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Geotechnical properties of Antarctic deep sea sediments

by

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With 11 figures and 1 table

Sedimentphysikalische Eigenschaften antarktischer Tiefseesedimente

Zusammenfassung

An zwei ungestörten, für das durchteufte Meeresbodenprofil repräsentativen Sedimentkernen aus dem atlantischen Sektor der westlichen Antarktis wurden sedimentphysikalische und sedimentologische Untersuchungen durchgeführt.

Sedimentkern 14882-2 (1951 m Wassertiefe) stammt aus einem abgeschlossenen Becken innerhalb der Bransfield-Straße. Die Sedimente dieses Kernes bestehen aus feinkörnigem hemipelagischem Material und Turbiditablagerungen. Kern 14875-1 (2914 m Wassertiefe) stammt vom nordwestlichen Kontinentalhang der Weddell-See und ist durch typisch glazialmarines Sediment gekennzeichnet. Die Veränderung der sedimentphysikalischen Eigenschaften mit zunehmender Sedimentauflast und/oder wechselnder Lithologie wird diskutiert.

Mit zunehmender Sedimentauflast wurden nur geringe Änderungen der sedimentphysikalischen Eigenschaften beobachtet. So nimmt im Kern 14882-2 die Porosität um 0,7 % pro Meter, der natürliche Wassergehalt um 6 % pro Meter ab. Das Feuchtraumgewicht sowie die Scherfestigkeit erhöhen sich um 0,015 g/cm³ bzw. 0,5 KPa pro Meter.

Verglichen mit diesen geringen Änderungen, die auf die Kompaktion zurückzuführen sind, bewirken lithologische Wechsel extreme Änderungen der sedimentphysikalischen Eigenschaften. In einer Turbiditlage des Kernes 14882-2 nimmt der natürliche Wassergehalt um 100 %, die Porosität um 14 % ab und das Feuchtraumgewicht erhöht sich um 0,23 g/cm³, verglichen zum homogenen Sediment ober- und unterhalb dieser Turbiditlage.

Im Kern 14875-1 wurden zwei Erosionsdiskordanzen nachgewiesen. Die Mächtigkeit des erodierten Materials beträgt jeweils etwa 10 m. Die in diesem Kern vorkommende Eisbergfracht verursacht eine generell niedrigere Porosität (64 %), einen niedrigeren natürlichen Wassergehalt (75 %) sowie ein generell höheres Feuchtraumgewicht (1,55 g/cm³) und ein höheres spezifisches Gewicht (2,62 g/cm³), verglichen mit dem Kern von der Bransfield-Straße (Porosität 77 %, natürlicher Wassergehalt 151 %, Feuchtraumgewicht 1,34 g/cm³, spezifisches Gewicht 2,47 g/cm³).

Abstract

Sedimentological and geotechnical analyses were carried out on two undisturbed large diameter deep sea cores from the Antarctic sector of the Atlantic ocean. One core, from a silled basin within the Bransfield Strait is characterized by fine grained hemipelagic material and turbidite layers. The other core, from the continental slope of the Weddell Sea represents a typical glacial marine environment. The variations of physical properties as related to both an increasing overburden pressure (or depth below top of core) and/or to lithological changes are discussed.

With increasing overburden pressure only small variations of physical properties were observed. In core 14882-2 the porosity decreases 0.7 % per meter, the natural water content 6 % per meter. The wet bulk

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density and the shear strength increase with rates of 0.015 g/cm³ and 0.5 KPa per meter.

Compared to small variations in consolidation, the changes of the lithology cause more extreme variations of physical properties: e.g. decreases the natural water content by 100 %, the porosity by 14 %, and the wet bulk density increases by 0.23 g/cm³ due to a turbidite layer in the core from the Bransfield Strait (core 14882-2).

In the core from the continental slope of the Weddell Sea (core 14875-1) two major unconformities have been detected. The ice-rafted debris of this core causes a generally lower porosity (64 %), a lower natural water content (75 %), a higher wet bulk density (1.55 g/cm³) and specific grain density (2.62 g/cm³), compared to the core from the Bransfield Strait (porosity 77 %, natural water content 151 %, wet bulk density 1.34 g/cm³, specific grain density 2.47 g/cm³).

1. Introduction

During the last few years, there has been increasing interest in the physical properties of marine sediments, particularly in relation to acoustic stratigraphy, paleoceanography, and pore water geochemistry (HAMILTON 1976, THIEDE et al. 1982). Also, the determination of physical properties serves as a framework for submarine slope stability analyses (PRIOR & COLEMAN 1984).

The comparison of physical properties from different sedimentary environments of the world's oceans also leads to a better understanding of consolidation processes of the younger sediments within these environments. It is also possible to detect general trends, which occur in every sedimentary environment (KELLER 1968, 1971, 1974, KELLER & LAMBERT 1972, KÖGLER 1967, BRYANT et al. 1974).

The aim of this paper is to show the variations of geotechnical properties with increasing overburden pressure (or burial depth) in a region of the ocean, characterized by a high biological primary production, the development of strong bottom currents, low carbonate contents and glacial influences.

2. Working area

The cores, described here, were aquired during R.V. "Meteor" cruise 56, leg 3 as a part of the German Antartic Expedition 1980—1981 (Fig. 1).

Core 14875-1 ("Meteor" station 224, length 705 cm, water depth 2914 m, longitude 052° 16.4′ W, latitude 62° 14.2′ S) was retrieved from the north westerly continental slope of the Weddell Sea (Fig. 1).

Core 14882-2 ("Meteor" station 278, length 1150 cm, water depth 1951 m, longitude 057° 38.7′ W, latitude 62° 16.5′ S) is from a silled basin within the Bransfield Strait (Fig. 1).

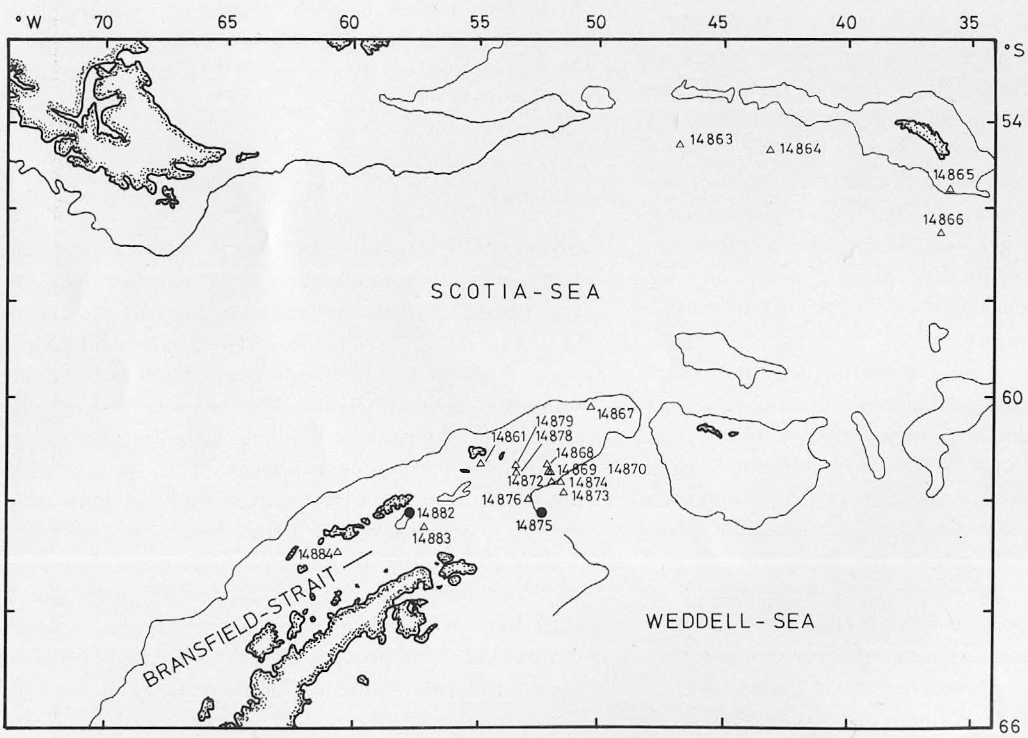

Fig. 1. Station map of R.V. "Meteor" cruise 56/3 (locations of core 14875-1 and 14882-2 are marked by full dots.

