AN ABSTRACT OF THE THESIS OF

William H. Busch for the degree of Doctor of Philosophy
in Oceanography presented on August 21, 1980

Title: THE PHYSICAL PROPERTIES, CONSOLIDATION BEHAVIOR, AND STABILITY OF THE SEDIMENTS OF THE PERU-CHILE CONTINENTAL MARGIN

Redacted for privacy

Abstract Approved: ______________________
George H. Keller

Coastal upwelling markedly influences sediment physical properties along the Peru-Chile continental margin by concentrating organic matter on the sea floor. Organic-rich sediments of a mud lens on the upper slope between 10.5° to 13.6°S, which formed beneath an area of intense upwelling, possess properties that differ significantly from those of the other margin deposits. The mud lens sediments are anomalously fine-grained and have the highest water content and plasticity and lowest wet bulk density. The ability of organic matter to adsorb water and aggregate clay particles to form an open fabric appears to cause the high water and plasticity and low density of these sediments. An inverse relationship between grain specific gravity and organic content contributes to the low density of the mud lens deposits. The undrained shear strength of these sediments is unexpectedly high, resulting apparently from the bonding of sediment particles by organic matter. A distinctive feature of the upper slope mud lens sediments is a surface layer (0-15 cm) characterized by organic carbon

concentrations up to 20%, extremely high water content (maximum 853%), and low wet bulk density (minimum 1.09 Mg/m^3). Organic contents are lower outside the mud lens and grain size decreases from south to north along the margin and with increasing distance from shore. The progressive increase in clay content is accompanied by an increase in water content and decrease in wet bulk density and shear strength.

One-dimensional consolidation tests were performed on eight samples from the Peru-Chile margin. These tests show that both the compressibility and rate of secondary compression increase with increasing organic content. The increase in void ratio with increasing organic content and the high deformability of organic matter appear responsible for these trends. Outside the mud lens the compressibility also increases with increasing clay content and abundance of smectite and illite. All of the sediments along the margin behave as if they are overconsolidated. Evidence of erosion as a cause of overconsolidation is present only at 13.6°S on the mud lens where ^{14}C dating verifies the erosion of 3.5 to 7 m of sediment. Numerous unconformities and intervals of deformed bedding in the core from 13.6°S attest to the past instability of sediments in this area. At the other locations along the margin the overconsolidation ratio increases with increasing organic content suggesting that organic matter-related interparticle bonding may be responsible for the apparent overconsolidation. Low sedimentation rates on the slope off northern Chile may contribute to the apparent overconsolidation of sediments in this area.

Potential sediment mass movement was assessed at ten locations along the Peru-Chile continental slope using shear strength parameters obtained from consolidated-undrained triaxial compression tests. Infinite slope analyses show that gravitational forces alone are not sufficient to cause sediment failure anywhere on the slope. Reduction of the resistance to gravitational sliding by excess pore pressure generated by rapid sedimentation does not appear likely on the Peru-Chile slope. Effects of earthquakes on the slope stability were evaluated by modelling the earthquake-induced inertia forces as static forces and estimating pore pressures developed during cyclic loading. This analysis shows that the sediments of the lower slope off Peru have the highest susceptibility to failure during earthquakes, whereas the lowest susceptibility is displayed by the upper slope mud lens deposits. Earthquake accelerations between 0.1 to 0.2 gravity, which are in the range measured for recent earthquakes off Peru, will trigger slumping at all ten slope locations.

THE PHYSICAL PROPERTIES, CONSOLIDATION BEHAVIOR, AND STABILITY OF THE SEDIMENTS OF THE PERU-CHILE CONTINENTAL MARGIN

by

William H. Busch

A THESIS

submitted to

Oregon State University

in partial fulfillment of
the requirements for the
degree of
Doctor of Philosophy

Completed August 1980

Commencement June 1981

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 presented August 21, 1980

Typed by Marcia Griffin and Pam Wegner for William H. Busch

ACKNOWLEDGEMENTS

I wish to acknowledge the support and supervision provided by my advisor, George Keller. I would also like to thank Vern Kulm, Erwin Suess, and Lee Schroeder for serving on my committee and providing comments and criticisms of this thesis. This work was funded by the Office of Naval Research.

TABLE OF CONTENTS

TABLE OF CONTENTS (Continued)

LIST OF FIGURES

LIST OF FIGURES (Continued)

LIST OF TABLES

PART I

THE PHYSICAL PROPERTIES OF PERU-CHILE CONTINENTAL MARGIN SEDIMENTS -- THE INFLUENCE OF COASTAL UPWELLING ON SEDIMENT PROPERTIES

Submitted to the Journal of Sedimentary Petrology

ABSTRACT

Physical properties (sediment texture, water content, wet bulk density, grain specific gravity, porosity, shear strength, and Atterberg limits) were determined for near-surface sediments (0 to 4m) based on 38 cores from the Peru-Chile continental slope and eastern Nazca Plate. Coastal upwelling along the Peru-Chile margin significantly influences the physical properties by concentrating organic matter in the slope deposits. Beneath an area of intense upwelling an organic-rich mud lens occurs along the upper slope between 10.5° to 13.6°S. These sediments are anomalously fine-grained (up to 68% clay) and have the highest water content and plasticity and lowest wet bulk density and grain specific gravity found along the margin. The average shear strength of the mud lens sediments (14.7 kPa) is high considering the high water content of these deposits (average 214% dry wt.). A distinctive feature of the upper slope mud lens is a surface layer (0 to 15 cm) characterized by organic carbon concentrations of up to 20%, extremely high water content (maximum 853%), and very low wet bulk density (minimum 1.09 Mg/m^3). Outside the mud lens organic contents are considerably lower and there is a decrease in grain size from south to north along the margin and with increasing distance from shore. Clay-size concentrations range from less than 10% on the northern Chile slope to more than 80% on the Nazca Plate off northern Peru. The progressive fining of the sediments is accompanied by an increase in water content and plasticity and a decrease in wet bulk density and shear strength.

Variability of sediment physical properties along the Peru-Chile margin appears to be largely related to differences in organic content. Organic matter's ability to adsorb water and aggregate clay particles to form an open fabric appears responsible for increases in water content and Atterberg limits and decreases in density with increasing organic content. Grain specific gravity decreases with increasing abundance of organic matter, thus contributing to the low wet bulk density of the organic-rich sediments. Formation of clay-organic aggregates also appears to influence the shear strength of the sediments and may cause the higher than expected strength on the upper slope mud lens. Clay content of the margin sediments has a secondary influence on the variation of the physical properties. Adsorption of water by clays and development of a flocculent fabric apparently are responsible for the increase in water content and accompanying decrease in wet bulk density and shear strength with increasing clay content. The effect of differences in sediment mineralogy on the physical properties is most noticeable on the northern Chile slope where high grain specific gravity is associated with the greater abundance of volcanic lithic fragments and ferro-manganese minerals. The effect of sedimentation rate on the physical properties does not show a consistent pattern and may be masked by compositional and textural differences.

INTRODUCTION

An understanding of the processes affecting the formation and distribution of hemipelagic sediments on the Peru-Chile continental slope and adjacent Nazca Plate has been the objective of a multidisciplinary study. Sedimentation along this margin is strongly affected by coastal upwelling and a particular goal of the research in this area has been to characterize the deposits of a coastal upwelling regime by examining the accumulation and preservation of terrigenous, biogenous, and organic constituents, and the sediment physical properties. Sediments and data used in this study were obtained primarily from a 1977 cruise off Peru and northern Chile and were supplemented with materials from previous cruises in the area.

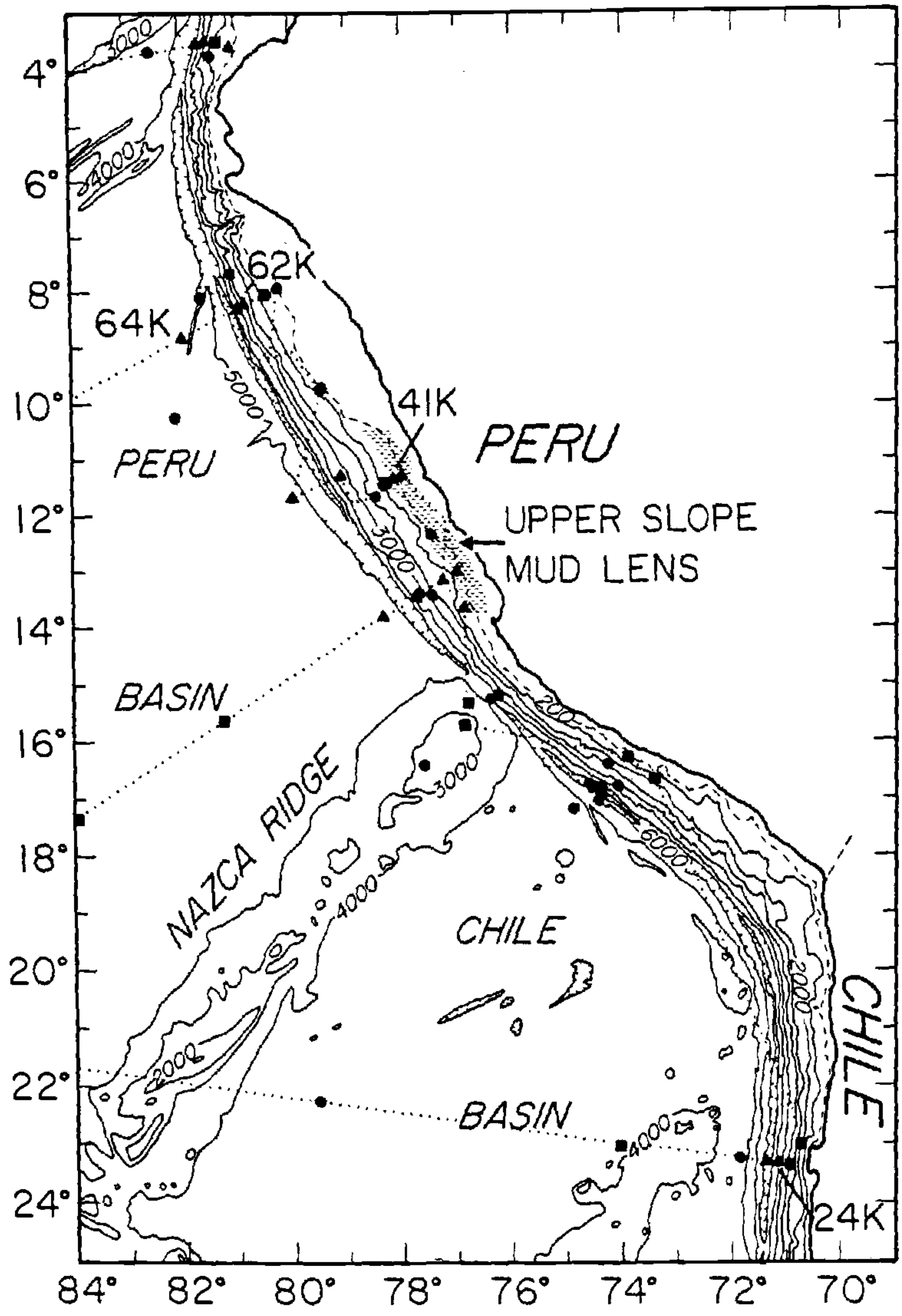
Sediment physical properties have been documented for a moderate number of continental slopes, largely to provide background information for slope stability analyses (Morelock, 1969; Ross, 1971; Almagor and Wiseman, 1977; Bennett and others, 1977; Booth and Garrision, 1978; Keller and others, 1979). The continental margin of western South America differs from the areas examined in these investigations because of the coastal upwelling process which is prominent off Peru. As a result of high biological productivity associated with the upwelling, organic-rich sediments have been deposited on the continental slope. The abundant organic matter in these sediments appears to significantly affect their physical properties. This paper examines the variation of sediment physical properties along the Peru-Chile continental margin, emphasizing the unique characteristics of the sediments associated with the areas of intense coastal upwelling.

GEOLOGICAL SETTING

The continental margin of Peru and northern Chile is part of the tectonic boundary between the converging Nazca and South America Plates. The Peru-Chile Trench is the dominant morphological feature of this boundary, ranging in depth from 8100 m at 23°S to 4500 m at 3°S (Fig. 1). Bounding the trench on the eastern Nazca Plate are two deep basins, the Peru and Chile Basins, separated by the aseismic Nazca Ridge. Landward of the trench is a narrow continental margin. Detailed information on the morphology and structure of the margin has been provided by a number of recent studies (Coulbourn and Moberly, 1976; Masias, 1976; Kulm and others, 1977). These studies have shown that the continental shelf is essentially flat and varies in width from 0 to 125 km. Off northern Peru the continental slope is extremely irregular, marked by several prominent submarine canyons. Size and frequency of occurrence of the canyons decreases to the south. Kulm and others (1977) recognized 19.5°S as a boundary between differing physiographic provinces on the continental slope. North of this latitude small basins are common on the lower and middle slope and prominent plateaus occur on the upper slope. South of 19.5°S benches and basins on the continental slope are smaller and occur less frequently.

Sediment cover on the Peru-Chile continental slope is thin and frequently confined to local basins. Along the slope 3.5 kHz profiles show 50 m or less of sub-bottom penetration. The geometry of sediment accumulations on the Peru margin has been mapped by Krissek and others (1980). The most notable sediment body they mapped is an upper slope mud lens located between 10.5° to 13.6°S. The location of this mud lens coincides with the occurrence of intense coastal upwelling in the surface

Figure 1. Sample locations on the Peru-Chile continental margin and eastern Nazca Plate. Trackline for the 1977 cruise is indicated by dotted lines. Bathymetry is modified from Mammerickx and Smith (1978). Analyses: ● texture; ▲ texture, water content, wet bulk density, undrained shear strength; ■ texture, water content, wet bulk density, undrained shear strength, grain specific gravity, Atterberg limits.



PERU
UPPER SLOPE
MUD LENS
62K
64K
41K
24K
PERU
BASIN
NAZCA RIDGE
CHILE
BASIN
CHILE
3000
4000
5000
6000
2000
200
4°
6°
8°
10°
12°
14°
16°
18°
20°
22°
24°
84°
82°
80°
78°
76°
74°
72°
70°

waters and the impingement of the shallow water oxygen-minimum layer on the continental slope. Off northern Chile the 3.5 kHz records are devoid of sub-bottom reflectors over much of the slope and dredges taken during the 1977 cruise suggest the presence of a manganese-crust-like pavement in this area. Sediment cover on the eastern Nazca Plate averages from 50 to 130 m thick (Ade-Hall, 1976).

Sedimentation rates were determined from ^{14}C dating and rates of dissolved SO_4-reduction in interstitial waters based on the relationship described by Berner (1978) (E. Suess, personal communication, 1979). The upper slope mud lens is an area of rapid sedimentation with rates of 17 to 140 cm/1000 years. Lowest rates of sediment deposition on the continental slope, approximately 5 cm/1000 years, occur off northern Chile. On the southern Peru slope, outside of the upper slope mud lens, rates are from 6 to 47 cm/1000 years. Sedimentation rates of 0.2 to 5 cm/1000 years have been determined on the eastern Nazca Plate (Moser, 1980).

Patterns of sediment distribution and composition on the Peru-Chile continental margin and Nazca Plate are strongly influenced by the surface-water circulation in the eastern Pacific (Scheidegger and Krissek, 1978; Krissek and others, 1980). Coastal upwelling is a prominent feature of the circulation pattern north of 20°S and has been described by Smith (1968, 1978), Zuta and others (1978), and others. Upwelling occurs within 50 km of shore in response to the prevalent trade winds that parallel the coast and drive the offshore directed Ekman transport. Displacement of the surface waters is compensated by water ascending from a depth of approximately 70 m (Smith, 1978). These nutrient-rich waters support a high biological productivity (Zuta and Guillen, 1970) which is accompanied by the rapid accumulation of organic matter in the underlying sediments. Coastal upwelling has apparently occurred throughout the time represented by the cored sediments. Diatom assemblages in rocks dredged from the continental slope suggest that the upwelling process has operated off the Peru coast since at least the late Miocene (H. Schrader, personal communication, 1980).

The influence of the bottom-water circulation on sedimentary processes along the Peru-Chile continental margin has not been adequately documented. Lonsdale (1976) has outlined the abyssal circulation in the Peru and Chile Basins, but information concerning bottom currents on the continental slope is lacking.

METHODS

Physical properties were determined on sediments from 10 Reineck box cores (5 to 75 cm long, average 34 cm) and 28 Kasten cores (0.74 to 4.74 m long, average 2.25 m). The large cross-sectional area of the cores, 20 x 30 cm and 15 x 15 cm respectively, provided excellent samples with minimal disturbance. Location of the sample sites and the cruise track are shown in Figure 1. Along the trackline the bottom morphology and shallow sediment structure were recorded with 12 and 3.5 kHz profiling systems.

The physical properties that were determined include: water content, wet bulk density, grain specific gravity, gross textural composition (sand, silt, and clay percentages), Atterberg limits, and undrained shear strength. Water content and wet bulk density were determined gravimetrically (ASTM, 1979a) on subsamples taken at depth intervals of 2 to 5 cm in the Reineck cores and 10 to 20 cm in the Kasten cores. A correction for the salinity of the interstitial water was not made in the water content calculations. Grain specific gravity and Atterberg limits were determined according to ASTM standards (ASTM, 1979b,c,d) on subsamples taken at 0.5 to 1 m intervals. The Atterberg limits procedure was modified to exclude sample drying before determining the indices. Textural composition was determined for all surface samples and at approximately 20 cm intervals in selected cores according to the method described by Thiede and others (1976). Undrained shear strength was measured with a miniature vane-shear apparatus (Wykeham-Farrance) using a 1.2 x 1.9 cm four-bladed vane and operating at a shear rate of 60 degrees per minute. Natural strength was measured normal to the bedding at intervals of 2 to 5 cm in Reineck cores and 25 to 75 cm in Kasten cores. Remolded strength was determined at most of these same intervals on sediment that had been thoroughly mixed with a spatula.

In addition to the sediment physical properties, organic carbon and calcium carbonate concentrations were determined on the texture subsamples using a Leco WR-12 Automatic Carbon Determinator. X-radiographs were also made for the purpose of examining sedimentary structures and other internal features.

AREAL VARIATION OF PHYSICAL PROPERTIES

Four sediment provinces can be identified along the Peru-Chile continental margin based on differences in sediment physical properties. The areas represented by the provinces are: (1) upper slope mud lens between 10.5° to 13.6°S; (2) Peru continental slope, excluding the upper slope mud lens; (3) northern Chile continental slope and trench; and (4) Nazca Plate. Wide spacing of sample locations does not allow the precise determination of boundaries between these provinces, particularly in the southern part of the study area (Fig. 1). Physical properties of the sediments from the four provinces are compared using averages determined for each property over the 0 to 2 m depth interval. This interval was used because most of the Kasten cores penetrated at least 2 m. Estimates from regression equations were used to compute averages for cores less than 2 m long. Data form the Reineck box cores were used to supplement information on the surface sediment properties.

Texture

Textural patterns on the Peru-Chile continental slope and Nazca Plate have recently been summarized by Krissek and others (1980). They recognized a progressive fining of the sediments along the slope from south to north and across the slope with increasing distance from shore (Fig. 2). Increased grain sorting accompanies the offshore decrease in grain size (Trask, 1961). The northward decrease in grain size is also evident on the Nazca Plate as the Peru Basin sediments are slightly finer than those of the Chile Basin. An anomaly to these general textural patterns occurs on the upper slope mud lens between 10.5° to 13.6°S. Sediments in this area are much finer than the surrounding continental slope deposits (Fig. 2) with clay-size material comprising 52 to 68% of the sediment and sand 2 to 10%. At water depths of 1500 m or less on the slope outside the area of intense upwelling and on the northern Chile continental slope the ranges of the clay and sand-size material are on the order of 2 to 57% and 9 to 90%, respectively. On the remainder of the Peru slope the clay content varies from 63 to 75% and the sand from 1 to 2%. Sediments of the eastern Nazca Plate are 45

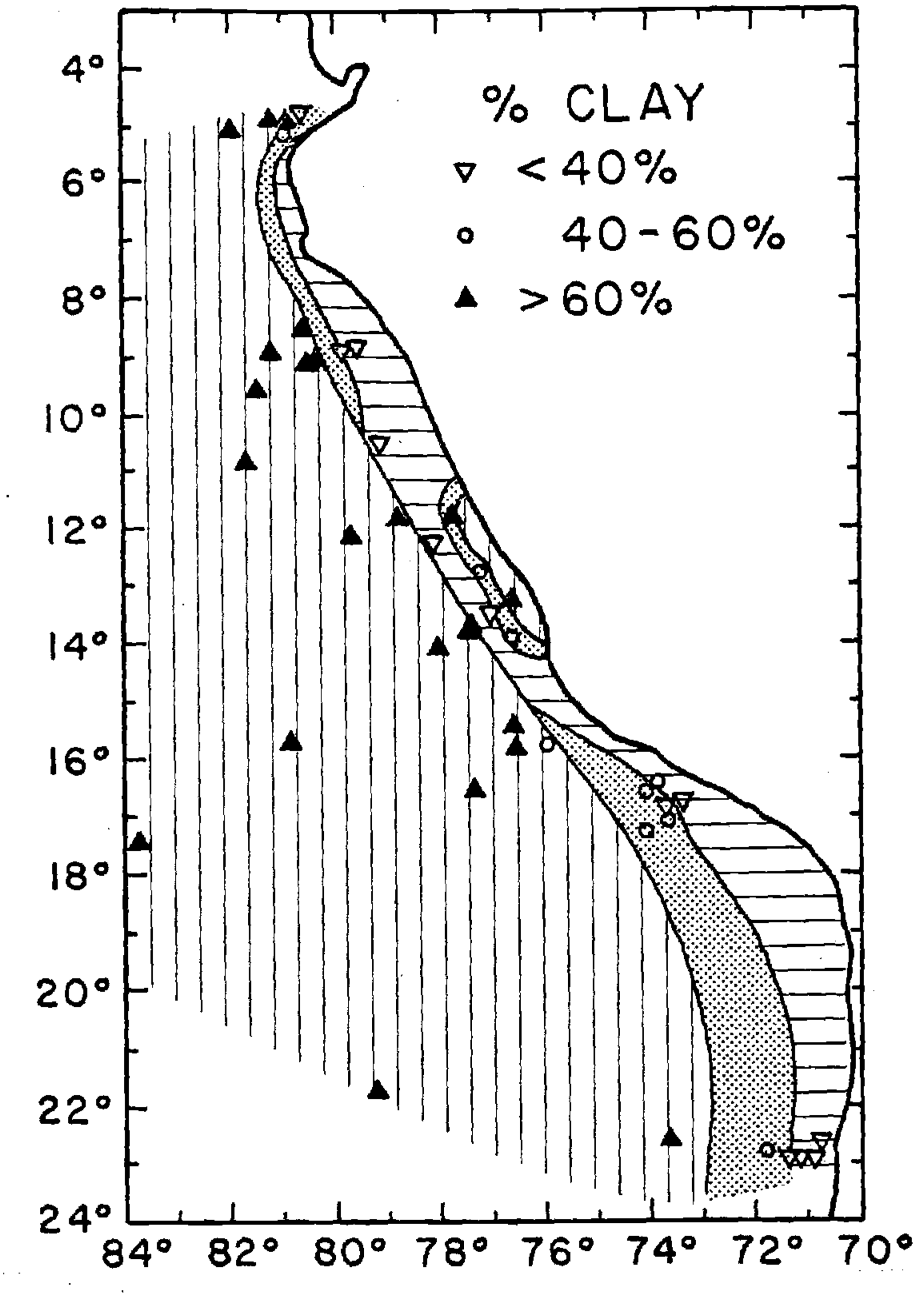


Figure 2. Textural distribution, clay content (<4 µm) of the surface sediments. Clay percentages were determined on an organic-free basis. Modified from Krissek and others (1980).

to 88% clay and less than 1 to 23% sand.

Krissek and others (1980) concluded that the textural patterns along the Peru-Chile margin reflect the influence of water depth, proximity to continental sediment sources, latitudinal changes in terrigenous input, accelerated settling of fecal pellets, and transport by bottom nepheloid layers. Offshore fining of the sediments was interpreted to be a product of the decrease in particle size that is maintained in suspension with increasing water depth and distance from shore. Climatic variation onshore is responsible for the decrease in grain size from south to north along the margin. Northern Peru has a humid climate and rivers draining this area deliver finer-grained sediment to the ocean. Anomalously fine sediments of the upper slope mud lens were apparently deposited by rapidly sinking fecal pellets. Small fecal pellets (<200 μm) have been observed in these sediments (W. H. Hutson, personal communication, 1978; DeVries, 1980). High primary productivity in the area of intense upwelling supports large zooplankton stocks which can incorporate fine terrigenous particles into fecal material. On the Nazca Plate the deposition of fine-grained sediments in the Peru Basin is associated with a well-developed bottom nepheloid layer. In the Chile Basin where the sediment is relatively coarser the nepheloid layer is poorly developed or absent. Water depth has an important influence on sediment texture seaward of the trench. Coarser-grained sediments are found on topographic highs that extend above the calcite compensation depth (approximately 4000 m).

Water Content

There is considerable variation in the water content of the sediments of the Peru-Chile continental slope and eastern Nazca Plate. Variability of the water content is primarily related to differences in sediment texture and organic content. The water content (expressed as % dry weight) ranges from a high of 853% in the organic-rich surface sediments of the upper slope at 13.6°S to a low of 29% in a coarse-grained subsurface sample from the trench at 23°S.

Sediments with the highest water content along the margin occur between 10° to 14°S (Fig. 3). This area includes the upper slope mud lens and extends to the lower slope at 13.5°S. Average water content for the 0 to 2 m interval of the upper slope mud lens is 214% (Table 1). Extremely high water content of the surface sediments of the mud lens makes them distinctive from the rest of the margin sediments. Average water content of the top 10 cm of the sediments from the area of intense upwelling is 475% (Table 1). At 13.6°S on the mud lens the average water content for the 0 to 2 m interval is slightly less than 200% (Fig. 3). Carbon-14 dating and one-dimensional consolidation tests suggest that the lower water content in this area may be the result of consolidation under a possible 7 m thick sediment overburden that has since been eroded (Busch and Keller, in review b).

Outside of the region influenced by intense coastal upwelling the sediment water content is much lower. Continental slope and trench sediments off northern Chile have the lowest water content in the study area, averaging 75%. This value is about one-half of the 141% found for the Peru slope deposits located outside of the area of intense upwelling. The average water content of the Nazca Plate sediments is 163%. In these three sediment provinces the difference between the average water contents of the surface sediment and the 0 to 2 m interval is much less

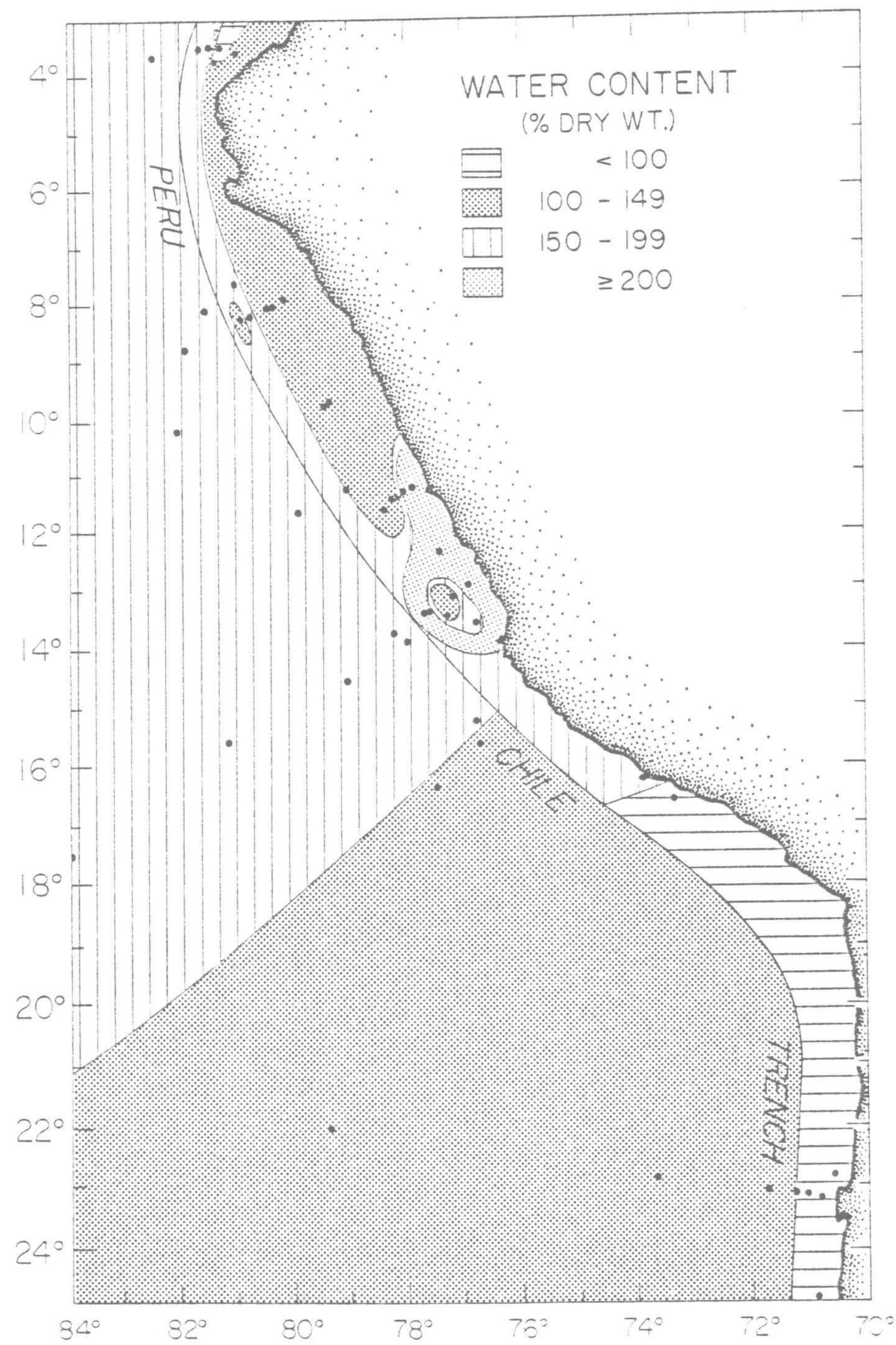


Figure 3. Water content distribution. Values are averages for the 0 to 2 m depth interval. Sample stations are represented by circles.

TABLE 1. Average Values of Water Content, Wet Bulk Density, Porosity, and Grain Specific Gravity

Area	Depth interval	Water content (% dry wt.)	Wet bulk density (Mg/m^3)	Porosity (%)	Grain specific gravity
Upper slope mud lens	0 - 0.1 m	475	1.18	86.0	2.30
	0 - 2 m	214	1.31	80.7	2.44
Peru slope	0 - 0.1 m	188	1.31	82.2	2.56
	0 - 2 m	141	1.39	79.1	2.57
Northern Chile slope and trench	0 - 0.1 m	74	1.62	65.3	2.79
	0 - 2 m	75	1.63	67.2	2.75
Eastern Nazca Plate	0 - 0.1 m	195	1.31	84.2	2.63
	0 - 2 m	163	1.33	81.6	2.66

than the difference on the upper slope mud lens (Table 1). Off northern Chile the two averages are nearly equal.

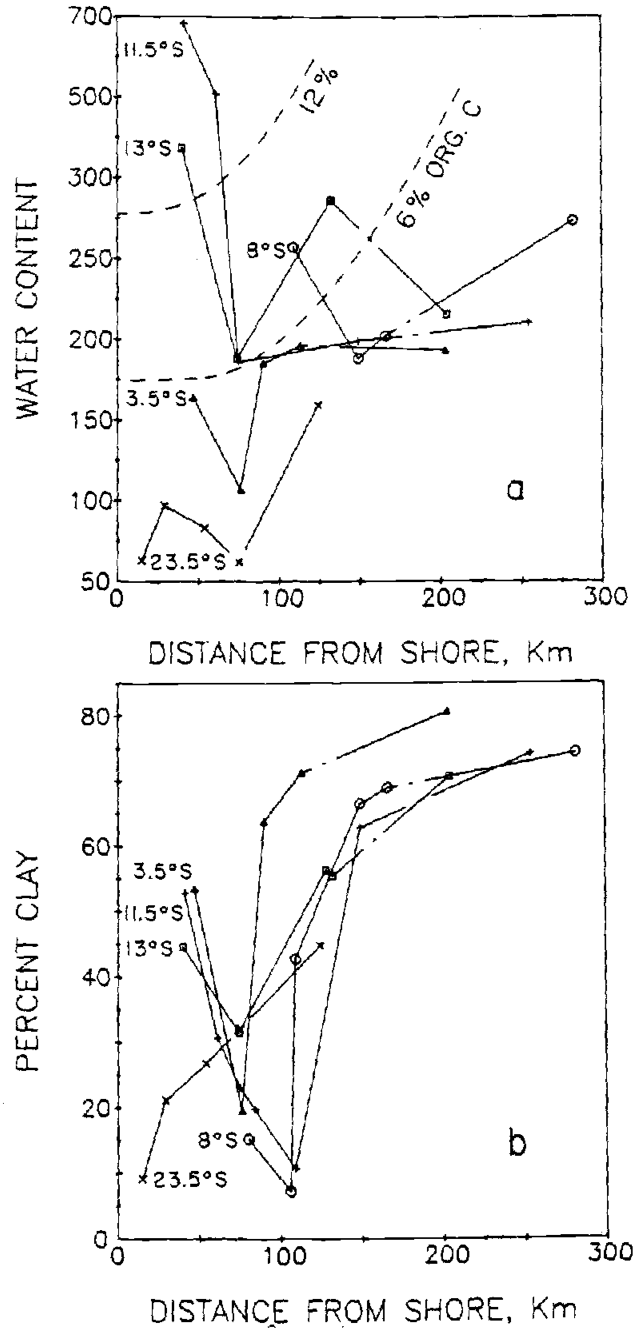
Variation in sediment water content on the Peru-Chile slope in part reflects the along and across margin changes in texture. The water content increases as the sediment becomes finer-grained from south to north and with increasing distance from shore (Fig. 3). With the exception of sediments from the upper slope mud lens there is a general increase in clay content and water content with distance from shore (Fig. 4). On the Nazca Plate the variation in water content also reflects textural differences. Peru Basin sediments have a higher water content than the slightly coarser Chile Basin sediments (Fig. 3).

