(2)

CLAY MICROSTRUCTURE

THE MICROSTRUCTURE OF FINE-GRAINED TERRIGENOUS MARINE SEDIMENTS- FROM MUDS TO SHALE

WORKSHOP AND CONFERENCE

October 4-7, 1988

NAVAL OCEAN RESEARCH AND DEVELOPMENT ACTIVITY
STENNIS SPACE CENTER
MISSISSIPPI
39529-5004
USA

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ACKNOWLEDGEMENTS

THE WORKSHOP ON CLAY MICROSTRUCTURE WAS SUPPORTED AND FUNDED BY: THE NAVAL OCEAN RESEARCH AND DEVELOPMENT ACTIVITY (NORDA), STENNIS SPACE CENTER, MS; THE OAK RIDGE NATIONAL LABORATORY, OAK RIDGE, TN; THE DEPARTMENT OF ENERGY- CHICAGO OFFICE, CHICAGO, IL; AND THE OFFICE OF NAVAL RESEARCH/CONTRACT RESEARCH DIVISION, ARLINGTON, VA. THE EFFORTS AND CONTRIBUTIONS OF MS MARGARET CHENAULT AND THE STAFF OF THE UNIVERSITY OF SOUTHERN MISSISSIPPI'S DIVISION OF LIFELONG LEARNING ARE GRATEFULLY ACKNOWLEDGED. SPECIAL APPRECIATION IS EXTENDED TO MS F. LEE NASTAV (NORDA) FOR HER FAITHFUL ASSISTANCE IN PREPARING VARIOUS VERSIONS OF THE TECHNICAL SESSIONS AGENDA, THE PROGRAM BOOKLET, AND FOR COORDINATING VARIOUS ASPECTS OF THE WORKSHOP WITH THE USM STAFF.

AGENDA

CLAY MICROSTRUCTURE WORKSHOP AND CONFERENCE

OUTLINE OF TECHNICAL PROGRAM

I. BASIC CLAY MICROSTRUCTURE

A. MICROSTRUCTURE: SIGNATURES
SEDIMENTARY SOURCES AND SOURCE MATERIALS
RECENT SEDIMENTARY ENVIRONMENTS
THE SEDIMENTARY COLUMN
ANCIENT SEDIMENTARY ENVIRONMENTS
THE ROCK COLUMN

B. ENVIRONMENTAL PROCESSES: A CONTINUUM
ATMOSPHERIC AEROSOLS/FLUVIAL PARTICULATES
COASTAL AND OPEN MARINE SUSPENSATES
SEDIMENT-WATER INTERFACE DYNAMICS
POST-DEPOSITIONAL PROCESSES
GEOLOGICAL/GEOCHEMICAL
GEOTECHNICAL
BIOLOGICAL

II. APPLIED CLAY MICROSTRUCTURE

A. MODELING: PAST AND PRESENT NEW DIRECTIONS
PHYSICO-CHEMISTRY
MICROFABRIC
POROMETRY
ISOTROPY/ANISOTROPY
MASS PHYSICAL/MECHANICAL PROPERTIES
RHEOLOGY

B. MEASUREMENTS/TECHNIQUES/SAMPLING STRATEGY
SEM/TEM
ORGANIC-CLAY INTERACTIONS
COMPUTERS - HARDWARE/SOFTWARE
FIELD METHODS
LABORATORY METHODS

C. APPLICATIONS PRESENT REQUIREMENTS
WASTE DISPOSAL -- CONTAINMENT/PACKING MATERIALS
CLAY BEHAVIOR
PETROLEUM RECOVERY PRIMARY/SECONDARY MIGRATION
STABILITY OF DEPOSITS
GEOPHYSICAL TECHNIQUES

III. FUTURE RESEARCH DIRECTIONS AND RECOMMENDATIONS: BASIC AND APPLIED

OPEN DISCUSSION - WORKSHOP FORUM

IV. INFORMAL POSTER DISPLAYS

CLAY MICROSTRUCTURE WORKSHOP AND CONFERENCE
October 4,5,6,7, 1988
STENNIS SPACE CENTER, MISSISSIPPI

TOPIC: THE MICROSTRUCTURE OF FINE-GRAINED TERRIGENOUS MARINE SEDIMENTS - FROM MUDS TO SHALE

THEME: The fundamental roles of microfabric and physico-chemistry as determinants of marine sediment properties: the significance of microstructure to diagenetic, mass physical, static, dynamic, and geoacoustic properties, and to micro-scale sedimentary features and the importance of these to applied problems.

PURPOSE: The purpose of this workshop is to provide an interdisciplinary forum for critical discussion of the microstructure of clay-rich sediments and rocks in order to accelerate future research studies in new directions. The ultimate goal is to facilitate solution of applied problems through application of fundamental scientific principles. The thrust of this approach is based on the concept that the microfabric and physico-chemistry of fine-grained geologic materials are the fundamental "building blocks" of sediments and rocks and the microstructure determines their characteristic physical, mechanical, and geoacoustic properties under static and dynamic stresses.

WORKSHOP SPONSORED BY:

The Naval Ocean Research & Development Activity, SSC, MS
The Department of Energy, Chicago Office, Chicago, IL
The Oak Ridge National Laboratory, Oak Ridge, TN
The Office of Naval Research/Contract Research Division, Arlington, VA

DEVELOPED AND ORGANIZED BY:

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Dr. William R. Bryant, Texas A&M University, College Station, TX

Wednesday October 5, 1988
Command Conference Facility (Rm A-32)
NORDA Bldg. 1005
Stennis Space Center, MS

7:30 - 7:50am

Good morning refreshments

WELCOMING COMMENTS - DIRECTIONS - OBJECTIVES

7:50 - 8:10am

Dr. William B. Moseley - Technical Director, NORDA

Capt. Anthony C. Esau - Commanding Officer, NORDA

Dr. Richard Bennett - NORDA

Dr. Tom Lomenick - Oak Ridge National Laboratories

Dr. John Kasprowicz - Department of Energy, Chicago Office

Wed. Oct 5, 1988
SSC, MS

8:10am

I - BASIC CLAY MICROSTRUCTURE

A. MICROSTRUCTURE: SIGNATURES
CHAIRMEN: DRS. NEAL O'BRIEN AND RICHARD FAAS

SESSION STATEMENT AND OBJECTIVES

Through the examination and study of recent sedimentary environments, geological materials, and the sedimentary column, microstructure signatures may be identified as characteristic of specific depositional environments and processes. The microstructure signatures may be used to understand ancient sedimentary environments and processes through the study of the rock record. Some of the questions that may be asked are: What is the role of sedimentary sources and source materials in determining the microstructure of sedimentary deposits? How is the development of the microstructure related to the physical and mechanical properties of the sediment? What post-depositional microfabric features result from specific environmental stress regimes, i.e., the time- and space-dependent energy potentials? How are these stress regimes modified by the geological processes, biological activities, geochemical environment and physical and mechanical properties of the deposit?

SEDIMENTARY SOURCES AND SOURCE MATERIALS:

PAST AND PRESENT
FLUVIAL/AEOLIAN: no submissions

RECENT SEDIMENTARY ENVIRONMENTS:

8:15 - 8:30am
William Bryant:
RED CLAYS [1]

8:35 - 8:50am
Steven Kuehl, Tina Hariu, Marc Sanford, Charles Nittrouer, and David DeMaster:
MILL IMETER-SCALE SEDIMENTARY STRUCTURE OF FINE-GRAINED SEDIMENTS: EXAMPLES FROM CONTINENTAL MARGIN ENVIRONMENTS [2]

8:55 - 9:10am
Les Shephard and Ann Rutledge:
CLAY FABRIC OF FINE-GRAINED TURBIDITE SEQUENCES: SOUTHERN NARES ABYSSAL PLAIN [3]

Wed. Oct 5, 1988
SSC, MS
I - Basic Clay Microstructure
Microstructure: Signatures (Cont'd)

THE SEDIMENTARY COLUMN:

9:15 - 9:30am

Richard Bennett, Neal O'Brien, and Matthew Hulbert:
DETERMINANTS OF CLAY AND SHALE MICROFABRIC SIGNATURES: PROCESSES AND MECHANISMS [4]

ANCIENT SEDIMENTARY ENVIRONMENTS:

no submissions

THE ROCK COLUMN:

9:35 - 9:50am

Jurgen Schieber:
SEDIMENTARY STRUCTURES, TEXTURES, AND DEPOSITIONAL SETTINGS OF SHALES FROM THE MID-PROTEROZOIC BELT BASIN [5]

9:55 - 10:10am

David Davies, Richard Vessell, William Bryant, and Patti Burkett:
POROSITIES, PERMEABILITIES AND MICROFABRICS OF DEVONIAN SHALES [6]

10:15 - 10:35am Break

Wed. Oct 5, 1988
SSC, MS
I - Basic Clay Microstructure

10:35am
B. ENVIRONMENTAL PROCESSES: A CONTINUUM
CHAIRMEN: DRS. WILLIAM R. BRYANT AND CHARLES WEAVER

SESSION STATEMENT AND OBJECTIVES

The response of the fine-grained particles to the physical, chemical, and mechanical environment encountered in the continuum associated with particle transport, deposition, and burial is often recorded by the microfabric. This record can be observed and studied to establish the major processes controlling microfabric variations. The record is examined to delineate the dominant processes responsible for spatial and temporal variations in the microfabric which occurred during the gradual transformation from individual particles to aggregates (multi-plate particles and domains) and floccules and ultimately to clay sediments and to shales. The totality of atmospheric, fluvial, biological, chemical and geotechnical processes is included.

ATMOSPHERIC AEROSOLS/FLUVIAL PARTICULATES:

10:40 - 10:55am
Kate Kranck:
INTERPARTICLE GRAIN SIZE RELATIONSHIPS RESULTING FROM FLOCCULATION [7]

COASTAL AND OPEN MARINE SUSPENSATES:

11:00 - 11:15am
James Syvitski:
THE CHANGING MICROFABRIC STRUCTURE OF SUSPENDED PARTICULATE MATTER - THE FLUVIAL TO MARINE TRANSITION: FLOCCULATION, AGGLOMERATION AND PELLETIZATION [8]

11:20 - 11:35am
Jack Pierce:
MICROSTRUCTURE OF SUSPENSATES: FROM STREAM TO SHELF [9]

Wed. Oct 5, 1988
SSC, MS
I - Basic Clay Microstructure
Environmental Processes: a continuum (cont'd)

SEDIMENT-WATER INTERFACE DYNAMICS:

11:40 - 11:55am
Emmanuel Partheniades:
EFFECT OF BED SHEAR STRESSES ON THE DEPOSITION AND STRENGTH OF DEPOSITED COHESIVE MUDS [10]

12:00 - 12:15pm
Brian Dade, Arthur Nowell, and Peter Jumars:
MASS ARRIVAL MECHANISMS AND CLAY DEPOSITION AT THE SEAFLOOR [11]

12:20 - 12:35pm
Mark Ross and Ashish Mehta:
FLUIDIZATION OF SOFT MUDS BY WAVES [12]

12:40 - 2:00pm Lunch

2:00 - 2:15pm
Frank Bohlen:
TRANSPORT DYNAMICS AND THE FABRIC OF THE SEDIMENT-WATER INTERFACE IN COASTAL WATERS [13]

2:20 - 2:35pm
Richard Faas:
RHEOLOGICAL CONTROLS OF FINE-GRAINED SEDIMENTOLOGY AND A MODEL FOR PREFERRED ORIENTATION IN BLACK FISSILE SHALES [14]

Wed. Oct 5, 1988
SSC, MS
I - Basic Clay Microstructure
Environmental Processes: a continuum (cont'd)

POST-DEPOSITIONAL PROCESSES:
GEOLOGICAL/GEOCHEMICAL:

2:40 - 2:55pm

Robert Kirby:
DISTINGUISHING FEATURES OF LAYERED MUDS DEPOSITED FROM SHALLOW WATER HIGH CONCENTRATION SUSPENSIONS [15]

3:00 - 3:15pm

Suzanne Reynolds:
MICROFABRICS OF DETRITAL MARINE MUDS AND MUDSTONES [16]

GEOTECHNICAL:

3:20 - 3:35pm

Kathleen Dadey, Margaret Leinen, Armand Silva:
ANOMALOUS STRESS HISTORY IN THE NW PACIFIC: THE ROLE OF MICROSTRUCTURE [17]

3:40 - 3:55pm

Elliott Taylor, Patti Burkett, Jeri Wackler, John Leonard and William Bryant:
STRUCTURAL FABRIC AND RELATED PHYSICAL PROPERTIES OF ACCRETED AND SUBDUCTED SEDIMENTS FROM THE BARBADOS ACCRETIONARY COMPLEX [18]

BIOLOGICAL:

4:00 - 4:15pm

Clark Alexander, Jr., Charles Nittrouer, and David DeMaster:
MICROSTRATIGRAPHY OF YELLOW SEA MUDS: RELATIONSHIP TO SEDIMENTOLOGICAL PROPERTIES AND COMPRESSIONAL-WAVE SEISMIC VELOCITY [19]

4:20 - 4:40m Break

Wed. Oct 5, 1988
SSC, MS

4:40pm

II - APPLIED CLAY MICROSTRUCTURE

A. MODELING - PAST AND PRESENT - NEW DIRECTIONS
CHAIRMEN: DRS. SIBEL PAMUKCU AND TOKUO YAMAMOTO

SESSION STATEMENT AND OBJECTIVES

Models of the elementary determinants of microstructure are reviewed to understand how existing and proposed models may be integrated to form more sophisticated models for reliable predictive solutions to basic scientific issues and applied engineering problems. Simplistic models may be combined with sophisticated conceptual models developed through an interdisciplinary approach to problem solving. This approach is indispensable in order to fully appreciate the complexity of the total environmental system of contemporaneous and time-dependent forcing functions that play a role in the developmental history of sediment microstructure. Models integrating concepts and principles of physico-chemistry, microfabric, porometry, and the fundamental mass physical and mechanical properties of sediment are essential ingredients of future formulations of reliable predictive models of microstructure and sediment behavior under static and dynamic stresses. The stresses of specific interest include physical, biological, chemical, and acoustical.

