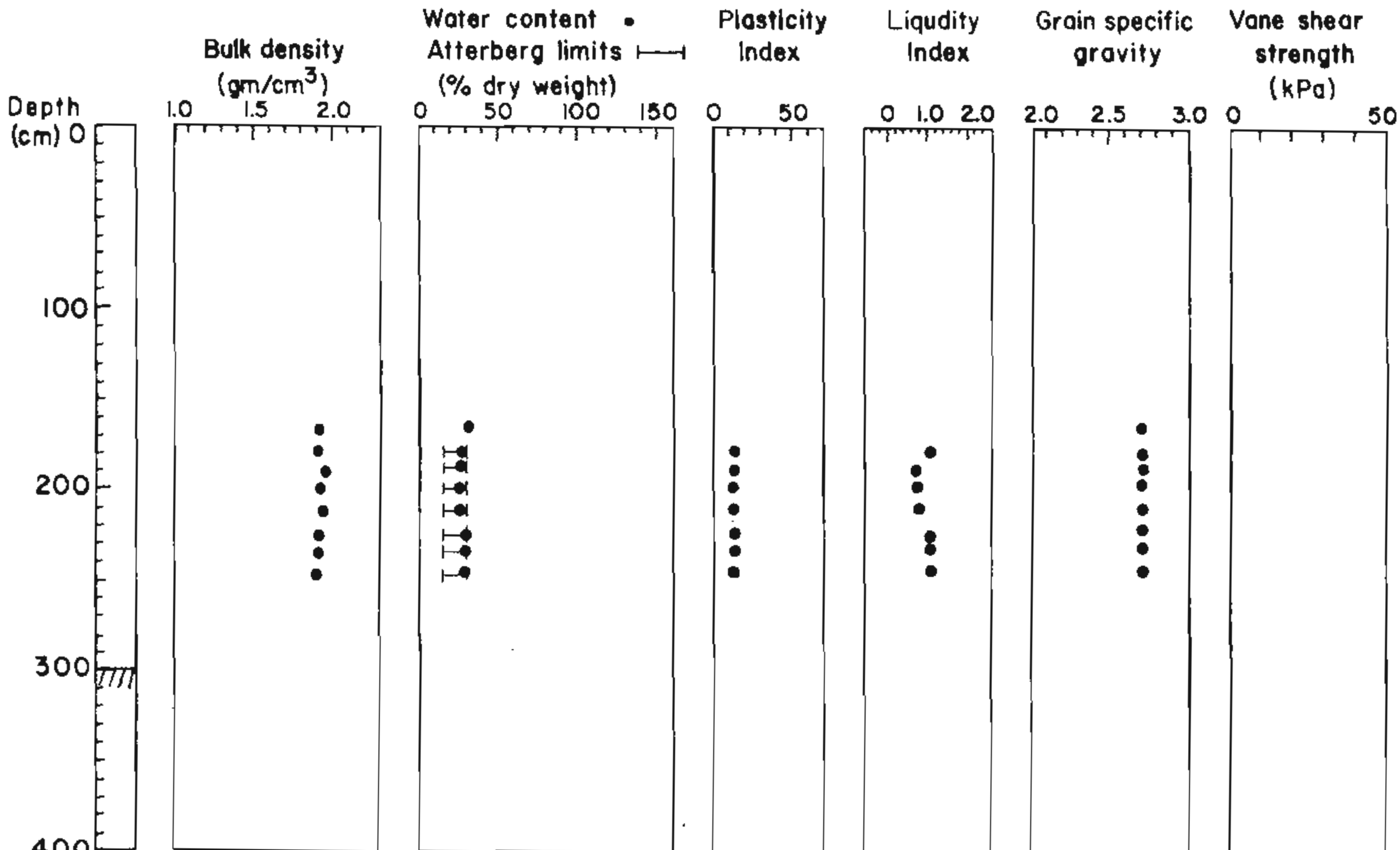
Average plasticity index: 15

Liquidity index at lm.: 1.30

Average grain specific gravity: 2.74

Vane shear strength at lm.: ____

Station 239 Physiographic area Upper Continental Slope



Bulk density at lm.: 1.91

Water content at lm.: 32

Average plastic limit: 17

Average liquid limit: 32

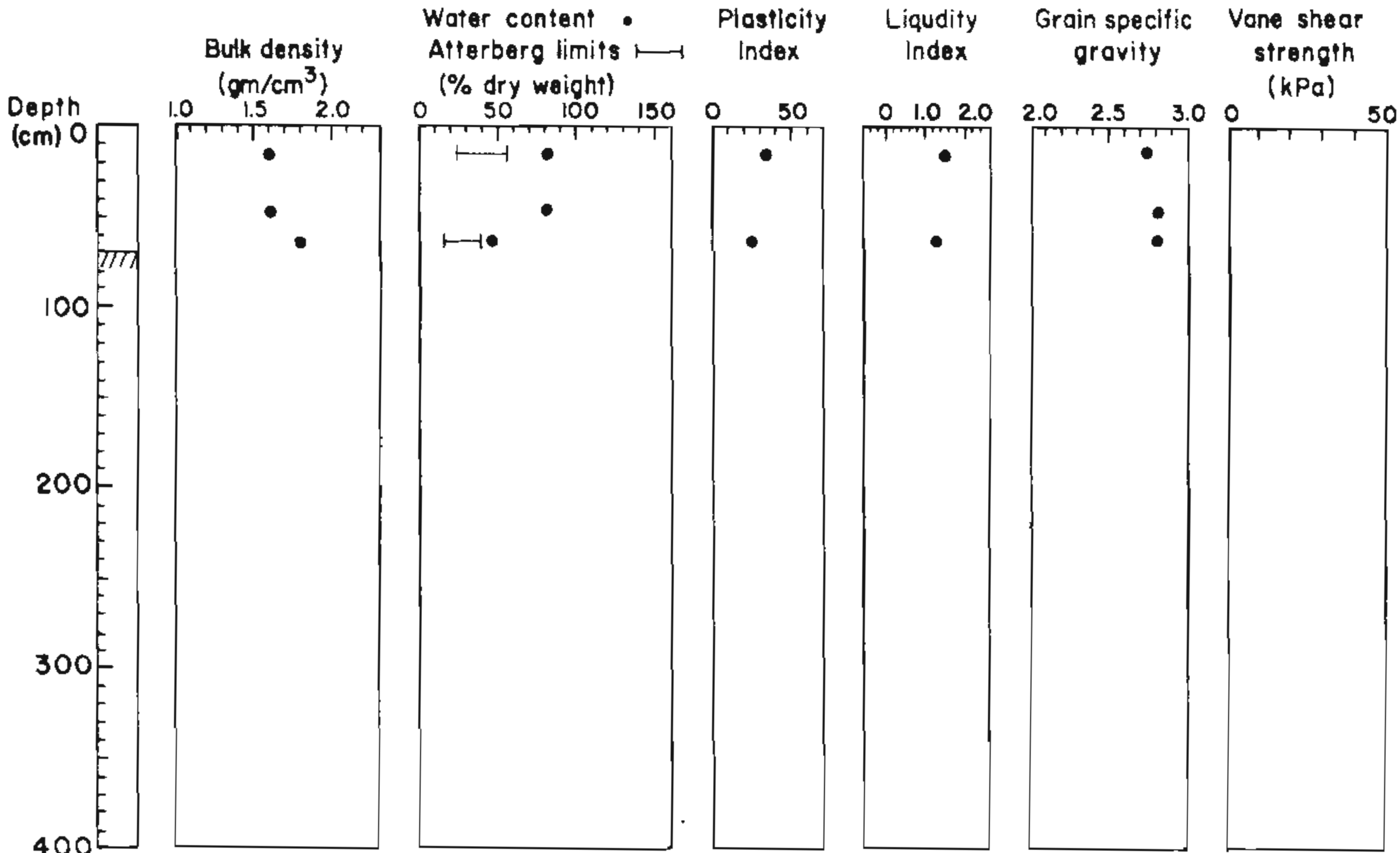
Average plasticity index: 15

Liquidity index at lm.:

Average grain specific gravity: 2.72

Vane shear strength at lm.:

Station 240 Physiographic area Upper Continental Slope



Bulk density at 1m.: 1.87

Water content at 1m.: 36

Average plastic limit: 20

Average liquid limit: 48

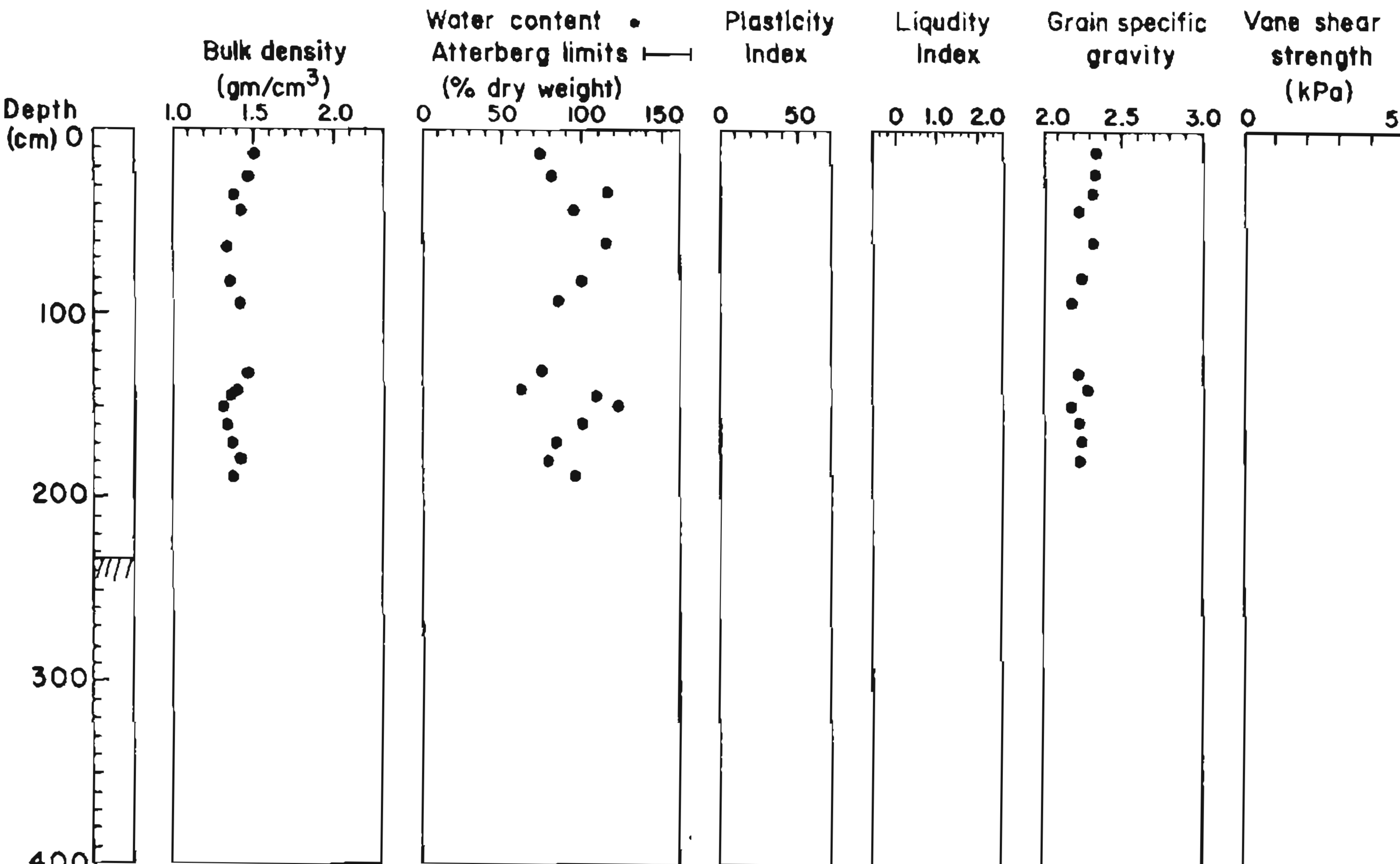
Average plasticity index: 27

Liquidity index at 1m.: 1.17

Average grain specific gravity: 2.79

Vane shear strength at 1m.: ______

Station 329 Physiographic area Chiniak Trough



Bulk density at lm.: 1.39

Water content at lm.: 93

Average plastic limit: ______

Average liquid limit: ______

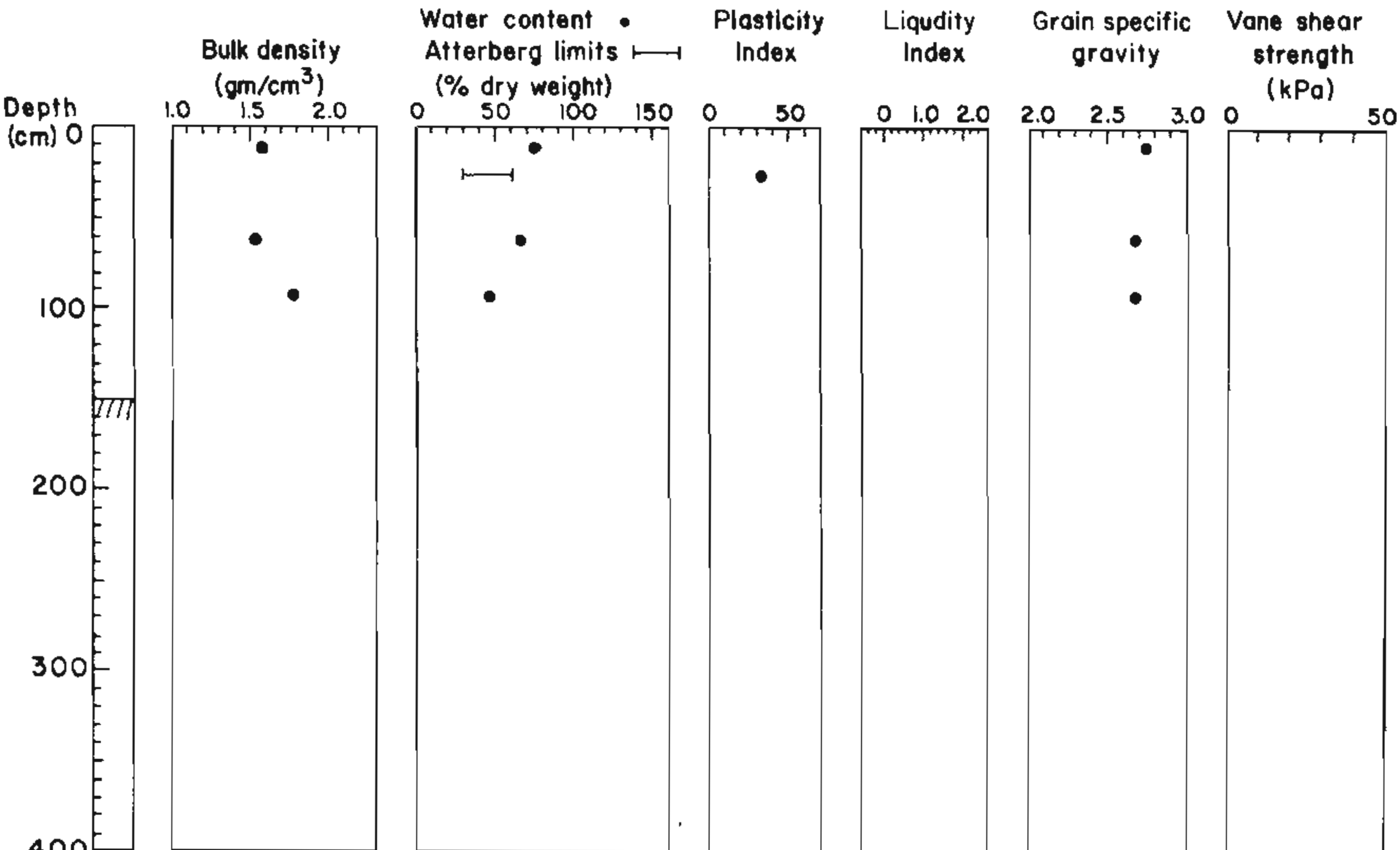
Average plasticity index: np

Liquidity index at lm.: ______

Average grain specific gravity: 2.26

Vane shear strength at lm.: ______

Station 336 Physiographic area Upper Continental Slope



Bulk density at 1m.: 1.74

Water content at 1m.: 48

Average plastic limit: 29

Average liquid limit: 60

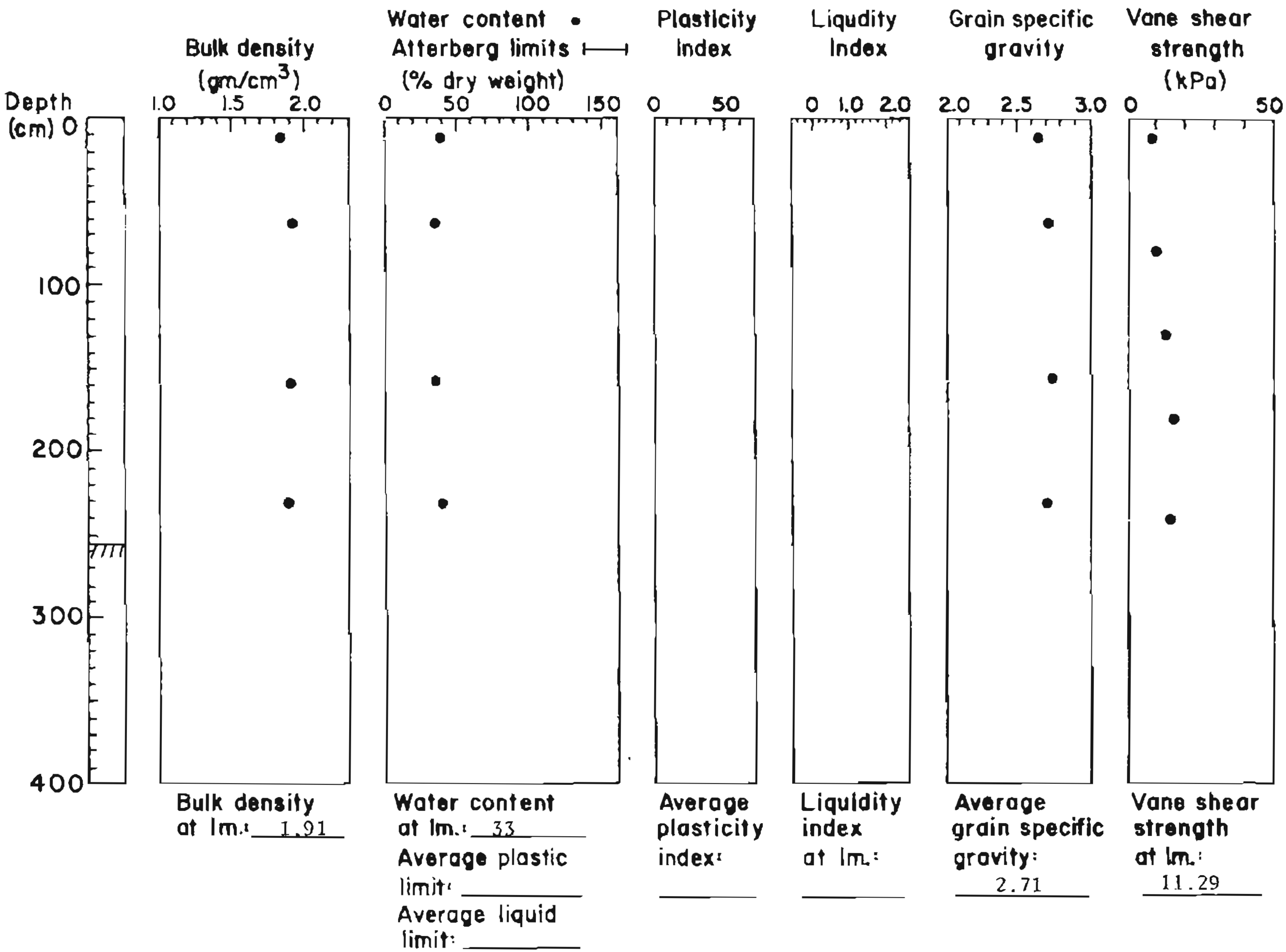
Average plasticity index: 29

Liquidity index at 1m.:

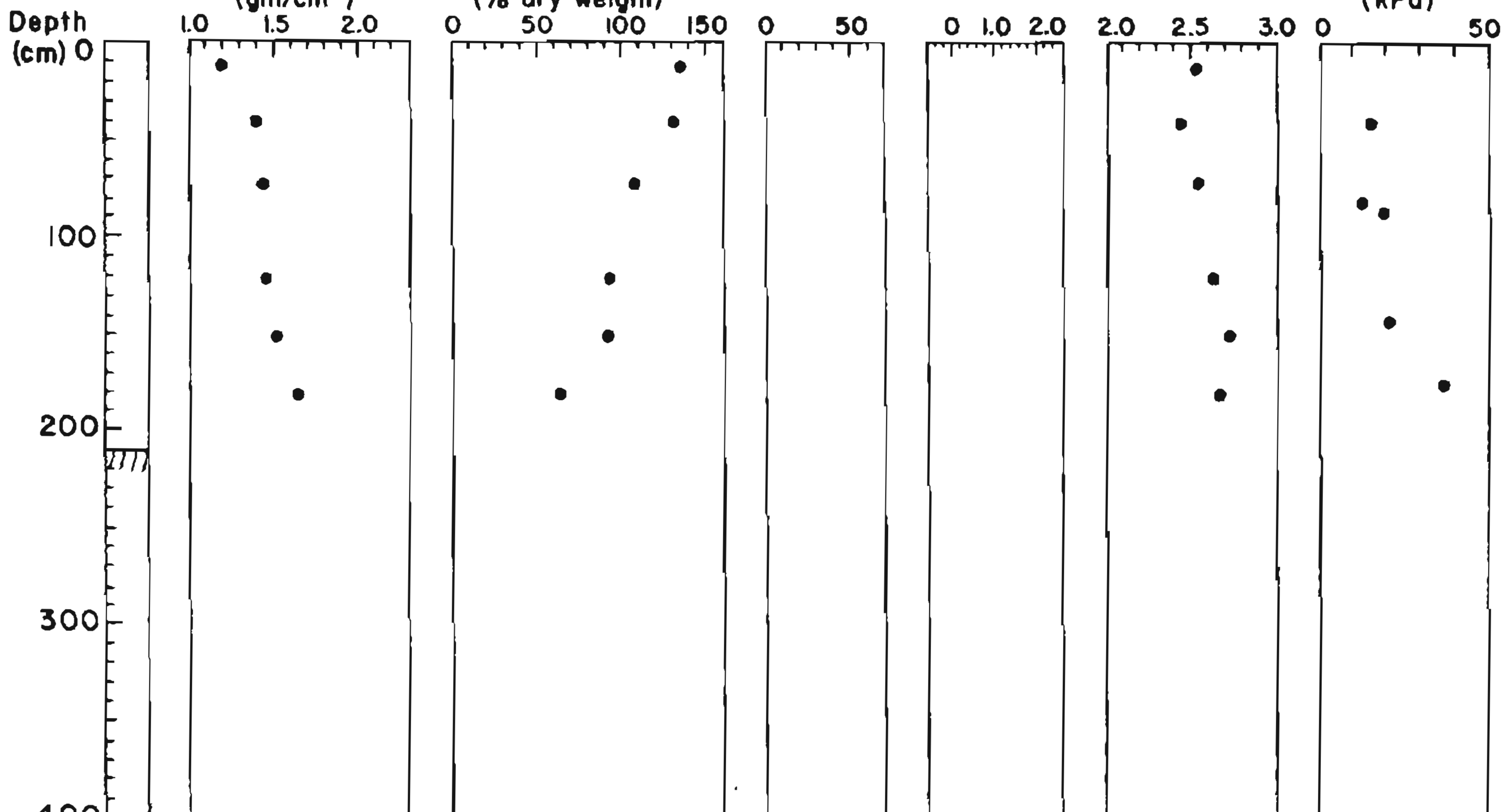
Average grain specific gravity: 2.69

Vane shear strength at 1m.:

Station 340 Physiographic area Upper Continental Slope



Station 343 Physiographic area Kiliuda Trough



Bulk density at lm.: 1.43

Water content at lm.: 105

Average plastic limit: ______

Average liquid limit: ______

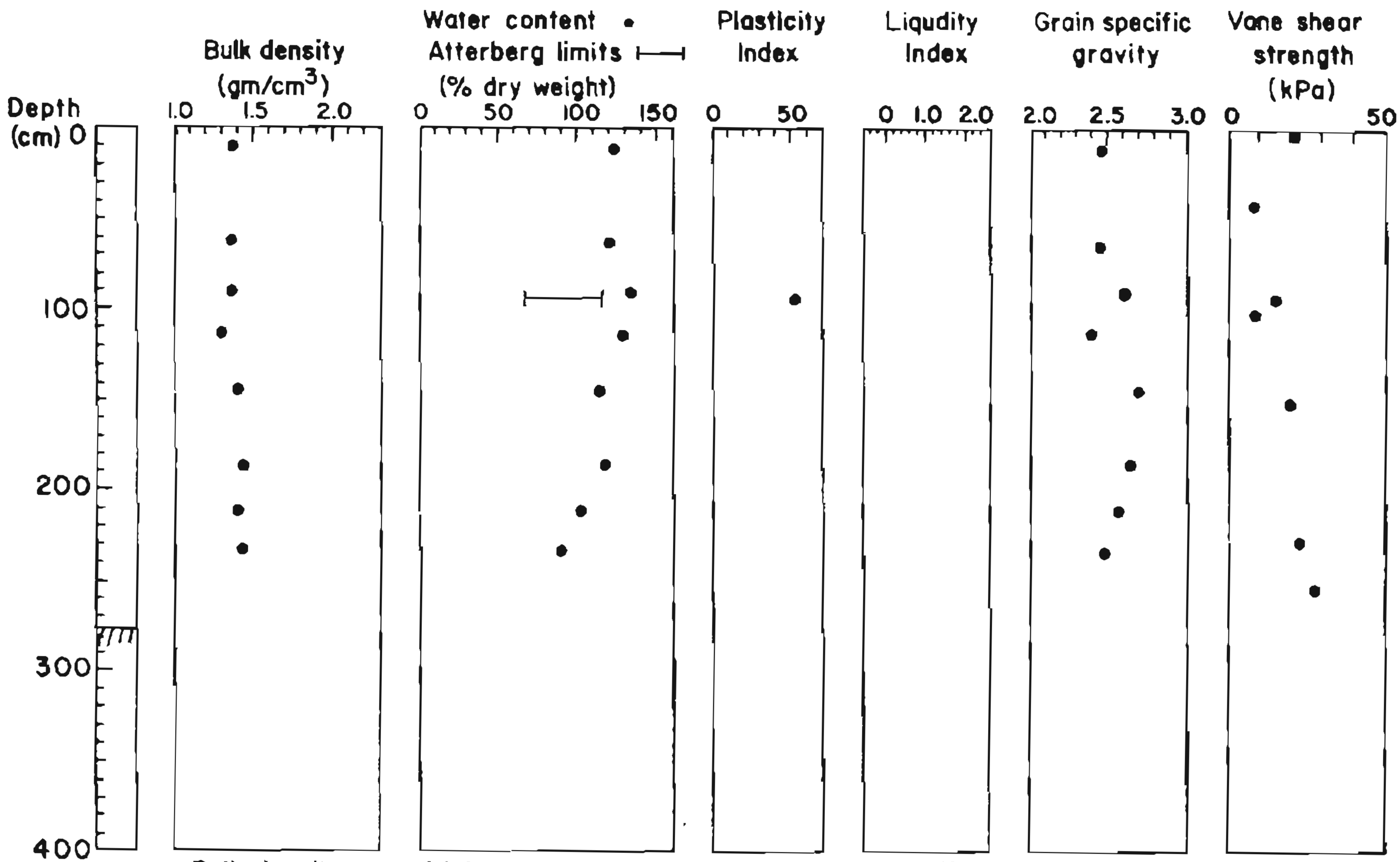
Average plasticity index: ______

Liquidity index at lm.: ______

Average grain specific gravity: 2.56

Vane shear strength at lm.: 19.69

Station 344 Physiographic area Kiliuda Trough



Bulk density at lm.: 1.37

Water content at lm.: 123

Average plastic limit: 68

Average liquid limit: 118

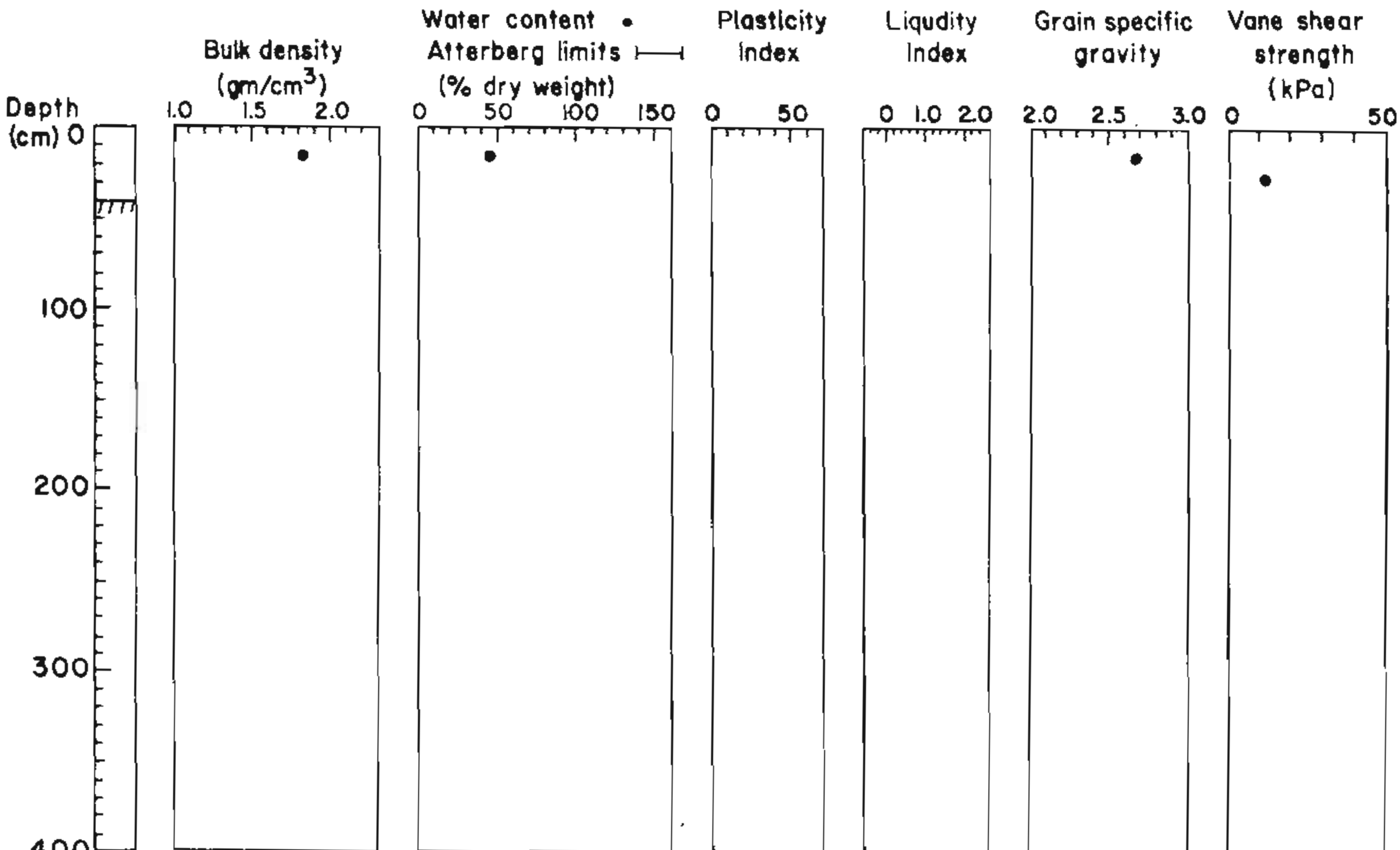
Average plasticity index: 50

Liquidity index at lm.: ______

Average grain specific gravity: 2.53

Vane shear strength at lm.: 16.71

Station 345 Physiographic area Kiliuda Trough



Bulk density at 1m.: ______

Water content at 1m.: ______
Average plastic limit: ______
Average liquid limit: ______

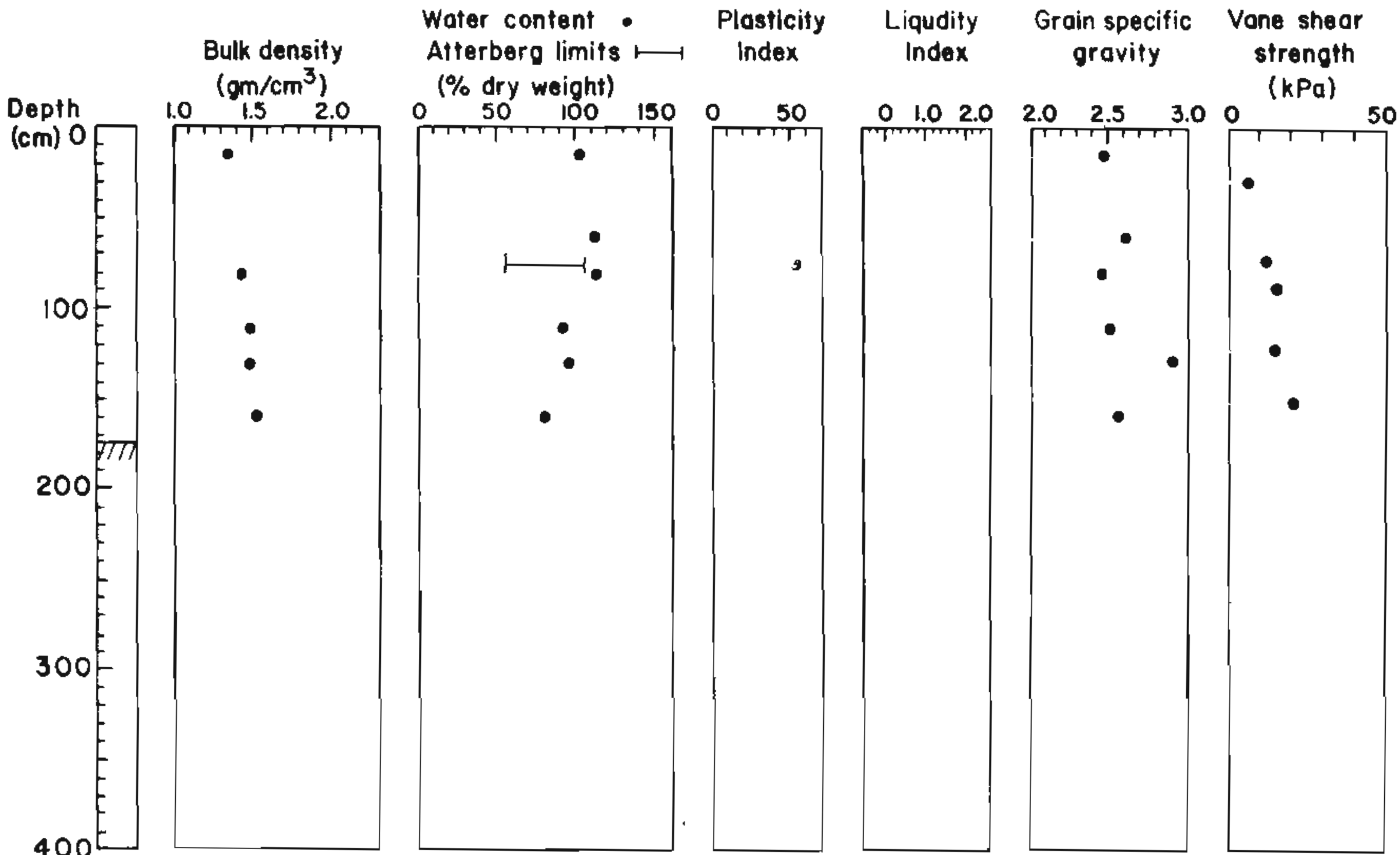
Average plasticity index: ______

Liquidity index at 1m.: ______

Average grain specific gravity: ______

Vane shear strength at 1m.: ______

Station 347 Physiographic area Kiliuda Trough



Bulk density at lm.: 1.44

Water content at lm.: 99

Average plastic limit: ______

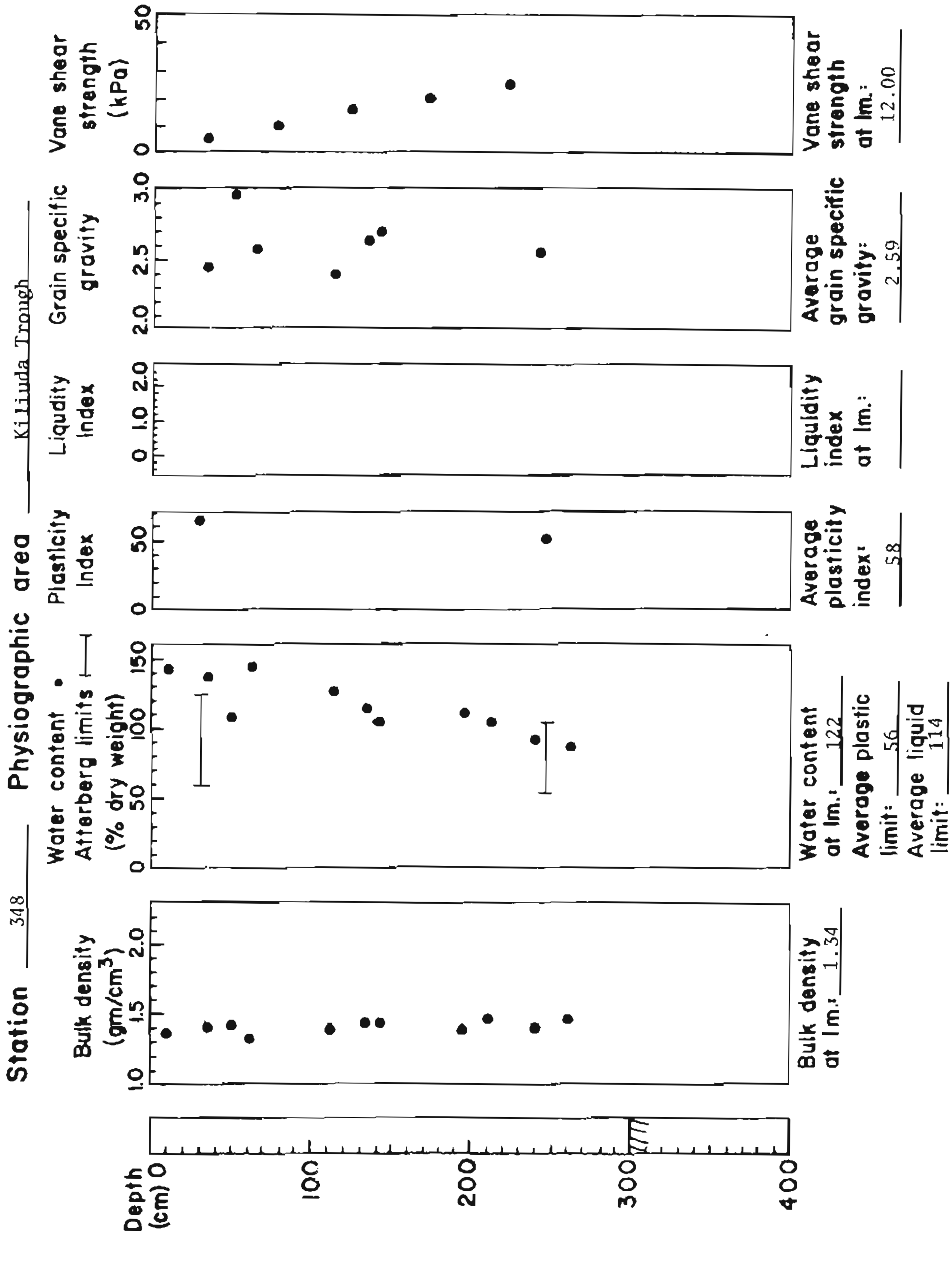
Average liquid limit: ______

Average plasticity index: ______

Liquidity index at lm.: ______

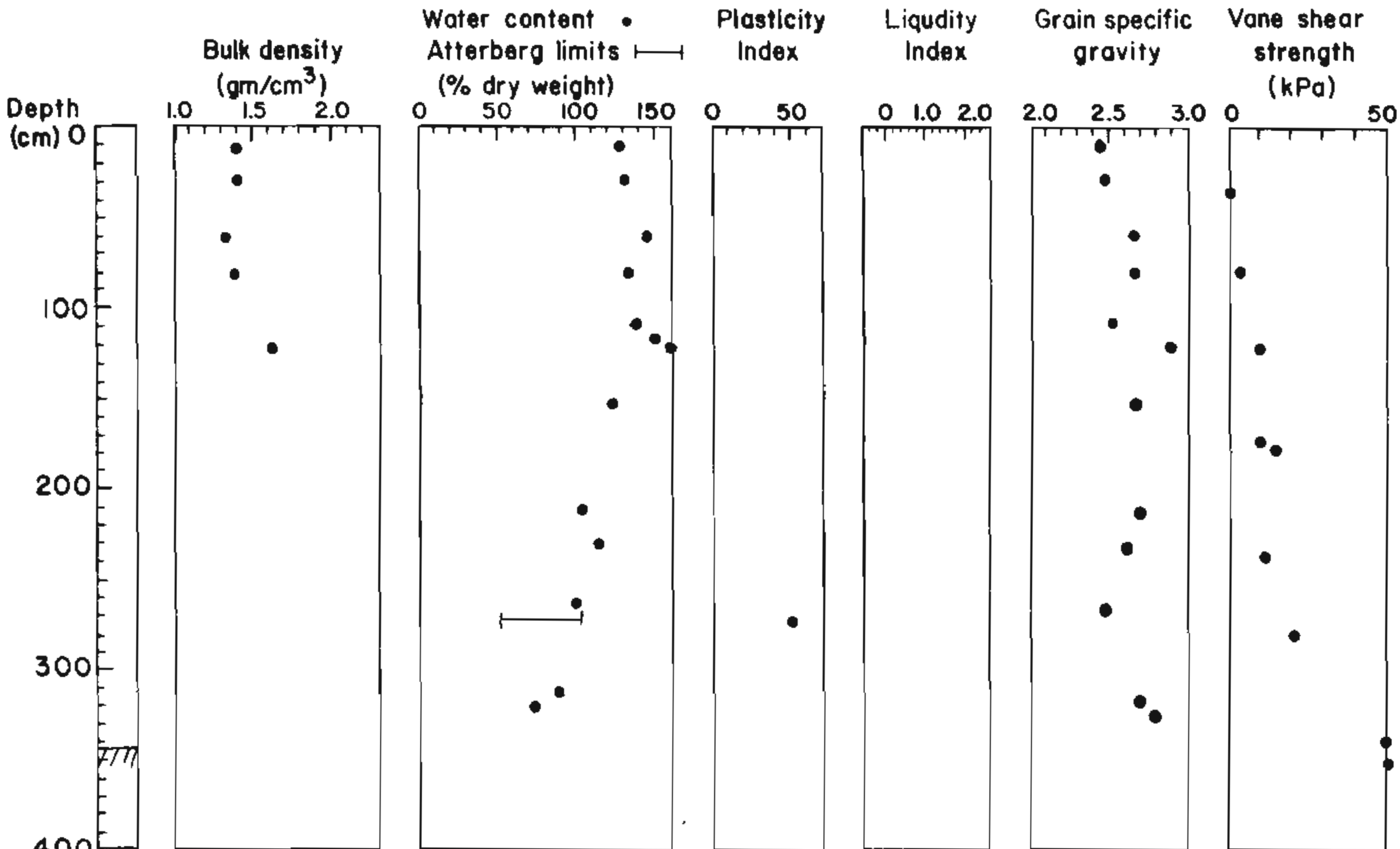
Average grain specific gravity: 2.59

Vane shear strength at lm.: 14.10



Station 348
Physiographic area Kiliuda Trough
Depth (cm)
0
100
200
300
400
Bulk density (gm/cm³)
1.0
1.5
2.0
Bulk density at Im.: 1.34
Water content •
Atterberg limits ⊢⊣
(% dry weight)
0
50
100
150
Water content at Im.: 122
Average plastic limit: 56
Average liquid limit: 114
Plasticity Index
0
50
Average plasticity index: 58
Liquidity Index
0
1.0
2.0
Liquidity index at Im.:
Grain specific gravity
2.0
2.5
3.0
Average grain specific gravity: 2.59
Vane shear strength (kPa)
0
50
Vane shear strength at Im.: 12.00

