AN ABSTRACT OF THE THESIS OF

William Patrick McDonald for the degree of Master of Science in
Oceanography presented on December 14, 1982
Title: Influence of Organic Matter on the Geotechnical Properties
and Consolidation Characteristics of Northern Oregon
Continental Slope Sediments

Abstract appproved: Redacted for privacy
George H. Keller

An earlier study of the Peru-Chile margin has shown that the presence of high concentrations of organic matter in continental slope near-surface deposits (0 to 4m) profoundly affects the geotechnical properties and consolidation behavior of such sediments. The relationships noted, however, were not adequately documented for low to moderate concentrations of organic matter (1 to 4% organic carbon), at which level it is believed that organic matter first begins to significantly alter the geotechnical properties. Geotechnical properties and consolidation characteristics of near surface sediments (0 to 3.0 m) were determined from 7 Kasten and 40 gravity cores collected from the lower slope off northern Oregon. As in the Peru-Chile study, coastal upwelling concentrates organic matter in the slope deposits, however, off Oregon the concentrations preserved in the sediments are on the order of 0.5 to 3% organic carbon. The Oregon margin deposits provide a good opportunity for a detailed study of the effects of low to moderate organic matter concentrations

on the geotechnical properties and consolidation behavior of continental slope deposits.

The data show that the ability of organic matter to adsorb water and aggregate clay particles is a major factor causing increases in the water content especially when dealing with concentrations above about 2% organic carbon. These same properties enable organic matter to decrease the grain specific gravity and the sediment wet bulk density when present in amounts greater than 2.5 or 3% organic carbon. The Atterberg limits (liquid limit, plastic limit, and plasticity index) are also found to be increased by the presence of organic matter in concentrations as low as 1.5% organic carbon. The increased water content associated with higher organic contents acts to increase the distance separating sediment particles thereby decreasing the forces of interaction between such particles. This leads to an overall decrease in bulk sediment shear strength as organic contents rise up to about 3% organic carbon. The increase in void ratio associated with increasing organic content as well as the ease of deformability of organic matter itself is apparently responsible for increases in the sediment compressibility and the rate of secondary compression especially at concentrations of organic carbon greater than 1%.

Below the concentrations cited, organic matter may still influence each of the physical properties noted, although it's influence is rapidly overshadowed by other factors such as the clay content and the sediment mineralogy. The ability of clay particles to adsorb water and form a flocculent structure in the marine environment are responsible for increases in the water content and decreases in the wet bulk density with increasing clay content. These same properties explain how increases in the clay content contribute to increases in the sediment compressibility as well. Mineralogical differences may be especially important when considering the Atterberg limits where increases in the percentage of smectite clay minerals may have a profound impact on the liquid limit and the plasticity index. Although organic contents below about 4% appear to influence certain geotechnical properties to some degree, this effect is relatively insignificant in comparison to the influence of high (>4%) concentrations of organic carbon.

Influence of Organic Matter on the Geotechnical Properties and Consolidation Characteristics of Northern Oregon Continental Slope Sediments

by

William P. McDonald

A THESIS

submitted to

Oregon State University

in partial fulfillment of
the requirements for the
degree of

Master of Science

Completed December 14, 1982

Commencement June 1983

APPROVED:

Redacted for privacy

Professor of Oceanography in charge of major

Redacted for privacy

Dean of School of Oceanography

Redacted for privacy

Dean of Graduate School

Date thesis is presented December 14, 1982

Typed by Marcia Griffin for William P. McDonald

ACKNOWLEDGEMENTS

I would like to gratefully acknowledge the support of my major professor, Dr. George Keller, for his patience and help over the past two years. In addition, I wish to thank Dr. Ken Scheidegger and Dr. Ted Vinson for serving on my committee and providing useful critiques of the manuscript.

Last, but by no means least, I wish to thank my wife, Sara, for her patience in all this.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

INFLUENCE OF ORGANIC MATTER ON THE GEOTECHNICAL PROPERTIES AND CONSOLIDATION CHARACTERISTICS OF NORTHERN OREGON CONTINENTAL SLOPE SEDIMENTS

INTRODUCTION

The purpose of this study is to determine the influence of organic matter at low to moderate concentrations (0.5 to 4.0% organic carbon) on the geotechnical properties of continental slope submarine deposits. A previous study has shown that higher concentrations of organic matter (up to 20%) profoundly affects certain geotechnical properties of deposits on the Peru continental slope (Busch, 1981). The study did not adequately document the sediment geotechnical property relationships for relatively low organic carbon concentrations (<4%), however, which created the opportunity for this study.

Geotechnical studies on sediments in general have shown that changes in the physical properties are closely related to changes in the texture (Bennett et al., 1977) and the clay mineralogy (Bryant et al., 1974; Silva and Hollister, 1979) as well as the organic content (Pusch, 1973; Rashid and Brown, 1975; and Busch, 1981).

The relationships noted between organic matter and the geotechnical properties have, for the most part, been determined on marine sediments derived from a terrestrial source were postulated on completely remolded samples from the marine environment. The work of Busch and Keller (1981 and 1982) on the Peru continental slope was one of the earlier efforts to determine the effect of organic matter on the geotechnical properties of undisturbed, or natural, submarine slope deposits. Off Peru, a prominent coastal upwelling regime spurs periodic increases in the biological productivity to extremely high levels of 2 to 10 gC/m^2/day (Harrison et al., 1980). The net result is the localized deposition of organic rich sediments on the continental slope with organic carbon contents of up to 20% (Busch, 1981). The Oregon continental margin is similarly endowed with a coastal upwelling regime, though of a more seasonal nature (Huyer et al., 1974). Productivity during upwelling averages .50 to .75 gC/m^2/day (Small et al., 1972) which is intermediate between Peru and the open ocean which is generally less than .15 gC/m^2/day (Gross, 1972). As a result of offshore transport associated with the upwelling process, much of the organic matter produced is carried seaward and deposited on the continental slope. The concentrations preserved in the lower slope deposits between 44° and 46.5°N varies from 0.5 to approximately 3.0% organic carbon and provide an ideal opportunity to determine the effects of low to moderate organic matter concentrations on the geotechnical properties of submarine sediments.

SETTING

The Oregon continental margin forms one part of the convergence zone between the North American plate to the east and the Gorda - Juan de Fuca plate to the west (Fig. 1). Convergence is estimated to be 2.6 cm/yr (Silver, 1969) and has a profound affect on the margin by creating a region with higher than normal stress regimes leading to a tectonically controlled morphology.

The continental slope in the study region (44°N to 46.5°N) ranges in width from 50 to 90 km. The gradient of the upper slope is on the order of 2 to 3° whereas the lower slope is considerably steeper with slope angles of 3 to 5° being common. The continental slope is characterized by a single large bench on the upper slope with a series of north to northwest trending linear ridges and intervening basins forming the lower slope. These features grade into small equidimensional hills and steep escarpments to the south in the vicinity of 45°N. Sediments on the continental slope off Oregon are predominantly olive-gray to olive-green silty clays or clayey silts and are composed of 40 to 60% silt and 40 to 60% clay-sized material with negligible sand content. Thicknesses may attain 200m or more in some continental slope basins, but are more commonly on the order of 100m (Kulm and Scheidegger, 1979). Occasional thin (<10 cm) sand-silt layers of up to 20% sand have been reported in cores from this area and are believed to be the result of turbidity currents carrying coarse-grained material from the continental shelf (Kulm and Scheidegger, 1979).

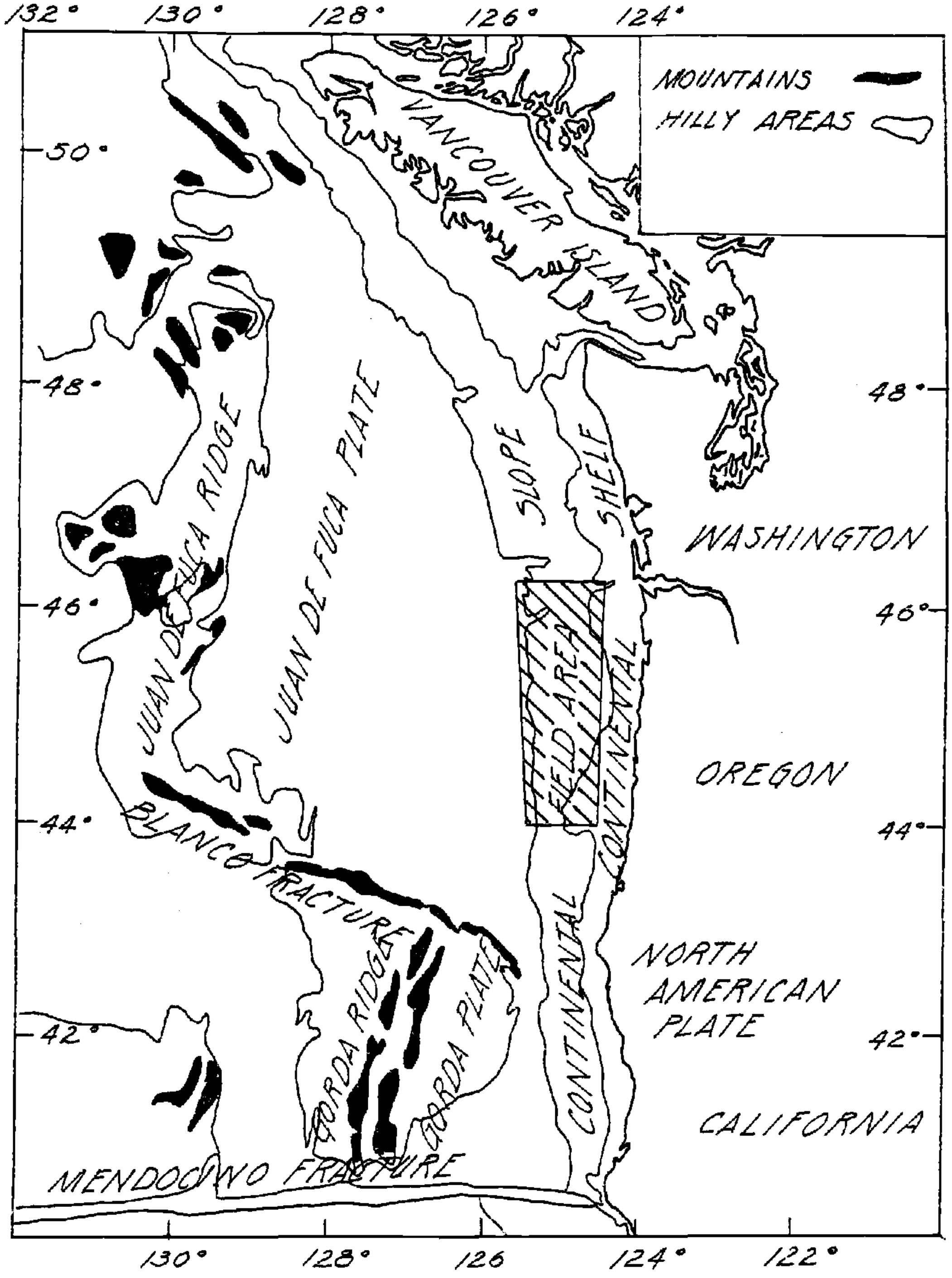

Figure 1. Location map of the study area within the tectonic framework of the Pacific Northwest.

The ubiquitous clayey silts to silty clays in this area are hemipelagically derived and thus are subject to the overall circulation pattern of waters along the Oregon margin. During the summer months (mid-May to mid-September) prevailing winds from the northwest push near-surface water offshore over the mid and outer shelf regions. This water is replaced by deeper water flowing shoreward along the shelf comprising an upwelling circulation system. A strong, southward flowing coastal water jet is also associated with the upwelling system and is found over the mid and outer shelf surface waters (Huyer, et al. 1974). Along the continental slope and outer shelf a semi-permanent, poleward flowing undercurrent predominates (Huyer, et al. 1974; Halpern, et al. 1978). During the winter months the prevailing winds shift and the dominant currents flow northward along the continental margin and the upwelling system no longer exists.

Oregon slope sediments contain low to moderate concentrations (<3.5%) of organic matter (Gross 1972). These concentrations are brought about by the summer upwelling circulation system which brings cold, nutrient rich subsurface water into the photic zone facilitating the rapid growth of phytoplankton. An increase in biomass and the offshore transport leads eventually to deposition of organic rich debris in sediments on the outer continental shelf and continental slope most probably in the form of fecal material (Small, 1979).

Rates of sedimentation on the continental slope during the Holocene are based on identification of Mazama ash horizons dated at 6600 years b.p. (Nelson et al., 1968). Rates of 20 to

65 cm/1000 yrs have been calculated for the lower slope. Such rates are found to decrease to less than 10 cm/1000 yrs on the upper slope (Kulm and Scheidegger, 1979). None of the cored sections associated with this study penetrated into Pleistocene deposits based on the lack of evidence for Mazama Ash horizons in any of the cores which precludes sampling before 6600 yrs before present.

METHODS AND PROCEDURES

Mass physical properties and consolidation characteristics were determined on sediments from 7 Kasten cores taken on the lower continental slope off northern Oregon (Figure 2). Due to the large cross-sectional area (15 cm x 15 cm) of the Kasten Corer (Kögler, 1963) the sediment samples exhibited minimal disturbance and proved to be excellent for geotechnical studies. In addition, data on the physical properties of 40 gravity cores from a previous cruise in the area are included in this study. Bottom morphology and shallow sub-bottom structures were recorded along the cruise trackline (Figure 2) using 3.5 and 12 kHz profiling systems. Upon retrieval, the core barrel ends were immediately sealed with polyurethane foam and plastic bags to prevent dehydration as well as to restrain sediment movement within the barrel. After the cruise the cores were held in a cold (4° celsius), humid room until being opened for analysis. After opening and visual description, sub-samples were taken at 5 cm-intervals from the top 50 cm and at 10 cm intervals for the remainder of the cored section for water content and wet unit weight (wet bulk density) determinations. These were determined gravimetrically using the standards set forth by the American Society for Testing and Materials (1979a). An interstitial water salinity correction was not applied to these measurements.

Undrained shear strength was measured using a Wykeham-Farrance laboratory vane shear apparatus with a 1.2 cm x 1.9 cm blade operated at a shear rate of 60° per minute. Both natural, or "undisturbed",

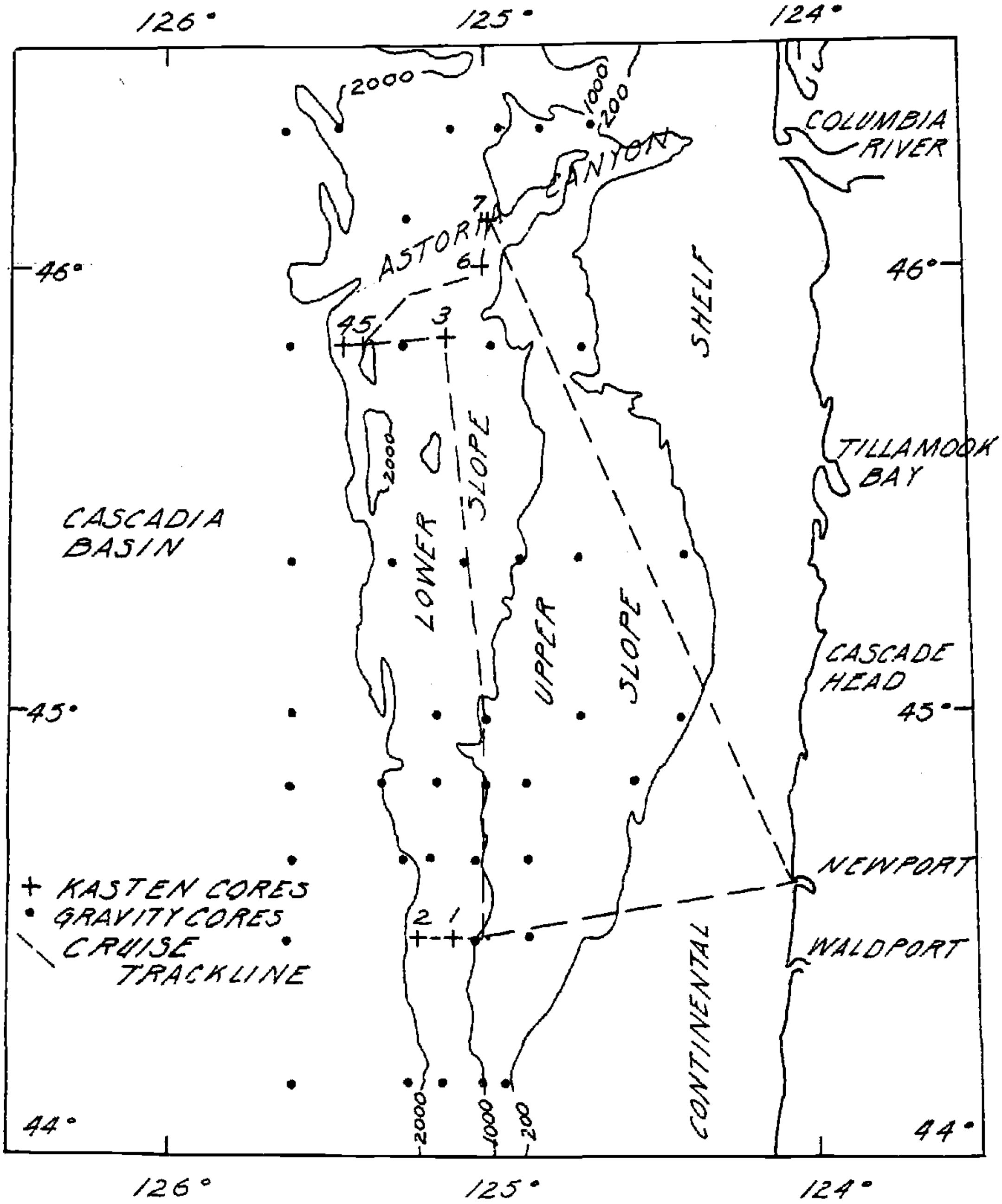

Figure 2. Bathymetric map of study area.

shear strength normal to bedding and remolded shear strength, by mixing with a spatula, were determined. Intervals of 10 cm in the top 50 cm of the core and 20 cm for the remainder of the core were chosen for this test.