PHYSICO-CHEMISTRY:

4:45 - 5:00pm

Sibel Pamukcu:
INFLUENCE OF SOME PHYSICO-CHEMICAL ACTIVITIES ON MECHANICAL BEHAVIOR OF CLAYS [20]

5:05 - 5:20pm

Jos Cenens, Robert Schoonheydt, and Rudy Heylen:
ORGANISATION OF CLAY PARTICLES IN DILUTE AQUEOUS SUSPENSION AS INFERRED FROM SPECTROSCOPY OF ADSORBED DYES [21]

5:25 - 5:40pm

Walter Drost-Hansen:
SOME EFFECTS OF VICINAL WATER ON THE SEDIMENTATION PROCESS, COMPACTION AND ULTIMATE PROPERTIES OF SEDIMENTS [22]

5:45pm Adjourn

Thurs. Oct 6, 1988
SSC, MS
II - Applied clay microstructure
Modeling - past & present - new directions (cont'd)

7:30- 8:00am Good morning refreshments

MICROFABRIC:
8:00 - 8:15am
James Syvitski:
THE FLOC CAMERA: A 3-D IMAGING SYSTEM OF SUSPENDED PARTICULATE MATTER [23]

8:20 - 8:35am
Adolph Altschaeffl and S. Thevanayagam:
CHARACTERIZATION OF CLAY FABRIC [24]

POROMETRY:
8:40 - 8:55am
Ray Ferrell, Jr. and Paul Carpenter:
MICROTEXTURE AND MICROCHEMISTRY OF CLAY-RICH SEDIMENT [25]

ISOTROPY/ANISOTROPY:
9:00- 9:15am
David Tapply:
COMPUTER MODEL FOR COHESIVE SEDIMENT TRANSPORT: A NEW APPROACH [26]

9:20 - 9:35am
Jane Schoonmaker Tribble and Fred Mackenzie:
PHYSICAL PROPERTY CHANGES ACCOMPANYING THE MUD TO SHALE CONVERSION, BARBADOS CONVERGENT MARGIN [27]

MASS PHYSICAL/MECHANICAL PROPERTIES:
9:40 - 9:55am
George Brunton:
QUANTITATIVE ROCK MINERAL ANALYSIS [28]

10:00 - 10:30am Coffee break

RHEOLOGY:
10:30 - 10:45am
Tom Chang, G. Lennon, Sibel Pamukcu and Bobb Carson:
COUPLED FLUID EXPULSION/DEFORMATION MODELING FOR DEWATERING SEDIMENTS [29]

10:50 - 11:05am
David Williams and P. Williams:
RHEOLOGY AND MICROSTRUCTURE OF CONCENTRATED ILLITE SUSPENSIONS [30]

Thurs. Oct 6, 1988
SSC, MS
II - Applied clay microstructure (cont'd)

11:10am

B. MEASUREMENTS/TECHNIQUES/SAMPLING STRATEGY
CHAIRMEN: DRS. PETER SMART AND WEN-AN CHIOU

SESSION STATEMENT AND OBJECTIVES

State-of-the-art techniques are examined to quantify and classify the microstructure of suspended sediments, unconsolidated and consolidated sediments, and rocks. Techniques are reviewed for applications at observational scales ranging from field scale to molecular scale. An understanding of the limitations of the techniques is essential in extending our present qualitative descriptions to quantitative measurements and models of microfabric and physico-chemistry. Thorough examination of the analytical capabilities of existing instrumentation and techniques is essential in order to improve and expand our theoretical basis for modeling. New and improved statistical methods, numerical techniques, and quality sampling procedures and instrumentation are essential in advancing the state-of-the-art in the investigations and applications of the microstructure of fine-grained sediments.

SEM/TEM:

11:15 - 11:30am
Akira Fukami:
OBSERVATION TECHNIQUE FOR WET CLAY MINERALS USING ENVIRONMENTAL CELL EQUIPMENT ATTACHED TO HIGH-RESOLUTION ELECTRON MICROSCOPE [31]

ORGANIC - CLAY INTERACTIONS:

11:35 - 11:50am
Kathleen Fischer:
POSSIBLE EFFECTS OF ORGANIC MATTER ON AGGREGATE FORMATION AND SEDIMENT MICROSTRUCTURE [32]

11:55 - 12:10pm
Yalcin Acar:
THE EFFECT OF ORGANIC FLUIDS ON THE FABRIC AND HYDRAULIC CONDUCTIVITY OF COMPACTED CLAY [33]

12:15 - 1:15pm Lunch

Thurs, Oct 6, 1988
SSC, Ms
II - Applied Clay Microstructure
Measurements/Techniques/Sampling Strategy (cont'd)

1:15 - 1:30pm
Wen-An Chiou, William Bryant, and Richard Bennett:
CLAY FABRIC OF GASSY SUBMARINE SEDIMENTS [34]

COMPUTERS: HARDWARE/SOFTWARE:

1:35 - 1:50pm
Shobha Bhatia:
APPLICATION OF IMAGE ANALYSIS TECHNIQUE TO STUDY THE MICROSTRUCTURE OF SOILS [35]

1:55 - 2:10pm
Peter Smart:
AUTOMATIC ANALYSIS OF ELECTRON MICROSTRUCTURE OF COHESIVE SEDIMENTS [36]

2:15 - 2:30pm
Robert Ehrlich and Sterling Crabtree:
DETERMINATION OF PORE/THROAT RELATIONSHIPS LEADS TO SUCCESSFUL PHYSICAL MODELLING OF POROUS MEDIA [37]

FIELD METHODS:

2:35 - 2:50pm
Michael Richardson, Enrico Muzi, and Luigi Troiano:
SHEAR WAVES IN SEDIMENTS: A COMPARISON OF IN SITU AND LABORATORY MEASUREMENTS [38]

2:55 - 3:10pm
Charles Libicki and Keith Bedford:
GEOACOUSTIC PROPERTIES OF THE NEAR-SURFACE SEDIMENT IN RESPONSE TO PERIODIC DEPOSITION [39]

3:15 - 3:30pm
Robert Stoll:
GEOACOUSTIC PROPERTIES OF A MARINE SILT [40]

3:35 - 3:40 Mini-Break

LABORATORY METHODS:

3:40 - 3:55pm
Tokuo Yamamoto, Mohsen Badiey, and Altan Turgut:
MEASUREMENTS OF BOND ENERGY OF MARINE CLAYS AND WAVE ATTENUATIONS [41]

4:00 - 4:15pm
Thomas Zimmie:
CYCLIC SIMPLE SHEAR BEHAVIOR OF MARINE CLAYS [42]

Thurs, Oct 6, 1988
SSC, Ms
II - Applied Clay Microstructure

4:20pm

C. APPLICATIONS: PRESENT REQUIREMENTS
CHAIRMEN: DRS. JOHN KASPROWICZ AND TOM LOMENICK

SESSION STATEMENT AND OBJECTIVES

The critical impact of microstructure upon engineering applications and problems is reviewed with illustration drawn from present practices and techniques used in investigations of fine-grained sediments and rocks. Typical problems involve the utilization of natural and artificially prepared geological materials for containment of waste materials, petroleum recovery, and isolation of various hazardous materials. Disciplines of geohydrolics, geotechnics, and remote sensing play critical roles in assessing the geological materials and formations selected for waste utilization and recovery of natural resources. Both of the activities impact the environment through time and space. It is essential that research advances made in understanding sediment microstructure, the under-pinning of the mass physical and mechanical properties, be transitioned to engineering problems and applications in a timely manner.

WASTE DISPOSAL - CONTAINMENT/PACKING MATERIALS:

4:25 - 4:40pm
Tom Lomenick:
DISPOSAL OF RADIOACTIVE WASTE INTO CLAY-RICH ROCKS [43]

4:45 - 5:00pm
Mysore Nataraj:
AN APPRAISAL OF THE MECHANICAL PROPERTIES OF CLAYS AS HOST ROCKS IN THE MATRIX BOREHOLE CONCEPT OF DISPOSAL [44]

5:05 - 5:20pm
Robert Quigley:
FABRIC AND POROSIMETRY OF CLAYS SUBJECTED TO LIQUID HYDROCARBONS AND MUNICIPAL LEACHATE [45]

Thurs, Oct 6, 1988
SSC, Ms
II - Applied Clay Microstructure
Applications: Present Requirements (cont'd)

5:25 - 5:40pm

Patti Burkett, Richard Bennett, and William Bryant:
THE SIGNIFICANCE OF THE MICROSTRUCTURE OF PACIFIC RED CLAYS TO NUCLEAR WASTE DISPOSAL [46]

CLAY BEHAVIOR:

5:45 - 6:00pm

Nolan Aughenbaugh:
THE GEOTECHNICAL IMPORTANCE OF CLAY FLEXIBILITY [47]

PETROLEUM RECOVERY: PRIMARY/SECONDARY MIGRATION:

Jack Gillott and E. Grabowski (unable to attend)
EFFECTS OF HYDROTHERMAL TREATMENT ON THE ENGINEERING PROPERTIES, MICROSTRUCTURE, AND COMPOSITION OF OIL WELL CEMENTS [48]

6:05pm Adjourn

Fri. Oct 7, 1988
SSC, MS
II - Applied Clay Microstructure
Applications: Present Requirements (cont'd)

7:30 - 8:00am Good morning refreshments

STABILITY OF DEPOSITS:

8:00 - 8:15am
Keith Tovey:
THE MICROFABRIC OF SOME HONG KONG MARINE SOILS [49]

8:20 - 8:35am
Kenneth Torrance:
INFLUENCES ON THE RHEOLOGY OF MARINE SEDIMENTS COMPOSED OF LOW-ACTIVITY MINERALS [50]

GEOPHYSICAL TECHNIQUES:

8:40 - 8:55am
Murli Manghnani:
ACOUSTIC AND ELECTRICAL PROPERTIES OF MARINE SEDIMENTS: ROLES OF PORE GEOMETRY AND PREFERRED ORIENTATIONS IN ANISOTROPIC BEHAVIOR [51]

9:00 -9:20am Coffee break

Fri. Oct 7, 1988
SSC, MS

9:30 - 12:30pm

III - FUTURE RESEARCH DIRECTIONS AND RECOMMENDATIONS: BASIC AND APPLIED

Chairmen: Drs. Matthew Hulbert, Richard Bennett, Sibel Pamukcu, and Richard Faas

SESSION STATEMENT AND OBJECTIVES

Presentations focused on the problematic, discipline-specific research and engineering issues that clearly represent current knowledge and intellectual direction in the areas relating to fine-grained sediment microstructure. Evaluation of the content of conference materials may raise questions such as:

Where are we now?
How can the various disciplines be integrated effectively?
How can present knowledge be applied to pressing problems for the protection of the environment?
How can we improve our observational capabilities?
How can we deal with the problems of scale which ranges from molecular to stratigraphic?
What are the best approaches to quantification and improved descriptions of microstructure?
How can microstructure signatures observed in recent sediments be used to interpret the geological record?
What new instrumentation is needed?
What are the limits to which existing instrumentation can be pushed?
What new models are required?
What are the best directions to take in developing statistical techniques?
What new field and laboratory studies will advance our understanding of microstructure and related fields?
What new data bases are required for solving specific problems?
Would artificial intelligence be useful?
What interlaboratory calibrations are required?
How do we prioritize our future research directions?
What are the significant scientific and technical problems that will seriously impact society and require solution?

OPEN DISCUSSION - WORKSHOP FORUM:

*Leading questions in science and engineering
*Required techniques/instrumentation
*New models - conceptual and numerical
*Deficiencies in data bases

Fri. Oct 7, 1988
SSC, MS

IV - INFORMAL POSTER DISPLAYS:

Richard Rezak, Dawn Lavoie, and Dennis Lavoie:
CARBONATE MICROFABRICS [52]

Sybil Callaway and William Busch:
BURIAL TRANSFORMATION OF CLAY FABRIC AT OCEAN DRILLING PROGRAM LEG 117 DRILL SITES [53]

Elliott Taylor, Patti Burkett, Jeri Wackler, John Leonard, and William Bryant:
STRUCTURAL FABRIC AND RELATED PHYSICAL PROPERTIES OF ACCRETED AND SUBDUCTED SEDIMENTS FROM THE BARBADOS ACCRETIONARY COMPLEX [18]

ABSTRACTS CONTRIBUTED (NOT FOR PRESENTATION):

Gao Guorui Iaeg:
APPLICATION OF MICROSTRUCTURE CLASSIFICATION OF MARINE SEDIMENT TO ENGINEERING GEOLOGICAL EVALUATION [54]

Ewa Stepkowska:
STRUCTURAL MODEL OF THE CLAY-WATER SYSTEM [55]

ANISOTROPY AND NON-HOMOGENEITY IN THE CLAY-WATER SYSTEM [56]

ALTERNATE SPEAKERS AND TOPICS

THE NONAMBIENT BEHAVIOR OF CLAY-RICH ROCKS IN IN SITU TESTS-
DR. A.F. FOSSUM, RE/SPEC, RAPID CITY, SD

FABRIC OF SHALES-
DR. CHARLES WEAVER, GEORGIA INSTITUTE OF TECHNOLOGY, ATLANTA, GA

THANK YOU FOR JOINING US!