Differences in the abundance of organic matter in the Peru-Chile deposits are largely responsible for the extreme variation in water content. The sediment water content increases with increasing organic carbon concentration (Fig. 5). This relationship is modified by the amount of clay-size material in the sediment. Clay-rich Nazca Plate sediments have a much higher water content than sediments of comparable organic content off northern Chile.

Wet Bulk Density and Grain Specific Gravity

The wet bulk density of the Peru-Chile sediments varies inversely with the water content (Fig. 6). Differences in grain specific gravity associated with variation in sediment composition contribute to a minor extent to the variability of the wet bulk density. Along the Peru-Chile margin the sediment density ranges from 1.09 Mg/m^3 in the surface sediment of the upper slope at 13.6°S to 1.96 Mg/m^3 in the subsurface in the trench at 23°S. Sediments of the upper slope mud lens have the lowest

Figure 4. Water content (a) and clay content (b) of surface sediments on the margin transects. Seaward fining of the sediment is accompanied by an increase in water content. High organic contents, particularly on the upper slope mud lens (11.5° and 13°S transects) modify this pattern and are associated with extremely high water content. Water content changes scale at 300%. Clay percentages are based on total sediment dry weight and are obtained from organic-free determinations by assuming organic carbon makes up 58% of the organic matter (Pusch, 1973). The break in the transect lines corresponds to the location of the trench axis.


700
500
300
250
200
150
100
50
0
100
200
300
WATER CONTENT
DISTANCE FROM SHORE, Km
11.5°S
13°S
8°S
3.5°S
23.5°S
12%
6% ORG. C
a
80
60
40
20
0
PERCENT CLAY
3.5°S
11.5°S
13°S
8°S
23.5°S
b
DISTANCE FROM SHORE, Km

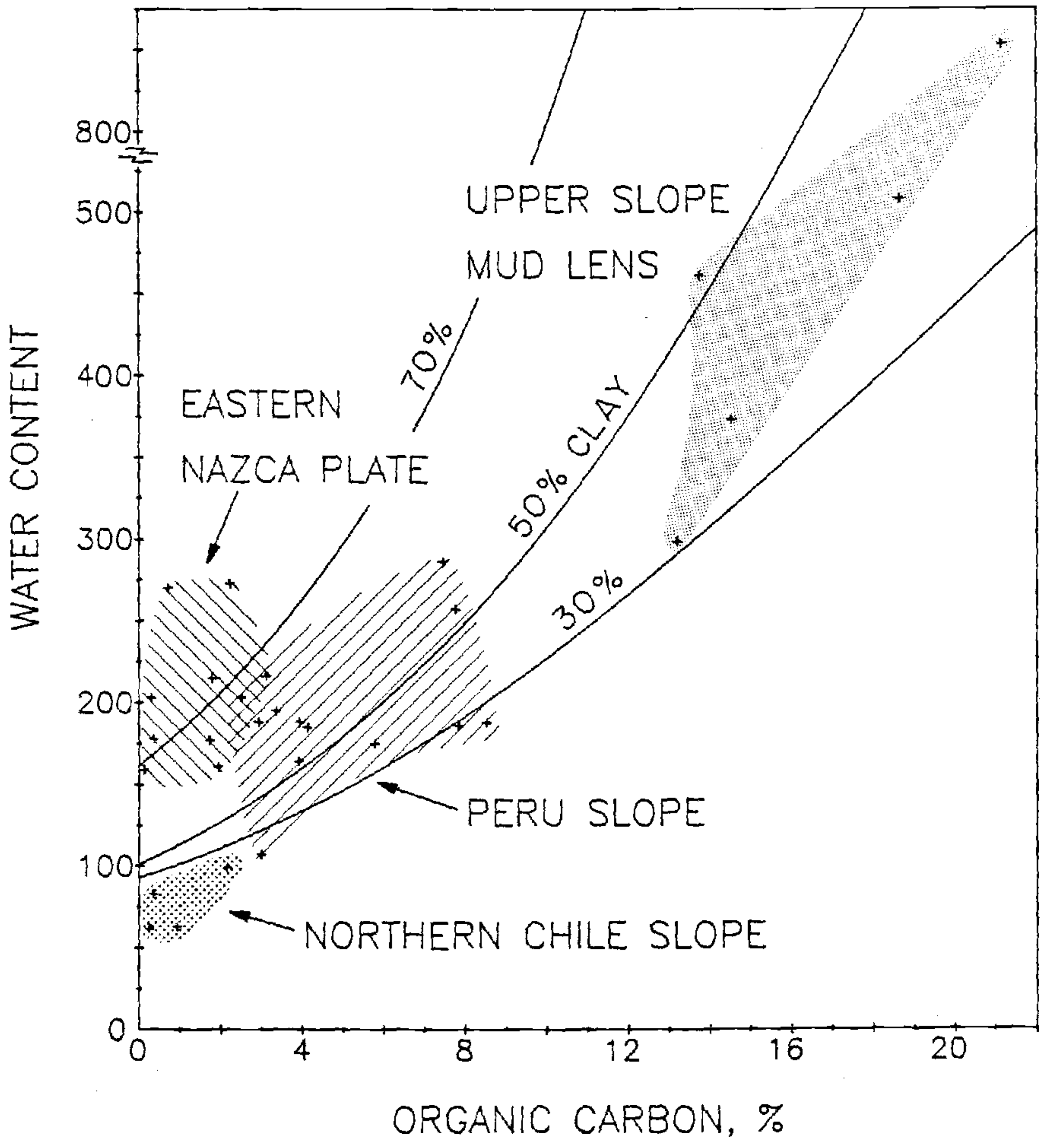


Figure 5. The relationship between water content and organic carbon concentration in the surface sediments. The amount of clay-size material influences the water content, particularly at low organic contents. The water content axis is shortened above 525%. Clay percentages are based on total sediment dry weight.

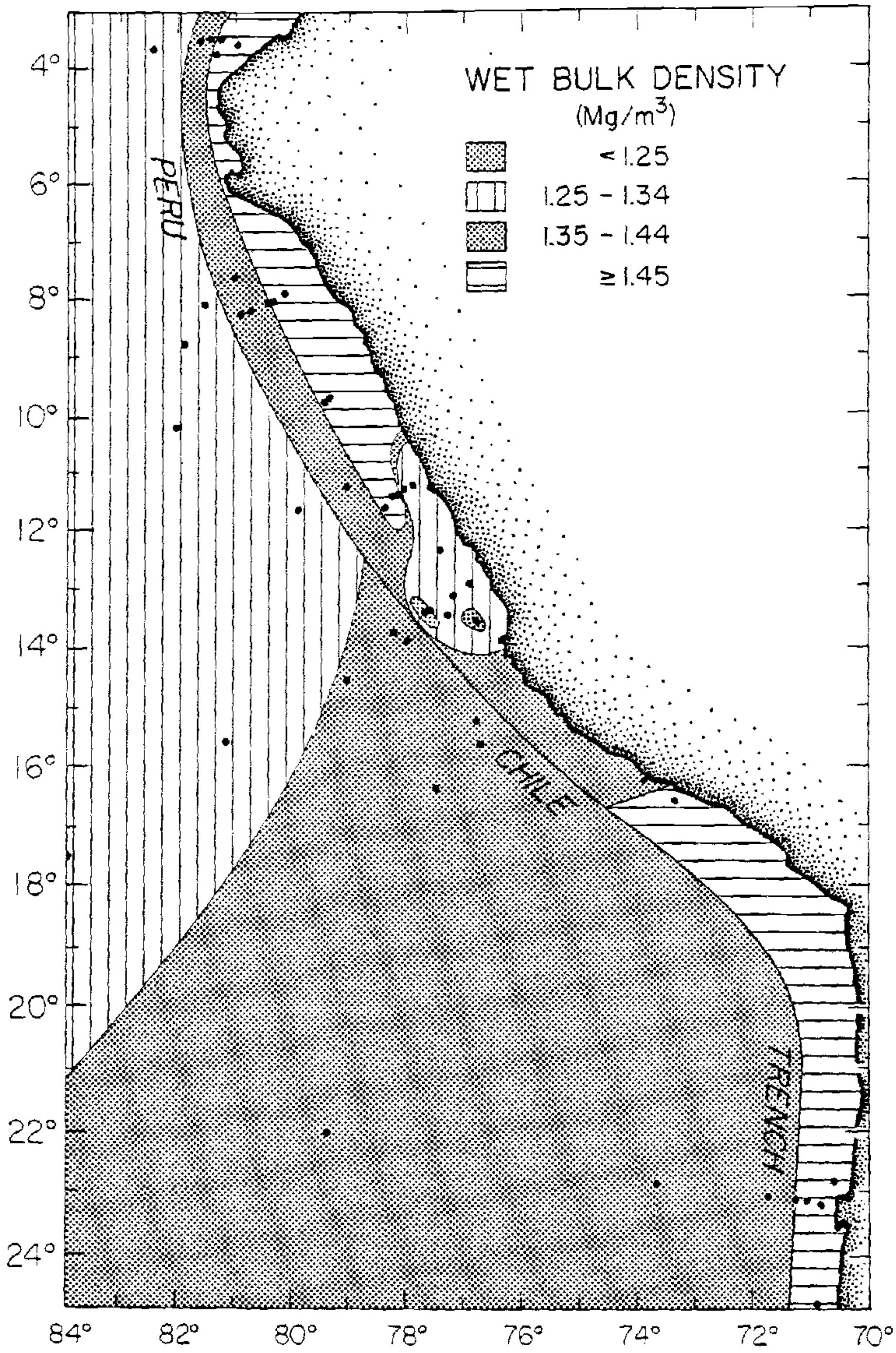


Figure 6. Wet bulk density distribution. Values are averages for the 0 to 2 m depth interval.

average wet bulk density of the four sediment provinces. The average of 1.31 Mg/m^3 (Table 1) is a product of the high water content and low grain specific gravity, 2.44 average (Table 1). Surface sediments of the mud lens have an extremely low wet bulk density, 1.18 Mg/m^3, and low grain specific gravity, 2.30. At 13.6°S the overconsolidated sediments (sediments previously consolidated under a pressure greater than the present overburden) are an anomaly and have a higher average density than the other mud lens sediments (Fig. 6). Slope and trench deposits off northern Chile with an average wet bulk density of 1.63 Mg/m^3 and a grain specific gravity of 2.75 are the densest sediments along the margin. In the Peru slope and Nazca Plate provinces the wet bulk density averages 1.39 and 1.33 Mg/m^3 respectively. The large difference between the density of the surface sediments and the average for the 0 to 2 m interval is not found outside the area of intense upwelling.

Sediment wet bulk density on the Peru-Chile margin and Nazca Plate is strongly influenced by the organic content of the sediments. With increasing abundance of organic matter the increase in water content (Fig. 5) and decrease in grain specific gravity (Fig. 7) combine to decrease the wet bulk density. The low specific gravity of organic matter, less than 2.0, is largely responsible for the decrease in grain specific gravity with increasing organic carbon concentration. Abundant siliceous biogenic remains (Schuette and Schrader, 1979) and the low specific gravity of opal, 2.20, contribute to the low grain specific gravity of the highly organic upper slope mud lens sediments. On the Nazca Plate and Peru slope, outside the mud lens, the grain specific gravity of most of the sediments is in the range expected for a mixture of quartz, feldspar, and clay minerals, 2.55-2.65, and differences in

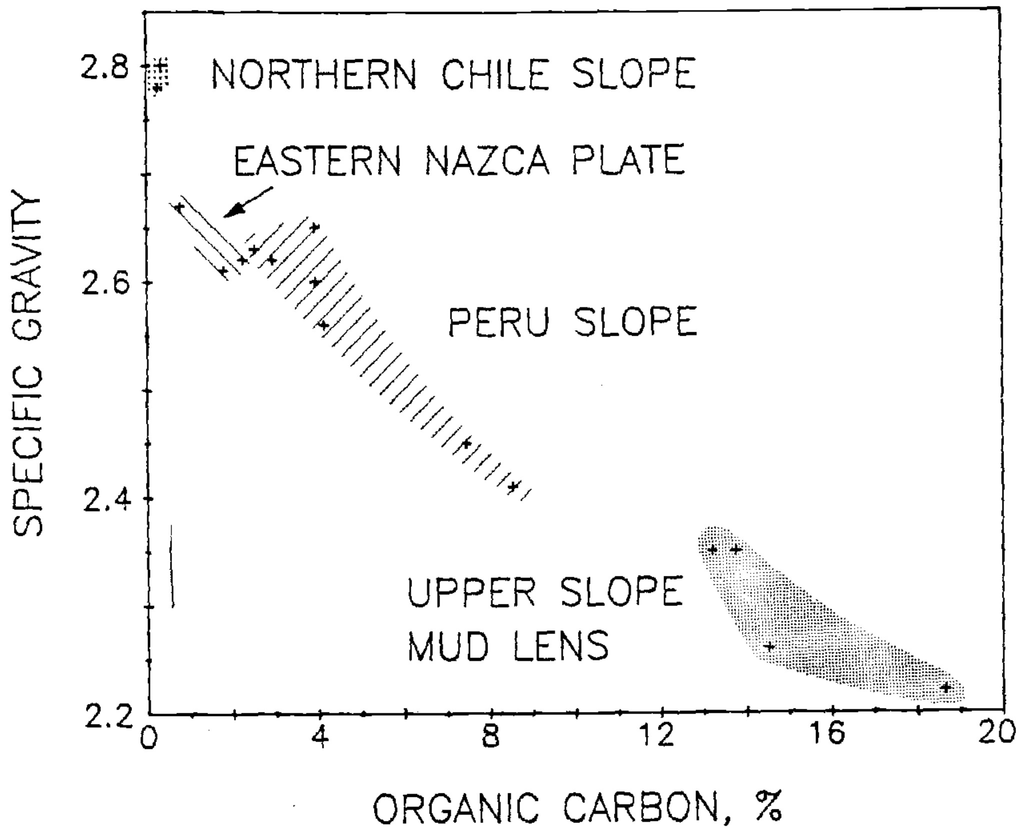


Figure 7. The relationship between grain specific gravity and organic carbon concentration for the surface sediments.

wet bulk density primarily result from texturally induced water content variation. At 23°S the high density of the sediments reflects the coarse texture, low organic content, and differences in mineralogy. Numerous volcanoes are active on the adjacent continent (Barazangi and Isacks, 1976) and the high grain specific gravity of the northern Chile sediments, 2.75-2.80, indicates the enrichment in lithic fragments and other volcanic debris. Ferromanganese micronodules and the manganese crust observed during sampling also contribute to the high sediment density.

Porosity

Porosity (percentage of the total sediment volume that is void space) of the Peru-Chile sediments was determined from wet bulk density and grain specific gravity values according to the method of Hamilton (1971). Variation of the porosity along the margin is similar to the pattern of sediment water content. Porosity ranges from a high of 89% at the surface on the upper slope mud lens to a low of 62% at the surface in the trench at 23°S. Sediments of the eastern Nazca Plate have the highest average porosity, 82% (Table 1). The average for the area of intense upwelling is slightly less, 81%, owing to the degree of overconsolidation of the sediments at 13.6°S. Coarse-grained sediments off northern Chile have the lowest porosity, averaging 67%. As with the water content and wet bulk density the mud lens deposits display a large difference between the average porosities of the surface sediment and the 0 to 2 m interval (Table 1). Off northern Chile the slope and trench are covered by a surface layer of coarse-grained sediment that has a lower porosity than the underlying sediment.

Shear Strength

Variation of sediment shear strength along the Peru-Chile margin is marked by anomalously high strength in the area of intense upwelling (Fig. 8). Sediments of the upper slope mud lens display a greater undrained shear strength than would be expected for their high water content. Shear strength variation in the remainder of the continental slope and the Nazca Plate deposits more closely agree with changes in sediment texture and water content. On the continental slope the decrease in grain size and increase in water content from south to north and with increasing distance from shore is accompanied by a decrease in shear strength. A similar trend is found in the Nazca Plate sediments where a northward fining and water content increase are associated with a decrease in shear strength.

The undrained shear strength, c_u, of the Peru-Chile sediments ranges from 0.3 kPa in the surface sediment of the upper slope at 13.6°S to 36.5 kPa at this same site, 1.55 m below the surface. High strength of the sediments at this site is apparently another product of overconsolidation. The average shear strength of the upper slope mud lens sediments, 14.7 kPa (Table 2) is slightly less than the average of 15.9 kPa of the coarse sediments off northern Chile. Lower strengths were determined for sediments from the Peru slope and Nazca Plate where in both provinces the shear strength averages 10.5 kPa.

The unexpected strength of the sediments from the area of intense upwelling is particularly evident when the measured shear strength values are normalized for changes with depth using the ratio $c_u/\bar{p}$. In this ratio $\bar{p}$, the pressure under which the sediment has been consolidated, equals the present effective overburden pressure if no excess pore

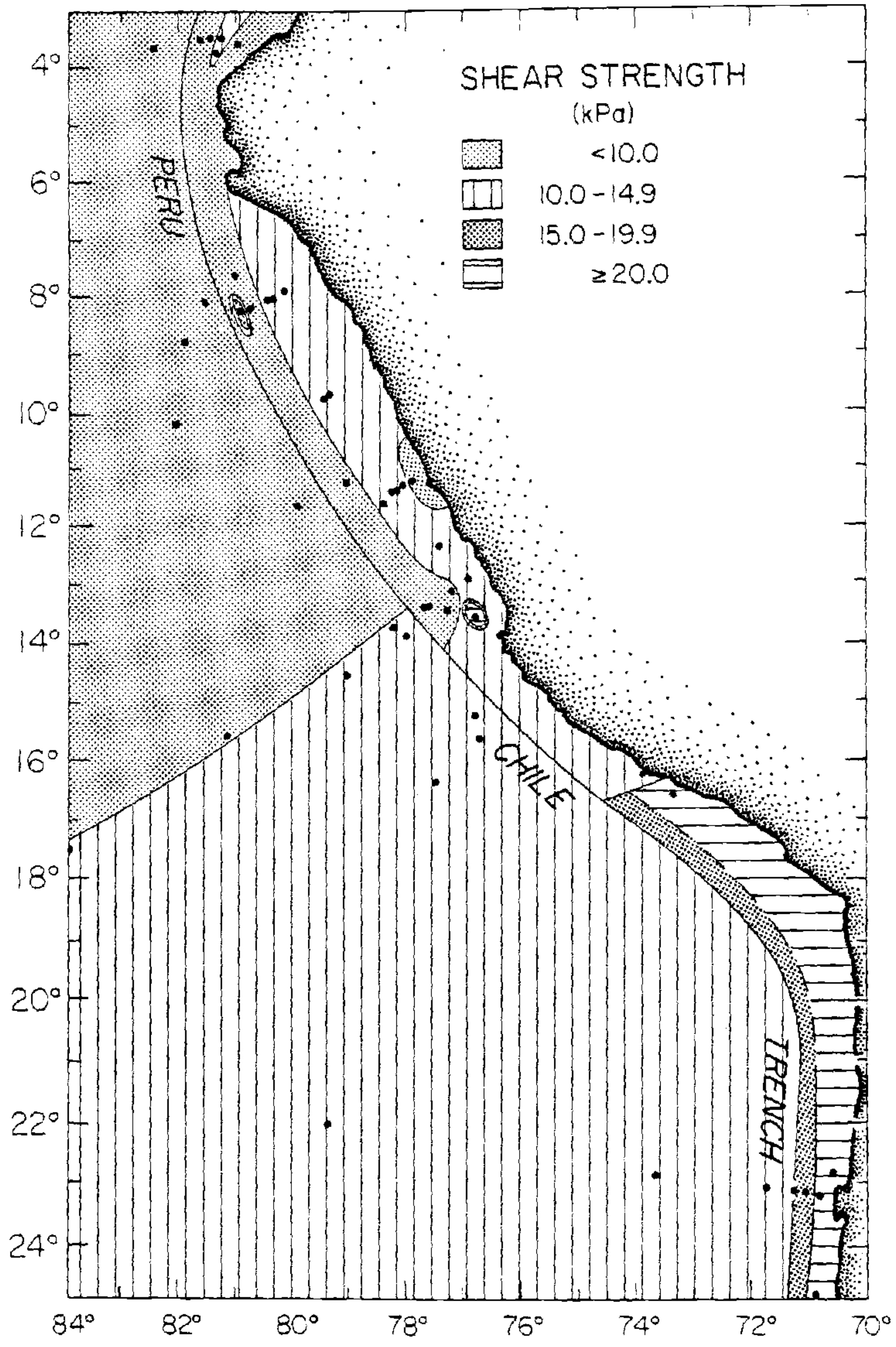


Figure 8. Shear strength distribution. Values are averages for the 0 to 2 m depth interval. Note that the area of high water content and low wet bulk density on the upper slope between 10.5° to 13.6°S (Figs. 3 and 6) has a relatively high strength.

TABLE 2. Average Values of Undrained Shear Strength Parameters for the 0-2m Interval

Area	c_u (kPa)	c_u, remolded (kPa)	Sensitivity	c_u/p*
Upper slope mud lens	14.7	2.0	8	4.77
Peru slope	10.5	2.0	7	2.61
Northern Chile slope and trench	15.9	2.7	7	2.30
Eastern Nazca Plate	10.5	1.4	9	2.47

* Determined at approximately 1.5 m depth.

pressure exists and overlying sediment has not been eroded. Except for the upper slope at 13.6°S, where there is evidence of erosion, these conditions appear to be satisfied along the Peru-Chile margin. Where there is no excess pore pressure or indication of erosion p equals the product of the buoyant unit weight of the sediment and the depth below the sea floor. A comparison of the values of c_u/p determined at a depth of approximately 1.5 m shows that the normalized shear strength is highest in the sediments of the upper slope mud lens (Table 2). On the mud lens c_u/p averages 4.77 at 1.5 m (the value from 13.6°S is excluded). Outside of this area the ratio varies from 2.30 off northern Chile to 2.61 on the Peru continental slope. The values of c_u/p in the area of intense upwelling reflect the high shear strength that has developed under conditions of low consolidation pressure. Interparticle bonding or cementation, probably related to the abundant organic matter in these sediments, is apparently responsible for the high normalized shear strength.

The amount of shear strength reduction resulting from the breakdown of the sediment fabric is indicated by the sensitivity, the ratio of the natural and remolded undrained shear strengths. According to the classification of Rosenquist (1953) sediments of the Peru-Chile margin are slightly sensitive to medium quick clays. Nazca Plate sediments are the most sensitive, averaging 9 (Table 2). A value of 27 for a sample from the Chile Basin is the highest sensitivity that was determined. On the continental slope the average sensitivty ranges from 7 to 8. Sediments of the upper slope mud lens have the highest sensitivity on the slope with a maximum of 21 at 13.6°S.

Atterberg Limits

Atterberg limits are the water contents that correspond to the boundaries of different states of consistency of a remolded sediment (Lambe and Whitman, 1969). The liquid limit and plastic limit are the lower bounds of the water contents at which the sediment behaves as a liquid and plastic material respectively. They reflect the ability of a sediment particle to attract water to its surface and increase with the particle's tendency to hold water. The difference between the liquid and plastic limits, referred to as the plasticity index, indicates the range of water contents over which the sediment behaves as a plastic material. It has been shown that the liquid limit, plastic limit, and plasticity index increase with both increasing clay and organic content (Odell and others, 1960). In the Peru-Chile sediments organic content appears primarily responsible for the variation of these indices. With increasing organic carbon concentration the liquid and plastic limits and plasticity index all increase (Fig. 9).

Atterberg limits are used by engineers as a means of classifying a soil by comparing the relationship between the liquid limit and plasticity index. Plotting the indices for the Peru-Chile sediments on Casagrande's plasticity chart (Casagrande, 1948) shows the differences in behavior between sediments of the four provinces (Fig. 10). Figure 10 indicates that the organic-rich sediments from the upper slope mud lens have the highest plasticity along the margin. A decrease in the plasticity of these sediments with depth of burial and the high plasticity of sediments adjacent to the mud lens is responsible for the overlap of the mud lens and Peru slope sediments on the plasticity chart. The much lower plasticity of the northern Chile sediments reflects their low

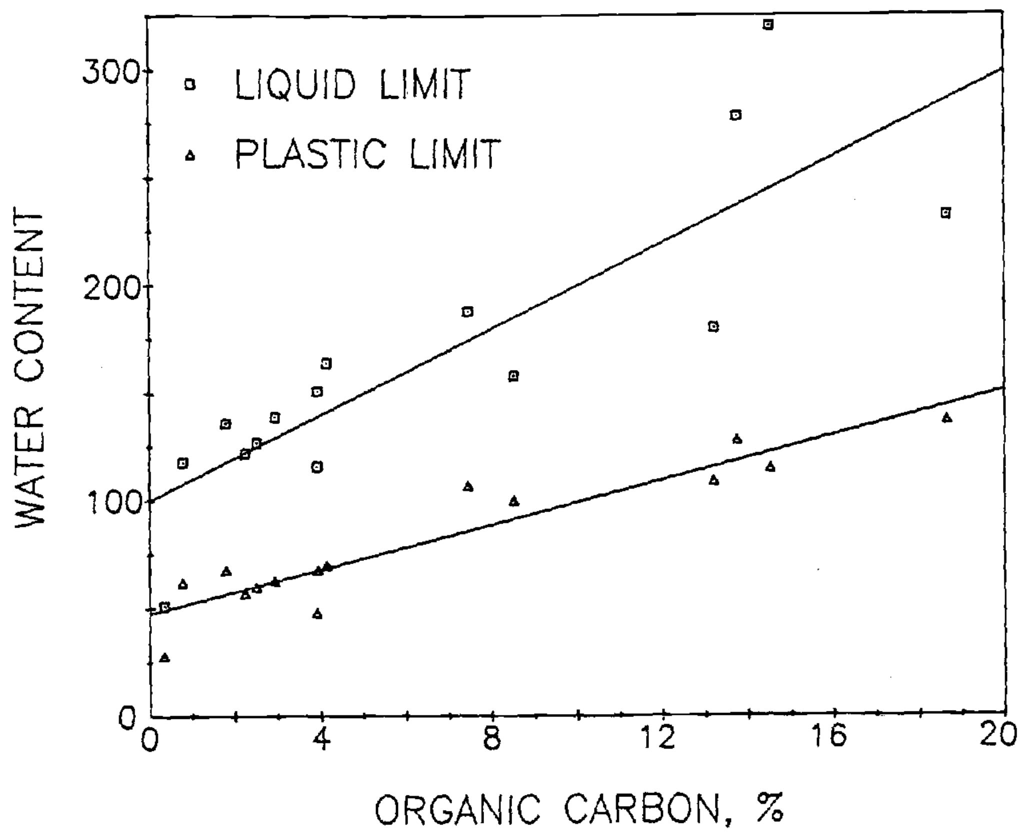


Figure 9. The relationship between the Atterberg limits and organic carbon concentration for the surface sediments. Lines are least square fits through the data. Scatter of the data reflects in part the variation in the clay content.

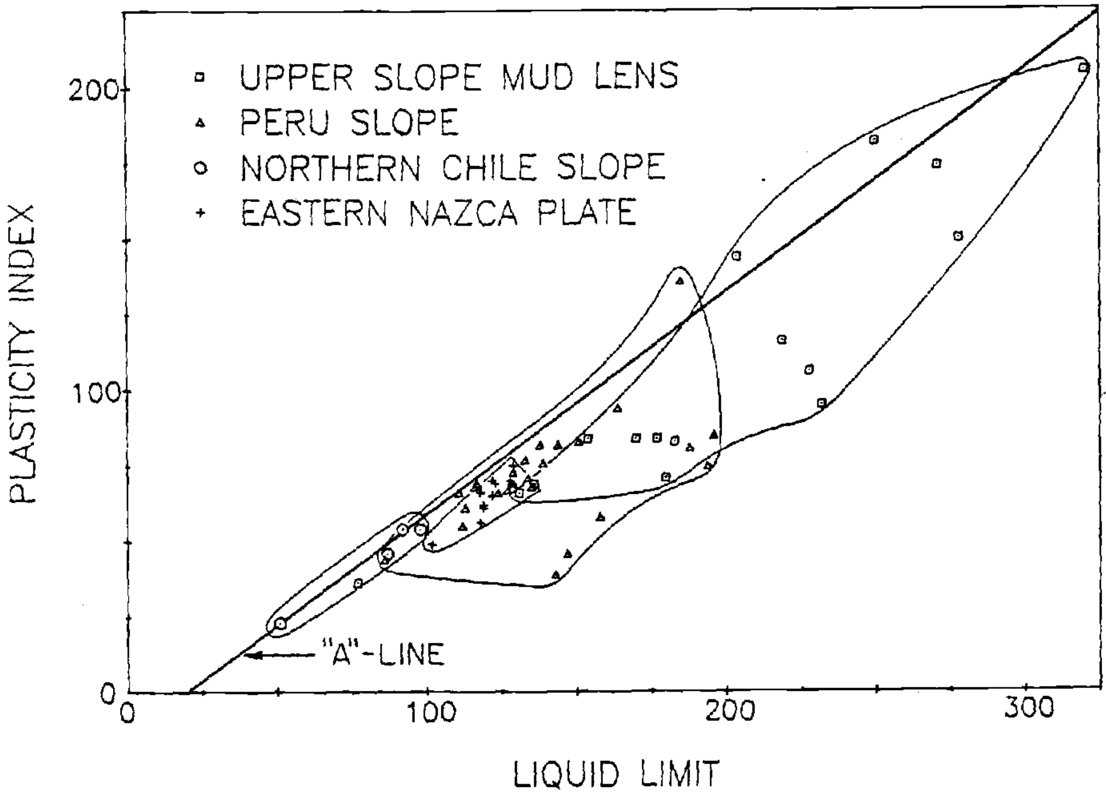


Figure 10. Plasticity chart. The data are from surface sediments and subsamples taken at 0.5 m to 1 m intervals over the length of the cores. Sediments below the A-line are in the engineering class of organic clays and inorganic silts of high compressibility. Sediments above the A-line are classified as inorganic clays of high plasticity (Lambe and Whitman, 1969).

clay and organic contents.

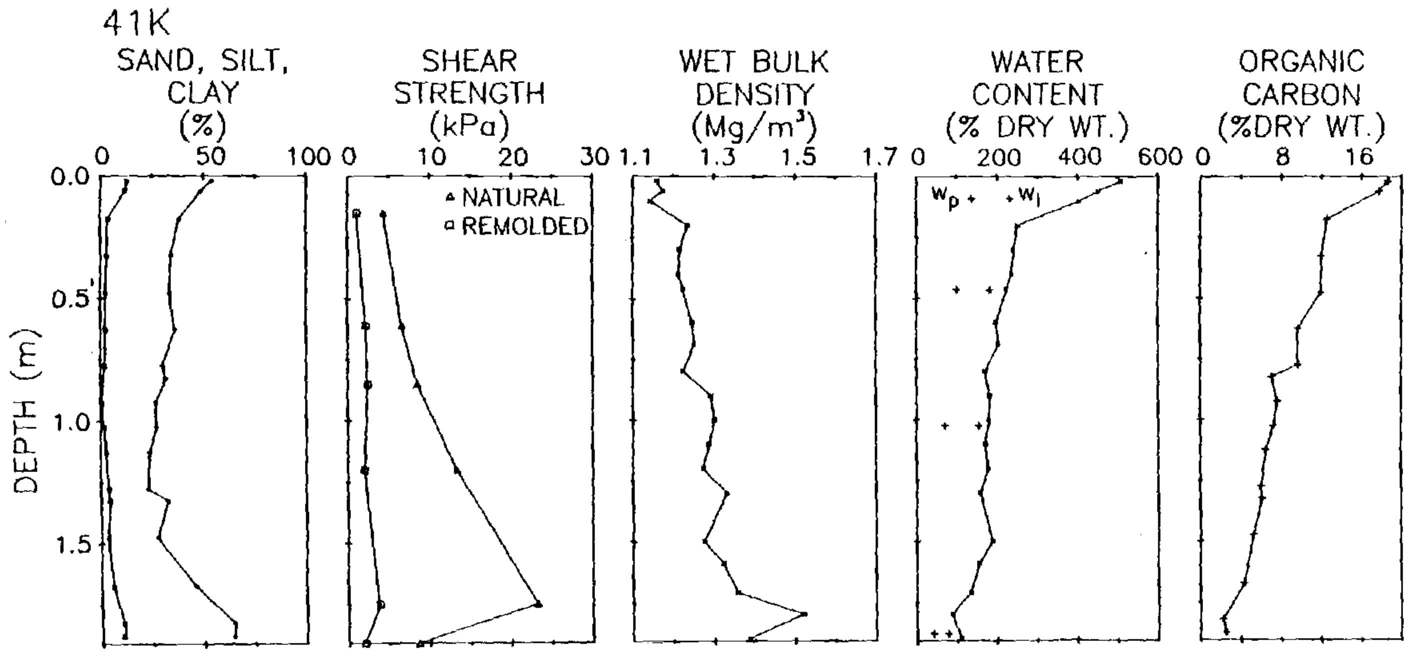
Information about the sediment microstructure and sediment compressibility can also be inferred from the Atterberg limits. In nearly all instances the in situ sediment water content is greater than the liquid limit. This disparity implies that the strength of the fabric allows the sediment to exist at a water content which in a remolded state would cause the sediment to flow. The largest difference between the liquid limit and natural water content occurs in the surface sediment of the upper slope mud lens. A positive correlation has been shown empirically to exist between the liquid limit and sediment compressibility (Lambe and Whitman, 1969). This relationship implies that the sediments from the area of intense upwelling have the highest compressibility and the northern Chile deposits are the least compressible. Results from one-dimensional consolidation tests performed on the Peru-Chile sediments verify this implied behavior (Busch and Keller, 1979, in review b).

VERTICAL VARIATION OF PHYSICAL PROPERTIES

The four sediment provinces along the Peru-Chile continental margin differ not only in the magnitude of their sediment physical properties, but in the manner in which the properties vary with depth of burial. Representative vertical profiles of the sediment physical properties from the four provinces are shown in Figure 11.