Grain specific gravity and Atterberg limits were determined on sub-samples taken from the surface, middle and bottom of each Kasten core according to American Society for Testing and Materials standards (1979b; 1979c). Determination of the Atterberg limits was modified from the standard procedure in that the sediment was not completely dried prior to testing nor was the sand-sized fraction, which normally comprises less than 2% of the sediment, removed before testing.

Gross textural composition (sand, silt, and clay content) was determined for subsamples taken at the surface and every 15 to 20 cm down core. Sand-size fractions were removed by sieving whereas silt and clay-size particles were determined by pipette analysis as described by Folk (1980).

Consolidation samples were taken from each core, held rigid in stainless steel containers, double wrapped with plastic, and kept refrigerated at 4°C until tested. All samples were tested on a Karol Warner-Conbel consolidometer where they were loaded up to 1600 kPa using a load increment ratio (pressure added divided by previously applied pressure) of one and allowed to rebound following the procedure of Bowles (1978).

In addition to the geotechnical tests, organic carbon concentrations were measured on subsamples taken at 10 cm intervals in the top 50 cm of each core and at 20 cm intervals thereafter. A Leco WR-12 Automatic Carbon Determinator was used and the procedure of Heath et al. (1977) followed. X-radiographs of 1 cm-thick slabs were made to document sedimentary structures and other internal features.

RESULTS

Comparison of the physical properties were made using averages for the top 150 cm of each core. This interval was used because all of the Kasten cores penetrated to this depth as well as many of the gravity cores. Regression equations were used to estimate averages for each parameter for those cores less than 150 cm long. For parameters such as specific gravity and Atterberg limits individual values are compared due to a lack of data sufficient to make averaging meaningful. General downcore trends are compared using linear regression analysis. Cross correlations between parameters were also made using a linear regression technique.

Organic Content

Mean organic contents on the continental slope for the top 150 cm of each core are expressed as percent organic carbon (dry weight basis) and range from a high of 3.0% to a low of 1.8%, which are classified as low to moderate organic contents. Examination of the areal distribution of the mean organic content (Fig. 3) reveals a general increase in organic contents offshore, reaching a maximum along the mid to upper slope, and then decreasing seaward into the abyssal plain environment. There appear to be regions of higher than average organic content flanking the Astoria submarine canyon in the northern half of the study region and in the southern half off Waldport. The high values in the regions flanking Astoria Canyon are probably due to an additional input of terrestrially derived nutrients transported offshore by the Columbia River sediment plume

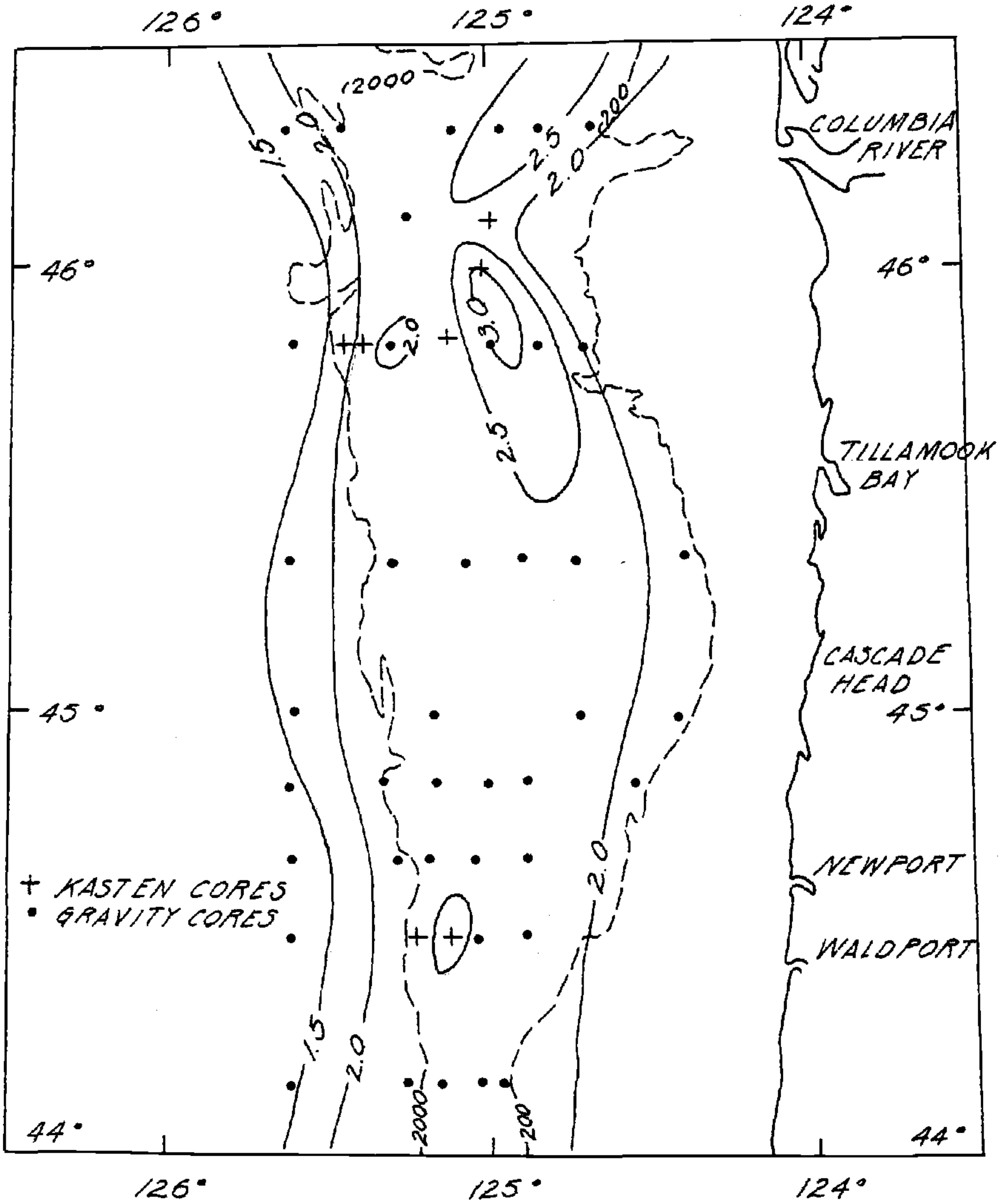

Figure 3. Mean organic content distribution (0 to 150 cm) determined as percent organic carbon (dry weight).

which spurs biological productivity in this area to higher than average values normally associated with the seasonal coastal upwelling. As a result, more organic matter produced in the photic zone is fecally transported to the surface sediments in this region. A greater input of sediment down the Astoria Canyon dilutes this organic matter to the point where values of org. carb. are as much as 1 to 1.5% lower. The region off Waldport where organic carbon values are high may be due to a similar mechanism as described above or may reflect an intensification of the upwelling current somewhere off Waldport resulting in a localized high organic matter content on the continental slope.

Texture

Textural patterns for the upper 150 cm of all cores show a progressive fining of grain size with increased distance offshore (Fig. 4a). The general pattern in a north-south direction is more complex. To the north, Astoria Canyon provides a conduit for coarse-grained material from the shelf to the abyssal plain. Some of this material comprises a notable proportion of the sediments adjacent to the canyon on the lower slope. Cores in this northern region exhibit silt percentages of 50 to 60% (Fig. 4b) and are classified as clayey silts (Folk, 1980). The canyon effect drops off to the south leading to a region of silty clays to approximately 45°N latitude. Clay-size particles comprise 59 to 67% of these sediments. South of 45°N the textural pattern becomes more complex. Along the lower slope percentages of clay-size material fluctuate between 26 and 54%.

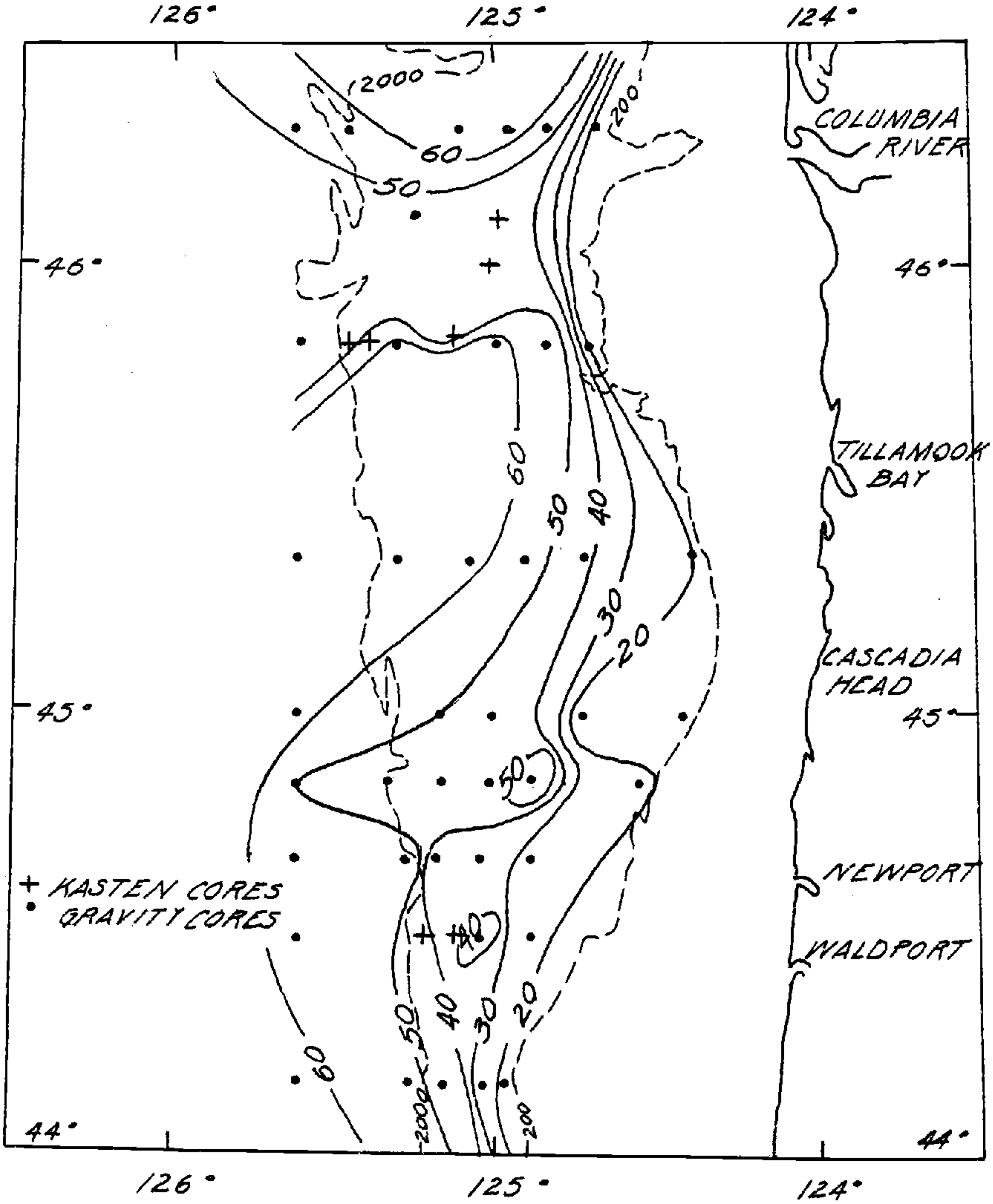

Figure 4a. Textural distribution, mean percent clay (0 to 150 cm) determined on an organic free basis.

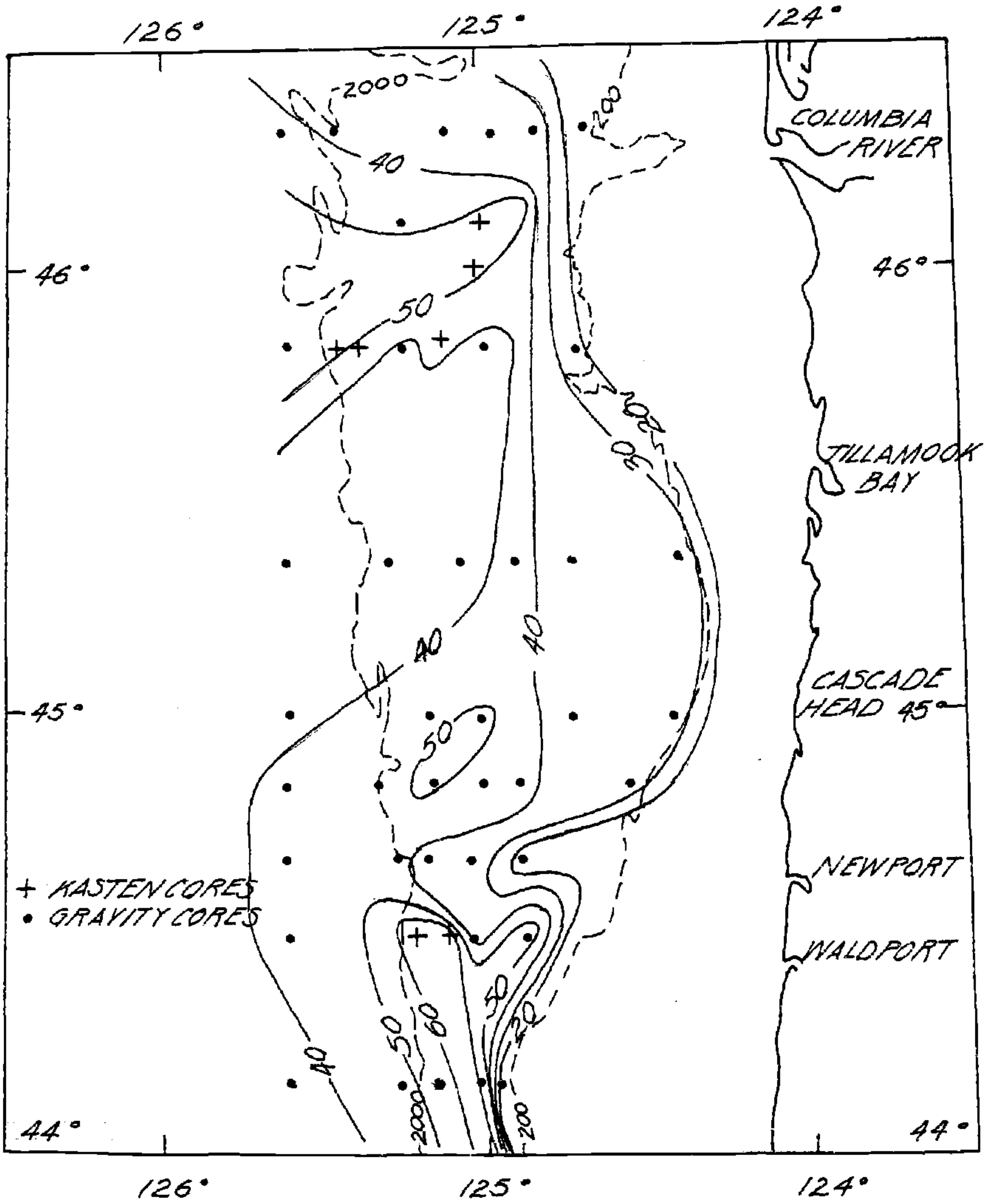

Figure 4b. Textural distribution, mean percent silt (0 to 150 cm) determined on an organic free basis.

This zone corresponds to a morphological region of steep escarpments and small equidimensional hills and basins which are especially prominent offshore between Waldport and Cascade Head (Kulm and Scheidegger, 1979). Due to the rapid morphological changes it is not surprising that textural variations in this area are relatively complex. In the southern half of the field area the texture once again shifts to a higher concentration of clay-size material, although the lower slope is also at its narrowest width here just seaward of Heceta Bank. Texture changes rapidly downslope from 31 to 57% clay-size particles. Cores throughout the study area exhibit layers of 3 to 20% sand-size particles ranging in thickness from 2 to 6 cm. Examination of the X-radiographs reveal laminated bedding in these layers which are probably the result of downslope movement of coarse-grained material via turbidity currents. Most of the continental slope along the Pacific Northwest is composed of clayey silts or silty clays which generally become finer grained downslope and are subject to modification by turbidity currents (Kulm and Scheidegger, 1979). The study area appears to be fairly typical of the slope environment described by Kulm and Scheidegger (1979).