Abb. 1. Stationskarte „Meteor" Reise 56/3.

3. Methods and definitions

In order to avoid misinterpretations related to core shortening and mechanical disturbances (RICHARDS 1961), undisturbed long sediment cores are required for the measurement of physical properties. HVORSLEV (1949) recommended three useful design criteria for coring tools, in order to obtain undisturbed sediment samples. These are (1) the inside clearence ratio c_i, controlled by the inside friction, (2) the outside clearence ratio c_o, controlled by the outside friction of the core barrel and (3) the area ratio c_a. This is the ratio between the volume of displaced sediment to the volume of the sample. For quantitative data see KÖGLER (1963).

The cores discussed in here, were required using a modified kastencorer (KÖGLER 1963), a gravity corer without piston and a rectangular cross section (30 cm × 30 cm). The length of this corer is 11.5 m. Due to the very small thickness of the core barrel (thickness of walls 0.2 cm) and the great cross sectional area (900 cm^2), HVORSLEV's recommendations for undisturbed sampling are fulfilled. The degree of undisturbance was also verified by X-ray radiographs.

Physical properties (shear strength, wet bulk density, natural water content, etc.) were determined immediately after retrieval of the coring device.

The determinations were carried out on samples from all different lithological units of the cores. The spacings of the samples in homogeneous parts of the cores was roughly every 50 cm.

Further subsamples for shore laboratory analyses (grain size distribution, Atterberg limits, etc.) were taken.

The grain size analyses were carried out by standard pipette method.

The mineralogy of the clay size fraction (< 0.002 mm) from selected samples were examined using the Philips X-ray diffractometer.

The natural water content (%-dry weight) was determined by drying special cylinder samples (10 cm^3) at 105 °C—110 °C, and calculated by means of the following equation:

$$w_c = M_w/M_s \cdot 100\ (\%)$$

w_c = natural water content, M_w = mass of water, M_s = mass of solids. Salt corrections have not been made.

The wet bulk density was determined from the cylinder samples, taken for the natural water content and calculated as follows:

$$\gamma_w = M_t/V_t\ (g/cm^3)$$

γ_w = wet bulk density, M_t = total mass (= mass of water (M_w) + mass of solids (M_s)), V_t = total volume.

The specific grain density (G_s) was determined using the Beckmann air comparison pycnometer

$$G_s = M_s/V_s\ (g/cm^3)$$

G_s = specific grain density, M_s = mass of solids, V_s = volume of solids.

The porosity (n) was calculated from the void ratio (e), using the equations from RICHARDS (1962):

$$n = (e/1 + e) \cdot 100\ (\%)$$

n = porosity, e = void ratio.

The void ratio (e) is defined as the volume of voids to the volume of solids in a sample.

$$e = V_v/V_s = ((G_s \cdot \gamma_{H_2O} \cdot V_t)/M_s) - 1$$

e = void ratio, V_v = volume of voids, V_s = volume of solids, V_t = total volume, M_s = mass of solids, G_s = specific grain density, γ_{H_2O} = density of water.

The effective overburden pressure (P_o) was calculated for every depth interval using the equation from RICHARDS (1962):

$$P_o = \gamma_b \cdot d\ (KPa)$$

P_o = effective overburden pressure, γ_b = boyant unit weight (wet bulk density — density of water), d = depth below sea floor.

The undrained shear strength in the natural and in the remolded state was determined by means of a miniature vane test device (Rotationsviskosimeter, RV 3 Haake). The size of the vane was 10 mm × 8.8 mm and the speed of rotation was 4 rpm. On each sample 5 to 8 determinations were carried out.

The sensitivity is defined as the quotient between the undrained shear strength in the natural state and the remolded state.

The C/P-ratio is the relationship between the undrained shear strength and the present effective overburden pressure. The C/P-ratio for each depth interval of the cores has been determined.

The Atterberg limits (liquid limit, plastic limit) were determined following the methods suggested by RICHARDS (1962), except drying the samples before the determination. The liquid limit represents the boundary between the liquid and the plastic state of a sediment, whereas the plastic limit is defined as the boundary between the plastic and the stiff state.

The plasticity index is defined as the difference between the liquid and the plastic limit and indicates the range of the natural water content in which the sediment behaves plastic.

The activity (A) is defined as the relationship between the plasticity index and the percentage of the clay size fraction (< 0.002 mm)

$$A = I_p/\%\text{-clay size fraction}$$

I_p = plasticity index.

The carbonate content and the content of organic carbon were determined using the LECO WR 12 automatic carbon determinator.

Because most carbonate is generally bonded with calcium to form calcium carbonate, the carbonate content is taken to be the same as % $CaCO_3$.

All laboratory determinations were at least carried out twice.

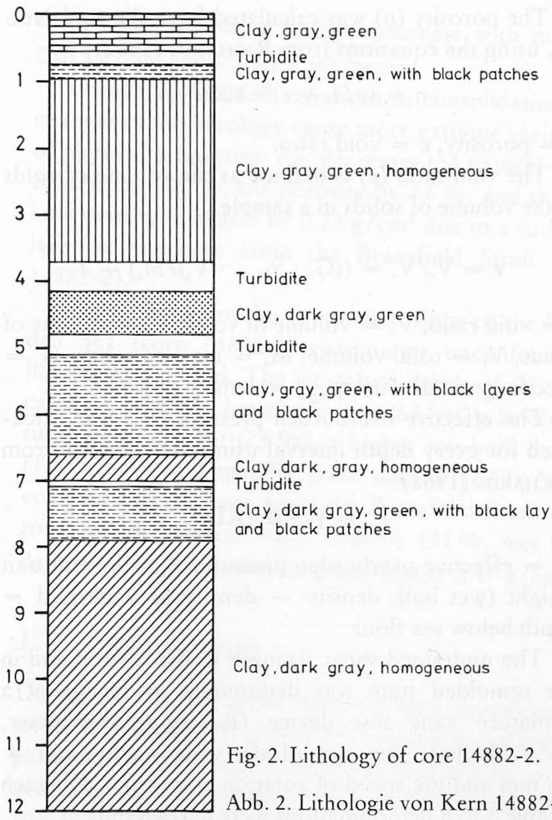

Fig. 2. Lithology of core 14882-2.

Abb. 2. Lithologie von Kern 14882-2.

Remarks

In core 14882-2 degassing cracks were observed below a depth of 250 cm. This degassing of the core caused an increase in the volume of the core and the geotechnical properties, including the volume of the sample (wet bulk density, natural water content) may show somewhat smaller values; e.g., the natural water content, determined by the cylinder technique, shows about 5 % lower values than the natural water content, determined from disturbed material.