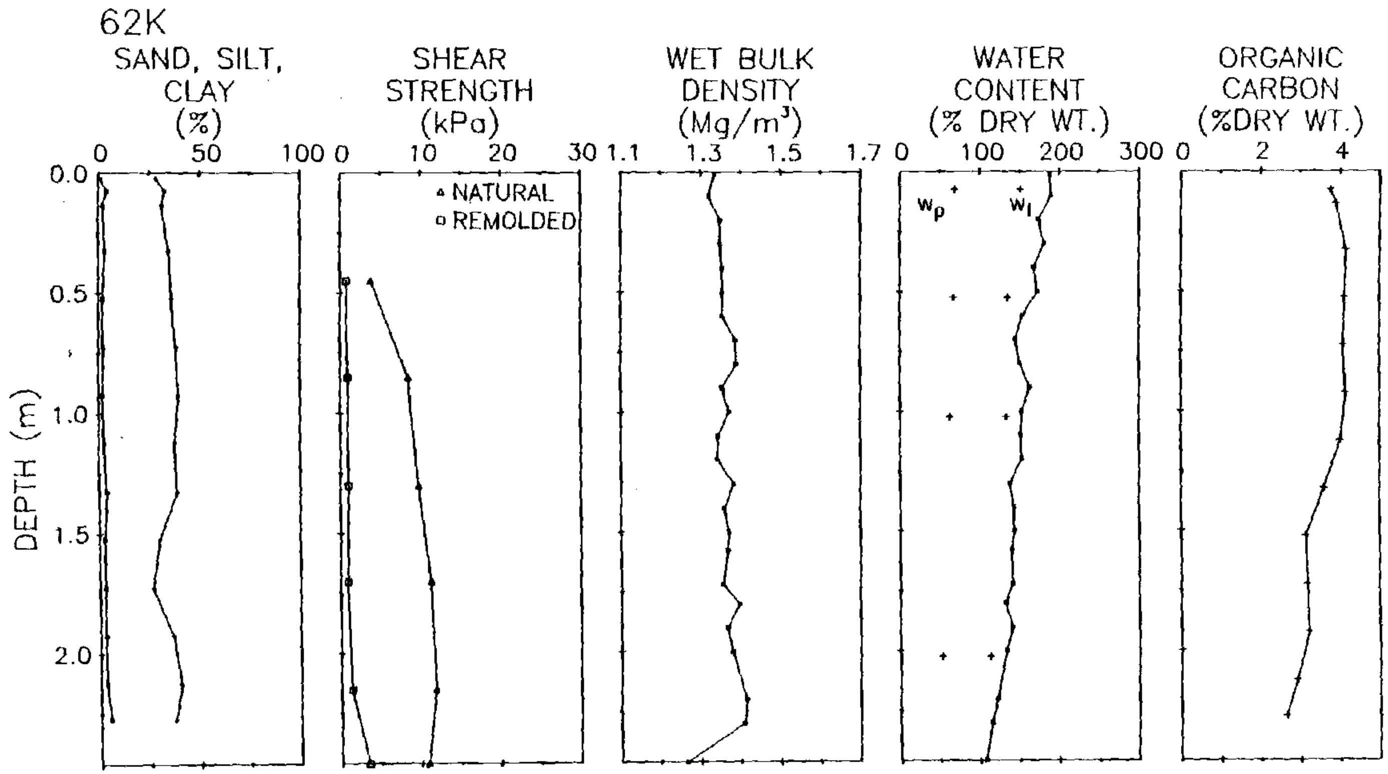
Sediments of the upper slope mud lens show the greatest change in physical properties with depth below the surface. Much of the change occurs in the top 20 cm of the sediment. A distinguishing feature of the mud lens sediments is a surface layer that has extremely high water content and low wet bulk density (Fig. 11a). The layer is typically 15

Figure 11. Vertical profiles of the physical properties of representative cores from the four sediment provinces. (a) Upper slope mud lens. Core 41K, water depth 411 m. Note the water content scale is twice as large as the water content scales for the other core profiles. The organic carbon scale is four times as large. (b) Peru slope outside the upper slope mud lens. Core 62K, water depth 2670 m. (c) Eastern Nazca Plate. Core 64K, water depth 4404 m. Water content, wet bulk density, and shear strength could not be determined between 0.20-0.90 m because of poor core recovery. (d) Northern Chile continental slope. Core 24K, water depth 5107 m. See Figure 1 for core locations.



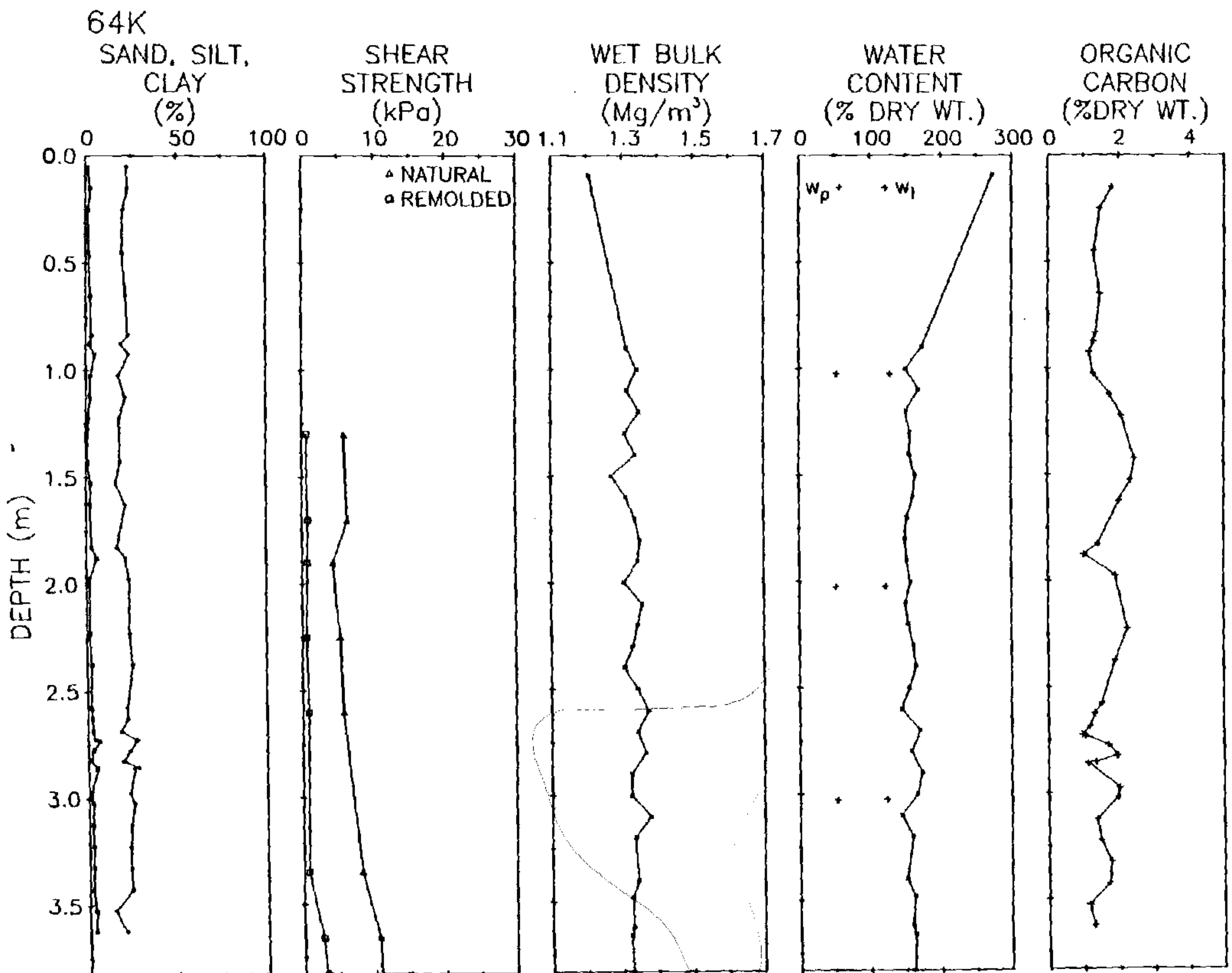
41K
SAND, SILT, CLAY (%)
0 50 100
SHEAR STRENGTH (kPa)
0 10 20 30
▵ NATURAL
▫ REMOLDED
WET BULK DENSITY (Mg/m³)
1.1 1.3 1.5 1.7
WATER CONTENT (% DRY WT.)
0 200 400 600
wp + + wl
ORGANIC CARBON (%DRY WT.)
0 8 16
DEPTH (m)
0.0 0.5 1.0 1.5

a



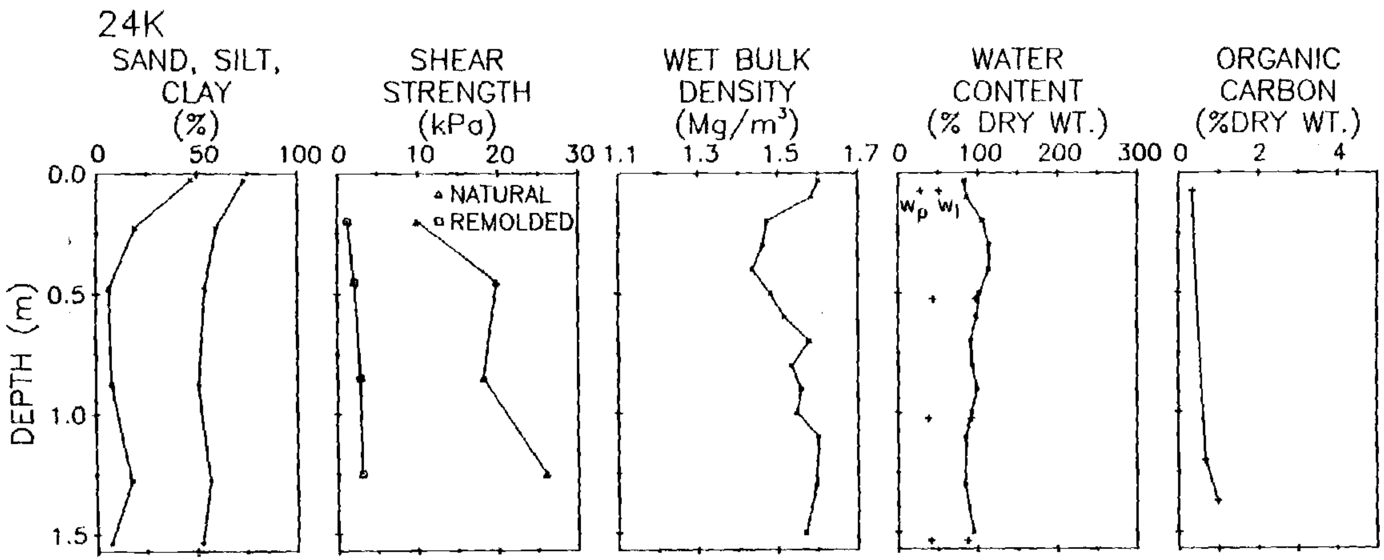
62K
SAND, SILT, CLAY (%)
0 50 100
SHEAR STRENGTH (kPa)
0 10 20 30
NATURAL
REMOLDED
WET BULK DENSITY (Mg/m³)
1.1 1.3 1.5 1.7
WATER CONTENT (% DRY WT.)
0 100 200 300
wp
wl
ORGANIC CARBON (%DRY WT.)
0 2 4
DEPTH (m)
0.0
0.5
1.0
1.5
2.0

b



64K
SAND, SILT, CLAY (%)
0 50 100
SHEAR STRENGTH (kPa)
0 10 20 30
NATURAL
REMOLDED
WET BULK DENSITY (Mg/m³)
1.1 1.3 1.5 1.7
WATER CONTENT (% DRY WT.)
0 100 200 300
w_p w_l
ORGANIC CARBON (%DRY WT.)
0 2 4
DEPTH (m)
0.0 0.5 1.0 1.5 2.0 2.5 3.0 3.5

c



24K
SAND, SILT, CLAY (%)
0 50 100
SHEAR STRENGTH (kPa)
0 10 20 30
NATURAL
REMOLDED
WET BULK DENSITY (Mg/m³)
1.1 1.3 1.5 1.7
WATER CONTENT (% DRY WT.)
0 100 200 300
w_p w_l
ORGANIC CARBON (%DRY WT.)
0 2 4
DEPTH (m)
0.0
0.5
1.0
1.5

d

cm or less thick and beneath it there is a sharp decrease in water content and increase in density. In core 41K (Fig. 11a) the water content decreases from 508% at the surface to 251% at 20 cm. Over this interval the wet bulk density increases from 1.16 to 1.23 Mg/m^3. Along with the change in water content and density there is a significant increase in grain specific gravity, 2.22 to 2.34, and a decrease in porosity and liquid and plastic limits. Undrained shear strength increases markedly beneath the surface layer on the mud lens. The shear strength of the surface sediments of core 41K was not determined; however, strength measurements at 13.6°S show an increase from 0.3 kPa at 2 cm to 5.8 kPa at 17 cm. Surface sediments in the area of intense upwelling have a high organic carbon concentration, up to 20% (% dry wt.), and locally contain an assemblage of filamentuous sulfur bacteria (Gallardo, 1977; Rowe and Haedrich, 1979). These two factors combine to give the surface layer its distinctive black color and spongy texture.

Beneath the highly organic surface layer the sediments of the upper slope mud lens continue to differ from the other Peru-Chile sediments. With increasing depth the rate of decrease in water content, porosity, and Atterberg limits and increase in wet bulk density is more rapid in the mud lens sediments than in the other sediments along the margin. Undrained shear strength increases rapidly with depth on the upper slope mud lens, although a higher rate of increase occurs in the northern Chile sediments. The changes in the physical properties of the mud lens sediments are associated with a large reduction in organic content with depth. This reduction is typified by the organic content profile of 41K (Fig. 11a) in which the organic carbon concentration decreases from 13% at 18 cm to 3% at 1.91 m.

The overall decrease in water content and increase in wet bulk density with depth is typically more variable in the sediments from the area of intense upwelling than in the other Peru-Chile sediments. Well-developed horizontal lamination is present in the mud lens sediments and differences in texture and composition of the laminae account for variation in water content and density. Preservation of these differences is enhanced by the impingement of the shallow water oxygen-minimum layer on the upper slope. Benthic macrofauna are lacking as a result of the anoxic bottom waters and bioturbation is minimal.

Outside the area of intense upwelling there is less change in the physical properties with depth of burial. The distinct high water content, low density surface layer is not present in these sediments. Instead, with increasing depth there is a gradual, relatively uniform decrease in water content and porosity and increase in wet bulk density (Fig. 11b,c). Grain specific gravity, sediment texture, and Atterberg limits change little with depth. Sediments of the northern Chile slope and trench show slightly different characteristics than those of the Peru slope and Nazca Plate. Off northern Chile a dense, low water content layer is present at the sediment surface (Fig. 11d). This layer has a coarse-grained texture with sand contents up to 71% and a high grain specific gravity of 2.80.

Lower and less variable organic content of sediments outside the intense upwelling area appears in part to be responsible for the lack of variation in sediment physical properties. Most of the sediments outside the upper slope mud lens have a total variation in organic carbon concentration of 2% or less (Fig. 11b,c,d). A slightly larger range is present in sediments bordering the mud lens. The absence of laminated sediments and the increased activity of benthic organisms also contribute to the reduced variability of the sediment physical properties. Radiographs reveal that much of the homogenous sediment outside the mud lens is intensely burrowed. In some instances large, recent burrows (1 cm diameter) are filled with high water content sediment and cause a localized variability of the sediment properties.

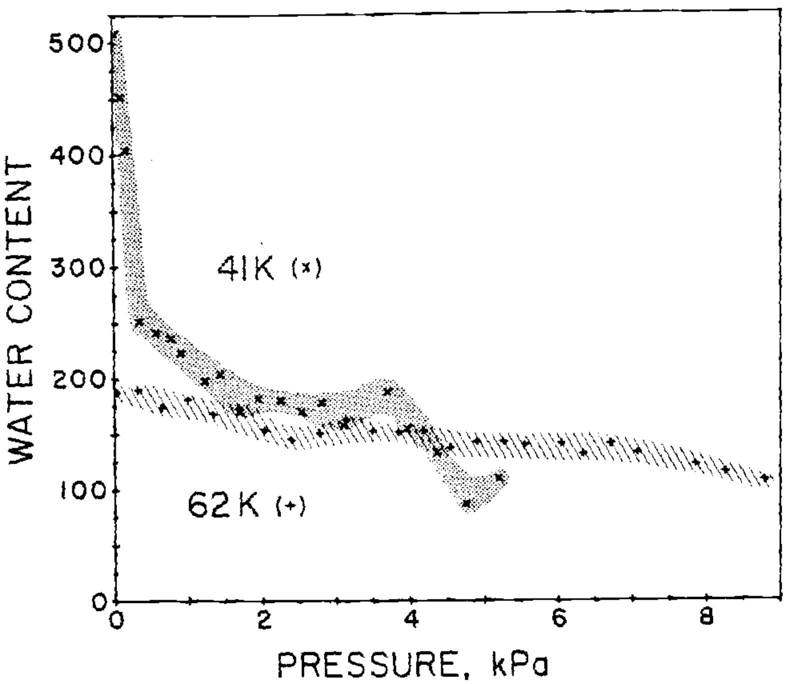
DISCUSSION

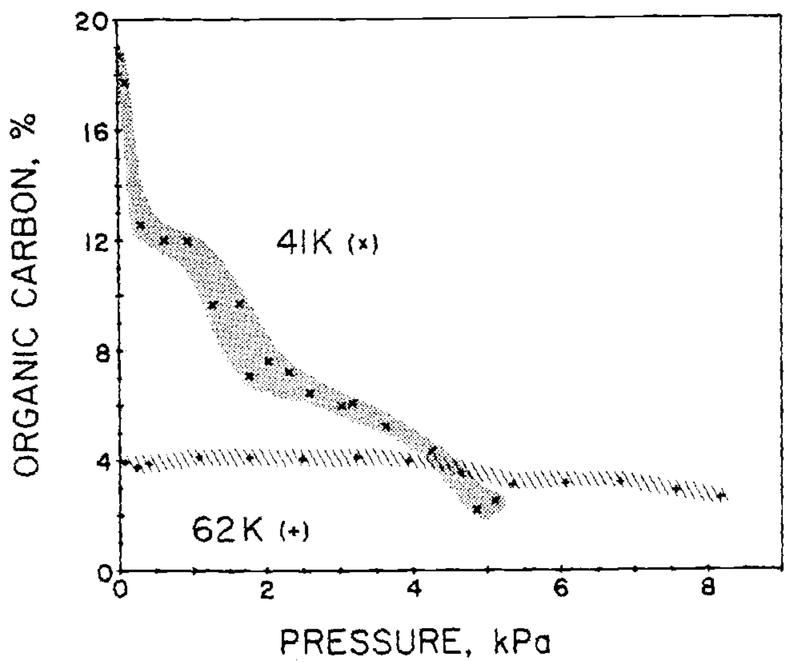
Variation of the physical properties of the sediments along the Peru-Chile continental margin is strongly influenced by coastal upwelling and the accompanying deposition of large amounts of organic matter on the slope. Differences in organic content appear to be primarily responsible for the diversity in sediment physical properties and the characteristics of the highly organic sediments deposited in the area of intense upwelling are unique. Changes in texture along the margin affect the other physical properties, but the magnitude of this variation is not as great. Also influencing the sediment physical properties, but to a lesser extent, are differences in mineralogy and sedimentation rate.

There are few detailed quantitative analyses of the effects of organic matter on sediment physical properties. Organic matter in deep-sea sediments occurs in three different forms: detrital organic matter, benthic biomass, and sorbed material (organo-clay complexes) (Suess and Müller, 1980). Relative abundance of these three forms varies with the environment. In areas of rapid sedimentation on the continental margin detrital organic matter dominates the organic fraction, whereas in pelagic environments benthic biomass and sorbed material are more important (Suess and Müller, 1980). The differing effects the three forms of organic matter might have on sediment properties is still being investigated (C. Reimers, personal communication, 1980).

Extremely high water content and low density of organic-rich surface sediments of the upper slope mud lens are conspicuous indicators of the influence of organic matter on sediment physical properties. In the sediments along the Peru-Chile margin there is a consistent increase in water content (Fig. 5) and decrease in grain specific gravity (Fig. 7) with increasing organic carbon concentration. Variation in specific gravity is primarily a simple function of the low density of organic substances. The high water content of organic-rich sediments is caused by the formation of clay-organic aggregates and the high water content of organic matter which results from the adsorption of water by organic substances and the open structure of organic matter (Pusch, 1973). The ability of organic particles to adsorb water increases not only the natural water content, but is apparently responsible for the increase in liquid and plastic limits with increasing organic carbon concentration (Fig. 9). The formation of clay-organic aggregates has been described by Greenland (1965), Mortland (1970), Pusch (1973), and others. Utilizing electron microscopy Pusch (1973) observed that clay particles and organic substances in marine sediments form dense aggregates separated by large voids. The maintenance of this type of structural arrangement with burial and the retention of water by organic matter is reflected in a comparison of profiles of water content versus effective overburden pressure for sediments from within and outside the upper slope mud lens (Fig. 12). At equivalent consolidation pressures the water content remains higher in the organic-rich mud lens sediment.

Figure 12. The relationship between water content, organic content, and consolidation pressure. At equal effective overburden pressures the higher organic content of the sediment of core 41K causes it to remain at a higher water content than the sediment of core 62K. The two cores have similar grain-size distributions for most of their lengths (Fig. 11). The texture of 41K becomes slightly coarser-grained near the bottom of the core.


WATER CONTENT
500
400
300
200
100
0
41K (x)
62K (+)
0
2
4
6
8
PRESSURE, kPa


ORGANIC CARBON, %
20
16
12
8
4
0
41K (x)
62K (+)
0
2
4
6
8
PRESSURE, kPa

The manner in which organic matter affects the undrained shear strength of the Peru-Chile sediments is less certain. Organic-rich, high water content sediments of the upper slope mud lens display unusually high strength. The presence of organic substances in sediments is commonly associated with low shear strength (Mitchell, 1976) and previous studies of submarine sediments have shown a consistent relationship of decreasing strength with increasing water content (Moore, 1964; Morelock, 1969; Ross, 1971). The ability of organic substances to increase sediment strength by acting as cementing agents has been discussed by Greenland (1965), Pusch (1973), and Rashid and Brown (1975). An increase in the shear strength of remolded sediment with the addition of organic matter was observed by Rashid and Brown (1975). Greenland (1965) and Pusch (1973) reported that the addition of organic matter produces an increase in the strength of individual sediment aggregates, but Greenland noted that this increase is not necessarily accompanied by an increase in bulk sediment strength. In a study of Gulf of Maine sediments Hulbert and Given (1975) concluded that the high normalized shear strength of the sediments, c_u/p, resulted from strengthening by labile organic matter. Values of c_u/p from the upper slope mud lens are much higher than those from the remainder of the Peru-Chile margin (Table 2) suggesting that the increased strength in this area may result from organic substances acting as cementing or bonding agents. Shear strengths measured in the upper slope mud lens deposits are in the range (greater than 14 kPa) stated by Nacci and others (1974) to be indicative of cementation in near surface sediments. However, the rigid interparticle bonding associated with cementation (Nacci and others, 1974) was not observed in the stress-strain behavior exhibited by the mud lens sediments in triaxial compression tests (Busch and Keller, in review a). A better understanding of how the abundant organic matter in the upper slope mud lens sediments is able to form an open fabric of unusual strength awaits further investigation of the sediment microstructure and organic matter composition.

Destruction of the fabric in the mud lens sediments by remolding results in a significant loss of strength as indicted by their high sensitivity. However, the average remolded shear strength on the upper slope mud lens is equal to that on the Peru slope (Table 2), despite the higher water content of the mud lens sediments. The equivalency of the strengths is consistent with the observations of Rashid and Brown (1975) that with increasing organic content the sediment can sustain the same remolded shear strength at higher water content.

Within the upper slope mud lens the abundant organic matter has a dominating influence on the sediment physical properties. Outside of this area the variation of the physical properties is more closely related to changes in sediment texture. The abundance of clay-size material is particularly important in influencing the physical properties. Engineering studies have shown that when clay-size particles comprise greater than one-third of the sediment they will dominate the behavior of the sediment (Mitchell, 1976). Attraction of water to the surfaces of clay minerals and the flocculation of clays in the marine environment result in an increase in water content with increasing clay content. Along the Peru-Chile margin the northward and offshore increase in clay-size material is accompanied by an increase in water content (Fig. 4). The amount of clay in the sediment modifies the relationship between organic carbon concentration and water content (Fig. 5). At low concentrations of organic carbon the clay content is primarily responsible for differences in water content. Associated with the concurrent increase in clay content and water content along the margin are a decrease in the wet bulk density and, outside the intense upwelling area, the more typical decrease in undrained shear strength. Based on the studies of Rashid and Brown (1975) high water content and low organic content may be responsible for the low remolded strength and high sensitivity of the clay-rich Nazca Plate sediments. Variation in the organic content masks the influence of the clay fraction on the Atterberg limits. The expected increase in Atterberg limits with increasing abundance of clay is evident only in a comparison of the low organic content sediments of the Nazca Plate and northern Chile margin.

Some of the variation of the sediment physical properties along the Peru-Chile margin can be attributed to differences in mineralogy and sedimentation rate. High grain specific gravity of the northern Chile sediments is the most notable mineralogy-related effect. Drainage of a continental volcanic terrane and the presence of ferromanganese micronodules and particle coatings is apparently responsible for the high particle density. Changes in clay mineralogy along the margin may cause differences in the physical properties. Nazca Plate sediments are enriched in smectite and mixed-layer clays relative to the slope deposits (Rosato, 1974). This greater abundance of expansive clay minerals may contribute to the high water content seaward of the trench; however, the increased water content in this area is also associated with a higher overall clay content. Patterns of increasing water content and decreasing shear strength with an increasing rate of sedimentation have been observed by Moore (1964). The high water content on the upper slope mud lens, where sediment is being deposited at rates up to 140 cm/1000 years, and the high shear strength on the northern Chile margin, where the sedimentation rate is less than 5 cm/1000 years, agree with the relationships recognized by Moore (1964). Compositional and textural variability on the Peru-Chile margin complicate the determination of the influence of sedimentation rate on the physical properties. Sedimentation rates on the northern Chile margin and eastern Nazca Plate are comparable, yet there are significant differences in sediment properties.

SUMMARY

Examination of the variation and the interrelationship of the physical properties of the sediments on the Peru-Chile continental margin and eastern Nazca Plate can be summarized by the following findings:

(1) Four sediment provinces can be recognized based on differences in physical properties. Properties of the sediments of the upper slope mud lens between 10.5° to 13.6°S are unique. These sediments were deposited beneath an area of intense coastal upwelling and are characterized by anomalously fine texture; high water content, Atterberg limits, and plasticity; low wet bulk density and grain specific gravity; and greater than expected strength.

(2) The manner in which the physical properties vary with depth differs between the four sediment provinces. The greatest variation in properties with depth occurs in the sediments of the upper slope mud lens. A distinctive surface layer (0 to 15 cm) with extremely high water content and low density characterizes the mud lens sediments. A sharp decrease in water content and increase in density occurs below the surface layer.

(3) Differences in organic content are closely correlated to the variation of the physical properties of the Peru-Chile sediments. Sediment water content increases with increasing organic content as a result of organic matter adsorbing water and forming an open sediment fabric. Because of the ability of organic matter to absorb water the Atterberg limits also increase with increasing organic content. The low density of organic matter causes a decrease in grain specific gravity with increasing organic content, which combined with the water content-organic content relationship produces the low wet bulk density of the organic-rich sediments. Strengthening of the sediment fabric by non-cementing organic substances is apparently responsible for the greater than anticipated strength of sediments from the upper slope mud lens.

(4) Differences in sediment texture affect the variation of the physical properties of the Peru-Chile sediments, but to a lesser extent than differences in organic content. Progressive northward and offshore fining of the sediments along the margin is accompanied by an increase in water content and decrease in wet bulk density. Outside the intense upwelling area the undrained shear strength of the sediments responds to texturally induced water content variation and decreases with increasing water content.

(5) Variation in mineralogy and sedimentation rate may affect the sediment physical properties. Enrichment in volcanic debris and ferromanganese minerals is associated with the high density of the northern Chile sediments. The influence of varying clay mineralogy is uncertain. Also uncertain is the influence of sedimentation rate on the physical properties which appears to be masked by compositional and textural variation.

REFERENCES

Ade-Hall, J. J., 1976, Underway surveys, Leg 34, in Yeats, R. S., Hart, S. R., et al., 1976, Initial Reports of the Deep Sea Drilling Project, Washington, U.S. Government Printing Office, v. 34, p. 163-181.

Almagor, G. and Wiseman, G., 1977, Analysis of submarine slumping in the continental slope of the southern coast of Israel: Mar. Geotech., v. 2, p. 349-388.

ASTM, 1979a, Laboratory determination of moisture content of soil: Ann. Book of ASTM Standards, Part 19, D2216-71, p. 338-339.

ASTM, 1979b, Liquid limit of soils: Ann. Book of Standards, Part 19, D423-66, p. 123-126.

ASTM, 1979c, Plastic limit and plasticity index of soils: Ann. Book of Standards, Part 19, D424-59, p. 127-128.

ASTM, 1979d, Specific gravity of soils: Ann. Book of Standards, Part 19, D854-58, p. 211-213.

Barazangi, M. and Isacks, B. L., 1976, Spatial distribution of earthquakes and subduction of the Nazca Plate beneath South America: Geology, v. 4, p. 686-692.

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

Berner, R. A., 1978, Sulfate reduction and the rate of deposition of marine sediments: Earth Planet. Sci. Lett., v. 37, p. 492-498.

Booth, J. S. and Garrison, L. E., 1978, A geologic and geotechnical analysis of the upper continental slope adjacent to the Mississippi Delta: 10th Offshore Tech. Conf., p. 1019-1028.

Busch, W. H. and Keller, G. H., 1979, Consolidation characteristics of continental slope sediments off Peru: Geol. Soc. America Abstracts with Programs, v. 11, p. 396.

Busch, W. H. and Keller, G. H, in review a, Analysis of sediment stability on the Peru-Chile continental slope.

Busch, W. H. and Keller, G. H., in review b, Consolidation characteristics of sediments from the Peru-Chile continental margin and implications for past sediment instability.

Casagrande, A., 1948, Classification and identification of soils: Trans. ASCE, v. 113, p. 901-991.

Coulbourn, W. T. and Moberly, R., 1976, Structural evolution of fore-arc basins off southern Peru and northern Chile: Can. Jour. Earth Sci., v. 14, p. 102-116.

DeVries, T. J., 1980, Nekton remains, diatoms, and Holocene upwelling off Peru: unpubl. M.S. thesis, Oregon State University, 85 p.

Gallardo, V. A., 1977, Large benthic microbial communities in sulphide biota under Peru-Chile subsurface counter current: Nature, v. 268, p. 331.

Greenland, D. H., 1965, Interaction between 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.

Hamilton, E. L., 1971, Prediction of in situ acoustic and elastic properties of marine sediments: Geophysics, v. 36, p. 266-284.

Hulbert, H. H. and Given, D. N., 1975, Geotechnical and chemical property relationships for Wilkinson Basin, Gulf of Maine, sediments: Jour. Sed. Petrology, v. 45, p. 504-512.

Keller, G. H., Lambert, D. W. and Bennett, R. H., 1979, Geotechincal properties of continental slope deposits - Cape Hatteras to Hydrographer Canyon, in Doyle, L. J. and Pilkey, O. H., eds., Geology of Continental Slopes: Soc. Econ. Paleontologists and Mineralogists Spec. Pub. 27, p. 131-151.

Krissek, L. A., Scheidegger, K. F. and Kulm, L. D., 1980, Surface sediments of the Peru-Chile continental margin and the Nazca Plate: Geol. Soc. America Bull., v. 91, p. 321-331.

Kulm, L. D., Schweller, W. J. and Masias, A., 1977, A preliminary analysis of the subduction process along the Andean continental margin, 6° to 45°S, in Talwani, M. and Pitman, W. E., III, eds., Island Arcs, Deep Sea Trenches and Back-Arc Basins, Maurice Ewing Series, Vol. 1: Am. Geoph. Union, p. 285-301.

Lambe, T. W. and Whitman, R. V., 1969, Soil Mechanics: New York, Wiley and Sons, 553 p.

Lonsdale, P., 1976, Abyssal circulation of the southeastern Pacific and some geological implications: Jour. Geophys. Res., v. 81, p. 1163-1176.

Mammerickx, J. and Smith, S. M., 1978, Bathymetry of the southeast Pacific: Geol. Soc. America Map and Chart Series MC-26.

Masias, J. A., 1976, Morphology, shallow structure, and evolution of the Peruvian continental margin, 6° to 18°S: unpubl. M.S. thesis, Oregon State University, 92 p.

Mitchell, K. K., 1976, Fundamentals of Soil Behavior: New York, Wiley and Sons, 422 p.

Moore, D. G., 1964, Shear strength and related properties of sediments from experimental Mohole (Guadalupe Site): Jour. Geophys. Res., v. 69, p. 4271-4291.

Morelock, J., 1969, Shear strength and stability of continentnal slope deposits, western Gulf of Mexico: Jour. Geophys. Res., v. 74, p. 465-482.

Mortland, M. M., 1970, Clay organic complexes and interactions: Adv. Agron., v. 22, p. 74-158.

Moser, J. C., 1980, Sedimentation and accumulation rates of Nazca Plate metalliferous sediments by high resolution Ge(Li) gamma-ray spectrometry of uranium series isotopes: unpubl. M.S. thesis, Oregon State University, 65 p.

Nacci, V. A., Kelly, W. E., Wang, M. C. and Demars, K. R., 1974, Strength and stress-strain characteristics of cemented deep-sea sediments, in Interbitzen, A. L., ed., Deep-Sea Sediments: Physical and Mechanical Properties: New York, Pleneum Press, p. 129-150.

Odell, R. T., Thornburn, T. H. and McKenzie, L. T., 1960, Relationships of Atterberg limits to some other properties of Illinois soils: Proc. Soil Sci. America, v. 24, p. 297-300.

