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The primary objective of this research was to delineate clay fabric microfeatures in sediment samples obtained by the use of a pressure core barrel. A secondary objective was to evaluate the difference in clay fabric between pressure core barrel samples and conventional core samples, and to enhance the understanding of the clay fabric of fine-grained gassy sediments.

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CHAPTER 37

Clay Fabric of Gassy Submarine Sediments

W.A. Chiou, William R. Bryant, and Richard H. Bennett

Introduction

Objectives

The primary objective of this research was to delineate clay fabric microfeatures in sediment samples obtained by the use of a pressure core barrel. A secondary objective was to evaluate the difference in clay fabric between pressure core barrel samples and conventional core samples, and to enhance the understanding of the clay fabric of fine-grained gassy sediments.

Historical Review and Previous Works

Geologists have long been interested in the fabric of sediments, in particular the fabric of clastic sediments, but chiefly on large grain-sized particles such as sands, gravels, and tills. Study of the fabric of fine-grained argillaceous sediments has been in abeyance due to the extremely fine texture and complex composition of these sediments, and the necessity of high-resolution techniques to delineate individual particles. Although Henry Clifton Sorby, the father of sedimentology, presented the first microscopic study of rocks by means of thin section as early as 1851, it appears to be true, as Burnham (1970) stated, "Many geological authors . . . have been content to describe the large particles, and to dismiss the finer materials as a featureless intergranular paste of very finely crystaline materials."

The early interest in clay fabric study arose from attempts to determine the relationship between clay particle arrangement and the mechanical properties of soil. The early concepts of clay fabric were conceived by Terzaghi (1925), Goldschmidt (1926), and Casagrande (1932). Since then, clay fabric research has been carried out sporadically primarily by civil engineers, soil scientists, and geologists. A very comprehensive and informative literature review tracing the history of clay fabric study, from early concept through current knowledge to the future perspective, has been published by Bennett et al. (1977) and Bennett and Hulbert (1986). Moon (1972) also reviewed some of the early clay fabric concepts, particularly in the microstructure of fresh clay and compacted clays. A large collection of different soil fabrics accompanied with a comprehensive review and description of sample preparation techniques, including techniques for quantifying the results was published by Smart and Tovey (1981, 1982).

During the last 15 years, due to the realization that the fabric of a clay fundamentally affects a soil's mechanical behavior, and to the availability of the electron microscope as a tool to study clay microfeatures, research on clay fabric has been gaining momentum significantly. Excellent studies were presented at several international meetings, such as the Southeastern Asian Conference on Soil Engineering in 1970 and 1971, the Roscoe Memorial Symposium (Parry, 1971), the Third International Conference on Expansive Soils in 1973, the International Symposium on Soil Structure (Barden and Pusch, 1973), the Fourth International Working-Meeting on Soil Structure (Rutherford, 1974), a symposium held at the Third Meeting of Geological Societies of the British Isles (Whalley, 1978), and the 8th International Clay Conference (Schultz et al., 1987). Papers presented in these meetings demonstrated the significance of using electron microscope techniques, and the important role that clay fabric plays in the mechanical behavior of soils.

The published record contains few reports of studies dealing with the fabric of natural sediments in contrast to numerous studies of laboratory-prepared sediment samples. The use of laboratory-prepared pure clay specimens with different microfabric features could lead to misinterpretation of the mechanical behavior of natural soils (Collins and McGown, 1974). Furthermore, during the past few years, several geologists have begun to focus their attention on the relationships between clay fabric and depositional environments (O'Brien and Hisatomi, 1978; Bennett et al., 1977, 1980; Chiou et al., 1980; O'Brien et al., 1980; Shephard et al., 1980, 1982), particularly in solving sedimentary facies problems. Thus, it is important that specific, quantitative studies on natural sediments from different environments be carried out to fully understand the nature of the fabric in a natural environment. However, due to the limitations of both coring devices and laboratory instruments, undisturbed clay fabric has been difficult to obtain. This is especially true for deeply buried, gassy sediments in which clay fabric may have changed due to the release of hydrostatic pressure. Thus, it is important to determine the clay fabric of gassy sediments that have not been affected by the loss of downhole pressure, and to compare these results with those of studies performed using conventional methods.

Theoretical Considerations

Definitions and Terminology

As a result of the increasing number of clay fabric studies in different scientific disciplines, and the broad variety and complexity of fabrics that have been observed, there has been a proliferation of terms for the description of fabrics and fabric features. To prevent an overlap in meaning of terms with previous investigators, a brief explanation of a few key terms is given herein, and will be used in presentation of the results and interpretations in this report.

Clay fabric: Fabric, as used by sedimentary petrologists, refers to "the orientation in space of the elements of which a sedimentary rock is composed" (Gary et al., 1972). A fabric element of a sedimentary rock may be a single crystal, a detrital fragment, a fossil, or any component that behaves as a single unit with respect to an applied force (Fairbairn, 1949). Thus, fabric constitutes three-dimensional patterns in space, and includes factors such as packing, boundary relationships, discontinuities, grain size, or the presence or absence of a matrix, shape and roundness of particles, and orientation. In this study, the fabric elements are composed mainly of clay-size particles (<4 µm). Thus, clay fabric refers here to the spatial distribution, orientation, and particle-to-particle relationships of the <4-µm solid particles (mainly clay minerals) in the sediment (Bennett, 1976).

Domain: A stack of face-to-face or slightly stepped face-to-face parallel clay plates (Aylmore and Quirk, 1960, 1962; Bennett et al., 1977). It is essentially the same as the so-called book or packet structure of Sloane and Kell (1966). An array of such aggregates is referred to as turbostratic fabric (Biscoe and Warren, 1942; Olsen, 1962). Yong and Sheeran (1973) describe the grouping of domains or aggregates into larger fabric units as clusters.

Floccule or floc: A well-defined clay aggregate composed of several particles or domains having spatial arrangements and particle contacts that produce relatively large intravoids relative to the thickness of the individual particles that compose the floc (Bennett et al., 1977). In general a floc consists of a very porous network of randomly oriented clay flakes or clumps of flakes. Also, it may be composed of numerous face-to-face flocculated flakes arranged in a cluster in a stairstep fashion (O'Brien, 1971).

Chain: A series of clay particles or domains that link together in stepped face-to-face and/or edge-to-edge contact (Bennett et al., 1977). Chains normally appear to be long and continuous. A three-dimensional network of twisted chains of clay platelets having a stepped face-to-face association is termed stairstep cardhouse fabric (O'Brien, 1971).

Particle: A well-defined entity that is resolved by electron microscopy. It can be a single clay platelet or several platelets forming a domain. The particle can be thought of as the elementary unit or building block of clay fabric (Bennett et al., 1977).

All the terms described here and applied in this research are strictly descriptive and do not imply mode of formation.

Assumptions

Clay fabric research involves sampling, sediment drying, embedding, ultrathin sectioning, and the use of various electron microscopy techniques. Due to the soft gassy nature of the sediments in question and some inherent limitations of the techniques, several assumptions must be made:

1. No mineralogical changes result from the slight temperature but relatively low pressure change and the substitution of interstitial water with different fluids (ethyl alcohol and amyl acetate) during the replacement process prior to critical point drying. Studies reported by Range et al. (1969) and results of mineralogical studies by the author from Lee (1980) have demonstrated the stability of clay minerals under similar temperatures and pressures as used in this study.
2. No significant fabric changes result from the build-up of pressure in the critical point-drying chamber or high local pressure in the specimen. To prevent this type disturbance, the final stage of the critical point-drying procedure was performed very slowly as suggested by Tovey (1970) and should have little effect on fabric features (Tovey and Wong, 1973, 1978; Wong, 1975; Smart and Tovey, 1982).
3. No fabric disturbance results while substituting interstitial water with ethyl alcohol, amyl acetate, and liquid CO_2 before critical point drying.
4. Little compression occurs between the diamond knife and specimen (i.e., no plastic deformation occurred) while ultrathin sectioning the specimen. Any possible disturbance by compression has been minimized by adjusting the section condition (specimen position, cutting speed, diamond knife position, etc.) and by applying xylene vapor over the ultrathin sections to relieve any possible compression.

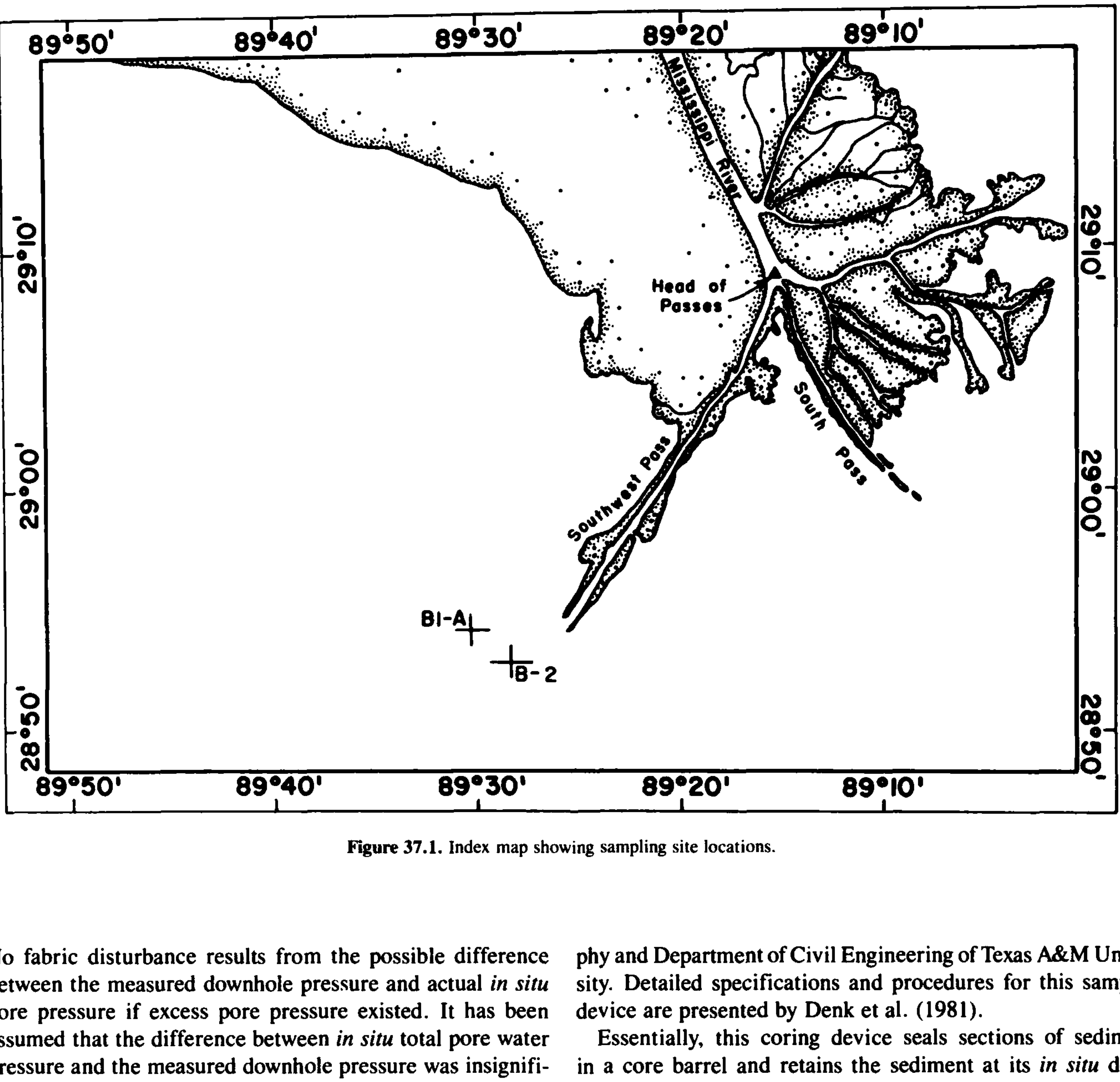

Figure 37.1. Index map showing sampling site locations.

5. No fabric disturbance results from the possible difference between the measured downhole pressure and actual *in situ* pore pressure if excess pore pressure existed. It has been assumed that the difference between *in situ* total pore water pressure and the measured downhole pressure was insignificant in terms of fabric changes.
6. No electron-optical or subsequent optical distortion of the image in the measurement and calculation of clay fabric orientation analysis exists.

Materials and Experimental Methods

Sample

General

Samples studied in this research were obtained using a "pressurized core barrel" sampling device that was developed at the Marine Geotechnical Laboratories, Department of Oceanography and Department of Civil Engineering of Texas A&M University. Detailed specifications and procedures for this sampling device are presented by Denk et al. (1981).

Essentially, this coring device seals sections of sediments in a core barrel and retains the sediment at its *in situ* downhole pressure. For further protection against pressure loss, downhole pressure is applied to the interior of the core barrel during withdrawal from the bore hole. This pressure is determined after the sample had been taken by applying helium gas pressure through a tube inserted into the interior of the core barrel just above the sample tube. Using a pressure regulator, the gas pressure is increased until a no-flow condition exists as indicated by a precise flow meter in the line. At this point the applied gas pressure just balances the downhole pressure (Denk et al., 1981). The sample should be maintained at the *in situ* pressure, but in reality, the pressure being maintained may well be that of the column of drilling fluid. The *in situ* downhole pressure on the cored sample was maintained during transport from the field to the laboratory and storage until laboratory analyses were made.