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ABSTRACTS

CLAY MICROSTRUCTURE WORKSHOP AND CONFERENCE

RED CLAYS

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Extensive examination of North Pacific Basin red clays by scanning and transmission electron microscopy reveals that the main constituents of the red clays are illite-rich argillaceous or shale clasts, quartz and authigenic smectite. The main source of the shale clasts and quartz are aeolian in nature and are derived mainly from African and Asian shales. Illite-rich argillaceous or shale clasts are identifiable by their morphology (high degree of roundness), selected area diffraction, and their unique fracture characteristics created by an ultra thin-sectioning process. This allows for the identification and differentiation of illite-rich shale clasts from other clays, including detrital illite, kaolinite, and smectite. Geotechnical examination of the red clays indicate that they are overconsolidated: the preconsolidation stress is in all cases larger than the vertical effective stress. The overconsolidation is attributed to the strong bonding of argillaceous or shale clasts, quartz and other particulate matter by x-ray amorphous and well developed crystalline sheets of authigenic smectite characterized by high surface activity.

Abst 2

MILLIMETER-SCALE SEDIMENTARY STRUCTURE OF FINE-GRAINED SEDIMENTS: EXAMPLES FROM CONTINENTAL MARGIN ENVIRONMENTS

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Thin sections of sediment cores collected from the Amazon and Bengal shelves, and from the continental slope off the U.S. East Coast, reveal several diagnostic structures not observable using other techniques (e.g., radiography, SEM). Muds from the Amazon subaqueous delta reveal a unique category of sedimentary structure termed plasmic fabric. Plasmic fabric results from preferential alignment of anisotropic clay minerals and mica, and in Amazon muds often occurs as horizontal laminae (~0.1 mm thickness) of oriented minerals which are interlaminated with randomly oriented minerals, producing a "striated" extinction pattern when observed using a polarizing microscope. The fabric is considered a primary (physical) structure; however, the mechanism for its formation is unknown. Characteristics of silt laminae for Amazon and Bengal muds often can be used as environmental indicators. For example, micro-cross-lamination and abrupt basal contacts indicate strong currents, with bedload transport and scouring, respectively. On the Bengal shelf, silt laminae with a convoluted appearance were observed in an area of extremely high sediment accumulation rate (>10 cm/y). Although these laminae appear bioturbated in radiographs, microscopic examination suggests that the structure results from penecontemporaneous deformation of the rapidly accumulating muds. Cores collected from the Wilmington canyon area, U.S. East Coast, generally reveal few physical structures in radiographs; however, features observed in thin sections provide important clues concerning recent evolution of these canyon systems. Some cores from the canyon floors reveal mm-scale clasts of pale brown mud in a matrix of modern olive-gray hemipelagic mud. The presence of these clasts, along with radiochemical and observational data, suggest that the canyon walls in this area presently are eroding, and are supplying sediment to the canyon floors. The above observations of micro-scale structures in modern continental margin environments provide important criteria for interpretation of ancient mudrocks.

CLAY FABRIC OF FINE-GRAINED TURBIDITE SEQUENCES: SOUTHERN NARES ABYSSAL PLAIN

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Transmission electron microscopy (TEM) techniques were used to evaluate the dominant clay facies composing the fine-grained turbidite sequences ubiquitous to the Southern Nares Abyssal Plain. Sediments associated with the turbiditic clay facies are characterized by a random distribution of clay particle domains mixed with large clay floccules, clay pellets, and silt grains. Turbiditic clay particle domains often appear to be randomly oriented and interspersed with other particles, possibly as a result of rapid deposition with limited sorting.

Sediments associated with the pelagic facies generally consist of well-defined domains containing clay particles oriented face-to-face. Many clay particle domains occur in chains with edge-to-face contacts. Small particle aggregates infill many of the voids between domains, while larger voids often contain a lacey microcrystalline material, possibly smectite. Material with a similar morphology has been identified in other depositional environments dominated by pelagic clay sediments and may be representative of this facies type. Particles in the pelagic facies exhibit moderate orientation that may result from both primary depositional fabric and that which has developed by post-depositional processes.

Significant variations in the type and size of particles evident on TEM micrographs, in addition to particle orientation, may be used to discriminate between pelagic clay and turbiditic clay facies types.

Abst 4

DETERMINANTS OF CLAY AND SHALE MICROFABRIC SIGNATURES: PROCESSES AND MECHANISMS

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Various modes of particle association are being observed and evaluated in terms of flocculation mechanisms, processes of particle aggregation, and post-depositional processes. Microfabric "signatures" are associated with various processes, mechanisms, and environments of deposition. In the continuum of microfabric development, the fundamental processes in which the individual mechanisms operate are described as : A) Physico-chemical, B) Bio-organic, and C) Burial diagenesis (Figure 1). Two or more mechanisms may operate contemporaneously but typically specific fundamental processes dominate at different periods of microfabric development. Recent fine-grained sediments, consolidated sediment, and shales from the geological record are being studied by scanning and transmission electron microscopy.

The important mechanisms are described as: 1)thermo-mechanical, 2) electro-chemical, 3) interface dynamics, 4) bio-physical(bio-sediment), 5) bio-mechanical (bioturbation), 6) bio-chemical (reaction processes), 7) mass gravity, and 8) diagenesis-cementation (post-depositional). These mechanisms, 1 through 6, occur for finite periods of time in a continuum of geological processes and environmental settings and the micro-environmental forcing functions lead to characteristic particle-to-particle/organo-clay particle associations and microfabric features. In contrast, post depositional/mechano-gravity mechanisms, 7 and 8, such as consolidation, bed motion (shearing and creep), and cementation, commonly occur over time periods that are many orders of magnitude longer than the processes that occur during sediment transport and deposition.

Thermo-mechanical and electro-chemical mechanisms produce high intravoid (edge-to-face) flocs and face-to-face sheet-like miltiplate particle associations. Bio-physical (bio-sediment) aggregates are clusters of randomly oriented clay-silt particles formed when lithogenic matter adheres to sticky organic mucus or is bound together by polymer bridging. Some "marine snow" is a good example of bio-sediment aggregates. Bio-mechanical (bioturbation) mechanisms produce a clay microfabric that possesses a randomness similar to the primary fabric of a flocculated (edge-to-face) clay, however, it is characterized by randomly oriented individual particles (as resolved by SEM) rather than the random domains common in electro-chemically and thermo-mechanically flocculated clays. The bio-chemical mechanisms describe the chemical transformations which are mediated by living organisms.

Thermo-mechanical mechanisms arise from thermally driven forces in the surrounding medium (e.g. in the water column) and from dynamic interaction of particles driven by wave, current, and gravity forces. Electro-chemical mechanisms arise from the interaction of particles in response to the electrolytic nature of the surrounding medium, the chemistry of associated organic materials, and the "fixed" electrical character of the specific minerals. Particles impinging on the sediment-water interface are in dynamic motion and collide with existing sedimentary particles in a variety of configurations depending, in part, upon the micro-relief (roughness) of the bottom. Post-depositional/mechano-gravity mechanisms arise from overburden stress and gravity- driven vertical and down-slope forces that can reorient the microfabric during consolidation and shearing processes. In some environments, cementation and diagenesis of mineral phases operating over a range of thermal regimes can alter the character of the fabric . The microfabric "signatures" resulting from the various processes and mechanisms are often recorded in the sediments and rock and are revealed by electron microscopy observations.

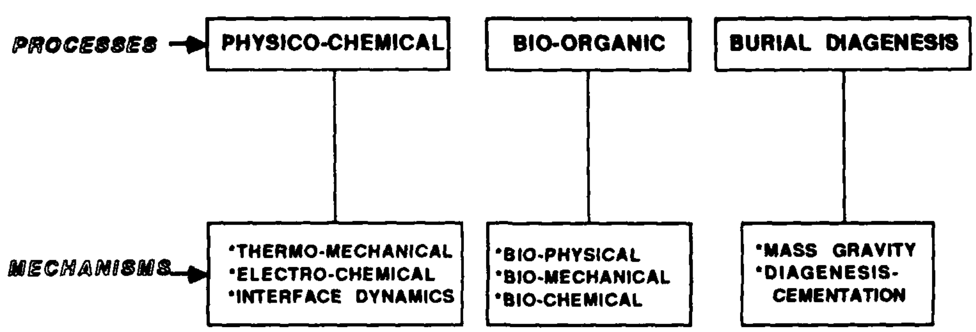

FIGURE 1. DETERMINANTS OF CLAY AND SHALE MICROFABRIC SIGNATURES: PROCESSES AND MECHANISMS - A CONTINUUM

SEDIMENTARY STRUCTURES, TEXTURES, AND DEPOSITIONAL SETTINGS OF SHALES FROM THE MID-PROTEROZOIC BELT BASIN

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The Belt Supergroup of Montana, Idaho, and British Columbia is a thick shale-dominated sequence that accumulated in an epicontinental basin between 1450-850 m.y. ago. Shales from the Newland Formation in the eastern part of the basin have been studied in detail, and six major shale facies types are distinguished on the basis of bedding characteristics, textural features, and the proportions of silt, clay and carbonate. Textural features of these shale types are related to sedimentary environments as deduced from associated lithologies. A variety of sedimentary features, such as graded silt/mud couplets, ripple cross-lamination, graded rhythmites, massive bedding, non-parallel uneven bedding planes, random arrangement of clays and micas, deformation of algal mat fragments, shrinkage cracks, intraformational conglomerates, wave ripples, gradual variations of sedimentary components, and the contacts between interbedded lithologies (sharp vs gradual) serve to elucidate the depositional environment of these shales. Their textural and sedimentary characteristics reflect subaqueous growth of microbial mats, erosion and deposition by storms, deposition of flocculated vs. dispersed clays, continuous slow background sedimentation, winnowing by waves or currents, and subaerial exposure. The various shale facies types reflect differences in the conditions of deposition, from nearshore to basinal. Shales from the variably metamorphosed Prichard Formation, a lateral equivalent of the Newland Formation to the west, still show clearly visible small scale sedimentary features (graded silt/mud couplets and tiny silt ripples are predominant). Deposited in a generally deeper setting than shales of the Newland Formation, they contain several distinguishable shale types, though differences between shale types are more subtle.

Abst 6

POROSITIES, PERMEABILITIES AND MICROFABRICS OF DEVONIAN SHALES

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The porosity of more than 100 ancient shale samples, commercially measured by Dean Stark analysis, ranges from 1 to 8% (mean = 4%). These porosity values are not affected by significant changes in shale fabric, mineralogy or texture. Permeability values (from commercial pulse permeametry) range from 10^2 to 10^{-2} microdarcies (mean = 2.23µd). Permeability values are controlled strongly by microfabric. Shales with parallel microfabric consistently have lower permeabilities (<1µd) than shales with chaotic microfabric (>1µd). The commercial techniques used in this analysis are considered state-of-the-art, yet the absolute values reported are at variance with evidence derived from direct observations and theoretical considerations.

Combined SEM/TEM observations of shale pore systems reveal that the pores are larger and more abundant than would be anticipated from the results of commercial porosity and permeability analyses. Imaging tomography, using micrographs of ultra-thin sections (800 - 1200 Å), has allowed for the actual reconstruction of shale pores in 3-dimensions. These pores are of variable size and shape, and commonly contain euhedral authigenic crystals (pyrite, zeolite). Image analysis of the micrographs indicates that ancient shales have porosities which are significantly higher than values derived from Dean Stark analysis. Laboratory experiments in consolidated muds and clays with porosity values from 10 to 20% yield permeabilities on the order of 10^{-5}µd. (10^{-9} cm/sec). Such values for permeability are significantly lower than the values derived using commercial pulse permeametry.

Comparison of the results of commercial laboratory analysis with the results of direct observation and theoretical considerations suggest that either 1) a large number of shale pores are not interconnected, or 2) that problems exist in current state-of-the-art commercial measurement techniques. Lack of connectivity of pores would result in Dean Stark porosity values which underestimate true porosity. This would explain the observed differences in porosity values. However, this explanation is inconsistent when applied to the results of the permeability analyses. Low values for measured porosity should be accompanied by low values for permeability. Experimental data suggest that permeabilities derived from pulse permeametry are too high. This apparent discrepancy is strong argument in favor of the necessity for changing or improving significantly upon existing commercial procedures for the measurement of porosity and permeability in tight, fine-grained rocks.

INTERPARTICLE GRAIN SIZE RELATIONSHIP RESULTING FROM FLOCCULATION

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Diagrams summarizing observations of the microfabrics formed by flocculated sediment emphasize a number of features which appear to confirm and are explained by postulated theories about flocculation mechanics of fine grained suspended sediment. Noteworthy are the facts that similar sized grains appear never to touch one another in a clay or mud and the largest silt grains in the fabric float in a matrix of finer material. Also each relict aggregate unit or floc is composed of a large range of grain sizes. This is seen as a result of the mechanics of the flocculation process. Grain size analysis and observations of settling experiments show that when a suspension flocculates a representative portion of every component of the suspension becomes a part of each floc. Flocculation proceeds from the finest grains in the suspension up the size scale so that flocs composed of smaller grains flocculate with larger grains. Deposition of flocs will always result in all or some portions of the resulting sediment having an unsorted size distribution. Flocculation is a size-selective process and results in a very specific pattern of grain arrangement analogous to the ordering of molecules in crystals. It is not surprising that disruption of this pattern markedly changes the structural behavior of sediments as illustrated by the difference in the bearing strength between undisturbed and remolded clays.