4. Results

4.1. Lithology and clay mineralogy

Visual description and the evaluation of X-ray radiographs reveals that core 14882-2 mainly consists of homogeneous silty clay and turbidite layers (Fig. 2). The homogeneous sediments are mainly composed of fecal pellets and are characterized by abundant siliceous microfossils (50—90 % in the sand size fraction). The turbidite layers (15 cm to 44 cm thick) consist of terrigeneous material, volcanic ashes, and glass shards as revealed by sediment petrographic techniques (HOLLER 1981). Small branch-like sulphide grains are concentrated between 720 cm and 750 cm

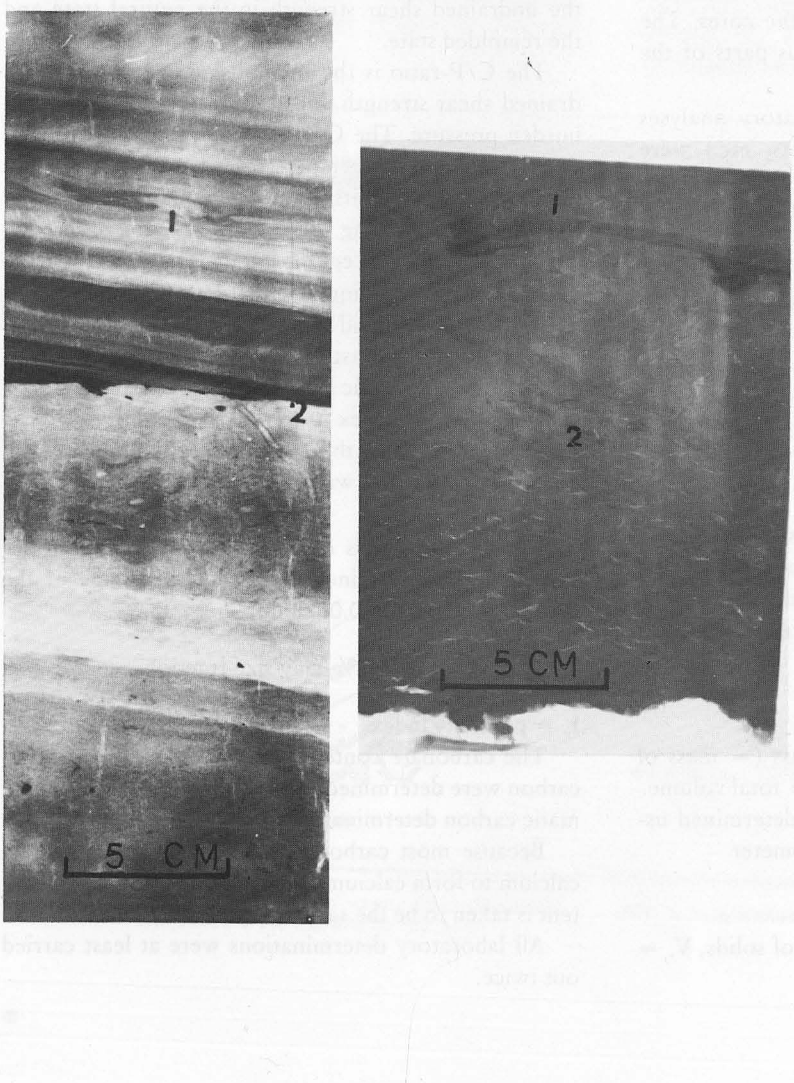

Fig. 3. X-ray radiographs (positives) of core 14882-2.
a) depth 705—739 cm. The X-ray radiograph shows a turbidite layer of core 14882-2. 1 = diapiric load cast, 2 = erosional unconformity beneath parallel bedded sediments. Note vertical degassing cracks over the whole depth interval. Scale = 5 cm.
b) depth interval 1122—1140 cm. Homogeneous sediments with horizontal degassing cracks (2) and a dark (= denser) load structure (1). Scale bar = 5 cm.

Abb. 3. Radiographie von Kern 14882-2.
a) Kernteufe 705—739 cm, Turbiditlage, vertikale Entgasungsspuren. 1 = diapirähnliche Belastungsmarke, 2 = Erosionsdiskordanz. Maßstab = 5 cm.
b) Kernteufe 1122—1140 cm, homogenes Sediment mit horizontalen Entgasungsspuren und dunkleren Belastungsmarken. Maßstab = 5 cm.

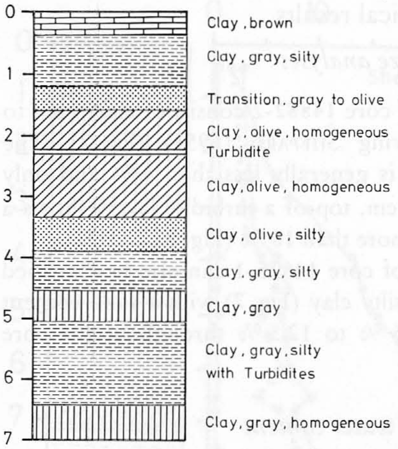

Fig. 4. Lithology of core 14875-1.
Abb. 4. Lithologie von Kern 14875-1.

Fig. 5

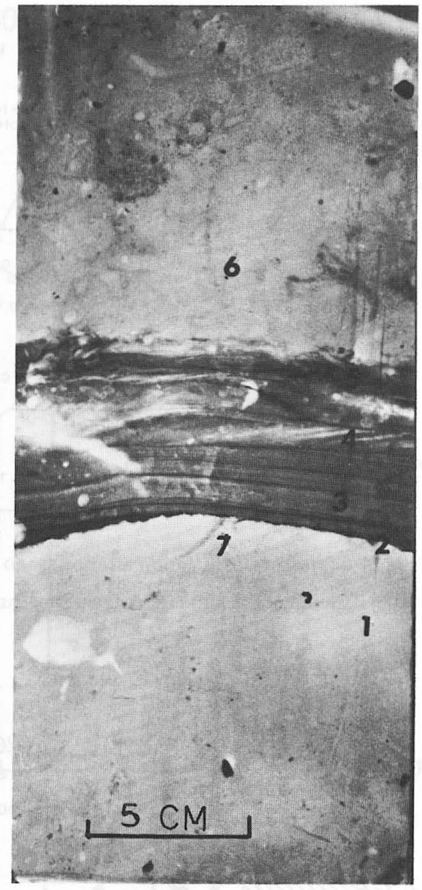

Fig. 6

Fig. 5. X-ray radiograph (positive) of small turbidite layer of core 14875-1 (214—241 cm). 1 = homogeneous sediments, 2 = erosional unconformity, 3 = laminated sequence, 4 = cross bedded material, 5 = upper parallel laminae, 6 = bioturbated homogeneous sediments, 7 = truncated burrow. Note also the occurrence of small unrounded pebbles. Scale bar = 5 cm.

Fig. 6. X-ray radiograph (positive) of core 14875-1 (depth interval 131—159 cm below top of core). This figure shows intensive bioturbated sediments and the occurrence of small unrounded pebbles (ice-rafted debris) over the whole depth interval. Scale bar = 5 cm.