Pusch, R., 1973, Influence of organic matter on the geotechnical properties of clays: Natl. Swedish Bldg. Res. Doc. 11, 64 p.

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

Rosato, V. J., 1974, Peruvian deep-sea sediments: Evidence for continental accretion: unpubl. M.S. thesis, Oregon State University, 93 p.

Rosenquist, I. Th., 1953, Considerations on the sensitivity of Norwegian quick clays: Geotechnique, v. 3., p. 195-200.

Rowe, G. T. and Haedrich, R. L., 1979, The biota and biological processes of the continental slope, in Doyle, L. J. and Pilkey, O. H., eds., Geology of Continental Slopes: Soc. Econ. Paleontologists and Mineralogists Spec. Pub. 27, p. 49-59.

Ross, D. A., 1971, Mass physical properties and slope stability of the sediments of the northern Middle America Trench: Jour. Geophys. Res., v. 76, p. 704-712.

Scheidegger, K. F. and Krissek, L. A., 1978, Distinguishing between fluvial and eolian sediment sources off Peru and Chile: Trans. Am. Geoph. Union, v. 59, p. 1114.

Schuette, G. and Schrader, H., 1979, Diatom taphocoenoses in the coastal upwelling area off western South America: Nova Hedwigia, Beih. 64, p. 359-378.

Smith, R. L., 1968, Upwelling: Mar. Biol. Ann. Rev., v. 6, p. 11-46.

Smith, R. L., 1978, Physical oceanography of coastal upwelling regions. A comparison: Northwest Africa, Oregon, and Peru: Symposium on the Canary Current: Upwelling and Living Resources, Intl. Council for the Exploration of the Sea, Las Palmas, Canary, Islands.

Suess, E. and Müller, P. J., 1980, Productivity, sedimentation rate and sedimentary organic matter in the oceans. II. Elemental fractionation: Colloq. Internat. du C.N.R.S., No. 293, Biogeochemie de la materie organque a l'interface eau. sediment marin, p. 17-26.

Thiede, J., Chriss, T., Clauson, M. and Swift, S. A., 1976, Settling tubes for size analysis of fine and coarse fractions of oceanic sediments: School of Oceanography, Oregon State University, Ref. 76-8, 87 p.

Trask, P. D., 1961, Sedimentation in a modern geosyncline off the arid coast of Peru and northern Chile: Proc. XXI Intl. Geol. Congress, v. 23, p. 103-118.

Zuta, S. and Guillen, O., 1970, Oceanographia de las aquas costeras del Peru: Instut. del Mar de Peru Bol., v. 2, p. 159-323.

Zuta, S., Rivera, T. and Bustamante, A., 1978, Hydrologic aspects of the main upwelling areas off Peru, _in_ Boje, R. and Tomczak, M., eds., Upwelling Ecosystems: New York, Springer-Verlag, p. 235-260.

PART II

CONSOLIDATION CHARACTERISTICS OF SEDIMENTS FROM THE PERU-CHILE CONTINENTAL MARGIN AND IMPLICATIONS FOR PAST SEDIMENT INSTABILITY

Submitted to Marine Geology

ABSTRACT

One-dimensional consolidation tests were performed on eight near-surface samples (0.5 to 3.5m) from the Peru-Chile continental margin. These tests show that the consolidation behavior of these deposits is strongly influenced by the presence of high concentrations of organic matter resulting from the occurrence of coastal upwelling along this margin of South America. Organic carbon concentrations as high as 12% are found in samples from an upper slope mud lens between 10.5° to 13.6°S that lies beneath an area of intense upwelling. With increasing organic content both the compressibility and rate of secondary compression are found to increase. The increase in void ratio with increasing organic content and the ease by which organic matter is deformed appear responsible for these trends. Outside the mud lens the compressibility also increases as a result of increasing concentrations of clay-size material and the abundance of smectite and illite. All of the sediments along the margin behave as if they were consolidated under a pressure greater than the present effective overburden pressure. Evidence of erosion as a cause of the overconsolidation is present only on the upper slope mud lens at 13.6°S where ^{14}C dating verifies the erosion of 3.5 to 7m of sediment. Numerous unconformities and intervals of deformed bedding in a core from 13.6°S attest to the past instability of sediments at this site. At the other locations along the margin the increase in the overconsolidation ratio with increasing organic carbon content suggests that the bonding of

sediment particles by organic matter may be responsible for the apparent overconsolidation. Low sedimentation rates on the slope off northern Chile may also be a contributing factor to the apparent overconsolidation of sediments in this area.

INTRODUCTION

Consolidation is the volume reduction that occurs as water is expelled from sediment void space. The rate and amount of volume reduction that occur under an applied load can be determined by the one-dimensional consolidation test (Terzaghi and Peck, 1967). This test has been long used by engineers studying the settlement of foundations and embankments; however, the results of consolidation tests can also be used to understand the behavior of sediments in natural environments. Rates of consolidation yield information on the modification of the sediment structure with time and the permeability of the sediment. From the amount of volume reduction that occurs during the consolidation test the sediment compressibility and stress history are determined. The compressibility can be used to estimate the reduction in sediment volume that accompanies burial beneath an increasing overburden. Determination of the stress history, or record of past loading, provides a means to identify previous episodes of sediment erosion. In submarine sediments the interpretation of stress history is complicated by bonding that develops between particles and time dependent adjustments of the sediment fabric at constant stress levels.

Knowledge of the consolidation behavior of deep-sea sediments and factors that affect this process is limited. Early investigations showed that it is common for submarine deposits to behave as overconsolidated sediments (sediments consolidated under a pressure greater than the present overburden) while lacking evidence of erosion (Hamilton, 1964; Bryant and others, 1967; Buchan and others, 1967; Richards and Hamilton, 1967). Underconsolidated sediments (sediments in which the consolidating pressure is less than the present overburden as a result of pore pressure in excess of hydrostatic pressure) were found in areas of rapid sediment accumulation such as the Mississippi Delta (Bryant and others, 1967). More recently investigations have attempted to relate differences in consolidation behavior to variation in sediment composition (Bryant and others, 1974; Silva and Hollister, 1979) and fabric (Bennett and others, 1977).

This paper examines the variation in the consolidation behavior of the sediments along the Peru-Chile continental margin. Variation in the behavior is associated with changes in sediment composition that occur along the margin. Coastal upwelling off Peru and the accompanying rapid accumulation of organic matter in the underlying deposits has a pronounced influence on the consolidation characteristics of the sediments. Differences in continental sediment sources, supply rates, and proximity to the continent also affect the sediment composition and behavior. The objective of this report is to examine the influence of organic matter, sediment texture, and clay mineralogy on the rate of consolidation, compressibility, and stress history of the Peru-Chile continental margin sediments.

GEOLOGICAL SETTING

Consolidation characteristics were determined for sediments from six locations on the Peru-Chile continental slope and one site on the adjacent Nazca Plate (Fig. 1). The morphology and structure of the continental slope in the area from which the samples were obtained have been described in a number of recent investigations (Coulbourn and Moberly, 1976; Masias, 1976; Kulm and others, 1977). In the study area the continental slope is narrow and is bounded by the Peru-Chile Trench

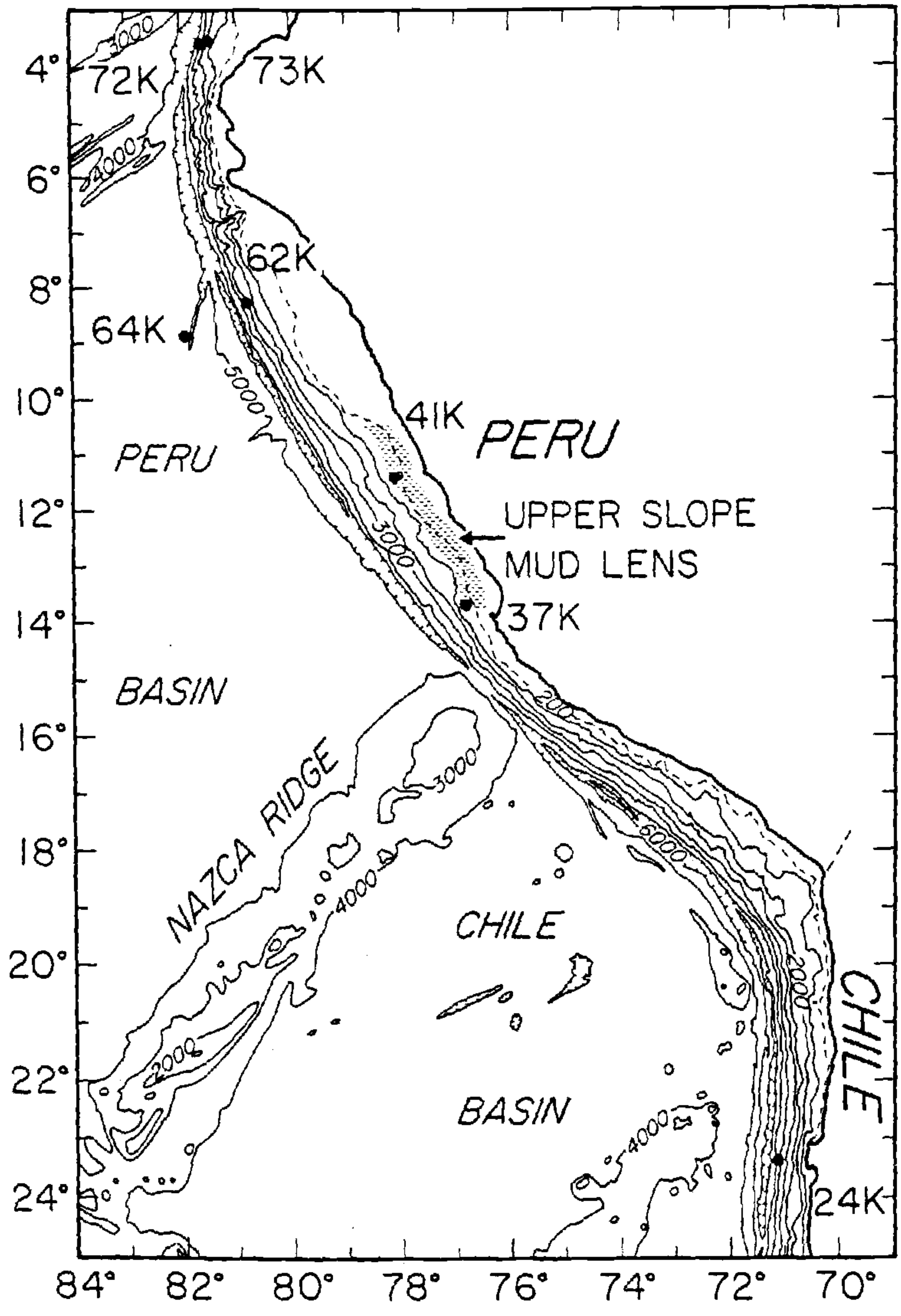


Figure 1. Sample locations on the Peru-Chile continental margin and eastern Nazca Plate. Bathymetry modified from Mammerickx and Smith (1978).

which varies in depth from 8100 m at 23°S to 4500 m at 3°S. Off northern Peru the slope is dissected by several large submarine canyons whereas to the south the canyons are smaller and less frequent. Small basins and benches are common on the lower and middle slope with prominent plateaus along the upper slope. A change in the slope physiography at 19.5°S is noted by the smaller size and less frequent occurrence of basins and benches along the slope (Kulm and others, 1977).

The continental slope is covered by a thin layer of sediment that is frequently confined to local basins. A thick sediment accumulation, at least 50 m, on the upper slope between 10.5° to 13.6°S was mapped from 3.5 kHz records by Krissek and others (1980). The location of this upper slope mud lens coincides with the occurrence of intense coastal upwelling and the impingement of the shallow water oxygen-minimum layer on the continental slope. On much of the slope off northern Chile sediment cover is extremely thin or absent as implied by the lack of subbottom reflectors on the 3.5 kHz records.

A limited number of sedimentation rates have been determined for the Peru-Chile margin from ^{14}C dating, ^{210}Pb dating (DeMaster, 1979), and rates of dissolved SO_4-reduction in interstitial waters based on the relationship described by Berner (1978) (E. Suess, personal communication, 1979). Sediments are presently being deposited on the upper slope mud lens at rates of 17 to 140 cm/1000 years. Outside the area of intense upwelling sedimentation rates on the Peru slope are only available south of 11°S where rates of 6 to 47 cm/1000 years were determined. Off northern Chile sediment deposition is slow with rates of 5 cm/1000 years or less. On the Nazca Plate in the area sampled for consolidation testing sediments are being deposited at a rate of 2.5 cm/1000 years (Moser, 1980).

Coastal upwelling exerts a strong influence on sediment composition and distribution on the Peru-Chile continental margin. Upwelling occurs within 50 km of shore north of 20°S in response to the prevalent southeasterly trade winds that parallel the coast (Smith, 1968, 1978; Zuta and others, 1978). As a result of the offshore directed Ekman transport of the surface waters nutrient-rich waters rise to the surface from a depth of approximately 70 m (Smith, 1978). These waters support a high biological productivity (Zuta and Guillen, 1970) which is accompanied by the concentration of organic matter in the sediments underlying the upwelling areas. Coastal upwelling has occurred off Peru since at least the late Miocene as indicated by diatom assemblages in rocks dredged from the continental slope (H. Schrader, personal communication, 1980).

PHYSICAL PROPERTIES AND COMPOSITION

Variation of the sediment physical properties along the Peru-Chile continental margin reflects the influence of the coastal upwelling process (Busch and Keller, in review). The properties of the organic-rich sediments of the upper slope mud lens are unique; anomalously fine texture, extremely high water content and plasticity, and low wet bulk density characterize these deposits. Abundant organic matter in the sediments affects interparticle bonding in a manner that results in undrained shear strength greater than would be expected for deposits with such high water content. Along the continental margin, outside the region of intense upwelling, there is a progressive fining of the sediments from south to north and with increasing distance from shore (Krissek and others, 1980). Coarse-grained slope and trench deposits off northern Chile have the lowest water content and highest density and shear strength on the margin. An increase in the clay-size fraction northward and offshore is accompanied by an increase in water content and decrease in wet bulk density. A general decrease in undrained shear strength is associated with the increase in water content.

The properties of the samples used in the consolidation tests are representative of the variation in sediment physical properties along the Peru-Chile margin (Table 1). Samples from the upper slope mud lens (core 41K, 0.5 and 1.4 m sample depths) have the highest water content and plasticity and lowest wet bulk density of those examined. The fine-grained texture of the mud lens sediments is similar to that of the samples from the lower continental slope off Peru. Upper slope mud lens sediments from 13.6°S (core 37K) differ from other deposits of the area of intense upwelling and display anomalously low water content and high density. The physical properties of the sample from the northern Chile slope (core 24K) are at the opposite end of the spectrum from those of the mud lens sediments. Core 24K has the coarsest texture, highest density, and lowest water content and plasticity of the consolidation samples. Properties of the Peru slope samples (cores 62K, 72K and 73K) are intermediate between those of the northern Chile slope and mud lens sediments. As a result of the offshore decrease in grain size the clay-size fraction of the Nazca Plate sediments (core 64K) is extremely high. High water content and low wet bulk density are associated with the fine-grained texture of these sediments.

The mineralogy of the clay-size material was determined from oriented clay mounts using a Norelco Phillips diffractometer. Methods of clay slide preparation and mineralogy determination were similar to those of Karlin (1980). Semi-quantitative percentages of the clay

TABLE 1. Physical Properties

Core	Water depth (m)	Depth in core (m)	Water content (% dry wt.)	Wet bulk density (Mg/m^3)	Void ratio, e	Liquid limit	Plastic limit	Grain Size Sand >62μm (%)	Grain Size Silt 62-4μm (%)	Grain Size Clay <4μm (%)
24K	5107	1.36-1.39	90	1.58	2.56	87	41	14	42	44
37K	370	1.33-1.36	136	1.39	3.14	227	64	6	36	58
41K	411	0.48-0.51	215	1.23	5.72	183	100	3	31	66
41K	411	1.40-1.43	202	1.30	5.50	154	70	4	26	70
62K	2670	2.05-2.15	122	1.41	3.09	113	52	3	37	60
64K	4404	3.50-3.60	177	1.31	4.46	123	54	4	11	85
72K	3601	2.40-2.50	157	1.35	4.11	133	56	2	36	62
73K	2116	2.45-2.55	155	1.35	3.86	134	56	2	29	69

minerals were obtained by comparing the peak areas of glycerol solvated samples using the weighting factors of Biscaye (1965). Differing abundances of smectite and chlorite account for most of the variation in clay mineralogy along the margin and reflect differences in continental sediment sources. Smectite concentration is lowest on the upper slope mud lens at 11°S (core 41K, Table 2) and increases to the north and south, and with increasing distance from shore (Rosato, 1974). Active volcanism occurs in Peru and Chile between 0° to 2°S and 15° to 27°S (Barazangi and Isacks, 1976). Alteration of debris from this volcanism is apparently responsible for the increased abundance of smectite in the northern and southern parts of the study area. Chlorite abundance varies inversely with that of smectite (Table 2) and sediments of the upper slope mud lens are enriched in chlorite. Sources of chlorite are the metamorphic terranes of the coastal region of Peru between 8° to 16°S.

Concentrations of organic carbon and calcium carbonate ($CaCO_3$) in the consolidation samples were measured with a Leco WR-12 Automatic Carbon Determinator. Organic carbon concentrations are highest in the upper slope mud lens sediments (Table 2) as a result of the high biological productivity associated with the strong coastal upwelling and the preservation in anoxic bottom waters. Mud lens sediments from 13.6°S (core 37K) are again anomalous and have a low organic content. Outside of the area of intense upwelling there is a decrease in the abundance of organic matter with increasing distance from shore. Sediments from the lower slope off northern Chile (core 24K) have the lowest organic content in the study area. Calcium carbonate concentrations are low in all of the consolidation samples (Table 2). Shoaling of the lysocline in the

TABLE 2. Clay Mineralogy and Carbon Composition

Core	Mineralogy (% of < 4µm fraction) Smectite/ mixed-layer	Illite	Chlorite	Kaolinite	Organic carbon (% dry wt.)	$CaCO_3$ (% dry wt.)
24K	42	28	22	8	0.98	0.45
37K	17	37	34	12	2.91	0.54
$41K_{.5m}$*	1	45	47	7	11.98	1.35
$41K_{1.4m}$*	5	45	38	12	5.62	6.01
62K	21	50	22	7	2.91	6.69
64K	26	51	14	9	1.15	1.25
72K	60	26	8	6	2.76	0.69
73K	77	18	4	1	3.66	5.09

* Core 41K was sampled at 2 depths, 0.5m and 1.4m

areas of high productivity and dilution by terrigenous components are apparently responsible for the low concentrations. The amount of $CaCO_3$ in the sediments does not have an observable effect on the consolidation behavior.

Organic matter in sediments acts to promote the development of an open fabric (Pusch, 1973). Along the Peru-Chile margin this effect is indicated by the increase in sediment water content with increasing organic content (Busch and Keller, in review). In the consolidation samples the relationship between organic matter and the development of an open particle arrangement is reflected by the increase in void ratio (volume of voids/volume of solids) with increasing organic carbon concentration (Fig. 2). Organic-rich sediments of the upper slope mud lens have the highest void ratios along the margin (Table 1). The relationship between void ratio and organic content is modified by the amount of clay-size material in the sediments, particularly at low concentrations of organic carbon (Fig. 2). The Nazca Plate sample (core 64K) is low in organic carbon (1.15%), but has a high void ratio as a result of a clay-size fraction of 85%.

PROCEDURES AND RESULTS

Procedures

Consolidation samples with minimal disturbance were obtained from Kasten cores, gravity cores with a large cross-sectional area (15 x 15 cm). Two different devices were used to perform the consolidation tests. Sediments from cores 24K, 37K, $41K_{0.5m}$, and $41K_{1.4m}$ were tested on a Karol-Warner Conbel consolidometer. The remainder of the samples (cores 62K, 64K, 72K, and 73K) were tested with an Anteus consolidometer

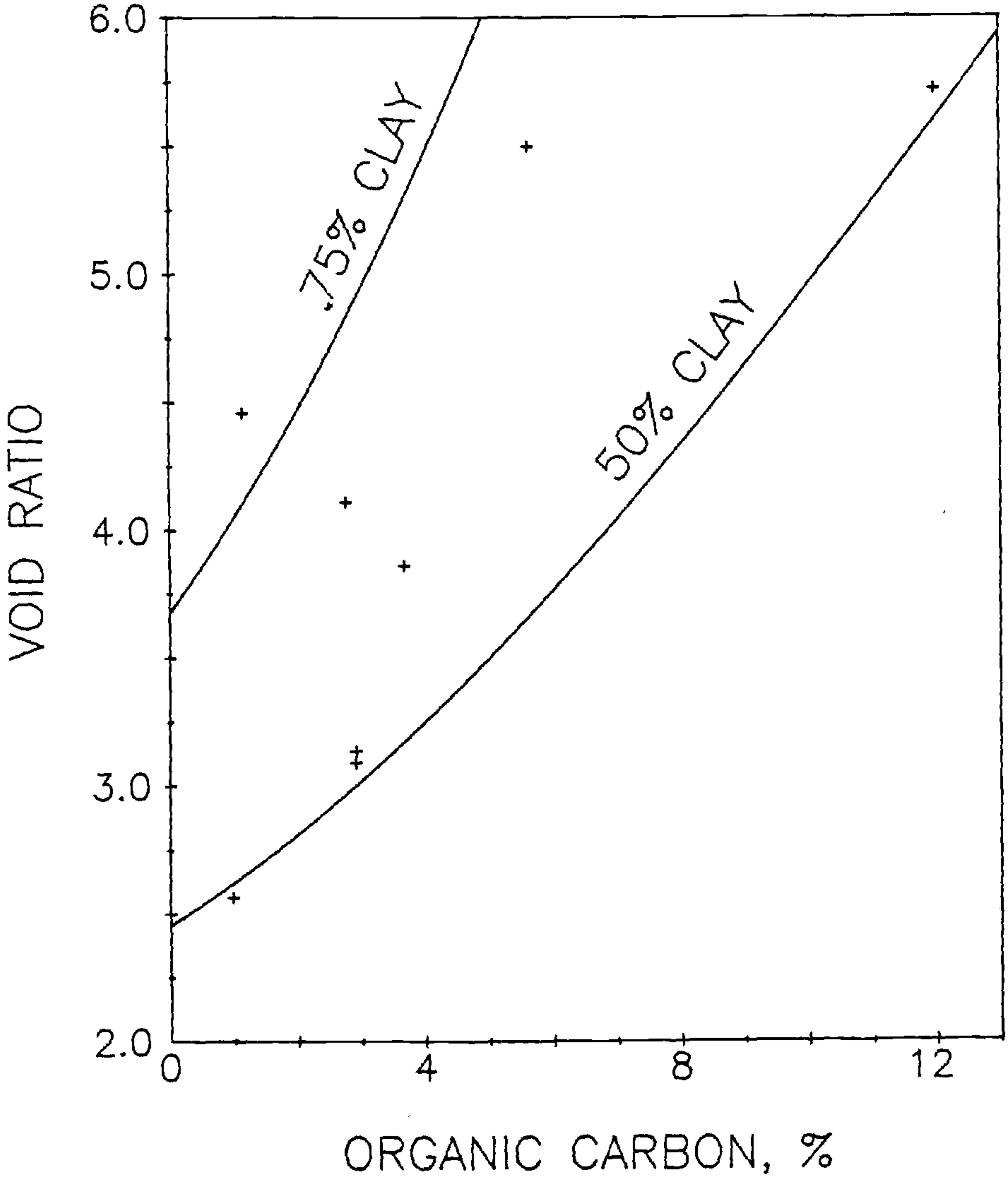


Figure 2. Initial void ratio and organic carbon concentration of the consolidation samples. The amount of clay-size material in the samples (based on total sediment dry weight) is indicated. Clay percentages are obtained from organic free determinations by assuming that organic carbon makes up 58% of the organic matter (Pusch, 1973).

at Texas A&M University. Loads were applied at 24 hour intervals to cylindrical samples 6.4 cm in diameter and 2.5 cm in height. At pressures below 100 kPa in tests using the Karol-Warner device a load increment ratio, $\Delta p/p$, of 0.5 was used to better estimate the preconsolidation pressure. At higher pressures in these tests and in the tests run on the Anteus consolidometer $\Delta p/p = 1$. Sediments were loaded to 3200 kPa and then allowed to rebound. Detailed descriptions of the one-dimensional consolidation test procedure are provided by Terzaghi and Peck (1967) and Bowles (1978).

Results of the eight consolidation tests are shown in Figure 3 through 6 in which the void ratio, e, is plotted as a function of the logarithm of the total applied pressure, p. Two pressures are labeled on the e-log p curves. P_o, the effective overburden pressure, is the weight of the overlying sediment at the sample depth. P_c, the preconsolidation pressure, is the supposed maximum pressure the sediment was subjected to in the past as determined using the method of Casagrande (1936). Table 3 summarizes the parameters obtained from the consolidation tests.

Compressibility

Sediment compressibility as determined from the consolidation tests is quantified by the compression index, C_c, the slope of the straight line portion of the e-log p curve at pressures greater than p_c. The consolidation curves (Figs. 3 through 6) show that the upper slope mud lens sediment of core 41K is much more compressible than the other Peru-Chile sediments. In 41K C_c equals 2.02 at 0.5 m and 2.15 at 1.4 m depth (Table 3). Sediments with the lowest compressibility along the margin

TABLE 3. Consolidation Test Parameters

Core	Compression index, C_c	Coeff. of permeability, k ($\times 10^{-8}$ cm^2/sec) 100 to 3200 kPa	Coeff. of secondary compression, $\varepsilon\alpha$ ($\times 10^{-2}$) 200 kPa	Pre-consolidation pressure, p_c (kPa)	Effective overburden pressure, p_o (kPa)	Over-consolidation ratio, p_c/p_o
24K	0.95	14.6 - 1.17	1.35	71.0	7.23	9.8
37K	1.38	16.2 - 2.38	1.72	72.5	5.04	14.4
$41K_{.5m}$	2.02	23.6 - 0.18	2.87	16.3	0.98	16.7
$41K_{1.4m}$	2.15	26.8 - 1.16	2.59	23.8	3.44	6.9
62K	1.20	259.7 - 0.64	2.15	21.6	7.47	2.9
64K	1.39	23.8 - 0.93	1.79	15.7	10.92	1.4
72K	1.47	17.9 - 0.14	2.05	19.6	9.09	2.2
73K	1.56	0.63 - 0.05	2.32	15.7	8.34	1.9

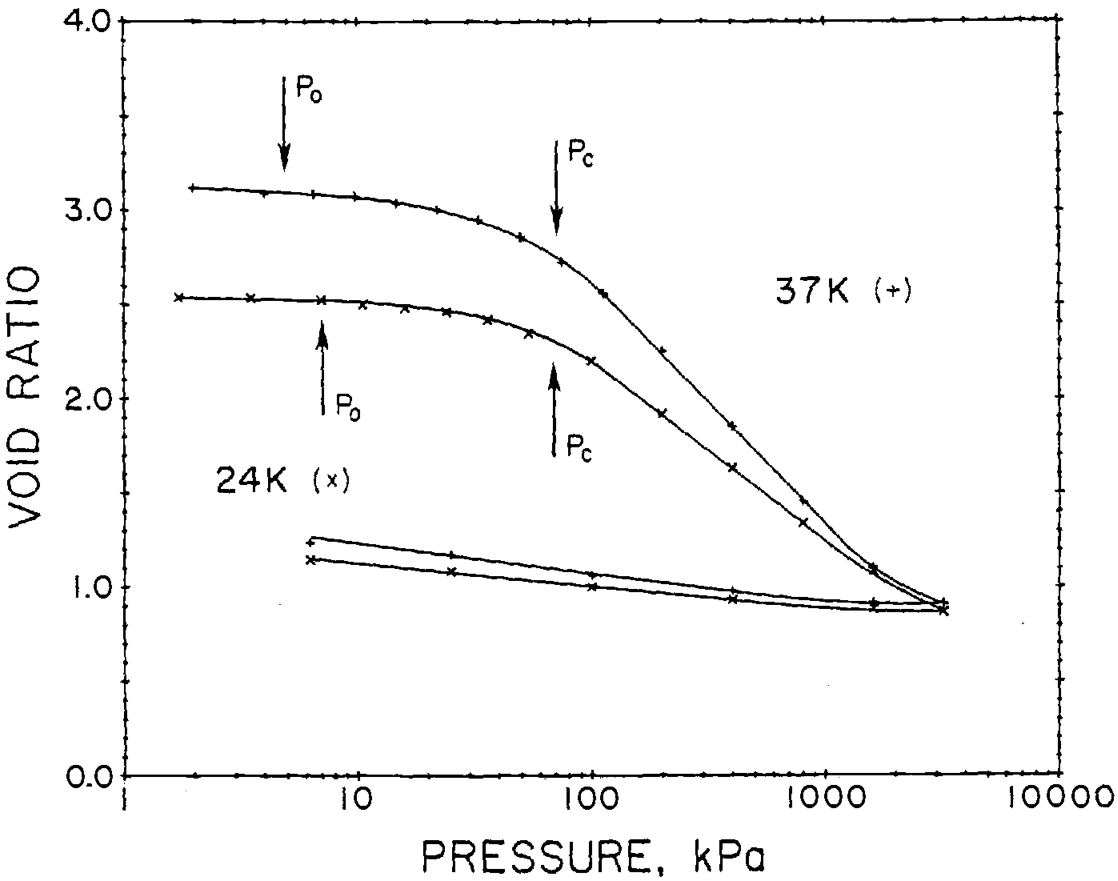


Figure 3. One-dimensional consolidation curves for samples from cores 24K and 37K. The effective overburden pressure, p_0, and preconsolidation pressure, p_c, are labeled. See Figure 1 for the location of the samples.

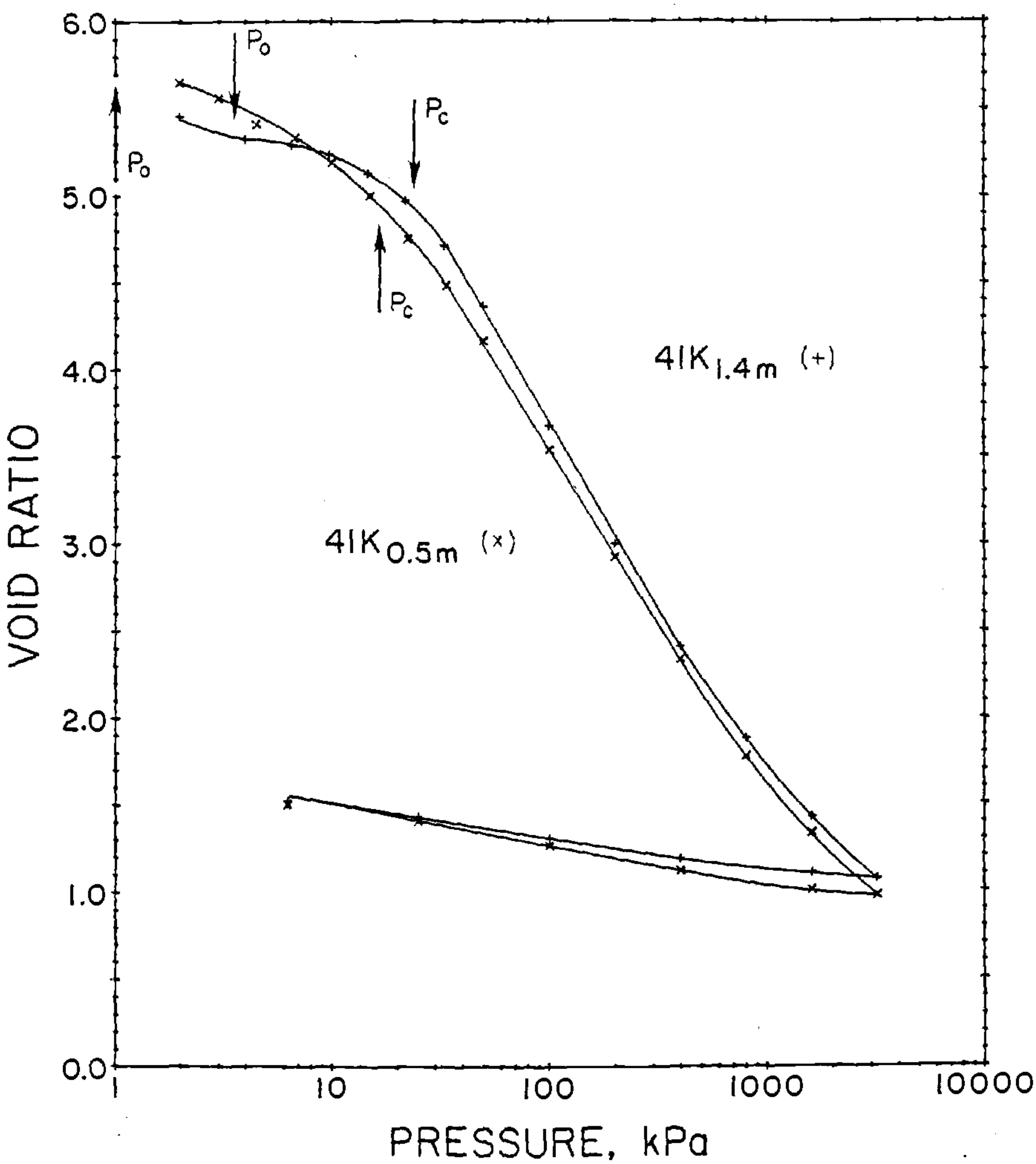


Figure 4. One-dimensional consolidation curves for two samples from 41K. Sample depths are 0.5 and 1.4 m.