THE CHANGING MICROFABRIC STRUCTURE OF SUSPENDED PARTICULATE MATTER - THE FLUVIAL TO MARINE TRANSITION: FLOCCULATION, AGGLOMERATION AND PELLETIZATION

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Suspended particles enter the sea dominantly by river plumes that ride bouyantly on the denser marine water. During their initial travel, mixing processes cause the quality of the supporting medium to change from fresh water containing nitrogen-rich organic matter to sea water containing carbon-rich organic matter. Particles enter the river plume normally as single entities, although clay clasts stripped from raised marine terraces and eroded soil aggregates can be locally important. Some of the fluvial particles will contain attached hydrous oxides, organic coatings, and/or freshwater microflora. Flocculation of silts and clays begins to occur within the halocline at salinities between 3 to 5 ppt. Nonplaty minerals may continue to fall as single entities, especially near the river mouth. In the marine water, organic cohesive/adhesive forces allow the attachment onto the flocs of organic detritus and biogenic debris (mostly phytoplankton material in various stages of mechanical destruction). Zooplankton just under the halocline begin to graze on those flocs and agglomerates, subsequently producing mineral-bearing fecal pellets. Many of the larger flocs and single grain particles, because of their size and settling velocity, escape the grazing by zooplankton; the flocs may continue to increase in size, eventually developing into mucous-coated particles (where water depth permits).

Mucoid filaments, long, thin and delicate, are found suspended vertically within stable water masses (i.e., those with negligible internal shear). Their size and concentration increases with depth and distance seaward, and they eventually become coated with suspended debris. The filaments may form from bacterial growth outward from decaying planktonic fecal pellets.

Examples of both in situ (underwater) photographs and SEM analysis of filtered suspended particles will be presented.

Abst 9

MICROSTRUCTURE OF SUSPENSATES: FROM STREAM TO SHELF

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Most of the particle volume suspended in natural waters is found in aggregates, even though single particles are more numerous. Some of the microstructure present in these suspended aggregates should be preserved in bottom sediments. It is doubtful if the very large, fragile marine snow, or its estuarine equivalent, could survive impact with the bottom, however gentle. However, fragments should survive and be incorporated into the bottom sediments.

As shown by scanning electron microscopy, stream suspensates are mainly single particles or simple aggregates of a few particles; some of these may be inherited from upland soils. Grain junctures are most often face to face. A few complex aggregates in fluvial waters may be from resuspension of bottom sediments or caving of bank material.

Microstructure becomes more complex after salinity reaches about 1. The first complex aggregates have an appearance similar to that ascribed to flocs, large number of particles with little to no matrix and a friable appearance. Most grain junctures are face-face with some edge-face. Farther down the salt gradient, associations of mineral particles, plankton, and biotic fragments are present in a matrix. There is little to no discernible orientation of the individual particles in these multi-component complex particles. These aggregates have neither the familiar edge-face or face-face structures. Aggregates from estuarine stations and those from shelf waters exhibit only minor differences in microstructure, suggesting that the controlling processes in formation differ little between estuarine and marine waters. Macroaggregates may become more prominent in more saline water.

Fecal pellets, common in bottom sediments, are seldom present in samples of estuarine or marine suspensate populations because high settling rates rapidly remove them from the water column. Nevertheless, fecal pellets remove large numbers of particles from the water column.

EFFECT OF BED SHEAR STRESSES ON THE DEPOSITION AND STRENGTH OF DEPOSITED COHESIVE MUDS

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This paper presents and discusses the most recent and most important research results on the dynamics of deposition and resuspension of cohesive sediments in a turbulent flow field and explains how the hydrodynamic interaction between the flow and cohesive sediment suspensions affects the microstructure and certain mechanical properties of deposited muds.

It has been shown that both deposition and resuspension are controlled by the near-bed flow dynamics, and, more specifically, by the bed shear stresses, while the far-bed turbulent flow field contributes only to the rate of flocculation. Under a given bed shear stress a portion of the total sediment remains in suspension while the remaining sediment deposits at relatively high rates. A stratified deposited bed is thus developed with respect to the density and cohesive strength of flocs. For the same reason the engineering properties of cohesive beds deposited in a dispersive flow field, such as an open channel, vary along the channel. Both the density and the resistance to erosion of deposited beds increase with depth. This increase is the result of the floc segregation during deposition rather than of mechanical consolidation. The erosive strength of the bed also increases with the time the bed remained at rest before the beginning of resuspension.

Abst 11

MASS ARRIVAL MECHANISMS AND CLAY DEPOSITION AT THE SEAFLOOR

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Mass arrives at the seafloor by gravitational settling, interception, inertial impaction, and Brownian or molecular diffusion. Transfer of dissolved substances and submicrometer particles to the bed is dominated by diffusion, while particles much larger than about 1 μm reach the bottom by gravitational settling. Interception of particles by roughness plays an important role for all particle sizes. Inertial impaction onto roughness is significant at high boundary shear stresses typical of those seen in wave-dominated environments. A simple analytical approach in which turbulent mass transport is modulated by mechanism-specific and roughness-dependent boundary conditions permits us to evaluate explicitly the importance of different fluid mechanical regimes to clay deposition and early diagenesis. Model results indicate that: 1) the combination of all transfer mechanisms results in minimal gross deposition velocity for primary clay-sized particles ($d \approx 0.1$ μm) and 2) gross deposition rate of clay-sized particles and dissolved substances is very sensitive to near-bed turbulence intensity (expressed in terms of friction velocity, in turn a function of flow speed and bed roughness).

FLUIDIZATION OF SOFT MUDS BY WAVES

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The mechanism by which waves suspend cohesive sediments in the estuarine and nearshore environments is characterized by the complex manner in which mud beds respond to wave loading. Field and laboratory based observations suggest a highly time-dependent variation of bed properties during wave action, leading to an eventual destruction of the porous solid matrix and generation of fluid mud. The soil mechanical definition of the boundary between the cohesive bed and fluid mud is based on the development of effective stress below the boundary. Laboratory flume measurements under progressive wave action show a gradual lowering of the cohesive bed boundary with time, consequently leading to fluid mud generation. Even though this boundary cannot be identified by any unique interfacial mud density, there is a strong engineering-based need to define the boundary in terms of a density, at least from the perspective of an operational definition of the cohesive bed. In this context it seems feasible to examine some limiting conditions for density ranges based on physical evidence.

Abst 13

TRANSPORT DYNAMICS AND THE FABRIC OF THE SEDIMENT-WATER INTERFACE IN COASTAL WATERS

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Time series observations using arrays of bottom mounted instruments in various coastal embayments within the northeastern United States show a moderate to high degree of spatial and temporal variability in the response of the sediment-water interface to velocity associated shear stress. In sediments dominated by sands and silts, interfacial response and associated resuspension is a simple function of stress magnitude with variations in near-bottom suspended material concentrations (SMC) proceeding in-phase with concurrent velocity. As the percentage of fine grained silts and clays increases interfacial response becomes increasingly sensitive to biotic factors including water column productivity and bioturbation. Under these conditions material concentrations just above the interface display variant phase relative to velocity with angles ranging from 0 to 90 degrees (Fig. 1). The observed response suggests that for fine-grained deposits only the immediate surface (thickness 0 (mm)) of the interface is involved in active suspension and deposition even under relatively extreme storm conditions. Deeper disturbance previously assumed to be storm related may be the result of stress induced readjustments of a bioturbated sediment column. These characteristics are used in the development of a "dusty-room" model where materials are alternately suspended and deposited on a relative stable surface. This view provides clear indication of the factors governing the fabric of the sediment-water interface in fine grained deposits and the parameters that must be measured in order to assess transport potential. This combination has direct application within several numerical schemes presently being used to estimate fine grained sediment transport in coastal waters.

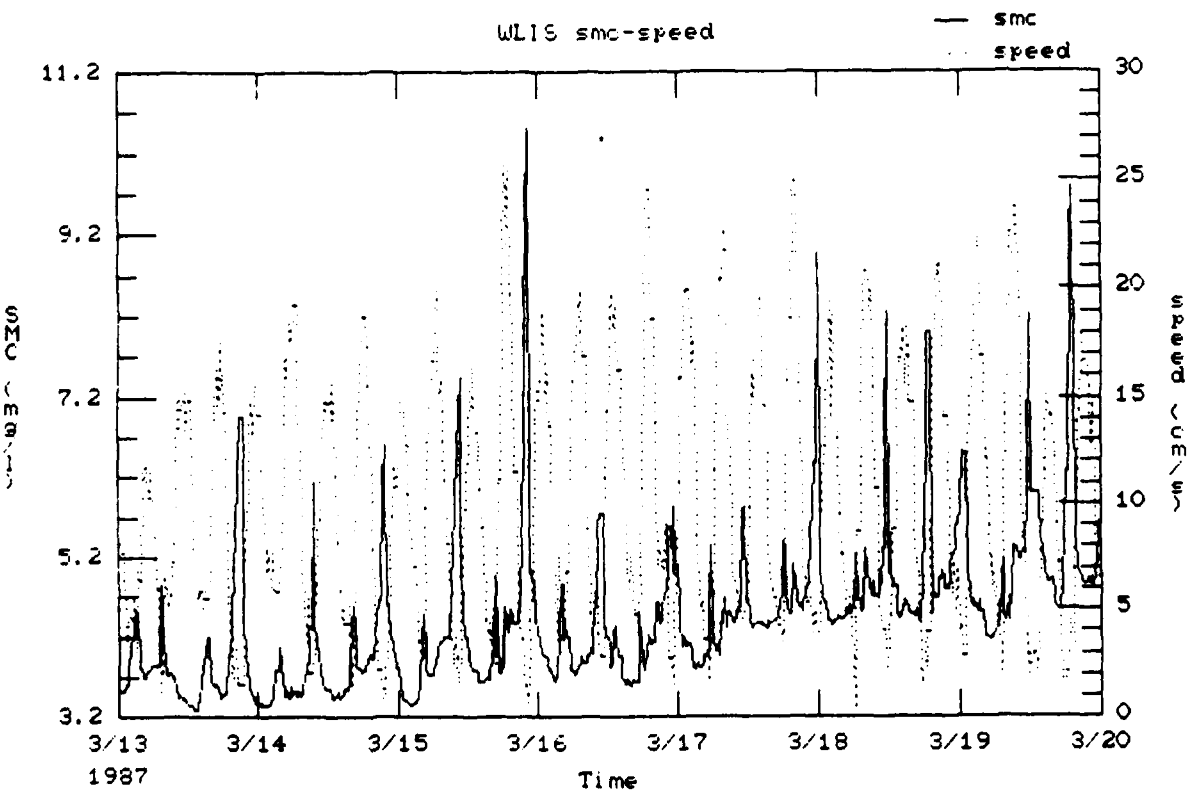

Figure 1a. Time Series Observations of Velocity and Near Bottom Suspended Materials Concentrations - LIS

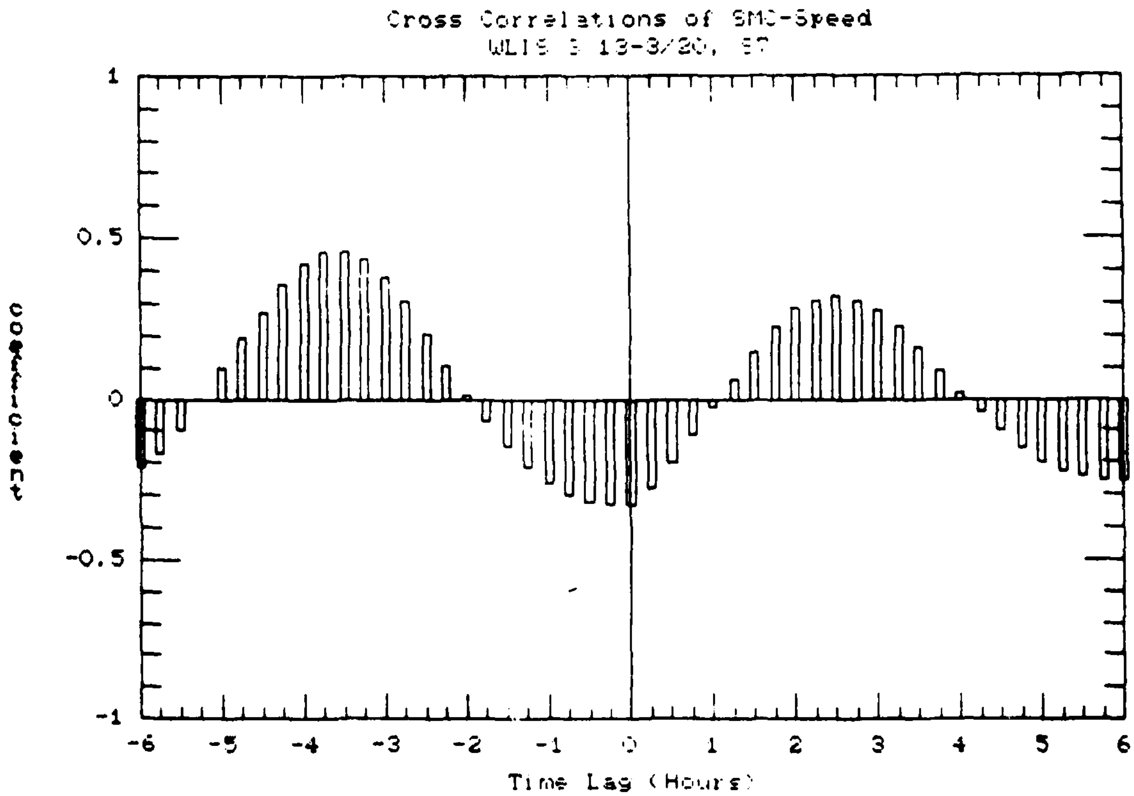

Figure 1b Cross-Correlation of Near Bottom Suspended Material Concentrations and Concurrent Speed - LIS

Abst 14

RHEOLOGICAL CONTROLS OF FINE-GRAINED SEDIMENTOLOGY AND A MODEL FOR PREFERRED ORIENTATION IN BLACK FISSILE SHALES

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Studies of rheological behavior patterns of dense fine-sediment suspensions which accumulate through hindered settling in estuaries and other turbid coastal environments leads to consideration of the role of rheological controls of cohesive sediment transport processes and suggests a new and dynamic model for the origin of preferred fabric development in black shales and mudstones.