Station 349 Physiographic area Kiliuda Trough



Bulk density at lm.: 1.38

Water content at lm.: 132

Average plastic limit: 52

Average liquid limit: 104

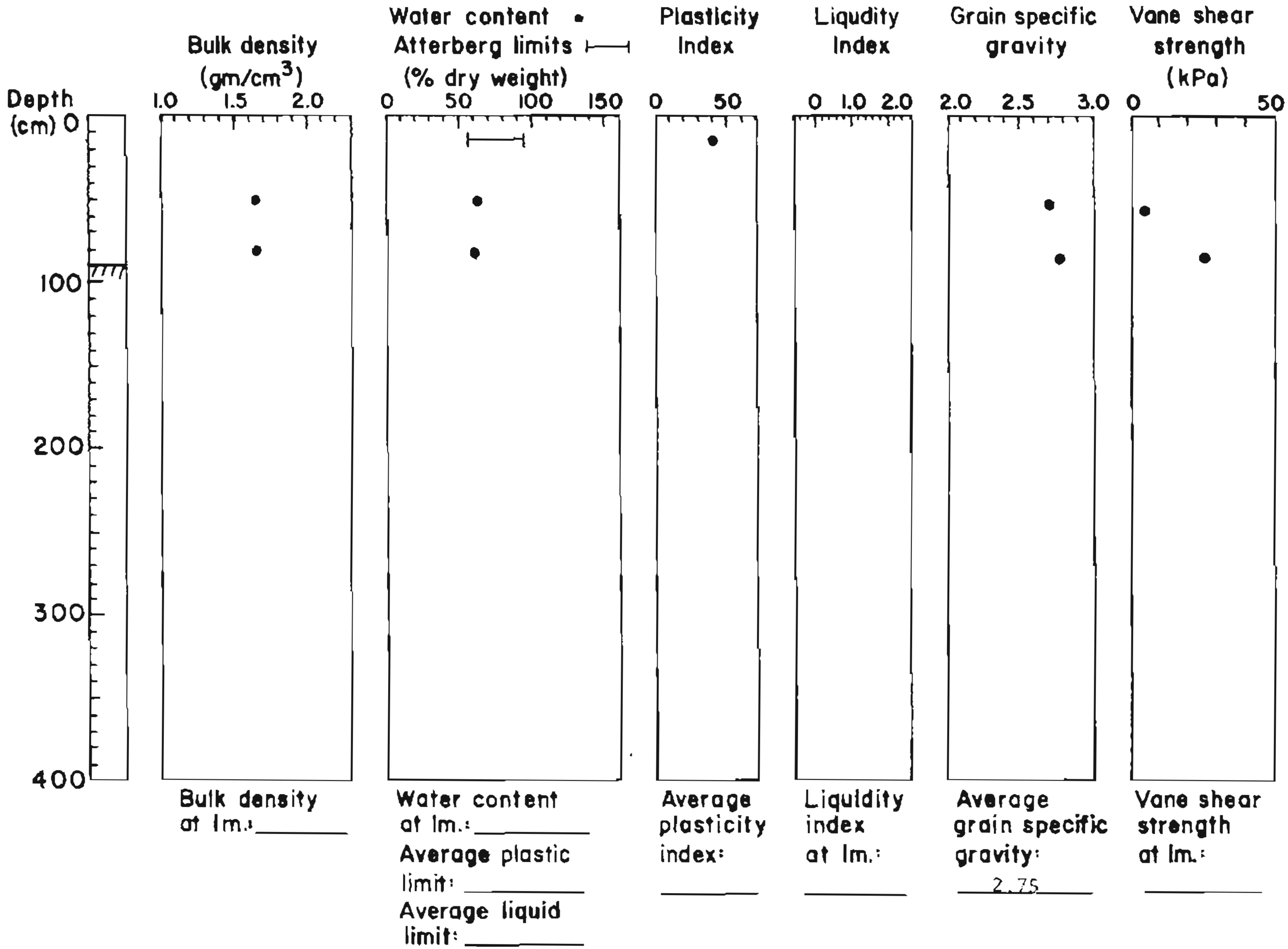
Average plasticity index: 52

Liquidity index at lm.:

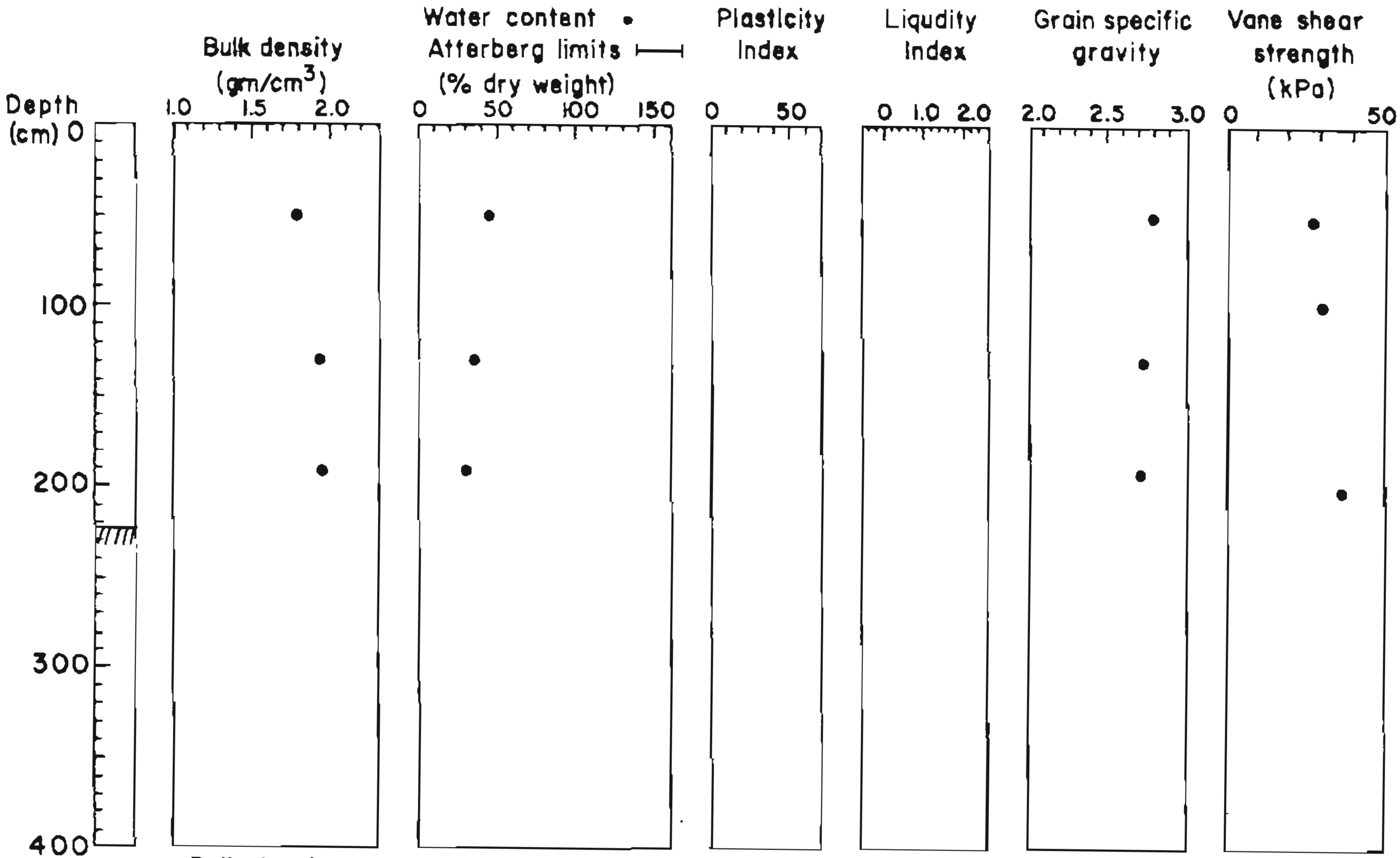
Average grain specific gravity: 2.63

Vane shear strength at lm.: 3.50

Station 350 Physiographic area Kiliuda Trough



Station 351 Physiographic area Kiliuda Trough



Bulk density at lm.: 1.89

Water content at lm.: 37

Average plastic limit: ____

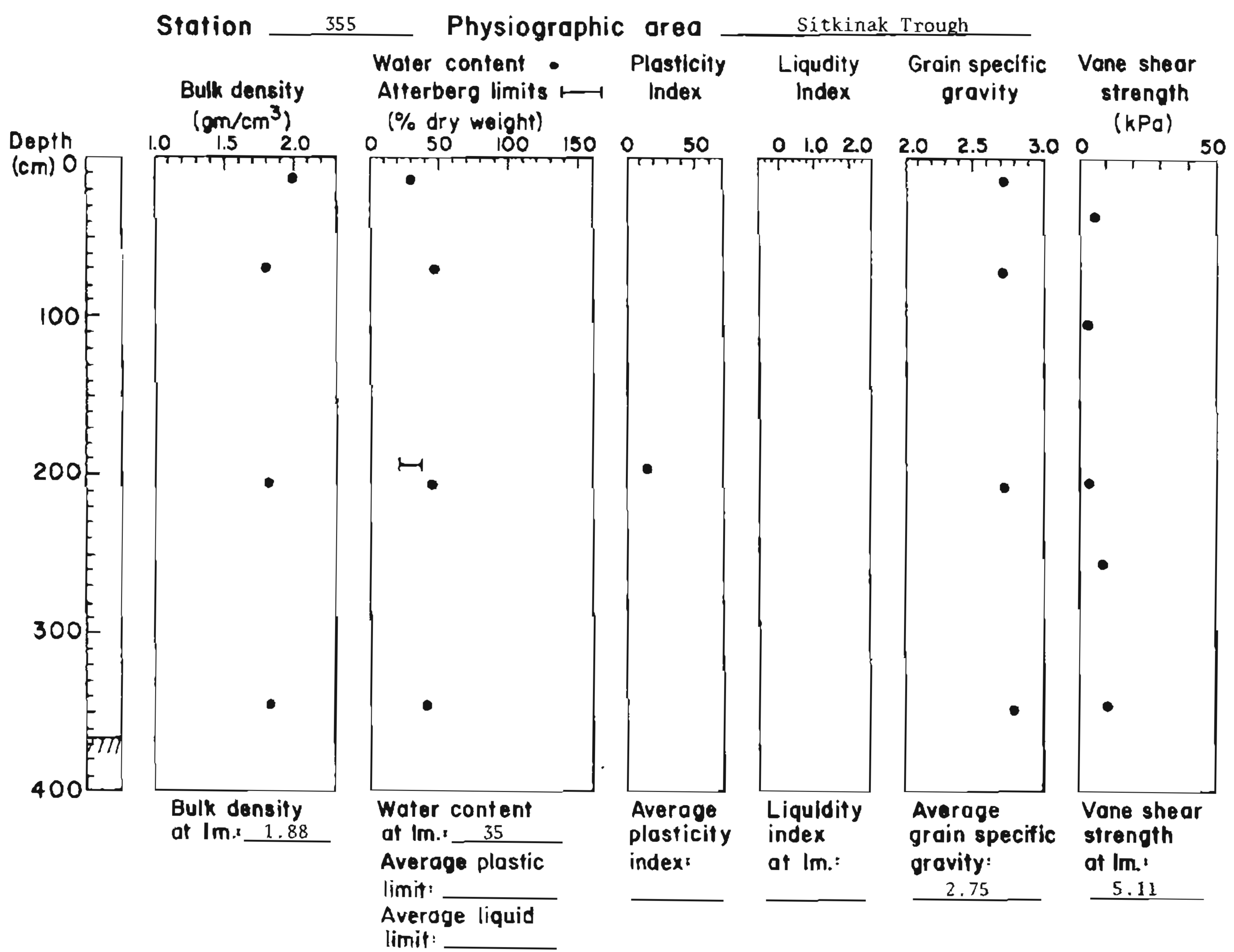
Average liquid limit: ____

Average plasticity index: ____

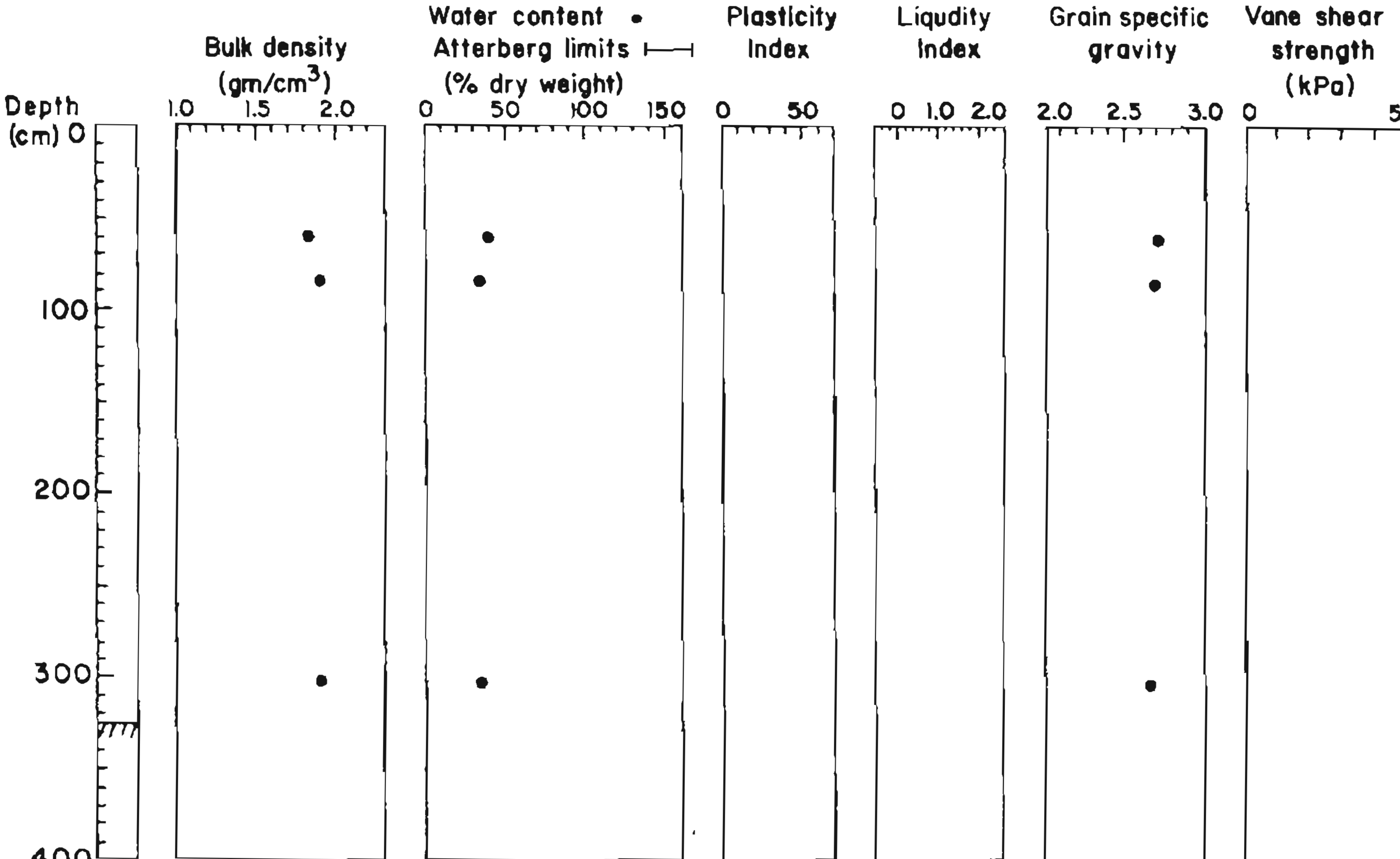
Liquidity index at lm.: ____

Average grain specific gravity: 2.75

Vane shear strength at lm.: 30.27


Station 355 Physiographic area Sitkinak Trough
Depth (cm)
0
100
200
300
400
Bulk density (gm/cm3)
1.0 1.5 2.0
Water content •
Atterberg limits ⊢⊣
(% dry weight)
0 50 100 150
Plasticity Index
0 50
Liqudity Index
0 1.0 2.0
Grain specific gravity
2.0 2.5 3.0
Vane shear strength (kPa)
0 50
Bulk density at Im.: 1.88
Water content at Im.: 35
Average plastic limit:
Average liquid limit:
Average plasticity index:
Liquidity index at Im.:
Average grain specific gravity: 2.75
Vane shear strength at Im.: 5.11