Abb. 5. Radiographie von Kern 14875-1, Kernteufe 214—241 cm. 1 = homogenes Sediment, 2 = Erosionsdiskordanz, 3 = laminierter Bereich, 4 = Kreuzschichtung, 5 = obere Parallelschichtung, 6 = bioturbates, homogenes Sediment, 7 = verfüllter Wühlgang. Maßstab = 5 cm.

Abb. 6. Radiographie von Kern 14875-1, Kernteufe 131—159 cm. Intensive Bioturbation und Eisfracht-Sedimentpartikel.

depth below top of the core. Degassing cracks start at a depth of 250 cm. The amount of bioturbation is generally weak (Fig. 3).

In core 14882-2 the dominant clay minerals are montmorillonite, illite and chlorite. The amount of quartz and feldspars was only minor, whereas a great amount of X-ray amorphous material has been detected.

Core 14875-1 (Fig. 4) is mainly composed of gray silty clayey sediments and turbidite layers, which are generally thinner (5 cm thickness) than in core 14882-2. The turbidite layer at a subbottom depth of 214 cm (Fig. 5) shows the Bouma sequences (Bouma 1962) "B—C—D—E". Further the examination of the X-ray radiographs revealed the common occurrence of small unrounded pebbles (0.4 cm—0.8 cm diameter) over the whole length of the core (Fig. 6). At a subbottom depth of 500 cm "fist-sized" pebbles occurred. The petrographical examination of these pebbles showed that they are rhyolithes and rhyodacites. The sediment is intensive bioturbated and Planolites, Chondrites, and Zoophycos associations (Wetzel 1979, 1981) were observed (Fig. 6).

In this core illite is the dominant clay mineral, followed by kaolinite, chlorite, and montmorillonite. The amount of quartz and feldspars in the clay size fraction is high, whereas there exists only little X-ray amorphous material.

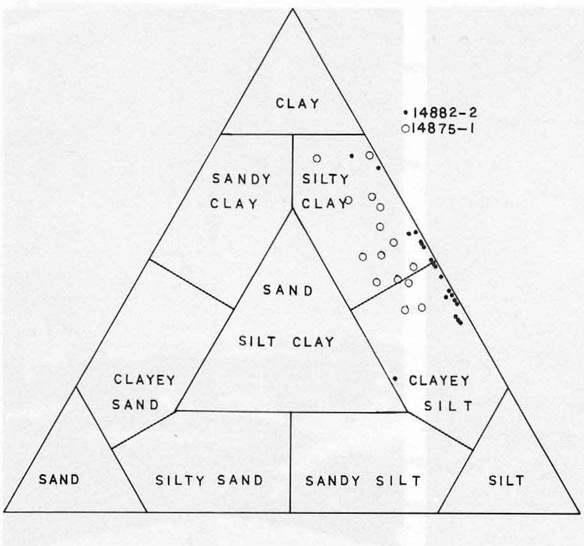

Fig. 7. Sediment classification after SHEPARD (1954).

Abb. 7. Sedimentklassifikation nach SHEPARD (1954).

4.2. Geotechnical results

4.2.1. *Grain size analyses*

The sediments of core 14882-2 consist of clayey silt to silty clay following SHEPARD (1954) (Fig. 7). The amount of sand is generally less than 4 % and only one sample (390 cm, top of a turbidite layer) shows a sand content of more than 18 % (Fig. 8).

The samples of core 14875-1 can also be classified as clayey silt to silty clay (Fig. 7) with a sand content ranging from 1.5 % to 12.5 % throughout the core (Fig. 9).

4.2.2. *Natural water content*

In core 14882-2 the natural water content varies between 226 % and 51 % (%-dry weight). The lowest natural water content is related to a turbidite layer at 390 cm depth. The highest values are related to layers of dark clay with black bands and black patches.

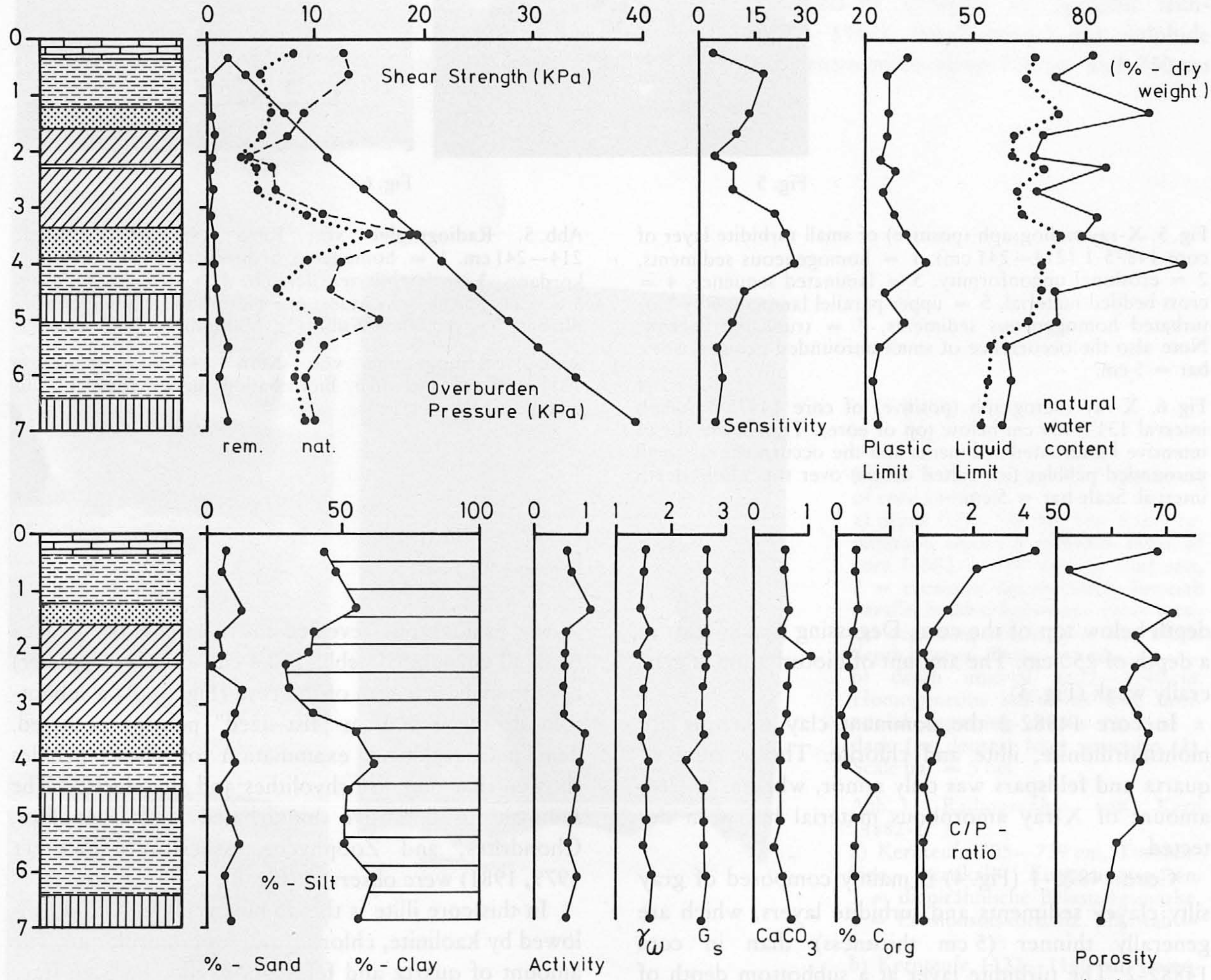

Fig. 9. Geotechnical properties of core 14875-1.