Water Content

Examination of the sediment water content, expressed as percent dry weight, indicates that mean values for the upper 150 cm of each core range from a high of 155% to a low of 86%. Although the coverage of data is sparse in some areas, it is possible to identify a low water content corridor coinciding with the Astoria submarine canyon. Immediately north and south of the canyon are areas where the highest water contents occur (150%). Off the Oregon coast south of Astoria canyon water contents decrease to form a region basically comprising most of the lower slope where water contents are between 125 and 150% (Fig. 5) except off Newport where they dip below 75%. Variability of the sediment water content on the northern Oregon lower continental slope appears to be affected by the grain size, organic matter content and possibly the clay mineralogy. The effect of grain size is evident when comparing the distribution of water content (Fig. 5) with the mean clay content (Fig. 4a). Low water contents, in the Astoria Canyon as well as in the region off Newport, tend to be regions of slightly coarser material with silt percentages generally greater than 50%. This relationship is supported by a bivariant plot of mean water content versus mean percent clay (Fig. 6) which shows an increase in water content as % clay increases. In regions where changes in texture are less pronounced the influence of organic matter on the water content seems to be of greater importance. Relatively high water contents immediately north and south of Astoria canyon coincide with the highest percentage of organic carbon (3.0%, dry weight). Textural changes in these areas do not appear to be entirely responsible for the high water contents. This coincidence of high water contents and high organic carbon percentages also occurs in the southern half of the field area off Waldport despite the slightly coarser grained texture there. A bivariant plot shows that water content increases as organic content increases (Fig. 7). Another factor which may influence the water content of Oregon slope

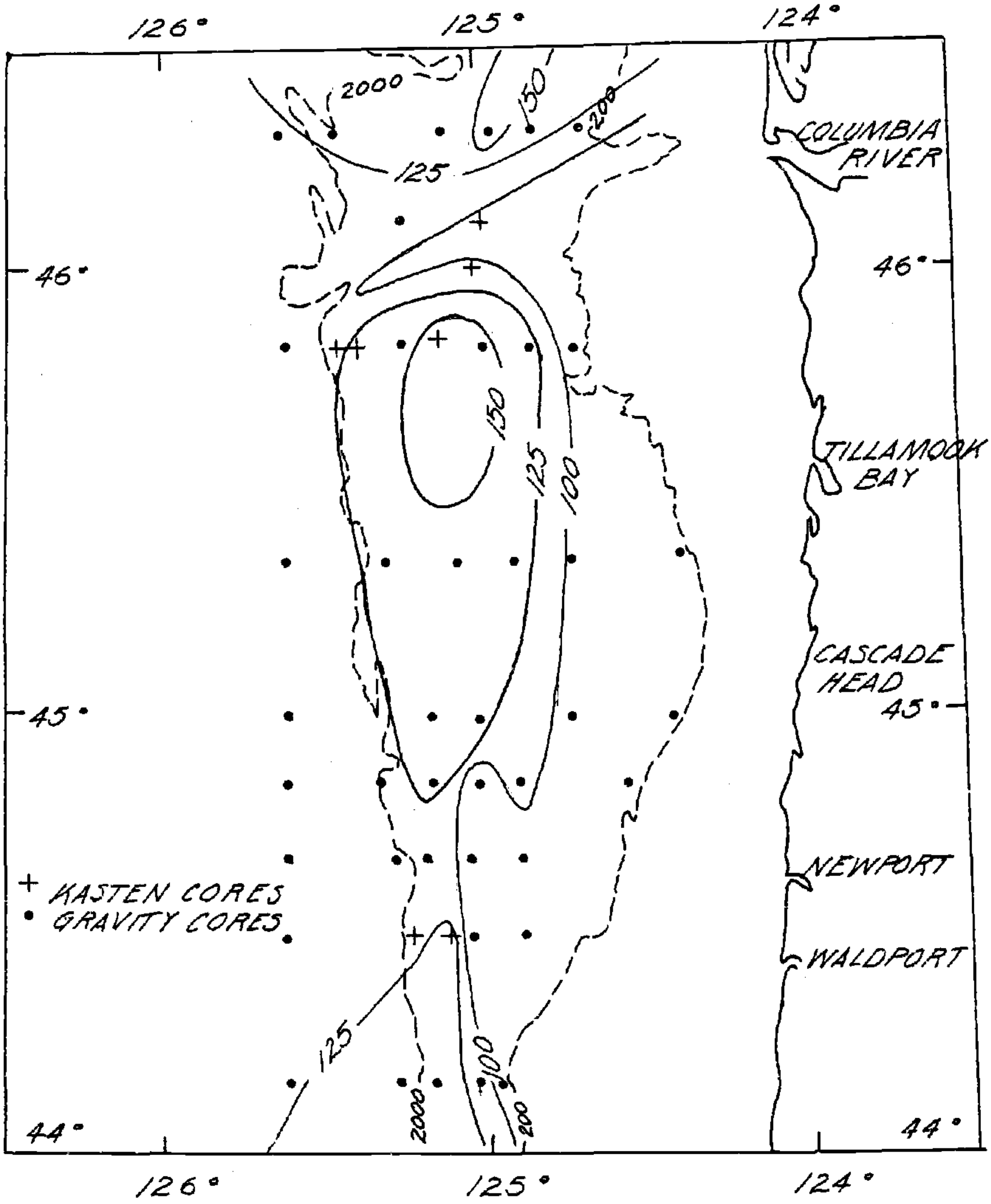

Figure 5. Mean water content distribution (0 to 150 cm).

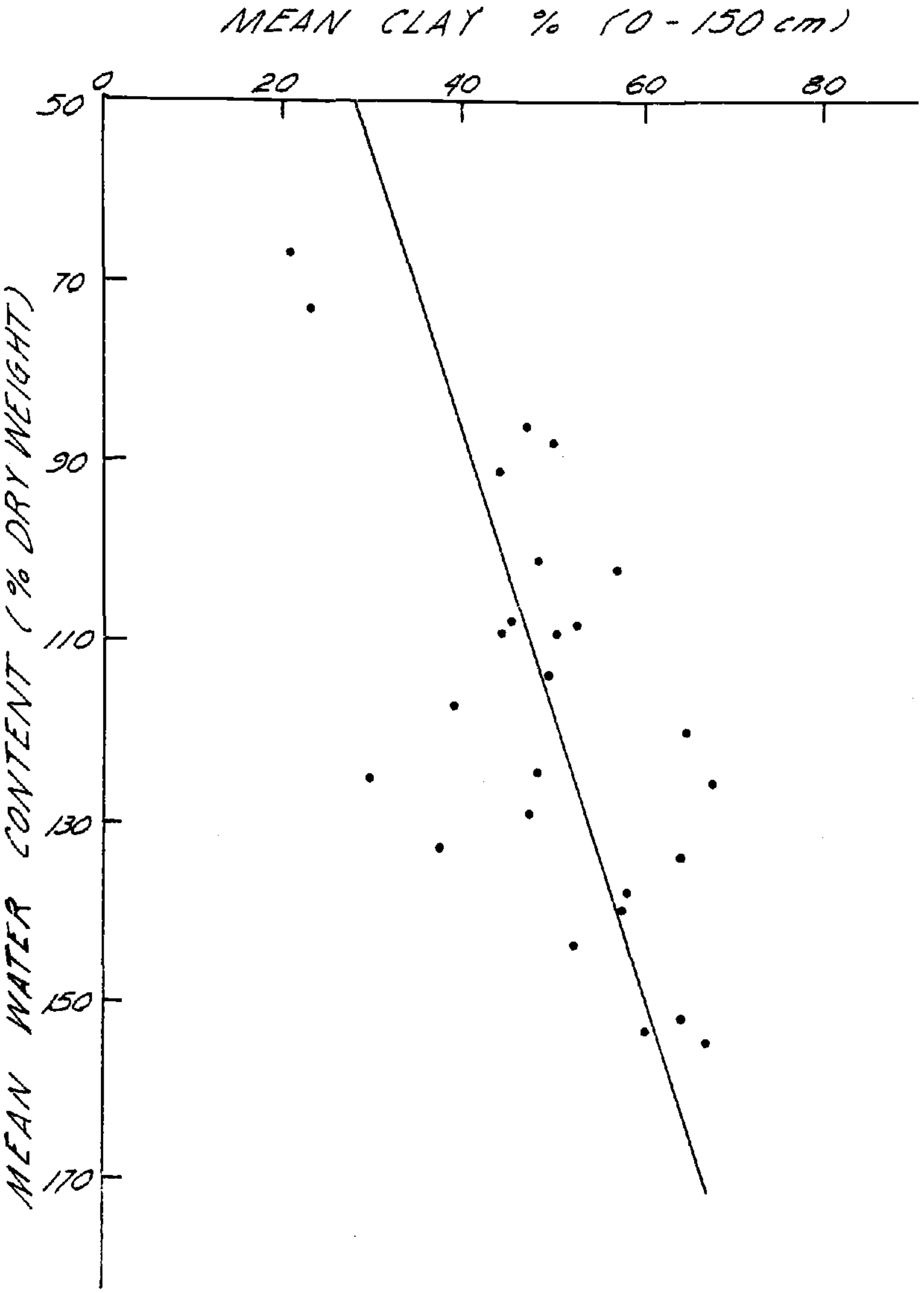

Figure 6. The relationship between mean water content and mean percent clay.

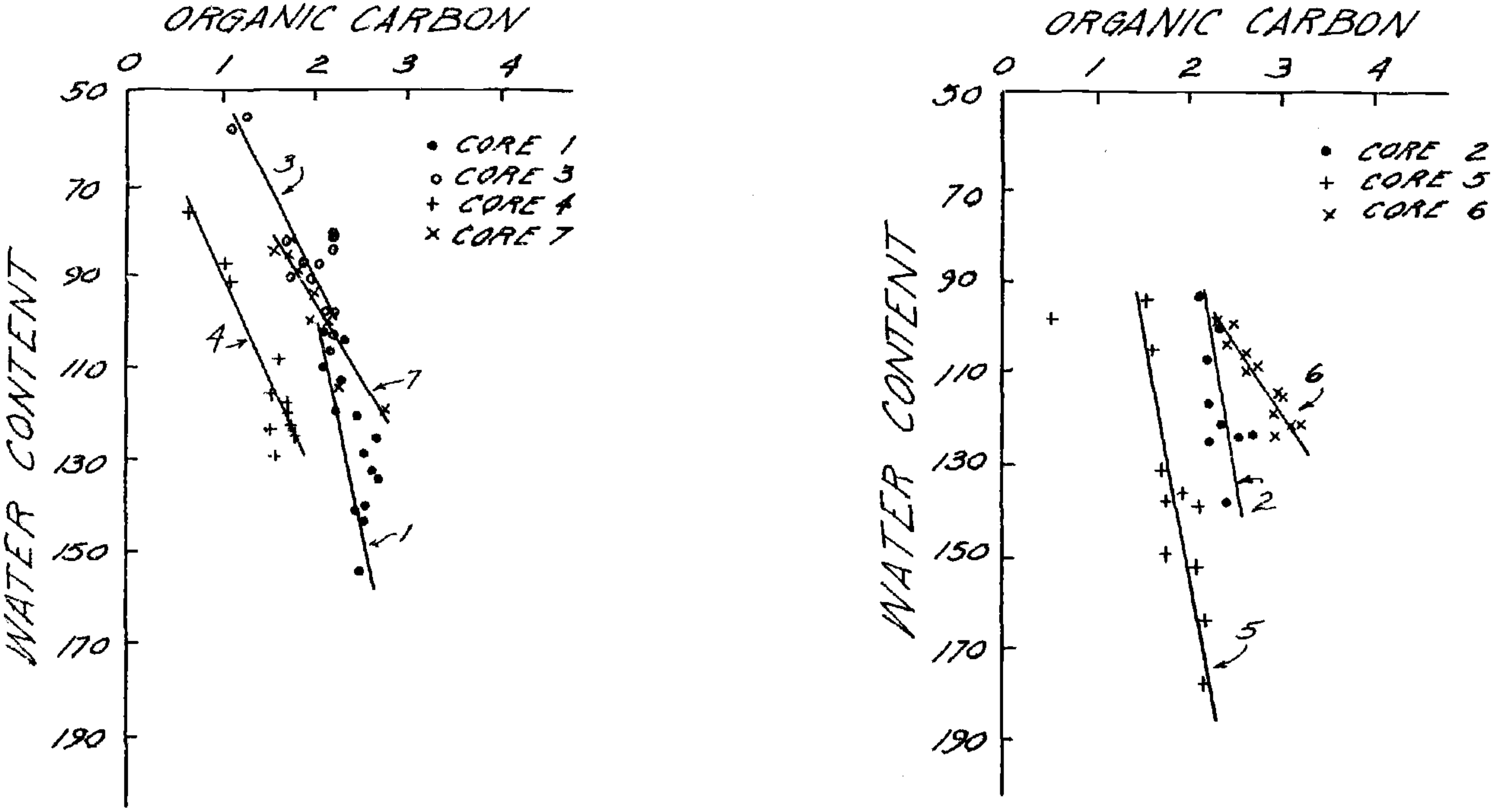

Figure 7. The relationship between the water content and the organic content.

sediment is the clay mineralogy. Quantitative analysis of the less than 2μm fraction of the Oregon and Washington slope sediments performed by Krissek (1982) indicates a dominance of smectite on the slope. It is well known that smectite, due primarily to the small size of the clay platelets adsorbs greater quantities of water to itself than other clay minerals. The percentage of smectite in the less than 2μm fraction varies from 60 to 90% on the lower slope and it seems possible that this may be an important contributing cause to the water contents here. Since the clay mineralogy for the Kasten cores was not performed, this relationship can only be postulated.

Wet Bulk Density

Mean wet bulk densities for the 0-150 cm interval ranges from a high of 1.55 Mg/m^3 to a low of 1.31 Mg/m^3. Examination of the areal distribution of these mean values reveals a general decrease in the wet bulk density downslope from the continental shelf reaching a minimum along a zone approximating the lower slope and increasing seaward toward the abyssal plain (Fig. 8). Two zones of relatively low bulk density are found in the northern region flanking Astoria Canyon off Waldport in the southern region. Comparison of the bulk density values with the area distribution of mean organic contents for the 0 to 150 cm interval (Fig. 3) indicates that these two parameters are closely related in that low wet bulk densities are associated with high organic contents. A plot of wet bulk density vs. organic content confirms this relationship (Fig. 9). This might explain the low densities in the north and south since these areas

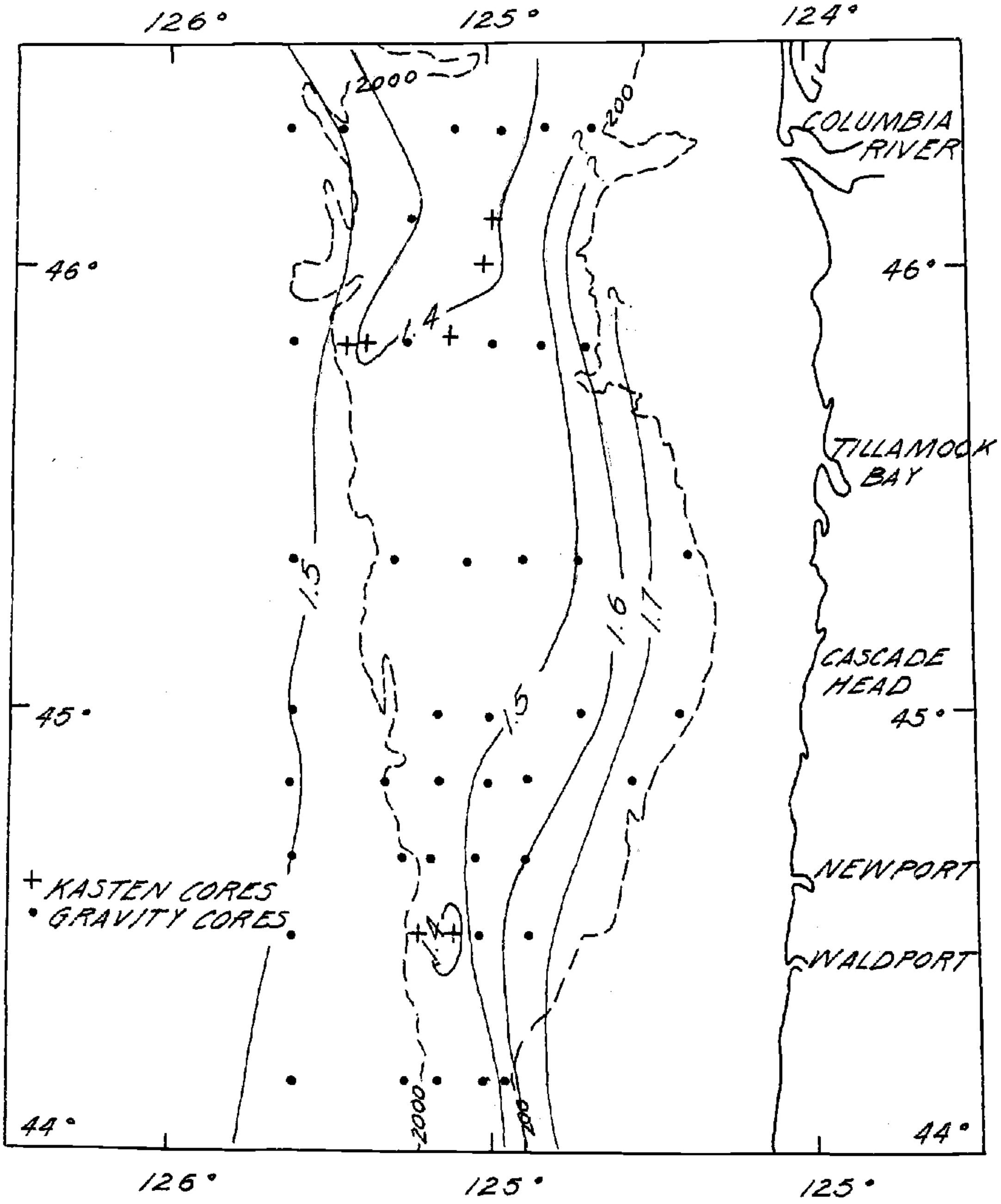

Figure 8. Mean wet bulk density distribution (0 to 150 cm) in Mg/m^3.