Station 356 Physiographic area Sitkinak Trough



Bulk density at lm.: 1.86

Water content at lm.: 36

Average plastic limit: ______

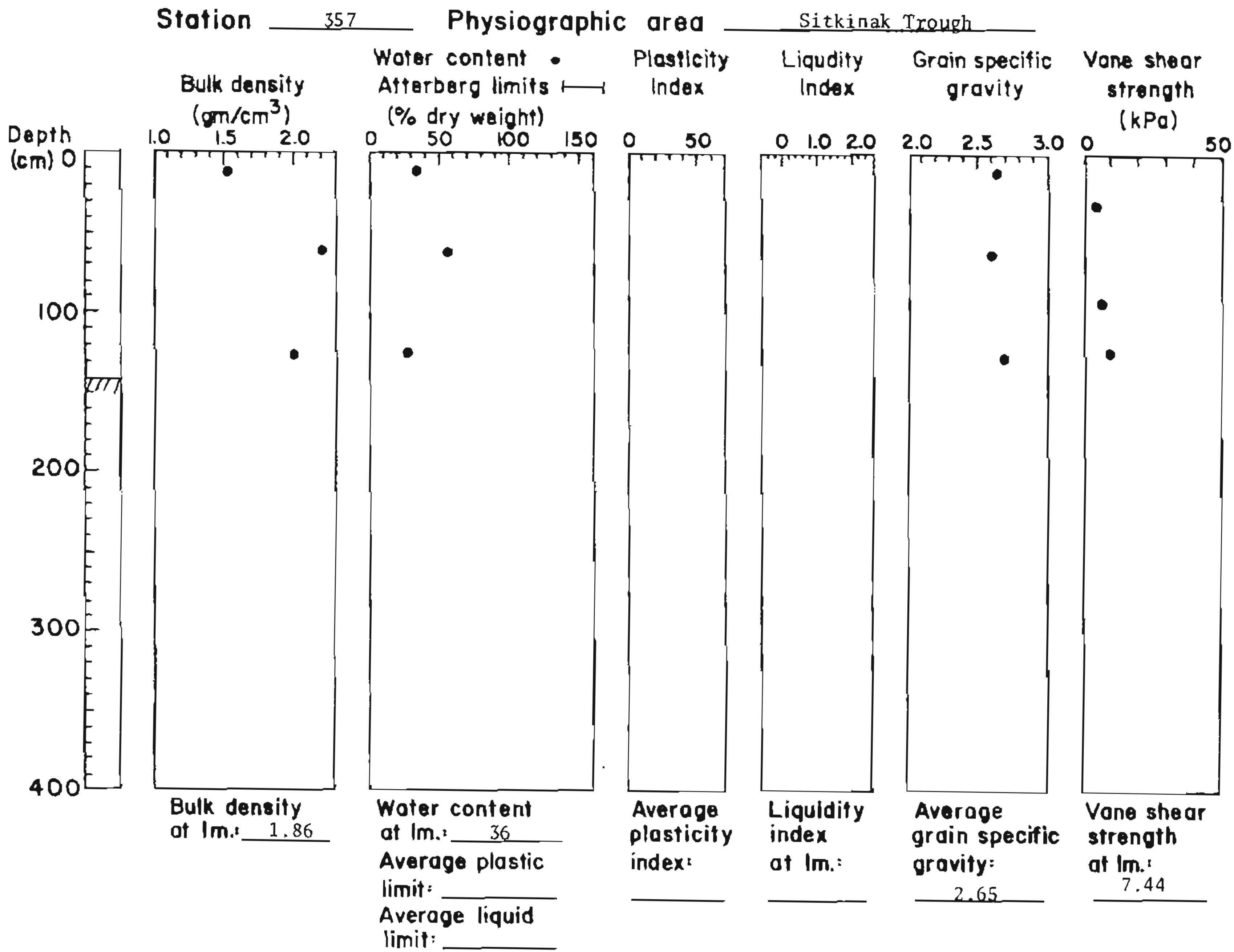
Average liquid limit: ______

Average plasticity index: ______

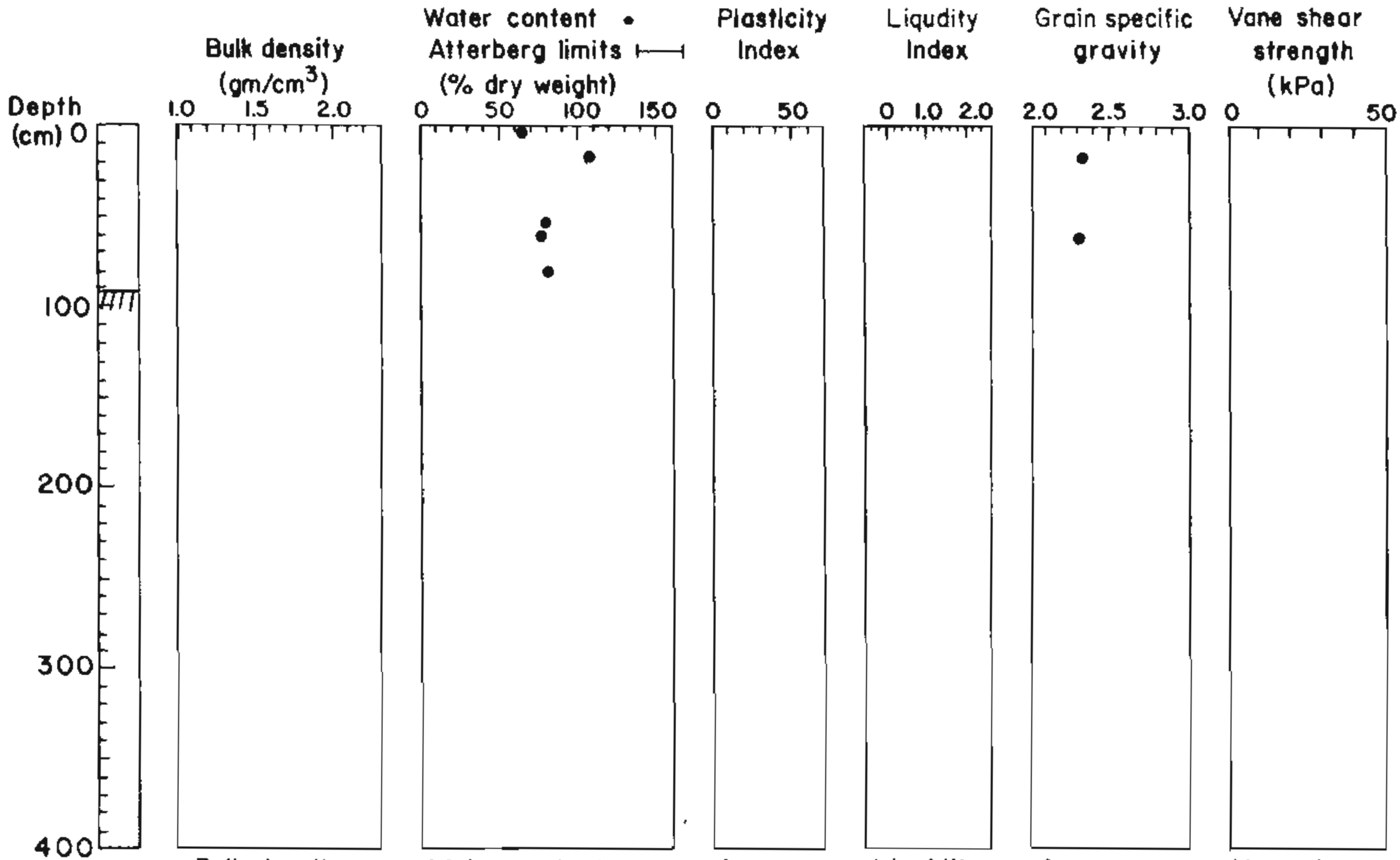
Liquidity index at lm.: ______

Average grain specific gravity: 2.70

Vane shear strength at lm.: ______


Station 357
Physiographic area Sitkinak Trough
Depth (cm)
0
100
200
300
400
Bulk density (gm/cm3)
1.0 1.5 2.0
Water content •
Atterberg limits
(% dry weight)
0 50 100 150
Plasticity Index
0 50
Liquidity Index
0 1.0 2.0
Grain specific gravity
2.0 2.5 3.0
Vane shear strength (kPa)
0 50
Bulk density at lm.: 1.86
Water content at lm.: 36
Average plastic limit:
Average liquid limit:
Average plasticity index:
Liquidity index at lm.:
Average grain specific gravity: 2.65
Vane shear strength at lm.: 7.44