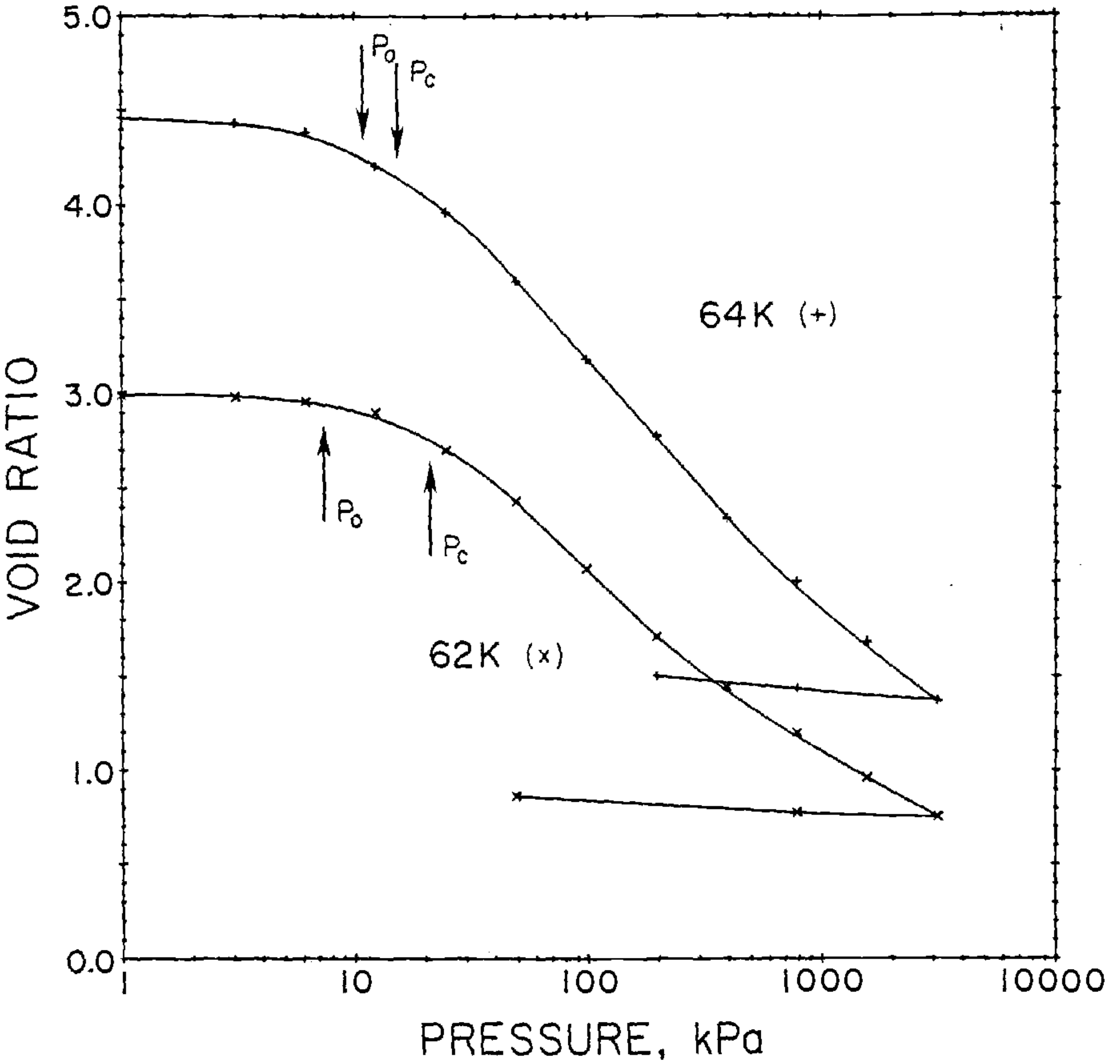


Figure 5. One-dimensional consolidation curves for samples from 62K and 64K.

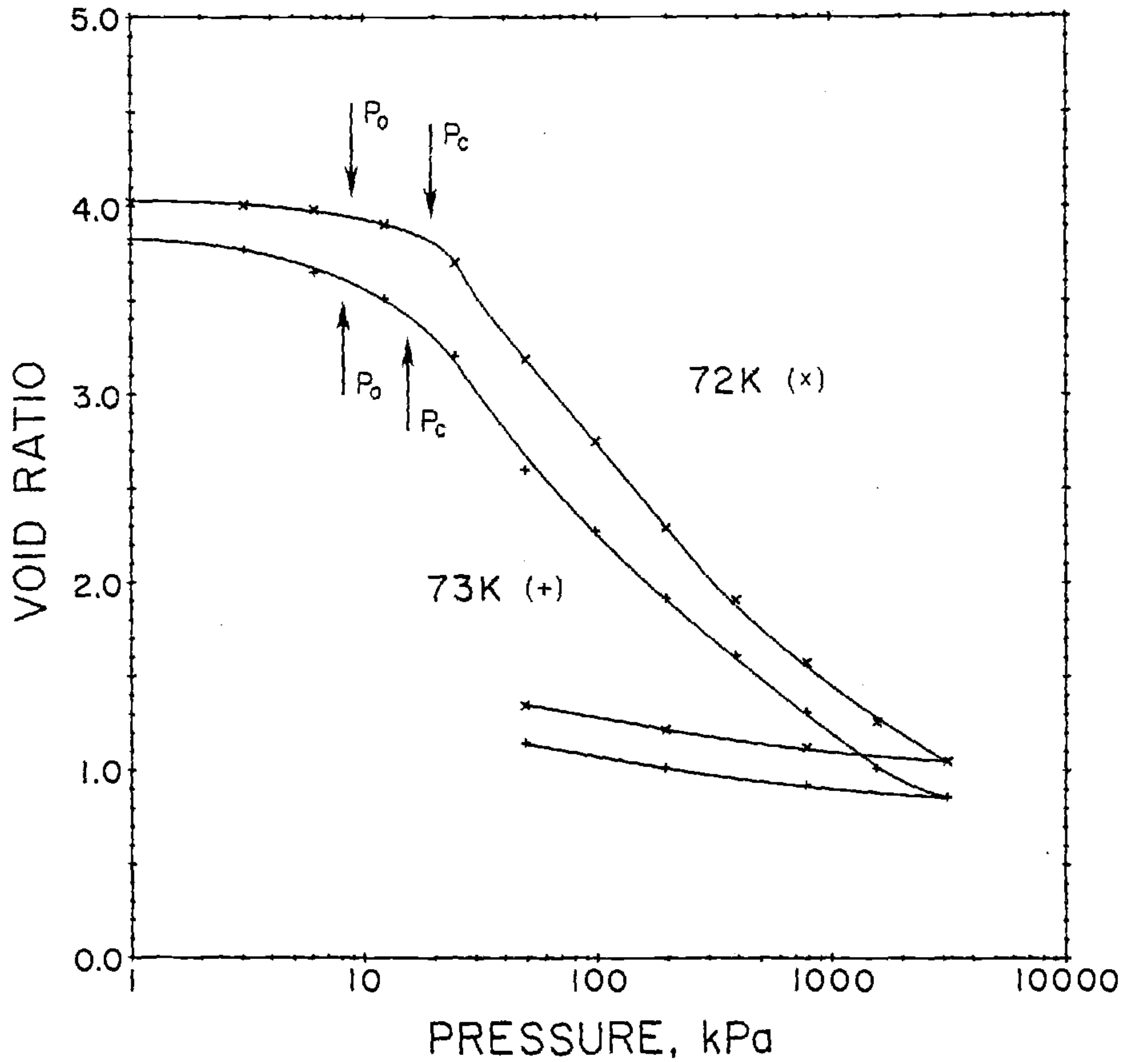


Figure 6. One-dimensional consolidation curves for samples from 72K and 73K.

occur off northern Chile where C_c equals 0.95 in core 24K.

The extremely high compressibility of sediments from the area of intense upwelling results from the abundant organic matter in these deposits. Comparing values of C_c and organic carbon concentration shows that the compressibility of the Peru-Chile sediments increases with increasing organic content (Fig. 7). A sharp increase in C_c occurs in the 0 to 5% organic carbon range. At higher organic carbon concentrations there is not a corresponding increase in compressibility.

The amount of clay-size material in the sediment and the mineralogy of this fraction also influence the compressibility. Figure 8 shows the compression index plotted as a function of the product of the sum of the smectite and illite percentages and the amount of clay in the sediment (expressed as a fraction). In the sediments from outside the area of intense upwelling C_c increases with increasing abundance of smectite and illite. For these sediments the compressibility is highest in core 73K in which smectite and illite make up 95% of the clay-size fraction (Table 1). In the upper slope mud lens sediments the effect of the abundant organic matter overshadows the influence of clay mineralogy and abundance. As a consequence the high values of C_c for the mud lens sediments plot in a separate region in Figure 8.

Rate of Consolidation

The volume reduction that occurs during a given load increment in a consolidation test is generally divided into two stages. Primary consolidation is the decrease in volume accompanying the dissipation of pore pressure in excess of hydrostatic pressure following the application of a load. Secondary compression is the volume reduction that occurs

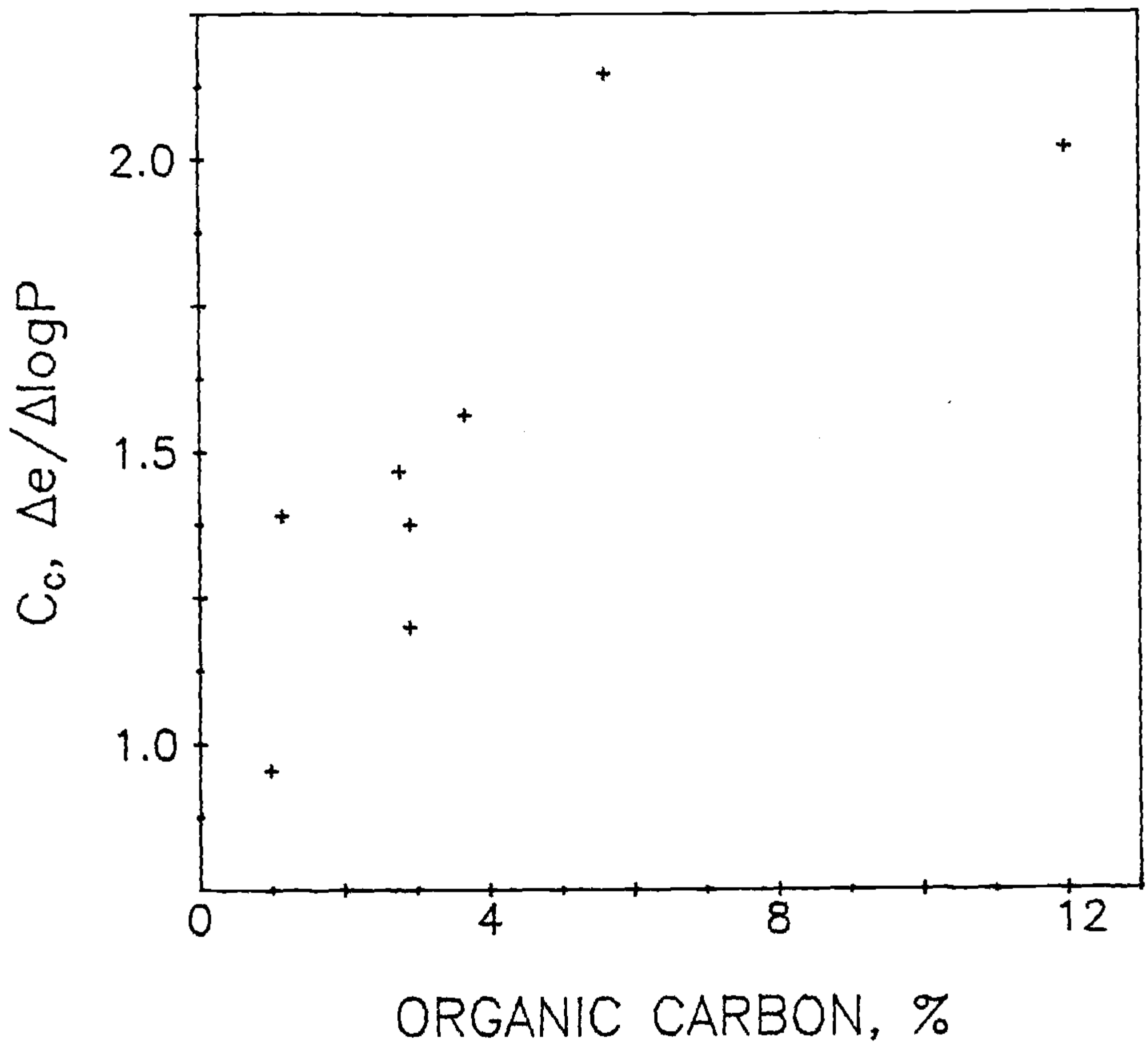


Figure 7. Relationship between the sediment compressibility, expressed as the compression index C_c, and the organic carbon concentration.

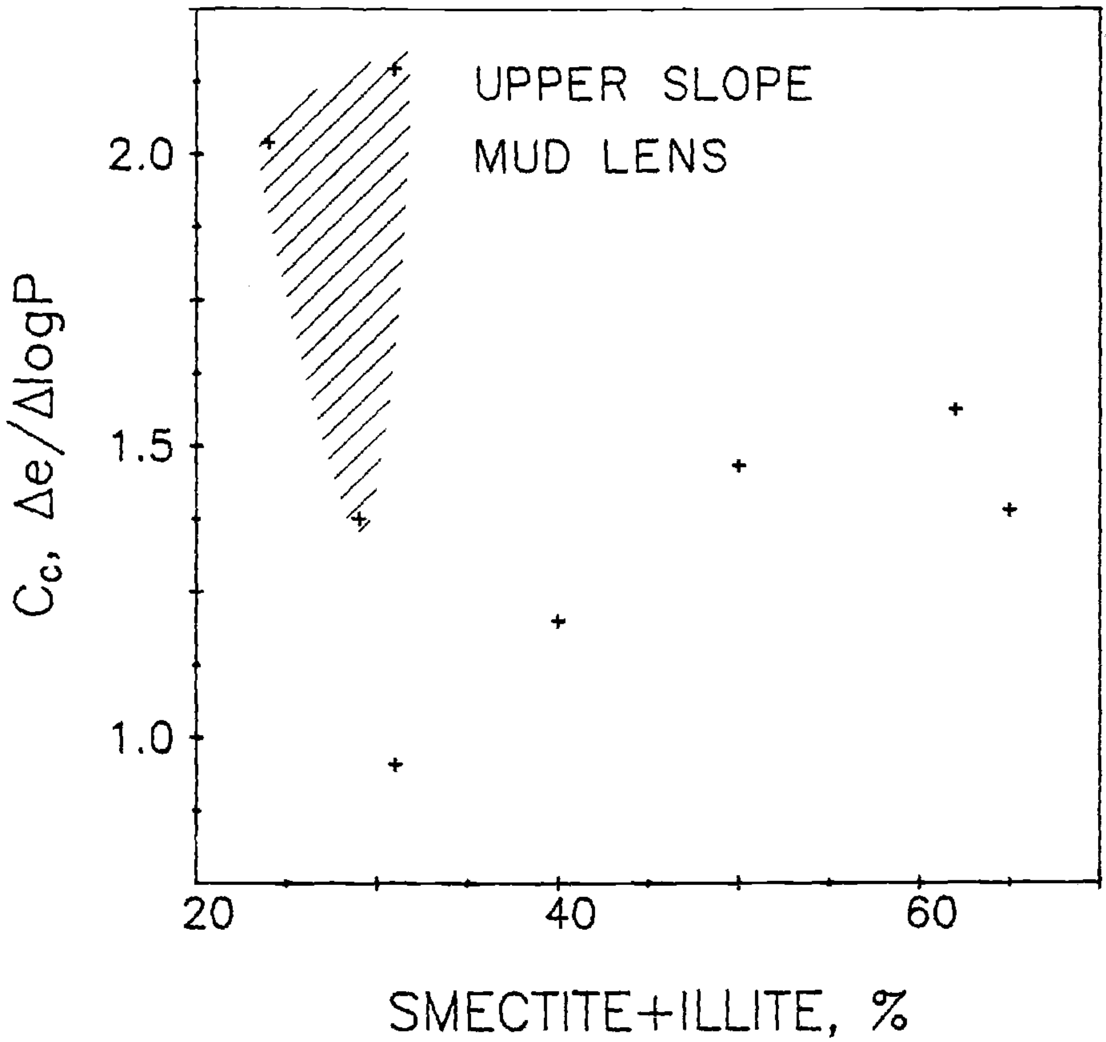


Figure 8. Relationship between the sediment compressibility and the abundance of clay and amount of smectite and illite in the clay-size fraction. The abscissa is the relative abundance of smectite and illite multiplied by the clay content (expressed as a fraction of the total sediment dry weight). High values of C_c for samples from the upper slope mud lens result from abundant organic matter.

under constant effective stress after the excess pore pressure has dissipated. Delineation of the primary and secondary stages in three example consolidation rate curves of Peru-Chile sediments with different organic contents is shown in Figure 9.

The rate of consolidation during the primary stage in reflected by the permeability, k. Procedures for determining k from one-dimensional consolidation tests are described by Terzaghi and Peck (1967). An inverse relationship is commonly assumed to exist between the sediment organic content and permeability (Pusch, 1973; Mitchell, 1976). This relationship is not apparent in the Peru-Chile sediments in that organic-rich sediments of the upper slope mud lens do not display the lowest permeability (Table 3). Instead, the clay-rich lower slope deposits at 3.5°S (cores 72K and 73K) have the lowest permeability along the margin. The highest values of k occur in the lower slope sediments from 8°S (core 62K).

Two coefficients are used to quantify the rate of secondary compression:

$$c_\alpha = \Delta e / \Delta \log t$$

$$\varepsilon_\alpha = (\Delta e / 1+e_0) / \Delta \log t = \Delta \varepsilon / \Delta \log t$$

where e = void ratio; e_0 = void ratio at the beginning of the load increment; and t = time (Mesri, 1973). c_α is the slope of the e - log t curve at the time after the excess pore pressure has dissipated. ε_α is this slope expressed in terms of strain and is used to account for differences in void ratio when comparing rates of secondary compression.

Organic content is the most important factor influencing the rate of secondary compression in the Peru-Chile sediments. Consolidation

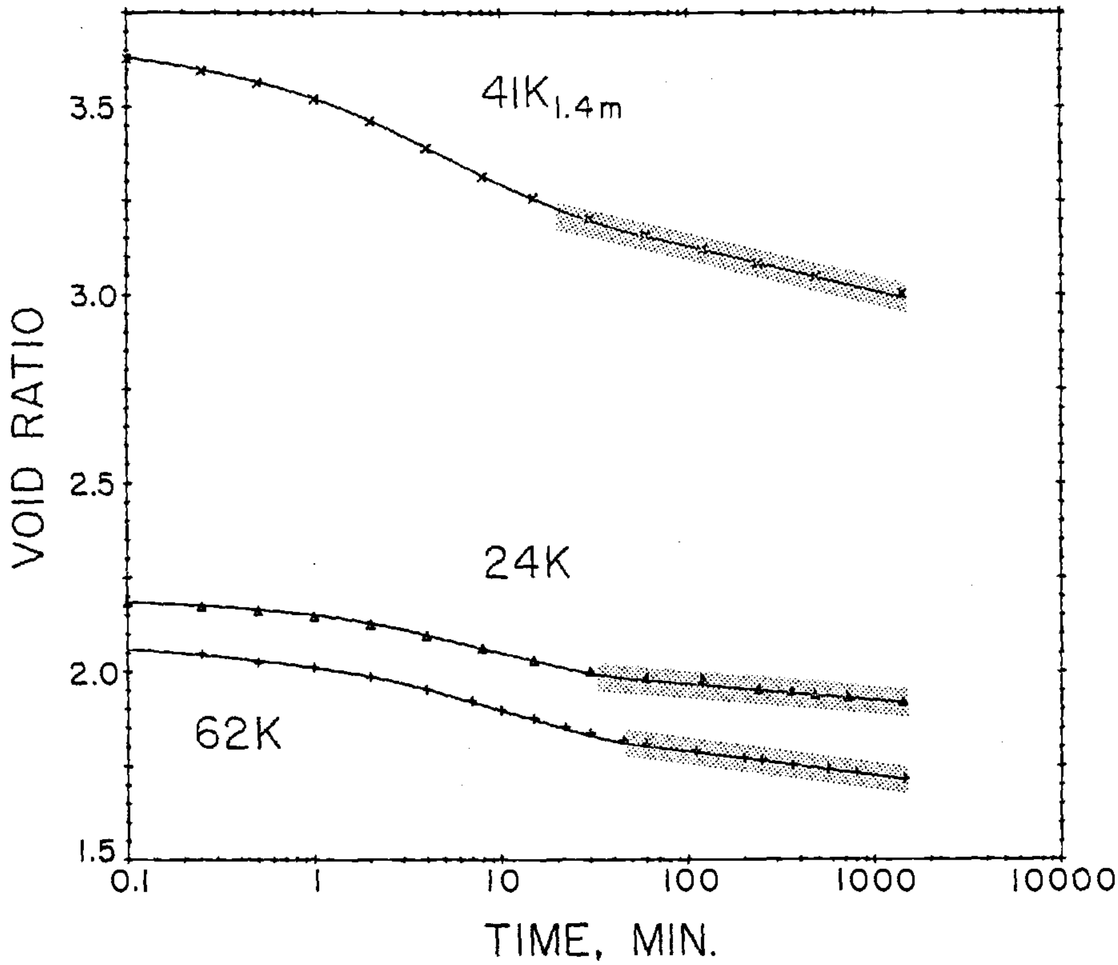


Figure 9. Consolidation rate curves for samples from 24K, 41K (1.4 m depth) and 62K. The applied load for each of the curves is 200 kPa. Shaded areas represent that part of the consolidation that is secondary compression. The boundary between the primary and secondary stages of consolidation was determined by the procedure of Casagrande and Fadum (1940).

rate curves (Fig. 9) show that the organic-rich upper slope mud lens sediments (core 41K) have the highest rate of secondary compression while the northern Chile slope deposits (core 24K) display the lowest rate. Comparing rates of secondary compression for these and other cores along the margin shows that ε_α increases with increasing organic content (Fig. 10). Rates of secondary compression have been shown to be higher in smectite and illite-dominated clays than in other clays (Mesri, 1973); however, the Peru-Chile sediments do not display this relationship.

<u>Stress History</u>

The consolidation curves (Figs. 3 through 6) show that for all of the samples tested the preconsolidation pressure is greater than the effective overburden pressure. This condition, overconsolidation, is quantified by the ratio p_c/p_o. Values of the overconsolidation ratio, p_c/p_o, range from 16.7 in core $41K_{0.5m}$ (upper slope mud lens) to 1.4 in core 64K (Nazca Plate, Table 3). Evidence that erosion is the cause of overconsolidation is present only in sediments from the upper slope at 13.6°S (core 37K). At the other locations along the margin there is no indication that the disparity between p_c and p_o results from unloading.

The magnitude of the apparent overconsolidation of the Peru-Chile sediments varies with the abundance of organic matter with the highest overconsolidation ratio occurring in organic-rich sediments of the upper slope mud lens. A general increase in p_c/p_o with increasing organic carbon concentration (Fig. 11) suggests that the bonding of sediment particles by organic substances may be a source of the apparent overconsolidation. Highly overconsolidated sediments from cores 24K and 37K do

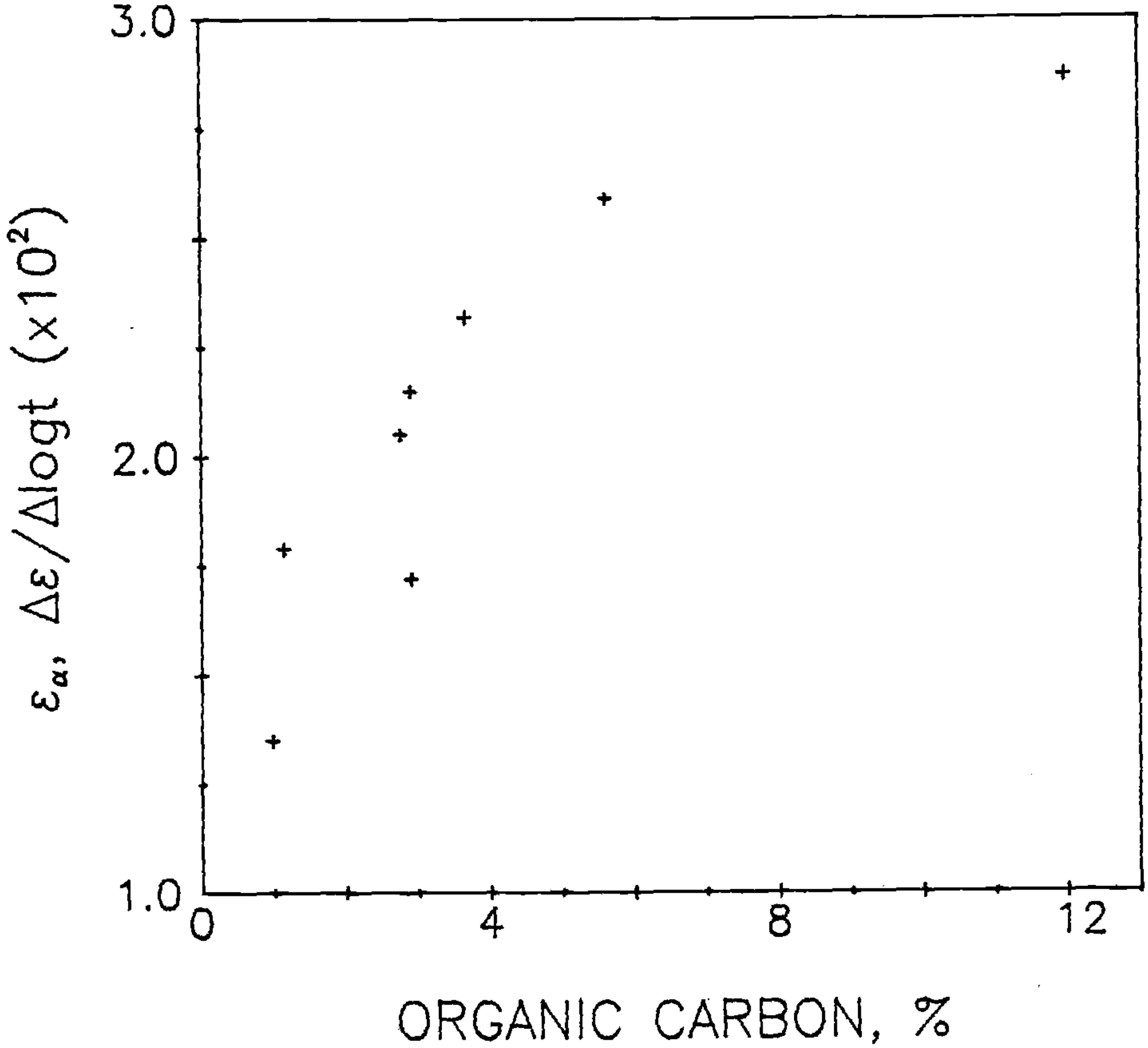


Figure 10. Relationship between the rate of secondary compression (for an applied load of 200 kPa) and the organic carbon concentration. The rate of secondary compression under the other load increments follows a similar pattern.

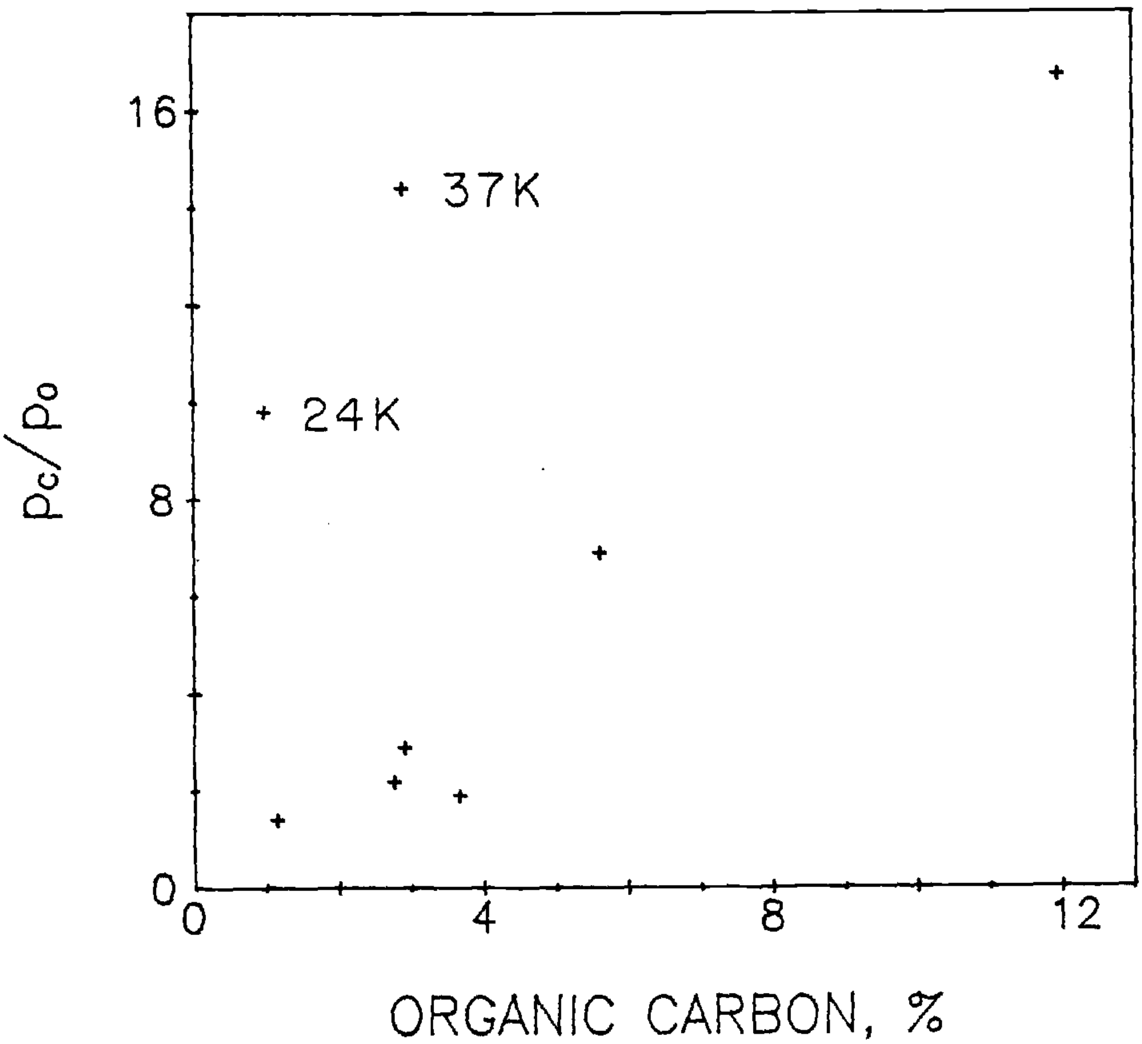


Figure 11. Relationship between the overconsolidation ratio, p_c/p_o, and the organic carbon concentration.

not follow this relationship. True overconsolidation of the sediment of 37K causes it to deviate from the trend and extremely slow sedimentation and coarse texture on the northern Chile slope is apparently responsible for the high value of p_c/p_o in 24K. The effect of the organic-related interparticle bonding appears to be greatest at shallow depth in the absence of significant overburden. With increasing depth of burial the degree of overconsolidation decreases (Fig. 12).

In contrast to the apparent overconsolidation displayed by most of the Peru-Chile sediments true overconsolidated behavior is exhibited by sediments from the upper slope mud lens at 13.6°S (core 37K). Six distinct erosional contacts are present in core 37K (Fig. 13). The erosional surface at 0.28 meters is associated with the greatest interval of missing sediment. Using the present sedimentation rate of 66 cm/1000 years, determined by ^{210}Pb dating (DeMaster, 1979), and ^{14}C ages (Fig. 13), it is found that the erosional surface at 0.28 m represents a hiatus of approximately 11,000 years. The present sedimentation rate and a rate of 33 cm/1000 years below the 0.28 m level, determined from the ^{14}C ages, suggest that during the 11,000 years 3.5 to 7 m of sediment may have been deposited.

The amount of sediment eroded at this site can also be estimated from the preconsolidation pressure if it is assumed that the weight of the eroded sediment applied a pressure equal to p_c. In order to determine the thickness of the pre-existing sediment load from the preconsolidation pressure that proportion of p_c related to apparent overconsolidation must be accounted for. Cores 37K and 41K were obtained from similar locations on the upper slope mud lens. If it is assumed that the fraction of p_c in 37K owing to apparent overconsolidation is equal

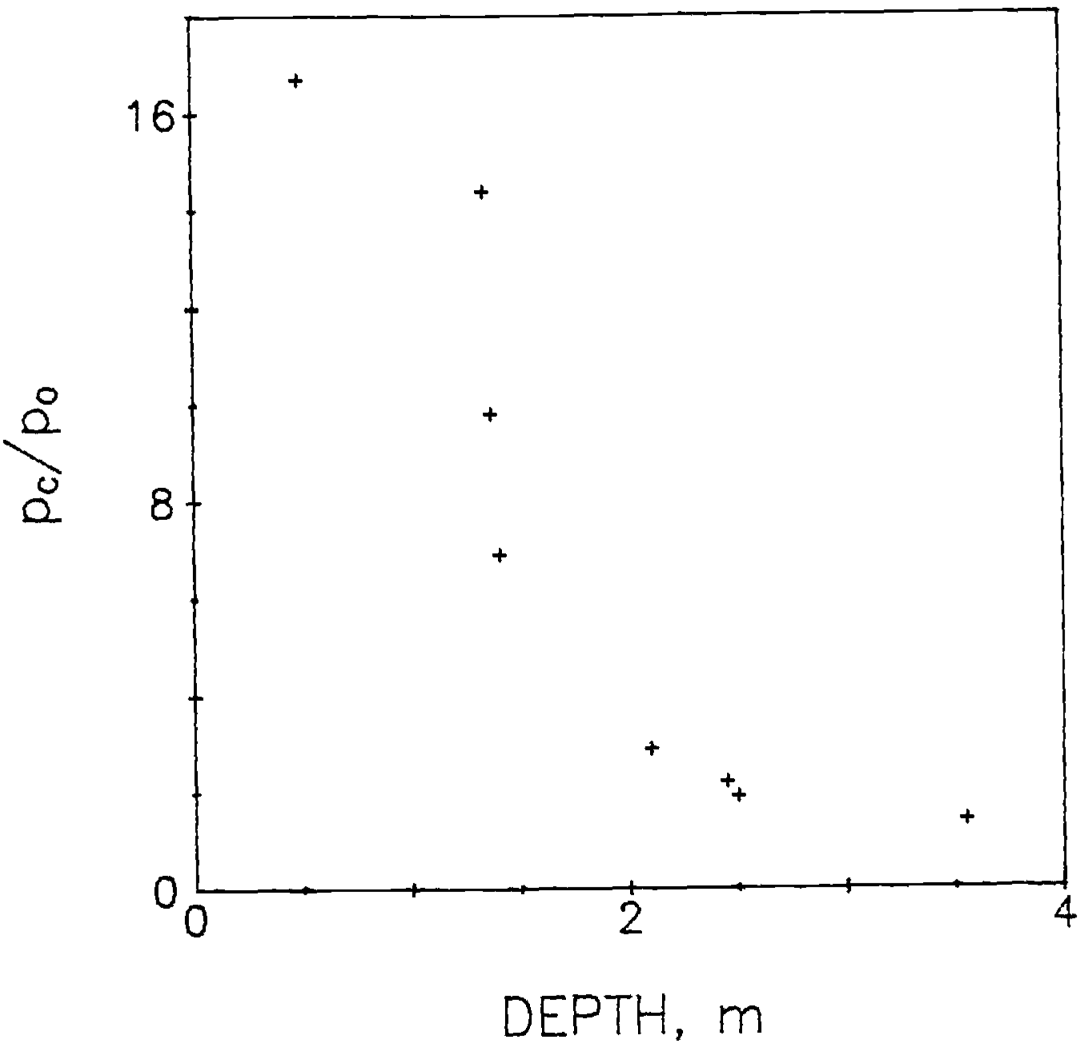


Figure 12. Overconsolidation ratio - burial depth relationship.