Table 37.1. Location and general information of sampling sites.*

Sample no.	Core no.	Location: Latitude	Location: Longitude	Water depth (m)	Water depth (ft)	Sample depth below mudline (m)	Sample depth below mudline (ft)	Measured downhole pressure (kPa)	Measured downhole pressure (psi)
1	B-1A	28°52′54″	89°28′39″	21	69	4.9	16	324	47
2	B-1A	28°52′54″	89°28′39″	21	69	7.9	26	365	53
3	B-1A	28°52′54″	89°28′29″	21	69	11.3	37	395	57
4	B-2	28°54′13″	89°30′10″	38	125	2.7	9	434	63
5	B-2	28°54′13″	89°30′10″	38	125	5.8	19	483	70
6	B-2	28°54′13″	89°30′10″	38	125	8.8	29	510	74
7	B-2	28°54′13″	89°30′10″	38	125	11.9	39	559	81

*The Lambert coordinates of Core B-1A: X = 2,594,001; Y = 82,970.
The Lambert coordinates of Core B-2: X = 2,585,823; Y = 90,832.

Location

The samples used in this study were obtained from an area located offshore Louisiana near the mouth of Southwest Pass within the Mississippi Delta complex (Fig. 37.1). The locations, water depth, sample depth, and measured downhole pressure of each sample are given in Table 37.1.

Geological Background

The birdfoot deltaic complex of the Mississippi River is situated on the continental shelf offshore Louisiana. The delta front represents the most recent area of deltaic sedimentation. Sediments are prograding seaward depositing clays and silty clays in the prodelta environment. During the past three decades, the geology, clay mineralogy, geochemistry, and geotechnical properties of these Mississippi deltaic sediments have been extensively studied. The present delta is probably one of the most thoroughly investigated marine environments in the world. Broad and extensive literature reviews of previous work in the Mississippi deltaic complex can be found in Shephard et al. (1979), Trabant and Bryant (1979), and references cited in these reports. Nevertheless, the only clay fabric research that has been carried out in the Mississippi Delta area was performed by Bowles, et al. (1969) and Bennett and associates (Bennett and Bryant, 1976; Bennett et al., 1977, 1979; Bohlke and Bennett, 1978, 1980).

Clay Fabric Analyses

Sample Preparation

The most critical steps in preparing samples for electron microscopic studies are the techniques employed in the dehydration of wet specimens and the process of embedding a specimen with an appropriate medium.

To accomplish this study, a special apparatus, "pressure vessel" (Fig. 37.2) for replacing interstitial water with intermediate fluid before critical point drying under equivalent *in situ* downhole pressure, was constructed. The detailed description of the special apparatus and procedures of drying specimens were presented in earlier papers (Chiou, 1980, 1981). Critical point-dried specimens were then embedded with a very low viscosity epoxy resin (SPURR) under vacuum, cured, and ultrathin sectioned (800–1000 Å thickness) with a diamond knife on a Sorvall MT-2 ultramicrotome for transmission electron microscopy (TEM) study. Detailed techniques of specimen embedding, thin sectioning, and ultramicrotoming, and electron microscopy [both TEM and scanning electron microscope (SEM)] observation were presented by Bennett et al. (1977), Baerwald et al. (this volume), Chiou (1981), and Chiou et al. (this volume).

To evaluate the difference in clay fabric between pressure core barrel samples and conventional core samples, sediments adjacent to those selected for the proposed pressurized clay fabric study were depressurized and then prepared at ambient pressure and analyzed by the same method (as that used for pressurized samples).

To ensure a more comprehensive and representative study of clay fabric sediment, specimens were cut as shown in Figure 37.3, so that the clay fabric of sediments could be viewed from different orientations of the sample relative to the core, i.e., side (thin sectioning parallel to core axis, A in Fig. 37.3), top (thin sectioning normal to core axis, B in Fig. 37.3), and random (C in Fig. 37.3). However, it was very difficult to maintain the precise orientation of ultrathin sections because of the difficulties encountered during sample preparation such as subsampling, embedding, and ultrathin sectioning. The orientation of ultrathin sections given here is thus rather rough, and is only an approximate orientation at best.

Orientation Analysis

The orientation of clay particles was based on the measured elongation direction of grain projection. To provide the simplest, fastest, and most accurate measurement of fabric orientation,

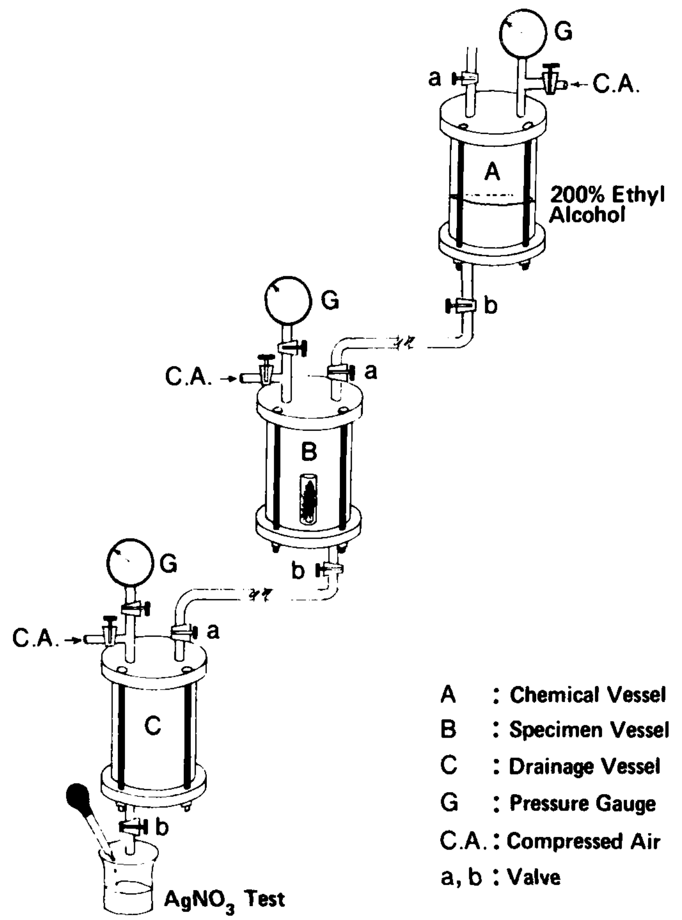

Figure 37.2. General arrangement of pressure vessels for substituting sediment interstitial water with intermediate fluid.

the point counting method was used in this study. The detailed counting technique followed those of Chiou (1981) and Chiou et al. (this volume).

Designation of Sample Number

Different processing procedures and variations in sediment orientation for ultrathin sectioning necessitated a systematic designation of sample number. Samples designated with postfix (A) were prepared and dehydrated using the new technique described herein (i.e., sample dehydration was carried out entirely under the equivalent *in situ* downhole pressure). Sample postfix (B) was designated for samples that were dehydrated only partially under equivalent *in situ* downhole conditions, i.e., after changing the samples' interstitial water with absolute ethyl alcohol. The samples were then exposed to ambient pressures. Sample postfix (C) was designated for samples that were dehydrated after *in situ* downhole pressures were released, i.e., the conventional method as described by Bennett et al. (1977).

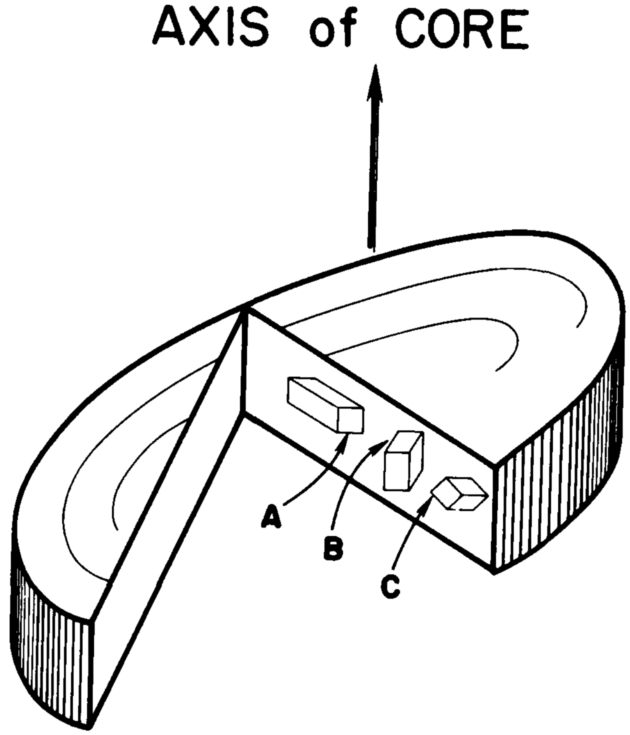

Figure 37.3. Schematic diagram showing the viewing orientation of embedded specimen. (A) Side or parallel to core axis view. (B) Top or normal to core axis view. (C) Random view.

The capital letter without parentheses following the sample postfix indicates the orientation of the thin section observed in the transmission electron microscope. For example, sample #1 (A)-B means that this is the sample number 1 (Table 37.1) that was prepared following the new technique described in Chiou (1980, 1981) and the picture is viewed from the top of the core, i.e., the ultrathin section was cut perpendicular to the sediment column (or the axis of the core).

In addition, due to experimental failure, some samples may have the capital letter F behind A, i.e., (A-F), which means the proposed (A) method failed to work correctly due to an accident. Where the technique has not been completed successfully, the reasons for failure and the treatment after failure will be described.

Results

Lithology and Grain Size Analysis

The general lithology of the cores used in this investigation and the results of selected geotechnical property tests are shown in Figures 37.4 and 37.5.

The results of grain size analyses were performed at the same time the sample was fractionated for the clay mineralogy study,

Table 37.2. Bulk mineralogy percentages (%) in the total sediments of boreholes B-1A and B-2 samples.

Core no.	Sample no.	Quartz	Feldspars	Calcite	Dolomite	Clays
B-1A	1	56	15	1	2	26
	2	56	13	1	2	28
	3	47	16	1	3	33
B-2	4	57	13	2	3	25
	5	47	12	1	2	38
	6	47	11	1	3	38
	7	47	11	1	2	39

Table 37.3. Qualitative and semi-quantitative analysis (relative %) of clay minerals in sediments of boreholes B-1A and B-2 from the Mississippi Delta.

Size fraction (μm)	Sample no.	Smectite	Chlorite	Illite	Kaolinite
<0.2	1	45	1	48	6
	2	50	1	42	7
	3	50	1	45	4
	4	46	1	48	5
	5	52	1	43	4
	6	48	1	45	6
	7	49	1	44	6
2–0.2	1	7	8	56	29
	2	7	11	63	19
	3	6	7	64	23
	4	6	10	60	24
	5	17	6	60	17
	6	12	8	60	20
	7	19	5	58	18
5–2	1	3	14	66	17
	2	3	14	66	17
	3	1	12	70	17
	4	3	14	66	17
	5	4	12	72	12
	6	3	13	68	16
	7	2	15	66	17

thus no further subdivision of the presented grain size classification was deemed necessary. Nevertheless, most of the sediments displayed a bimodal distribution with the strongest mode at the medium and fine clay particles (≤2 μm) and the second mode at both coarse silts and medium-grained silts (62.5–5 μm).

The major constituent of all samples analyzed in this study is clay size (<2-μm fraction), particularly less than 0.2-μm fractions. The amount of the <0.2-μm fraction increases with depth, from 33.8 to 40.2% in borehole B-1A and from 35.2 to 46% in borehole B-2, although the percentage of coarse clay (2–0.2 μm) fraction remains rather constant (10.7–14.2%) in sediments from both cores. The weight percent of total silts (coarse, medium, and fine silts) is nearly equal to that of total clays. The major constituent of the silts was quartz. The sand-size fraction was generally a very minor constituent (<1%) of these sediments and was composed mainly of quartz with minor amounts of feldspars or shell fragments.

The grain size analyses results parallel those Scafe's (1968) report (sample 64-A-6 #1). His results also depicted the uniformity of grain size distribution. Similar homogeneity of mineralogical constituents also was found in these sediments. This will be discussed in the following sections.

Mineralogical Analysis

Bulk Mineralogy

The bulk analyses (Table 37.2) show a uniform distribution of mineral constituents in sediments throughout the two core samples. Quartz decreases slightly (approximately 10%) with depth. Clay minerals range from 25 to 39% and increase slightly with depth. Small amounts of feldspars (11–16%), and trace amounts of dolomite (2–3%) and calcite (1–2%) were also present throughout the cored sediments.