Rheological controls include the time and density-dependent factors of yield stress, thixotropy, and various forms of non-Newtonian flow behavior ranging from pseudoplastic (shear-thinning) to dilatant (shear-thickening). Flow behavior interaction with tidal dynamics may result in one or several intervals of resuspension on an accelerating tide, or resuspension may be inhibited through shear-thickening flow behavior. Yield stress development during an asymmetrical tidal cycle (e.g., longer period of slack water before ebb than before flood) may result in net up-estuary sediment transport or sediment may be exported from the estuary, depending on the direction and duration of the asymmetry.

Consideration of the role of non-Newtonian flow behavior in the depositional process, particularly in the retention phase resulting from shear-thickening flow provides an explanation for the preferred orientation of the clay particles in black shales. Rheological measurements of highly reduced suspensions from Cape Lookout Bight, North Carolina and the Scheldt estuary, Belgium indicated that an interval of shear-thickening (dilatant) flow consistently occurred between shear rates from 1.0 to 10/s (inverse seconds) in the more concentrated suspensions (>300 g/l). Such behavior results from parallel alignment (FF) of clay particles, reduction of intra-floc water, and increased mass which behaves elastically under tidal shear stresses. Once so stressed, there is little likelihood that the preferred orientation of the particles of the suspension should change as the magnitude of tidal shear stress decreases. The conditions under which this phenomenon occurs include high sediment accumulation rates (>10 cm/yr) high particulate and dissolved organic content (>10%), energetic tidal and storm wave energies (1.64 hurricanes/yr at Cape Lookout, NC - 15 m tidal range in the Scheldt Estuary), and anoxic conditions. The rock originating under these conditions would be a black, fissile shale.

DISTINGUISHING FEATURES OF LAYERED MUDS DEPOSITED FROM SHALLOW WATER HIGH CONCENTRATION SUSPENSIONS

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Latest findings on the behaviour of fine sediment suspensions in nature reveal a break-point in behaviour at a depth mean concentration close to 500 mg l^{-1}. Below this value aggregates settle vertically from dispersed suspension and apparently form undifferentiated bed deposits. Such deposits are commonly subject to intense bioturbation when the primary fabric is overprinted and virtually destroyed by animals enhancing the interpretation problems. In contrast, high concentration suspensions are advected across the bed and may already exhibit a layered structure whilst still moving. Deposition has been likened to sudden "freezing" although the term deposition is difficult to apply to these materials. Emplacement in such regimes is characterised by sudden episodic events, which are separated by longer periods of non-deposition or erosion. Dewatered dense suspensions are typically abiotic with the advantage that the primary fabric is preserved in great detail.

Long, 100 mm diameter cores taken from these deposits show the types of sedimentary texture these high concentration suspensions give rise to. Thin (3 mm) slices cut down the maximum diameter of these cores and x-radiographed show two types of bedding. Submillitmetre, horizontal, alternating silt and clay layers occur commonly in the sequence. One interpretation is that these have been laid down as "tidal laminations". Also in the sequence are massive and apparently undifferentiated units, which probably represent dewatered dense layers deposited from a single event. The uniformity in grain-size and magnetic fabric of the massive units supports such a conclusion.

A distinctive feature of these massive units is the strong tendency for a "felty-textured" basal layer up to 10 cm thick, possibly arising from crushed macro-aggregates, to be present. Such distinctive bed deposits appear to identify muds deposited from advected high concentration suspensions. However, this explanation contrasts with the selective segregation from suspension and deposition favoured as an explanation by other authors.

The notion that layered deposits do not invariably arise from sequential deposition may assist the understanding of the mechanisms by which fine sediment is deposited. Similarly, the recognition of the breakpoint separating high and low

concentration suspension phenomena is an aid to interpretation. Finally, the identification of specific features of beds deposited from high concentration suspensions should aid the identification of deep water and fossil analogs.

MICROFABRICS OF DETRITAL MARINE MUDS AND MUDSTONES

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The purpose of this research was to develop a method of examining detrital marine mud(stone)s whereby more information about their depositional history could be obtained. Recent muds from Santa Monica Basin, California Continental Borderland, and closely analogous mudstones from the Los Angeles and Ventura Basins, were the focus of this study. In order to isolate different factors within the environment of deposition, the following facies were specified for this research: unbioturbated pelagic mud(stone)s; unbioturbated turbiditic mud(stone)s; and bioturbated mud(stone)s.

The basic building blocks of the clay fabric in these muds were flocs 2 to 200 microns in diameter. "Physico-chemical flocs" were interpreted as forming from the electrostatic attraction of clay particles. These had an open fabric of clays in dominantly edge/face (EF) clay particle contacts. Flocs were roughly equidimensional, usually ovoid, and individual flocs were well-defined.

"Bio-flocs" were thought to represent degraded fecal pellets. These were more densely-packed flocs containing mostly face/face (FF) or low-angle EF clay particle contacts; organism tests were a common constituent.

Bioturbated sediments near the sediment/water interface contained abundant bio-flocs, silts, micas, and tests. Large voids (greater than 5 microns) were abundant. Below 15 cm burial depth, large pores disappeared and boundaries between flocs became more blurred. With increasing burial depth (1000 feet) these bioflocs were squeezed between silt particles to form welded packets of clays which exhibited abundant clay faces. At burial depths of 2000 feet, consolidated and diagenesis had changed these packets to crenulate and intergrown clays.

Turbidite muds near the sediment/water interface were dominantly composed of physico-chemical flocs. Silts were enmeshed within a continuously flocculated mass of dominantly high-angle EF particle contacts. Small pores (about 1 micron) were abundant. As burial depth increased, high-angle EF clay particle contacts changed to low-angle contacts. At burial depths of 1000 feet, low-angle EF contacts changed to very-low-angle EF and edge-on FF domains. Some preferred orientation of clay particles was developed in thin laminae wrapped around adjacent silts. Clay edges dominated over faces. At burial depths of 2000 feet, diagenesis and consolidation produced densely welded zones of

crenulate, intergrown clays virtually indistinguishable from nearby bioturbated mudstones.

Pelagic muds contained both bio-flocs and physico-chemical flocs in various proportions. With increasing burial depth, bio-flocs became more densely welded and intergrown with other fabric features, making individual packets more difficult to discern. These physico-chemical flocs reoriented to moderately well-developed preferred orientation with very low angle EF and edge-on FF particle contacts.

Abst 17

ANOMALOUS STRESS HISTORY IN THE N.W. PACIFIC: THE ROLE OF MICROSTRUCTURE

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A detailed investigation of the geologic and stress history of "red clay" sediments in the N.W. Pacific was undertaken to identify the dominant depositional and post-depositional phenomena operating in this region. Sampling included hydraulic piston core (HPC) 576A from DSDP Leg 86, to depths of 64 meters and regional coverage with standard piston cores.

Results indicate that these deposits are overconsolidated to depths of approximately 20 meters throughout the study area. Sediments below 20 meters are normally to underconsolidated. Extensive Scanning Electron Microscopy (SEM) investigations, coupled with Energy Dispersive Spectrometry leads us to propose an explanation for this anomalous behavior.

We hypothesize that these sediments possess an unusually strong microstructure capable of resisting consolidation, in the laboratory and in situ. During the consolidation test, the shallow samples (depths less than 20 meters) retain high void ratios and exhibit minimal compression to stresses greater than the overburden stress. Microstructure of the deeper samples withstands consolidation imposed by overburden in situ and therefore appears underconsolidated when tested in the laboratory.

Intergrown domains, recognized as continuous regions of microfabric, are believed to provide the primary resistance against compression in the field and in the laboratory. Limited data suggests that cementation of particle contacts may be locally important. These components are likely authigenic and/or diagenetic phases and are related to the very slow sedimentation rates and relatively high percentages of iron and other metals in these "red clay" deposits.

Abst 18

STRUCTURAL FABRIC AND RELATED PHYSICAL PROPERTIES OF ACCRETED AND SUBDUCTED SEDIMENTS FROM THE BARBADOS ACCRETIONARY COMPLEX

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Three sites cored across the toe of the Barbados accretionary complex are represented by offscraped and subducted hemipelagic sediments. The decollement plane separating the Atlantic and Caribbean plates is localized along a stratigraphic layer of higher porosity siliceous claystone. Sites 671 and 676 are located on the arc, 4 km and 600 m behind the deformation front, respectively. Site 672 is a reference site located 6 km seaward of the front.

The incorporation of sediments into the accretionary complex is accompanied by only minor dewatering, representing about a 10% volume reduction between sediments at a Site 672 and Site 671. This reduction contrasts with the nearly 25% volume reduction that takes place along equivalent horizons corresponding to the statigraphic level of the decollement. All sediments from the transect along the toe of the Barbados prism are underconsolidated, despite the apparent structural shortening and volume reduction associated with accretion.

X-radiograph, SEM, and TEM microstructure and fabric analyses of the Leg 110 sediments cover a wide scale of deformational fabrics. Sediments exhibit a progressive increase of complexity and diversity of deformational structures from Site 672 to 671. Interparticulate relationships show that accreted sediments contain a moderate degree of preferential orientation, whereas the structural collapse of sediments in the decollement is evident in strongly preferred orientations and development of a scaly cleavage. Incipient subvertical dewatering veins, reverse micro-fault displacements, fluid escape structures, sheared vane arrays, and apparent micro-drag features are examples of small scale deformation accompanying the offscaping and incorporation of sediments into the accretionary prism. Most notably, microstructural deformation and lateral shortening of offscraped sediments occur without substantial geotechnical evidence of lateral compression across the arc.

MICROSTRATIGRAPHY OF YELLOW SEA MUDS: RELATIONSHIP TO SEDIMENTOLOGICAL PROPERTIES AND COMPRESSIONAL-WAVE SEISMIC VELOCITY

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The Yellow Sea is one of the few modern analogues to ancient epicontinental seas which is actively receiving large amounts of sediment. Sedimentary microstructure in the modern, fine-grained deposits of the Yellow Sea has been examined in over 20 cores using thin-section techniques. Thin-section (mm scale) studies of these modern sediments are particularly important because similar techniques are employed routinely in petrographic studies of ancient mudrocks.

Examination of sedimentary microstructure in thin sections from the Yellow Sea generally reveals a transition from interlaminated to mottled silt and clay, to homogenous clays southward along the dispersal system. Micrographs with physical stratification exhibit parallel-laminated (often graded) and cross-laminated sediments. Larger particles consist of fine sand to silt-sized detrital grains or fecal pellets. Burrows are observed to truncate individual laminae. Mottled micrographs exhibit some residual lamination, as well as burrows filled with pellets, silt-sized detrital grains, framboidal pyrite, clay, or a mixture of these components. Homogenous micrographs are characterized by disseminated pellets or silt-sized detrital grains in a clay matrix. Plasmic fabric (resulting from preferential alignment of platey minerals) is rarely observed in the Yellow Sea because of the prevalence of biological mixing. Homogenous sedimentary structure is dominant in the study area because of the high ratio of biological mixing rate to sediment accumulation rate.

Compressional-wave seismic velocity has been measured on selected cores representing the upper few meters of the seabed. Velocities range from about 1420-1550 m/sec. Velocity seems to be strongly correlated with grain size (through porosity) and to be less sensitive to microstructural variability.

Abst 20

INFLUENCE OF SOME PHYSICO-CHEMICAL ACTIVITIES ON MECHANICAL BEHAVIOR OF CLAYS

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Clays are chemically active electrolyte-gas-solid systems. Their physico-chemical properties, thus the spatial arrangement of particles, are subject to change over time under environmental influences. The microstructure and physico-chemical forces determine much of the physical properties and subsequent mechanical behavior of clays. The changing environmental conditions such as temperature, pH, salinity, degree of saturation, and type and concentration of chemicals in the pore fluid need to be taken into account in predicting long-term mechanical performance of clay deposits both on land and offshore.

Introduction of various inorganic and/or organic ions into the pore fluid influences the colloidal stability of fine grained soils. Activities such as adsorption and ion-exchange, and environmental conditions such as temperature, pH, and degree of saturation under which these activities take place determine the new fabric and structure of the soil. New particle associations, pore sizes and pore fluid properties are attained. This new structure then determines the ability of the clay to carry effective stresses; its permeability, consistency and volume change behavior. Therefore, it could safely be stated that mechanical performance of clays is related to their depositional and physico-chemical properties. These properties are not constant factors and altered in time with changing environmental conditions. Prediction of long-term performance of soils must be based on consideration of all conceivable physical, chemical and biological changes within the soil-water-electrolyte system.