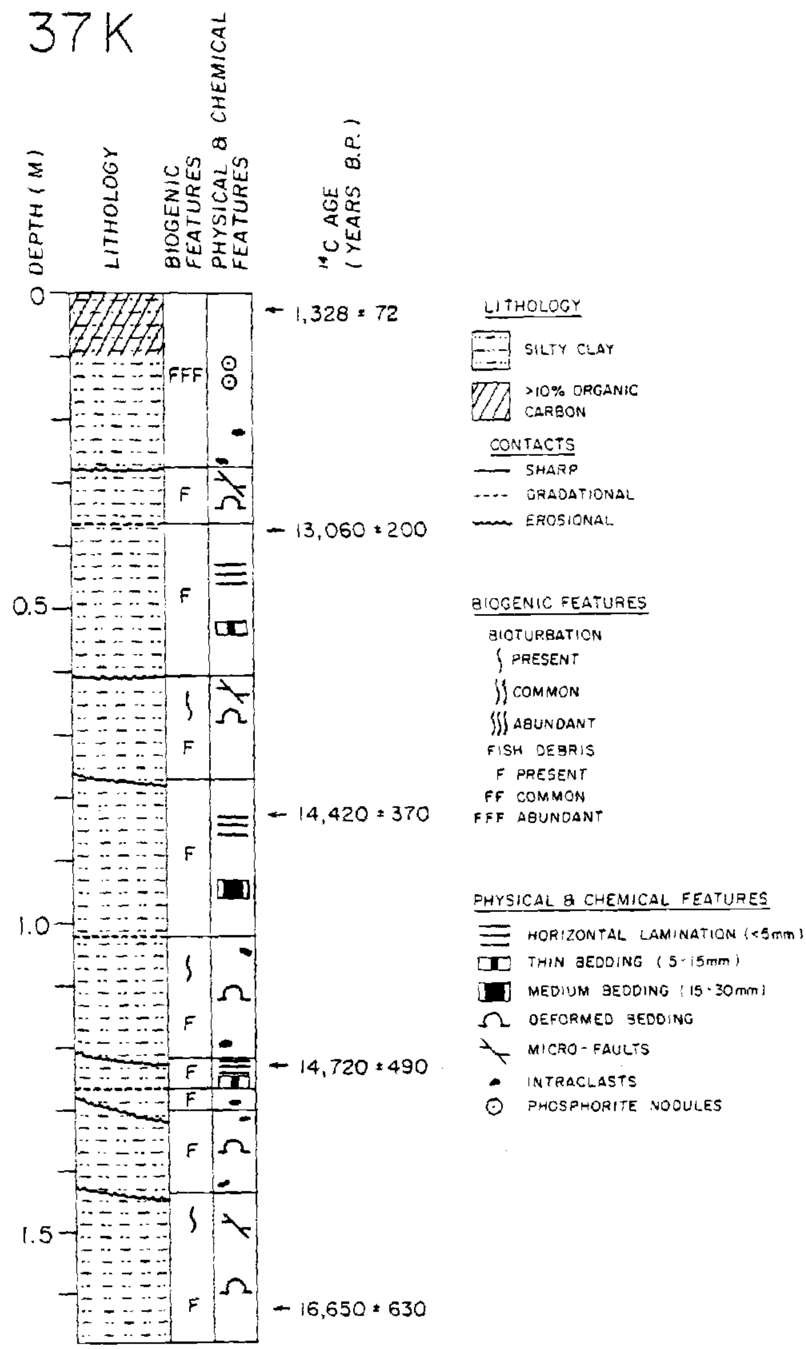
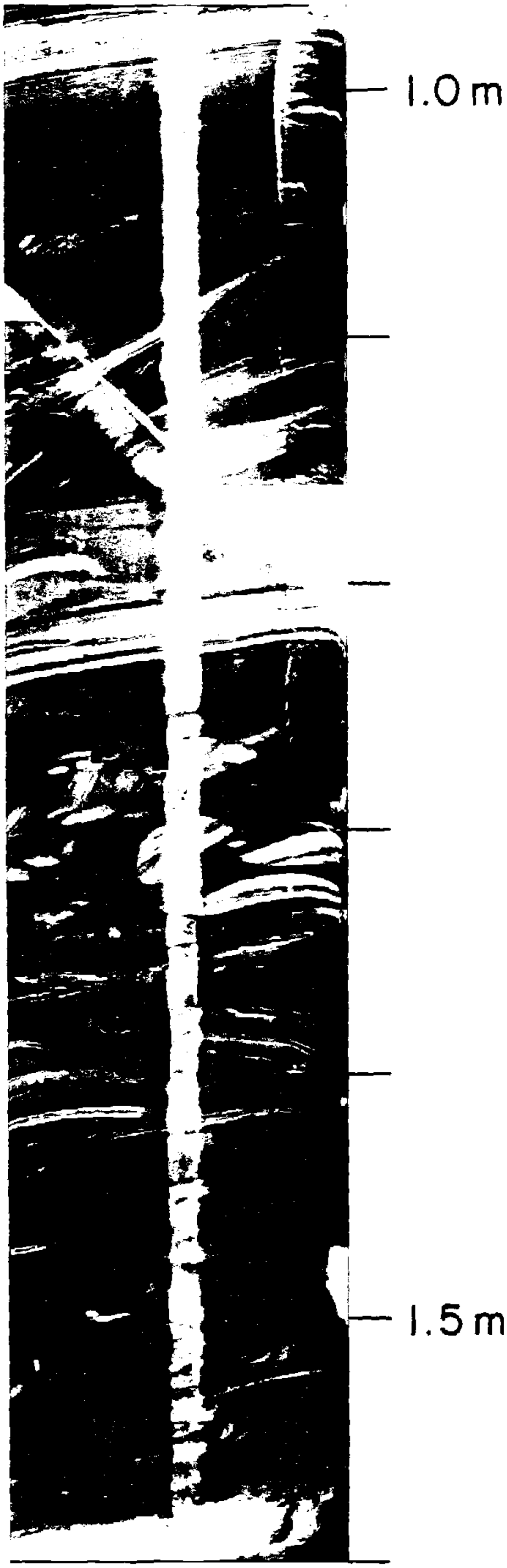


Figure 13. Sequence of sedimentary structures in core 37K, determined from X-radiographs. The sequence is marked by numerous erosional surfaces and intervals of deformed bedding. See Figure 14 for the X-radiograph of the interval between 1.00 to 1.60 m.

Figure 14. X-radiograph of the 1.00 to 1.60 m interval in 37K showing laminated mud intraclasts (1.3 m), contorted laminations (1.4 m), and microfaults (1.5 m). (The light band in the center of the radiograph is a product of coring disturbance).



1.0 m
1.5 m

to the value of p_c in $41K_{1.4m}$ (which contains no evidence of significant erosion) and that the wet bulk density of the missing sediment in 37K was 1.40 Mg/m^3 the calculated thickness of missing sediment is approximately 3.5 m.

In addition to the erosional surfaces, other sedimentary structures in core 37K clearly indicate past periods of sediment instability. Intervals of deformed bedding containing microfaults, laminated mud intraclasts, and contorted laminations are common in 37K (Figs. 13 and 14). Features similar to these have been observed in sediments from the California Borderland (Hein and Thornton, 1979) and Mississippi Delta (Roberts and others, 1976) and have been inferred to be deposits of mass flows.

DISCUSSION

Coastal upwelling appears to be indirectly responsible for much of the variation of sediment physical properties along the Peru-Chile continental margin as a result of concentrating organic matter in the sediments (Busch and Keller, in review). Results of one-dimensional consolidation tests show that the consolidation behavior of the sediments is similarly affected by the abundance of organic matter. Variation in the compressibility, rate of secondary compression, and apparent overconsolidation correlate well with differences in sediment organic content. The amount and composition of the clay-size material also influence the consolidation behavior and are in part responsible for the variation of the sediment compressibility. Other factors influencing the stress history of the sediments include low sedimentation rates which may contribute to the apparent overconsolidation and sediment erosion which is responsible for the true overconsolidation of upper slope mud lens sediments at 13.6°S.

Results of consolidation tests have recently been used to interpret the porosity reduction and density increase that accompanies the burial of deep-sea sediments (Hamilton, 1976). The laboratory-determined compressibility, as a measure of volume reduction occurring under increasing pressure, can be used to estimate changes in sediment porosity, density, and thickness that occur as the overburden pressure increases. An increase in compressibility reflects an increase in the volumetric changes the sediment will experience with burial.

Sediment compressibility along the Peru-Chile margin increases with increasing organic content (Fig. 7). Previous studies have shown that organic matter influences sediment compressibility through the establishment of an open sediment fabric and the ease of deformation of the organic substances (Pusch, 1973, Rashid and Brown, 1975). In a sediment fabric study utilizing electron microscopy Pusch (1973) concluded that the main effect of organic substances in sediments is the aggregation of clay particles to form an open microstructural network. The increase in void ratio with increasing organic carbon concentration (Fig. 2) is evidence of this effect on the fabric of the Peru-Chile sediments. Consolidation curves of the highly organic, high void ratio sediments of the upper slope mud lens (Fig. 4) show that at pressures in excess of the preconsolidation pressure the breakdown of the sediment microstructure results in large volume reductions. Contributing to the compressibility of organic-rich sediments is the high deformability of the clay-organic aggregates and other forms of organic matter which are able to undergo large displacements without rupture (Pusch, 1973). Rashid and

Brown (1975) concluded that the ability of organic matter to increase the moisture holding capacity of sediments by increasing the thickness of adsorbed water layers increases the compressibility as a result of a greater mobility of the sediment particles.

Variation of the amount of clay-size material and clay mineralogy along the Peru-Chile margin has a secondary effect on the sediment compressibility. Compressibility of the Peru-Chile sediments increases as a function of the abundance of clay and the amount of smectite and illite in the clay-size fraction (Fig. 8). Part of the greater compressibility results from the increase in void ratio with increasing amounts of clay-size material. The influence of clay content on the void ratio is particularly evident at low concentrations of organic carbon (<3%, Fig. 2). Variation of consolidation behavior as a function of clay mineralogy has been studied in a number of investigations and the sequence of increasing compressibility of kaolinite < illite < smectite is well established (Olson and Mesri, 1970; Einsele and others, 1974; Mitchell, 1976). In this sequence the reduction in particle size is accompanied by an increase in particle surface area and thickness of adsorbed water layers. With increasing thickness of adsorbed water the compressibility increases as mechanical interactions between particles become less important and interaction through adsorbed water exerts a greater control on the sediment behavior (Olson and Mesri, 1970). Silva and Hollister (1979) observed that an increased abundance of smectite and illite was associated with an increase in the compressibility of sediments from the Blake-Bahama Outer Ridge; however, they concluded that the stress history and calcium carbonate content of the sediments were more influential in controlling the compressibility. Along the

Peru-Chile continental margin the relationship between the amount of smectite and illite and the compressibility is best displayed by sediments outside of the upper slope mud lens (Fig. 8).

In addition to influencing the amount of volume reduction, the organic content of the sediments affects the process by which it occurs. In the Peru-Chile sediments the rate of secondary compression is directly related to the organic content (Fig. 10). For submarine sediments the rate of secondary compression is of interest because in deep-sea environments natural loads are commonly applied at rates slow enough that deformation essentially occurs under constant effective stress. The mechanism by which secondary compression occurs is similar to that of shear displacements by creep (Tavenas and others, 1978) suggesting that high rates of secondary compression may be indicative of a greater susceptibility to creep deformation.

Several explanations have been proposed for the high rate of secondary compression in organic clays. Expulsion of water from micropores of organic complexes after the drainage of the void space between aggregates was cited by Barden (1968) as a cause of the pronounced secondary compression in highly organic sediments. Pusch (1973) identified three factors responsible for the domination of secondary compression in organic-rich sediments: (1) very low permeability caused by the blocking of pores by humic complexes; (2) creep of humic complexes producing large visco-elastic and plastic deformations during and after the dissipation of excess pore pressure; and (3) structural viscosity (visco-elasticity of the clay-organic networks) producing creep soon after load application. Variation of the permeability of the Peru-Chile sediments is apparently independent of the organic content suggesting that the deformation of the organic matter and clay-organic aggregates is primarily repsonsible for the pattern of increasing rate of secondary compression with increasing organic carbon concentration.

The ability to sustain a pressure greater than the effective overburden pressure before undergoing significant consolidation is a common characteristic of deep-sea sediments (Richards and Hamilton, 1967). In the absence of evidence of sediment erosion this apparent overconsolidation has been attributed to some form of interparticle bonding or cementation. Precipitates of substances dissolved from calcareous biogenic remains and volcanic debris are often cited as agents that bind sediment particles together (Bryant and others, 1967; Richard and Hamilton, 1967; Bryant and others, 1974). In the Peru-Chile sediments organic substances appear to be responsible for the interparticle bonding and apparent overconsolidation. With the exception of sediments from the northern Chile slope (core 24K) and mud lens at 13.6°S (core 37K) there is a consistent increase in the overconsolidation ratio with increasing organic content (Fig. 11). The effect of organic matter strengthening the sediment is also indicated by the variation of undrained shear strength along the Peru-Chile margin. Organic-rich sediments from the area of intense upwelling are much stronger than would normally be anticipated for material with such high water content (Busch and Keller, in review). Greenland (1965) and Pusch (1973) have described the bonding of clay particles by organic substances and the influence of aggregate formation on sediment physical properties, although systematic testing of the role of the clay-organic complexes in causing apparent overconsolidation has not been carried out. Sediment strengthening by organic matter has been observed by Rashid and Brown (1975), who showed that the addition of organic matter to sediments increases the remolded shear strength. The high value of p_c/p_o for the sediment of 0.5 m depth in core 41K and the decrease in p_c/p_o with depth of burial (Fig. 12) suggest that the organic-related apparent overconsolidation is a near-surface phenomena and at greater depths the Peru-Chile sediments approach the condition of normal consolidation ($p_c = p_o$).

Slow sedimentation which leads to an apparent "aging" of the sediment under essentially constant stress levels has also been cited as a source of apparent overconsolidation in deep-sea sediments (Richards and Hamilton, 1967). Experiments have shown that subjecting sediment to sustained loading at a constant pressure can increase the preconsolidation pressure causing the appearance of overconsolidated behavior (Leonards and Ramiah, 1960). Bjerrum (1967, 1972) concluded that the ratio p_c/p_o depends on the amount of secondary compression that occurs in the sediment. During time-dependent volume reduction a more stable arrangement of sediment particles is established and the sediment develops an added resistance to further consolidation. Compositional and textural variability along the Peru-Chile margin make it difficult to isolate the effects of sedimentation rate on the consolidation behavior of the sediments. Highly overconsolidated sediments of the northern Chile slope (core 24K, $p_c/p_o = 9.8$) are from the area that has the lowest rate of sedimentation on the continental slope, <5 cm/1000 years. On the Nazca Plate, where sedimentation rates are slightly lower, sediments of core 64K have an overconsolidation ratio of 1.4. While it is likely that time-dependent change in the sediment microstructure is a major contributor to the overconsolidation in core 24K the low value of p_c/p_o in core 64K suggests that other factors such as the coarser texture on the northern Chile slope may influence the consolidation behavior.

Sediments from the upper slope mud lens at 13.6°S (core 37K) differ from the other continental margin deposits in that the overconsolidated behavior is caused by sediment removal (3.5 to 7 m). Associated with the overconsolidation of these sediments are anomalously low water content and high wet bulk density and undrained shear strength (Busch and Keller, in review). Core 37K contains five intervals of deformed bedding having erosional basal contacts which suggests mass flow played an important role in the deposition and erosion at this site. It does not appear that the features in 37K were produced by the action of bottom currents. Although information concerning bottom currents on the Peru-Chile slope is lacking, the location of core 37K within a structural embayment and the persistence of the impingement of the shallow water oxygen-minimum layer on the upper slope in this area suggest that bottom currents are weak. Mass flows that may have occurred on the upper slope at 13.6°S were probably of a small scale since major slumps are not evident on 3.5 kHz profiles.

SUMMARY

Eight one-dimensional consolidation tests were performed on sediments from the Peru-Chile continental slope and eastern Nazca Plate. Analysis of the results of these tests along with the composition and physical properties of the sediments leads to a number of findings:

(1) The compressibility of the Peru-Chile sediments increases with increasing organic content. Sediments deposited in the area of intense coastal upwelling are highly compressible as a result of their containing abundant organic matter. Outside of this area there is a pattern of

increasing compressibility with increases in the clay-size fraction and the abundance of smectite and illite.

(2) Sediments from the Peru-Chile margin show pronounced secondary effects during consolidation. The rate of secondary compression increases with increasing organic content. Organic-rich sediments of the upper slope mud lens have the highest rates of secondary compression relative to the other margin deposits.

(3) All of the Peru-Chile sediments that were tested behave as if they were previously consolidated under a pressure greater than the present effective overburden pressure. Only sediments from the upper slope mud lens at 13.6°S (core 37K) contain evidence that the overconsolidation results from the erosion of a previous sediment overburden. Intervals of deformed bedding and erosional surfaces within core 37K attest to the past instability of sediments at this site. At the other sites the increase in the overconsolidation ratio with increasing organic content implies that the bonding of sediment particles by organic matter may be the cause of the apparent overconsolidation. The highest degree of overconsolidation is displayed by organic-rich near surface sediments from the upper slope mud lens. Low rates of sedimentation may contribute to the apparent overconsolidation, particularly off northern Chile, although evidence for the influence of sedimentation rate is not conclusive.

REFERENCES

Barazangi, M., and Isacks, B. L., 1976, Spatial distribution of earthquakes and subduction of the Nazca Plate beneath South America: Geology, v. 4, p. 686-692.

Barden, L., 1968, Primary and secondary consolidation of clay and peat: Geotechnique, v. 18, p. 1-24.

Bennett, R. H., Bryant, W. R., and Keller, G. H., 1977, Clay fabric and geotechnical properties of selected submarine sediment cores from the Mississippi Delta: NOAA Prof. Paper No. 9, U.S. Dept. of Commerce, Rockville, MD, 86 p.

Berner, R. A., 1978, Sulfate reduction and the rate of deposition of marine sediments: Earth Planet. Sci. Lett., v. 37, p. 492-498.

Biscaye, P. E., 1965, Mineralogy and sedimentation of Recent deep-sea clay in the Atlantic ocean and adjacent seas and oceans: Geol. Soc. America Bull., v. 76, p. 803-832.

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

Bjerrum, L., 1972, Embankments on soft ground: Proc. ASCE Speciality Conference on Performance of Earth and Earth-Supported Structures, v. 2, p. 1-54.

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

Bryant, W. R., Cernock, P., and Morelock, J., 1967, Shear strength and consolidation characteristics of marine sediments from the western Gulf of Mexico, in Richards, A. F., ed., Marine Geotechnique: Urbana, University of Illinois Press, p. 41-62.

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

Buchan, S., Dewes, F.C.D., McCann, D.M., and Smith, D.T., 1967, Measurements of the acoustic and geotechnical properties of marine sediment cores, in Richards, A.F., ed., Marine Geotechnique: Urbana, University of Illinois Press, p. 65-92.

Busch, W. H., and Keller, G. H., in review, The physical properties of Peru-Chile continental margin sediments - The influence of coastal upwelling on sediment properties.

Casagrande, A., 1936, The determination of the pre-consolidation load and its practical significance: Proc. 1st Conf. on Soil Mech., v. 3, p. 60-64.

Casagrande, A., and Fadum, R. E., 1940, Notes on soil testing for engineering purposes: Soil Mechanics Ser. No. 8, Harvard Graduate School of Engineering.

Coulbourn, W. T., and Moberly, R., 1976, Structural evolution of fore-arc basins off southern Peru and northern Chile: Can. Jour. Earth Sci., v. 14, p. 102-116.

DeMaster, D. J., 1979, The marine budgets of Si and Si-32: unpubl. Ph.D. dissertation, Yale University, 308 p.

Einsele, G., Overbeck, R., Schwarz, H.U., and Unsöld, G., 1974, Mass physical properties, sliding, and erodibility of experimentally deposited and differently consolidated clayey muds: Sedimentology, v. 21, p. 339-372.

Greenland, D. J., 1965, Interaction between 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.

Hamilton, E. L., 1964, Consolidation characteristics and related properties of sediments from Experimental Mohole (Guadalupe Site): Jour. Geophys. Res., v. 69, p. 4257-4269.

Hamilton, E. L., 1976, Variations of density and porosity with depth in deep-sea sediments: Jour. Sed. Petrology, v. 46, p. 280-300.

Hein, F. J., and Thornton, S. E., 1979, Fine-grained mass-flow deposits in slope and slope apron settings: Examples from the California Borderland: Geol. Soc. America Abstracts with Programs, v. 11, p. 441-442.

Karlin, R., 1980, Sediment sources and clay mineral distributions off the Oregon coast: Jour. Sed. Petrology, v. 50, p. 543-560.

Krissek, L. A., Scheidegger, K. F., and Kulm, L.D., 1980, Surface sediments of the Peru-Chile continental margin and the Nazca Plate: Geol. Soc. America Bull., v. 91, p. 321-331.

Kulm, L. D., Schweller, W. J., and Masias, A., 1977, A preliminary analysis of the subduction process along the Andean continental margin, 6° to 45°S, in Talwani, M., and Pitman, W. C., III, eds., Island Arcs, Deep Sea Trenches and Back-Arc Basins, Maurice Ewing Series, Vol. 1: Am. Geoph. Union, p. 285-301.

Leonards, G. A., and Ramiah, B. K., 1960, Time effects in the consolidation of clays: ASTM Special Tech. Pub. 265, p. 116-130.

Mammerickx, J., and Smith, S. M., 1978, Bathymetry of the southeast Pacific: Geol. Soc. America Map and Chart Series MC-26.

Masias, J. A., 1976, Morphology, shallow structure, and evolution of the Peruvian continental margin, 6° to 18° S: unpubl. M.S. thesis, Oregon State University, 92 p.

Mesri, G., 1973, Coefficient of secondary compression: Jour. Soil Mech. and Found. Div. ASCE, v. 99, SM1, p. 123-137.

Mitchell, J. K., 1976, Fundamentals of Soil Behavior: New York, Wiley and Sons, 422 p.

Moser, J. C., 1980, Sedimentation and accumulation rates of Nazca Plate metalliferous sediments by high resolution Ge(Li) gamma-ray spectrometry of uranium series isotopes: unpubl. M.S. thesis, Oregon State University, 65 p.

Olson, R. E., and Mesri, G., 1970, Mechanisms controlling compressibility of clays: Jour. Soil Mech. and Found. Div. ASCE, v. 96, SM6, p. 1863-1878.

Pusch, R., 1973, Influence of organic matter on the geotechnical properties of clays: Natl. Swedish Bldg. Res. Doc. 11, 64 p.

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

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

Roberts, H.H., Cratsky, D.W., and Whelan, T., 1976, Stability of Mississippi Delta sediments are evaluated by analysis of structural features in sediment borings: 8th Offshore Tech. Conf. p. 9-28.

Rosato, V. J., 1974, Peruvian deep-sea sediments: Evidence for continental accretion: unpubl. M.S. thesis, Oregon State University, 93 p.

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

Smith, R. L., 1968, Upwelling: Mar. Biol. Ann. Rev., v. 6, p. 11-46.

Smith, R. L., 1978, Physical oceanography of coastal upwelling regions. A comparison: Northwest Africa, Oregon, and Peru: Symposium on the Canary Current: Upwelling and Living Resources, Intl. Council for the Exploration of the Sea, Las Palmas, Canary Islands.

Tavenas, F., Leroueil, P., La Rochelle, P., and Roy, M., 1978, Creep behavior of an undisturbed lightly overconsolidated clay: Can. Geotech. Jour., v. 15, p. 402-423.

Terzaghi, K., and Peck, R. B., 1967, Soil Mechanics in Engineering Practice: New York, Wiley and Sons, 729 p.

Zuta, S., and Guillen, O., 1970, Oceanographia de las aquas costeras del Peru: Instit del Mar de Peru Bol., v. 2, p. 159-323.

Zuta, S., Rivera, T., and Bustamante, A., 1978, Hydrologic aspects of the main upwelling areas off Peru, in Boje, R., and Tomczak, M., eds., Upwelling Ecosystems: New York, Springer-Verlag, p. 235-260.

PART III

ANALYSIS OF SEDIMENT STABILITY ON THE PERU-CHILE CONTINENTAL SLOPE

Submitted to Marine Geotechnology

ABSTRACT

Potential sediment mass movement was analysed at ten locations along the continental slope off Peru and northern Chile using samples obtained from up to 3 m below the sea floor. Sediment stability on the Peru-Chile slope is influenced by the active seismicity and occurrence of coastal upwelling along this margin. Upwelling indirectly affects sediment behavior by concentrating organic matter in the slope deposits as is especially evident in sediments of an upper slope mud lens between 10.5°S to 13.6°S which lies beneath an area of intense upwelling. Inclination of the slope at the ten sample locations varies from less than 1° on the mud lens to 13° on the lower slope off Peru.

Shear strength parameters for the stability analyses were obtained from consolidated-undrained triaxial compression tests. Results of these tests reflect the influence of organic matter on sediment behavior. With increasing organic content sediment failure becomes increasingly progressive as a result of the high water content of the organic-rich sediments and the flexibility of the organic matter. Aggregation of clays by organic matter is apparently responsible for the high friction angles displayed by the slope deposits. Friction angles as high as 44° characterize sediments of the upper slope mud lens.

Sediment stability was assessed using infinite slope analyses. These analyses indicate that gravitational forces alone are not sufficient to cause sediment failure at any of the slope locations.

Although sedimentation rates are high on the upper slope (140 cm/1000 years) and consolidation rates of clay-rich lower slope deposits are low, reduction of the resistance to gravitational sliding by excess pore pressure generated by rapid sediment accumulation does not appear likely on the Peru-Chile slope. Effects of earthquakes on slope stability were evaluated by modelling earthquake-induced inertia forces as static forces and estimating pore pressures developed during cyclic loading. This analysis showed that sediments of the lower slope off Peru have the highest susceptibility to failure during earthquakes, whereas the lowest susceptibility is displayed by the upper slope mud lens deposits. Earthquake accelerations between 0.1 to 0.2 gravity, which are in the range measured for recent earthquakes off Peru, will trigger slumping at all ten slope locations. Other possible means of sediment failure include: (1) liquefaction, implied by the moderately high sensitivity of the slope deposits; (2) creep, indicated by the high water content, plasticity, and rates of secondary compression, and progressive failure of the organic-rich sediments; and (3) mass movements initiated at shallow water depths, inferred from erosional features and mass flow deposits in the upper slope sediments.

INTRODUCTION

Located between the continental shelf and continental rise, or as in the case of western South America a deep-sea trench, the continental slope is a major pathway for the transport of sediment to the deep ocean. The continental slope commonly possesses the steepest gradient on the continental margin and, where dissected by submarine canyons, the most irregular topography. Although most of the studies of the slope environment have been concerned with submarine canyon-fan systems increased attention is now being focused on the open areas outside the canyons (Doyle and Pilkey, 1979). Sediments are delivered to the open slope primarily by hemipelagic sedimentation and spillover from the continental shelf. Once on the slope it is believed that the principal transport processes that affect the sediments are slumping and other types of mass movement (Nardin and others, 1979). This downslope movement is typically initiated by rapid sediment accumulation, sudden loads applied by earthquakes or large waves, or tectonic upwarping resulting from salt diapirism or localized faulting and folding accompanying subduction (Bouma, 1979).

Slumps and mass flow deposits on continental slopes have been documented in a number of recent investigations using seismic reflection and 3.5 kHz profiles as well as side-scan sonar (Jacobi, 1976; Hampton and Bouma, 1977; McGregor and Bennett, 1977, 1979; Coleman and Garrison, 1977; Haner and Gorsline, 1978; Knebel and Carson, 1979; Summerhayes and others, 1979). These studies have been primarily concerned with the morphology and structure of the slumps and the sedimentological characteristics of the deposits, but for the most part have not dealt with the behavioral aspects responsible for the mass movement. In order to better understand the processes that initiate slumping, sediment physical properties have been documented and stability analyses performed on a number of continental slopes (Moore, 1961; Morelock, 1969; Ross, 1971; Almagor and Wiseman, 1977; Hampton and others, 1978; Keller and others, 1979; Prior and Suhayda, 1979). These studies have analysed the potential movement of the slope sediments using various limit equilibrium methods with shear strength values obtained mainly from vane shear tests and less frequently from direct shear and triaxial compression tests.

This paper presents an analysis of the stability of sediments at ten locations on the Peru-Chile continental slope (Fig. 1). Sediment stability on the slope is indirectly influenced by the processes of coastal upwelling and subduction which occur along this margin. By concentrating organic matter in the slope deposits, coastal upwelling affects the sediment physical properties and behavior. As a result of the subduction of the Nazca Plate beneath the South American continent the Peru-Chile slope is seismically active and sediment stability is reduced significantly by earthquake shaking. At the ten locations the stability of the sediments was analysed for conditions of loading by gravitational forces and earthquake shaking using shear strength data obtained from a series of triaxial compression tests.

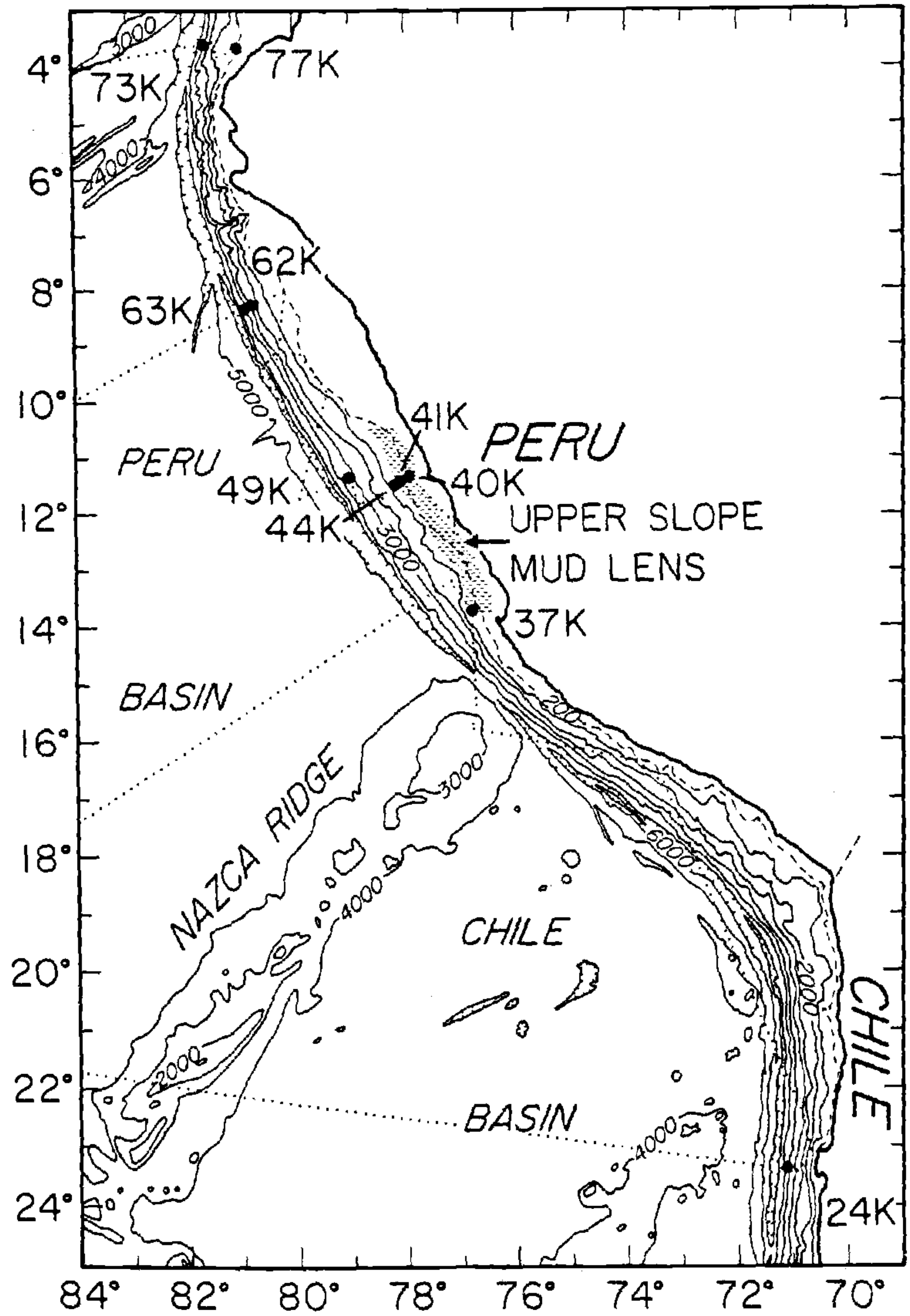


Figure 1. Sediment core locations. The dotted line is the 1977 trackline of the R/V WECOMA. Bathymetry modified from Mammerickx and Smith (1978).