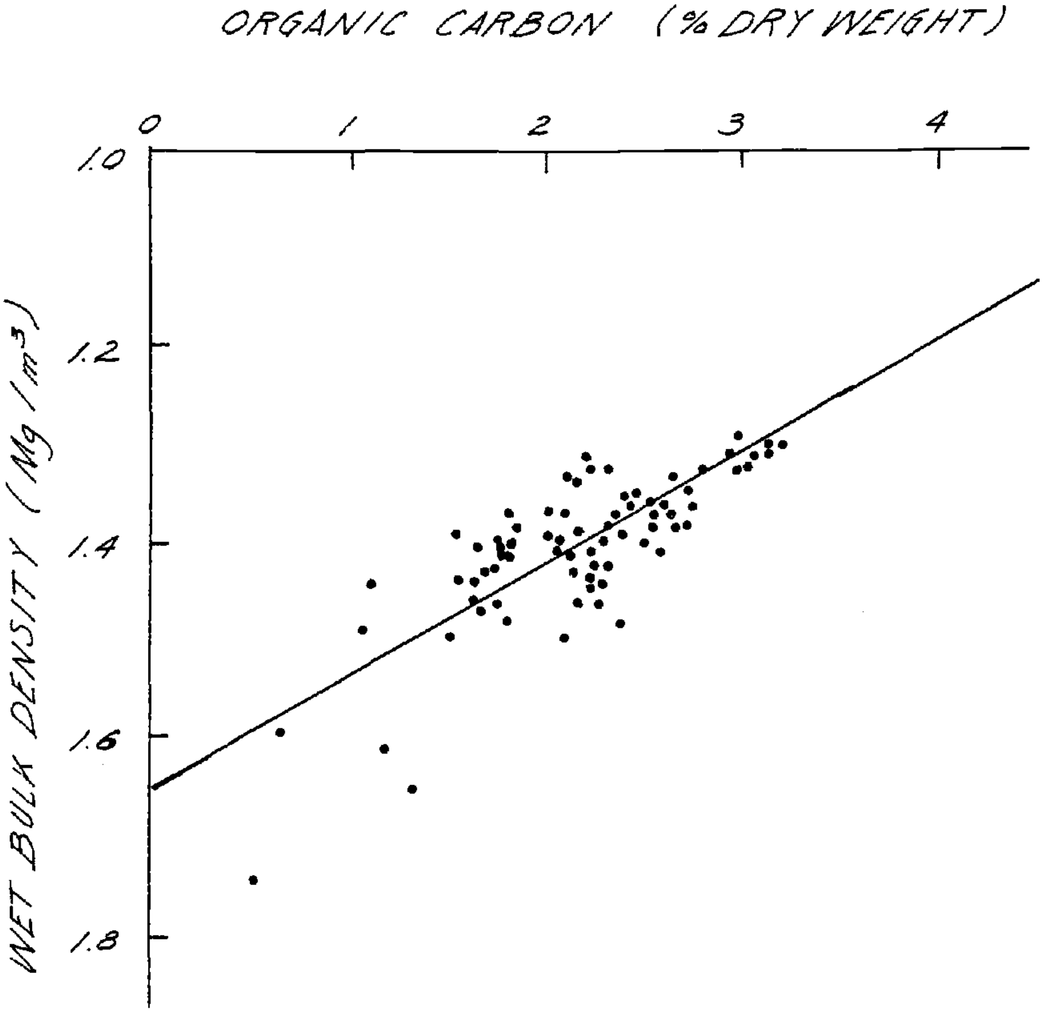

Figure 9. The relationship between wet bulk density and the percent organic carbon. Line represents a least squares fit through data.

correlate with slightly higher concentration of organic matter relative to the other slope deposits. It is postulated that the combination of the increase in water content associated with the higher concentrations of organic matter (Fig. 7) combined with the low density of organic matter itself (0.6 to 1.3 Mg/m^3) is responsible for this relationship. Wet bulk density does not appear to be significantly affected by the texture according to a plot of bulk density versus percent clay (Fig. 10).

Grain Specific Gravity

Individual values for the grain specific gravity range from a high of 2.79 in the finer grained material in the northern portion of the study area to a low of 2.64 in a coarser grained sample from the southern half of the study region. Mean values for the 7 Kasten cores fall within the range of 2.67 to 2.74 which typify values reported for marine clayey-silts and silty-clays (Wu, 1976). Busch (1981) showed a decrease in grain specific gravity associated with the presence of large amounts of organic matter. The specific gravity of sediments from the northern Oregon lower continental slope appear to follow a similar trend as that observed by Busch (1981) (Fig. 11) even though texturally and mineralogically the two areas are dissimilar. From this comparison, it is evident that organic matter has a strong affect on the specific gravity. Also of importance in the determination of grain specific gravities is the mineralogy. Quantitative analysis of the mineralogy of the bulk sediment in this area has not been done, although examination of the <20μm fraction

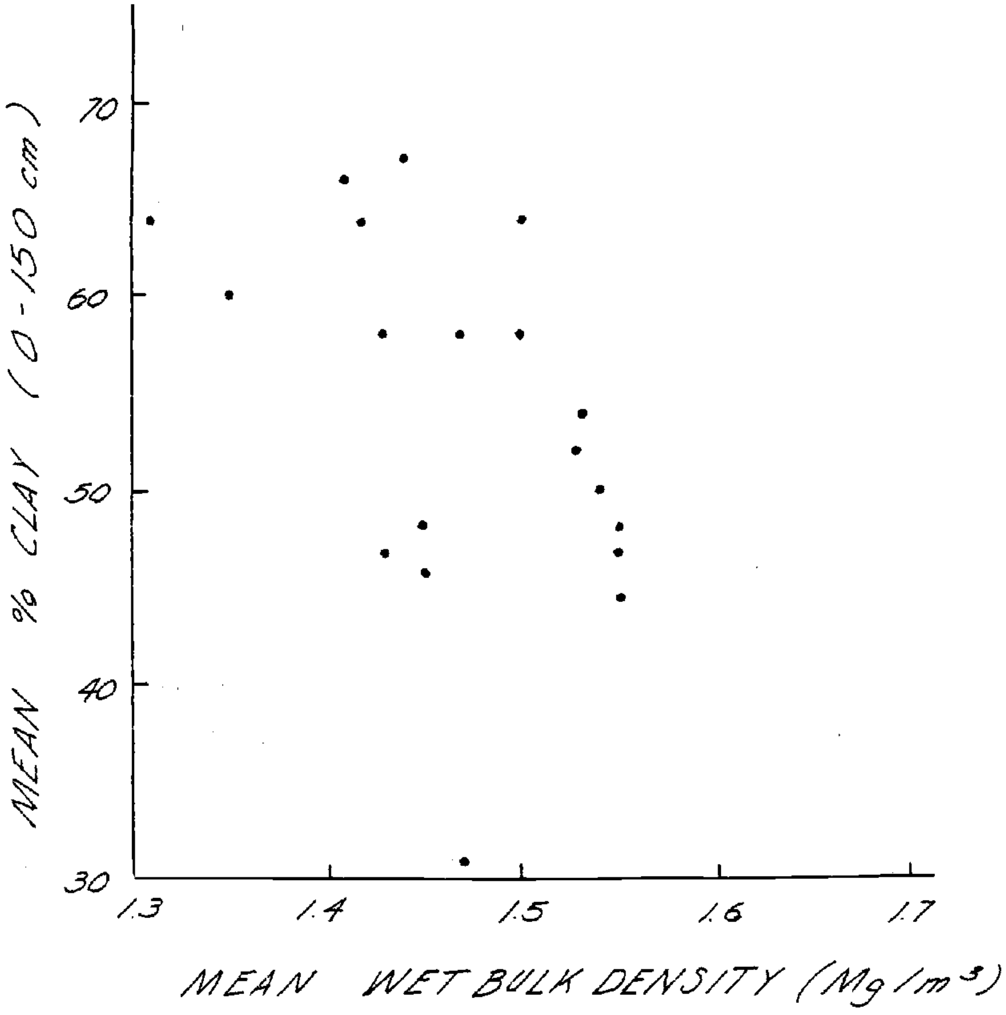

Figure 10. The relationship between the mean wet bulk density in Mg/m^3 and the mean percent clay.

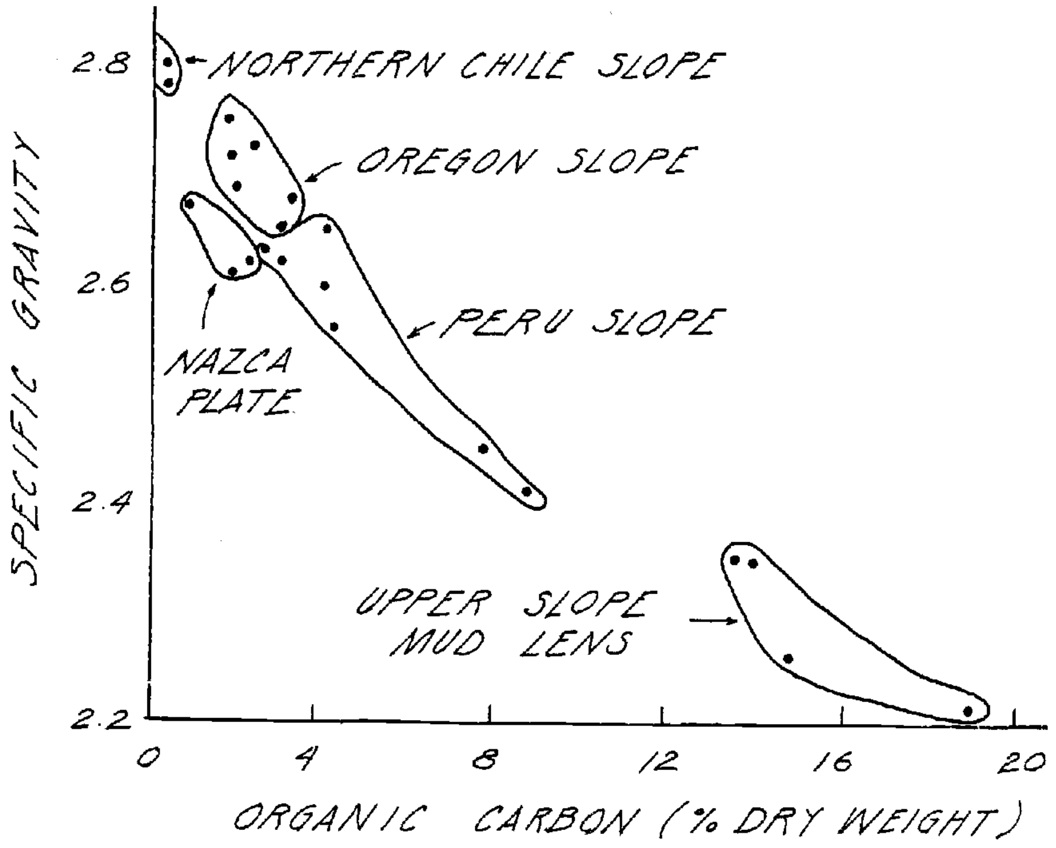

Figure 11. The relationship between the grain specific gravity and the organic content for surface sediments from the Peru-Chile margin and the northern Oregon continental slope.

(Krissek, 1982) which comprises the bulk of the sediment on the lower slope does not show a strong correlation between the presence of heavy minerals (e.g. hornblende) and the specific gravity. The presence of heavy minerals in the >20μm fraction may play an important role as yet undiscovered.

Atterberg Limits

Atterberg limits are water contents corresponding to the boundaries between different states of soil consistency. They are determined for the fine-grained fraction of a soil which is remolded during their determination. The liquid limit corresponds to a water content above which the sediment behaves as a liquid whereas the plastic limit is the water content marking the transition from the semi-solid (or non-plastic) to the plastic state. The range of water contents over which the sediment behaves as a plastic material is referred to as the Plasticity Index and is quantified by the difference between the liquid and plastic limits. Atterberg limits are primarily used as a means of classifying sediments along with their grain size. The use of grain size alone is insufficient since the properties of clay minerals versus clay-size particles of non-clay minerals may vary widely and result in considerable variations in the physical properties of the bulk sediment. Atterberg limits serve as an index for the properties of the clay-size fraction. A classification scheme devised by Casagrande (1948) is commonly utilized and incorporates the plasticity index and the liquid limit (Fig. 12). The northern Oregon lower continental slope deposits all plot within the region designated for organic clays and highly

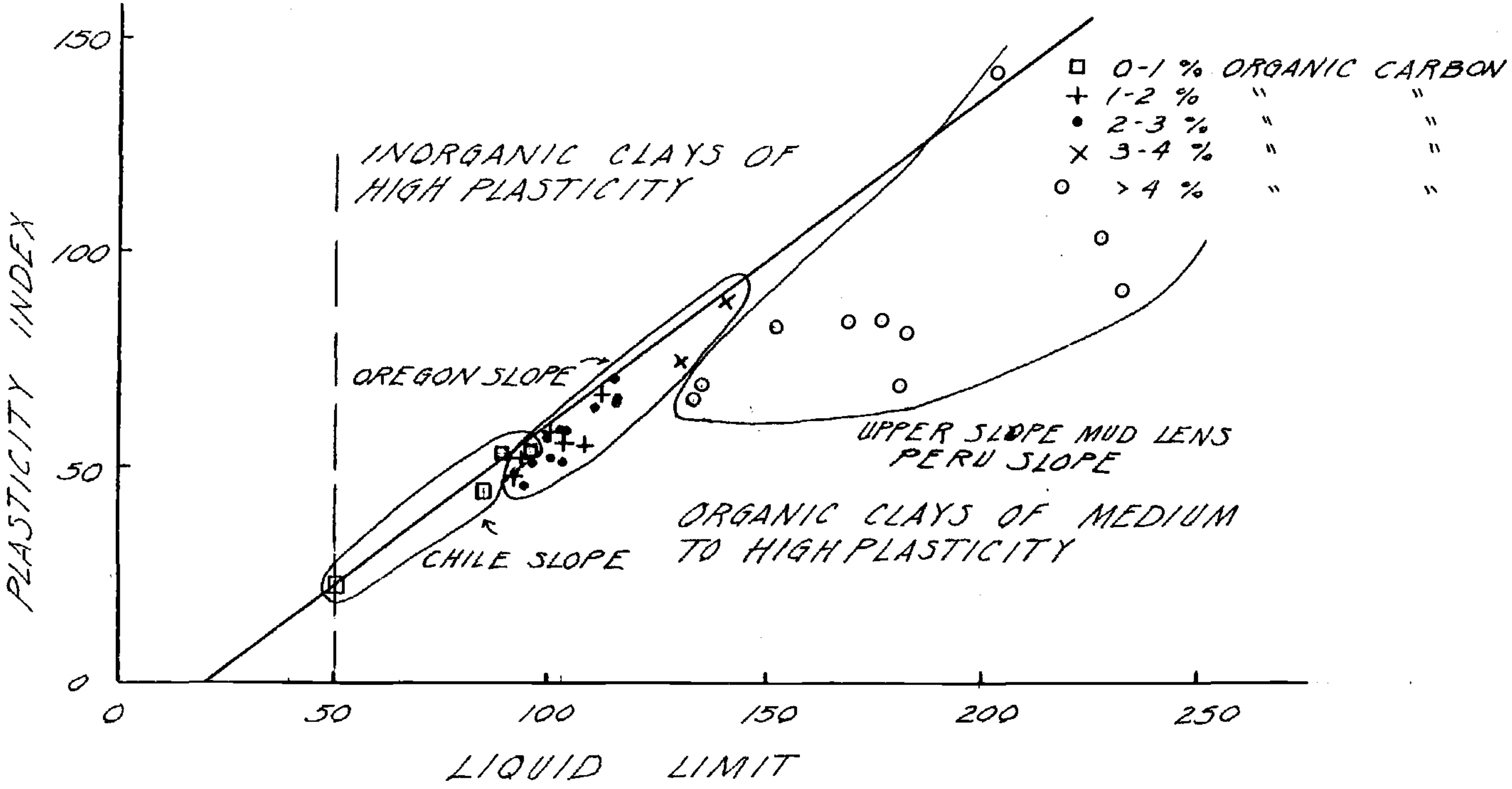

Figure 12. Plasticity chart. Data is from top, middle, and bottom of each Oregon Kasten core. Also shown are data from Peru and Chile slopes (Busch, 1981).

plastic organic silts and silty clays. This is similar to the information reported by Busch (1981) for sediments on the Peru slope with similar organic content. Oregon slope sediments have considerably lower liquid limits and plasticity indices than higher organic sediments from the upper slope environment off Peru while at the same time they exhibit higher liquid limits and plasticity indices than sediments from the Chile slope which has lower organic contents. Plotting the liquid and plastic limits versus organic content reveals a good correlation between these two parameters in this study (Fig. 13). A similar relationship was reported by Busch (1981) for the organic-rich Peruvian slope deposits. Another common factor which may influence the Atterberg limits is the clay content. It is well known that certain clay minerals have a greater ability to adsorb water than others which then results in much higher liquid limits and slightly greater plastic limits (Wu, 1976). Smectite is one such mineral with a high water adsorptive capability.