This study attempts to evaluate the time dependent influence of some environmental stresses and depositional factors on the mechanical behavior of saturated-unsaturated clays. The time variation of triaxial compressive strength, low strain modulus, low frequency cyclic response and permeability are evaluated for laboratory constructed specimens of soft clay exposed to various compounds in the pore fluid. Factors such as degree of saturation, temperature, pH and salinity of pore fluid are also varied or monitored throughout the tests. Empirical correlations are made between mechanical and environmental parameters. Work is underway to investigate the implications of various physico-chemical activity associated with each environmental factor on the measured mechanical behavior.

Abst 21

ORGANISATION OF CLAY PARTICLES IN DILUTE AQUEOUS SUSPENSION AS INFERRED FROM SPECTROSCOPY OF ADSORBED DYES

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After ion exchange at loadings below 10% of the CEC methylene blue (MB) and proflavine (PF) are present on the surface of smectites as monomers, dimers and trimers. In general, the surface concentration of dimers increases with the loading, but this process is influenced by (1) the particle size of the clays and (2) by the type of exchangeable cation.

Clays, consisting of small particles, have a relatively large external surface and the dimerisation and trimerisation processes mainly occur at the external surface. The absorption maximum of the monomer is shifted to the red with respect to its solution value and the dimer consists of 2 almost perfectly parallel monomers.

With Na^+ and Ca^{2+} as exchangeable cations the total surface area of the clays is available for adsorption of the dyes. The dimerisation and trimerisation reactions on the surface can be described quantitatively in exactly the same way as in solution chemistry. With K^+, NH_4^+ and Cs^+ as exchangeable cations the interlamellar surface is not readily available for dye adsorption. The dimerisation reactions of the dyes mainly occur on the external surface, while there is a majority of monomers on the interlamellar surface.

These results suggest that the smectites occur as aggregates of individual clay platelets even in the case of Na^+ as exchangeable cation. Only the extent of aggregation depends on the type of exchangeable cation.

Abst 22

SOME EFFECTS OF VICINAL WATER ON THE SEDIMENTATION PROCESS, COMPACTION AND ULTIMATE PROPERTIES OF SEDIMENTS

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The short-range, highly energetic hydration of solid surfaces in an aqueous environment has been studied in detail. However, far less well described are the long-range hydration effects referred to as the "vicinal water structures".

A brief overview of the structural properties of vicinal water (v.w.) will be presented. Next will be described some effects of v.w. on the sedimentation process (based on our own measurements) and the effects of v.w. on the compaction process. Finally, v.w. significantly affects the overall properties of the sediments: highly non-classical, strongly temperature dependent ion partitioning occurs, tending to exclude from the interstitial water those ions which are strong water-structure makers, such as Li^+ and Na^+, while structure-breaking ions, such as K^+, will be preferentially retained. The specific heat of the sediment will exceed the values normally calculated on the basis of the mineral contents present plus the amount of water. Other thermodynamic properties also differ, including density, thermal expansion coefficient, as well as isothermal and adiabatic compressibilities (thus also affecting the acoustic properties). In unconsolidated sediments the rheological properties are affected by the v.w. and in consolidated sediments the permeability will be affected by the anomalous viscosity of the v.w. Finally, direct and indirect effects of v.w. are expected on the activity of micro-organisms in the sediments.

THE FLOC CAMERA: A 3-D IMAGING SYSTEM OF SUSPENDED PARTICULATE MATTER

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Suspended particulate matter (SPM) in the ocean is difficult to study. Conventional sampling of SPM, including rosette-triggered water samplers, in situ pumps, monochromatic light attenuance meters and high frequency acoustic profiling, have provided proxy information on the quantity and nature of suspended particles. Each method has specific limitations. For instance, water samplers and submerged pumps can alter the characteristics of flocculated particles, the path length of attenuance meters may be too short, and acoustic profilers are calibrated on constant density spherical particles. Therefore these conventional methods require "ground truth" from in situ experiments and observations.

SPM observations through portholes of submersible have noted useful parameters not previously addressed using conventional sampling or profiling techniques. Specifically of interest are: 1) the number of particles in a given volume of water, 2) the spacing between these particles, 3) the volume-size distribution of the particles within that volume, 4) the relative or absolute settling velocity of the different suspended particle types, and 5) the variation with time or depth of these properties. For example, two different ocean environments may have similar bulk composition and concentration of SPM, yet have very different SPM types each with different settling characteristics. Interesting submersible observations include: 1) long stringers of marine snow joined together by delicate bacterial or mucoiod filaments are excellent indicators of turbulent-free water layers; 2) copepods engage in selective and purposeful feeding on large suspended particles, noted as they swam rapidly from one floccule to the next; 3) shear zones within the "fine structure" of stratified water masses are capable of decreasing the size of marine snow producing an increase in fine flocculent material, yet retaining a constant SPM concentration, and 4) the spacing between SPM particles increases with depth and distance seaward of the discharge plume.

To further assist submersible observations, a floc camera assembly has been developed at BIO to provide quantitative SPM information. The assembly consists of a collimated Xenon flash, three cameras, a depth sensor, and a computer controller to link and operate the components in a programmable manner. The position co-ordinates and particle dimensions are latter determined on a Lietz TAS image analysis system, linked to a

mainframe computer. Instantaneous particle velocities are determined in a relative sense from changes in the spatial coordinates of the particles between successive photographs. Absolute velocities can be calculated with the camera fixed rigidly in the water column. The shape, minimum and maximum diameters, and particle volume are determined. The method is a viable method to obtain quantitative data on the in situ properties of suspended particulate matter.

CHARACTERIZATION OF CLAY FABRIC

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Behavior of clays is controlled by fabric - the initial and subsequent internal arrangement of particles. The past has been a number of studies on characterization of fabric qualitatively, i.e., using scalar terms (e.g., pore size distribution). However, the directional-dependent nature of natural clays is best modelled by a tensorial representation of fabric. More importantly it is necessary to trace the induced changes of fabric, if major strides are to be made in modelling soil behavior.

Fabric and strain refer to the initial and subsequent arrangement of material points in the clay. Further, yielding is related to drastic changes in fabric. Thus, yielding is closely related to strain also. Using these analogies, a mathematical relationship is developed between fabric and strain and its uniqueness is examined. The theory is validated using SEM data on a natural clay. Such a fabric-strain relation allows the consideration of anisotropy induced by the loading in a quantitative manner. More importantly, the development of such relation allows an investigation of a new 'tool' - the idea of the uniqueness of the strain yield locus - that could permit major strides in the use of strain space theory of plasticity for modelling soil behavior.

Abst 25

MICROTEXTURE AND MICROCHEMISTRY OF CLAY-RICH SEDIMENTS

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The microtexture and microchemistry of clay-rich sediments are important properties of the materials, reflecting their geologic histories and controlling their behavior in industrial and environmental applications. Particle-to-particle arrangements that are the result of depositional and post-depositional conditions may promote the leaching of chemical constituents as in "quick clays" or retard the flow of contaminants from landfills. In all situations it is essential to relate micro-characteristics to the macroscopic structures observed in the field.

X-ray radiographs of slabs of sediment or sections of rock provide an effective means of correlating micro-and macrotextures. The contact radiographs illustrate variations that are not readily visible to the naked eye and often highlight special features that are the keys to understanding the microtextural behavior of the materials. X-ray radiography should be the first step in any microtextural analysis.

Microtextural studies have proven useful in attempts to determine fluid flow mechanisms in clay-rich sediments. Scanning and transmission electronmicrographs of marine clays from Scandinavia and other parts of the world have revealed the open network of flocculated clay particles and domains responsible for the intergranular flow and leaching of Na. In more consolidated clayey sediments of the Gulf Coastal Plain, intergranular flow is restricted and fluid transfer is confined to structural features such as cracks and slickensides formed in response to microtextural rearrangements associated with dewatering and soil forming processes.

Microchemical studies provide important supplemental information for microtextural studies. Chemical determinations are often the only way to determine the identity of the particles forming a particular feature. Spot determinations and area mapping with an energy dispersive x-ray spectrometer illustrate mineralogical and chemical variability at the micrometer scale. Small geothite crystals lining a microfissure provide evidence for the transport of oxidizing solutions through the clayey sediments. Microchemical changes in glauconite pellets reveal diagenetic changes that are not apparent in the bulk sediment.

Work in progress is attempting to combine the microtextural and microchemical observations and produce a numerical value for the textural variables in different sedimentary environments. For example, the pore structure revealed by the ratio of pore perimeter to pore area in digital images may be characteristic of a particular environment, or particle size and shape may provide important evidence for post-depositional changes. These and other advances in microtextural studies should greatly expand our knowledge of the geology and industrial use of clay-rich sediments

COMPUTER MODEL FOR COHESIVE SEDIMENT TRANSPORT: A NEW APPROACH

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Models of cohesive sediment transport have previously concentrated on dispersion and diffusion of sediment, and have not really included the flocculation process, but have approached the problem using a volume concentration, and an empirical relationship relating settling velocity to volume concentration to account for coagulation. Examples include Odd and Owen (1972), Ariathurai and Krone (1976) and many other models since.

This paper presents a different approach, following on from the work of Chang (1972), and similar to the Aerosol work of Friedlander (1977). It describes the development of a simulation model of flocculent settling using a stochastic approach using a number of concentration of particles of different sizes. The model is so structured that the effects of turbulence, settling and flocculation on particles are considered simultaneously by means of a combined population and dispersion equation. Using field data gathered from the Hamble estuary as input, with an assumed discrete particle size distribution, a one-dimensional finite difference model is used to simulate the settling behavior of the sediments.

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Abst 27

PHYSICAL PROPERTY CHANGES ACCOMPANYING THE MUD IN SHALE CONVERSION, BARBADOS CONVERGENT MARGIN

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In general, relationships between acoustic and density properties of sediments have been obtained empirically by fitting regression curves to the velocity-density data base. These curves usually have been constructed separately for muds and shaly rocks. From analysis of muds, mudstones and shales of similar lithologic composition from the Barbados convergent margin, we obtained the following equation representing the compressional velocity (V_P)-bulk density (ρ_B) relationship (see Fig. 1):

$$V_P = 3.95 + (2.70\ \rho_B - 7.02)/(2.75 - \rho_B).$$

This curve approximates the shale curve of Hamilton (1978) for ρ_B values greater than about 2.2 g cm^{-3} and the continental terrace sediment curve of Hamilton and Bachman (1982) for ρ_B values less than this value. Barbados muds exhibit low positive and negative values of velocity anisotropy. With increasing density above 2.2 g cm^{-3}, however, anisotropy becomes strongly positive reaching values of nearly +80%, with the horizontal component of velocity greater than the vertical component. Development of anisotropy is accompanied by an increased V_P- ρ_B gradient above a threshold ρ_B value of about 2.2 g cm^{-3}. This change in response apparently reflects the development of structural rigidity of the mudstones.

Our observations indicate that the relationship between V_P and ρ_B for the Barbados mudstones is governed principally by collapse of the "house of cards" structure of freshly-deposited sediment, compaction, diagenetic transformation of smectite to illite, and the development of fissility. This conclusion is confirmed by TEM analysis. The V_P- ρ_B curve should be applicable to other terrigenous mud to shale conversion sequences.

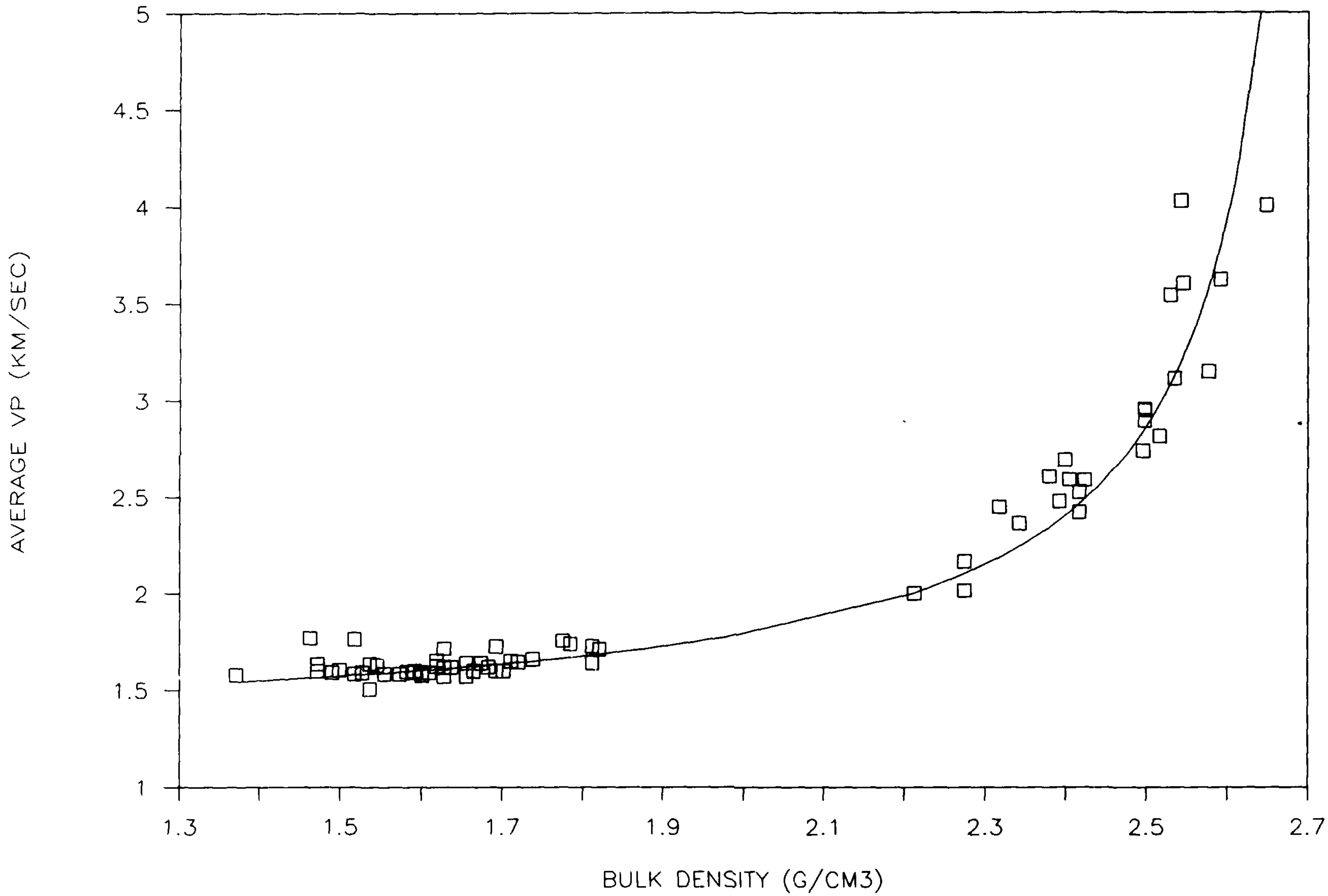

Figure 1. Variation of the average of measurements of horizontal and vertical compressional velocity with bulk density for muds, mudstones, and shales from the Barbados convergent margin. The curve fit to the data is a rectangular hyperbola.