Clay Mineralogy

Although the clay mineralogy in the Mississippi Delta has been extensively studied, no study has been reported in any great detail. To understand the relationship between clay fabric and clay mineralogy, detailed clay mineral analyses of different size fractions were performed. The results of clay mineral analyses (Table 37.3) indicate a fairly uniform distribution of clay minerals in the sediments studied. The major clay minerals identified in the 5- to 2-μm fractions were illite (66–72%), kaolinite (12–17%), chlorite (12–15%), and smectite (1–4%). The clay minerals in the 2- to 0.2-μm fractions were composed mainly of illite (56–64%) with fair amounts of kaolinite (17–29%) and small amounts of chlorite 5–11%) and smectite (6–19%). The less than 0.2-μm fine fraction of these sediments contained primarily smectite (46–50%) and illite (42–48%) with very small amounts of kaolinite (4–7%) and trace amounts of chlorite (1%).

The semiquantitative nature of estimating mineralogical composition and the fact that all calculations are based on 100% clay in each sample should be kept in mind. These percentages are difficult to compare with the results of previous investigations since only clay minerals in the less than 2-μm range are reported in the literature. However, a comparison of the relative percentage of clay minerals downhole is useful. In this study, it shows that illite was the dominant mineral in the coarse and medium clays. Percentage of kaolinite and chlorite also decreases as grain size decreases. Smectite was the predominant species in the less than 0.2-μm clays. This result agrees with the general relationship between clay particle size and clay mineral species.

Clay Fabric Analysis

Method (A)

Clay fabric samples prepared using the new method, i.e., downhole pressure maintained until the sample was critical point dried, are characterized by relatively well-oriented clay particles or

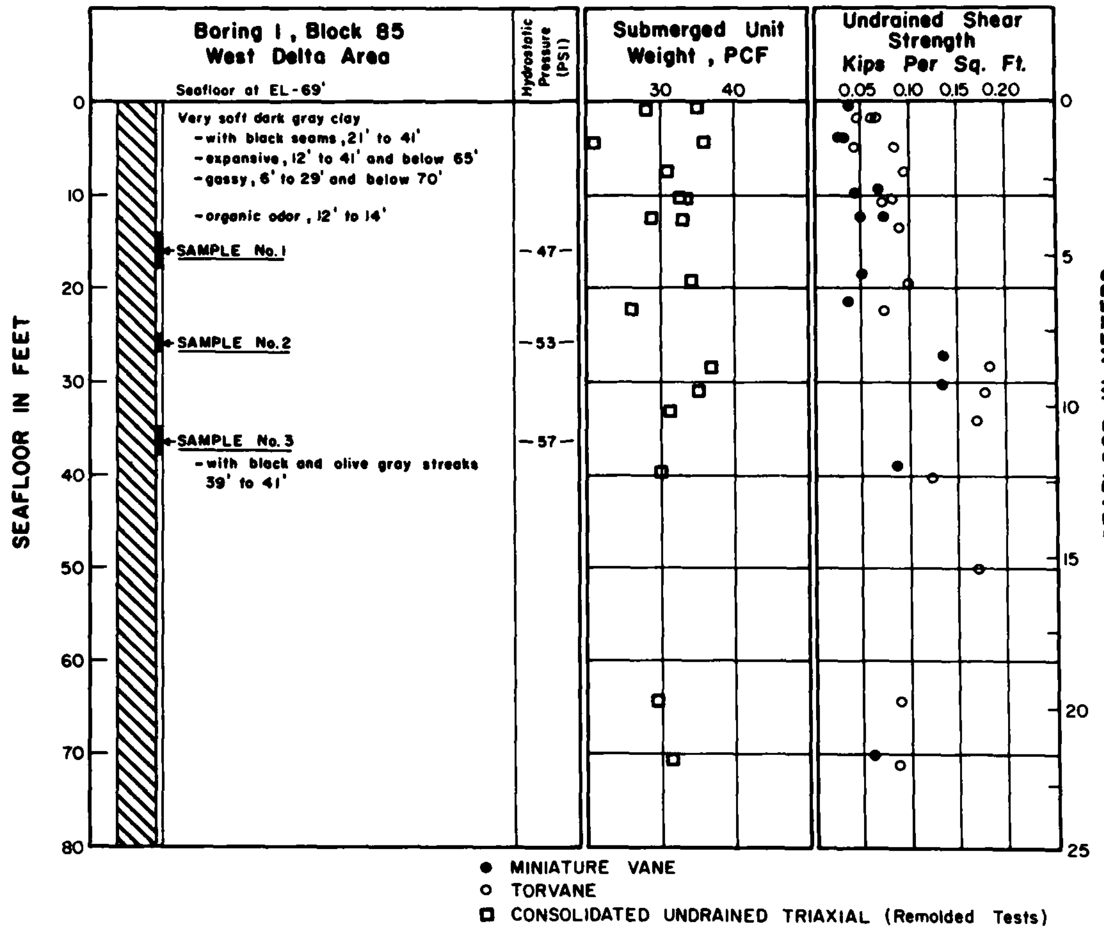

Figure 37.4. Profiles showing general lithology and results of field tests from boring 1.

domains, with random structures occurring only locally (Figs. 37.6 through 37.8). Domains are composed of face-to-face (or side-by-side) clay platelets forming a nearly perfect stack. The domains appear to vary over a considerable range of size, but most of them are relatively large. Large voids are clearly depicted between clay particles or domains. These voids could have been occupied by gases and/or interstitial waters. Some clay particles are also aligned step-by-step, forming either short or long chains. Although some random arrangements are also shown in the TEM observations, it appears that clay particles are predominantly aligned in a preferred orientation. A typical rose diagram of clay particle orientation and narrowly distributed clay orientation frequency curve, as shown in Figures 37.6 and 37.7 reveals the statistical calculation of well-oriented clay fabric.

Scanning electron micrography observations (Fig. 37.8) also reveal fairly well-oriented nature of clay platelets although some may not show as distinctly as those in TEM micrographs. It is obvious that the entire orientation is difficult to determine on a SEM micrograph, and, thus, the best way to perform an orientation analysis is on a TEM micrograph.

Method (B)

If the *in situ* downhole pressure was released before complete dehydration of the sediment, the clay fabric appears from semi-oriented to fairly nonoriented microfeatures. Although electron microscopy observations show that some samples contained both oriented and random microfeatures, it appears that the random microfeatures were predominant in most cases. TEM micrographs (Figs. 37.9 and 37.10) reveal numerous edge-to-edge contacts of clay particles, and the size of individual domains decreases. Many of the particles seen in the micrographs do not appear to be in contact with other particles, but seem to be "floating" in space. Thus, large voids are revealed in the micrographs. However, the microfeature is being observed in two dimensions, and the point contacts are either above or below the plane of the ultrathin sections. The clay particle orientation diagram depicts a random arrange-

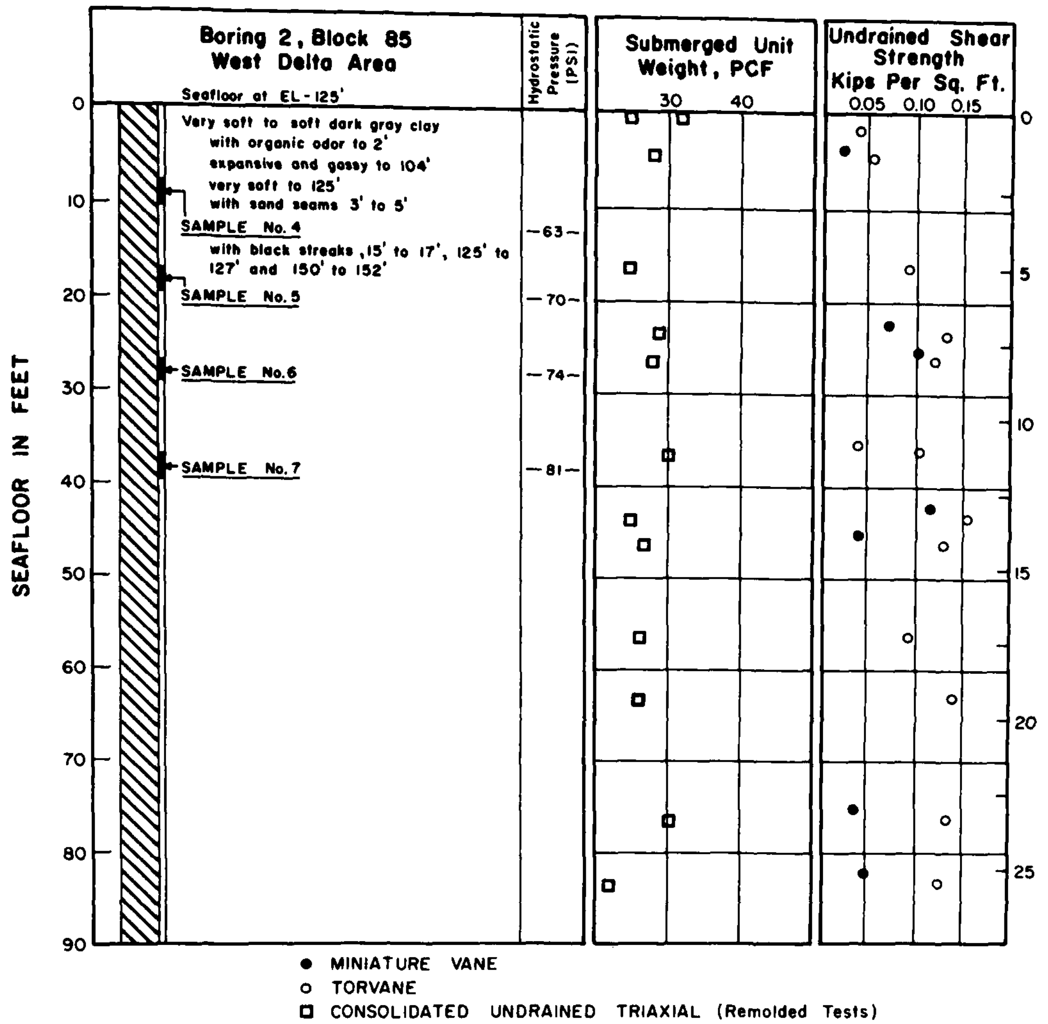

Figure 37.5. Profiles showing general lithology and results of field tests from boring 2.

ment, and the corresponding frequency curve also shows a widely spread orientation spectrum.

Method (C)

Clay fabric samples prepared using the conventional method, i.e., the downhole pressure was released before any process of dehydration of the sample, are typified by a highly random arrangement of clay particles or domains (Figs. 37.11 through 37.14) although in some areas preferred orientations are observed. Many particles appear to be "floating" in space and large void spaces are present. Void spaces appear to be very well connected. In some cases these void spaces are wide enough to form a "channel-like" feature. Although these channel-like features may be due to irregular fracturing of the sample during preparation, they still indicate some type of discontinuity (natural or artificial). A few large "pocket-like" pore spaces are present as are some void spaces of possible organic origin (Fig. 37.14).

These pocket-like pores may represent the gas expansion due to depressurization of the specimen. Other interesting features, e.g., slight "swirl" pattern and some "doughnut-like" clay fabric, have been observed in these specimens. A typical orientation diagram and frequency curve (Figs. 37.11 and 37.12) illustrate the highly random clay particle arrangement. The SEM micrographs also show similar clay microfeatures (Fig. 37.13).

Method (A-F)

Two types of interesting phenomenon were observed in the experiments. In two cases, samples 2(A-F) and 7(A-F), samples during dehydration process were accidentally degassed for about 10 sec and 45 min, respectively, the clay fabric observed in EM

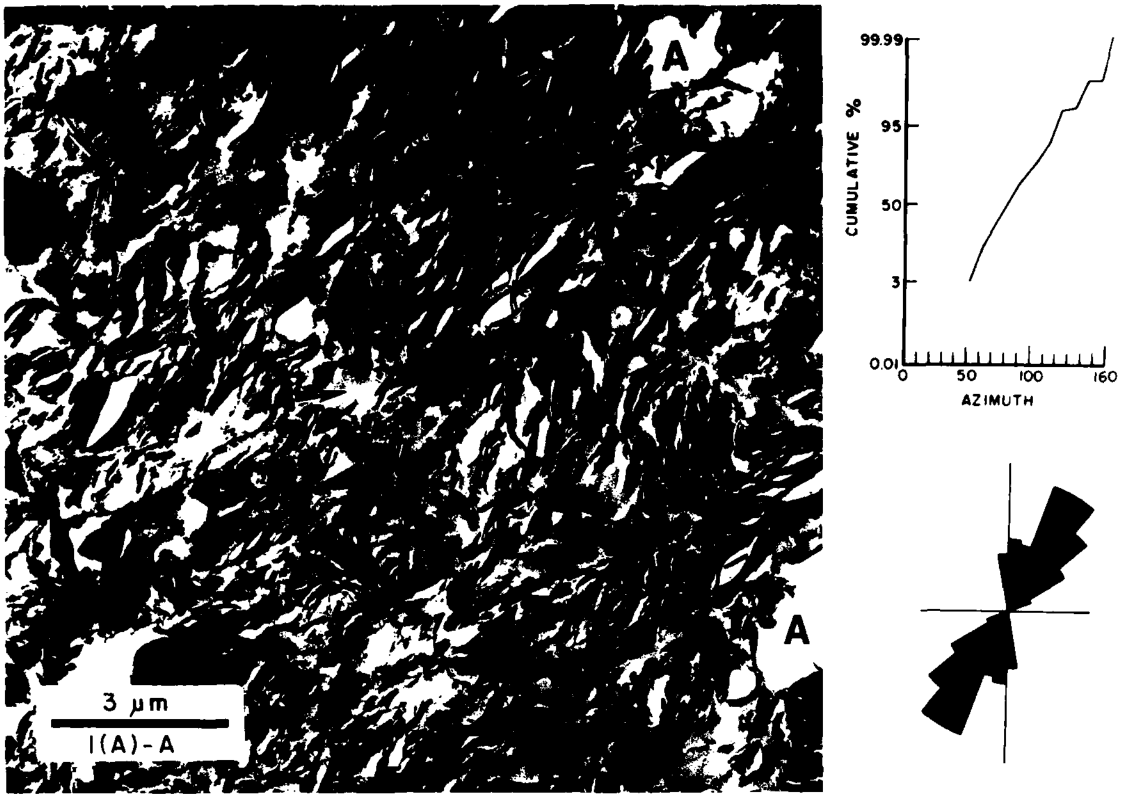

Figure 37.6. Clay fabric and orientation analysis of sample 1(A)-A. Left: Low magnification TEM micrograph showing preferentially oriented clay particles and domains. The white areas (A) represent artifact "holes." The gray areas (shown by arrow) represent pore spaces of the specimen. Upper right: Narrowly distributed clay particle orientation. Lower right: A rose diagram revealing well-oriented clay fabric.