Abb. 9. Sedimentphysikalische Parameter Kern 14875-1.

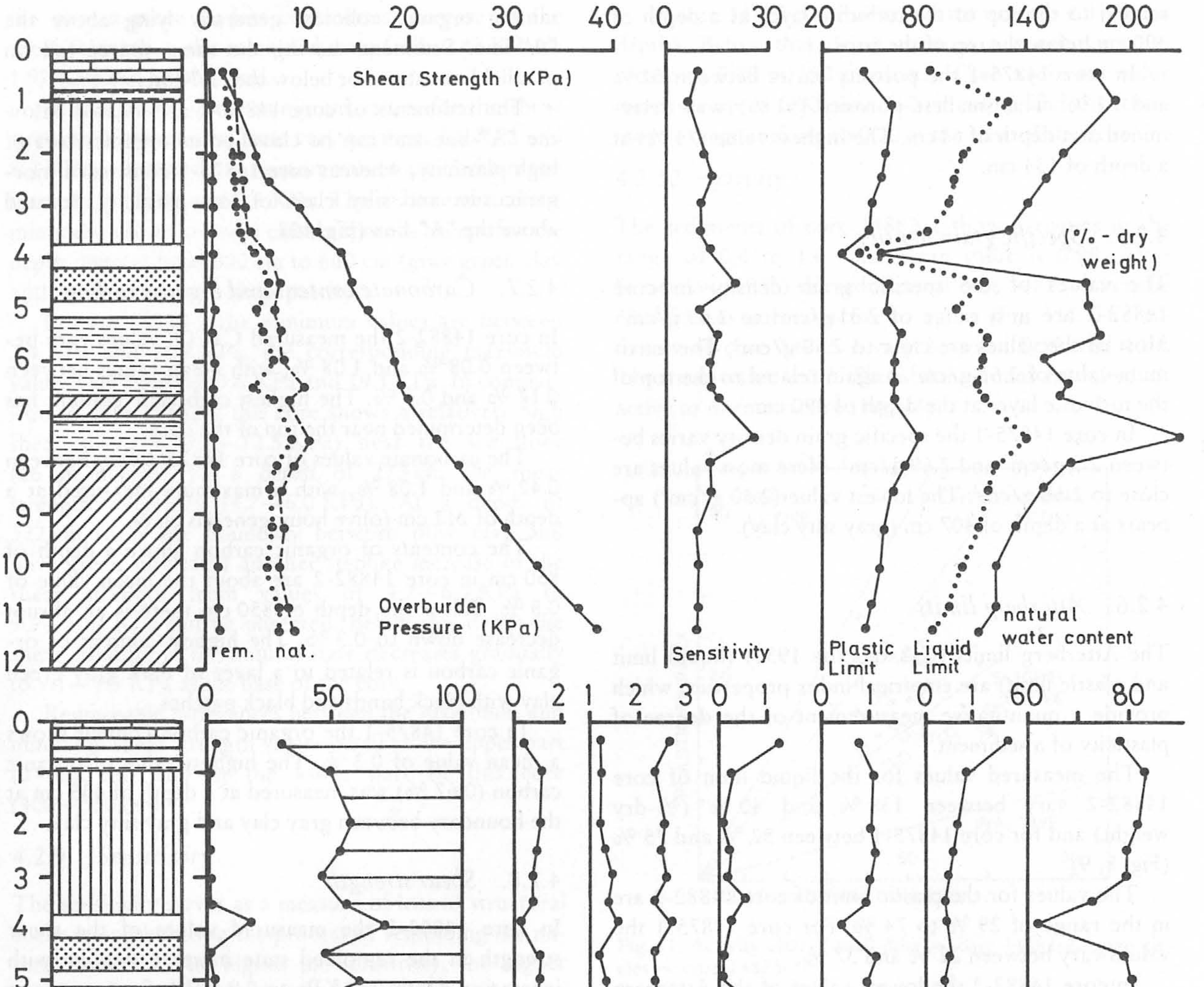

Fig. 8. Geotechnical properties of core 14882-2.

Abb. 8. Sedimentphysikalische Parameter Kern 14882-2.

The values of the natural water content of core 14875-1 vary between 105 % and 57 %. From top of the core to a depth of 400 cm there exists a strong variation between 65 % and 105 %. Below this depth the natural water content decreases to 57 % near the base of the core.

4.2.3. *Wet bulk density*

In core 14882-2 measured values of the wet bulk density vary between 1.15 g/cm^3 and 1.55 g/cm^3. In this core the highest wet bulk density (1.55 g/cm^3) is associated to the top of a turbidite layer (390 cm depth), whereas the lowest value (1.15 g/cm^3) is related to dark gray green clay with black bands and black patches.

In core 14875-1 the values vary between 1.41 g/cm^3 and 1.69 g/cm^3.

4.2.4. *Porosity*

In core 14882-2 the values of the porosity vary between 61 % and 81 %. The minimum value of 61 % is related to the top of the turbidite layer at a depth of 390 cm below the top of the core.

In core 14875-1 the porosity varies between 51 % and 71 %. The smallest porosity (51 %) was determined at a depth of 61 cm. The highest value (71 %) at a depth of 134 cm.

4.2.5. *Specific grain density*

The values of the specific grain density in core 14882-2 are in a range of 2.31 g/cm^3 to 2.63 g/cm^3. Most of the values are close to 2.50 g/cm^3. The maximum value of 2.63 g/cm^3 is again related to the top of the turbidite layer at the depth of 390 cm.

In core 14875-1 the specific grain density varies between 2.3 g/cm^3 and 2.69 g/cm^3. Here most values are close to 2.66 g/cm^3. The lowest value (2.30 g/cm^3) appears at a depth of 407 cm (gray silty clay).

4.2.6. *Atterberg limits*

The Atterberg limits (Casagrande 1932) (liquid limit and plastic limit) are empirical index properties, which provide a quantitative measurement of the degree of plasticity of a sediment.

The measured values for the liquid limit of core 14882-2 vary between 138 % and 40 % (%-dry weight) and for core 14875-1 between 52 % and 75 % (Fig. 8, 9).

The values for the plastic limit of core 14882-2 are in the range of 29 % to 74 %. For core 14875-1 the values vary between 22 % and 37 %.

In core 14882-2 the lowest values of the Atterberg limits were observed at a depth of 390 cm at the top of a turbidite layer. The maximum values occur at a depth of 750 cm and are related to dark gray green clay with black bands and black patches.

In the plasticity chart (Casagrande 1948) the "A"-line represents an empirical boundary between organic clays, generally located below the "A"-line and inorganic silts and silty clays and plastic sediments, containing organic colloids, generally lying above the "A"-line. Sediments having the same source fall on parallel lines above or below the "A"-line.

The sediments of core 14882-2 are located below the "A"-line and can be classified as organic clays of high plasticity, whereas core 14875-1 consists of inorganic silts and silty clays of low plasticity, located above the "A"-line (Fig. 10).

4.2.7. *Carbonate content and organic carbon*

In core 14882-2 the measured $CaCO_3$ values vary between 0.08 % and 1.08 %, with mean values between 0.17 % and 0.6 %. The highest carbonate content has been determined near the top of the core.

The carbonate values of core 14875-1 vary between 0.42 % and 1.08 %, with a maximum measured at a depth of 212 cm (olive homogeneous clay).