QUANTITATIVE ROCK MINERAL ANALYSIS

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The proposed technique consists of dispersing a known volume of fine powder of pulverized samples of the rock in aqueous suspension and measuring sonic velocities of the suspension at several temperature values. The equation for the sonic velocity of an aqueous suspension of particles;

$$V^2 = 1/(FwBw + Sum(FciBci))(FwRw + Sum(FciRci))$$

where V = the acoustic velocity in the suspension described by the denominator, Fw = volume fraction of water, Fc = the volume fraction of each of the minerals i, Rw = the density of water, RC = the density of each mineral i, Bw = the compressibility of water, and Bc = the compressibility of each mineral i in suspension, will be used for non-linear least-squares determination of the volume fraction of each of the minerals in the powder. The densities and compressibilities of each of the expected mineral fractions will be predetermined for this purpose.

Abst 29

COUPLED FLUID EXPULSION/DEFORMATION MODELING FOR DEWATERING SEDIMENTS

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A finite element model is developed to describe the coupled fluid expulsion/deformation behavior of dewatering sediments under lateral stresses. This model is intended to simulate the gross response of sediments which form the accretionary prisms in deep sea under tectonic loading.

In the mathematical formulation of this model, the deformation equation is coupled with the fluid equation. The well known modified Cam Clay model is employed in the displacement equation to characterize the time independent stress-strain behavior of solid grains. The time independent strain is divided into an elastic part and a plastic part. The plastic strain is evaluated using the normality rule and the consistency requirement on the yield surface. The flow equation employed to characterize the dewatering behavior of fluids is coupled with the displacement equation, which is based on the continuity of fluid mass combined with the generalized Darcy's law. The model allows temporal and spatial variations of the pore pressure, porosity, fluid density, and temperature field. It is demonstrated that the coupled fluid expulsion/deformation behavior of a sample problem of dewatering sediments is predicted more closely using this model.

Abst 30

RHEOLOGY AND MICROSTRUCTURE OF CONCENTRATED ILLITE SUSPENSIONS

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The influence of microstructure on the elastico-viscous and yield behavior of concentrated K-illite suspensions is investigated as a function of physico-chemical environment, using torsional shear wave propagation and constant applied stress rheometry.

The variation of elastic moduli and yield stresses as a function of ionic strength, pH and volume fraction of solids $\phi > \phi_c$ where ϕ_c is the critical volume fraction at which measurable elastic behavior occurs, is discussed.

The role of colloidal forces in determining suspension microstructure, ϕ_c, and associated rheological behavior is identified by an analysis of possible modes of interaction between pairs of illite particles as a function of ionic strength and pH.

OBSERVATION TECHNIQUE FOR WET CLAY MINERALS USING ENVIRONMENTAL CELL EQUIPMENT ATTACHED TO HIGH-RESOLUTION ELECTRON MICROSCOPE

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We have very long history of the study on wet cell microscopy which aims to examine specimens in hydrated state.(1) In order to observe hydrated materials such as wet clay minerals intactly and their dynamic change due to the change of environmental conditions, new environmental cell (or hydration chamber; abbreviated as EC) equipments were recently developed for JEM-2000EX electron microscope provided with on line video processing system.(2) The main equipments are side-entry EC specimen holder in which the film-sealed EC can be set and control system of gas environment around the specimens in the EC. The diameter of the EC specimen holder is 18 mm which is fairly larger than that of the standard specimen holder. This large specimen holder carries components for EC operation; four stainless steel pipes used for gas circulation, liquid injection, etc., and a sealing block containing the EC connected to the pipes head. The film-sealed EC held in the sealing block is composed of two copper disks which are separated by a spacer having gaps for circulating gas, and tightly fastened with two gaskets to prevent the gas leakage to the microscope column. The copper disk has nine holes of 100 μm diameter as the windows for electron beam and these holes are covered with evaporated carbon film of 20 nm thick. A large eucentric goniometer which can tilt the specimens up to $\pm 10^{\circ}$ is attached to the microscope column. The gas control system consists of four gas flow lines with which various kinds of reactions are introduced in the EC; two lines are used to control the gas pressure in the EC and in the pre-evacuation chamber respectively, and the others are used to carry liquids or gasses into the EC. The gas pressure in the EC can be adjusted to any value up to 760 Torr. The electron beam transmittance of the EC is 90% at 200 kV and image resolution higher than 1 nm can be obtained in wet gas environment. Using the EC observation technique, we can get useful information on the microstructure of wet materials over the whole process from fully hydrated state to hydrated state continuously.

We have already reported some results obtained from experiments on wet clay minerals by using the EC technique.(3,4) Layer lattice image of fully hydrated tubular halloysite could be clearly observed in wet air environment. Tubular and spherical halloysite and their hydrazine complexes were observed both in wet air and in vacuum, and their structural and morphological change could be recognized. It was clearly revealed that their morphological change is influenced by the crystal domain behavior under the phase transition. By means of electron diffraction technique, it was confirmed that the basal spacing of smectite changed from 1.7 nm in hydrated state to 1.0 nm after removing the interlayer water. The information of lattice defect, such as dislocation, was also obtained from the results of in situ observation on layer lattice image of the smectite. Recently, we are trying to get information of mixed-layer illite/smectite in hydrated state. We are further planning to extend our EC technique to make dynamical observation of chemical reaction processes between specimens and injected liquid chemicals.

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Abst 32

POSSIBLE EFFECTS OF ORGANIC MATTER ON AGGREGATE FORMATION AND SEDIMENT MICROSTRUCTURE

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The organic carbon content of most marine sediments is less than 5%, with most deep-sea sediments containing less than 2% organic carbon. The bulk of the organic carbon near the surface of most deep-sea sediments is highly refractory; i.e., resistant to decomposition or alteration. This refractory material is the end product of the decomposition and diagenesis of biogenic compounds, such as proteins, carbohydrates, and lipids, which have occurred in the water column and near the sediment-water interface. This refractory organic matter consists of complex materials which cannot be described by well-defined chemical formulae. These materials are isolated by extraction techniques and are operationally defined into categories such as humic acid, fulvic acid, hydrolyzable humin, humin, and lipids. In near-shore marine areas with higher organic carbon contents (approximately 5%), a larger fraction of the organic matter found in the sediments is more labile (reactive) and provides a food source for more numerous benthic populations and the chemical driving force for several reactions within the sediments.

Clay surfaces adsorb many organic compounds, and these organic compounds, in turn, may react to form bonds between clay particles. The resistance of the adsorbed organic matter to decomposition or alteration and the strength of the bonds between adsorbed organic species may play significant roles in the microstructure and physical and geotechnical properties of clay-rich sediments. In this talk, recent studies reported in the literature which relate to the identification, quantification, and diagenetic reactivity of organic matter associated with clay sediments will be described. The impact of the adsorbed organic material to the microstructure and to the physical and geotechnical properties of these sediments will be discussed where data is available.

Abst 33

THE EFFECT OF ORGANIC FLUIDS ON THE FABRIC AND HYDRAULIC CONDUCTIVITY OF COMPACTED CLAY

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Hydraulic conductivity tests are conducted in flexible wall permeameters to assess the effect of organic fluids on compacted clay. Fabric of the specimens were quantified before and after permeation with the specific fluid. The results are presented and discussed within the present state of understanding of clay microstructure and its interactions with the pore fluid.

Abst 34

CLAY FABRIC OF GASSY SUBMARINE SEDIMENTS

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High concentrations of biogenic methane, found in many offshore submarine sediments around the world, pose unique problems in understanding geochemical, geophysical, and geotechnical properties of these sediments. To better understand the role of methane in sediment behavior, selected pressurized core sediments from the Mississippi River Delta were studied to delineate the degassing effect on clay fabric and associated geotechnical properties of the sediments.

To obtain the in situ clay fabric, a special apparatus has been designed and employed. The new method allows drying of clay specimen under in situ downhole pressure conditions, thus preventing possible fabric disturbance due to the removal of downhole pressure. Various tests, including undrained shear strength and gas content, were performed at the downhole pressure in a hyperbaric chamber.

Results of detailed investigation, by means of transmission electron microscopy and scanning electron microscopy techniques, not only reveal in situ clay fabric microfeatures but also demonstrate the degassing effect on clay fabric configuration. Clay fabric of sediments prepared by the new techniques is characterized by well oriented clay particles and domains. In contrast, clay fabric of the same sediment prepared by the conventional method is composed of relatively non-oriented and highly randomly arranged clay particles. The fabric microfeatures also show that the effect of degassing on clay fabric is time dependent, and probably also sample size related. The comparison of clay fabric and vane shear strength tests in different experiments demonstrates the close relationship between these two important geotechnical properties.

APPLICATION OF IMAGE ANALYSIS TECHNIQUE TO STUDY THE MICROSTRUCTURE OF SOILS

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In the past decade, considerable progress has been made in geotechnical engineering toward understanding the behavior of granular materials. Despite this progress, the topic of microstructure fabric remains neglected. Soil microstructure may be defined as the basic framework or arrangement of individual constituents of an assemblage consisting of different components. A comprehensive description of the microstructure of a granular material would involve reconstruction of the complex, three dimensional spatial arrangement of individual grains, which is extremely difficult to achieve.

The microstructure has been studied for some time by use of thin section technique. An image analyzer can greatly enhance the measurement from the thin sections. An image analyzer is used to study the microstructure of three different granular material in loose, medium and dense state. Results for all these materials are presented in this paper. In addition, advantage and disadvantages of using an image analyzer to study microstructure are also discussed.

Abst 36

AUTOMATIC ANALYSIS OF ELECTRON MICROSTRUCTURE OF COHESIVE SEDIMENTS

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Early workers were obliged to use hand-mapping to define features, such as domains or random clusters, which they had recognized in micrographs. Later, the intensity gradient technique was used to give an over-all measurement of anisotropy. Recent work has shown how the intensity gradient technique can be developed for automatic mapping of features and how this can be extended for intra-domain measurement of anisotropy. An alternative method of mapping, based on local fast fourier transforms, will also be discussed.

DETERMINATION OF PORE/THROAT RELATIONSHIPS LEADS TO SUCCESSFUL PHYSICAL MODELLING OF POROUS MEDIA

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Porosity in most porous media exists as a three-dimensional network consisting of pores (large voids) interconnected at sites of minimal cross sectional area (pore throats). Whereas some physical properties (e.g., bulk density) are functions of pore fraction, others (permeability, electrical conductivity, shear strength, dispersivity, and diffusivity) are strongly dependent on the spatial distribution of the porosity. Such parameterization of the pore system requires knowledge of the types, sizes, and abundance of pores, the distribution of throat sizes, and the rules for assigning throats to pores. Such parameterization can be achieved by combining pore information obtained from image analysis of porosity patterns exposed on planar section through the medium with physical data such as capillary pressure curves.

"Petrographic Image Analysis" refers to a collection of algorithms designed to classify porosity in terms of geometry and size, and to relate such data to physical properties. An important finding not usually recognized by physical modelers is that the pore system consists of several discrete sub-populations of pores differing from one another in terms of shape and size. A product of the synthesis of pore information with throat data is the determination of the degree of pore/throat association--the range of throat sizes associated with each pore type. Such data are sufficient to construct very simple physical models (e.g., tube models) of permeability (evaluated using Darcies' Law), and electrical conductivity (Ohms' Law). Comparison of model results with experimental data over ranges of several orders of magnitude indicates strong agreement. A major feature of these models is that they are additive--the contribution of each pore type is calculated.

Experience with rocks of very low permeability (>.1 md) indicates that the model values are significantly better than measured values. Other applications of Petrographic Image Analysis include relating pore and other fabric data to fracture toughness and with NMR relaxation time.