Station 432 Physiographic area Chiniak Trough



Bulk density at lm.: 1.47

Water content at lm.: 81

Average plastic limit: ____

Average liquid limit: ____

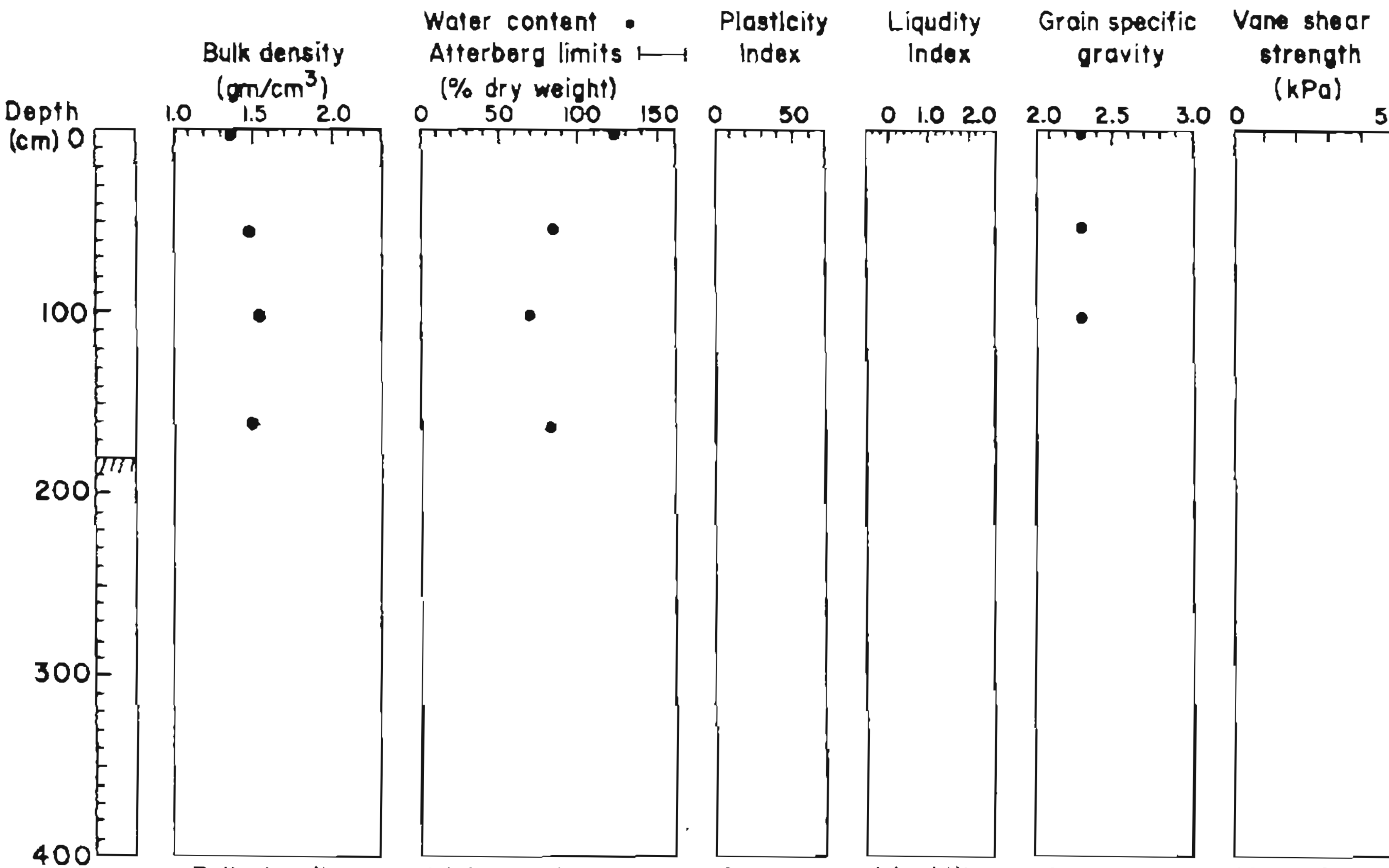
Average plasticity index: ____

Liquidity index at lm.: ____

Average grain specific gravity: 2.32

Vane shear strength at lm.: ____

Station 432 Physiographic area Chiniak Trough



Bulk density at 1m.: 1.53

Water content at 1m.: 86

Average plastic limit: ______

Average liquid limit: ______

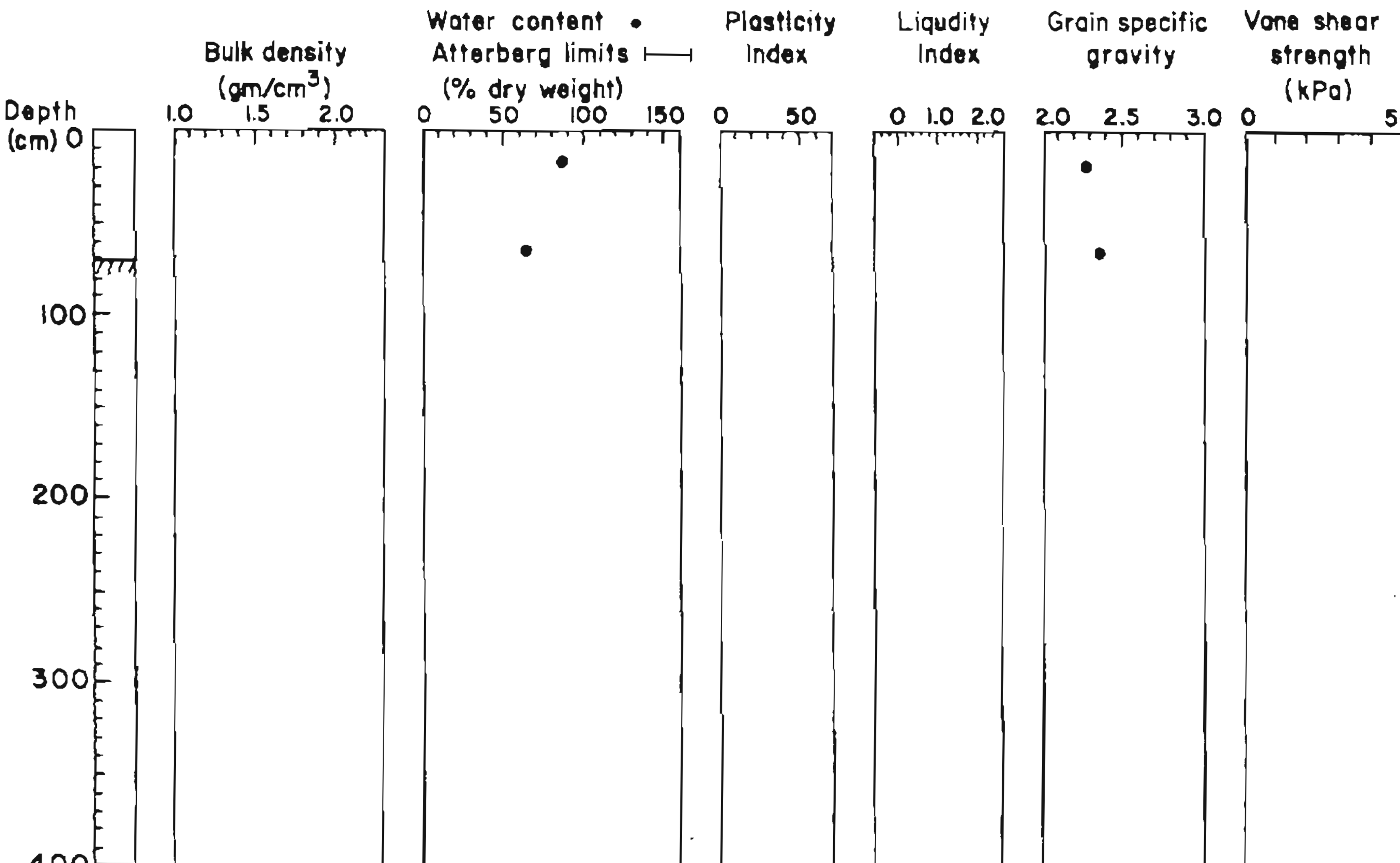
Average plasticity index: ______

Liquidity index at 1m.: ______

Average grain specific gravity: 2.30

Vane shear strength at 1m.: ______

Station 433 Physiographic area Chiniak Trough



Bulk density at Im.: ______

Water content at Im.: 67

Average plastic limit: ______

Average liquid limit: ______

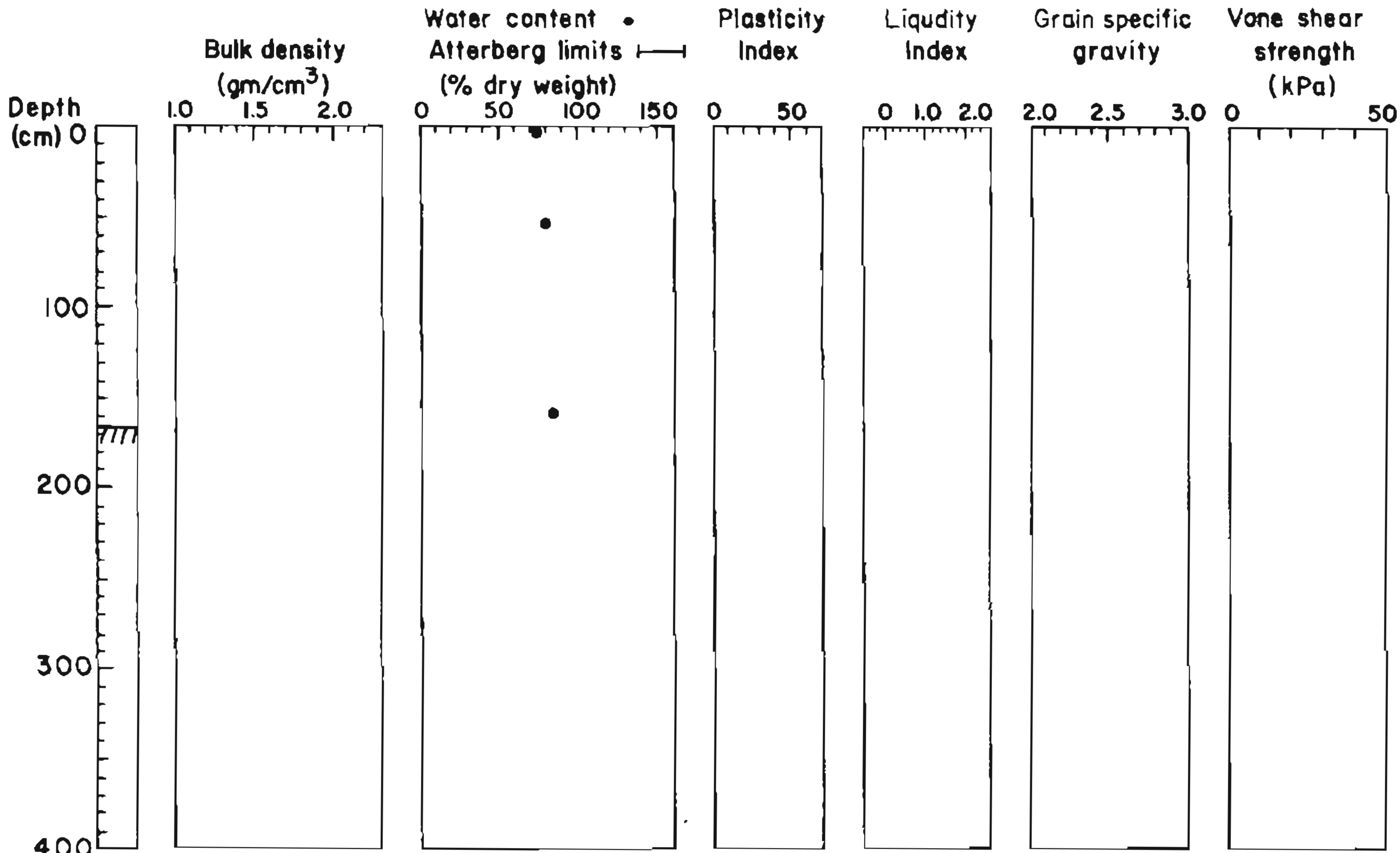
Average plasticity index: ______

Liquidity index at Im.: ______

Average grain specific gravity: 2.30

Vane shear strength at Im.: ______

Station 433 Physiographic area Chiniak Trough



Bulk density at lm.: ______

Water content at lm.: 67

Average plastic limit: ______

Average liquid limit: ______

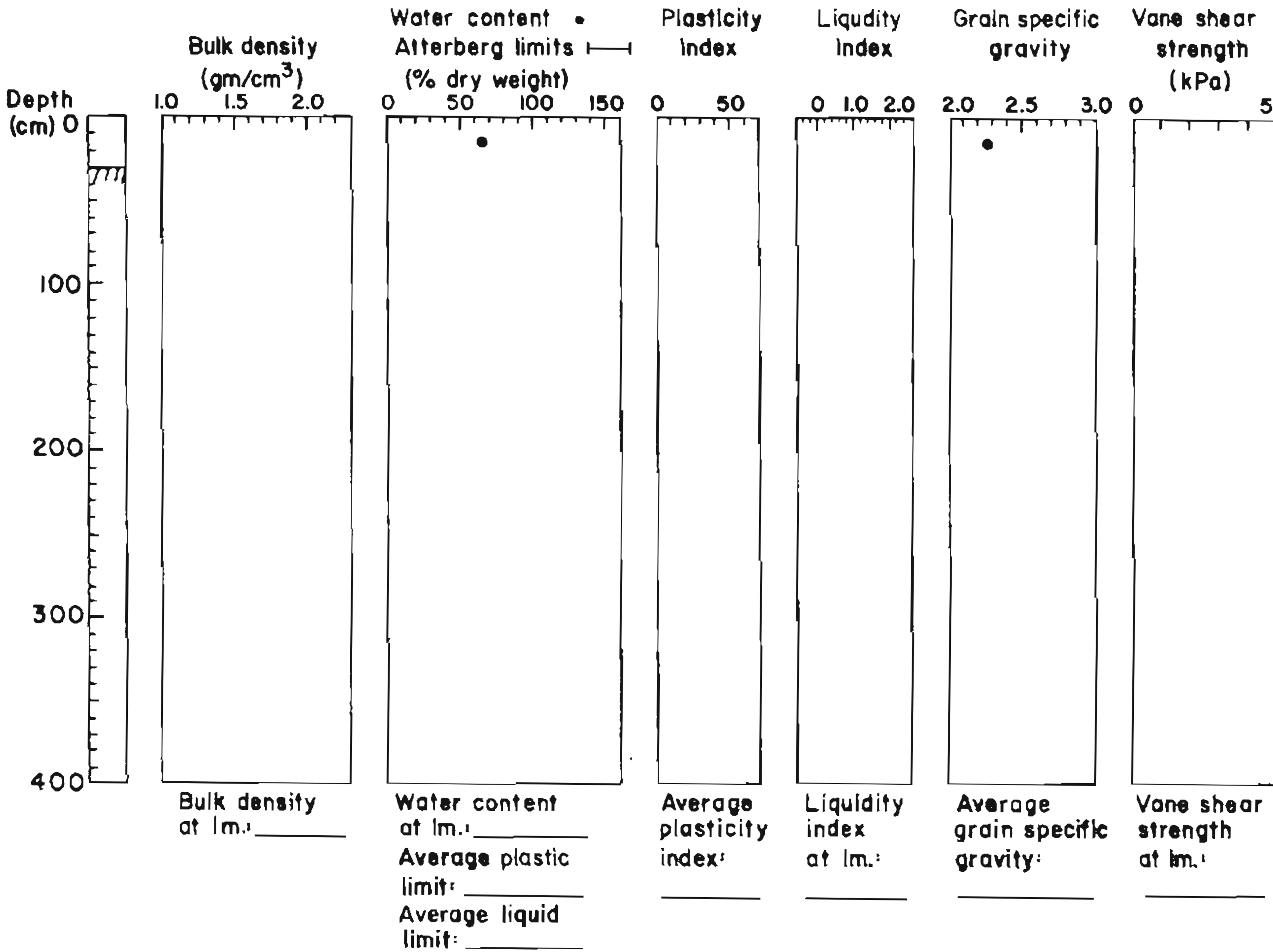
Average plasticity index: ______

Liquidity index at lm.: ______

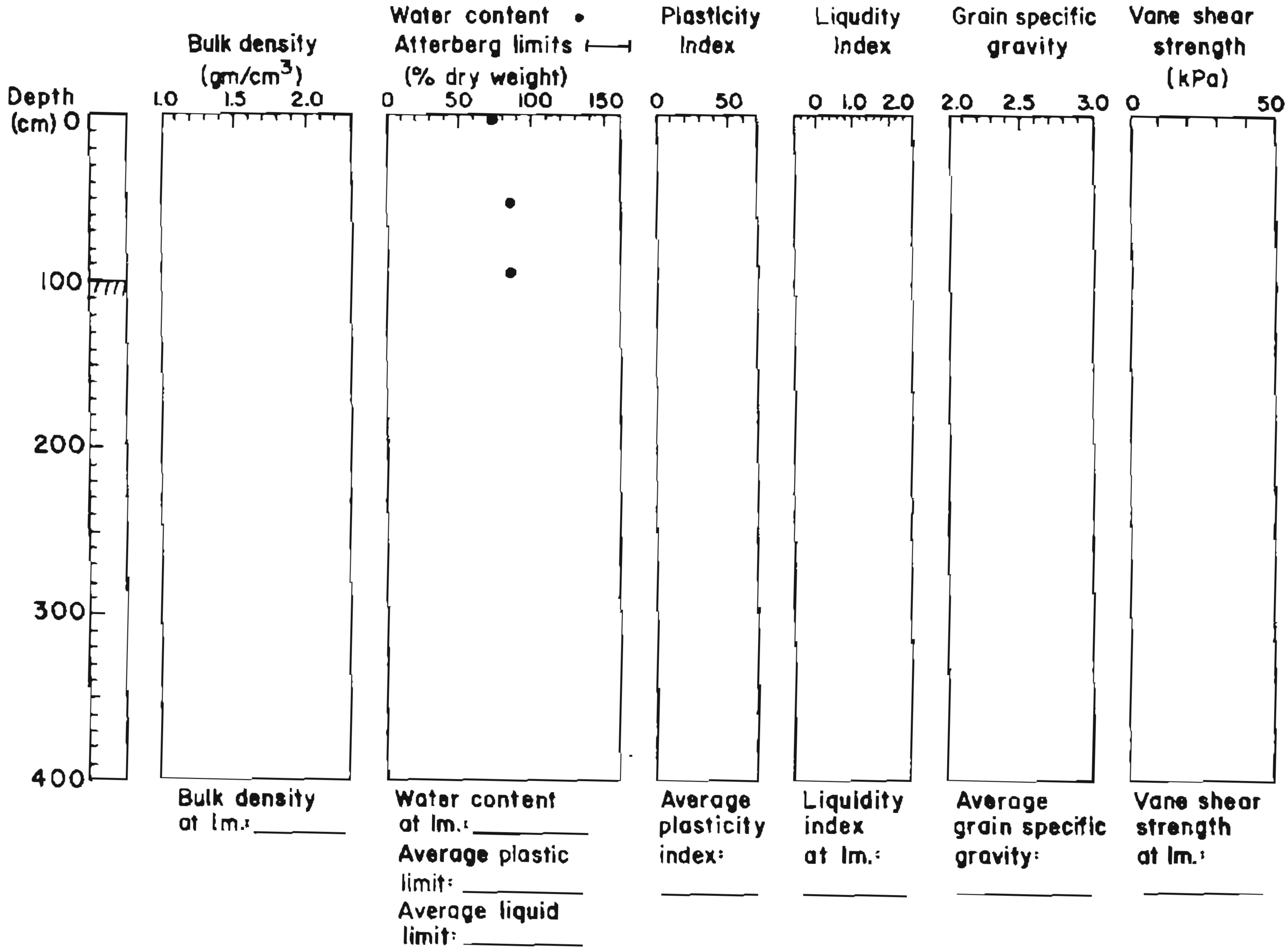
Average grain specific gravity: 2.31

Vane shear strength at lm.: ______

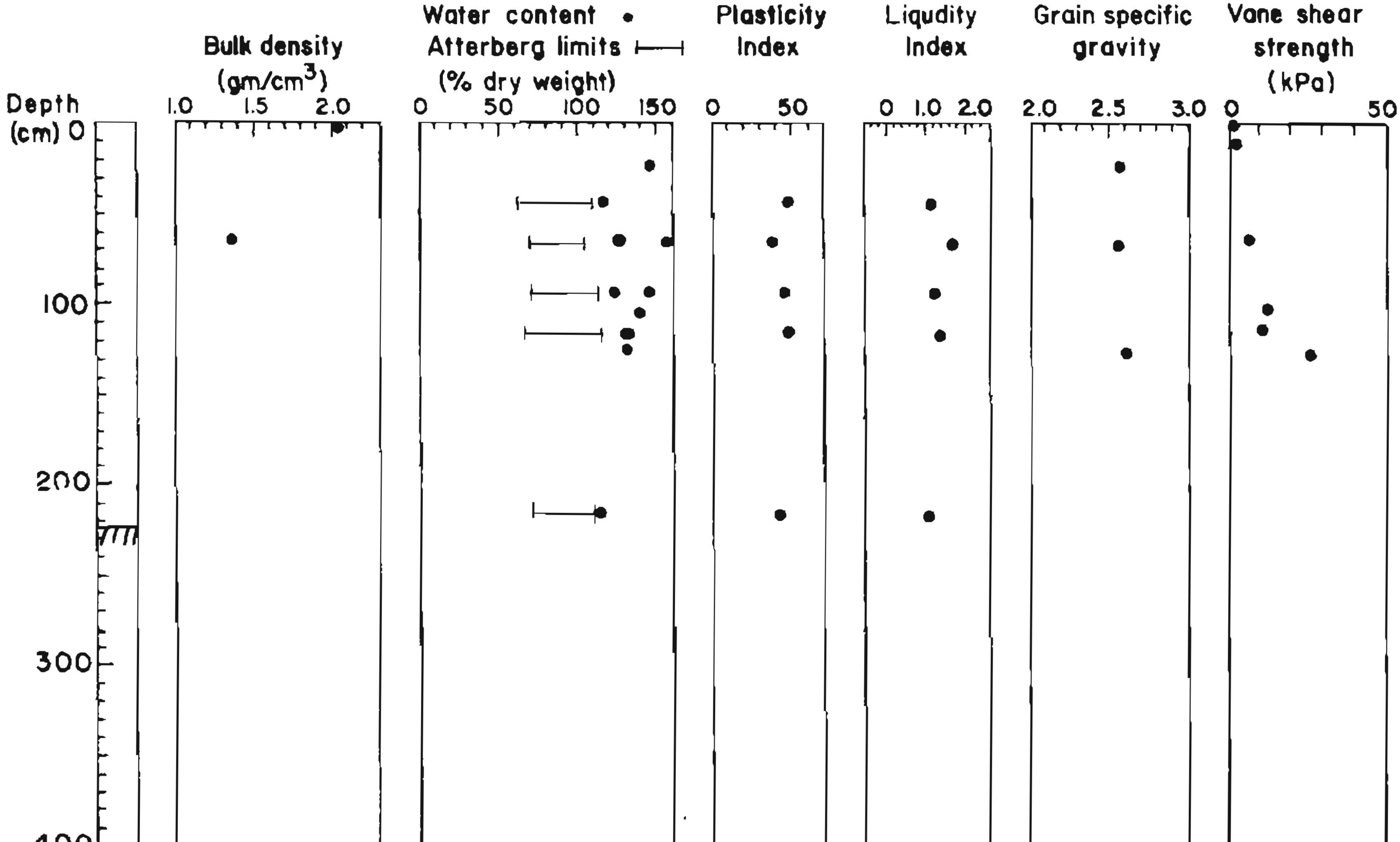
Station 434 Physiographic area Chiniak Trough