The contents of organic carbon above a depth of 850 cm in core 14882-2 are about the mean value of 0.8 %. Below the depth of 850 cm there is an abrupt decrease down to 0.3 %. The highest content of organic carbon is related to a layer of dark gray green clay with black bands and black patches.

In core 14875-1 the organic carbon content shows a mean value of 0.3 %. The highest value of organic carbon (0.67 %) was measured at a depth of 455 cm at the boundary between gray clay and gray silty clay.

4.2.8. *Shear strength*

In core 14882-2 the measured values of the shear strength in the remolded state increase steplike with increasing depth (0.2 KPa to 0.9 KPa). Steps occur at a depth of 390 cm (top of a turbidite layer), 450 cm (upper boundary of dark gray clay), and 750 cm (dark gray green clay with black bands and black patches).

In core 14875-1 the values of the shear strength are generally higher and show a greater variation (0.4 KPa to 2.3 KPa). It is worth noting, that this core possesses the highest value (2.3 KPa) near the top of the core (26 cm depth). From the depth of 61 cm to the base of

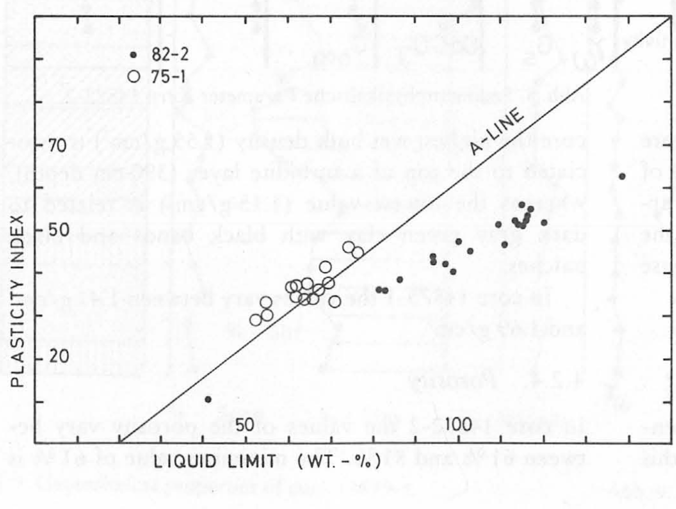

Fig. 10. Plasticity chart.
Abb. 10. Plastizitätsdiagramm.

the core a more or less continuous increase of the shear strength in the remolded state from 0.47 KPa to 1.97 KPa can be observed.

In core 14882-2 the minimum values for the shear strength in the natural state vary between 1.6 KPa and 8.2 KPa, whereas the maximum values are in the range between 2.0 KPa and 9.5 KPa. The maximum and the minimum values are very closely spaced, except for the depth interval from 500 cm to 650 cm (gray green clay with black bands and black patches).

In core 14875-1 the minimum values are between 3.4 KPa and 14.9 KPa, the corresponding maximum values vary between 3.6 KPa and 19.1 KPa. In comparison to core 14882-2 this core shows a relatively high shear strength (7.8—12.3 KPa) near the sea floor (26 cm depth). To a depth of 273 cm the shear strength decreases (4.7—6.0 KPa). At a depth of 322 cm (near the boundary between olive clay and olive green silty clay) another steplike increase of the shear strength from values of 4.7—6.0 KPa to 9.3—10.4 KPa can be observed. Below this depth the shear strength in the natural state decreases gradually to 9.1—9.5 KPa at the base of the core.

Remarkable differences between the maximum and minimum shear strength values occur in the upper part (0—200 cm) and in the lower part of this core (400—550 cm).

4.2.9. *Sensitivity*

The sensitivity serves as a measure of loss of structural shear strength during the process of remolding the natural material. The higher the sensitivity, the higher the loss of structural shear strength. Applying the classification of Rosenquist (1953) to the cores, core 14882-2 is in general slightly quick (loss of structural shear strength 87.5 %—93.8 %). Only the depth interval between 450 cm and 750 cm may be called medium quick (loss of structural shear strength 93.8 %—96.9 %).

The sensitivities of core 14875-1 range between very sensitive (loss of structural shear strength 75 %—87.5 %) and medium quick (loss structural shear strength 93.8 %—96.9 %).

4.2.10. *Overburden pressure*

In core 14882-2 the present effective overburden pressure reaches a maximum value of 37 KPa at a depth of 1120 cm below the top of the core. In core 14875-1 the maximum value is 38 KPa at the depth of 705 cm below the top of the core.

4.2.11. *C/P-ratio*

The C/P-ratio profile of core 14882-2 starts with a value 1.5 near the top of the core (40 cm) and decreases continuously to a value of 0.20 at the depth of 1120 cm.

In core 14875-1 the near surface value is 4.5 (26 cm depth). Below that depth there is a continuous decrease to 0.20 at 350 cm depth. Then again the value increases up to 0.90 near 360 cm depth and decreases more or less uniform to 0.20 at the base of the core.

4.2.12. *Activity*

The sediments of core 14882-2 show activities in the range of 0.4 to 1.6. The mean value is 0.98. After Skempton (1933) the sediment of core 14882-2 may be classified as normal active to active (Fig. 11). The activities of core 14875-1 vary between 0.53 and 1.01. The mean value is 0.7. This sediment may be called inactive to normal active (Fig. 11).

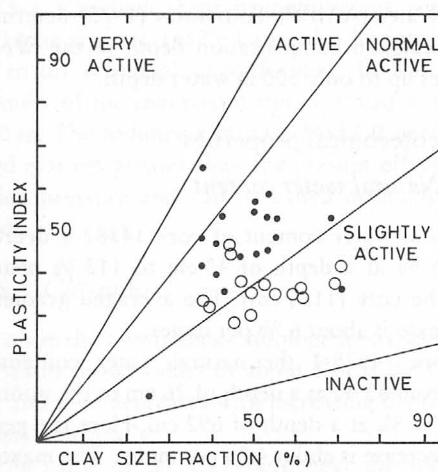

Fig. 11. Activity chart (small dots = core 14882-2, open circles = core 14875-1).

Abb. 11. Aktivitätsdiagramm. Punkte = Kern 14882-2, Kreise = Kern 14875-1.

5. Discussion of results

5.1. Lithology

The sediments of core 14882-2 are classified as diatomaceous ooze (Cooke & Hays 1977), whereas core 14875-1 consists of diatomaceous clay. Cooke & Hays (1977) pointed out that diatomaceous ooze is the characteristic sediment of interglacial periods. Erlenkeuser (pers. comm.) completed a first radiocarbon dating of core 14882-2, which shows that this core consists totally of Holocene sediments. In this core no kaolinite was detected in the clay size fraction, and ice rafted debris is also lacking. The crystallinity of the montmorillonite in this core, measured by the crystallinity index after Biscaye (1965) is also higher than in core 14875-1. Because of this high crystallinity and the occurrence of glass shards and zeolithes it is assumed that the montmorillonite in this core is an alteration product of volcanic material.

Diatomaceous clay is the typical sediment for glacial periods (Cooke & Hays 1977) and is characterized by a high amount of sand sized material and the occurrence of ice rafted debris. The evaluation of X-ray radiographs of core 14875-1 revealed that unrounded pebbles occur throughout the core. The grain size analyses show a significant higher amount of sand sized material, compared to core 14882-2. Because of this texture and the great distance to the continent, the sediments of core 14875-1 are interpreted as glacial marine diatomaceous clay. This interpretation is also strengthened by the occurrence of kaolinite in the clay size fraction, indicating ice berg transport from the Antarctic continent.