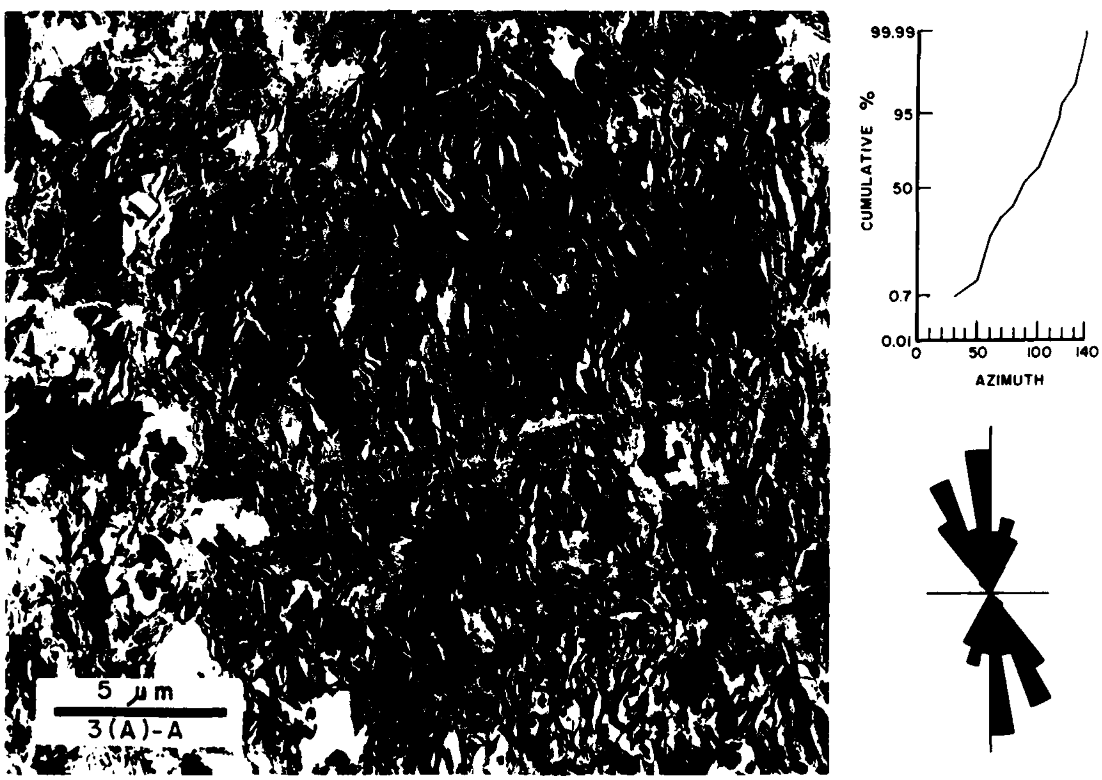

Figure 37.7. Clay fabric and orientation analysis of sample 3(A)-A. Left: Low magnification TEM micrograph showing the preferentially oriented clay fabric. Upper right: Clay particle orientation frequency distribution curve showing narrowly distributed orientation spectrum. Lower right: Rose diagram showing clay orientation in the TEM micrograph.

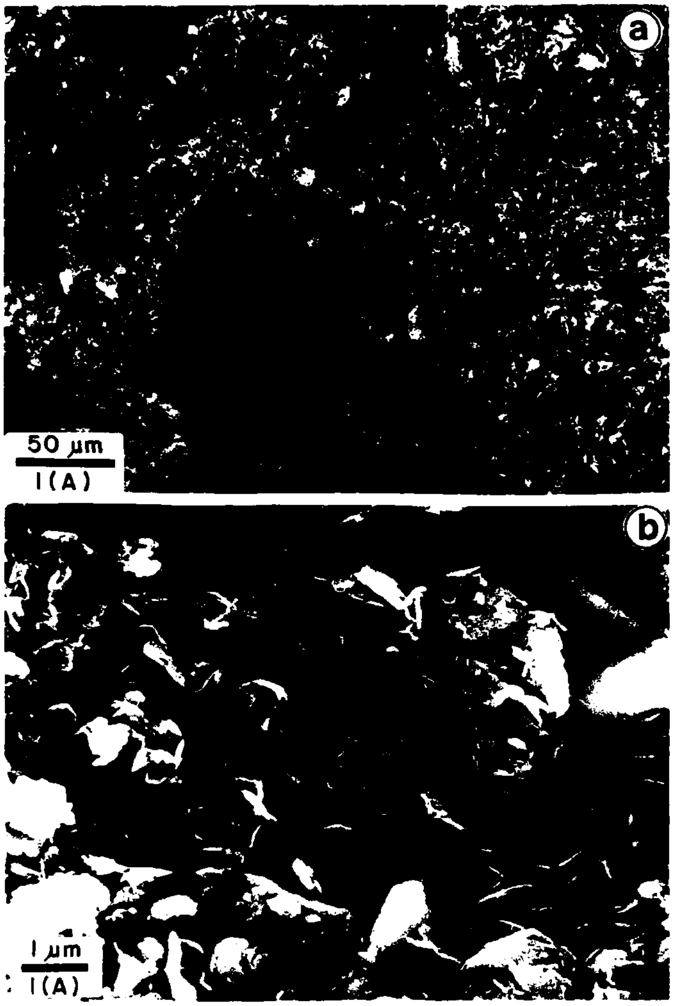

Figure 37.8. Clay fabric of sample 1(A). Top: SEM micrograph showing the porous nature of the sediment in low magnification. The oval-shape depression is thought to be created by a large gas bubble. Bottom: SEM micrograph showing well-oriented clay fabric from the wall of the gas bubble-like depression.

study appears to be preserved fairly well. At low magnification clay particles are aligned in a general direction. Clay orientation and frequency distribution curves also indicate the material consists of fairly well-oriented clay particles over a relatively wide angle range. However, in some areas of the thin section, the clay fabric shows slightly random arrangement. Figures 37.15 and 37.16 illustrate these combined features. It also was found that clay fabric near large pore spaces seems to lie more randomly. In general, results of these two samples show mixed microfeatures of fairly oriented with some slightly randomly arranged clay fabric.

Samples 4(A-F) and 6(A-F) had been degassed to ambient pressure for 2 and 5 hr, respectively, during the dehydration of these specimens, although the original *in situ* downhole pressures were reapplied after degassing. Both TEM and SEM observations of these long degassed specimens show randomly arranged clay domains and clay platelets as compared to the others, even though some areas may consist of mixed microfeatures (Figs. 37.17–37.19). Fairly large void spaces and other swirl and channel-like features are also present. The framework of clay fabric in these long degassed samples is similar to those prepared by method (C).

Discussion

The Sediment

Based on the grain size, bulk mineralogy, and clay mineralogy analyses, the constituents of the sediments were the same throughout the two cored sections, although sample Nos. 1, 2, 4, and 6 showed a slightly higher weight percentage of coarse silt fraction than the others. Neither grain size analyses nor bulk and clay mineralogical analyses showed significant variations in these samples. The grain size distribution and mineralogical composition of the seven samples were very uniform, and the sediment can be classified as silty clay or mud (Folk, 1974).

There are several factors, both physical and chemical, that can influence fabric microfeatures of a clayey sediment. In this study, the physical factors such as grain size, bulk mineralogy, clay mineralogy, rate of deposition, and depth of burial (*in situ* downhole pressure or effective pressure) were taken into account. Because of sediment uniformity in the relatively short cores, and the high deposition rate during Pleistocene time, the sediment can be considered as being homogeneous. The clay fabric in the different samples discussed has been subjected to similar geological conditions and the relationship between the clay fabric and the effects of the *in situ* downhole pressure on the sediment can be compared.

Comparison of Clay Fabric Using Conventional and New Techniques

The clay fabric of samples prepared by method (B) or (C) of this research was similar to the previous studies of Mississippi Delta sediments (Bowles, 1969; Bowles et al., 1969; Bennett et al., 1977; Bohlke and Bennett, 1980). Bennett et al. (1977) found random arrangement of clay particles predominating over the greater portion of the ranges in void ratio in shallow buried sediments in the northwestern Gulf of Mexico and the Mississippi Delta. Bennett did not encounter noticeable preferred particle orientation in sediments buried less than 100 m in the Mississippi prodelta. These clay fabric observations appeared similar to those in sediments where the *in situ* downhole pressure was released before dehydrating the sample. Samples studied by Bennett had low to negligible gas content, thus, the comparison of results from this study to those of Bennett's is rather difficult.

In contrast, preferred orientation of clay particles was revealed by the new sample preparation method, although the

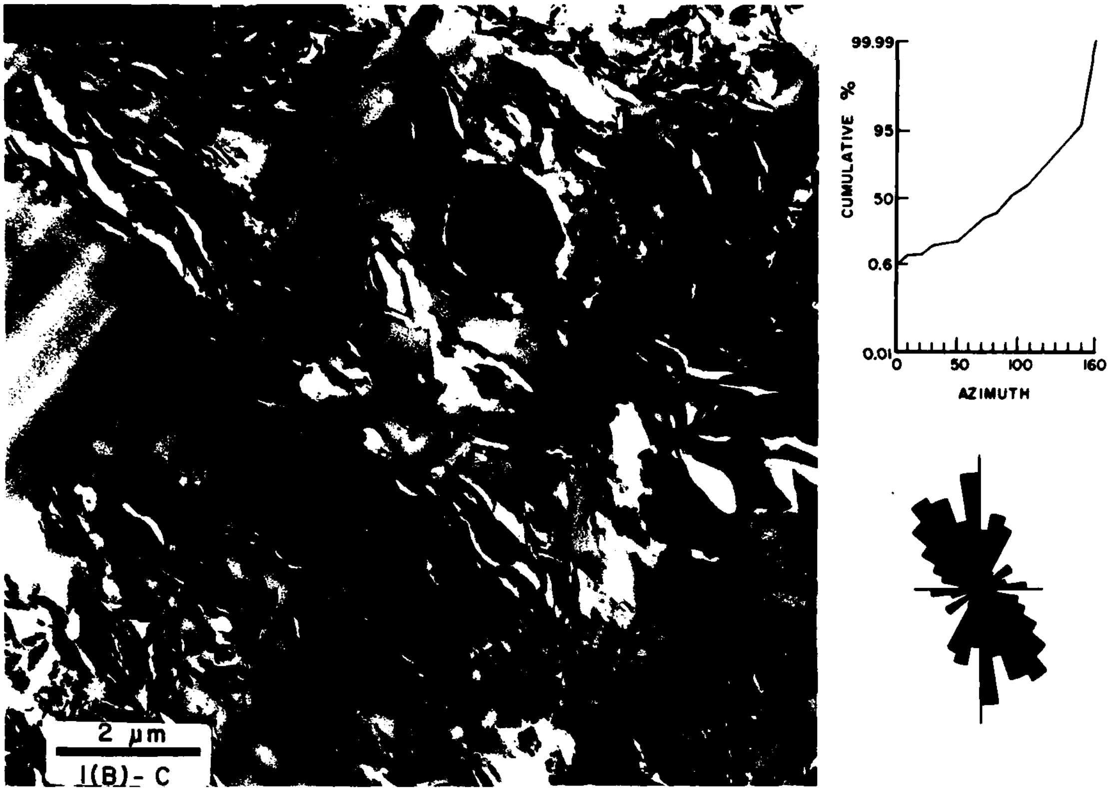

Figure 37.9. Clay fabric and orientation analysis of sample 1(B)-C. Left: Low magnification TEM micrograph depicting nonoriented clay fabric and large voids in the sediment. Upper right: Gentle slope of clay orientation distribution curve indicating randomly arranged clay fabric. Lower right: Rose diagram of clay fabric from this TEM micrograph (021826).