Both type and amount of clay minerals are reflected in the Atterberg limits. To separate the effect of each, Skempton (1953) defined the activity of a soil as the ratio of the plasticity index to the percent clay (<2 μm). Generally, the higher the activity, the greater the importance of the clay-size fraction on the physical properties. This can be correlated to the importance of the types of exchangeable cations available in the sediment as well as the importance of the pore fluid composition. Activity for Oregon slope sediments ranges from 0.94 to 1.82 with a mean for all values of 1.28. According to the classification of Skempton (1953) these sediments

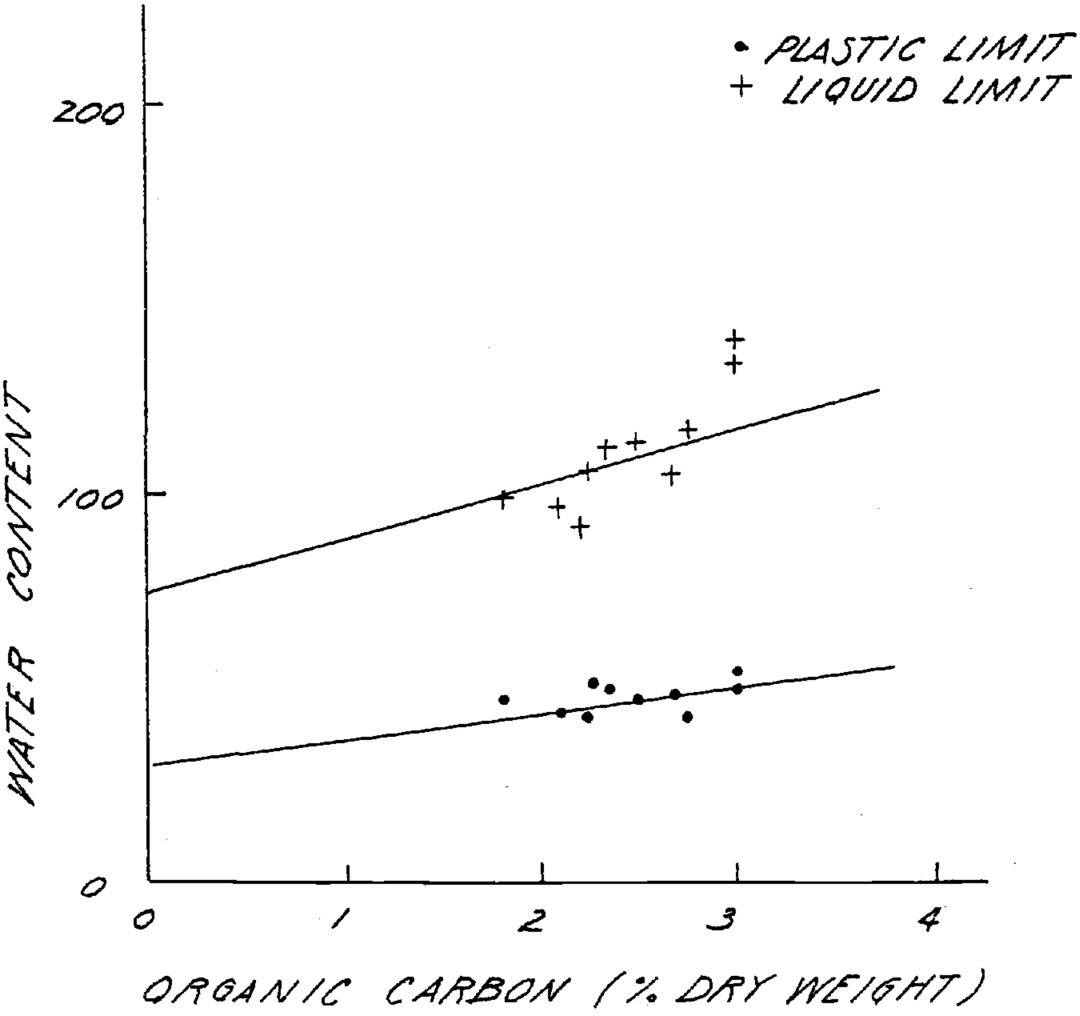

Figure 13. The relationship between the liquid and plastic limits and the organic content. Lines represent least squares fit through data.

are considered active with activity values between those of illite and Ca-montmorillonite. The values are not as great as would be expected based on the smectite abundance of Krissek (1982) where 70 to 90% of the bulk sample less than 2 μm was quantitatively determined as smectite. If in fact 70 to 90% of the clay-size fraction was smectite, much higher values for the activity (up to 7) would be expected. From this it is inferred that smectite may not play an important role in determining the physical properties of Oregon slope sediments.

Shear Strength

Mean sediment undrained shear strength for the 0 to 150 cm interval of each Kasten core ranges from a high of 9.7 kPa to a low of 5.5 kPa. The only shear strength data available is from the 7 Kasten cores, therefore, delineation of any areal trends is difficult due to the insufficient coverage of the data.

Within each core changes in the shear strength are indicated by the water content. Generally, decreasing water content correlates with increases in the shear strength (Fig. 14). For a clay sediment this decrease may be related to the increased separation of particles as water content increases. This separation acts to decrease the interaction between particles which ultimately leads to decreased shear strength. Such factors as sediment consolidation, texture, and organic content all exert an influence on the water content, therefore, these factors must be considered before an explanation of shear strength behavior on the Oregon slope can be offered.

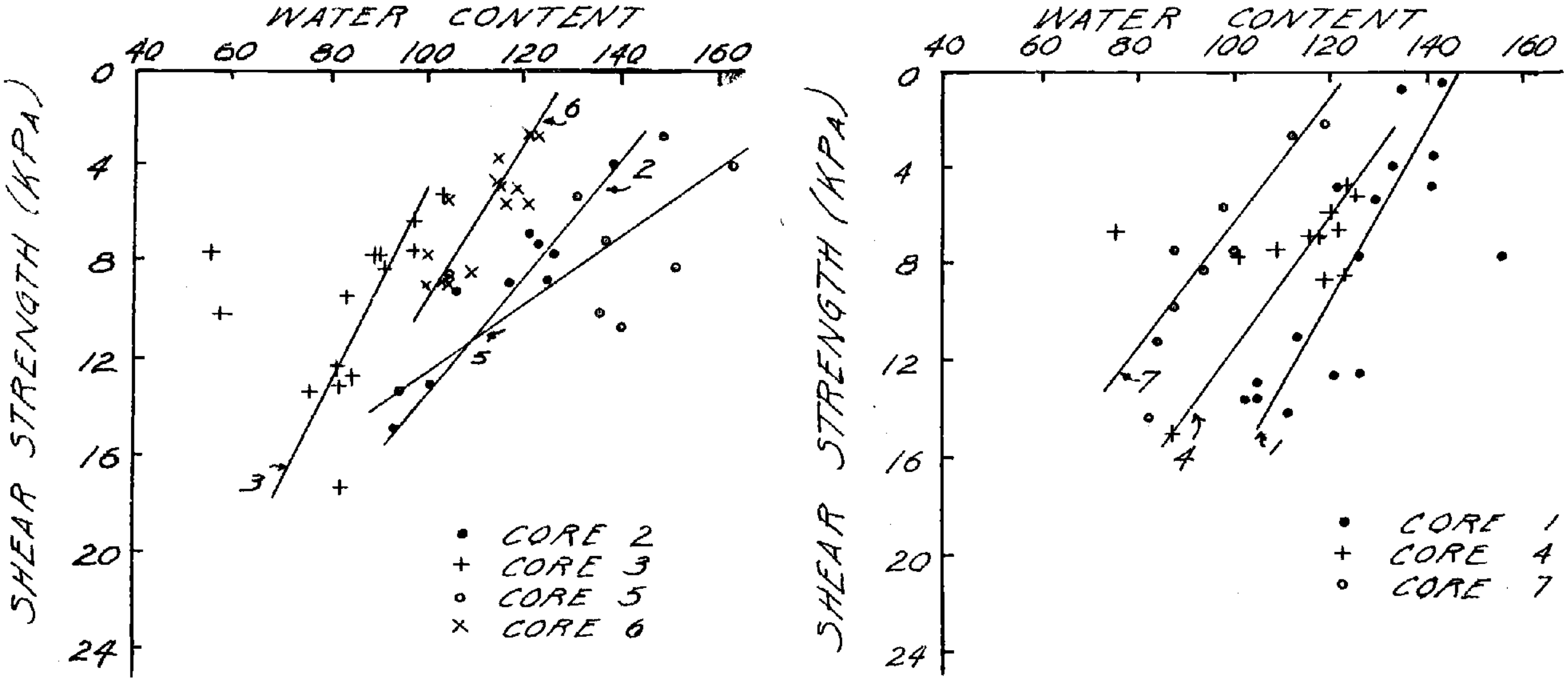

Figure 14. The relationship between the water content and the shear strength.

Sediment consolidation occurs by the expulsion of water from void spaces upon loading. This expulsion allows sediment particles to move closer together due to the removal of the incompressible fluid filling the voids. As overburden pressures increase downcore the amount of sediment consolidation increases with an associated decrease in the water content. The net result is a downcore increase in the sediment shear strength under normal conditions (Fig. 15). The relationship between texture and shear strength is less pronounced. As shown earlier, increases in the mean grain size are related to decreases in the water content. However, a comparison of the downcore textural trends and the downcore shear strength reveals few instances where increases in the silt content and/or the sand content can be directly related to increases in the shear strength. It is possible that the changes in the texture are not great enough to influence the shear strength to a large extent. Finally, increases in the organic content have been found to increase the water content of a sediment. A plot of shear strength versus organic content (Fig. 16) does not show a very strong relationship between these two parameters, however, linear regression analysis of the data does indicate that generally shear strength decreases as the organic content increases. Busch (1981) reported an increase in the shear strength associated with the presence of organic matter. Citing the work of Pusch (1973) in Swedish clays, and that of Rashid and Brown (1975) working in remolded sediments, Busch concluded that the shear strength increase was due to bonding between the organic and mineral constituents in the sediment. This relationship is apparently

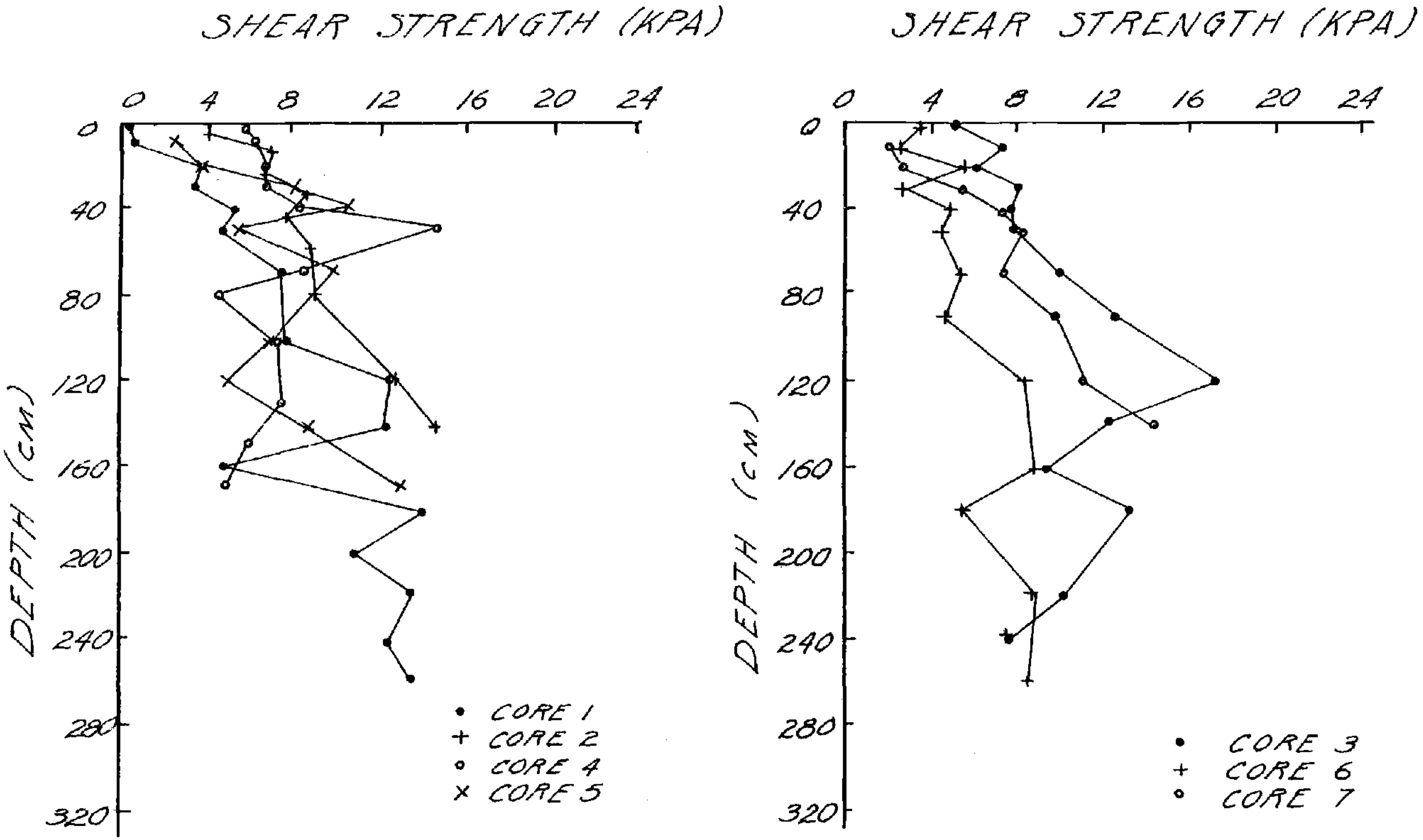

Figure 15. The relationship between the shear strength and the depth downcore.

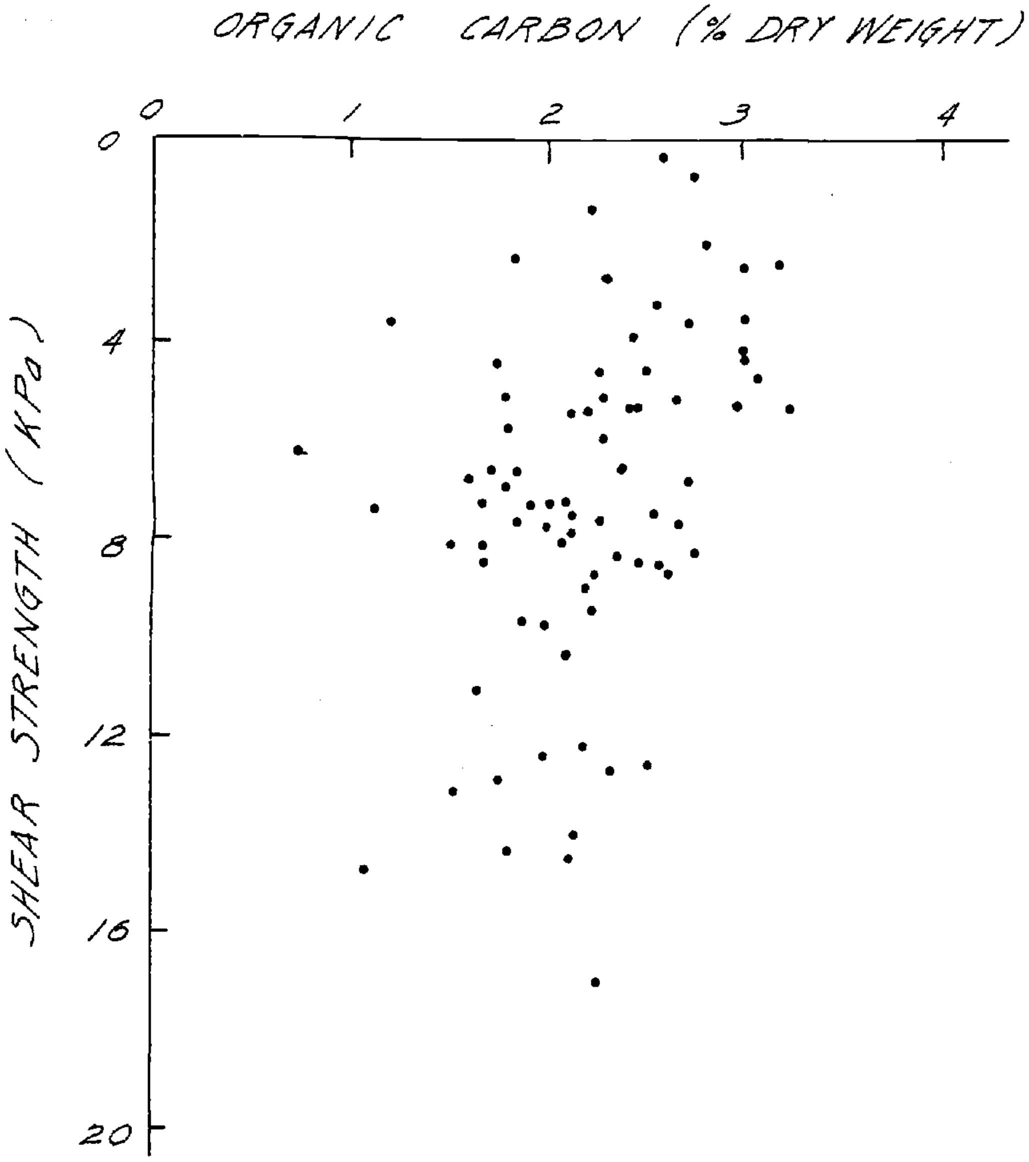

Figure 16. The relationship between the shear strength and the organic content.

limited to the high organic content sediments which Busch encountered on the Peru upper slope (4 to 20% organic carbon). For sediments with organic contents of less than about 3%, it appears that the organic matter acts to decrease the shear strength.

The ratio of the undisturbed to the remolded shear strength, the sensitivity, is a means of determining the amount of shear strength loss resulting from a breakdown of the sediment fabric. Mean sensitivities for the 0 to 150 cm interval range from 4.0 to 5.4 with individual values as high as 10.0 being measured. Such mean values indicate that the sediment losses 75 to 82% of its strength when disturbed (Skempton and Northey, 1952). According to the classification of Rosenqvist (1953) these sediments are considered very sensitive. Although the coverage of data is sparse the sensitivity of Oregon slope sediments does not seem to follow any areal trends nor does it appear to show any distinct relationship to the organic matter content (Fig. 17) as reported by other studies (Pusch, 1973; Busch, 1981). As was the case for undisturbed shear strength, organic matter apparently affects the sensitivity of slope deposits at slightly higher concentrations than those found off Oregon. A threshold concentration of around 4% organic carbon is indicated above which organic matter influences the sensitivity as well as the undisturbed shear strength. Below such a concentration, however, the organic content appears to be of minor importance regarding the shear strength.