Station 435 Physiographic area Chiniak Trough



Station 439 **Physiographic area** Kiliuda Trough



Bulk density at lm.: 1.37

Water content at lm.: 133

Average plastic limit: 67

Average liquid limit: 110

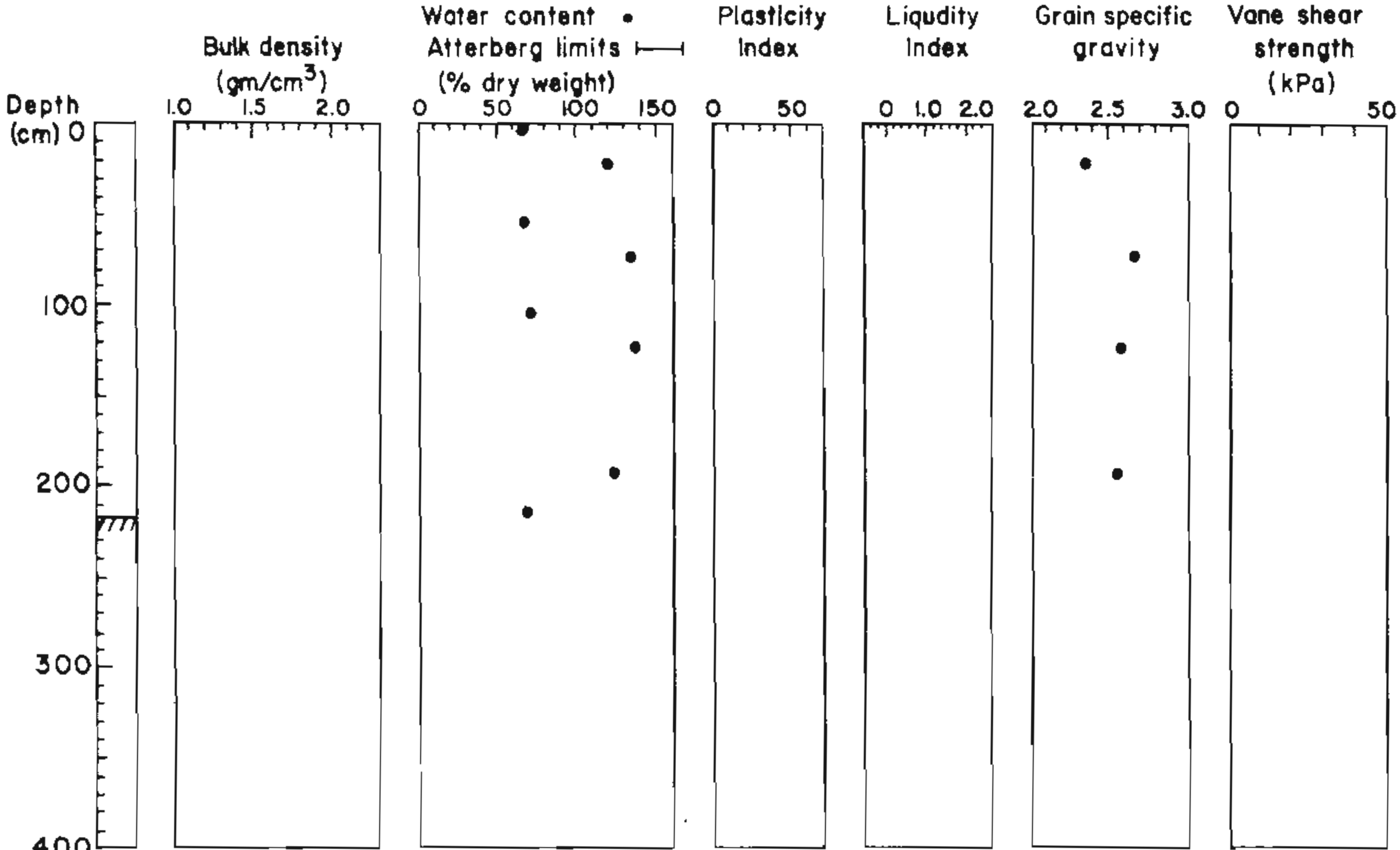
Average plasticity index: 43

Liquidity index at lm.: 1.31

Average grain specific gravity: 2.57

Vane shear strength at lm.: 10.12

Station 439 **Physiographic area** Kiliuda Trough



Bulk density at lm.: ______

Water content at lm.: 99

Average plastic limit: ______

Average liquid limit: ______

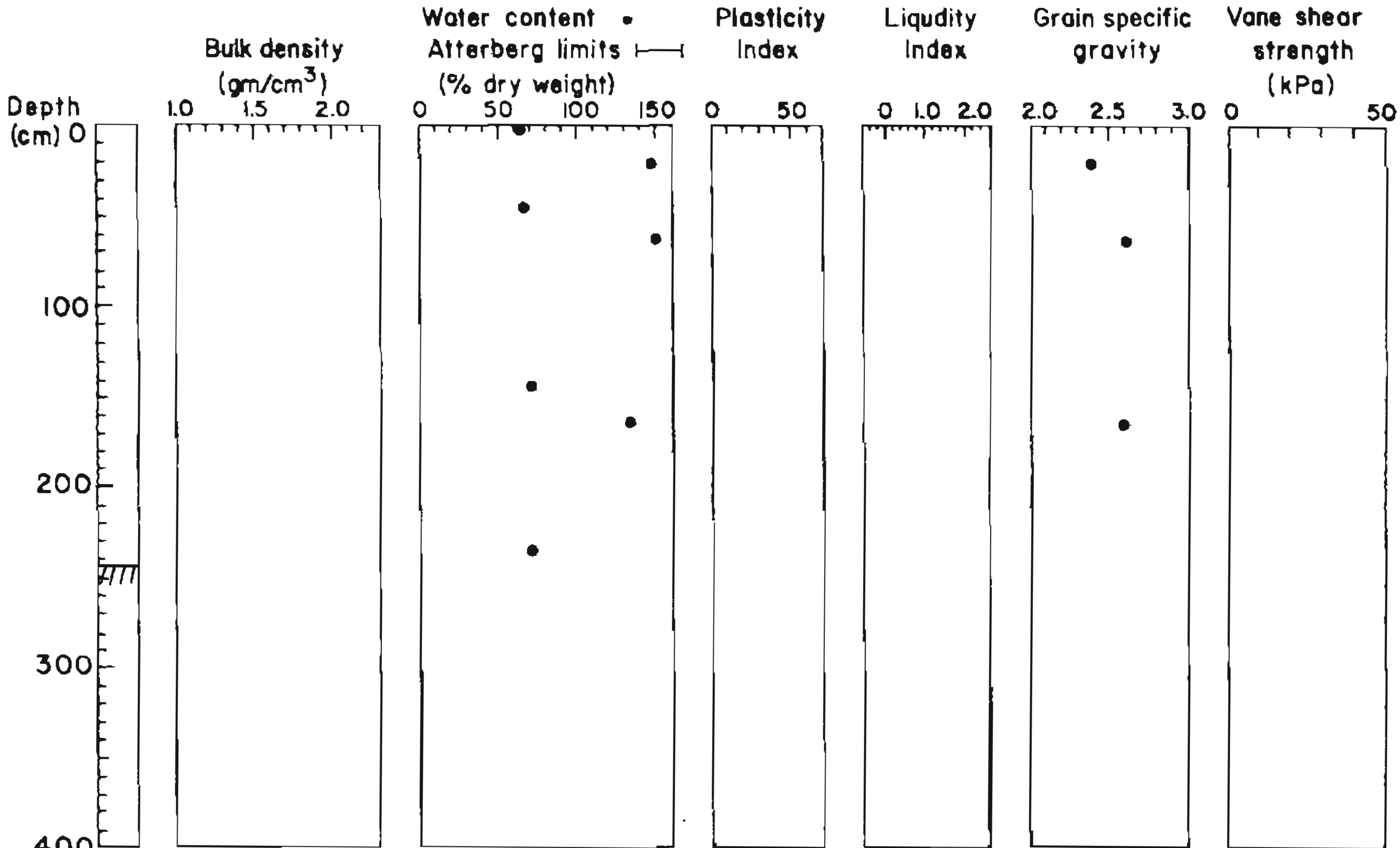
Average plasticity index: ______

Liquidity index at lm.: ______

Average grain specific gravity: 2.52

Vane shear strength at lm.: ______

Station 440 **Physiographic area** Kiliuda Trough



Bulk density at lm.: ________

Water content at lm.: 100

Average plastic limit: ________

Average liquid limit: ________

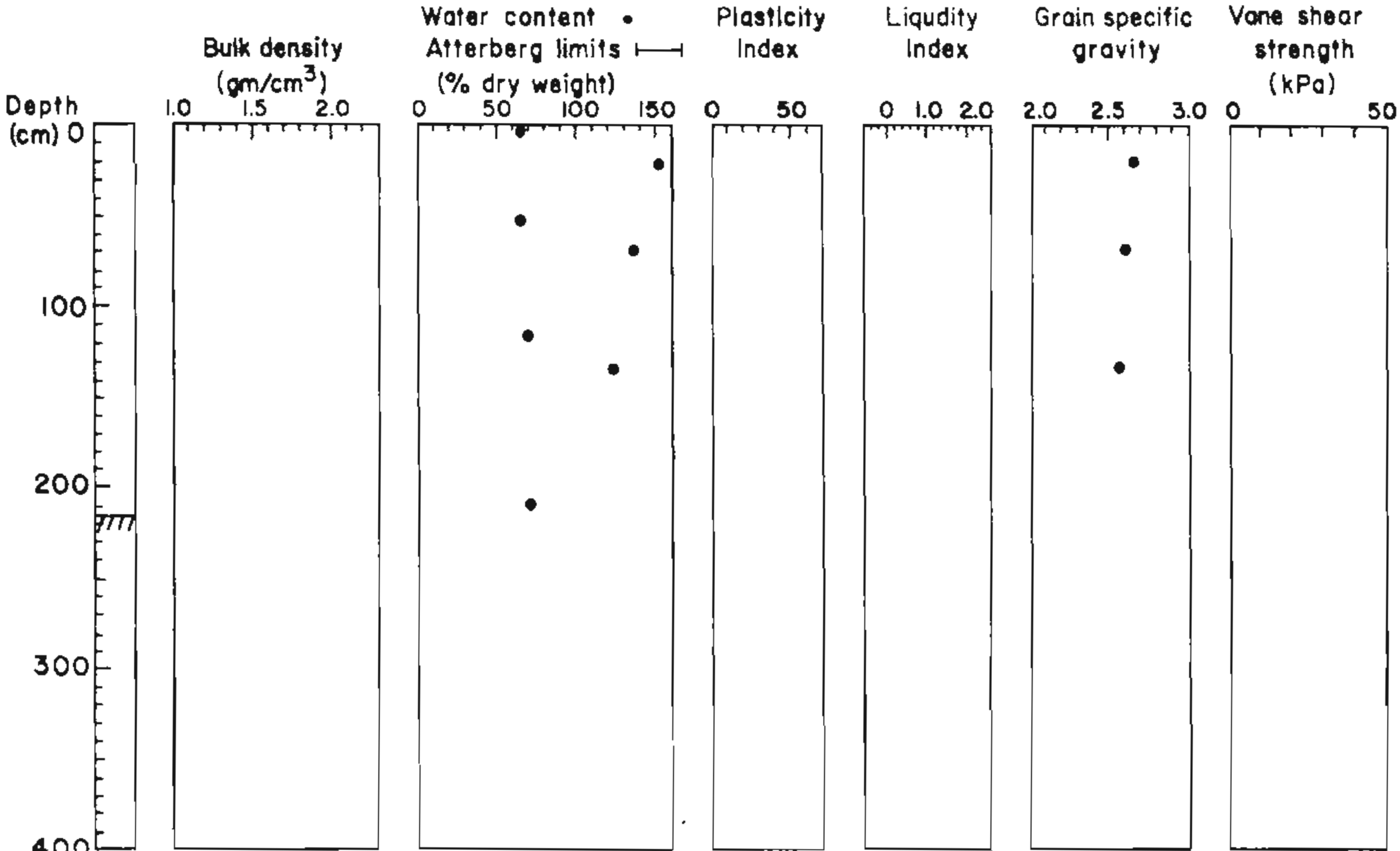
Average plasticity index: ________

Liquidity index at lm.: ________

Average grain specific gravity: 2.52

Vane shear strength at lm.: ________

Station 441 Physiographic area Kiliuda Trough



Bulk density at lm.: ________

Water content at lm.: 97

Average plastic limit: ________

Average liquid limit: ________

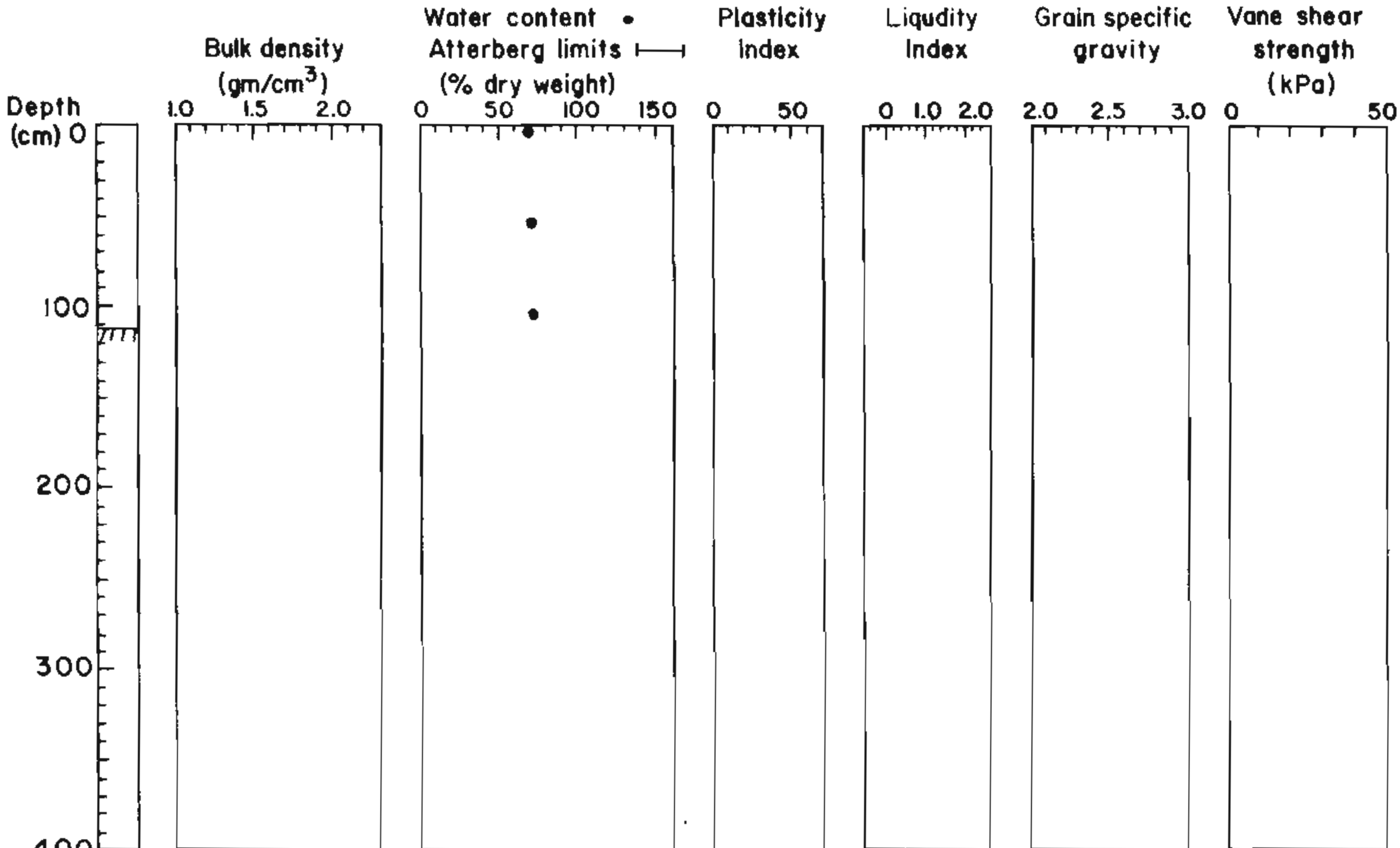
Average plasticity index: ________

Liquidity index at lm.: ________

Average grain specific gravity: 2.60

Vane shear strength at lm.: ________

Station 442 Physiographic area Kiliuda Trough



Bulk density at 1m.: ________

Water content at 1m.: 70

Average plastic limit: ________

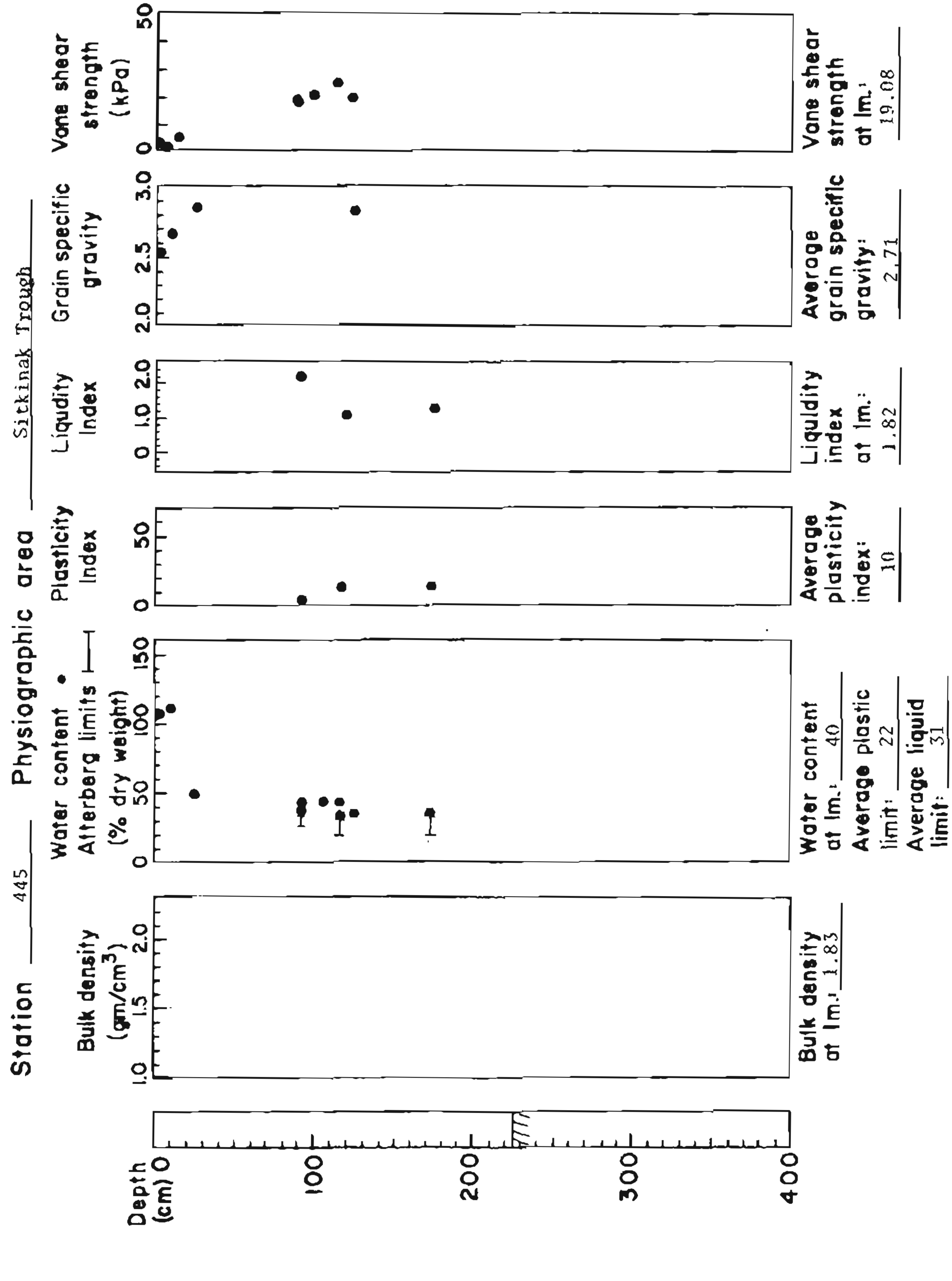
Average liquid limit: ________

Average plasticity index: ________

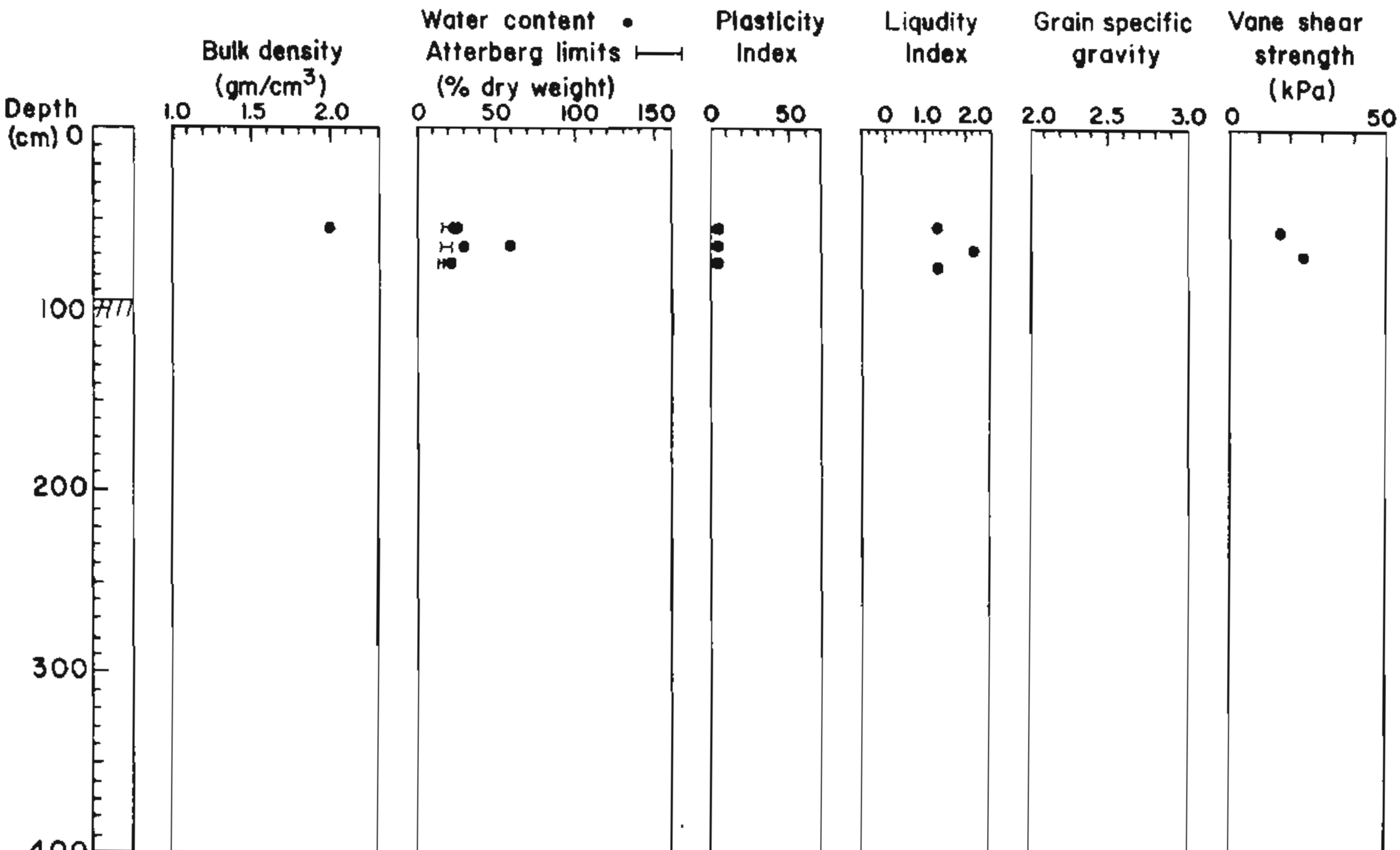
Liquidity index at 1m.: ________

Average grain specific gravity: ________

Vane shear strength at 1m.: ________


Station 445
Physiographic area Sitkinak Trough
Depth (cm)
0
100
200
300
400
Bulk density (gm/cm3)
1.0
1.5
2.0
Water content •
Atterberg limits
(% dry weight)
0
50
100
150
Plasticity index
0
50
Liquidity index
0
1.0
2.0
Grain specific gravity
2.0
2.5
3.0
Vane shear strength (kPa)
0
50
Bulk density at lm.: 1.83
Water content at lm.: 40
Average plastic limit: 22
Average liquid limit: 31
Average plasticity index: 10
Liquidity index at lm.: 1.82
Average grain specific gravity: 2.71
Vane shear strength at lm.: 19.08