GEOLOGICAL SETTING

The continental slope of Peru and northern Chile is located along the boundary between the converging Nazca and South American Plates. At its seaward extent the slope is bounded by the Peru-Chile Trench which varies in depth from 8100 m at 23°S to 4500 m at 3°S (Fig. 1). Landward the slope is bounded by a relatively flat continental shelf, 0 to 125 km in width. Recent studies have provided detailed information on the morphology and structure of the slope off Peru and Chile (Coulbourn and Moberly, 1976; Masias, 1976; Kulm and others, 1977). These studies have shown that the morphology of the slope varies along the margin. Off northern Peru the slope is dissected by several prominent submarine canyons and the topography is extremely irregular. To the south submarine canyons are less common and the continental slope is marked by benches and small basins on the lower and middle slope and prominent plateaus on the upper slope. A notable change in the slope physiography occurs at 19.5°S (Kulm and others, 1977). To the north, the inclination of the continental slope averages 5.7° on the lower slope and 3.5° on the middle and upper slope. South of 19.5°S there are fewer benches and basins and the slope is steeper. Average gradients in this region are 6.5° and 4.4° on the lower and middle-upper slope respectively. Gradients on the continental slope at the ten sample locations were determined from 3.5 and 12 kHz profiles and range from a low of 0.6° on the upper slope at 11.5°S (core 41K) to a high of 12.8° on the lower slope at 8°S (core 62K) (see Table 1).

The Peru-Chile slope is covered by a thin layer of sediments

TABLE 1. Water Depth and Slope Gradient

Core	Water depth (m)	Slope gradient
24K	5107	5.9°
37K	370	0.9°
40K	186	0.7°
41K	411	0.6°
44K	580	3.3°
49K	3970	3.5°
62K	2670	12.8°
63K	4513	7.8°
73K	2116	7.7°
77K	366	3.2°

that is frequently confined to local basins. A relatively thick lens of sediment on the upper slope between 10.5° to 13.6°S was mapped by means of 3.5 kHz profiles by Krissek and others (1980). This upper slope mud lens is at least 50 m thick and coincides with an area of intense coastal upwelling and the impingement of the shallow water oxygen-minimum layer on the slope. Sedimentation rates along the margin, determined by ^{14}C dating, ^{210}Pb dating (DeMaster, 1979), and rates of SO_4-reduction in interstitial waters based on the relationship described by Berner (1978) (E. Suess, personal communication, 1979), are highest in the vicinity of the upper slope mud lens, ranging from 17 to 140 cm/1000 years. Lower rates, 6 to 47 cm/1000 years, were determined for the Peru slope outside the mud lens area. A very thin sediment cover is present on the continental slope off northern Chile and the sedimentation rate of approximately 5 cm/1000 years is the lowest on the margin.

Coastal upwelling significantly influences the composition and distribution of sediments on the Peru-Chile continental slope (Krissek and others, 1980). Upwelling occurs within 50 km of shore north of 20°S in response to the prevalent southeasterly trade winds that parallel the coast and drive an offshore directed Ekman transport of the surface waters (Smith, 1968; 1978; Zuta and others, 1978). Nutrient-rich waters rise from approximately 70m depth to compensate for this seaward displacement (Smith, 1978) and support a high biological productivity (Zuta and Guillen, 1970). As a result of the high productivity and preservation in anoxic bottom waters, organic matter is concentrated in the sediments underlying the upwelling areas. Coastal upwelling has been a persistent process along the Peru-Chile margin as indicated by diatom assemblages diagnostic of upwelling which are found in late Miocene rocks dredged from the continental slope (H. Schrader, personal communication, 1980).

PHYSICAL PROPERTIES AND COMPOSITION

The variation of the physical properties of the Peru-Chile continental margin sediments and the factors that influence these properties have been recently summarized by Busch and Keller (in review b). Properties of the ten continental slope samples examined in this paper reflect the variation in physical properties along the margin (Table 2). Sediments deposited on the upper slope mud lens beneath the area of intense upwelling are characterized by high organic carbon content, fine grained texture, extremely high water content and plasticity, and low wet bulk density. These high water content sediments have an unusually high undrained shear strength that is an apparent product of organic matter binding sediment particles together. The mud lens sediments at 13.6°S have anomalously low water content and high density and shear strength as a result of the consolidation under a 3.5 to 7 m sediment overburden that has since been eroded (Busch and Keller, in review a). Outside the upper slope mud lens the sediment texture becomes progressively finer from south to north along the margin and with increasing distance from shore. The northern Chile slope deposits are the coarsest sediments on the margin and have the lowest water content and plasticity and the highest wet

TABLE 2. Physical Properties

Core	Sample depth (m)	Water content (% dry wt.)	Wet bulk density (Mg/m^3)	Void ratio	Liquid limit	Plastic limit	Texture: Sand >62μm (%)	Texture: Silt 62-4μm (%)	Texture: Clay <4μm (%)	Average unit weight (0-2m interval) kN/m^3
24K	1.15-1.25	94	1.60	2.00	90	39	18	39	43	15.3
37K	1.45-1.55	106	1.58	1.83	204	60	6	55	39	14.0
40K	1.25-1.35	306	1.24	5.04	160	81	6	34	60	12.8
41K	1.60-1.70	146	1.34	3.92	154	70	6	40	54	12.5
44K	1.95-2.05	95	1.56	2.08	---	--	20	50	30	14.5
49K	1.80-1.90	129	1.36	3.90	124	58	1	38	61	13.3
62K	1.60-1.70	145	1.36	3.88	121	56	3	24	73	13.3
63K	1.60-1.70	127	1.41	3.23	112	56	2	32	66	13.5
73K	2.80-2.90	144	1.36	3.87	129	56	3	27	70	13.1
77K	1.80-1.90	103	1.57	2.01	111	44	5	46	49	14.7

bulk density and undrained shear strength. As the amount of clay-size material in the sediment increases northward and offshore there is an accompanying increase in water content and plasticity and decrease in density and shear strength.

The mineralogy of the clay fraction of the ten continental slope samples was determined from oriented clay mounts with a Norelco-Phillips diffractometer. Sample preparation and mineral identification techniques were similar to those of Karlin (1980). Semi-quantitative abundances of smectite, illite, chlorite, and kaolinite were obtained from glycerol solvated samples using the weighting factors of Biscaye (1965). The clay-mineral analyses show that the clay fraction of the upper slope mud lens sediments (cores 37K, 40K, and 41K) consists primarily of chlorite and illite (Table 3). Metamorphic terranes along the coast adjacent to this area are the apparent sources of these minerals. With increasing distance from the mud lens, north, south, and offshore, the amount of chlorite decreases and smectite abundance increases. Active volcanism in northern Peru and northern Chile and the fine particle size of smectite minerals appear responsible for these trends.

Organic carbon and calcium carbonate concentrations in the slope samples were determined with a Leco WR-12 Automatic Carbon Determinator. Upper slope mud lens sediments at 11.5°S (cores 40K and 41K) have the highest organic contents, 9.63 and 4.33% (Table 3), as a result of the high productivity associated with the intense upwelling in this area. Mud lens sediments at 13.6°S (core 37K), which were

TABLE 3. Clay Mineralogy and Carbon Composition

Core	Sample depth (m)	Mineralogy (% of <4μ fraction) Smectite/ mixed-layer	Illite	Chlorite	Kaolinite	Organic carbon (% dry wt.)	$CaCO_3$ (% dry wt.)
24K	1.15-1.25	42	28	22	8	0.68	0.37
37K	1.45-1.55	17	37	34	12	2.15	0.72
40K	1.25-1.35	5	49	34	12	9.63	2.44
41K	1.60-1.70	5	45	38	12	4.35	1.13
44K	1.95-2.05	11	55	25	9	3.36	37.85
49K	1.80-1.90	27	46	19	8	2.99	5.67
62K	1.60-1.70	21	50	22	7	3.17	4.55
63K	1.60-1.70	7	54	27	12	2.45	1.16
73K	2.80-2.90	77	18	4	1	3.63	2.84
77K	1.80-1.90	45	29	15	9	4.13	2.65

more deeply buried in the past, have a much lower organic content, 2.15%. Peru slope samples from outside the mud lens have moderately high concentrations of organic carbon, ranging from 2.45 to 4.13%. Coinciding with the low sedimentation rate on the northern Chile slope is the lowest organic content, 0.68% (core 24K).

The carbonate content of most of the Peru-Chile sediments is low, resulting apparently from the shoaling of the lysocline in areas of high productivity and dilution by terrigenous components. Excluding core 44K, the calcium carbonate concentrations range from 0.37 to 5.67% (Table 3). Core 44K, located adjacent to the upper slope mud lens at 11.5°S, contains intervals of abundant Foraminifera and at the depth sampled has a carbonate content of approximately 38%.

TRIAXIAL TEST PROCEDURE

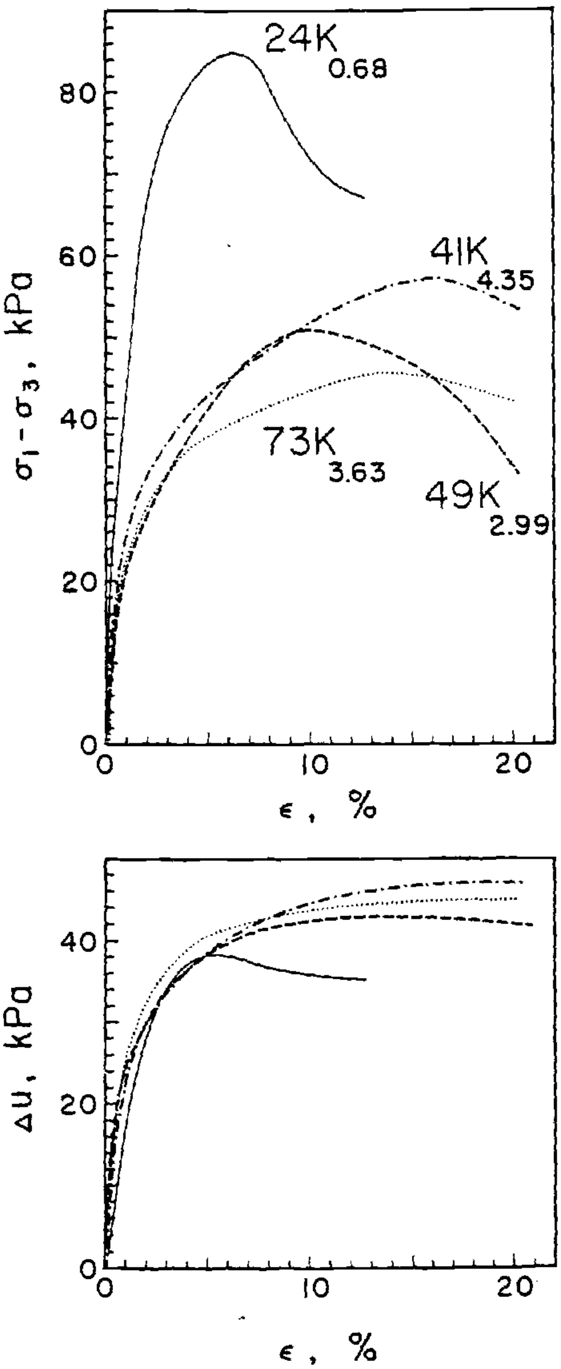
Shear strength parameters used in the analysis of the stability of the Peru-Chile continental slope sediments were determined from consolidated-undrained triaxial compression tests with pore pressure measurements (CU tests). Samples used in these tests were obtained with a Kasten corer, a type of gravity corer with a cross-sectional area 15 x 15 cm. The triaxial tests were performed on samples trimmed to cylindrical shape, 3.6 cm in diameter and 8.0 to 8.9 cm in height. Because of the large cross-sectional area of the Kasten corer, there was minimal sample disturbance and it was possible to obtain four test samples from a given depth interval. Tests were carried out in Wykeham-Farrance triaxial cells at confining pressures of 10, 50, 125, and 250 kPa. The length of the initial consolidation stage was determined by monitoring the volume reduction of the sample and using the method of Taylor (1948) to calculate the point at which the sediment was fully consolidated. Filter paper drains were used to accelerate drainage during consolidation and to equalize the pore pressure during the shearing stage. Upon completion of the consolidation stage the samples were sheared at a constant rate of strain of 0.006 cm/min. During the shearing stage the pore pressure in the sediment was measured at the base of the sample with a strain gauge type pressure transducer. Detailed descriptions of the CU test procedure can be found in Bishop and Henkel (1962) and Bowles (1978).

SHEAR STRENGTH CHARACTERISTICS

Stress-Strain Behavior

Triaxial tests show that in the Peru-Chile slope deposits there is a smooth continuous increase in stress with increasing axial strain. In most of the samples peak strengths were attained at strains greater than 10%. Typical examples of the stress-strain behavior of the slope sediments are shown in Figure 2. These stress-strain curves reveal that there is an apparent correlation between organic content and response of the sediments to increasing stress. As the organic content of the sediments increases there is an increase in the axial strain at which the peak strength is mobilized (Fig. 2). This relationship is also shown in Figure 3 where values of the axial strain at failure, ε_f, and organic carbon concentration are plotted for all of the slope samples. The highest values of ε_f are displayed by

Figure 2. Stress-strain curves, deviator stress (σ_1-σ_3) and pore pressure change (Δ_u) versus axial strain (ε). The curves are from triaxial tests in which the confining pressure was 50 kPa. Organic carbon concentrations (in % dry wt.) are listed beneath the core numbers. See Figure 1 for core locations.


24K
0.68
41K
4.35
73K
3.63
49K
2.99
$\sigma_1 - \sigma_3$, kPa
0
20
40
60
80
0
10
20
ε, %
ΔU, kPa
0
20
40
0
10
20
ε, %

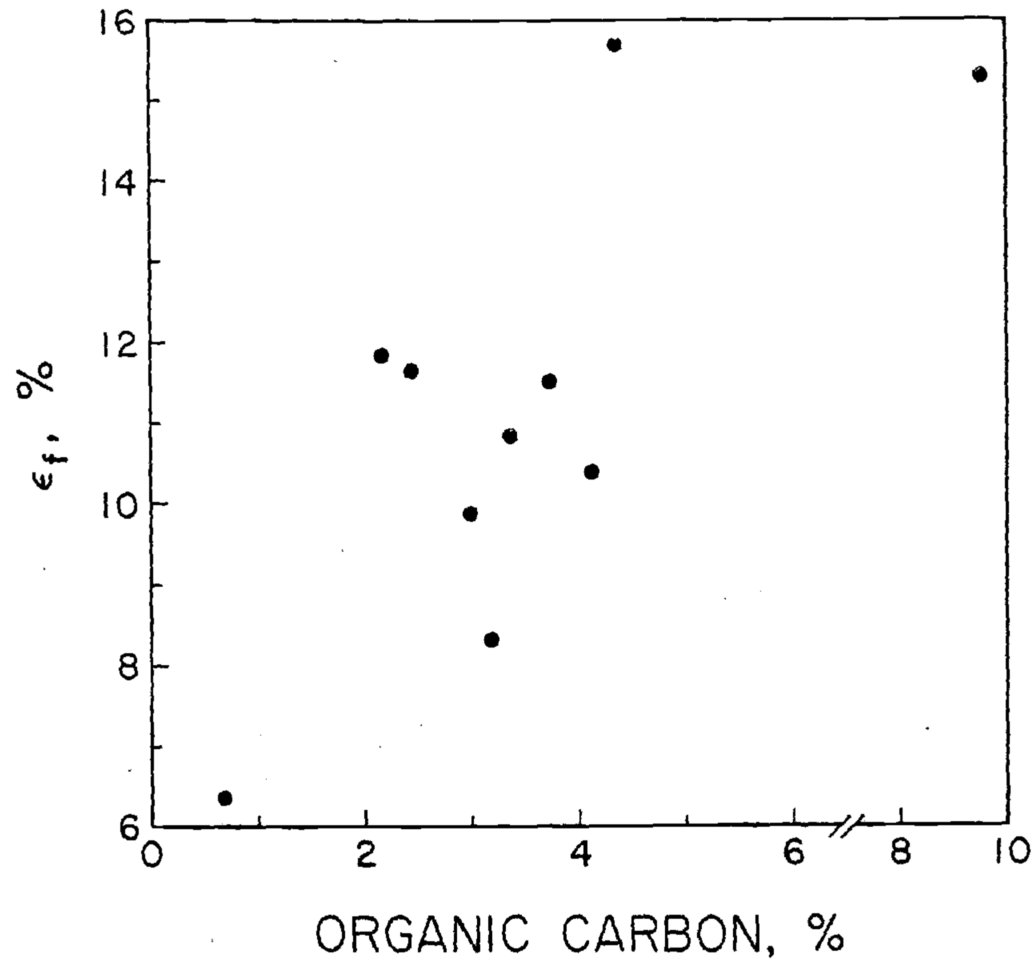


Figure 3. Axial strain at failure (ϵ_f) and organic carbon concentration. Axial strain values are from triaxial tests performed at a confining pressure of 50 kPa. Note the scale change for organic carbon concentrations greater than 6%.

the organic-rich sediments of the upper slope mud lens (cores 40K and 41K) while the low organic content sediments of the northern Chile slope (core 24K) fail at the lowest axial strain (Table 4). Coarse-grained texture and relatively high density at this latter site contribute to the low value of ε_f. The markedly progressive failure displayed by the organic-rich Peru-Chile sediments is a common characteristic of organic-rich clays (Pusch, 1973). Causes for this type of behavior are: (1) high water content of organic-rich sediments resulting from the ability of organic matter to adsorb water and aggregate clay particles to form an open fabric and (2) high flexibility and low activation energy of organic compounds which cause large local deformations when subjected to shear stresses (Pusch, 1973). Although organic content apparently has a strong influence on the strain at which the peak strength is reached in the Peru-Chile sediments, it does not have a similar effect on the magnitude of this strength. Figure 2 shows that the peak strength of the sediments of core 41K is greater than that of the less-organic sediments of the lower Peru slope (cores 49K and 73K).

Several other aspects of the behavior of the Peru-Chile sediments are revealed by the shape of the stress-strain curves. Patterns of variation of undrained shear strength (determined by vane shear tests) suggest that the aggregation of clays by organic matter may act to increase the sediment strength (Busch and Keller, in review b). Some form of organic matter-related interparticle bonding is also indicated by the results of consolidation tests which show that the degree of

TABLE 4. Shear Strength and Pore Pressure Parameters

Core	Sample depth (m)	ε_f (at 50 kPa) (%)	c' (kPa)	ϕ'	R_u
24K	1.15-1.25	6.4	10.39	32.6°	0.60
37K	1.45-1.55	11.8	18.76	37.5°	0.61
40K	1.25-1.35	15.3	9.20	43.8°	----
41K	1.60-1.70	15.7	7.97	44.2°	0.72
44K	1.95-2.05	10.8	1.83	36.6°	----
49K	1.80-1.90	9.9	10.36	33.0°	----
62K	1.60-1.70	8.3	8.38	31.0°	0.76
63K	1.60-1.70	11.7	9.69	42.1°	----
73K	2.80-2.90	13.5	10.59	32.5°	0.61
77K	1.80-1.90	10.4	7.53	31.6°	----

apparent overconsolidation of the Peru-Chile sediments increases with increasing organic content (Busch and Keller, in review a). The stress-strain behavior of the slope deposits indicates that the bonding which appears responsible for the high strengths and apparent overconsolidation does not involve a rigid cementing of particles. Sharp peaks at maximum strengths or secondary peaks at low strains, which characterize rigid cementation (Nacci and others, 1974), are not present in the stress-strain curves.

There is also no indication from the stress-strain behavior that the slope deposits possess a metastable fabric. The Peru-Chile sediments have moderately high sensitivities; average values determined for the 0 to 2m depth interval are 8, 7, and 7 for the upper slope mud lens, Peru slope (outside the mud lens), and northern Chile slope respectively (Busch and Keller, in review b). These values are in the range typical for metastable sediments; however, stress-strain curves of the slope deposits do not show the leveling off and then sharp increase in deviator stress and pore pressure that characterize metastable fabrics (Morgenstern, 1967; Mitchell, 1976).

Strength Parameters

The shear strength of the Peru-Chile slope sediments was defined using the Mohr-Coulomb failure criteria:

$$S = c + \sigma_n \tan \phi \qquad (1)$$

Values of the cohesion intercept, c, and friction angle, ϕ, were obtained from the peak shear strengths plotted on a p-q diagram, where $p = (\sigma_1 + \sigma_3)/2$ and $q = (\sigma_1 - \sigma_3)/2$. The failure envelope was determined by fitting a line, K_f-line, through the points on this stress point representation and computing c and ϕ from the K_f-line using the relationships given by Lambe and Whitman (1969). Failure envelopes for the sediments are essentially straight lines over the stress range used in the triaxial tests.

The stability analyses of the continental slope sediments were performed using effective stress parameters. Values of the effective cohesion intercept, c', range from 1.83 kPa in the coarse, foram-rich sediment from the mid-slope at 11.5°S (core 44K) to 18.76 kPa in the highly overconsolidated sediment of the upper slope mud lens at 13.6°S (core 37K) (Table 4). Sediments at this latter site, where 3.5 to 7m of sediment has been removed, are the only sediments along the margin that display overconsolidation caused by the erosion of a previous overburden (Busch and Keller, in review a). Variation of c' between the ten slope samples shows no consistent relationship to sediment composition, texture, or depth below the sea floor. The effective friction angle, ϕ', varies in the slope deposits from 31.0° to 44.2° (Table 4). These values are high and are in the range that commonly characterizes sediments with much higher abundance of sand-size material (Lambe and Whitman, 1969). Sediments of the upper slope mud lens (cores 37K, 40K, and 41K) have exceptionally high friction angles. Lambe (1960) concluded that fine-grained sediments can display high values of ϕ' as a result of the aggregation of particles by various cementing agents. High friction angles in the mud lens sediments may reflect the effect of the formation of clay-organic aggregates. Olson (1974) demonstrated the influence of clay mineralogy on the variation of ϕ', showing that ϕ' decreases in the clay sequence of kaolinite > illite > smectite. In the Peru-Chile slope deposits the effect of varying clay mineralogy appears minor, but may contribute to the lower friction angles observed outside the mud lens where the combined smectite-illite abundance is greater.

STABILITY ANALYSIS

Stability analyses of the Peru-Chile continental slope sediments were made assuming that the slope in the vicinity of the ten respective sample locations is long and continuous and that mass movement occurs by sliding on a plane parallel to the sea floor. Bathymetric profiles support the validity of this "infinite slope" assumption. The infinite slope model is one of a number of limit equilibrium methods of analysis, recently reviewed by Chowdhury (1978) and Morgenstern and Sangrey (1978), in which the stability of a mass of sediment is assessed by assuming incipient failure along a potential slip surface. From statics the disturbing and resisting forces above the failure surface can be estimated and equations formulated for force equilibrium of the sliding mass. In the analyses that follow it is also assumed that: (1) the geometry of the potential sliding mass is such that end effects can be neglected and the problem can be treated in two dimensions;

and (2) the shear strength mobilized along the failure surface is equal to the peak strength determined from the triaxial tests. Using a limit equilibrium approach it is recognized that there are a number of factors which cannot be accounted for, but may have a significant effect on sediment stability, including discontinuities in the sediment, variation of sediment properties with depth, variable pore pressures, stress deformation characteristics, and initial stress level.

Sampling limitations must also be considered when evaluating the results of the stability analyses. Strength parameters were determined for samples obtained from depths up to 3m. It is assumed that the sediment behavior at greater depths can be predicted from the sediment response under the range of confining pressures in the triaxial tests. Variation in sediment strength that might result from changes in composition or texture at greater depths, however, cannot be predicted.

Gravitational Loading

The simplest analysis of sediment stability is that where the sole force causing downslope movement is the weight of the sediment mass. In this model there is a long continuous slope with an inclination of α (Fig. 4a). The thickness of the potential sliding block of sediment is z and its width is b. Assuming a unit value for b, the effective weight of the sediment mass is:

$$W' = \gamma' z \qquad (2)$$

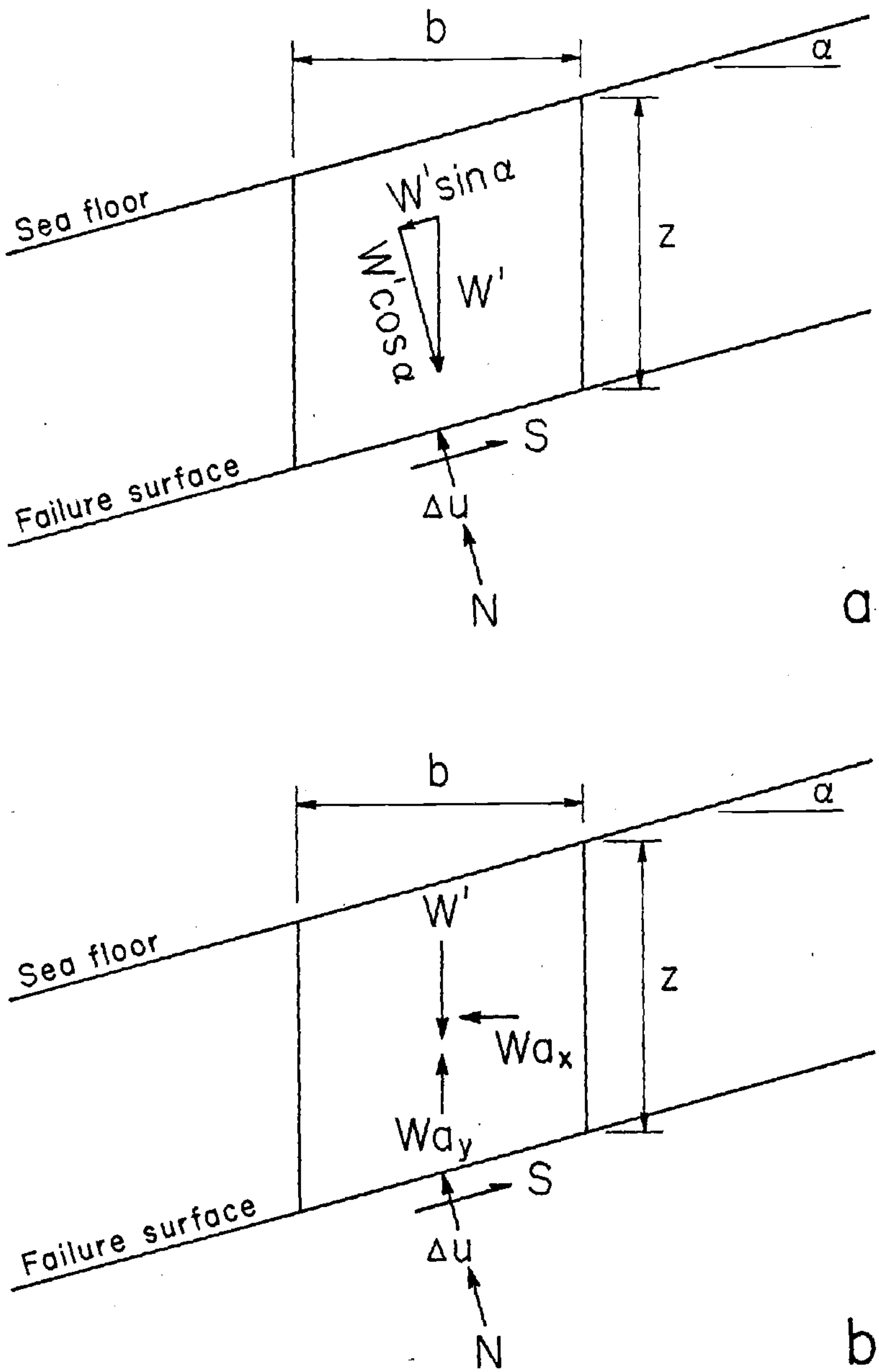


Figure 4. Infinite slope models. (a) Loading by gravitational forces. (b) Earthquake loading. Modified from Hampton and others (1978).

where γ' is the bouyant unit weight, $\gamma' = \gamma - \gamma_w$. (See Appendix 2 for a list of the symbols). The disturbing force, that force causing sediment movement, is the downslope component of the effective weight of the sediment:

$$F_D = \gamma' z \sin\alpha \qquad (3)$$

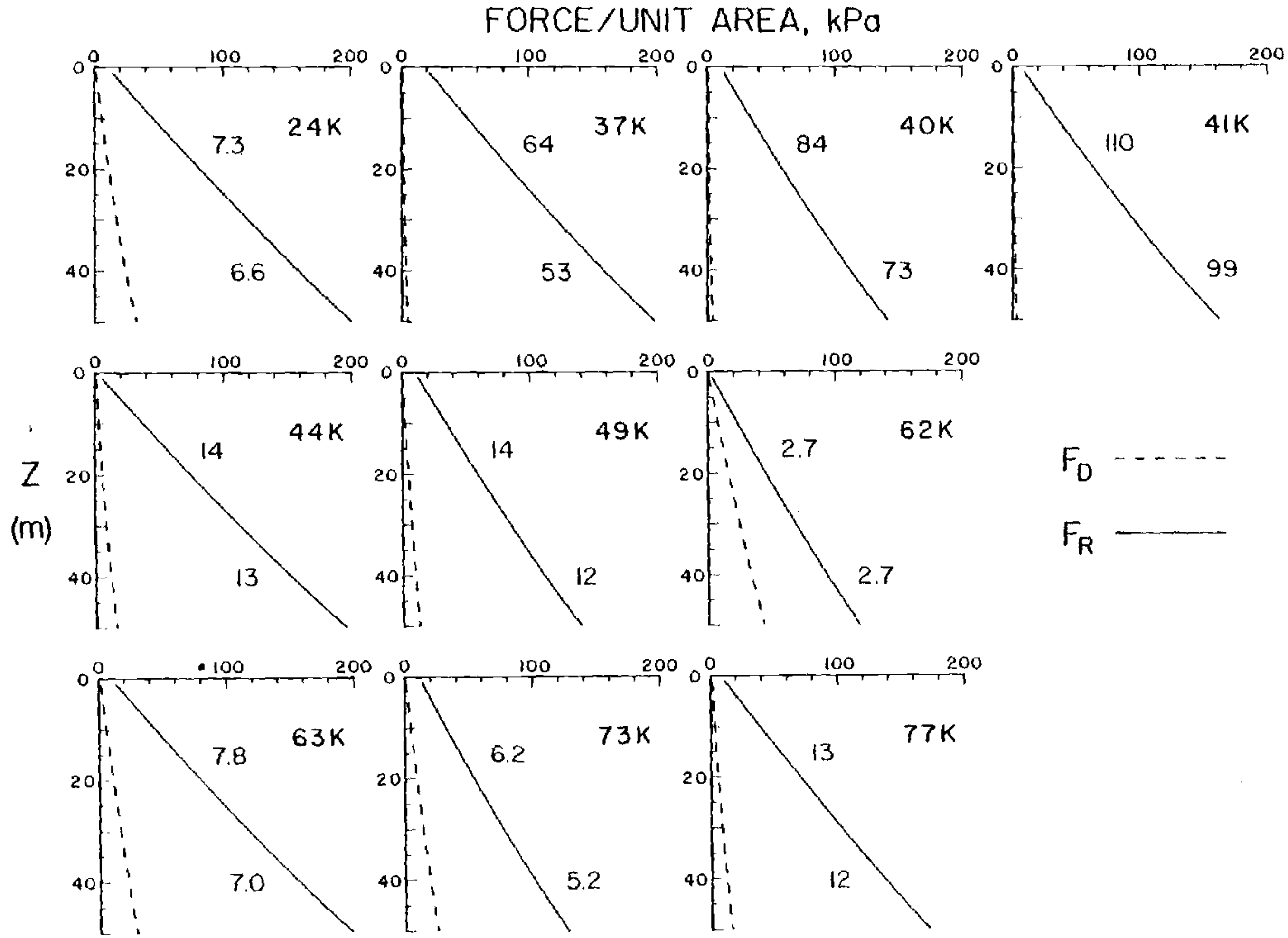
Resisting this force is the shear strength of the sediment (given by Eq. 1) mobilized over the area of the base of the sediment block. Because this analysis is an examination of the long term stability of a natural slope the use of effective strength parameters is required. Assuming a unit width, the basal area of the sediment block is equal to $\sec\alpha$. The resisting force is then:

$$F_R = [\ c' + (\gamma' z \cos^2\alpha - \Delta u) \tan\phi'\ ] \sec\alpha \qquad (4)$$

where $\gamma' z \cos^2\alpha$ is the effective normal stress and Δu equals that pore water pressure in excess of hydrostatic pressure. For the initial analysis it will be assumed that there is no excess pore pressure ($\Delta u = 0$).

A comparison of the values of F_D and F_R for the ten sample locations on the Peru-Chile continental slope is shown in Figure 5. In this comparison the disturbing and resisting forces were calculated for failure surfaces from 1 to 50 m depth. This interval was selected because 50 m was the maximum thickness of sediment observed in 3.5 kHz profiles along the margin. For the calculation of the forces the unit weight was assumed to increase linearly with depth from a value initially equal to the average unit weight for the 0 to 2 m depth interval

Figure 5. Results of the infinite slope analyses for gravitational loading. F_D is the disturbing force. F_R is the resisting force. The estimated factor of safety (F_R/F_D) at 15 and 40m is listed for each site.


FORCE/UNIT AREA, kPa
0 100 200
Z (m)
0 20 40
24K 7.3 6.6
37K 64 53
40K 84 73
41K 110 99
44K 14 13
49K 14 12
62K 2.7 2.7
63K 7.8 7.0
73K 6.2 5.2
77K 13 12
F_D
F_R

(Table 2). A rate of increase of 0.02 $kN/m^3/m$ was determined from density gradients for deep-sea sediments proposed by Hamilton (1976).