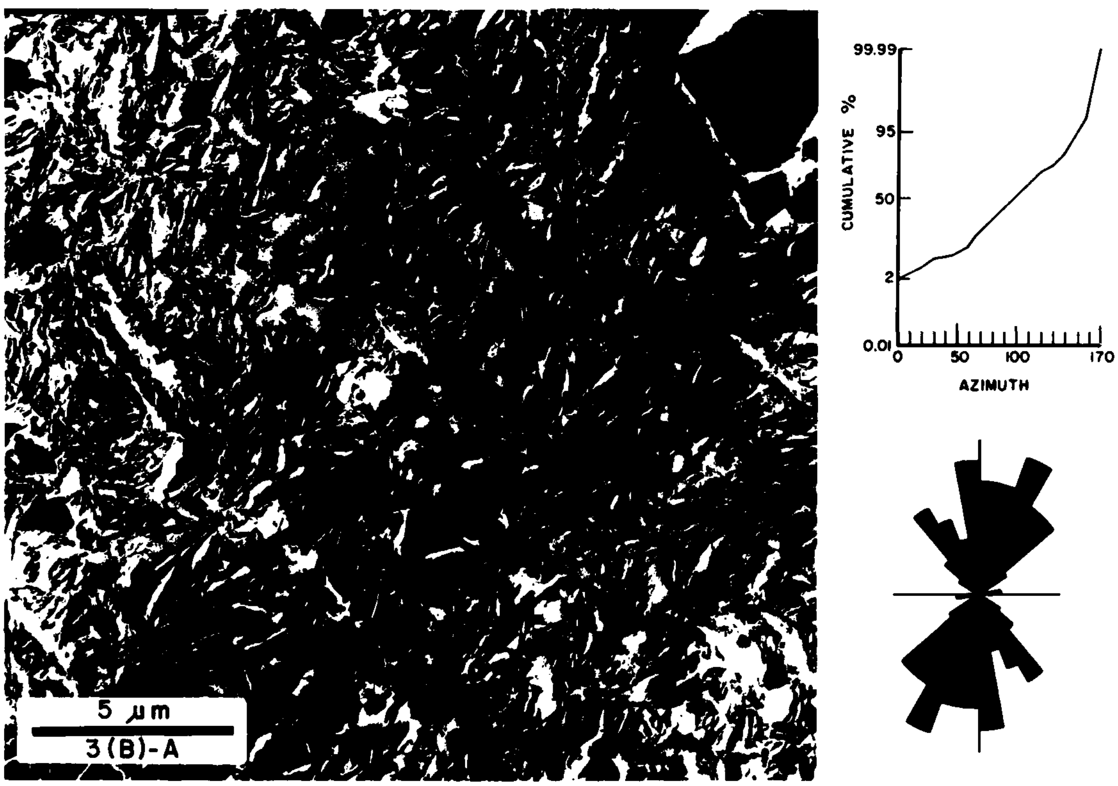

Figure 37.10. Clay fabric and orientation analysis of sample 3(B)-A. Left: Low magnification TEM showing the randomly arranged clay particles and domains spread through this specimen. Upper right: Clay particle orientation distribution curve revealing the typical randomly fabric. Lower right: Rose diagram showing clay orientation in the TEM micrograph.

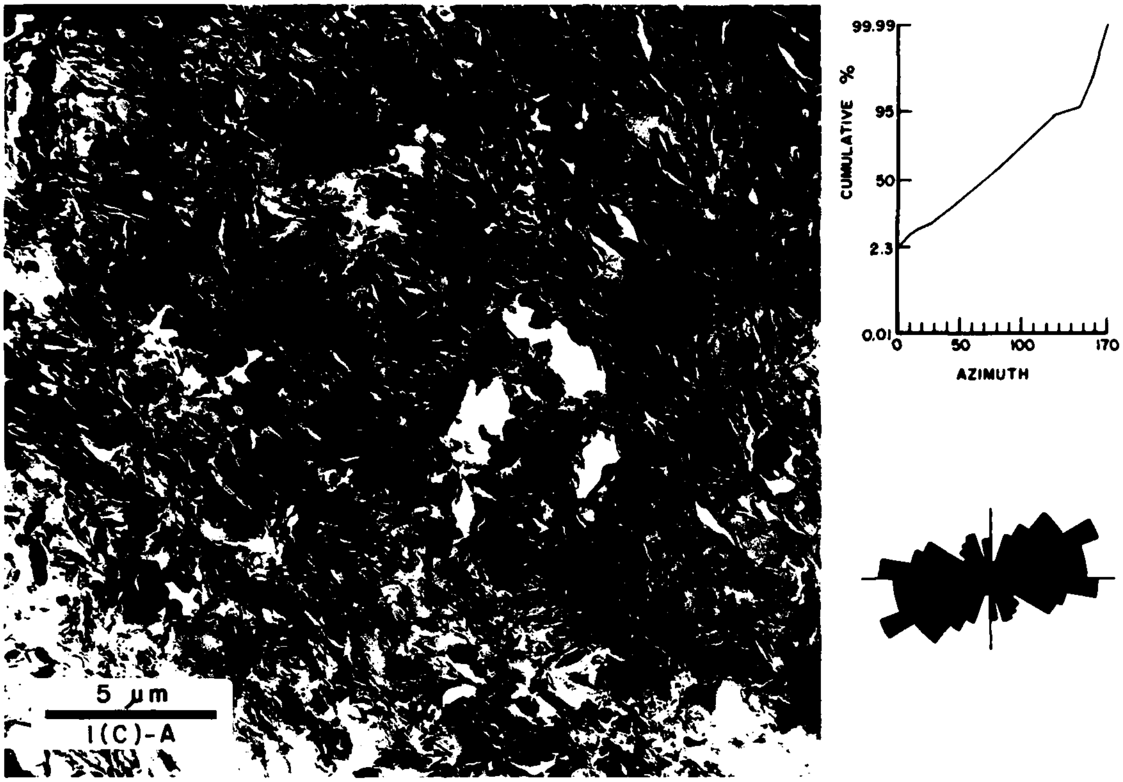

Figure 37.11. Clay fabric and orientation analysis of sample 1(C)-A. Left: Low magnification TEM micrograph revealing highly disoriented clay fabric. Upper right: Clay fabric analysis showing widely distributed clay orientation, i.e., poorly oriented fabric. Lower right: Rose diagram showing the same result of the same micrograph.

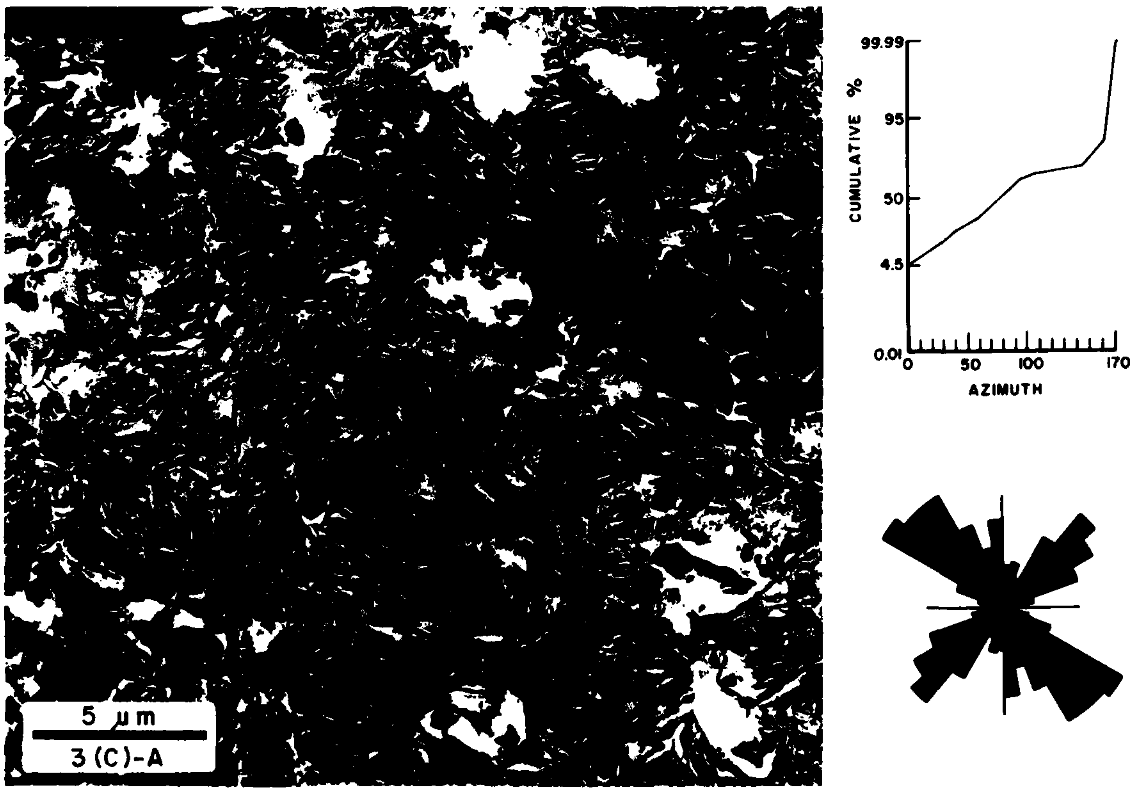

Figure 37.12. Clay fabric and orientation analysis of sample 3(C)-A. Left: Low magnification TEM micrograph depicting highly nonoriented and slightly swirled clay fabric. Upper right: Widely distributed clay orientation from the fabric measurement of TEM micrograph 022145. Lower right: Rose diagram showing randomly arranged clay particles in the TEM micrograph 022145.

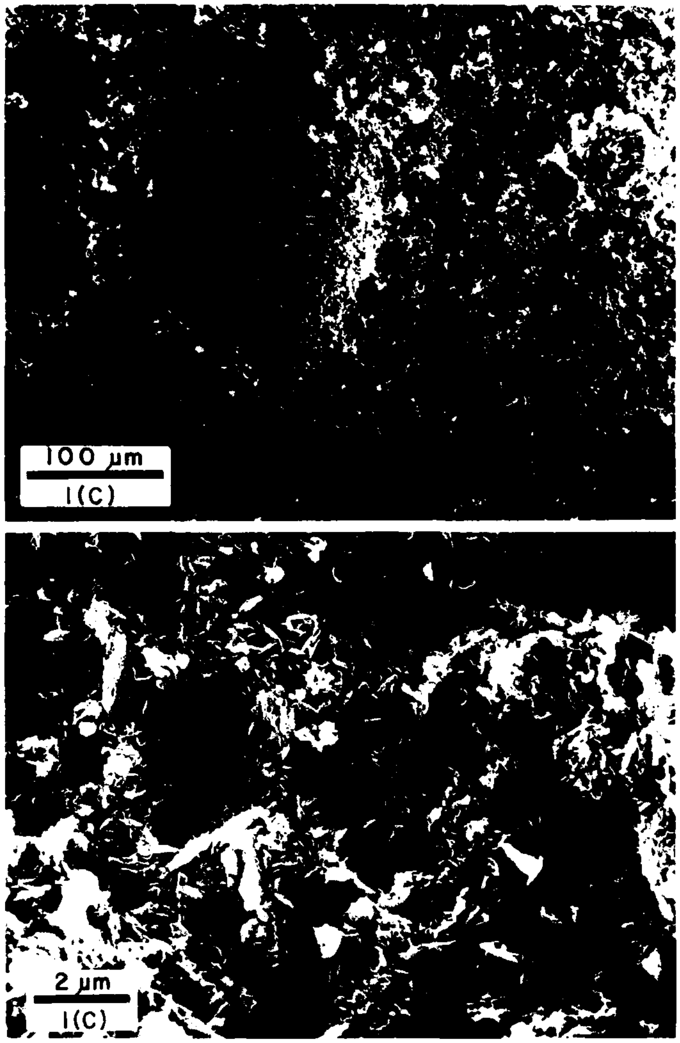

Figure 37.13. Clay fabric of sample 1(C)-A. Top: SEM micrograph of the porous sediment. No difference observed from Figure 37.8a. Bottom: Higher magnification of the "depression" area of the top micrograph revealing the randomly arranged clay fabric.

Figure 37.14. Clay fabric of sample 6(C)-A (TEM). Top: TEM micrograph showing large "pocket-like" pore space. It may be due to the degassing effect, i.e., gas expansion. Bottom: TEM micrograph showing large void spaces. The lines shown in the large void may be biogenic in origin.

preferred orientation was not always perfect in samples subjected to lower downhole pressures or effective overburden pressures. Since most of the clay particles are of plate-like shape, the clay particles tend to be aligned in a similar orientation due to the overburden pressure exerted across the maximum surface area of a clay particle (preferential orientation). While *in situ*, the overburden pressure (downward) was much greater than (or at least equal to) gas pressure (upward). The preferred clay orientation thus was maintained.