Both cores show an extremely low carbonate content. The apparent reason for these very low values is carbonate dissolution by the very aggressive Antarctic Bottom Water (AABW). ANDERSON (1975) determined that the calcium compensation depth in the Weddell Sea comes up to only 500 m water depth.

5.2. Geotechnical properties

5.2.1. *Natural water content*

The natural water content of core 14882-2 decreases from 178 % at a depth of 40 cm to 112 % near the base of the core (1120 cm). The averaged gradient of this decrease is about 6 % per meter.

In core 14875-1 the natural water content decreases from 83 % at a depth of 26 cm to the minimum value of 57 % at a depth of 692 cm. Here the general rate of decrease is about 4 % per meter. The maximum value of 107 % is related to gray silty clay at a subbottom depth of 407 cm.

The generally lower natural water content of core 14875-1 compared to core 14882-2 can be explained by the higher amount of sand sized material of the core.

5.2.2. *Wet bulk density*

In both cores the wet bulk density increases with increasing overburden pressure (or depth below top of core). The rate of increase is 0.015 g/cm^3 per meter for core 14882-2 and 0.016 g/cm^3 per meter for core 14875-1.

There exists also a direct proportionality between the wet bulk density and the amount of sand sized material (core 14882-2, 390 cm depth). The generally higher wet bulk densities of the sediments of core 14875-1 are related to the greater amount of sand sized material of this core, due to ice rafted debris, and to effects of compaction.

5.2.3. *Specific grain density*

The specific grain density of core 14882-2 (2.31 g/cm^3—2.63 g/cm^3) is in the typical range for clayey marine sediments (see RICHARDS 1961, 1962). The low specific grain density at a depth of 350 cm (green gray homogeneous clay) may be due to a high content of siliceous microfossils in the silt size fraction (EINSELE 1982), but no quantitative data are available.

The average specific grain density of core 14875-1 (2.62 g/cm^3) is higher than the average specific grain density of core 14882-2 (2.47 g/cm^3). This higher specific grain density is due to the greater amount of sand sized material in this core, caused by the presence of ice-rafted debris.

5.2.4. *Overburden pressure*

In core 14882-2 the effective overburden pressure increases at a rate of 3.4 KPa per meter, whereas for core 14875-1 an increase of 5.7 KPa per meter was calculated. The effective overburden pressure is greatly influenced by the specific grain density and the degree of compaction, mirrored by the wet bulk density. The generally higher overburden pressure of core 14875-1 compared to core 14882-2 can be explained by the generally higher wet bulk density of this core, caused by the generally higher specific grain density, due to the greater amount of coarse material. But from this two cores alone it is not possible to quantify the influence of the degree of consolidation to the wet bulk density, but the greater gradient of the overburden pressure of core 14875-1 indicates a higher degree of consolidation for this core.

5.2.5. *Atterberg limits*

In both cores the values of the liquid limit are smaller than the natural water content. The average difference between the natural water content and the liquid limit has a value of 50 % (%-dry weight) for core 14882-2 and 10 % for core 14875-1. Although both cores show a higher liquid limit than the natural water content, the samples show a distinctive shear strength and are only liquid in the remolded state. With increasing overburden pressure the liquid limit of core 14882-2 decreases at a rate of 2.8 % per meter, whereas core 14875-1 shows a decrease of 2.1 % per meter. The rates of change for the plastic limit are 1.3 % per meter for core 14882-2 and 1.0 % per meter for core 14875-1.

The generally lower values of the Atterberg limits of core 14875-1 can be related to the greater amount of sand sized material in this core.

5.2.6. *Porosity*

With increasing overburden pressure (or depth below top of core) the porosity of core 14882-2 decreases at an averaged rate of 0.73 % per meter depth, core 14875-1 shows a decrease of 1.3 % per meter. The generally lower porosity of core 14875-1 can be related to the higher amount of sand sized material of this core. A straight correlation between the porosity and the content of sand exists at a depth of 390 cm in core 14882-2, whereas an increasing sand content of up to 18 % causes a reduction of the porosity of over 10 %.

5.2.7. *Undrained shear strength*

5.2.7.1. Remolded state

Due to the remolding of the sample the structural shear strength is greatly destroyed. Because the remaining remolded shear strength is only influenced by grain size distribution, clay mineral composition, content of organic carbon, and pore water geochemistry it can be seen as a "material constant".

In core 14882-2 the remolded shear strength increases continuously with a rate of $6 \cdot 10^{-2}$ KPa per meter. This shear strength profile indicates a more or less continuous sedimentation and the lack of major erosional events (except for the turbidite layer at 390 cm depth).

The shear strength profile of core 14875-1 is totally different. Here the highest values occur near the top of the core and then a steplike increase can be observed. From a depth of 61 cm to the base of the core, the averaged gradient is about 0.2 KPa per meter depth.

5.2.7.2. Natural state

The shear strength in the natural state of core 14882-2 shows an increasing trend with overburden pressure (or depth below top of core). The rate of increase of the average values is 0.5 KPa per meter. The differences between the maximum and minimum values (490—660 cm depth) are a result of coarser layers (turbidites), a different degree of bioturbation, and the occurrence of degassing cracks, caused by the expansion of gas.

Core 14875-1 shows a totally different shear strength profile. The shear strength values are generally higher than in core 14882-2 and show very high values (7.85—12.26 KPa) near the surface of the core (26 cm depth). These high values can neither be explained by a higher content of coarser material, nor by fluctuations in other physical properties. The shear strength in the remolded state also shows a very high value at this depth. Similar high values (14.9—19.0 KPa) have been measured at a depth of 354 cm (near the boundary of olive clay to olive silty clay).

The compression of a sediment under an applied load, such as the accumulation of sediment, is called consolidation or compaction. The consolidation processes cause changes in the microstructure of the sediments (Bryant et al. 1974). These processes are irreversible (Skempton 1964, 1970, McClelland 1956) except for a rebounding of the sediment due to the removal of the overlying material. When the maximum past overburden pressure (preconsolidation stress) is greater than the present effective overburden pressure, the sediment is called overconsolidated. Overconsolidated sediments retain most of their original shear strength. The processes that cause overconsolidation are (1) removal of overlying sediments by erosion, sliding and slumping, (2) desiccation during the Pleistocene low sea level stands, or (3) cementation (Einsele & Werner 1968, Almagor & Wiseman 1977, Holler, in prep., Bjerrum 1973, McClelland 1967, Bryant et al. 1974). For terrigenous sediments, like core 14875-1, it is possible to estimate the thickness of the removed sediments from the shear strength data and the present effective overburden pressure. This estimation shows that sediments with a thickness of up to 10 m must have been removed from top of core 14875-1. The high shear strength values at the depth of 354 cm in core 14875-1 can also be interpreted as due to an erosional unconformity. In this case the thickness of the removed material is also in the range of 10 m. The sediments of core 14882-2 never experienced a stress greater than the present effective overburden pressure and can be called normally consolidated.

5.2.8. *C/P-ratio*

In a normally consolidated homogeneous sediment the C/P-ratio shows values of about 1 near the top or the core and then decreases with increasing depth more or less asymptotically.