One-Dimensional Consolidation

The decrease in sediment volume in response to loading is termed

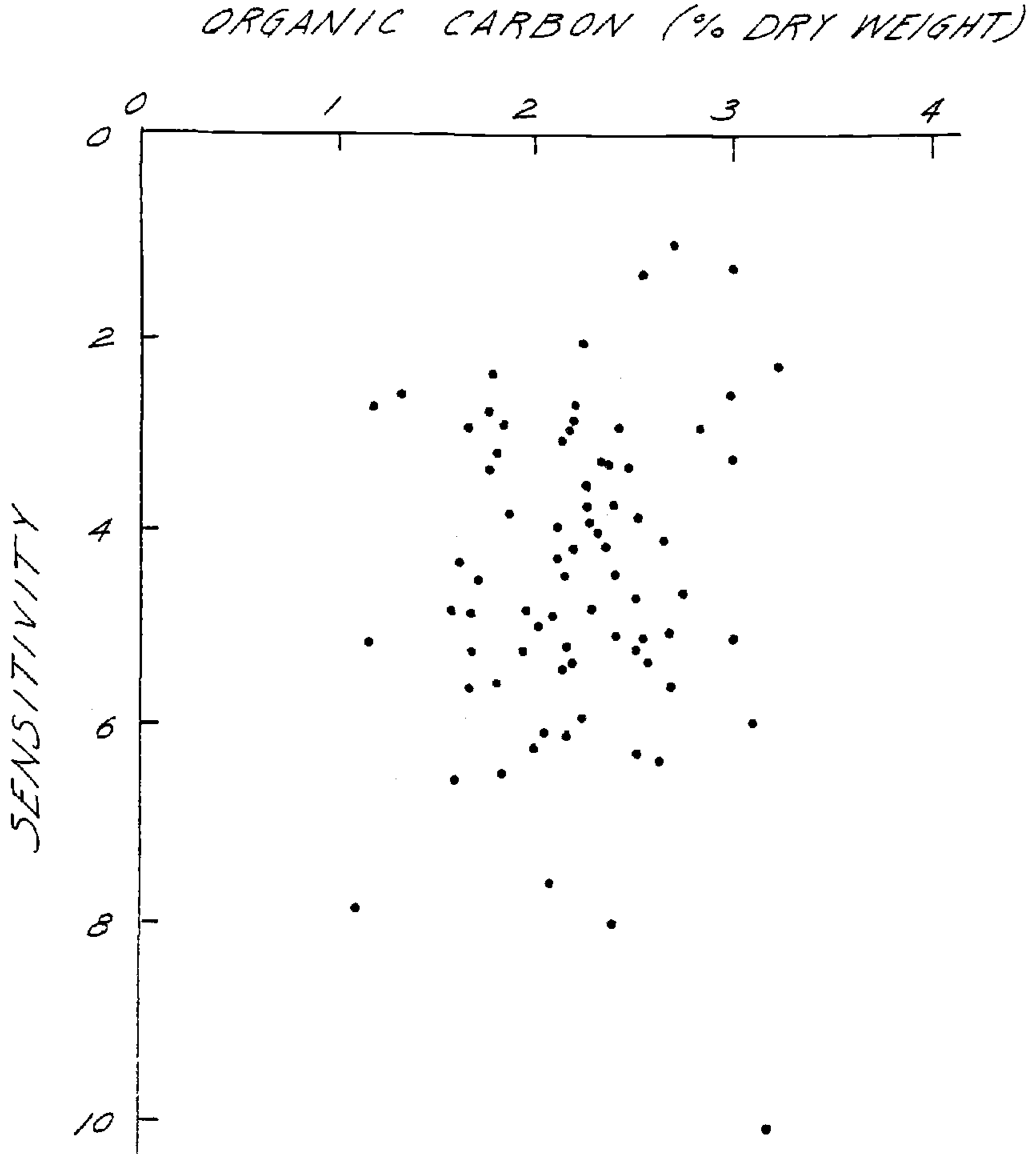

Figure 17. The relationship between the sensitivity and the organic content.

soil compression and is dependent on the amount of water expelled from the void spaces in a water saturated sediment. Under a given load, this compression may occur at varying rates. Soil compressibility is the total amount of compression, or volume change, which will occur, regardless of the rate. This information can be used in marine geology to estimate the volume reduction in marine sediments due to increasing overburden and has a bearing on accumulation rates, porosity, density, and total sediment thickness. Furthermore, the past record of maximum loading, the stress history, can be determined from the total compression. This information is often useful in identifying episodes of sediment erosion. The rate of consolidation (or compression) is important as it yields information on the modifications of sediment structure with time and has a bearing on sediment permeability (Wu, 1976). In addition, high rates of secondary compression, to be explained later, may indicate a greater susceptibility to creep deformation (Tavenas et al., 1978).

Compressibility is quantified by the compression index (Cc) which is a measure of the decrease in void ratio (volume of sediment voids to the volume of the sediments solids) per load increment. This is determined from an estimate of the field behavior of a sediment utilizing a void ratio versus log pressure curve and the method of Perloff and Baron (1976). The compression index of northern Oregon lower continental slope sediments varies from a high of 1.78 in an organic-rich sample to a low of 0.40 in a relatively organic-poor sample (Table I). It has been found that finer grain sizes, increasing organic content, and increases in the percentage of the

Table I. Comparison Between Cc, % Organic Carbon and % Clay

Core #	Depth Downcore (cm)	Cc	% Organic Carbon	% Clay
1	243	.71	2.1	41
2	95	.72	2.2	38
4	200	.49	1.1	58
6	150	1.08	1.6	50
8	206	2.2	2.5	53
9	100	1.01	1.9	50

clay mineral group of smectites are associated with increasing compressibility indexes (Wu, 1976). As far as the northern Oregon lower slope is concerned, organic content seems to be in effect to the greatest degree. Linear regression analysis shows a fairly good correlation between Cc and the percent organic carbon (Fig. 18). This relationship was also reported by Busch (1981) on the organic-rich sediments of the Peru continental slope. A comparison of Cc versus the percent clay-sized material shows a poor correlation.

Rates of consolidation in saturated, fine-grained sediments are generally divided into two stages. The first, or primary stage is the response of a sediment immediately after application of a load. This load is translated into excess hydrostatic pressure throughout the sample. If drainage of the sample is allowed, this excess hydrostatic pressure is dissipated by flow of the pore water from the region of high pressure to a region of low pressure until such a gradient no longer exists, i.e. the excess hydrostatic pressure due to the application of a load has been dissipated. The second, or secondary stage occurs after dissipation of the hydrostatic pressure and relates to the period of time during which the sediment particles themselves readjusts to bear the applied load.

Since primary consolidation relates to the rate at which water can move from regions of high to low pressure, it is controlled by the permeability of the sediment as a whole. Ranges for the permeability coefficient of the six one-dimensional consolidation test samples were estimated using the procedure of Lambe (1967) which utilizes the compressibility (Cc), the void ratio (e), and a

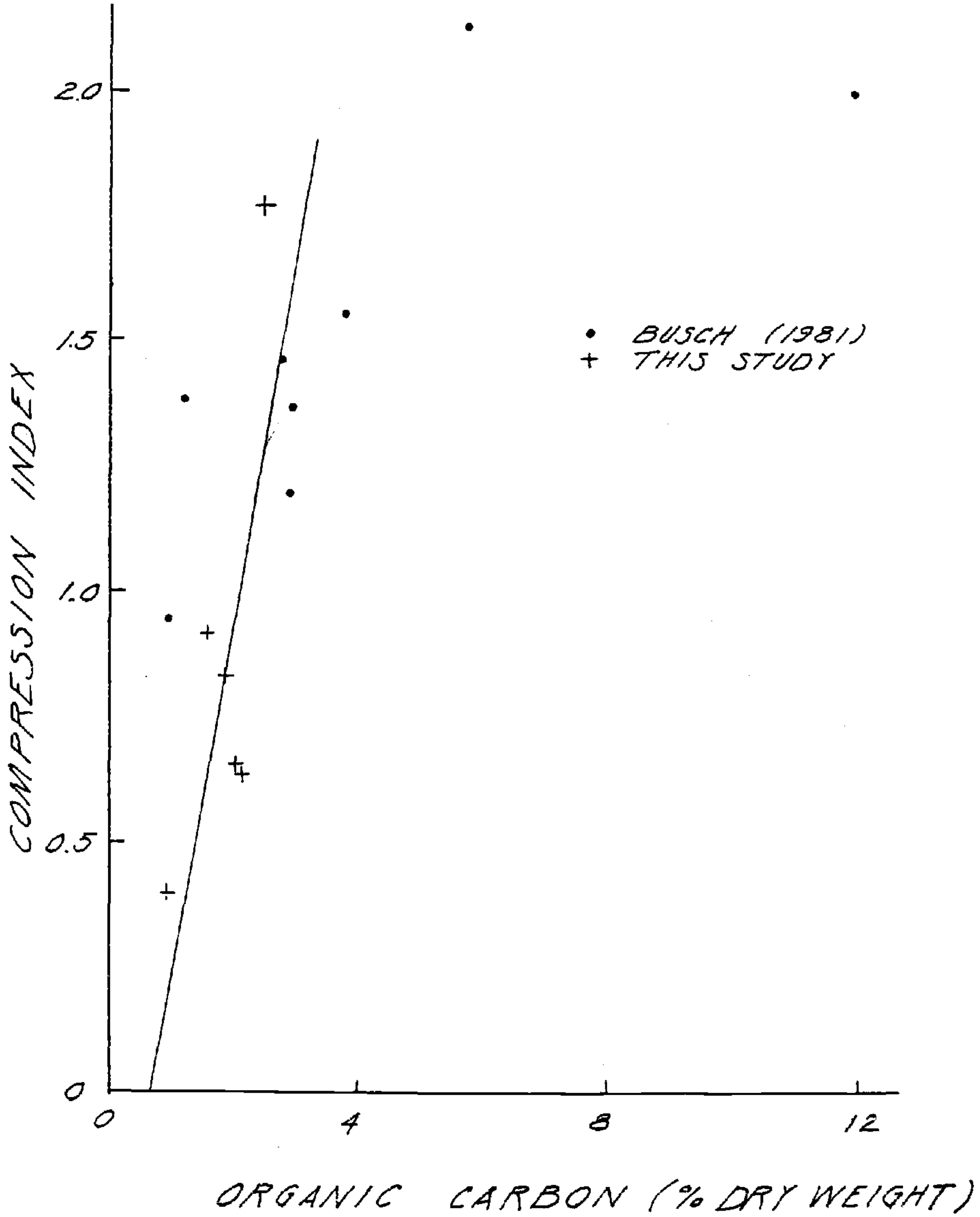

Figure 18. The relationship between the compression index and the organic content. Line represents a least squares fit through Peru and Oregon data combined up to 6% organic carbon.

coefficient relating the length of the drainage path and time of consolidation for each load increment applied. The permeability coefficient of these samples ranges from 7 to 70 x 10^{-7}cm/s for load increments between 80 and 800 kpa (Table II). These values tend to be on the low side of typical silty clays and clays as determined by Bryant et al. (1974). The permeability coefficient is largely a function of the particle size (Wu, 1976) however, Pusch (1973) has reported that an inverse relationship between organic content and permeability exists. Such an inverse relationship is not found in Oregon lower slope sediments (Table II) nor was it evident in the studies of Busch (1981) on the Peru continental slope deposits.

The rate of secondary compression ($E\alpha$) is quantified by determining the log time rate of change of the void ratio, as expressed in terms of strain. Comparing rates of secondary compression, determined for both the Peru-Chile and northern Oregon continental slope sediments, shows that $E\alpha$ increases with increasing organic content (Fig. 19). This correlation supports the relationship reported by Busch (1981) at higher organic contents and higher rates of secondary compression. Organic matter appears to be the most important factor influencing rates of secondary compression in both the northern Oregon and Peru-Chile slope sediments despite differences in mineralogy and texture between the two areas. The pre-consolidation pressure (Pc) is the maximum effective stress a sediment has been subjected to can be estimated from the plot of void ratio versus log pressure curve obtained by the one-dimensional consolidation tests. According to Casagrande (1936) Pc may be determined by intersection between a line drawn from the point of maximum curvature and a line extending the

Table II. Comparison Between Permeability (k), Coefficient of Secondary Compression, % Organic Carbon and % Clay

Core #	Depth Downcore (cm)	k cm/s ($x10^{-7}$)	Ex	% Organic Carbon	% Clay
1	243	26 - 70	.78	2.1	41
2	95	16 - 48	1.13	2.2	38
4	200	31 - 67	.46	1.1	58
6	150	17 - 46	.77	1.6	60
8	206	18 - 44	1.54	2.5	53
9	100	7 - 58	1.00	1.9	50

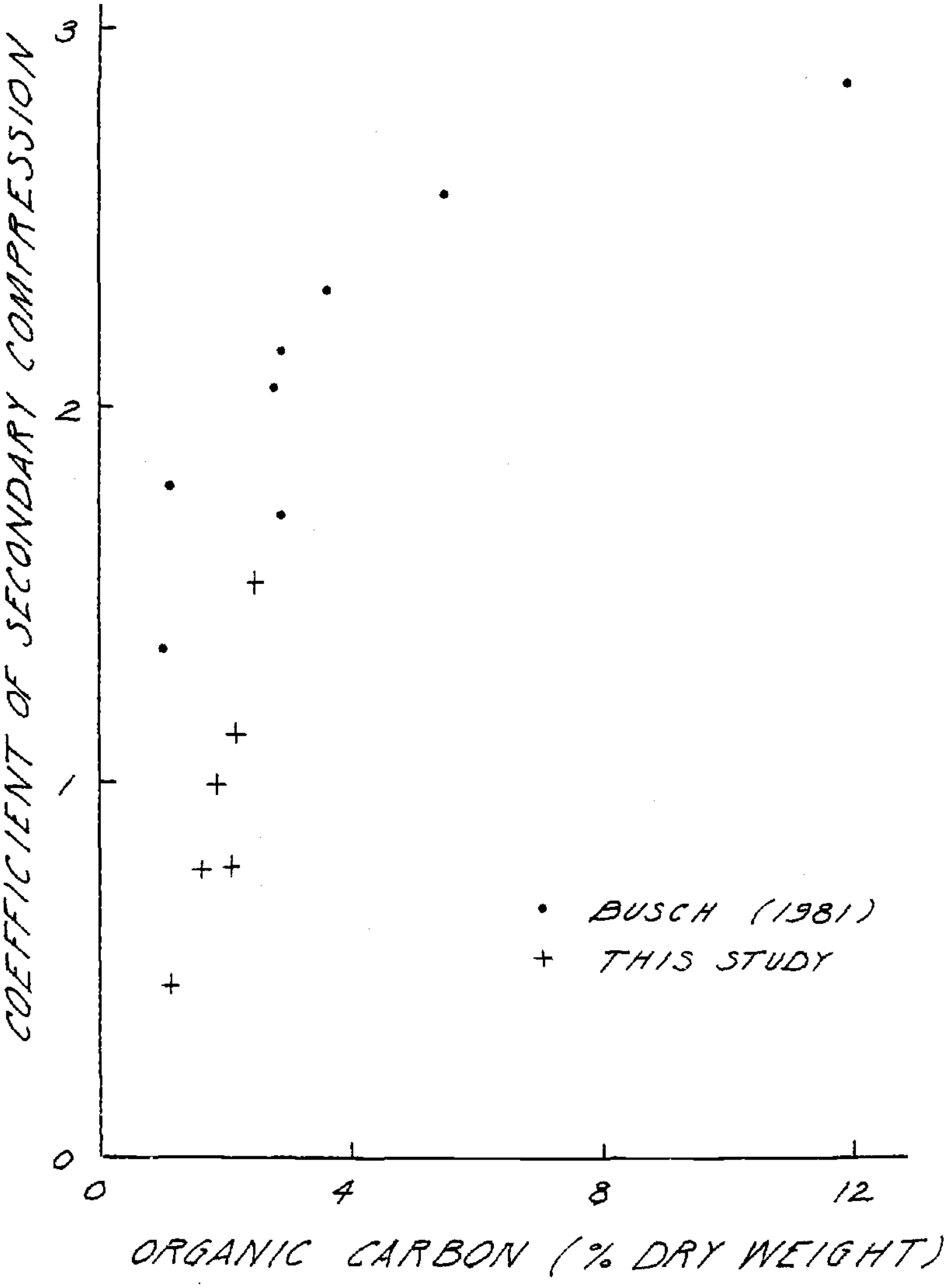

Figure 19. The relationship between the coefficient of secondary compression and the organic content.

straight-line portion of the void ratio versus log pressure curve. The existing pressure due to overburden, Po, can be calculated using the buoyant unit weight of the overlying sediment. The ratio of Pc to Po, the consolidation ratio denotes whether or not the sediment has been consolidated under a stress different than that which can be attributed to the present overburden. When Pc:Po equals one, the sediment is said to be normally consolidated and reflects the effects of the present overburden. When Pc:Po is greater than one, stresses greater than the existing overburden are considered to be responsible for sediment consolidation. Values of Pc:Po less than one classify a deposit as underconsolidated and generally reflect the effects of a buildup of pore water pressure.