According to Whelan et al. (1981), methane concentration measured from the same pressurized core sediments used in this study ranged from 3450 to 137,140 ppm (μl CH_4(STP)/liter wet sediment). These values are generally higher than values found in companion samples taken with conventional wire-line equipment. Their results also showed that at least 98% of the methane was released from the sediment matrix within 3–5 hr after opening the pressure core barrel. The release of such a relatively high concentration of gas from the sediment would destroy the equilibrium system in the sediment matrix. Thus, the clay particles must undergo motion or rearrangement toward a new equilibrium system when exerting forces eased (i.e., when the gas or the overburden pressure was released).

Shear forces (stresses) exerted on clay particles must be created whenever the pressure changes (degassing) due to the release of *in situ* pressure. Consequently, clay particles will be realigned to another stable condition because of this force change. The mainly nonoriented but partially oriented clay fabric as shown in the results of method (B) and (C) probably resulted from the shearing stress and rearrangement of clay particles. Similar fabric relationships with regard to shear stresses and soil deformation have also been discussed by Sloane and Kell (1966), Morgenstern and Tchalenko (1967a,b), Smart (1967), Pusch (1970), Barden (1972), and Mitchell (1976).

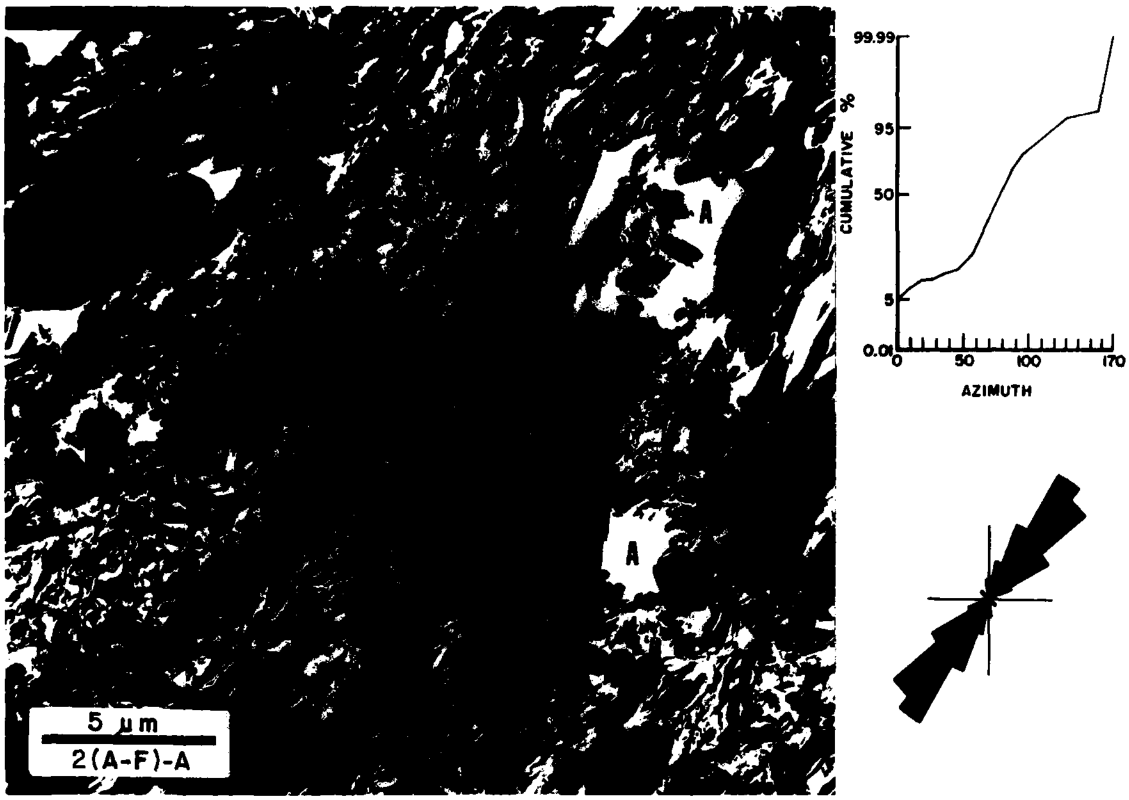

Figure 37.15. Clay fabric and orientation analysis of sample 2(A-F)-A. Left: Low magnification TEM micrographs showing the general direction of clay arrangement although slightly randomly arranged clay fabric occurs in some places. The abundant fine silts are also shown in the micrograph. The rather poor quality of this ultrathin section is mainly due to the large amounts of silt-size grains. It was also found that areas containing silts were not well impregnated with the embedding medium and were therefore torn out (areas A). Clay fabric in the central portion (from lower left to upper right) clay has been compressed a little as shown by elliptical-shaped clay aggregate (lower left). Thus, the orientation analysis of this micrograph is rather questionable. Upper right: Clay particle orientation distribution curve showing the mixed oriented and nonoriented fabric pattern. Lower right: Rose diagram showing clay orientation in the TEM micrograph (022836).

The highly nonoriented random microfeature depicted in samples prepared by method (C) probably represents disturbed microfeatures primarily due to the disequilibrium of sediment matrix by the release of *in situ* gas pressure. The channel-like void spaces with randomly arranged clay particles may reflect the avenues created by escaping gases.

Similar results between methods (B) and (C) suggest that clay fabric microfeatures of gassy sediment are rather delicate and that the fabric orientation can be altered if the *in situ* pressure is released before the sediment is completely dry regardless of drying time.

Clay Fabric vs. Degassing Time

During the course of this research, the accidental release of *in situ* downhole pressure in the exchange Plexiglas pressure vessel occurred during the testing of some samples. Although this was not the original intent, it did offer an opportunity to examine the effects of degassing as a function of time. Samples 2, 4, 6, and 7 offered such an opportunity.

Both sample 2(A-F) and sample 7(A-F) were accidentally degassed for approximately 10 sec and 45 min, respectively, and the clay fabric observed in TEM seems to be preserved fairly well. On the other hand, samples 4(A-F) and 6(A-F) had been exposed to ambient pressure for approximately 2 and 5 hr, respectively, and revealed highly random microfeatures showing the same fabric as from conventional samples 7(C) and 6(C). The degassing effect on disrupting clay fabric is time dependent. Although it was not possible to study this aspect in detail (i.e., degree of clay particle orientation versus length of time of degassing, rate of degassing and specimen size), it appeared that with a specimen size of 7 × 7 × 20 mm the clay fabric in the central portion of a specimen will not be disturbed if the length of degassing time is less than an hour. Of course, it also depends on the rate of leaking and gas concentration in the sample. This observation parallels the methane gas concentration studies made on the saline pressurized core barrel sediments (Whelan et al., 1981), which showed that at least 98% of the methane was released from the sediment matrix within 3-5 hr after opening the pressure core barrel.

The concurrence of well-oriented and highly random microfeatures in one sample examined [7(C)] is difficult to interpret. They may result from a partially disturbed sample or from an artifact created during sample preparation. Random microfeatures observed in sample 2(A-F) at high magnification probably indicate slightly degassed sediment near the sample edge. Clay fabric results of repressurized sediments also demonstrated the principle of clay fabric chemical irreversibility for marine sediment as proposed by Bennett et al. (1977).

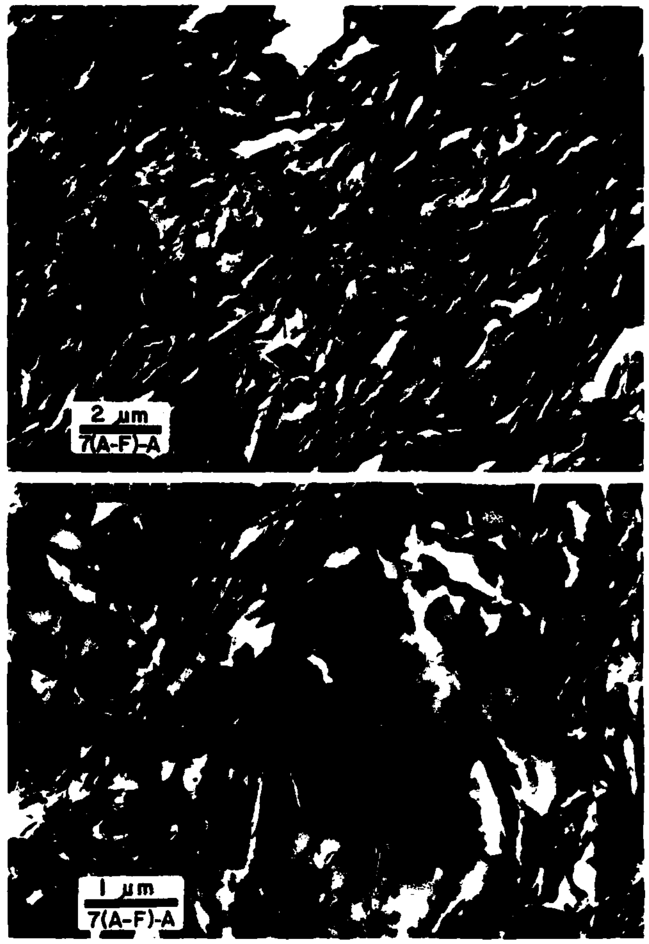

Figure 37.16. Clay fabric of sample 7(A-F)-A (TEM). Top: TEM micrograph showing that slightly swirled fabric pattern (center) that occurs in a generally well-oriented clay sediment. Bottom: TEM micrograph showing locally nonoriented clay fabric and large void spaces. Fluffy appearance (arrow) may be organic in origin.

Clay Fabric and Shear Strength

One of the major purposes of the pressure core barrel sampling project was to compare the *in situ* (pressurized) and conventional vane shear strengths. To accomplish this, vane shear equipment was taken into a hyperbaric chamber and shear tests were performed while at *in situ* downhole pressure. The same sample was then depressurized in the laboratory and the shear strength measured again using the same vane shear instrument.

By comparing both clay fabric and vane shear strength (1) in the hyperbaric chamber and (2) by the conventional method, the important relationship between these features is clearly shown (Fig. 37.20). Clay sediment with preferred orientation displays high shear strength, while clay sediment with random microstructure has lower shear strength. This observation is similar to the results presented by Matsuo and Kamon (1973) and Koff et al. (1973). Clay fabric with preferred orientation provides better sediment integrity and higher shear strength because of the greater surface area contact, and higher bonding force.

Conclusions

Based on the results of clay fabric studies on sediments recovered by the pressurized corer the following conclusions may be drawn:

1. The results presented in this research demonstrate that the pressure core apparatus and pressurized fabric techniques were successful. The new method, (method A) in this study, was able to remove gas and dehydrate the wet sediment samples by critical point-drying techniques without noticeably disturbing the clay fabric microfeatures. Nongassy sediment does not require the new method (A) described herein.
2. The results of detailed investigations of electron micrographs obtained by TEM and SEM observations, statistical calculations, and graphic analyses show that clay fabric microfeatures of gassy, deltaic sediments are affected by different sample dehydration techniques. The clay fabric reflected by these different methods of dehydration can be summarized as follows:

   a. The clay fabric of sediments prepared by the new method (A) was characterized by relatively well-oriented clay particles and domains, although random structures may occur locally. It appeared that the degree of preferred orientation increases with the overburden pressure. The size of domains was larger than those prepared by methods (B) and (C). Chains are well developed and relatively long. Void spaces are more elongate in shape. Orientation frequency curves are narrowly distributed and form a relatively steep slope.

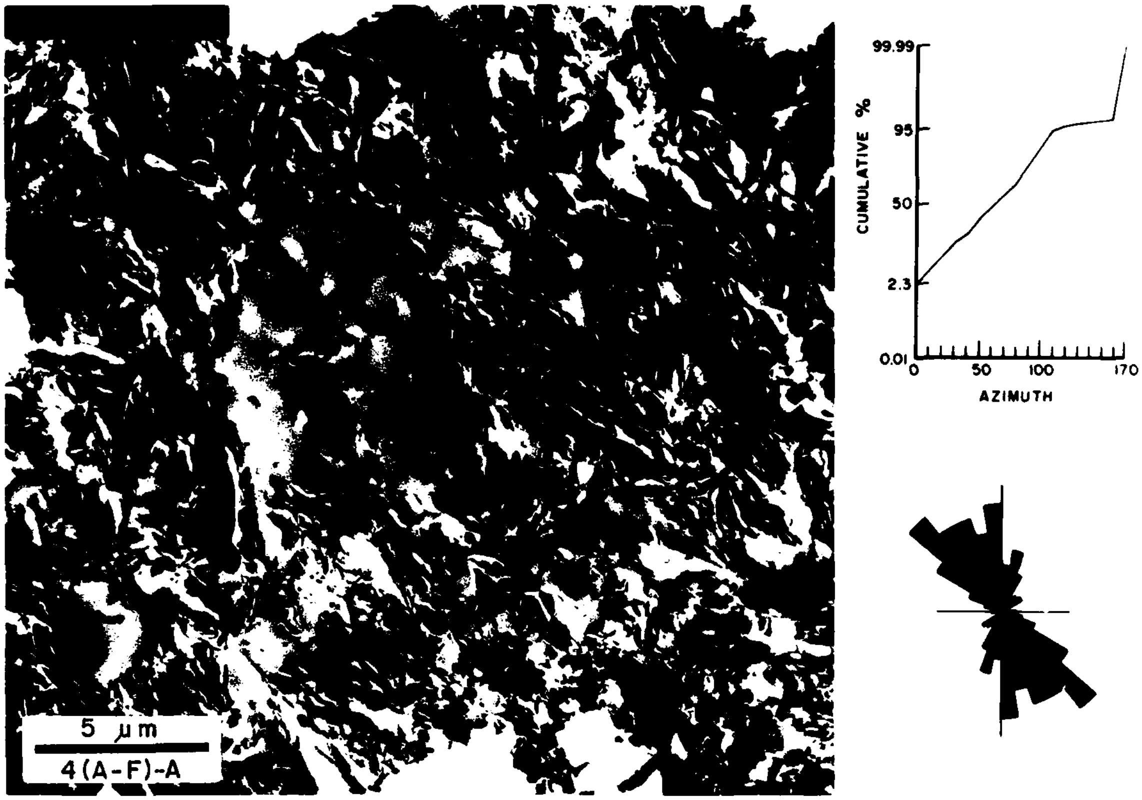

Figure 37.17. Clay fabric and orientation analysis of sample 4(A-F)-A. Left: Low magnification TEM micrograph revealing the high void spaces and the clay particles that seem to be floating in the spaces. Right: Clay particle orientation distribution frequency (top) and rose diagram (bottom) showing the mixed pattern of oriented and nonoriented clay fabric in the TEM micrograph (022866).