The value of the C/P-ratio near the top of core 14882-2 (40 cm depth) is 1.5. This slightly higher value can be explained by consolidation, caused by burrowing organisms. Between 400 cm and 470 cm depth small steps occur in the C/P profile. These small steps are mainly related to the deposition of turbidite layers.

The strong irregularities in the C/P profile of core 14875-1 are related to the overconsolidated depth intervals of this core. This observation coincides with the occurrence of unconformities, as discussed in the shear strength section.

5.2.9. *Activity*

In both cores the activity is directly related to the composition of the clay minerals. The higher activities of core 14882-2 are caused by the dominant clay mineral montmorillonite in the clay size fraction.

5.3. Influence of lithological changes on physical properties

In order to show the influence of lithological changes, the geotechnical properties of a turbidite layer (390 cm below top of core) and a layer of dark gray green clay with black bands and black patches (750 cm depth) of core 14882-2 are discussed and compared to the geotechnical properties just above and below this layers.

Table 1. Comparison between influence of compaction and influence of lithological changes on geotechnical properties of core 14882-2 (γ_w = wet bulk density, G_s = specific grain density, n = porosity, τ_{nat} = shear strength in the natural state). — = decrease, + = increase.

Tabelle 1. Einfluß von Kompaktion und Lithologie auf die sedimentphysikalischen Eigenschaften von Kern 14882-2. γ_w = Feuchtraumgewicht, G_s = spezifisches Gewicht, n = Porosität, τ_{nat} = Scherfestigkeit.

	W_c (%-dry)	γ_w (g/cm³)	G_s (g/cm³)	n (%)	τ_{nat} (KPa)	τ_{rem} (KPa)
Trends, due to compaction (per meter overburden pressure)	− 6	+0.015	—	−0.73	+0.5	+0.06
Lithological change:						
I: turbidite	−100	+0.23	+0.3	−14	—	+0.41
II: dark layer	+ 60	—	−0.05	—	−1.5	−0.20

5.3.1. *Turbidite layer*

The sample at a depth of 390 cm was taken from the upper part of a turbidite layer. This part of the turbidite could be classified as division D (upper parallel laminae) of the Bouma sequence (Bouma 1962), by means of X-ray radiographs.

The content of sand sized material (18 %) increases dramatically compared to the host sediments (0.38 %—0.39 %) and causes a decrease of the natural water content from 130 % (above) and 173 % (below) to the value of 52 %. Similar drastically variations occur for the Atterberg limits. The porosity of the turbidite layer is 10—18 % lower than in the host sediments (72 %—79 %). The wet bulk density is 0.14 g/cm³—0.32 g/cm³ higher, compared to the wet bulk densities just above and below the turbidite layer (1.41—1.23 g/cm³). The specific grain density increases in the turbidite layer by a value of up to 0.3 g/cm³. The undrained shear strength in the natural state is not influenced by the turbidite layer, but the shear strength in the remolded state increases from values of 0.36 KPa to 0.45 KPa. This is in agreement with shear strength measurements from sandy turbidite layers (Keller & Lambert 1972) and can be related to the higher sand content of the samples.

The content of organic carbon (0.35 %) is generally smaller than in the host sediments (0.7—1.03 %), and the activity is reduced to 0.4 (0.8—1.1). Most of the above mentioned changes in the geotechnical properties are due to the increased content of sand sized material.

5.3.2. *Dark layer*

The dark gray green layer with black bands and black patches at a depth of 750 cm shows the highest natural water content (226 %) and Atterberg limits (liquid limit 138 %, plastic limit 74 %) of core 14882-2. Compared to homogeneous sediments above and below, the natural water content is increased by 60 %, the liquid limit by 20 %, and the plastic limit by 7—15 %. The specific grain density is only slightly lower (2.4 g/cm³ compared to 2.45—2.48 g/cm³). The wet bulk density and porosity are not influenced by this lithological change, but the content of organic carbon is increased by 0.20 % (homogeneous sediments 0.90—0.96 %). The average values of the shear strength in the natural state are 1.5 KPa higher than in the surrounding sediments (7.0—7.11 KPa), and the shear strength in the remolded state is roughly 0.20 KPa lower (0.53—0.59 KPa). The activity shows the highest value of core 14882-2 (1.63) and is increased by 0.64—0.86, compared to the homogeneous sediments above and below this layer. Although the content of clay sized material has only a value of 39 % (54—69 % in homogeneous sediments), X-ray diffractometric analyses revealed that montmorillonite is the major clay mineral of this layer. The high natural water content and the higher amount of organic carbon can be explained by the higher capability of bonding these constituents, due to the higher surface activity of montmorillonite, compared to other clay minerals.

Another explanation could be a higher amount of biogenous opaline in the silt size fraction. The higher values of the shear strength in the natural state and the relatively high porosity (80 %) would point into that direction (Einsele 1982).

A comparison between the influence of compaction and the influence of lithological changes to the geotechnical properties of core 14882-2 reveals, that the influence of compaction causes only small changes of the geotechnical properties, whereas lithological changes cause abrupt variations (Table 1).

6. Summary

Geotechnical and sedimentological analyses were carried out on two large diameter undisturbed kastencores. The determination of physical properties which may alter during transport and storage (shear strength, natural water content, etc.) were carried out immediately after the coring device was retrieved.

Core 14875-1

Core 14875-1 was located on the north westerly continental slope of the Weddell Sea (water depth 2914 m) and consists of typical glacial marine sediments.

1. The typical Antarctic glacial marine sediments influence the geotechnical properties, due to the great amount of sand sized material as follows:

The natural water content, Atterberg limits, and the porosity are smaller, compared to sediments with less sand sized material. The wet bulk density and the specific grain density increase due to the greater amount of coarse material.

2. Two major unconformities have been detected by measurements of the shear strength. The thickness of the eroded material is estimated to be in the range of 10 m for each unconformity. The occurrence of this unconformities strongly strengthens the interpretation of the sediments as diatomaceous clay in the sense of COOKE & HAYS (1977).

3. Low activities can be related to the dominance of illite and chlorite in the clay size fraction.

Core 14882-2

Core 14882-2 (water depth 1951 m) has been retrieved from a silled basin within the Bransfield Strait, south of King George Island. The sediments are interpreted as diatomaceous ooze (COOKE & HAYS 1977) and are characterized as follows:

1. Due to the lack of coarse material (except turbidite layers) the values of the natural water content (226 %), the Atterberg limits, and the porosity (80 %) are higher than in core 14875-1. The wet bulk density and the specific grain density are generally lower.

2. In this core, no major erosional hiatuses were detected and (except for the turbidite layers) a more or less continuously sedimentation is assumed.

3. High values of the activity (up to 1.6) can be related to the dominance of montmorillonite in the clay size fraction.

General trends

With increasing overburden pressure (or depth below top of the cores) only small variations of physical properties can be observed. The porosity decreases 0.7—1.3 % per meter, the natural water content by 4—6 % per meter. The wet bulk density increases at a rate of 0.015 g/cm^3 per meter and the shear strength in the natural state at 0.5 KPa per meter.

In contrary to these smooth changes, the lithological variations have a more dramatically influence on the geotechnical properties. A change of the natural water content of 100 % can, e.g., be observed at a depth of 390 cm in core 14882-2, due to a turbidite layer. This turbidite layer also causes an increase of 0.23 g/cm^3 to the wet bulk density and of 0.3 g/cm^3 to the specific grain density. This is a much greater scatter of data than one would expect from the influence of compaction on the physical properties alone.

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