For the northern Oregon lower slope deposits examined the consolidation ratio ranges from a high of 10.2, in two cores from both the northern and southern halves of the study region, to a low of 3.5, in a highly organic sample from the northern half of the study region (Table III). All of the samples tested are considered overconsolidated based on the above definition. With depth downcore the degree of overconsolidation apparently decreases (Fig. 20) as was also found by Busch (1981) off Peru. A common cause of overconsolidation is erosion of overlying sediment. Examination of the X-radiographs of all Kasten cores reveals numerous disturbed and convoluted sediment layers which tend to indicate some process such as slumping or bottom currents has effected these deposits. Unfortunately, radiometric age dates are not available to better define a hiatus in the cored intervals so that evidence for erosion

Table III. Comparison Between Overconsolidation Ratio and % Organic Carbon

Core #	Depth Downcore (cm)	Po (kPa)	Pc (kPa)	Pc/Po	% Organic Carbon
1	240	8.78	36	4.1	2.1
2	95	3.8	39	10.2	2.2
4	200	8.8	48	5.5	1.1
6	150	5.4	41	7.5	1.6
8	206	6.6	23	3.5	2.5
9	100	3.7	38	10.2	1.9

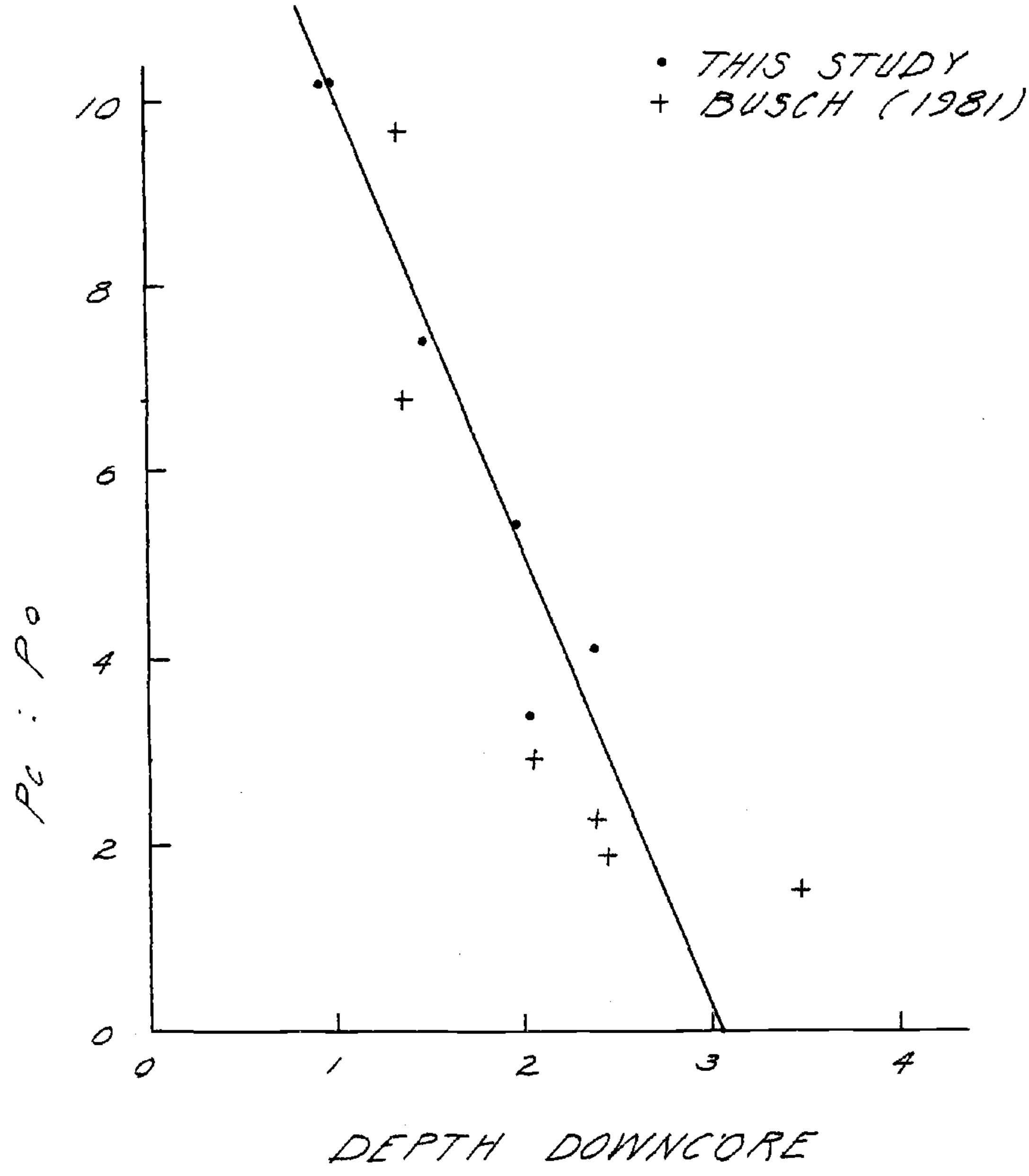

Figure 20. The relationship between the consolidation ratio and the depth downcore. Line represents a least squares fit through data.

or deposition due to the above processes is not conclusive.

An additional cause of overconsolidation, cited by Carson (1977), may be the application of lateral stresses such as those encountered at a convergent margin. With only 6 values for the consolidation ratio in this study area, it is difficult to assess the degree to which this factor may be responsible for the high Pc:Po ratios.

Evidence that the organic matter concentration may affect the consolidation state, as was reported for the organic-rich sediments of the Peruvian continental slope (Busch and Keller, 1982), is not found in cores from the northern Oregon lower continental slope (Fig. 21). The reason cited by Busch and Keller for this relationship was the enhancement of interparticle bonds by organic substances. At low concentrations of organic matter (<3%), this ability must be smaller and more variable and therefore may not result in significant alteration of the consolidation state. Other bonding agents such as calcite cannot be discounted at present.

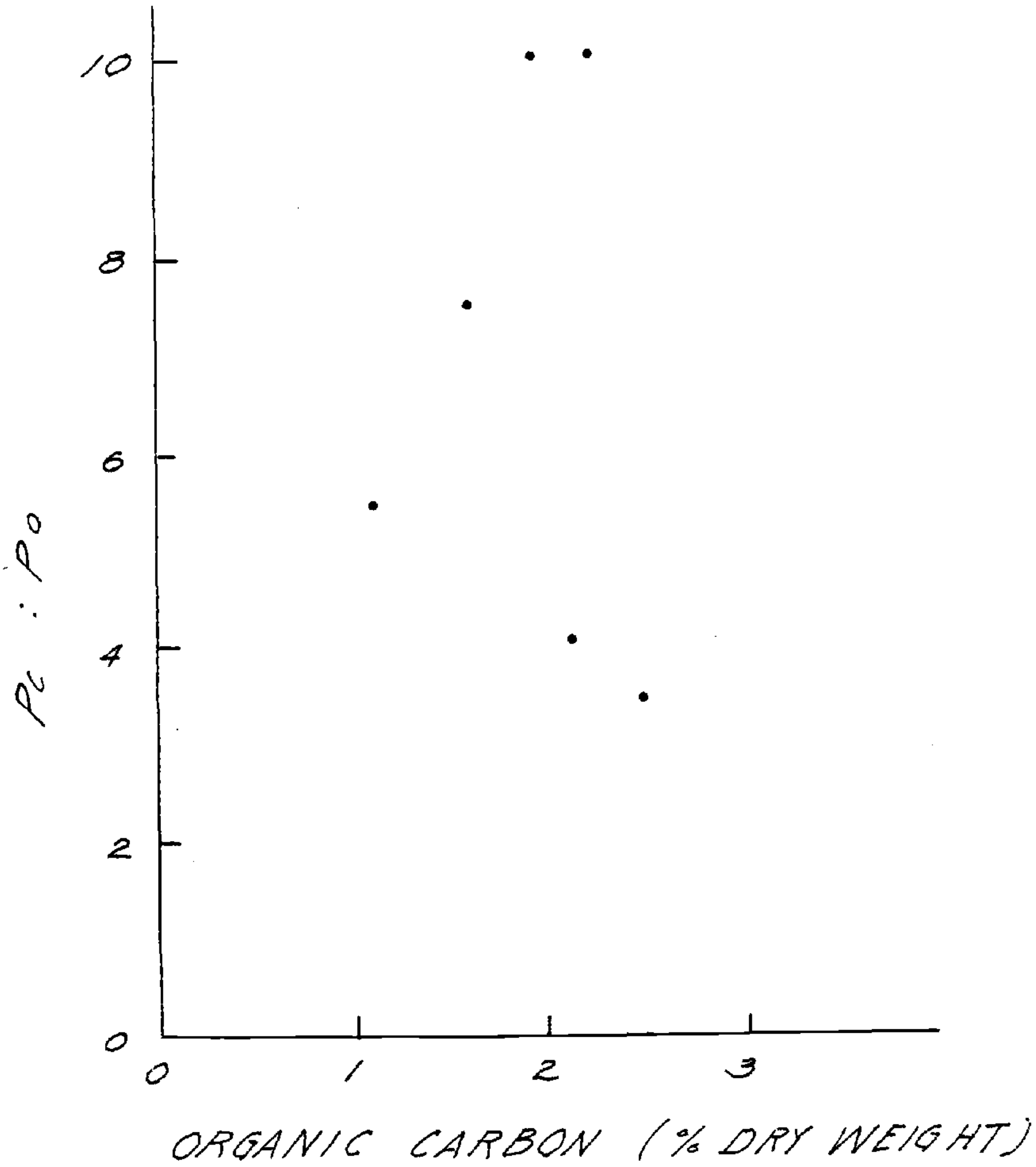

Figure 21. The relationship between the consolidation ratio and the organic content.

DISCUSSION

Variations of the geotechnical properties and consolidation characteristics of sediments from the northern Oregon lower continental slope appear to be influenced to some degree by the presence of organic matter. At the low to moderate concentrations of organic matter present in this area (0.5 to 3.2% organic carbon) different sediment properties seem to initially "feel" the effects of organic matter at differing concentrations. Changes in grain size also appear to play an important role in influencing many of these properties while the effects of clay mineralogy appear to be minor. The purpose of this study has been to determine what effect, if any, organic matter has on the various geotechnical properties of slope sediments and at what concentration those effects may become significant.

Water content is often used as an index of sediment consistency or degree of firmness. As a sediment changes its consistency some of its physical properties also change, such as shearing strength. For this reason, a simple textural classification of a sediment is often insufficient to explain the sediment characteristics. On the northern Oregon lower continental slope increases in water content are found to correlate with increases in organic content (Fig. 9). This study confirms the relationship noted by Busch (1981) in his study of the organic-rich deposits of the Peru-Chile continental slope. The reason for this relationship is apparently twofold. First, organic matter has a high water content resulting from the adsorption of water to organic substances (Pusch, 1973) and second, by the formation of clay-organic aggregates creating large void spaces which fill with water (Pusch, 1973; Reimers, 1981). At low to moderate concentrations of organic matter the relative role of such properties as texture and clay mineralogy become increasingly more important and influential in affecting the sediment geotechnical properties. This is illustrated by the finding that the highest water contents are not always associated with the highest organic contents off Oregon. Textural effects stem from the greater adsorptive attraction that smaller clay-size particles have for water owing to their surface charge imbalances leading to dipolar attraction of water. In addition, surface area per unit weight of material increases as particle size decreases leading to even greater surface attraction of water. This argument extends to include the mineralogy of the clay-size particles. Smectite tends not only to have much smaller platelets and thus greater surface areas, but its structural charge imbalance lies closer to the surface of the clay platelet (Grimm, 1968). By this mechanism, greater amounts of water are held to the surface of a smectite platelet than to the platelets of other clay minerals such as chlorite and illite which tend to have surface areas per unit weight of material an order of magnitude less than smectite. Busch (1981) also reported an increase in water content primarily attributed to increases in clay-size material in deposits with organic contents of less than 3% and clay-sized percentages on the order of 70%. The relative influence of texture versus organic content on the water content is quite variable off

Oregon. Apparently, when the concentration of clay-size particles fluctuates over a wide range, texture influences the water content to a greater extent than the organic content between 0 and 3% organic carbon.

Wet bulk density can be used to determine the weight of a sediment column for stress history information. It is also an index of sediment compressibility and plays an important role in determining permeability and porosity in sediments. Wet bulk density on the lower continental slope of northern Oregon appears to decrease as the organic matter concentration increases (Fig. 9). This relationship was also observed on the Peru and Chile continental slopes (Busch 1981). The increasing water content associated with increasing organic content combined with the low density of organic matter itself (<1.5 Mg/m^3) act together to decrease the wet bulk density. Texture influences the wet bulk density by its influence on the water content. As grain size decreases the water content increases which in turn decreases the sediment wet bulk density. Examination of the relationship between wet bulk density and the organic carbon concentration (Fig. 9) indicates that above about 2.5 to 3.0% organic carbon the data lie much closer to the trend determined by linear regression. Below this level the scatter of the data about the trend indicates an increase in the importance of other factors, notably texture, in the bulk density. Apparently above 2.5 to 3% organic matter starts to be the dominant controlling agent regarding wet bulk density.

It has been found that at the same water content, different clays may have widely different consistencies. In addition, while a small change in water content may not affect one clay it may change another from a liquid to a very stiff condition. For this reason, water content alone is not an adequate index as to sediment condition. In order to bring some order to the classification of fine-grained sediments as to consistency, Atterberg limits were developed. On the Oregon lower slope these limits, specifically the liquid and plastic limits, appear to be controlled by the organic content, the grain size and possibly the clay mineralogy. Atterberg limits increase as the ability to adsorb water increases. Several factors may be responsible for increasing this attraction including grain size, grain shape, mineral composition and chemical composition (in this case, organic content). As grain size decreases, surface active forces of attraction increase and act to increase the thickness of the bound water layer. Particle shape is also important. Flat particles have greater surface area than spherical particles which increases the area available for water to attach. Mineral composition, especially among the clay minerals, can be important, however, the activity of Oregon slope samples seems to preclude a heavy influence from the smectite (or montmorillonite) clays. Other types of clays, notably the more amorphous types which will not show up in quantitative X-ray diffraction, may still be an important factor to consider, however, it is unknown whether these minerals are in fact present off Oregon. The presence of organic matter also acts to increase the water content and may play a role increasing the Atterberg limits. Use of Atterberg limits gives information on the relative importance each of these factors plays in determining physical property variations of Oregon lower slope sediments. On the Oregon slope indications are that the concentration of organic matter has a more significant influence on the Atterberg limits than the texture. This is especially evident when data from the Peru-Chile slope (Busch, 1981) is considered as well (Fig. 12). The Oregon slope data lies on the same trend as the Peru-Chile data which shows an increase in plasticity and in liquid limits between 0 and 20% organic carbon even though the two areas are texturally and mineralogically slightly different. The affect of increasing clay content tending to increase the Atterberg limits is not clear. Apparently, fluctuations in the clay content off Oregon (40 to 60%) are not great enough to alter these limits in the presence of organic matter concentrations between 0.5 and 3.0%. Activity values indicate that the effect of smectite may be minimal.

Shear strength is often the principal factor in defining the behavior of a sediment under a load. This load may be external, such as tectonism, or internal, as from the overlying sediment. Determination of sediment shear strength, therefore, is important in determining such aspects of sediment behavior as slope stability. Among clay soils, changes in the water content have a direct influence on the particle spacing and hence the magnitude of the interparticle forces. Varying these forces of attraction has a profound influence on the shear strength. Such factors as sediment consolidation, grain size, and organic content may all contribute to changes in the water content. These same factors usually act to change the shear strength.

Downcore increases in overburden pressure result in consolidation of sediment via expulsion of the water in the void spaces. This also results in the closer proximity of the sediment particles which acts to increase the bulk sediment shear strength. The resultant increase in shear strength with depth of burial is evident in cores from the Oregon slope (Fig. 15).

Decreasing grain size acts to increase the distance of separation between sediment particles since smaller particles tend to have a greater surface area attracting larger amounts of water, by electrostatic forces, to their surfaces. Not only are the particles further apart but water is filling the spaces. Therefore, decreasing grain size is generally associated with decreasing shear strength. The Oregon slope does not exhibit this correlation extremely well. The reason for this is probably due to two factors. First, the grain size does not fluctuate to a great degree and second, it appears that the organic content may have a more important role influencing sediment strength.

Increasing organic matter contents have been found to correlate with increases in the water content (Fig. 7). This was due to several factors explained earlier. Insofar as shear strength is concerned, this increase in water content should act to decrease the shear strength. This correlation was found in Oregon slope sediments to some extent (Fig. 16), however, Busch (1981) reported an increase in shear strength associated with high concentrations of organic matter (4 to 20% organic carbon). Citing the studies of

Greenland (1965), Pusch (1973), and Rashid and Brown (1975), Busch attributes the high strength to the action of organic matter as a cementing agent between clay particles. Shear strength of Oregon lower slope deposits does not display this increase with higher organic matter concentrations (Fig. 16). A possible explanation might be that at low to moderate concentrations (0.5 to 3.0%) organic matter is not significant enough in relation to the effects of grain size and clay mineralogy to increase the bulk sediment shear strength. It is possible, however, that the cementing of clay particles does occur, but not on a scale large enough to increase the bulk sediment strength.

Compressibility of a sediment is a measure of the volume reduction which occurs due to increasing pressure. It can be used to estimate changes in porosity, permeability, density, and sediment thickness. Higher values of the compression index indicates the sediment will experience greater volume changes with burial. Compressibility along the northern Oregon lower continental slope increases with increasing contents of organic matter (Fig. 18). This result compares favorably with that of Busch (1981) on the Peru continental slope though the Oregon data is a bit more scattered. Previous studies have shown that organic matter affects the sediment compressibility by the establishment of an open microstructural sediment fabric and by virtue of the ease of deformation of the organic substances themselves (Pusch, 1973; Rashid and Brown, 1975; Reimers, 1981). Electron microscopy of organic-rich slope sediments from off Peru (Reimers, 1981) reveals a highly porous microstructure composed of organic-mineral aggregates, organic sheath structures, and siliceous tests. With depth of burial Reimers found that the number of sheath structures decreased but postulated that microporosity within the aggregates remained high. There is no evidence that such sheath structures exist in Oregon slope sediments, however, a slight increase in the void ratio with increasing organic content (Fig. 22) and the increase in compressibility with increasing organic content (Fig. 18) indicate that organic matter does affect the sediment microstructure off Oregon. This results in larger volume reductions at pressures greater than the preconsolidation pressure for sediments with higher organic matter content. Also of importance to this discussion is the reported high deformability of the mineral-organic aggregates (Pusch, 1973; Rashid and Brown, 1975) allowing large volume changes under a load and thus increasing the compression index. This may be due to the increased thickness of the adsorbed water layer associated with the addition of organic matter which increases the compressibility by allowing greater sediment particle mobility, especially with regards to the clay mineral platelets.