Station 450 Physiographic area Upper Continental Slope



Bulk density at lm.: ______

Water content at lm.: 21

Average plastic limit: 19

Average liquid limit: 20

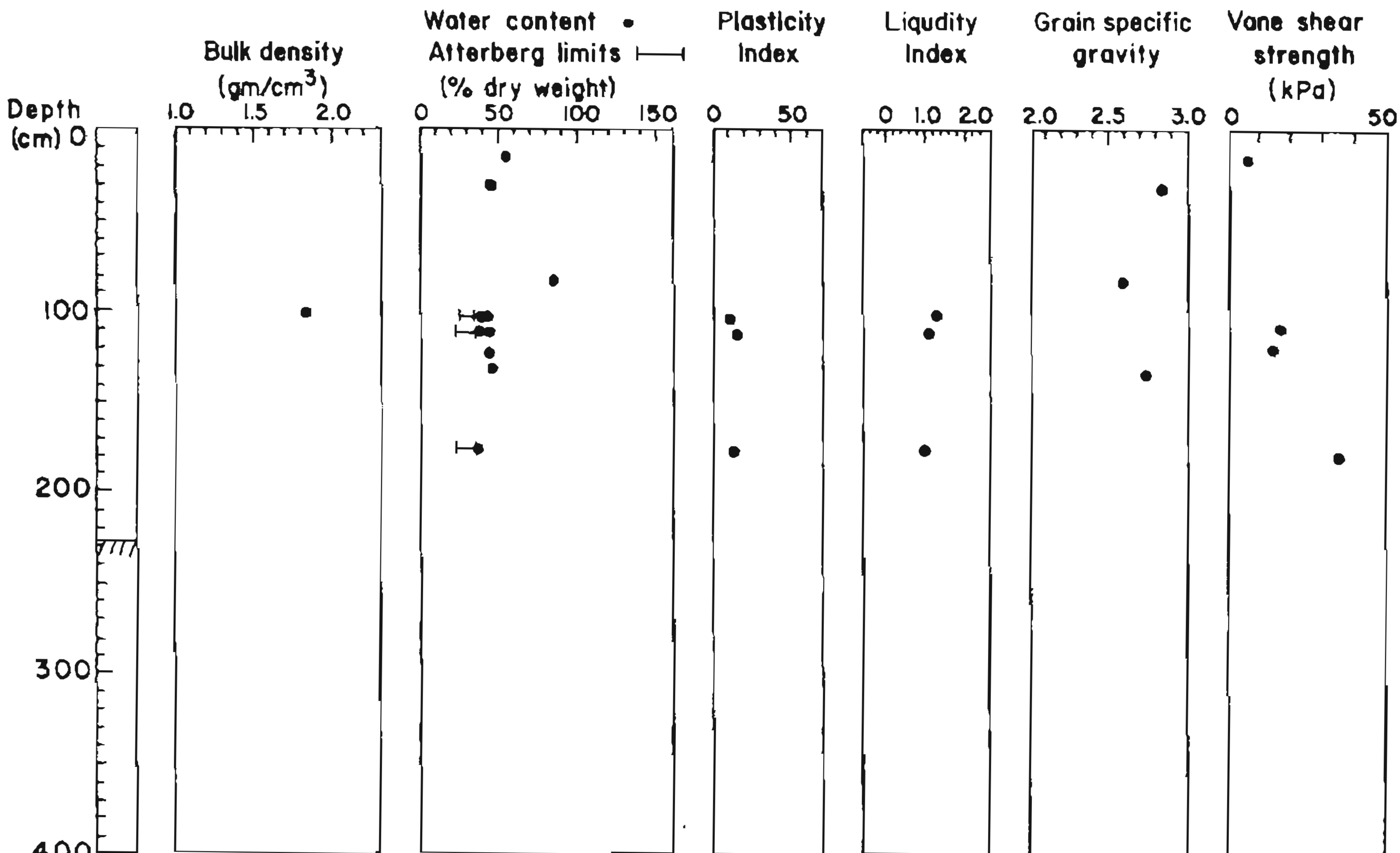
Average plasticity index: 4

Liquidity index at lm.: ______

Average grain specific gravity: ______

Vane shear strength at lm.: ______

Station 455 Physiographic area Sitkinak Trough



Bulk density at Im.: 1.77

Water content at Im.: 45

Average plastic limit: 23

Average liquid limit: 36

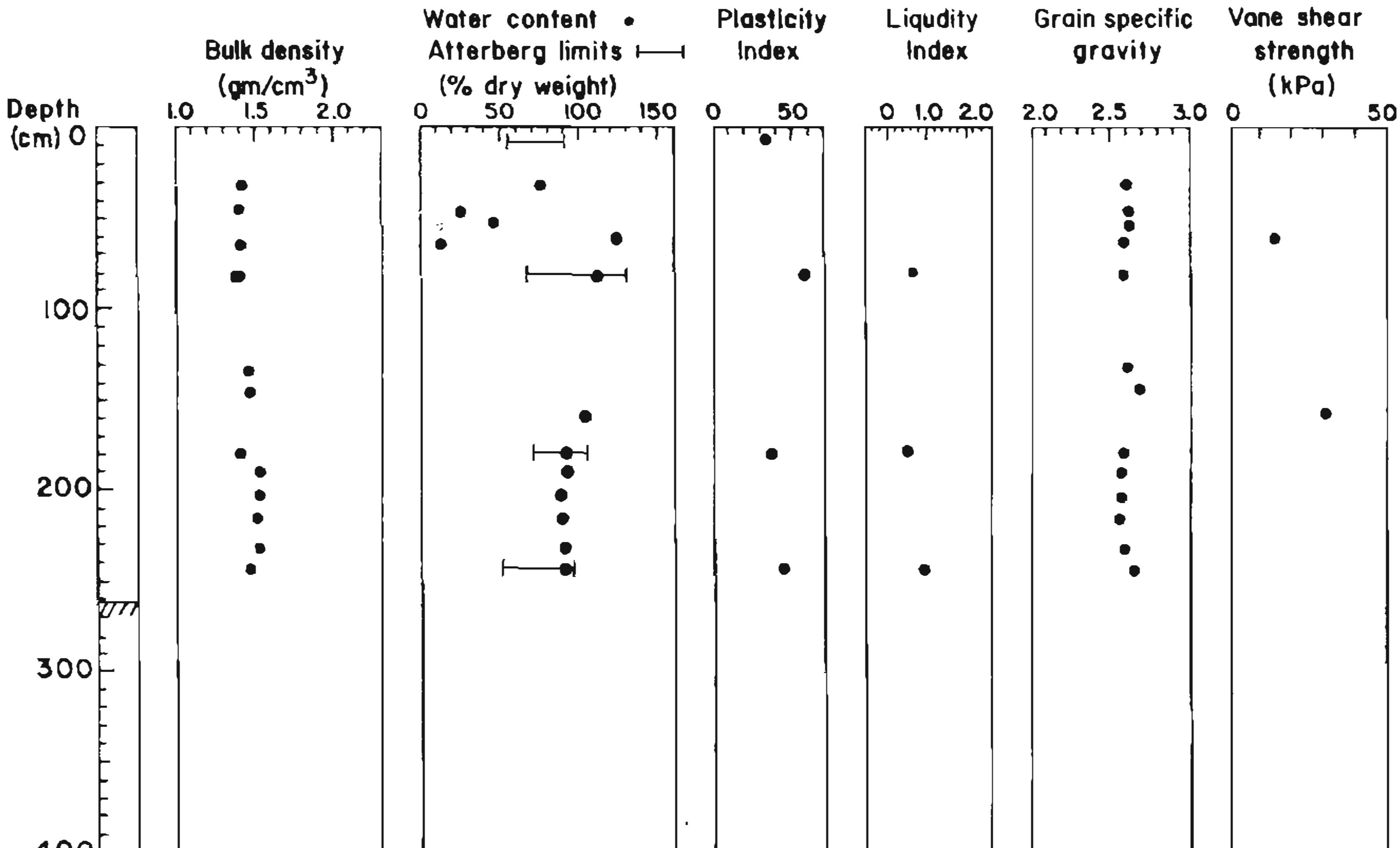
Average plasticity index: 12

Liquidity index at Im.: 1.24

Average grain specific gravity: 2.69

Vane shear strength at Im.: 15.23

Station 578 **Physiographic area** Kiliuda Trough



Bulk density at lm.: 1.39

Water content at lm.: 105

Average plastic limit: 64

Average liquid limit: 106

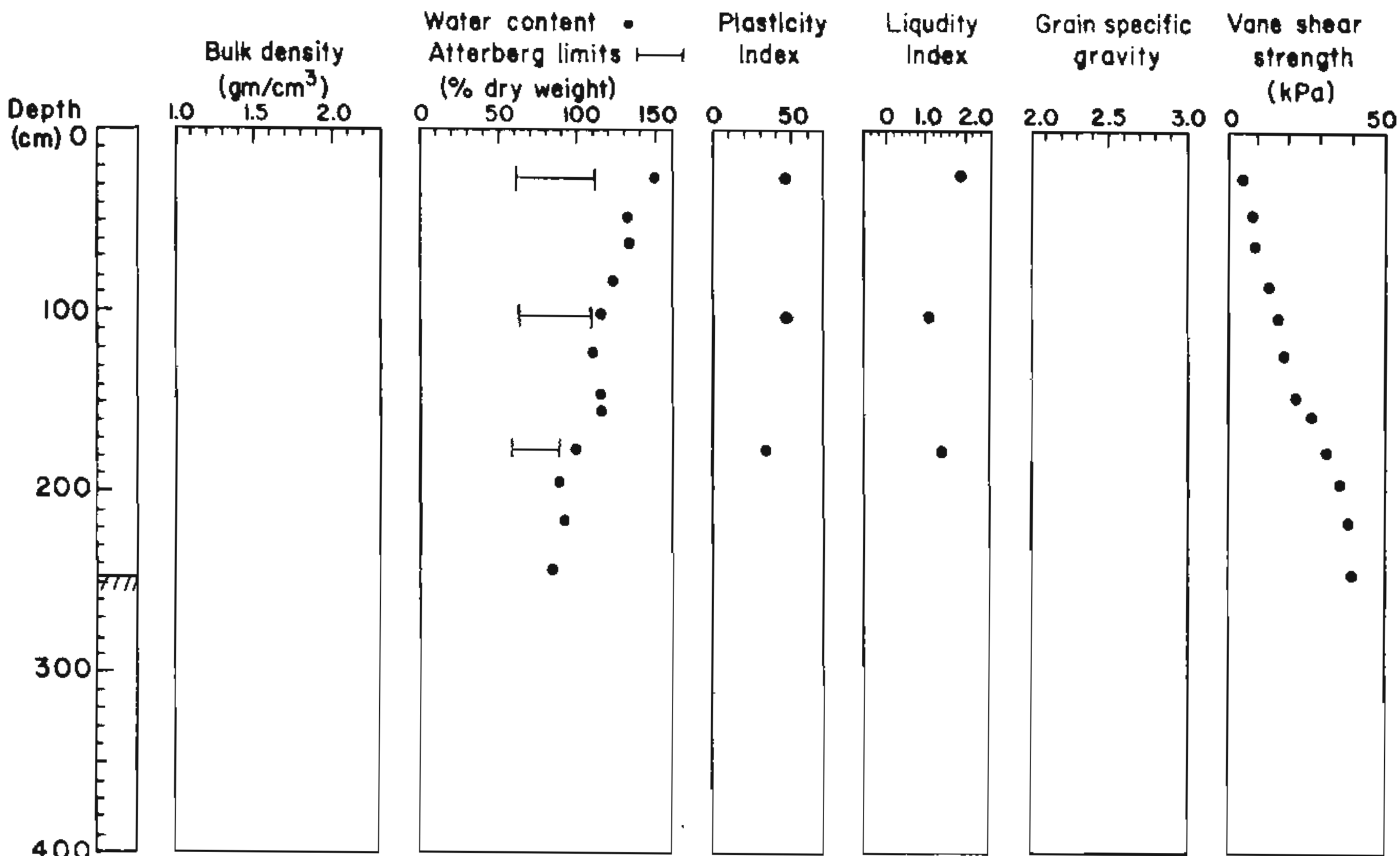
Average plasticity index: 42

Liquidity index at lm.: 0.6

Average grain specific gravity: 2.58

Vane shear strength at lm.: 15.90

Station 578 Physiographic area Kiliuda Trough



Bulk density at 1m.: ______

Water content at 1m.: 122

Average plastic limit: 60

Average liquid limit: 102

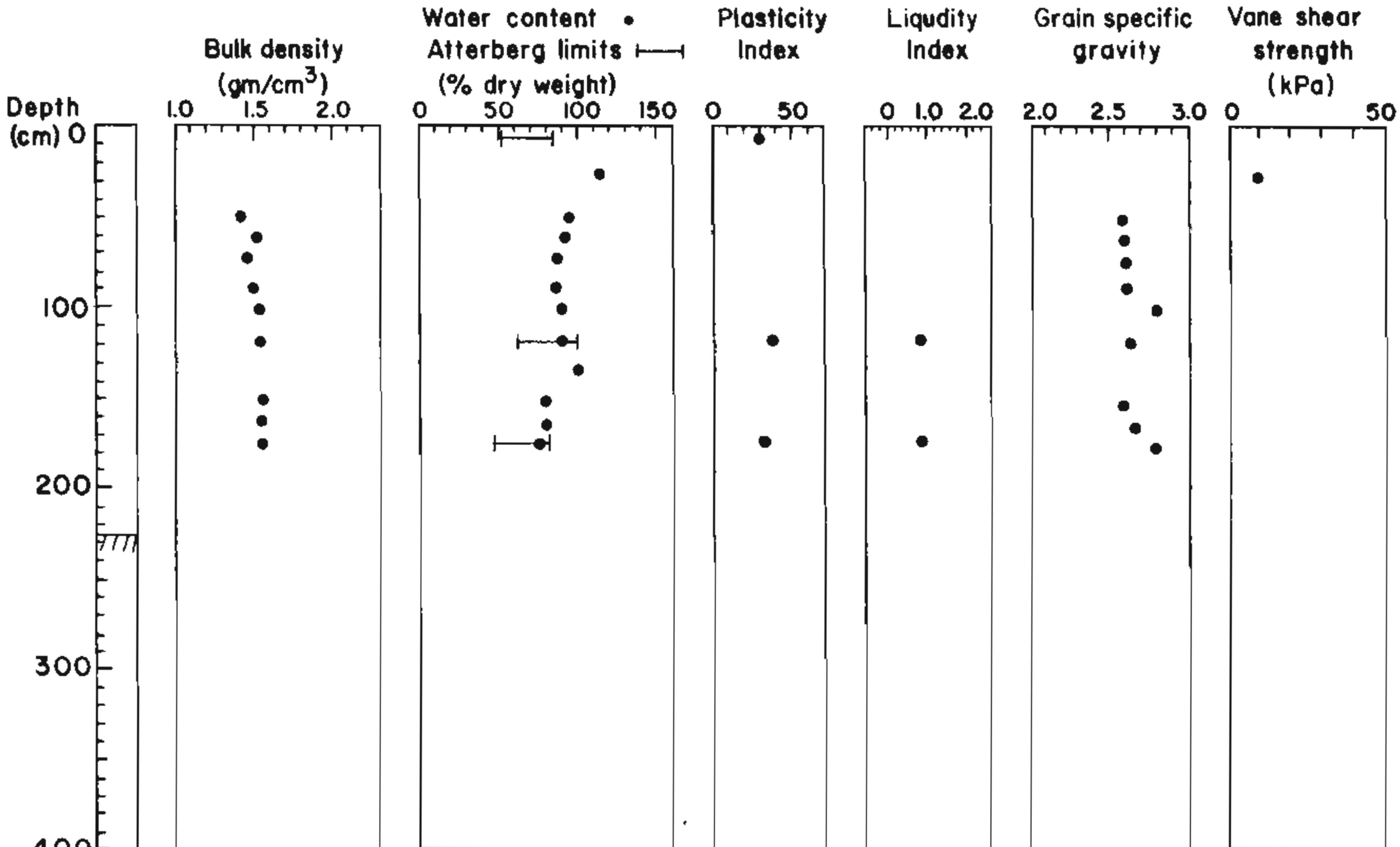
Average plasticity index: 42

Liquidity index at 1m.: 1.47

Average grain specific gravity: ______

Vane shear strength at 1m.: 15.90

Station 579 Physiographic area Kiliuda Trough



Bulk density at lm.: 1.48

Water content at lm.: 91

Average plastic limit: 54

Average liquid limit: 87

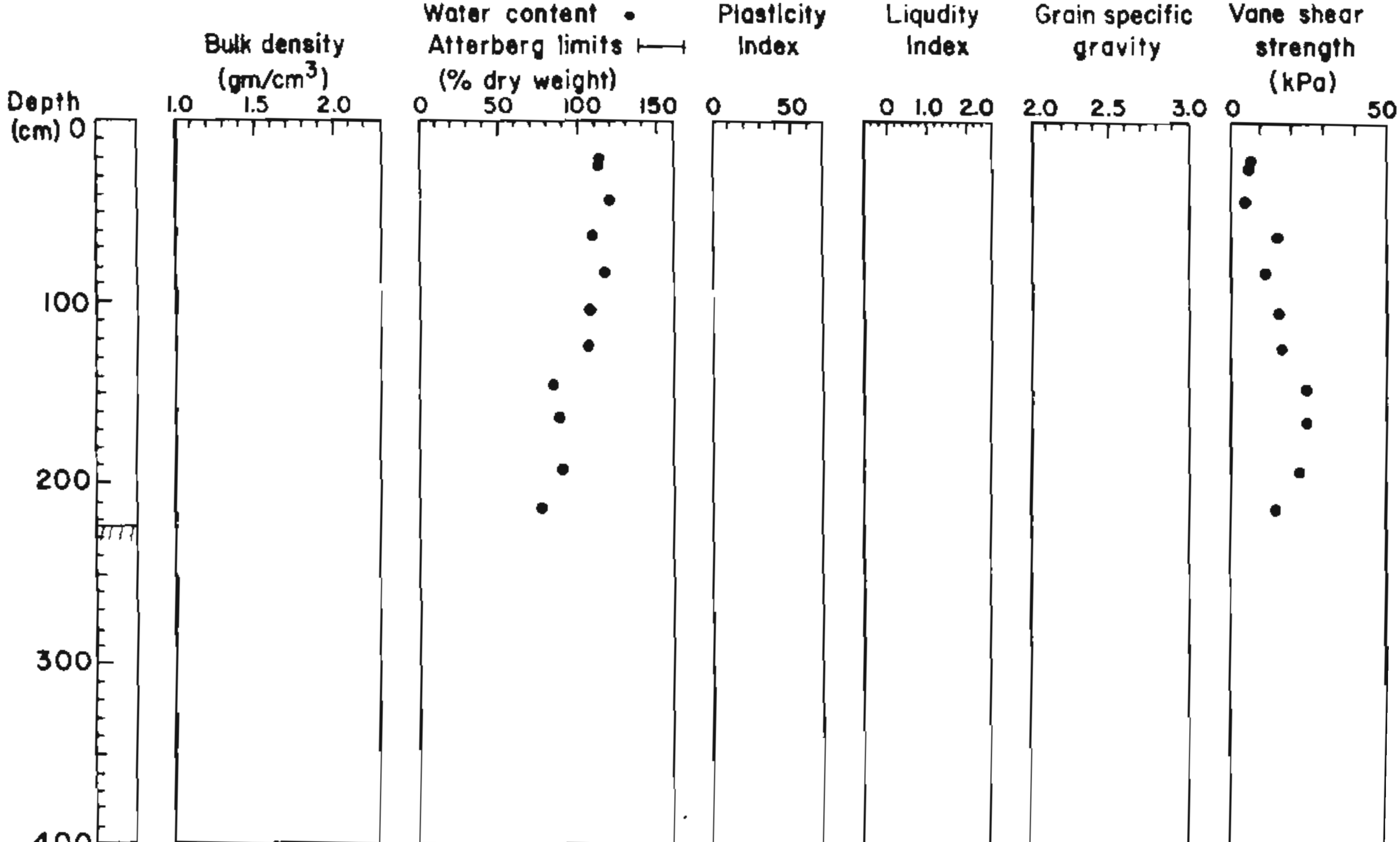
Average plasticity index: 33

Liquidity index at lm.: 0.8

Average grain specific gravity: 2.64

Vane shear strength at lm.: ______

Station 579 Physiographic area Kiliuda Trough



Bulk density at 1m.: ______

Water content at 1m.: 100

Average plastic limit: ______

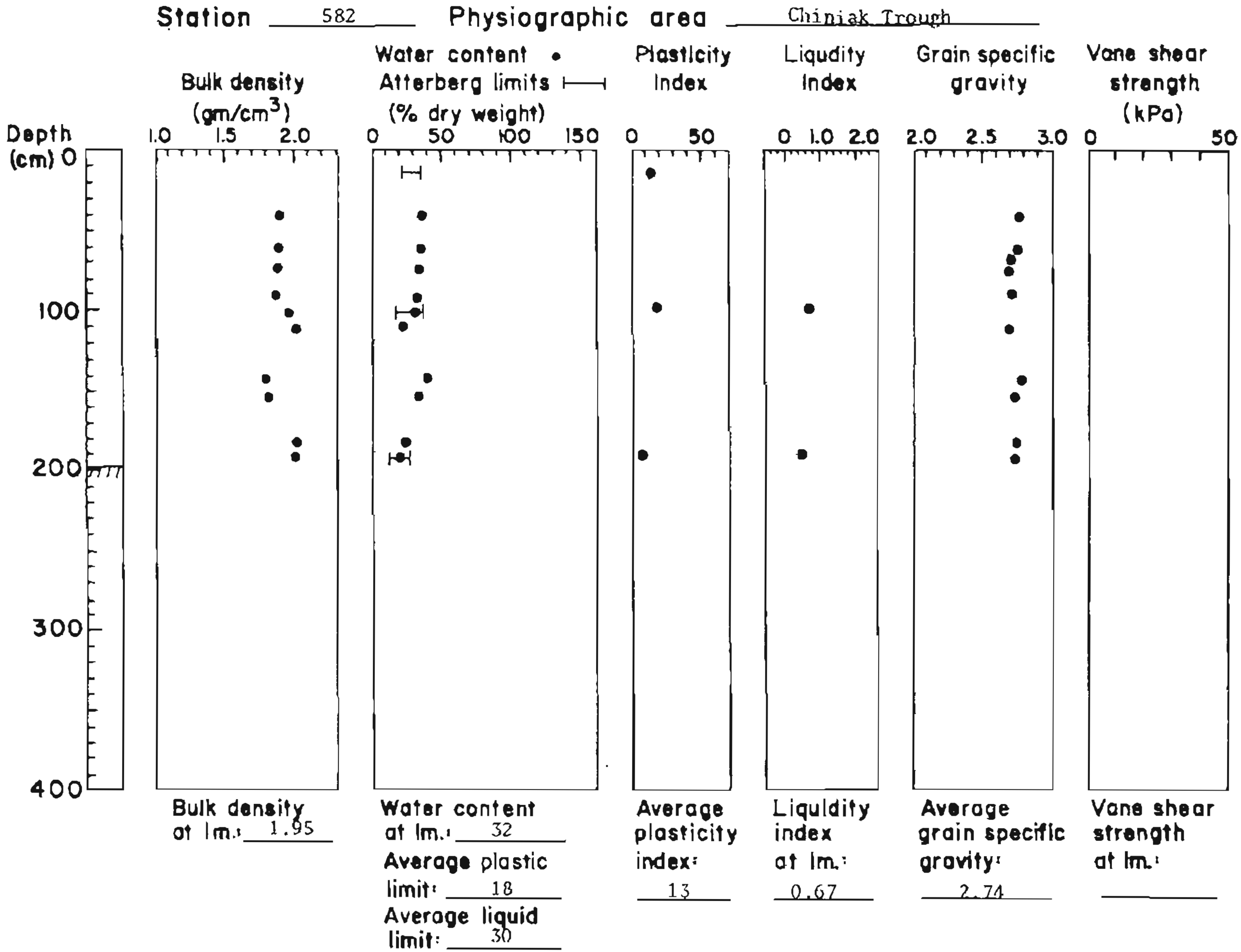
Average liquid limit: ______

Average plasticity index: ______

Liquidity index at 1m.: ______

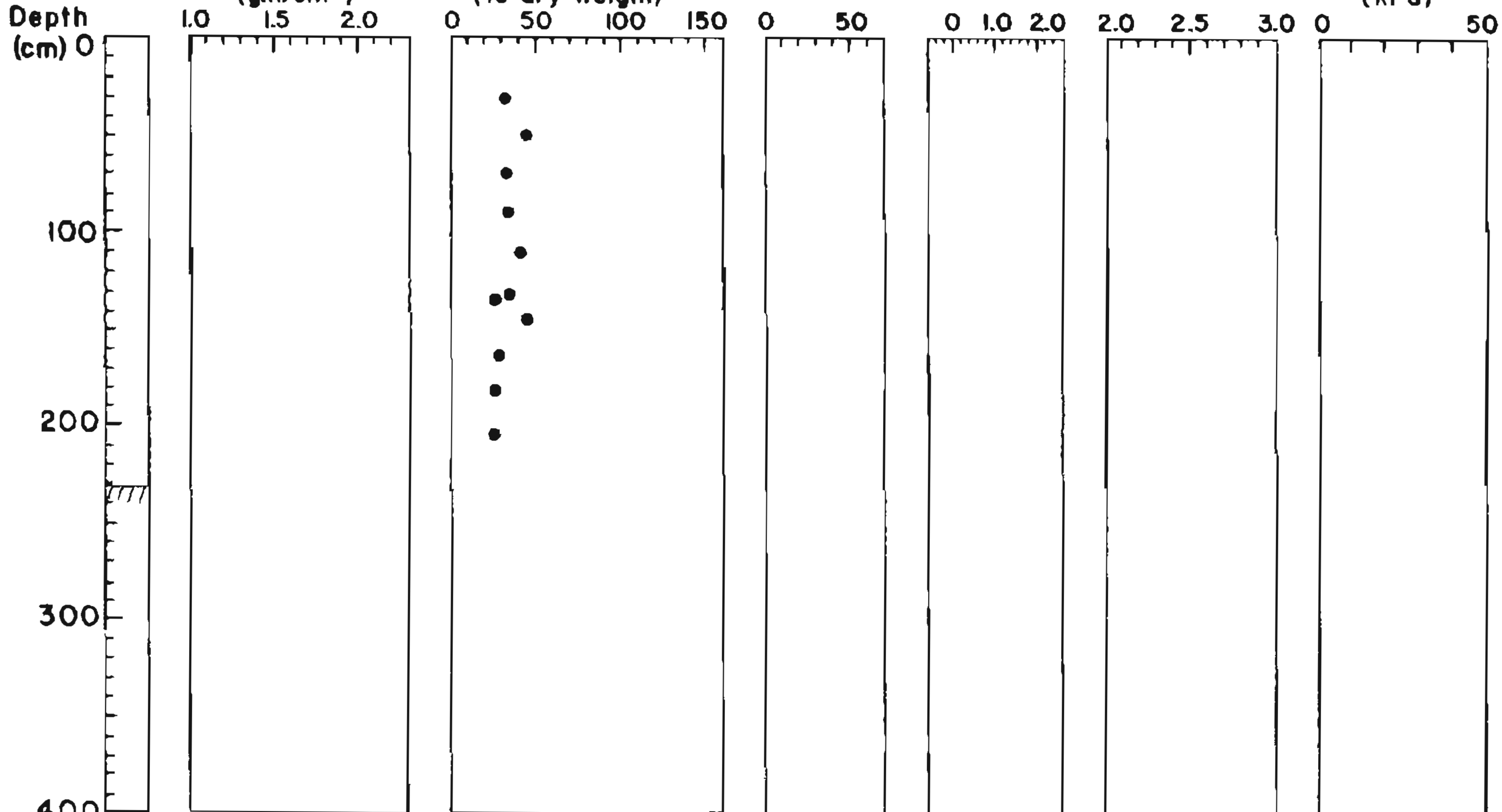
Average grain specific gravity: ______

Vane shear strength at 1m.: 13.63



Station 582 Physiographic area Chiniak Trough
Water content •
Atterberg limits ⊢⊣
Bulk density (gm/cm³)
(% dry weight)
Plasticity Index
Liqudity Index
Grain specific gravity
Vane shear strength (kPa)
Depth (cm)
0
100
200
300
400
1.0 1.5 2.0
0 50 100 150
0 50
0 1.0 2.0
2.0 2.5 3.0
0 50
Bulk density at lm.: 1.95
Water content at lm.: 32
Average plastic limit: 18
Average liquid limit: 30
Average plasticity index: 13
Liquidity index at lm.: 0.67
Average grain specific gravity: 2.74
Vane shear strength at lm.:

Station 582 Physiographic area Chiniak Trough



Bulk density at lm.: ______

Water content at lm.: 32

Average plastic limit: ______

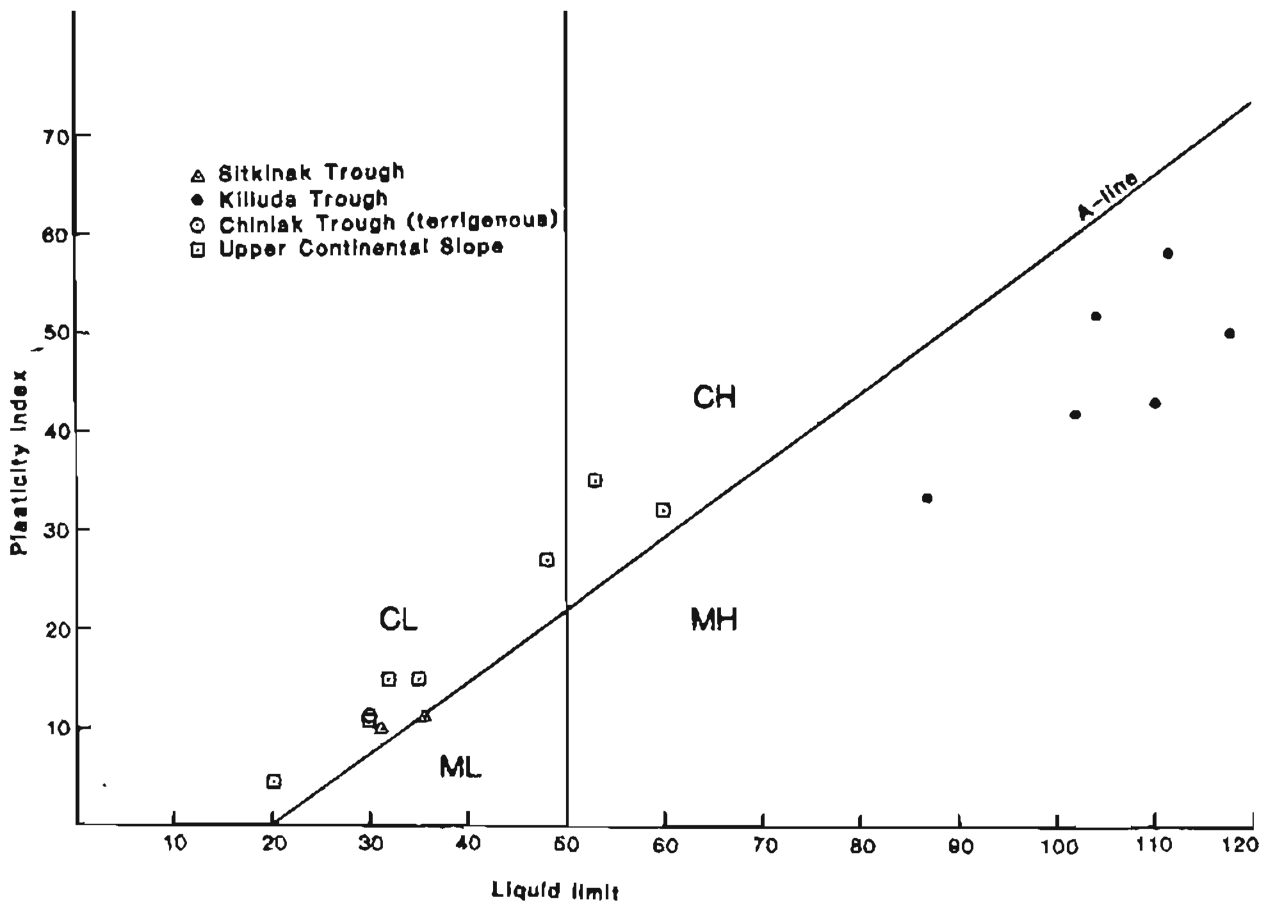
Average liquid limit: ______

Average plasticity index: ______

Liquidity index at lm.: ______

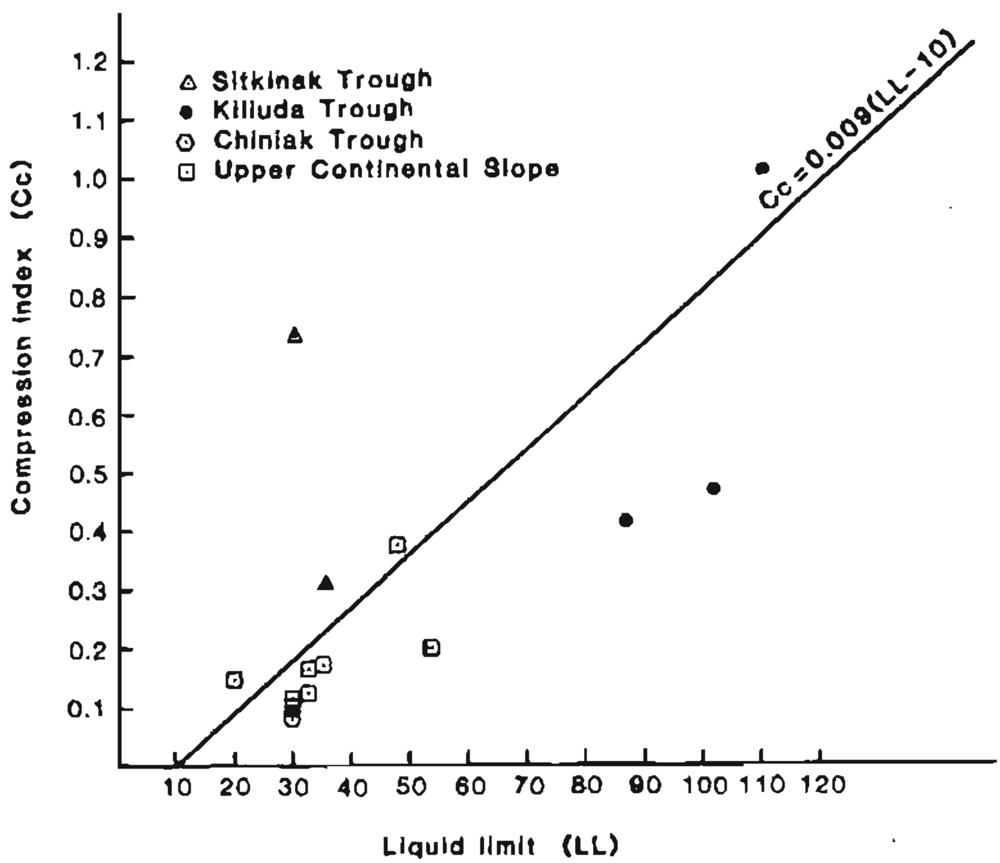
Average grain specific gravity: ______

Vane shear strength at lm.: ______



Sitkinak Trough
Kiliuda Trough
Chiniak Trough (terrigenous)
Upper Continental Slope
A-line
CH
CL
MH
ML
Plasticity Index
Liquid limit
10
20
30
40
50
60
70
80
90
100
110
120

Fig. 6



Sitkinak Trough
Kiliuda Trough
Chiniak Trough
Upper Continental Slope
Cc=0.009(LL-10)
Compression index (Cc)
1.2
1.1
1.0
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
10 20 30 40 50 60 70 80 90 100 110 120
Liquid limit (LL)

Fig. 7

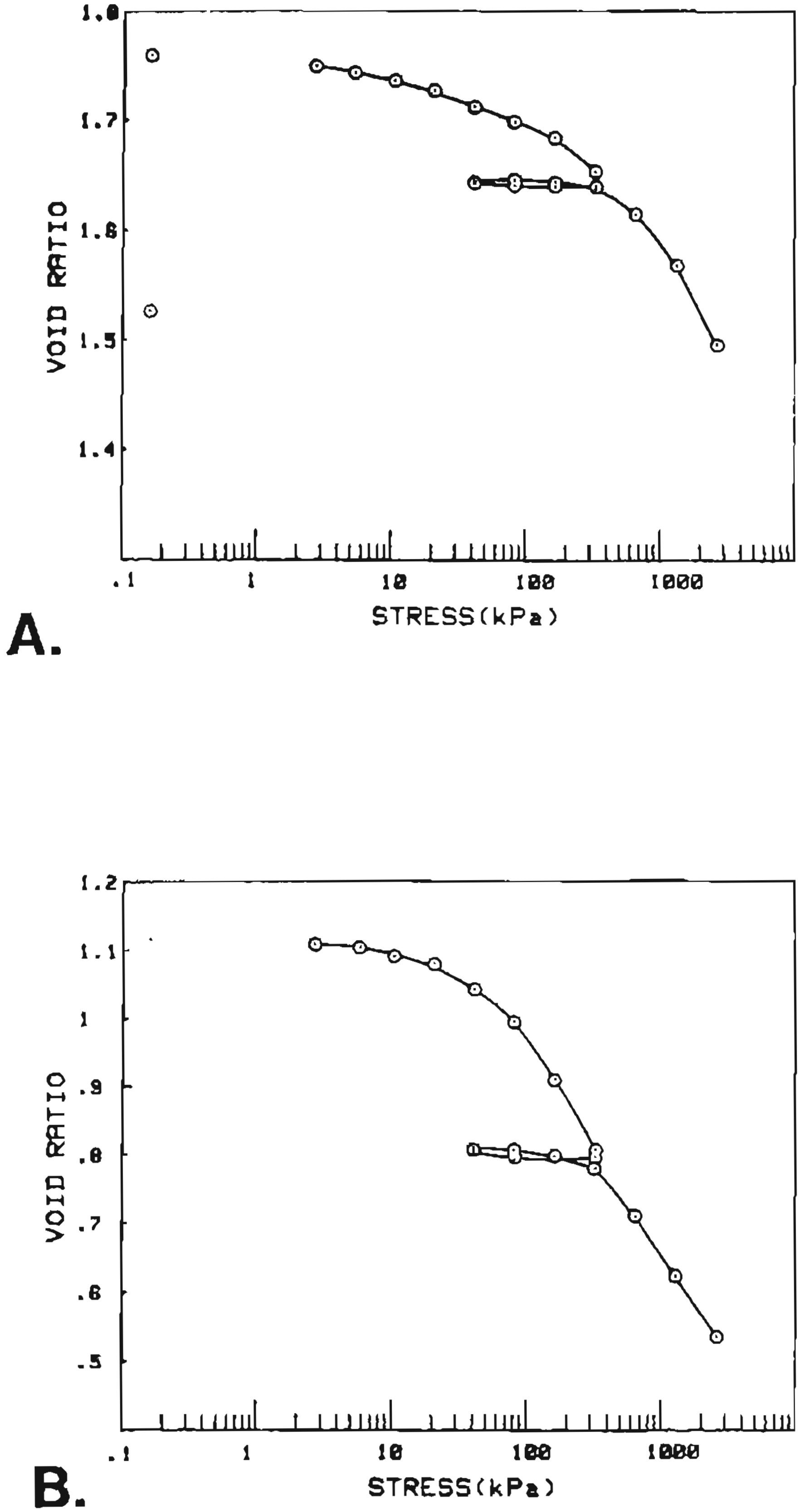

1.8
1.7
1.6
1.5
1.4
VOID RATIO
.1
1
10
100
1000
STRESS(kPa)
A.
1.2
1.1
1
.9
.8
.7
.6
.5
VOID RATIO
.1
1
10
100
1000
STRESS(kPa)
B.

Fig. 8

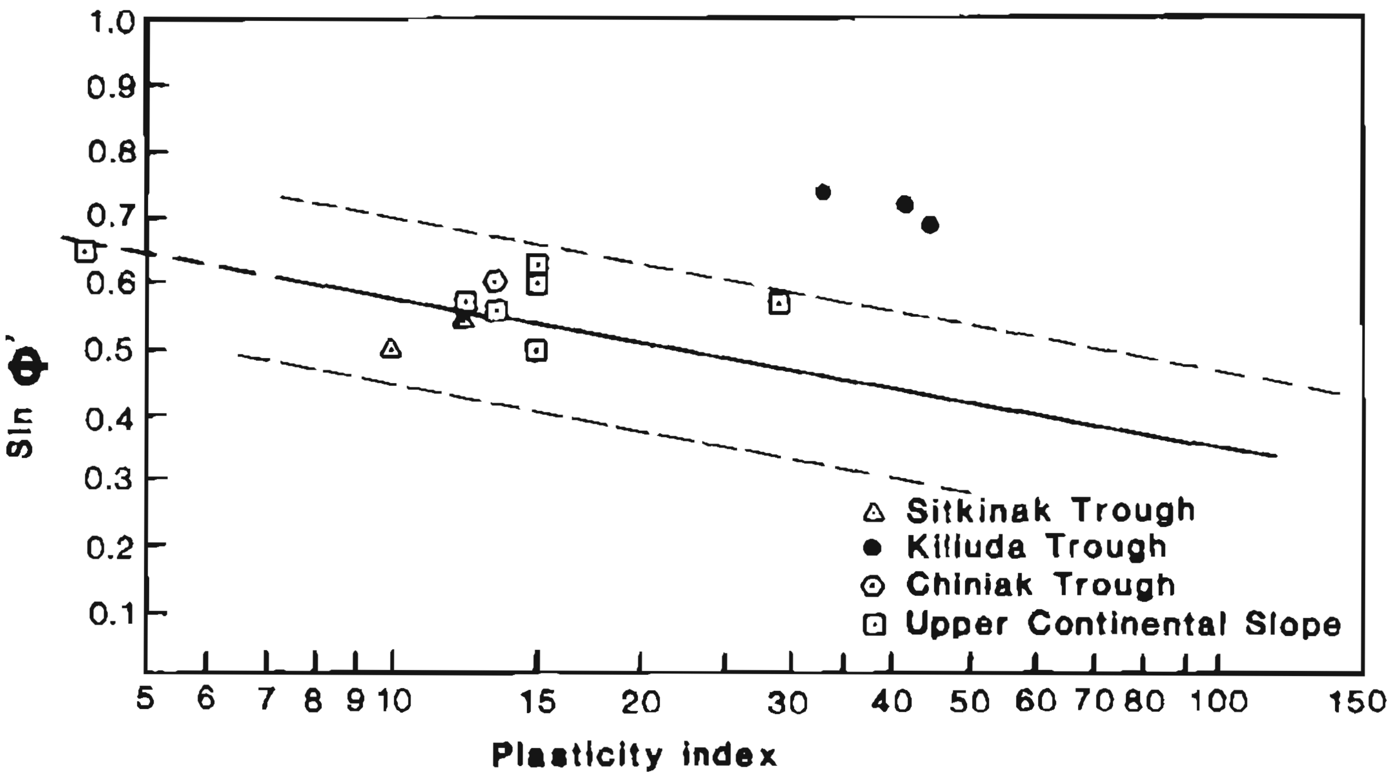
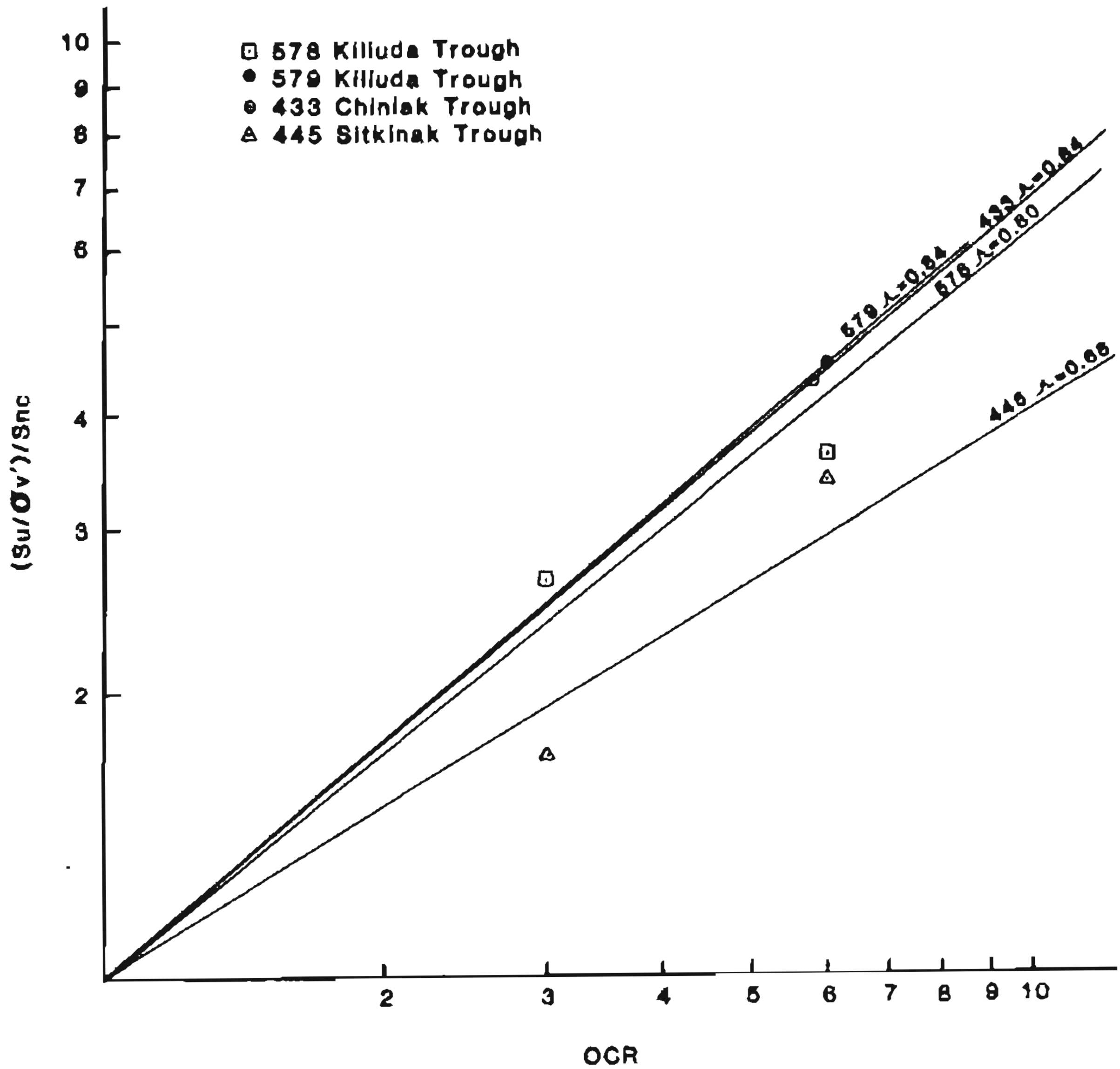
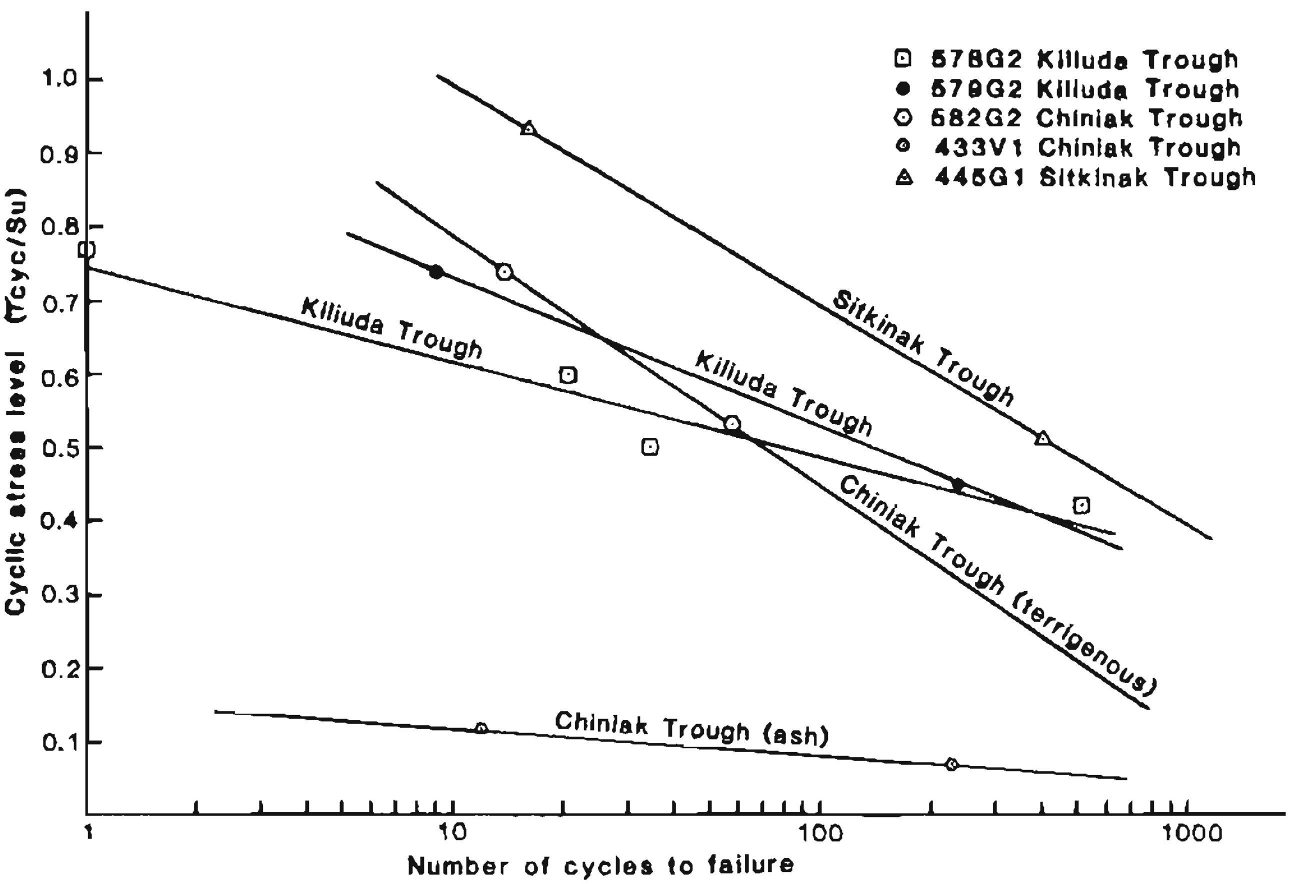

1.0
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
Sin Φ'
5
6
7
8
9
10
15
20
30
40
50
60
70
80
100
150
Plasticity index
Sitkinak Trough
Kiliuda Trough
Chiniak Trough
Upper Continental Slope

Fig. 9



□ 578 Kiliuda Trough
● 579 Kiliuda Trough
⊖ 433 Chiniak Trough
△ 445 Sitkinak Trough
579 Λ=0.84
433 Λ=0.84
578 Λ=0.80
445 Λ=0.66
(Su/σv')/Snc
OCR
10
9
8
7
6
4
3
2
2
3
4
5
6
7
8
9
10

Fig. 10



578G2 Killuda Trough
579G2 Killuda Trough
582G2 Chiniak Trough
433V1 Chiniak Trough
445G1 Sitkinak Trough
Cyclic stress level (Tcyc/Su)
1.0
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
Killuda Trough
Killuda Trough
Sitkinak Trough
Chiniak Trough (terrigenous)
Chiniak Trough (ash)
1
10
100
1000
Number of cycles to failure

Fig. 11