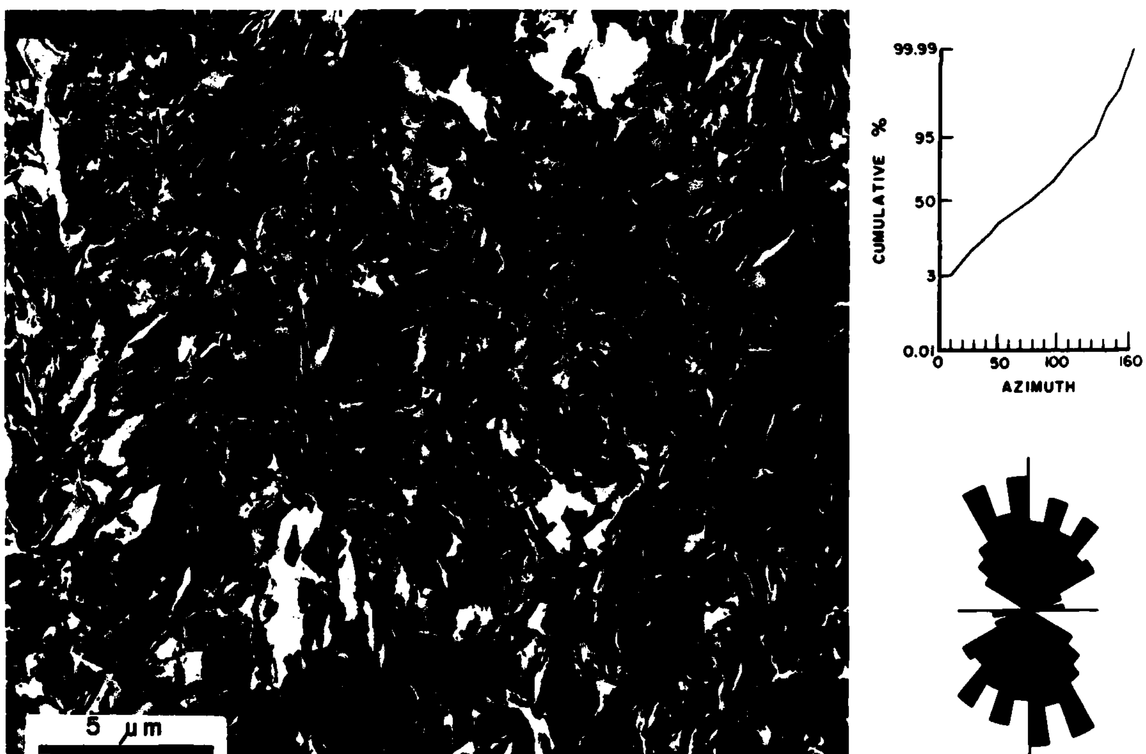

Figure 37.18. Clay fabric and orientation analysis of sample 6(A-F)-A. Left: Low magnification TEM micrograph revealing the randomly arranged clay particles and domains, and somewhat swirled pattern in the studied ultrathin sections. Right: Clay particle orientation analysis, as shown by orientation frequency distribution curve (top) and rose diagram (bottom) showing the highly randomly arranged clay fabric in this sample (TEM micrograph 022917).

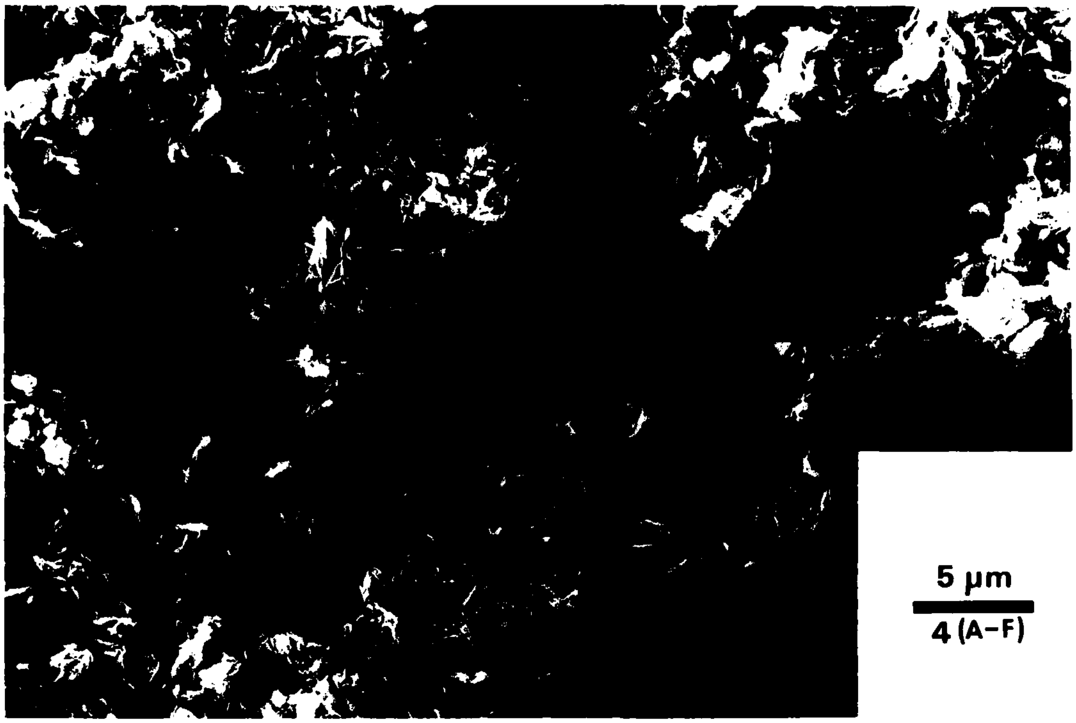

Figure 37.19. Clay fabric of sample 4(A-F). A mosaic of SEM micrographs giving a general view over a relatively large area. Somewhat oriented clay arrangement is shown in upper portion of the micrograph whereas randomly arranged clay flakes associated with channel-like features (canyon-like in this micrograph) meandering through the central portion of the micrograph.

b. The clay fabric of sediments prepared by method (B) depressurized gassy sediment was typified by a random arrangement of clay particles. Degree of randomness seems to decrease with overburden pressure. The size of domains was smaller as compared to those of method (A). Clay particles appear to be floating in irregular void spaces. Clay particle orientation frequency curves are widely spread with gentle to low slopes.
c. The clay fabric of gassy sediments prepared using method (C) is primarily characterized by highly nonoriented clay particles (except one case in sample no. 7). The fabric appears to result in more randomness than method (B). Clay particle orientation frequency curves are widely distributed with a flat or slightly concave shape toward the lower frequency.

3. The comparison of clay fabric microfeatures in different stages of sediment degassing shows that the degassing (depressurizing) effect on the clay fabric texture in a sediment matrix is time dependent.
4. The relationship of clay fabric microfeatures and vane shear strengths in both *in situ* pressure and ambient pressure conditions illustrates the close correlation between these two important geotechnical properties. Sediment with preferred clay orientation at *in situ* pressures has higher shear strength than degassed nonoriented clay fabric at ambient conditions.

Suggested Areas for Future Research

This investigation represents only an initial step toward an understanding of the mechanisms that may influence the complex clay fabric microfeatures in gassy, clayey sediments. The present research has attempted to evaluate the effect of only the physical pressure factor (release of pressure on gassy sediment) on the many complex variables that may interfere with the clay fabric of a sediment. During the course of this research several areas for future study were identified.

1. How deep or to what depth will clay fabric microfeatures of a gassy sediment still be affected by the release of in situ pressure?
2. What is the detailed relationship between clay fabric and degassing time with different sampling (or burial) depth?
3. What are some statistical and mathematical technique(s) or formula(s) that can be developed to describe the relationship between clay fabric and shear strength or other geotechnical properties?

Based on the observation of thousands of TEM micrographs, the writers found that if the clay particles in the ultrathin sections can be identified easily and correctly, clay petrology, analogous to clastic sedimentary petrology, sandstone, or carbonate petrology, can be developed and applied to the understanding of fine grained particles. The most important aspect

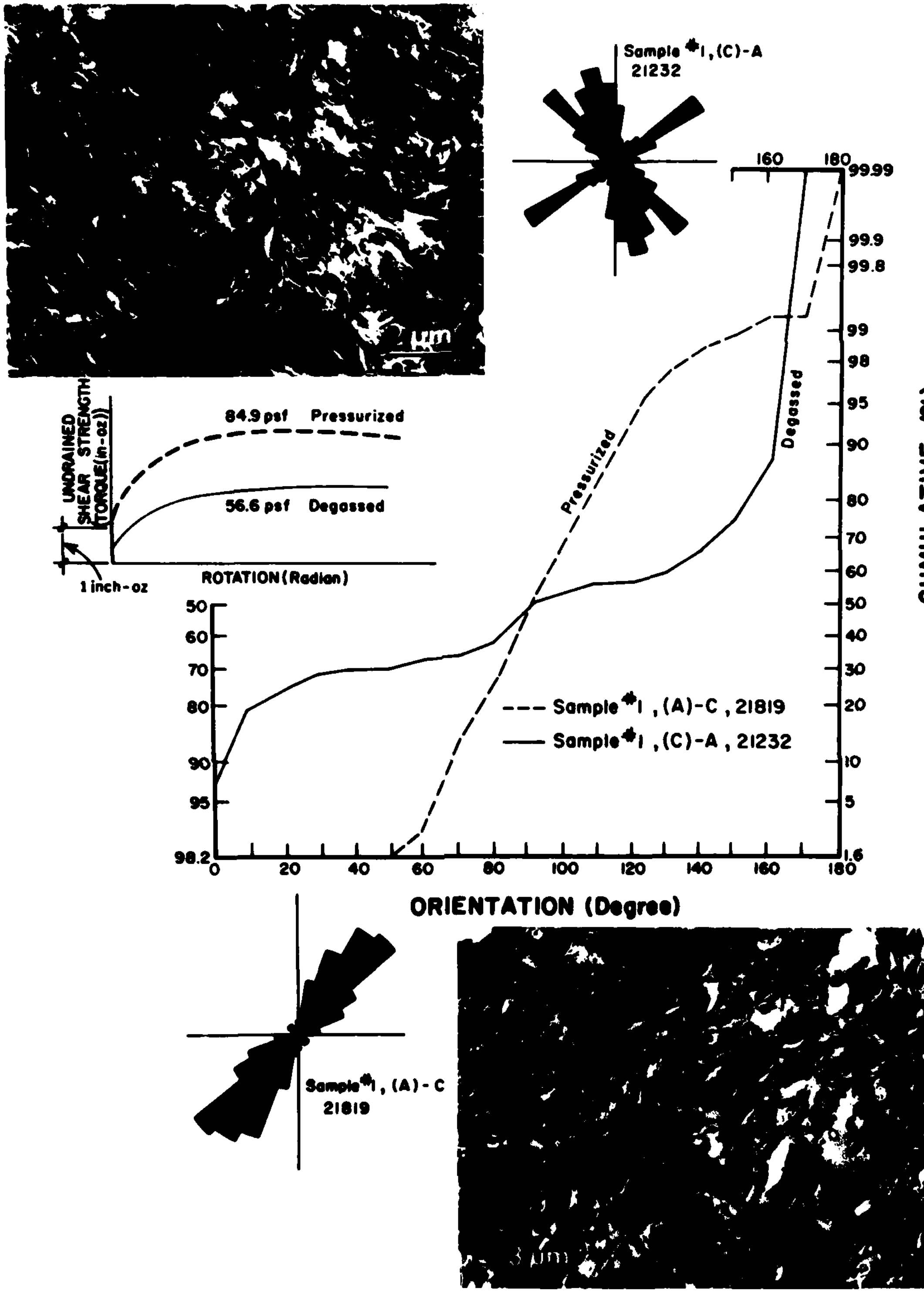

Figure 37.20. Comparison of clay fabric and shear strength. Clay fabric and shear strength between pressurized (new technique developed in this study) and degassed (conventional technique) sediment samples. TEM micrograph and orientation analysis (cumulative orientation frequency curve and rose diagram) indicating well-oriented clay fabric from the pressurized sample whereas the degassed sample reveals randomly arranged clay fabric.

of such a future research area is to improve the software and hardware of the X-ray (EDS) system to become a highly efficient particle composition analyzer, so that the texture, morphology, mineralogical, and chemical composition can be studied at the same time.