Changes in the amount of clay-size material off Oregon do not seem to have as great an impact on the compressibility (Table I) at the organic contents tested, however, it is still an important factor to consider. Decreasing grain size tends to correlate with an increase in the thickness of the adsorbed water layer coating mineral grains which in turn allows greater particle mobility under a load. As noted by Busch (1981) off Peru, the influence of increasing clay content on the void ratio, and thus compressibility, is

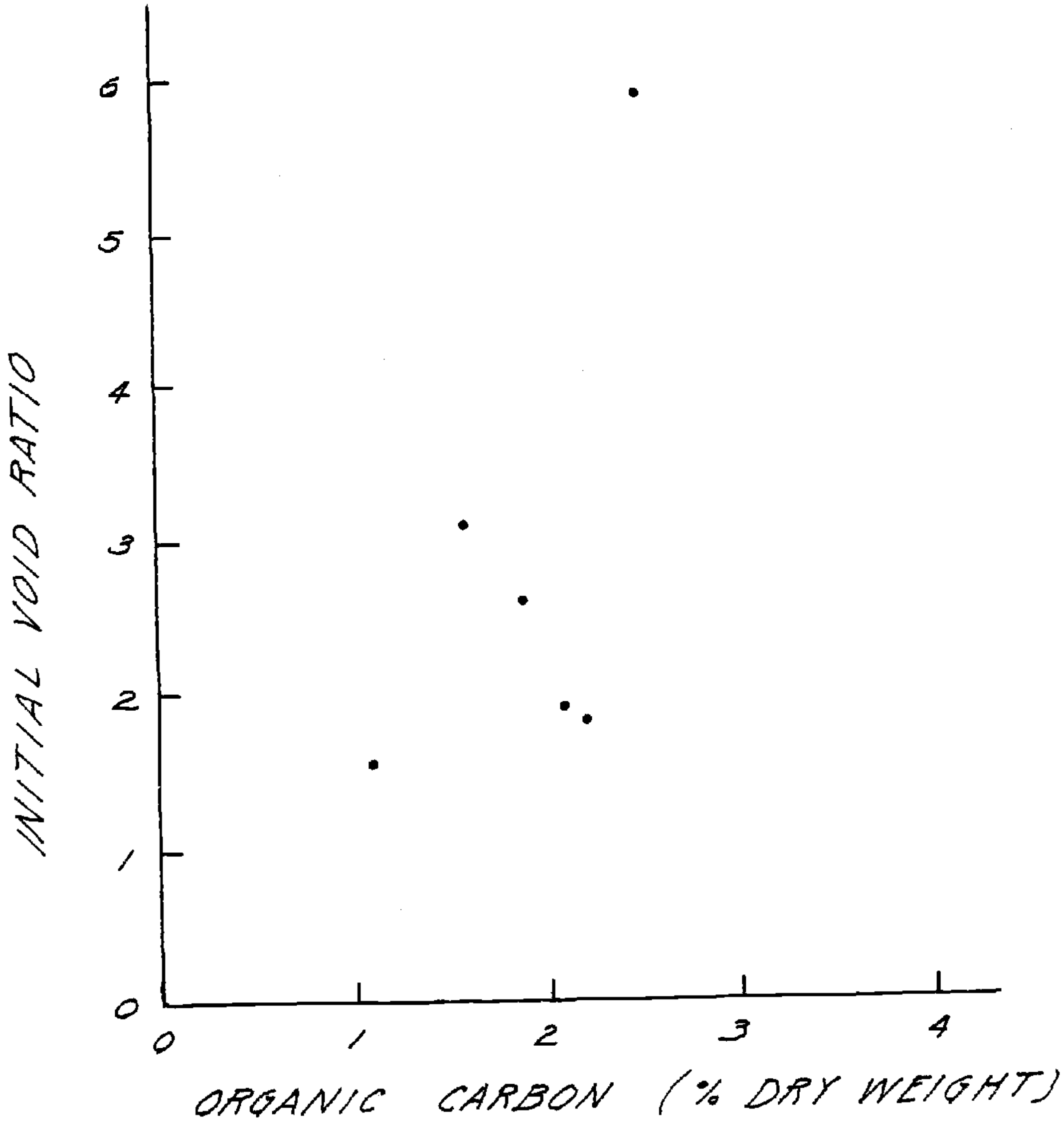

Figure 22. The relationship between the initial void ratio and the organic content.

evident at low organic contents (<3% organic carbon) however, off Oregon, fluctuations in the grain size are apparently not great enough to show any relationship with compressibility. A sequence of increased compressibility of smectite over illite and kaolinite has been observed and reflects the decrease in particle size which results in greater surface area and increased thickness of the adsorbed water layer affecting compressibility as above (Wu, 1976). This effect may only be of a secondary nature, but is worth noting as a possible explanation for compressibility variations at low organic matter concentrations.

Rates of consolidation provide information on the modification of sediment structure with time. The rate of secondary compression is of interest since sedimentation on the continental slope occurs at such a low rate that deformation occurs under a constant effective stress. In other words, the excess hydrostatic pressure is applied at rates slower than the ability of the sediment to dissipate it making primary consolidation insignificant in the natural marine environment of the Oregon continental slope.

Rate of secondary compression is also influenced by the organic content. With increasing concentrations of organic matter the rate of secondary compression increases (Fig. 19). The reason for this correlation, commonly observed in organic clays, is not well defined, but Pusch (1973), offered three possible causes. The first is the blocking of pore passages by organic substances leading to lowered permeability and delayed consolidation. Due to the poor correlation between organic content and permeability (Table II) this process is probably not important in these sediments at these organic contents. Second and third are the visco-elastic and plastic properties of the organic matter, and the clay-organic aggregates respectively. Both of these properties act throughout the primary and secondary stages during consolidation yet have a greater impact on the secondary stage because of the longer time span involved.

Finally, the apparent stress history of sediments is often used to determine past episodes of erosion or, if evidence for erosion is absent, can be used to infer the existence of sediment bonding or cementation. Precipitates derived from calcareous organisms and volcanic debris have been cited as cementing agents (Bryant et al., 1974; Richards and Hamilton, 1967).

Busch (1981) explained the apparent overconsolidation of the Peruvian slope deposits by the presence of organic substance acting as a bonding agent. He supported his hypothesis based on the studies of Pusch (1973) and Reimers (1982) who describe interparticle bonding by organic substances based on electron microscopic examination of the sediment fabric. Slow sedimentation may lead to an apparent overconsolidation as well. Bjerrum (1967) concluded that the overconsolidation ratio is time dependent reflecting the influence of secondary compression. The sediment adjusts to the load and gains added resistance to further loading even though an additional load has not been applied. Oregon slope sedimentation rates may not be low enough for this process to be important, however.

On the Oregon slope, Pc/Po does not appear to be related to the organic content (Fig. 21). Overconsolidation does occur and in some cases it seems likely that sediment erosion is responsible. The preconsolidation pressure (Pc) maintains the memory of being loaded by an overburden which no longer exists. This results in an overburden pressure (Po) relatively less than Pc, so Pc/Po is greater than 1. In sediments where evidence for erosion is tentative, other factors may be responsible for apparent overconsolidation. A possible explanation may be the role of laterally applied stresses associated with convergence of the North American and Juan de Fuca plates. Sediments on the Washington continental slope exhibit low near surface water contents which have been related to tectonism in that area (Carson, 1977). This mechanism would be equivalent to vertical consolidation due to overburden.

Organic bonding may not be important at low concentrations. In order to be effective as a cementing agent and cause apparent overconsolidation it appears that organic matter must be prevalent enough to affect a significant percentage of the sediment fabric. In a natural environment, where local variations in organic content may be great, it appears to take relatively high concentrations of organic matter before most or all of the sediment fabric is bonded by it. The lower threshold of influence is difficult to narrow down, however, it seems likely that organic matter concentrations must be greater than 3% and possibly greater than 4%. The results of Rashid and Brown (1975) indicating significant bonding at concentrations <3% may be due to their working with remolded sediments and a high degree of mixing of the organic matter.

Values for the consolidation ratio are quite high, however, for shallow samples where evidence of erosion is tentative. Therefore, it is possible that other cementing or bonding agents may be present in these sediments and affecting their consolidation state. Solution and redeposition of silica, calcium carbonate, iron, or manganese have been cited before (Richards and Hamilton, 1967) and may be partially responsible here as well.

CONCLUSIONS

Geotechnical properties of no-thern Oregon lower continental slope deposits are affected to some degree by the presence of organic matter at low to moderate concentrations (0.5 to 3.2% organic carbon). At these concentrations however, other influences on these properties may be equally or more important than the organic factor in some cases. The combination of organic matter, sediment grain size, and clay mineralogy produces unique responses of the sediment physical properties and the consolidation characteristics.

1) Sediment water content is influenced by organic contents in excess of approximately 2% organic carbon. The addition of organic matter into sediment is accompanied by a rise in water content. At concentrations less than this, increases in clay content are probably more important in bringing about a rise in water content, however, wide fluctuations in the clay content of 20% or more may still overshadow the influence of organic matter at concentrations between 2 and 3% organic carbon.

2) Grain specific gravity decreases with the addition of organic matter due to the low density of organic matter itself. This effect is evident at low organic carbon concentrations even below 1%. The wet bulk density also decreases with increasing organic contents especially at concentrations greater than 2.5 to 3.0% organic carbon. Once again below these concentrations, grain size effects overshadow those of the organic content where increasing clay content corresponds to an increase in wet bulk density.

3) This investigation found slight decreases in shear strength due to the presence of organic matter in concentrations up to 3.2% organic carbon. The results of other investigators (Busch and Keller, 1982; Pusch, 1973) showing shear strength increases apparently due to organic matter bonding is not seen in natural continental slope sediments off Oregon at these organic contents. Decreasing grain size does not seem to consistently correlate with decreases in shear strength at any organic content encountered.

4) Organic matter is an important determining factor of Atterberg limits at concentrations as low as 1.5% organic carbon. Generally, the liquid limit, plastic limit, and plasticity index all increase with increasing organic content. At lower organic contents, clay mineralogy may be important in determining these limits.

5) Compressibility of Oregon slope sediments shows an increase in the compressibility index (Cc) with increasing organic content, especially above 2 to 3% organic carbon. Below 2 to 3% organic carbon, Cc is apparently influenced by the clay content. Generally increasing clay content correlates with increasing values of Cc.

6) The rate of secondary compression ($E\alpha$) appears to be strongly influenced by the presence of organic matter at contents as low as 1% organic carbon where an increase in organic content is accompanied by increases in $E\alpha$.

7) Stress history does not seem to be affected by organic contents of 2.5% or less. The study by Busch and Keller (1982) of the Peru-Chile margin shows that Pc/Po is increased by organic contents greater than about 3.0%. The region between 2.5 and 3%

organic carbon then may effectively be the lower limit of significant organic matter influence on the consolidation state. On the Oregon lower slope conventional explanations for overconsolidation, such as erosion are probably more important than organic content on the consolidation state.

BIBLIOGRAPHY

American Society for Testing and Materials, 1979a, Laboratory Determination of Moisture Content of Soil: in Annual Book of ASTM Standards, Part 19, D2217-71, p. 338-339.

American Society for Testing and Materials, 1979b, Liquid Limit of Soils: in Annual Book of ASTM Standards, Part 19, D423-66, p. 123-126.

American Society for Testing and Materials, 1979c, Plastic Limit and Plasticity Index: in Annual Book of ASTM Standards, Part 19, D424-59, p. 127-128.

Bennett, R. H., D. N. Lambert, and M. H. Hulbert, 1977, Geotechnical properties of a submarine slide area on the U.S. continental slope northeast of Wilmington Canyon: Marine Geotechnique, v. 2, p. 245-261.

Bjerrum, L., 1967, Engineering geology of Norwegian normally consolidated clays as related to settlements of buildings: Geotechnique, v. 17, p. 81-118.

Bowles, J. E., 1978, Engineering Properties of Soils and their Measurement: McGraw-Hill Book Company, New York, p. 213.

Bryant, W. R., A. O. Deflache, and P. K. Trabant, 1974, Consolidation of marine clays and carbonates: in Inderbitzen, A. L., ed., Deep Sea Sediments: Physical and Mechanical Properties, Plenum Press, New York, p. 209-244.

Busch, W. H., 1981, The physical properties consolidation behavior, and stability of the sediments of the Peru-Chile continental margin: Ph.D. Thesis, Oregon State University, Corvallis, Oregon, 149 p.

Busch, W. H. and G. H. Keller, 1981, The physical properties of Peru-Chile continental margin sediments: Influence of coastal upwelling on sediment properties: Journal of Sedimentary Petrology, v. 51, p. 705-719.

Busch, W. H. and G. H. Keller, 1982, Consolidation characteristics of sediments from the Peru-Chile continental margin and implications for past sediment instability: Marine Geology, v. 45, no. 1/2, p. 17-39.

Carson, B., 1977, Tectonically induced deformation of deep sea sediments off Washington and northern Oregon: Mechanical consolidation: Marine Geology, v. 24, p. 289-307.

Casagrande, A., 1936, The determination of the Pre-Consolidation Pressure and its practical significance: Proceedings of the First International Conference on Soil Mechanics and Foundation Engineering, v. III, p. 60-64.

Casagrande, A., 1948, Classification and identification of soils: Transactions of the American Society of Civil Engineers, v. 113, p. 901-991.

Folk, R. L., 1980, Petrology of Sedimentary Rocks: Hemphill Publishing Co., Austin, p. 184.

Greenland, D. H., 1965, Interaction of clays and organic compounds in soils, part II, Adsorption of soil organic compounds and its effect on solid properties: Soils and Fertilizers, v. 28, p. 521-532.

Grimm, R. E., 1968, Clay Mineralogy: McGraw-Hill, New York, 596 p.

Gross, M. G., 1972, Oceanography: A view of the Earth: Prentice-Hall, Inc., New Jersey, 581 p.

Halpern, D., R. L. Smith and R. K. Reed, 1978, On the California undercurrent over the continental slope off Oregon: Journal of Geophysical Research v. 83, p. 1366-1377.

Harrison, W. G., T. Platt, R. Calienes, and N. Ochoa, 1981, Photosynthetic parameters and primary productivity of phytoplankton populations off the northern coast of Peru: in Richards, F. A., ed., Coastal Upwelling, American Geophysical Union, 529 p.

Heath, G. R., T. C. Moore and J. P. Dauphin, 1977, Organic carbon in deep-sea sediments: The Fate of Fossil Fuel CO_2 in the Oceans, N. R. Andersen and A. Malahoff, eds., p. 605-625, Plenum Press.

Huyer, A., R. L. Smith and R. D. Pillsbury, 1974, Observations in a coastal upwelling region during a period of variable winds (Oregon coast, July 1972): Tethys, v. 6, p. 391-404.

Krissek, L. A., 1982, Sources, dispersal, and contributions of fine-grained terrigenous sediments on the Oregon and Washington continental slope: Ph.D. Thesis, Oregon State University, Corvallis, Oregon, 226 p.

Kögler, F. C., 1963, Das Kastenlot: Meyniana, v. 13, p. 1-7.

Kulm, L. D., and K. F. Scheidegger, 1979, Quaternary sedimentation on the tectonically active Oregon continental slope: Society of Economic Paleontologists and Mineralogists Special Publication, no. 27, p. 247-263.

Lambe, T. W., 1967, Soil Testing for Engineers: Wiley and Sons, New York, p. 15-19.

Nelson, C. H., L. D. Kulm, P. R. Carlson, and J. R. Duncan, 1968, Mazama Ash in the northeastern Pacific: Science, v. 161, p. 46-49.

Perloff, W. H., and W. Baron, 1976, Soil Mechanics - Principles and Applications: Wiley and Sons, New York, 745 p.

Pusch, R., 1973, Influence of organic matter on the geotechnical properties of clays: National Swedish Building Research Document 11, p. 64.

Rashid, M. A., and J. D. Brown, 1975, Influence of marine organic compounds on the engineering properties of remolded sediment: Engineering Geology, v. 9, p. 141-154.

Reimers, C., 1981, Sedimentary organic matter: Distribution and alteration processes in the coastal upwelling region off Peru: Ph.D. Thesis, Oregon State University, Corvallis, Oregon, p. 219.

Richards, A. F., and E. L. Hamilton, 1967, Investigations of deep-sea sediment cores, III; Consolidation: in Marine Geotechnique, University of Illinois Press, p. 93-117.

Rosenqvist, I. T., 1953, Considerations of the sensitivity of Norwegian quick clays: Geotechnique, v. 3, p. 195-200.

Silva, A. J. and C. D. Hollister, 1979, Geotechnical properties of ocean sediments recovered with the giant piston corer; Blake-Bahama Outer Ridge: Marine Geology v. 29, p. 1-22.

Silver, E. A., 1969, Late Cenozoic underthrusting of the continental margin off northern California: Science, v. 166, p. 1265-1266.

Skempton, A. W., and R. D. Northey, 1952, The sensitivity of clays: Geotechnique v. 2, p. 30-53.

Skempton, A. W., 1953, The Colloidal "Activity" of Clays: Third International Conference on Soil Mechanics and Foundation Engineering, v. 1, p. 57-62.

Small, L. F., H. Curl, and W. A. Glooschenko, 1972, Effect of solar radiation on daily primary productivity off Oregon: Journal of Fisheries Research, Canada, no. 29, p. 1269-1275.

Small, L. F., 1979, Sinking rates of natural copepod fecal pellets: Marine Biology, v. 51, p. 233-241.

Tavenas, F., P. Leroueil, P. LaRochelle, and M. Roy, 1978, Creep behavior of an undisturbed lightly overconsolidated clay: Canadian Geotechnical Journal, v. 15, p. 402-423.

Wu, T. H., 1976, Soil Mechanics: Allyn and Bacon Inc., Boston, 440 p.