Figure 5 shows that at all locations along the margin $F_R > F_D$, implying that the sediments are not susceptible to failure under gravitational forces in the absence of excess pore pressure. The magnitude of the differences between the disturbing and resisting forces is reflected by the factor of safety (F_R/F_D) which was calculated at arbitrary depths of 15 and 40 m. The greatest difference between the two forces is displayed by sediments from the upper slope mud lens (cores 37K, 40K, and 41K). Low unit weight and unusually high strength of these sediments and low slope gradients in this area account for the large difference between F_D and F_R. On the steeper lower slope at 3.5°S (core 73K) and 8°S (core 62K) there is a marked reduction in the difference between F_D and F_R, but the reduction is not sufficient to suggest instability.

The presence of excess pore pressure could significantly reduce the resistance to gravitational sliding. Possible mechanisms by which excess pore pressure can be generated in submarine sediments include cyclic loading by waves or earthquakes, rapid sedimentation, and the presence of methane or carbon dioxide gas. Pore pressures generated by earthquake shaking and their effect on slope stability will be discussed in a subsequent section. Cyclic loading by waves and the presence of gas in the sediments can be disregarded as possible means of producing excess pore pressure on the Peru-Chile slope. It has been shown that sediment failures resulting from pressure changes associated with the passage of waves occur at depths up to 120 m on the Mississippi Delta (Henkel, 1970) and 150 m in the Gulf of Alaska (Hampton and others, 1978). Most of the continental slope sediments off Peru and Chile lie at depths substantially greater than these depths (Table 1) and would not be expected to be influenced by waves. Gas-generated excess pore pressure can be neglected as there was no evidence of gas-related expansion features in the cores obtained from the Peru-Chile slope.

Sedimentation rates are variable along the Peru-Chile margin with areas of rapid deposition coinciding with those areas of intense coastal upwelling. The potential for excess pore water pressures in the areas with high rates of sedimentation can be evaluated using a theoretical analysis of pore pressure in a rapidly accreting sediment layer, developed by Gibson (1958). Gibson's solution for pore pressure distribution can be applied if it is assumed that deposition has occurred at a uniform rate and that vertical deformation of the sediment is small relative to the thickness of the bed. Carbon-14 dating indicates that sedimentation rates off Peru have not been constant and deposition occurred at lower rates in the past. In order to maximize the estimated excess pore pressure the present rate of sedimentation is used in the analysis presented here.

Assuming a constant rate of sedimentation and small vertical deformation, the thickness of a sediment layer is given by:

$$z = rt \qquad (5)$$

where r is the sedimentation rate and t is time. To solve for the pore pressure Gibson defined a dimensionless time factor:

$$T = r^2 t/c_v \qquad (6)$$

where c_v is the consolidation coefficient obtained from one-dimensional consolidation tests. Gibson determined the potential excess pore pressure for sediment layers overlying either permeable or impermeable bases using a pore pressure parameter, $\Delta u/\gamma' z$, expressed as a function of T and a dimensionless depth in the sediment.

Estimates of the pore pressure distribution in the Peru-Chile sediments can be made at five locations on the slope where consolidation test data are available (cores 24K, 37K, 41K, 62K, and 73K) (Busch and Keller, in review a). At these five sites the likelihood of generating excess pore pressure by rapid sedimentation is greatest on the upper slope mud lens (core 41K), where the highest sedimentation rates on the slope occur, and on the lower slope at 3.5°S (core 73K), where sediments display the slowest rate of consolidation. Although sedimentation rates were not determined for these two cores, rates were determined for nearby cores. The present sedimentation rate for sediments of core 41K should be close to the 140 cm/1000 years calculated for the nearby core 40K. Although it is probably high, a rate of 47 cm/1000 years, determined for the lower slope at 11°S (core 49K), is assumed for core 73K for the purpose of this discussion. Consolidation coefficients are approximately 1.00 x 10^{-3} cm^2/sec for 41K and 2.5 x 10^{-4} cm^2/sec for 73K. Using these values in Eq. 5 and Eq. 6 the time factor calculated at a depth of 50 m is 0.02 and 0.03 for cores 41K and 73K respectively. These values of T are very low and, according to the tables of Gibson (1958), sedimentation-induced excess pore pressure is negligible. For comparison, a time factor of 0.25 at the base of a sediment layer overlying an impermeable bed will produce only a small excess pore pressure gradient of $\Delta u/\gamma' z = 0.1$. Equations 5 and 6 show that T increases with depth; however, at sites 41K and 73K the sediment thicknesses required for T to become significant are unrealistically high. Therefore, it appears that sedimentation rates along the Peru-Chile slope are not high enough to generate excess pore pressure that might reduce the resistance to slumping.

Earthquake Loading

Sediment stability is affected by earthquakes as a result of the excess pore pressure and large inertia forces that are generated by pulsating stresses associated with earthquake shaking. The influence of earthquakes on the stability of the Peru-Chile slope can be modelled using a simplified pseudo-static method of analysis. This method has been used in continental slope stability analyses by Almagor and Wiseman (1977) and Hampton and others (1978) and has been described in detail by Chowdhury (1978). It assumes that the effect of earthquake shaking can be represented by orthogonal acceleration components, a_x and a_y, which are expressed as a fraction of gravity. For this analysis it is assumed that the vertical acceleration, a_y, is negligible compared to the horizontal acceleration, a_x, and the inertia force induced by the horizontal acceleration can be considered a static force and not a dynamic force. Hampton and others (1978) point out that the static force assumption requires the size of the sliding mass to be less than the wavelength of the propagating earthquake energy in order for the sediment block to be considered to lie in a constant acceleration field. Where this condition is not met, however, they concluded that the pseudo-static approach still reflects the significance of earthquake loading on sediment stability.

Additional forces associated with earthquake loading can be superimposed on the gravitational forces in the infinite slope model as shown in Figure 4b. The disturbing force is increased by the downslope component of the earthquake induced inertia force and is given by:

$$F_D = \gamma' z \sin\alpha + \gamma z a_x \cos\alpha \qquad (7)$$

The resisting force is decreased as a result of the reduction of the normal force acting on the failure plane by the slope-normal component of the inertia force and the excess pore pressure generated by the cyclic loading. The resulting equation for the resisting force is:

$$F_R = [c' + (\gamma' z \cos^2\alpha - \Delta u - \gamma z a_x \sin\alpha)\tan\phi']\sec\alpha \qquad (8)$$

Note that in the equations for F_D and F_R the horizontal acceleration acts on the total sediment mass (γz), accelerating both the sediment particles and the pore fluid.

If force equilibrium on the potential failure plane is assumed, the magnitude of the earthquake acceleration required to initiate sliding can be determined from Eq. 7 and Eq. 8. By setting $F_D = F_R$

the following equation can be derived for the horizontal acceleration:

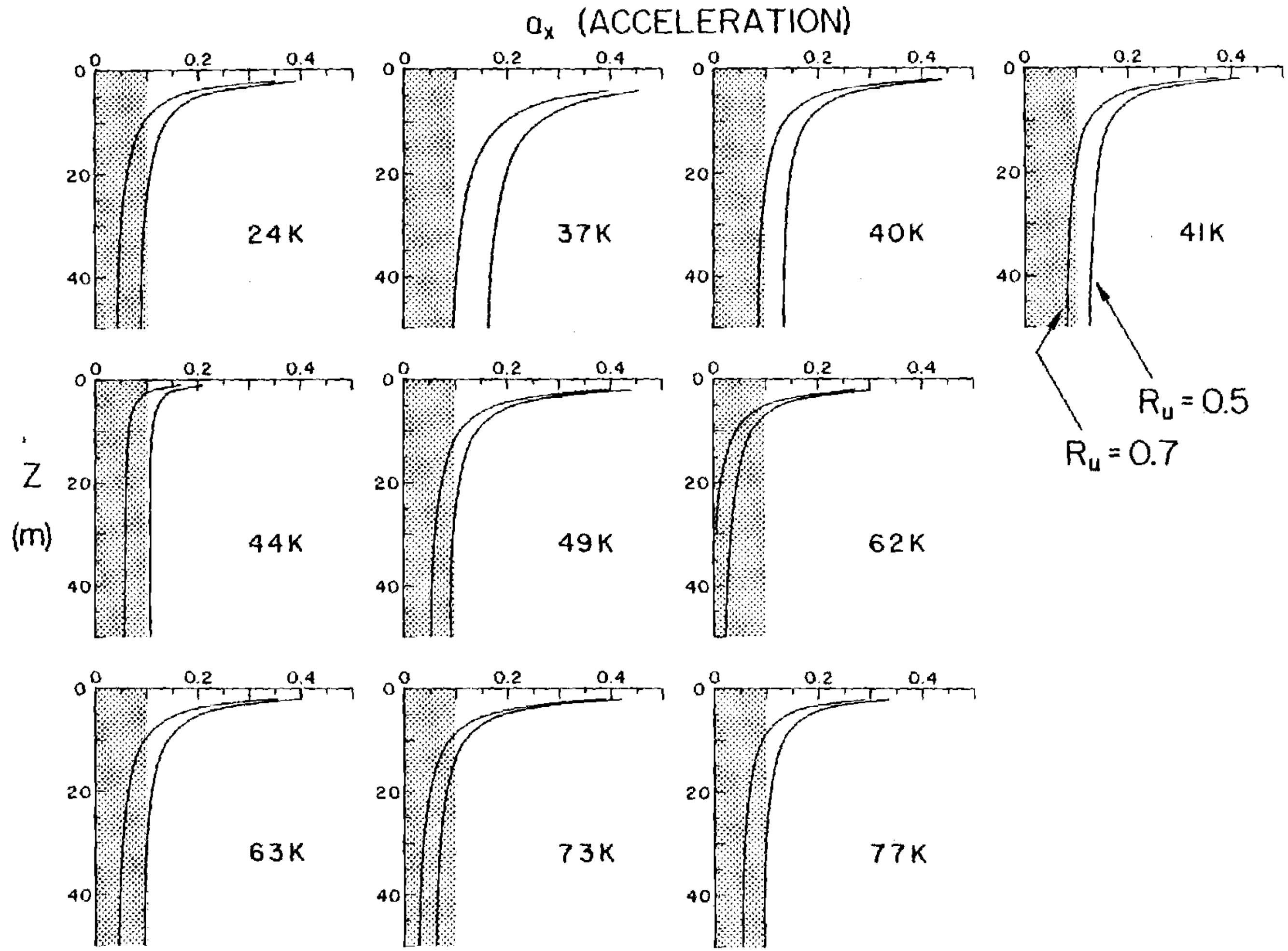
$$a_x = \frac{\gamma'}{\gamma} \frac{c'/\gamma'z - R_u\tan\phi' + \cos^2\alpha(\tan\phi' - \tan\alpha)}{\cos^2\alpha(1+\tan\phi'\tan\alpha)} \qquad (9)$$

where $R_u = \Delta u/\gamma'z$.

Excess pore pressures that develop during earthquake shaking can be estimated using the method of Egan and Sangrey (1978) for determining pore pressure generated by cyclic loading (see Appendix 1). Values of the pore pressure parameter, R_u, that were computed for the Peru-Chile slope sediments using this method are in the range $0.60 < R_u < 0.76$ (Table 4). In order to compare the earthquake accelerations required to initiate slumping at the ten slope locations R_u values of 0.5 and 0.7 were used in Eq. 9. The horizontal acceleration was calculated over a 1 to 50 m depth interval using the same density assumptions as those used in the gravitational loading model. Values of a_x obtained from these calculations are shown in Figure 6.

Figure 6 shows that the slope deposits most susceptible to slumping when subjected to earthquake shaking are those sediments on the lower slope at 3.5°S (core 73K) and 8°S (core 62K). Steep inclination and the relatively low strength of sediments in these areas are again responsible for their displaying the lowest resistance to failure. Deposits least susceptible to slumping during an earthquake are those of the gently inclined upper slope mud lens (cores 37K, 40K, and 41K). As the mass of the potential slump block increases (depth to the failure surface increases) the accelerations required for sediment failure

Figure 6. Results of the infinite slope analyses for earthquake loading. The horizontal component of the earthquake acceleration required for failure, a_x, is given for pore pressure parameter ($R_u = \Delta u/\gamma' z$) values of 0.5 and 0.7.


ax (ACCELERATION)
0
0.2
0.4
Z
(m)
0
20
40
24K
37K
40K
41K
44K
49K
62K
63K
73K
77K
Ru = 0.5
Ru = 0.7

decrease. At all ten sites on the continental slope it appears that the sediments are likely to fail at depths greater than 20 m under accelerations of 0.1 to 0.2 gravity (Fig. 6).

Estimates of the accelerations that might be experienced on the Peru-Chile slope can be approximated from data derived from 1966 and 1970 earthquakes which had epicenters offshore and Richter scale magnitudes of 7.5 and 7.75 respectively. During the May 1970 earthquake a seismograph in Lima, 385 km from the epicenter, recorded a maximum acceleration of 0.1 gravity (Cluff, 1971). In October 1966 the epicenter was 225 km from Lima and several pulses greater than 0.3 gravity and one pulse as high as 0.4 gravity were recorded (Lee and Monge, 1968). From Figure 6 it can be seen that accelerations of the magnitude recorded during the 1966 earthquake are more than sufficient to cause sediment failure on the continental slope.

The use of a pseudo-static approach to determine the stability of a slope subjected to earthquake loading has several major drawbacks, such as: (1) assuming the slope behaves as a rigid body; (2) using a static force to represent the earthquake inertia force, rather than a dynamic force of short duration; and (3) assuming that the acceleration that induces the inertia force is equal to the maximum ground acceleration (Chowdhury, 1978). Seed (1968) compared acceleration coefficients obtained from pseudo-static and dynamic analyses of the same slope failure and showed that the pseudo-static approach yielded a higher value of a_x than that computed from the more rigorous dynamic analysis. While the calculated values of the earthquake acceleration required to initiate slumping in the Peru-Chile sediments probably differ from the true values they do provide a comparison of the relative stability of the different areas on the continental slope and indicate that inertia forces induced by earthquakes along this margin may be large enough to cause sediment failure.

Other Failure Mechanisms

The previous sections have analysed the initiation of slumping by gravitational forces alone, rapid sedimentation, and earthquake shaking. Other mechanisms, such as liquefaction and creep, are also responsible for mass movements on submarine slopes (Morgenstern, 1967). Although a formal analysis of these mechanisms will not be performed their influence on sediment stability on the Peru-Chile slope can be inferred from characteristics of the slope deposits.

Liquefaction is the transformation of a sediment from a solid to a fluid state as a result of increased pore pressure. Sediments most susceptible to this type of failure are those in which the sediment fabric readily collapses under the application of a shear stress (Terzaghi, 1956; Morgenstern, 1967). Liquefaction occurs in such metastable sediments as excess pore pressure increases rapidly in response to the volume reduction accompanying the fabric collapse. Although the sensitivity of the Peru-Chile slope deposits is in the range that is typical for metastable sediments (Busch and Keller, in review b) they lack other features that characterize sediments highly susceptible to liquefaction. The texture of most of the Peru-Chile sediments is finer-grained (Table 2) than that of typical metastable sediments, which consist predominantly of silt and fine sand (Terzaghi, 1956). Also, the stress-strain behavior of the slope deposits does not indicate sediment collapse during shear (Fig. 2). However, because of the potential generation of significant excess pore pressure during earthquake shaking, described in the preceding section, and the moderately high sensitivity of the slope deposits liquefaction must be considered to be a possibility.

Time-dependent, creep deformation can cause sediment movement on slopes at stresses lower than calculated failure stresses and through breakage of interparticle bonds, changes in water content, or changes in effective stress can lead to a decrease in shear strength and sediment failure (Mitchell, 1976). Abundant organic matter in the sediments of the Peru-Chile slope may increase the potential for creep deformation. Both water content and plasticity of the slope deposits increase with increasing organic content (Busch and Keller, in review b). With increasing water content and plasticity the magnitude of creep deformation increases (Mitchell, 1976), suggesting that the organic-rich sediments of the upper slope mud lens which are characterized by extremely high water content and plasticity may be highly susceptible to creep. High rates of secondary compression in consolidation tests (Busch and Keller, in review a) and progressive failure in triaxial compression tests also suggest that the mud lens sediments may possess a high susceptibility to time-dependent deformation. As was shown in the infinite slope analysis, the downslope gravitational force is low in the mud lens area as a result of the low unit weight of the sediments and low inclination of the slope and as a consequence the amount of creep deformation will likely be limited.

Sedimentary structures in cores from the upper slope mud lens (cores 37K, 40K, and 41K) indicate the occurrence of mass movements of sediments in the past. Core 37K (13.6°S) contains five intervals of chaotic bedding up to 20 cm thick which are interpreted to be mass flow deposits (Busch and Keller, in review a). In addition to these features the removal of 3.5 to 7 m of sediment at this site is indicated by results of one-dimensional consolidation tests and ^{14}C dating (Busch and Keller, in review a). Cores 40K and 41K do not have features similar to those of core 37K, but do contain occasional intervals of soft sediment deformation, minor unconformities, and thin (<5 cm) silt turbidites. The infinite slope analyses show that the near-surface sediments in this area appear to be stable. Mass movement triggered by earthquakes would be expected to occur at depths greater than the 3 m represented in the cores (Fig. 6). A possible origin of the mass flow features in the mud lens sediments may be flows initiated in shallower water where loading by waves, tidal changes, or rapid influx of terrigenous material might result in sediment instability.

SUMMARY

The potential mass movement of sediments on the Peru-Chile continental slope is influenced by both the tectonic and oceanographic regimes of this margin. As a result of the convergence of the Nazca

and South America Plates the continental slope is steep and seismically active. Deposits of the lower slope are the most steeply inclined and display the highest susceptibility to slumping. The occurrence of earthquakes significantly increases the potential for sliding at all locations along the continental slope. Coastal upwelling is a prominent feature of the surface water circulation off Peru and indirectly influences sediment stability by causing large amounts of organic matter to be deposited on the sea floor. Slope stability is affected by the pronounced influence organic matter has on the shear strength and other physical properties of the sediments.

Stability analyses were performed for ten locations on the continental slope off Peru and Chile using shear strength parameters determined by consolidated undrained triaxial compression tests with pore pressure measurements. The stress-strain behavior demonstrated in these tests reflects the influence of organic matter in the sediments. High water content associated with the presence of organic matter and the high deformability of organic matter are apparently responsible for the progressive failure displayed by most slope sediments in the triaxial tests. Axial strains at which peak strengths are mobilized are typically greater than 10%, with values as high as 16% in the organic-rich upper slope mud lens sediments which have been deposited beneath an area of intense coastal upwelling. Characteristics of the Mohr-Coulomb failure envelopes of the Peru-Chile sediments also reflect the influence of organic matter. Aggregation of clay particles by organic matter appears to be responsible for the high friction angles (over 30°) displayed by the slope deposits. Angles of up to 44° were determined for the highly organic sediments of the upper slope mud lens. All of the Mohr-Coulomb failure envelopes exhibit an apparent cohesion with the largest values occurring in the highly overconsolidated mud lens sediments at 13.6°S (core 37K).

The stability of the continental slope sediments was analyzed using a model which assumed a long continuous slope and a potential failure surface parallel to the sea floor. Application of the infinite slope model to the condition of the long term stability of the slope indicates that sediments at all ten locations along the margin would not fail due to gravitational forces alone. The greatest difference between the gravitational forces and those forces resisting failure is displayed by sediments of the upper slope mud lens. Low unit weight, resulting from the high organic content of these sediments, and a gradient of less than 1° in this area combine to produce a low downslope component of gravity. Unusually high strength of the mud lens sediments resulting from the formation of clay-organic aggregates contributes to the large difference between the forces resisting and those causing mass movement. Outside the mud lens the slope deposits are more steeply inclined and the ratio between the resisting force and disturbing force is less. This ratio is lowest on the lower slope off Peru where the inclination is as high as 13° and sediments display relatively lower shear strengths.

Susceptibility to slumping is increased by the development of pore water pressures in the sediments that are in excess of hydrostatic pressure. Causal mechanisms for excess pore pressures which might affect the stability of the Peru-Chile continental slope include rapid sedimentation and cyclic loading by earthquakes. Generation of excess pore pressure in the slope deposits by rapid sedimentation was analysed using the theoretical approach of Gibson (1958). This analysis shows that although sedimentation rates are high on the upper slope mud lens, up to 140 cm/1000 years, the rates are not sufficient to generate excess pore pressure. On the lower slope off Peru deposition occurs at a slower rate, less than 50 cm/1000 years, but the rate at which the sediments consolidate is also less. In this area, as elsewhere on the slope, it was found that the sediments are fully consolidated and excess pore pressure owing to rapid sedimentation is not a factor in the slope stability.

Slope stability is reduced during earthquakes as a result of the excess pore pressures and inertia forces that are generated by the shaking motion of the substrate. The response of the Peru-Chile continental slope sediments to earthquake activity was analysed by assuming the inertia forces induced by earthquake shaking are static forces that can be superimposed on the gravitational forces in the infinite slope model. Excess pore pressures generated by earthquake shaking were estimated using the method of Egan and Sangrey (1978) for determining pore pressures that develop during cyclic loading. The analyses for the influence of earthquakes on sediment stability, like the analyses for loading by gravitational forces alone, reflect the importance of the variation of the slope inclination. Sediments of the lower slope off Peru are the most susceptible to slumping during earthquakes, while the less steeply inclined and less dense deposits of the upper slope mud lens display a lower susceptibility. Sediments at all ten slope locations might be expected to fail at depths greater than 20 m under earthquake accelerations of 0.1 to 0.2 gravity. These accelerations are well within the range of maximum accelerations that have been recorded during recent large earthquakes along the Peru margin.

Liquefaction, creep, and flows initiated at shallower depths on the continental slope or shelf may also affect the stability of the Peru-Chile slope sediments. The slope deposits do not possess the texture or stress-strain behavior that characterize sediments highly susceptible to liquefaction. However, they do display moderately high sensitivity and might be subject to liquefaction as a result of the generation of excess pore pressure and sediment remolding during earthquakes. Abundant organic matter in the slope deposits, particularly those of the upper slope mud lens, may increase their susceptibility to creep. High water content and plasticity, high rates of secondary compression, and progressive failure in the organic-rich sediments suggest the likelihood of creep deformation. Evidence of mass flows believed to have been generated at shallower water depths is contained in cores from the upper slope mud lens. Features in these sediments that are indicative of mass movement include silt turbidites, intervals of chaotic bedding, and unconformities, one of which at 13.6°S represents the removal of 3.5 to 7 m of sediment.

APPENDIX 1: Excess Pore Pressure Due to Cyclic Loading

A means of predicting the pore pressures generated by cyclic loading has been developed by Egan and Sangrey (1978) using the concepts of critical state soil mechanics. The method they proposed is applicable to all levels of cyclic loading and the expression that was derived for potential excess pore pressure at the cyclic stress peak is:

$$\Delta u_{max} = [1 - \exp(-\Pi/\kappa)(1-M/3)]p_o$$

Π = volume change potential, $\Pi = 0.006\ (1 + e_{max})$; 0.006 is an average value for the volumetric strain potential, suggested by Egan and Sangrey; e_{max} was assumed by Egan and Sangrey to be equivalent to the void ratio at the liquid limit. Because the natural water content of the Peru-Chile sediments is in most instances greater than the liquid limit the in situ void ratio of the sediments was assumed to be equal to e_{max}.

κ = recompression index from one-dimensional consolidation tests expressed as a natural logarithm, $\kappa = C_s/2.3$.

M = effective stress ratio in a failure state, $M = 6 \sin\phi'/(3-\sin\phi')$

p_o = effective normal stress

R_u was obtained from the ratio $\Delta u_{max}/p_o$. Values of R_u determined for the Peru-Chile sediments, listed in Table 4, compare favorably with the empirical data of Egan and Sangrey (1978).

APPENDIX 2: List of Symbols

a_x = horizontal component of earthquake acceleration

a_y = vertical component of earthquake acceleration

b = width of sediment element in infinite slope model

c' = effective cohesion intercept

c_v = consolidation coefficient

e = void ratio

F_D = disturbing force in infinite slope model

F_R = resisting force in infinite slope model

N = normal force on failure surface in infinite slope model

r = sedimentation rate

R_u = pore pressure parameter

S = shear force on failure surface in infinite slope model

t = time

T = consolidation time factor

Δu = excess pore pressure, pore pressure change in stress-strain curves

W,W' = total (W) and bouyant (W') weight of sediment element in infinite slope model

z = depth below sea floor, height of sediment element in infinite slope model

α = angle of slope inclination

$\varepsilon, \varepsilon_f$ = axial strain, axial strain at failure (ε_f)

γ = saturated unit weight

γ' = bouyant unit weight

γ' = unit weight of water

ϕ' = effective friction angle

σ_1, σ_3 = principal stresses, major (σ_1) and minor (σ_3)

σ_n = normal stress

REFERENCES

Almagor, G., and Wiseman, G., 1977, Analysis of submarine slumping in the continental slope of the southern coast of Israel: Mar. Geotech., v. 2, p. 349-388.

Berner, R.A., 1978, Sulfate reduction and the rate of deposition of marine sediments: Earth Planet. Sci. Lett., v. 37, p. 492-498.

Biscaye, P.E., 1965, Mineralogy and sedimentation of Recent deep-sea clay in the Atlantic ocean and adjacent seas and oceans: Geol. Soc. America Bull., v. 76, p. 803-832.

Bishop, A. W., and Henkel, D. J., 1962, The Measurement of Soil Properties in the Triaxial Test: London, Edward Arnold, 227 p.

Bouma, A. H., 1979, Continental slopes, in Doyle, L. J., and Pilkey, O. H., eds., Geology of Continental Slopes: Soc. Econ. Paleontologists and Mineralogists Spec. Pub. 27: p. 1-15.

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

Busch, W. H., and Keller, G. H., in review a, Consolidation characteristics of sediments from the Peru-Chile continental margin and implications for past sediment instability.

Busch, W. H., and Keller, G. H., in review b, The physical properties of Peru-Chile continental margin sediments - The influence of coastal upwelling on sediment properties.

Cluff, L. S., 1971, Peru earthquake of May 31, 1970: Engineering geology observations: Bull. Seism. Soc. America, v. 61, p. 511-533.

Coleman, J. M., and Garrison, L. E., 1977, Geological aspects of marine slope stability, northwestern Gulf of Mexico: Mar. Geotech., v. 2, p. 9-44.

Coulbourn, W. T., and Moberly, R., 1976, Structural evolution of fore-arc basins off southern Peru and northern Chile: Can. Jour. Earth Sci., v. 14, p. 102-116.

Chowdhury, R. N., 1978, Slope Analysis: Amsterdam, Elsevier, 423 p.

DeMaster, D. J., 1979, The marine budgets of Si and Si-32: unpubl. Ph.D. dissertation, Yale University, 308 p.

Doyle, L. J., and Pilkey, O. H., eds., 1979, Geology of Continental Slopes: Soc. Econ. Paleontologists and Mineralogists Spec. Pub. 27, 374 p.

Egan, J.A., and Sangrey, D.A., 1978, Critical state model for cyclic load pore pressure: ASCE Specialty Conf. on Earthquake Engineering and Soil Dynamics, p. 410-424.

Gibson, R.E., 1958, The progress of consolidation in a clay layer increasing in thickness with time: Geotechnique, v. 8, p. 171-182.

Hamilton, E.L., 1976, Variation of density and porosity with depth in deep-sea sediments: Jour. Sed. Petrology, v. 46, p. 280-300.

Hampton, M.A., and Bouma, A.H., 1977, Slope instability near the shelf break, western Gulf of Alaska: Mar. Geotech., v. 2, p. 309-331.

Hampton, M.A., Bouma, A.H., Carlson, P.R., Molnia, B.F., Clukey, E.C., and Sangrey, D.A., 1978, Quantitative study of slope instability in the Gulf of Alaska: 10th Offshore Tech. Conf., p. 2307-2318.

Haner, B.E., and Gorsline, D.S., 1978, Processes and morphology of continental slope between Santa Monica and Dume Submarine Canyons, southern California: Mar. Geol., v. 28, p. 77-87.

Henkel, D.J., 1970, The role of waves in causing submarine landslides: Geotechnique, v. 20, p. 75-80.

Jacobi, R.D., 1976, Sediment slides on the northwestern continental margin of Africa: Mar. Geol., v. 22, p. 157-173.

Karlin, R., 1980, Sediment sources and clay mineral distributions off the Oregon coast: Jour. Sed. Petrology, v. 50, p. 543-559.

Keller, G.H., Lambert, D.W., and Bennett, R.H., 1979, Geotechnical properties of continental slope deposits -- Cape Hatteras to Hydrographer Canyon, _in_ Doyle, L.J., and Pilkey, O.H., eds., Geology of Continental Slopes: Soc. Econ. Paleontologists and Mineralogists Spec. Pub. 27, p. 131-151.

Knebel, H.J., and Carson, B., 1979, Small-scale slump deposits, Middle Atlantic Continental Slope, off eastern United States: Mar. Geol., v. 29, p. 221-236.

Krissek, L.A., Scheidegger, K.F., and Kulm, L.D., 1980, Surface sediments of the Peru-Chile continental margin and the Nazca plate: Geol. Soc. America Bull., v. 91, p. 321-331.

Kulm, L.D., Schweller, W.J., and Masias, A., 1977, A preliminary analysis of the subduction process along the Andean continental margin, 6° to 45°S, in Talwani, M., and Pitman, W.C., III, eds., Island Arcs, Deep-Sea Trenches and Back-Arc Basins, Maurice Ewing Series, Vol. 1: Am. Geoph. Union, p. 285-305.

Lambe, T.W., 1960, A mechanistic picture of shear strength in clay: Proc. ASCE Res. Conf. Shear Strength of Cohesive soils, p. 555-580.

Lambe, T.W., and Whitman, R.V., 1969, Soil Mechanics: New York, Wiley and Sons, 553 p.

Lee, K.L., and Monge, J.E., 1968, Effect of soil conditions on damage in the Peru earthquake of October 17, 1966: Bull. Seism. Soc. America, v. 58, p. 937-962.

Mammerickx, J., and Smith, S.M., 1978, Bathymetry of the southeast Pacific: Geol. Soc. America Map and Chart Series MC-26.

Masias, J.A., 1976, Morphology, shallow structure, and evolution of the Peruvian continental margin, 6° to 18°S: unpubl. M.S. thesis, Oregon State University, 92p.

McGregor, B.A., and Bennett, R.H., 1977, Continental slope sediment instability northeast of Wilmington Canyon: Am. Assoc. Petroleum Geologists Bull., v. 61, p. 918-928.

McGregor, B.A., and Bennett, R.H., 1979, Mass movement of sediment on the continental slope and rise seaward of the Baltimore Canyon Trough: Mar. Geol., v. 33, p. 163-174.

Mitchell, J. K., 1976, Fundamentals of Soil Behavior: New York, Wiley and Sons, 422 p.

Moore, D.G., 1961, Submarine slumps: Jour. Sed. Petrology, v. 31, p. 343-357.

Morelock, J., 1969, Shear strength and stability of continental slope deposits, western Gulf of Mexico: Jour. Geophys. Res., v. 74, p. 465-482.

Morgenstern, N.R., 1967, Submarine slumping and initiation of turbidity currents, in Richards, A.F., ed., Marine Geotechnique: Urbana, University of Illinois Press, p. 189-220.

Morgenstern, N.R., and Sangrey, D.A., 1978, Methods of stability analysis, in Landslides: Analysis and Control: Transportation Research Board, National Research Council, Washington, D.C., p. 155-171.

Nacci, V.A., Kelly, W.E., Wang, M.C., and Demars, K.R., 1974, Strength and stress-strain characteristics of cemented deep-sea sediments, in Interbitzen, A.L., ed., Deep-Sea Sediments: Physical and Mechanical Properties: New York, Plenum Press, p. 129-150.

Nardin, T.R., Hein, F.J., Gorsline, D.S., and Edwards, B.D., 1979, A review of mass movement processes, sediment and acoustic characteristics, and contrasts in slope and base-of-slope systems versus canyon-fan-basin floor systems, in Doyle, L.J., and Pilkey, O.H., eds., Geology of Continental Slopes: Soc. Econ. Paleontologists and Mineralogists Spec. Pub. 27 p. 61-73.

Olson, R.E., 1974, Shearing strengths of kaolinite, illite, and montmorillonite: Jour. Geotech. Eng. Div. ASCE, v. 100, p. 1215-1229.

Prior, D.B., and Suhayda, J.N., 1979, Application of infinite slope analysis to subaqueous sediment instability, Mississippi delta: Eng. Geol., v. 14, p. 1-10.

Pusch, R., 1973, Influence of organic matter on the geotechnical properties of clays: Natl. Swedish Bldg. Res. Doc. 11, 64 p.

Ross, D.A., 1971, Mass physical properties and slope stability of the sediments of the northern Middle America Trench: Jour. Geophys. Res., v. 76, p. 704-712.

Seed, H.B., 1968, Landslides during earthquakes due to soil liquefaction: Jour. Soil Mech. and Found. Div. ASCE, v. 94, SM5, p. 1055-1122.

Smith, R.L., 1968, Upwelling: Mar. Biol. Ann. Rev., v. 6, p. 11-46.

Smith, R.L., 1978, Physical oceanography of coastal upwelling regions. A comparison: Northwest Africa, Oregon, and Peru: Symposium on the Canary Current: Upwelling and Living Resources, Intl. Council for the Exploration of the Sea, Las Palmas, Canary Islands.

Summerhayes, C.P., Bornhold, B.D., and Embley, R.W., 1979, Surficial slides and slumps on the continental slope and rise of South West Africa: A reconnaissance study: Mar. Geol., v. 31, p. 265-277.

Taylor, D.W., 1948, Fundamentals of Soil Mechanics, New York, Wiley, 700 p.

Terzaghi, K., 1956, Varieties of submarine slope failures: Proc. 8th Texas Conf. Soil Mechanics and Foundation Engineering, no. 29, 40 p.

Zuta, S., and Guillen, O., 1970, Oceanographia de las aquas costeras del Peru: Instit del Mar. de Peru Vol., v. 2, p. 159-323.

Zuta, S., Rivera, T., and Bustamante, A., 1978, Hydrologic aspects of the main upwelling areas off Peru, in Boje, R., and Tomczak, M., eds., Upwelling Ecosystems: New York, Springer - Verlag, p. 235-260.