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References

Aylmore, L.A.G., and J.P. Quirk, 1960. Domain or turbostratic structure of clay. Nature, v. 187, p. 1046-1043.

Aylmore, L.A.G., and J.P. Quirk, 1962. The structural status of clay systems. Clays and Clay Minerals, v. 9, p. 104-130.

Barden, L., 1972. The influence of structure on deformation and failure in clay soils. Geotechnique, v. 22, p. 153-163.

Barden, L., and R. Pusch (eds.), 1973. Proceedings of the International Symposium on Soil Structure, Gothenburg, Sweden. Swedish Geotechnical Society and Swedish Society for Clay Research, 251 p., with 44 p. Appendix.

Bennett, R.H., 1976. Clay fabric and geotechnical properties of selected submarine sediment cores from the Mississippi Delta. Ph.D. dissertation, Texas A&M University, College Station, TX, 269 p.

Bennett, R.H., and W.E. Bryant. 1976. Clay fabric and selected geotechnical properties (abs.). 25th Annual Clay Minerals Conference, Corvallis, Oregon, p. 32.

Bennett, R.H., and M.H. Hulbert, 1986. Clay Microstructure. International Human Resources Development Corporation, Boston, MA, 161 p.

Bennett, R.H., W.R. Bryant, and G.H. Keller, 1977. Clay Fabric and Geotechnical Properties of Selected Submarine Sediment Cores from the Mississippi Delta. NOAA Professional Paper 9, U.S. Department of Commerce, NOAA, Rockville, MD, 86 p.

Bennett, R.H., W.R. Bryant, and G.H. Keller, 1979. Clay fabric and related pore geometry of selected submarine sediment. Mississippi Delta. In: O'Hare, A.M.F. (ed.), Scanning Electron Microscopy, Vol. 1, AMF O'Hare, Chicago, IL., Scanning Electron Microscopy, Incorporated, p. 519-524.

Bennett, R.H., D.N. Lambert, M.H. Hulbert, H. Schmoll, and B.M. Bohlke, 1980. Clay fabric of sediments from various depositional environments (abs.). 29th Annual Clay Minerals Conference, Clay Minerals Society, Waco, TX, p. 22.

Biscoe, J., and B.E. Warren, 1942. An x-ray study of carbon black. Journal of Applied Physics, v. 13, p. 364-371.

Bohlke, B.M., and R.H. Bennett, 1978. Mississippi prodelta crusts: a clay fabric and geotechnical analysis: Phase I report for the U.S. Geological Survey. NOAA, AOML, Miami, FL, 67 p.

Bohlke, B.M., and R.H. Bennett, 1980. Mississippi prodelta crusts: a clay fabric and geotechnical analysis. Marine Geotechnology, v. 4, p. 55-82.

Bowles, F.A., 1969. Electron microscopy of the microstructure in sediment samples from the Gulf of Mexico. Ph.D. dissertation, Texas A&M University, College Station, TX, 113 p.

Bowles, F.A., W.R. Bryant, and C. Wallin, 1969. Microstructures of unconsolidated and consolidated marine sediments. Journal of Sedimentary Petrology, v. 39, p. 1546-1551.

Burnham, C.P., 1970. The micromorphology of argillaceous sediments: particularly calcareous clays and siltstones. In: Osmond, D.A., and P. Bullock (eds.), Micromorphological Techniques and Applications. Soil Survey Techniques Monograph, No. 2, p. 83-96.

Casagrande, A., 1932. The structure of clay and its importance in foundation engineering. Journal Boston Society of Civil Engineering, v. 19, p. 168-208.

Chiou, W.A., 1980. A new technique in preparing *in situ* marine sediments for clay fabric study. Proceedings of the 38th Electron Microscopy Society of America Annual Meeting, p. 204-205.

Chiou, W.A., 1981. Clay fabric of gassy submarine sediments. Ph.D. dissertation, Texas A&M University, College Station, TX, 248 p.

Chiou, W.A., L.E. Shephard, and W.R. Bryant, 1980. Clay fabric and geotechnical properties of trench sediments (abs.). 29th Annual Clay Minerals Conference, Clay Minerals Society, Waco, TX, p. 28.

Collins, K., and A. McGown, 1974. The form and function of microfabric features in a variety of natural soils. Geotechnique, v. 24, p. 223-254.

Denk, E., W.A. Dunlap, W.R. Bryant, L.J. Milberger, and T.J. Whelan, 1981. A pressurized core barrel for sampling gas-charged marine sediments. Proceedings of the 13th Annual Offshore Technology Conference, p. 43-52.

Fairbairn, H.W., 1949. Structural Petrology of Deformed Rocks. Addison-Wesley, Cambridge, 344 p.

Folk, R.L., 1974. Petrology of Sedimentary Rocks. Hemphill Publishing Co., Austin, TX, 182 p.

Gary, M., R. McAfee, Jr., and C.L. Wolf, eds., 1972. Glossary of Geology. American Geological Institute, Washington, D.C., 805 p.

Goldschmidt, V.M., 1926. Undersolkelser over lersedimenter. Nordisk jourbrugsforkning, No. 4-7, p. 434-445.

Koff, C.L., A.S. Polyakov, and E.M. Sergeev, 1973. Changes in microtexture of marine clay sediments during their diagenesis. In: Barden L., and R. Pusch (eds.), Proceedings of the International Symposium on Soil Structure, Gothenburg, 1972. Swedish Geotechnical Society and Swedish Society for Clay Research, p. 227-242.

Lee, H.T., 1980. Compressibility and permeability of clays at high pressure. M.S. Thesis, Texas A&M University, College Station, TX, 148 p.

Matsuo, S.I., and M. Kamon, 1973. Microscopic research on the consolidated samples of clayey soils. In: Barden, L., and R. Pusch (eds.), Proceedings of the International Symposium on Soil Structure, Gothenburg. Swedish Geotechnical Society and Swedish Society for Clay Research, p. 197-199.

Mitchell, J.L., 1976. Fundamentals of Soil Behavior. Wiley, New York, 422 p.

Moon, C.F., 1972. The microstructure of clay sediments. Earth-Science Reviews, v. 8, p. 303-321.

Morgenstern, M.R., and J.S. Tchalenko, 1967a. Microscopic structure in kaolin subjected to direct shear. Geotechnique, v. 17, p. 309-328.

Morgenstern, M.R., and J.S. Tchalenko, 1967b. Microstructure observation on shear zones from slips in natural clays. Proceedings of Geotechnical Conference, Oslo, Norway, Norwegian Geotechnical Institute, v. 1, p. 147-152.

O'Brien, N.R., 1971. Fabric of kaolinite and illite floccules. Clays and Clay Minerals, v. 19, p. 353-359.

O'Brien, N.R., and E. Hisatomi, 1978. Sedimentological study of a turbidite cycle, Kii Peninsula, Japan. Memoirs of the Faculty of Science, Kyoto University, Series of Geology and Mineralogy, v. XLL(2), p. 177-186.

O'Brien, N.R., K. Nakazawa, and S. Toluhashi, 1980. Use of clay fabric to distinguish turbiditic and hemipelagic siltstones and silts. Sedimentology, v. 27, p. 47-61.

Olsen, H.W., 1962. Hydraulic flow through saturated clay. Clays and Clay Minerals, v. 9, p. 131-161.

Parry, R.H. (ed.), 1971. Stress-strain behavior of soils. Proceedings of the Roscoe Memorial Symposium, Cambridge University, Oxfordshire, England, G.T. Foulis and Company, Ltd., 752 p.

Pusch, R., 1970. Microstructural changes in soft quick clay at failure. Canadian Geotechnical Journal, v. 7, p. 1-7.

Range, K.J., A. Range, and A. Weiss, 1969. Fire-clay type kaolinite or fire clay mineral? Experimental classification of kaolinite-halloysite minerals. In: Heller, L. (ed. in chief), Proceedings of the International Clay Conference, Tokyo, Japan. Israel Universities Press, Jerusalem, p. 3-13.

Rutherford, C.K. (ed.), 1974. Soil microscopy. Proceedings of the 4th International Working Meeting on Soil Micromorphology, Kingston, Ontario, Canada, Aug. 27-31, 1973. The Limestone Press, Kingston, Ontario, Canada, 857 p.

Scafe, D.W., 1968. A clay mineral investigation six cores from the Gulf of Mexico. Ph.D. dissertation, Texas A&M University, College Station, TX, 75 p.

Schultz, L.G., H. van Olphen, and F.A. Mumpton (eds.), 1987. Proceedings of the International Clay Conference, Denver, 1985. The Clay Minerals Society, Bloomington, IN, 456 p.

Shephard, L.E., W.R. Bryant, and W.A. Dunlap, 1979. Geotechnical properties and their relation to geologic processes in South Pass Outer Continental Shelf Lease Area, Block 28, 47 and 48, Offshore Louisiana. Technical Report 79-5-T, Dept. of Oceanography, Texas A&M University, 125 p.

Shephard, L.E., W.A. Chiou, and W.R. Bryant, 1980. Consolidation characteristics and clay fabric of Japan Trench sediments. Geological Society of America Annual Meeting, Atlanta, GA, Abstracts with program, v. 12, p. 521.

Shephard, L.E., W.R. Bryant, and W.A. Chiou, 1982. Geotechnical properties of Mid-American Trench sediments. In: More, J.C., and J.S. Watkins (eds.), Initial Reports of the Deep Sea Drilling Project, v. 66. U.S. Government Printing Office, Washington, D.C., p. 475-504.

Sloane, R.L., and T.R. Kell, 1966. The fabric of mechanically compacted kaolinite. Clays and Clay Minerals, v. 14, p. 289-296.

Smart, P., 1967. Particle arrangements in kaolin. Clays and Clay Minerals, v. 15, p. 241-254.

Smart, P., and N.K. Tovey, 1981. Electron Microscopy of Soils and Sediments–Examples. Oxford University Press, Oxford, 176 p.

Smart, P., and N.K. Tovey, 1982. Electron Microscopy of Soils and Sediments–Techniques. Oxford University Press, Oxford, 264 p.

Sorby, H.C., 1851. On the microscopic structure of the calcareous grit of the Yorkshire coast. Quarterly Journal Geological Society, London, v. 7, p. 1-6.

Terzaghi, K., 1925. Erdbau Mechanik auf Bodenphysikalischer Grundlage. Franz Deutiche, Leipzig und Wien, 399 p.

Tovey, N.K., 1970. Electron microscopy of clays. Ph.D. Dissertation, University of Cambridge, Cambridge, England.

Tovey, N.K., and K.Y. Wong, 1973. The preparation of solid and other geological materials for the SEM. In: Barden, L., and R. Pusch (eds.), Proceedings of the International Symposium on Soil Structure, Gothenburg, Sweden. Swedish Geotechnical Society and Swedish Society for Clay Research, p. 59-67.

Tovey, N.K., and K.Y. Wong, 1978. Preparation, selection and interpretation problems in scanning electron microscope studies in sediments. In: Whalley, W.B. (ed.), Scanning Electron Microscopy in Study of Sediments. Geo Abstracts, Norwich, England, p. 181-199.

Trabant, P.K., and W.R. Bryant, 1979. Submarine geomorphology and geology of the Mississippi River Delta front. Technical Report 79-1-T, Dept. of Oceanography, Texas A&M University, 118 p.

Whalley, N.B. (ed.), 1978. Scanning Electron Microscopy in the Study of Sediments. A symposium held at the 3rd Meeting of Geological Societies of the British Isles, University College of Wales, Swansea, Sept. 24-25, 1977, Norwich, England, Geo Abstracts, 414 p.

Whelan, T. III, W.R. Bryant, and N.A. Dunlap, 1981. Methane concentrations and distribution in pressure core samples from Mississippi Delta sediments. (abs.), American Association Petroleum Geologists Bulletin, v. 65, 1981 AAPG-SEPM Annual Meeting, San Francisco, CA, p. 1007.

Wong, K.Y., 1975. Microfabric changes during the deformation of clays. Ph.D. dissertation, Cambridge University, Cambridge, England.

Yong, R.N., and D.E. Sheeran, 1973. Fabric unit interaction and soil behavior. In: Barden, L., and R. Pusch (eds.), Proceedings of the International Symposium on Soil Structure, Gothenburg, Sweden. Swedish Geotechnical Society, p. 176-183.