SHEAR WAVES IN SEDIMENTS: A COMPARISON OF *IN SITU* AND LABORATORY MEASUREMENTS

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Surfical sediment shear wave velocity measurements were made at 6 sites in the vicinity of La Spezia, Italy. Shear wave velocities measured *in situ* ranged from 20 m/s in flocculent muds to 80 m/s in hard packed sands. Laboratory shear wave velocities made on cores collected from the same sites averaged 40% lower than in situ values. Within site variability of shear wave velocities were primarily a result of small scale (10-100 cm) variations in sediment type. The limited data suggests laboratory measurements of shear wave velocity can be corrected to in situ values.

Further studies are required to determine the relative effects of sample disturbance and reduction of "confining pressure" on laboratory measured shear wave velocities.

GEOACOUSTIC PROPERTIES OF THE NEAR-SURFACE SEDIMENT IN RESPONSE TO PERIODIC DEPOSITION

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It has been argued that the resuspendability of the surface sediment depends not only on the hydrodynamic forcing and makeup of the bulk sediment, but also on the history of prior deposition. Currently, there are a number of field experiments, either underway or planned that seek a synoptic picture of the settling and deposition process. We adopt here an idealization of such an experiment, in which episodes of deposition occur periodically, and model the acoustic signature (at vertical incidence) of the resulting sediment water interface. The primary model begins with a sediment loading and projects deposition, with progressive flocculation in the case of cohesive sediments. The second phase predicts accretion and consolidation, either under gravitational overburden in the case of cohesive sediments, or due to the action of waves for noncohesive sandy sediments. Finally, the derived physical properties of the bulk and suspended sediment are picked up by the acoustic transmission and attenuation model to predict the acoustic signature. The periodic nature of deposition becomes important in the three controlling parameters of acoustic sensing: sensitivity, range and resolution. Specifically, 1) will the acoustic system be able to discern the discontinuities of the layering, 2) through how many layers will the signal penetrate, and at the other extreme, 3) will the layers (in certain depositional scenarios) be so closely spaced as to be indistinguishable.

The exercise then consists of adjoining models of sediment settling and flocculation in the benthic boundary layer with sediment consolidation and finally with acoustic propagation models. The results indicate which types of events and scenarios will be visible to acoustic sensing, and conversely, what is the optimal acoustic frequency for observing a given range of depositional events.

Abst 40

GEOACOUSTIC PROPERTIES OF A MARINE SILT

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In the unlithified sediments just beneath the seafloor the propagation characteristics of both dilatational and shear waves play key roles in choosing a realistic geoacoustic model. In this near-bottom region the dynamic moduli of the sediment are complex functions of frequency that change rapidly with depth as a result of the changing overburden pressure. Moreover, there appears to be a fundamental difference between the viscous damping that occurs in coarse sediments such as sand owing to overall fluid motion and the damping observed in fine sediments which is attributed to local "squeeze film" motion. We have carried out laboratory experiments on a micaceous silt of glacial origin to measure the complex shear and Young's moduli over a wide range of frequencies extending from about 1 Hz to over 1.5 kHz. The experiments were performed by exciting torsional, flexural and extensional modes of motion at very low amplitudes. At high frequencies the response at several different resonant frequencies was studied using a variant of the resonant column method while at low frequencies, the phase difference between the driving force and resulting motion was measured to determine intrinsic damping. We have incorporated the results of our experiments into the Biot theory by describing the stiffness of the sediment frame with a simple viscoelastic model, with parameters chosen on the basis of our experimental data.

Abst 41

MEASUREMENTS OF BOND ENERGY OF MARINE CLAYS AND WAVE ATTENUATIONS

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The bond energy and bond densities of oceanic clays are measured using a torsional shear apparatus based on Rate Process Theory. Compressional wave attenuation through clays are also measured using a pulse transmission technique. Gravity water wave attenuations by a clay bed are also measured in wave tank. Data suggests that wave energy absorption by clays is due to the breakage of bonds between the clay particles.

Abst 42

CYCLIC SIMPLE SHEAR BEHAVIOR OF MARINE CLAYS

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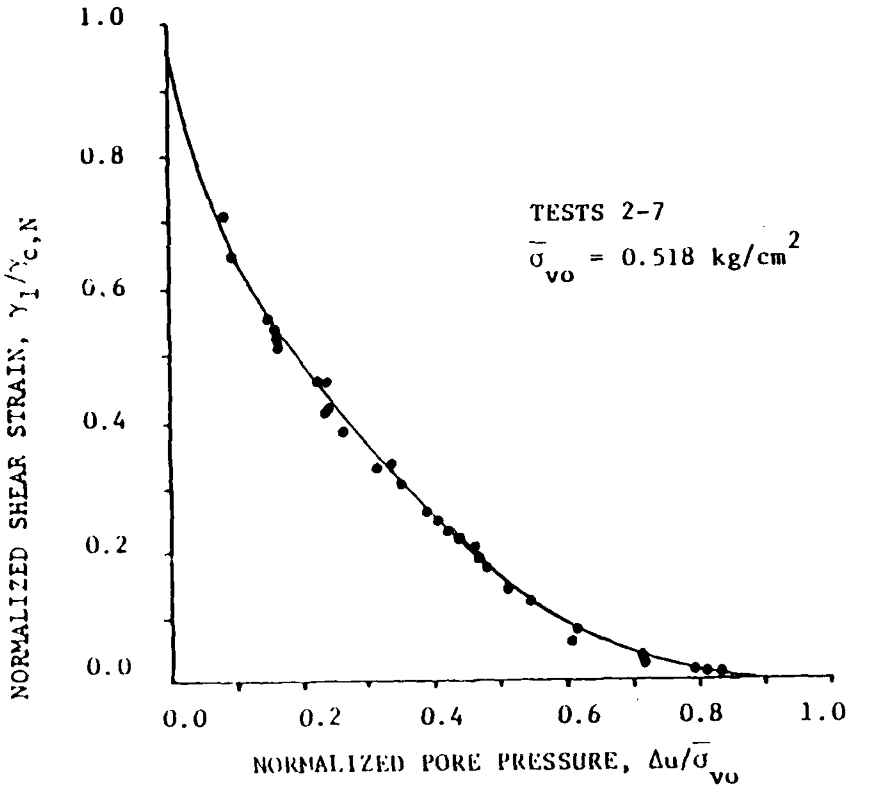
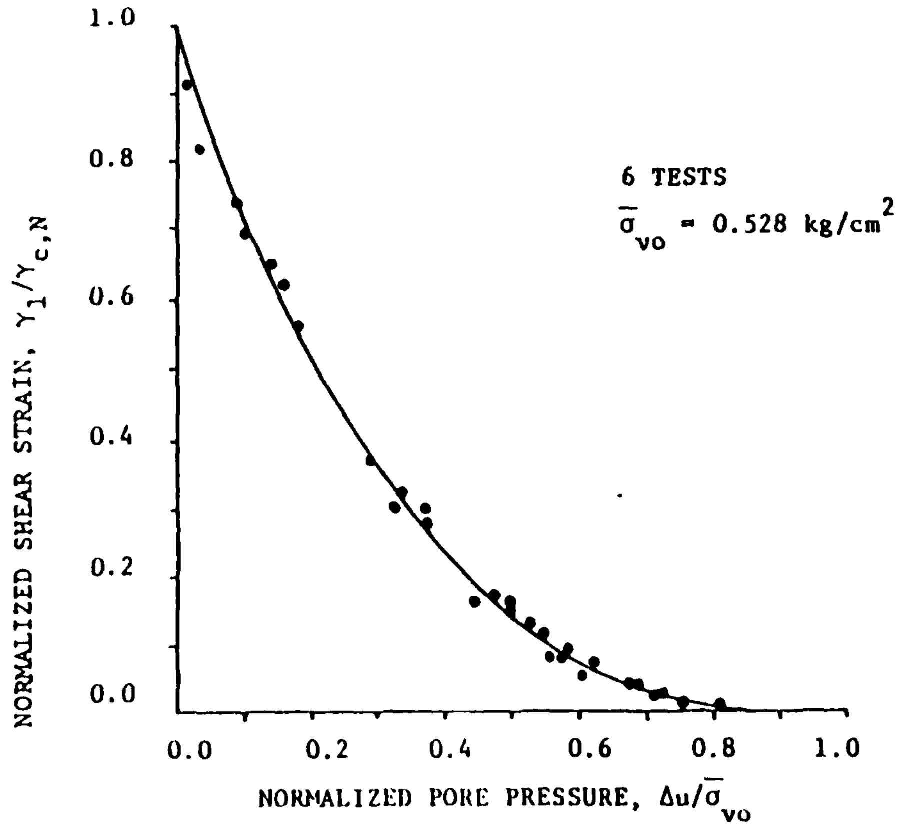
Consolidated, constant volume cyclic laboratory shear tests were performed on marine clay soils. The Norwegian Geotechnical Institute (NGI) direct simple shear device was used for the tests. Three clays were used--two undisturbed clays, Gulf of Alaska clay and Gulf of Mexico clay, and a reconstituted Pacific illite.

The amount of degradation in a soil subjected to cyclic loading is indicated by the increase in cyclic strains or decrease in modulus. It is also indicated by the increase in excess pore pressures. The decreasing modulus can be normalized to the modulus in the first cycle of the test. Since the tests were stress controlled, the cyclic shear stress level cancels in the normalized modulus and becomes simply a ratio of the shear strain in the first cycle to the shear strain in the Nth cycle. When this normalized modulus or strain ratio is plotted versus normalized excess pore pressure, all the tests for a given clay fall on the same curve (Figure 1). This therefore is a unique relationship between excess pore pressure and strain for a given clay. If these relationships could be related to simple clay index properties or other easily obtained properties, the cyclic behavior could be predicted without the need for a lengthy and expensive laboratory cyclic testing program.



NORMALIZED CYCLIC SHEAR STRAIN ($\gamma_1/\gamma_{c,N}$) VERSUS NORMALIZED PORE PRESSURE – PACIFIC ILLITE



NORMALIZED CYCLIC SHEAR STRAIN ($\gamma_1/\gamma_{c,N}$) VERSUS NORMALIZED PORE PRESSURE – GULF OF ALASKA CLAY

FIGURE 1

Abst 43

DISPOSAL OF RADIOACTIVE HAZARDOUS WASTE INTO CLAY-RICH ROCKS

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For several decades, clay-rich rocks have been widely utilized as host media for the disposal of low-level radioactive wastes and hazardous materials. In the future, these rocks are certain to be prominent in disposal strategies as their characteristics for containment are consistent with regulations that mandate the disposal of wastes in a manner than will ensure the health and safety of the public.

For low-level radioactive wastes, dose-based, performance assessment models are employed to optimize disposal operation into near-surface landfills. Deep, geologic disposal is a strong option for the remaining low-level wastes, high-level radioactive materials, and hazardous wastes. Specific disposal methodologies include burial in mined openings and waste emplacements in large-diameter boreholes. Data discussed bear on the behavior of clay-rich rocks as host media for the disposal of wastes.

AN APPRAISAL OF THE MECHANICAL PROPERTIES OF CLAYS AS HOST ROCKS IN THE MATRIX BOREHOLE CONCEPT OF DISPOSAL

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Preliminary assessment of clay-rich rocks and clays, as potential host materials for waste disposal purposes, has been made from geotechnical engineering considerations. The geotechnical properties of Pierre, Rhinestreet, typical illite shales, and of Porters Creek and Yazoo clays were used in preliminary engineering analysis. The allowable bearing pressure was estimated for shales and clays, and stability of boreholes in these materials has been examined. Based on preliminary analysis, the values of unconfined compressive strength and cohesion that are necessary for adequate borehole stability are indicated. Further investigations that are necessary are mentioned.

FABRIC AND POROSIMETRY OF CLAYS SUBJECTED TO LIQUID HYDROCARBONS AND MUNICIPAL LEACHATE

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The fabric and porosimetry created by exposure of natural clays to various leachates is discussed in relation to the hydraulic conductivity of the same clays. The leachates include domestic waste leachate, domestic waste leachate mixed with soluble liquid hydrocarbons and pure organics. The soils include compacted soils moulded with both water and leachate and a field soil directly below a landfill.

Use of leachate bearing solutions as the moulding fluid is not recommended since it causes soil flocculation and hydraulic conductivity values significantly higher than pure water compacted clays subsequently permeated with the same solutions.

Low dielectric, water soluble organic liquids and their flocculating influence on water-wet clays (related to double layer collapse) do little damage to barriers up to concentrations of ~70%. The highly structured state of double layer water seems also to increase its lyophobicity compared to pure water preventing organic molecule entry into the double layers up to ~70%. Above 70%, up to 1000-fold increases in k occur at low effective stresses.

Laboratory tests on local clayey samples compacted by kneading methods yield almost fracture-free samples at void ratios of 0.8. At normal field values of 0.3 to 0.4, compaction induced fractures cause pronounced chemical tailing problems that make chemical interpretation of clay/leachate compatibility tests very difficult.

Abst 46

THE SIGNIFICANCE OF THE MICROSTRUCTURE OF PACIFIC RED CLAYS TO NUCLEAR WASTE DISPOSAL

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The microstructure of deep-sea illitic red clays from the Central Pacific Basin was investigated using electron microscopy techniques. Illite is the dominant mineral and a significant portion of which appears to be a product of aeolian processes originating from argillites of eastern Asia. Constituents of minor abundance consist of chlorite, kaolinite, smectite, and quartz. "Undisturbed" core samples and disturbed dredge sediments were used in the investigations. Dredged samples were remolded and reconsolidated to equivalent in situ porosities for use in a scaled simulation test for the Subseabed Disposal Program, Sandia National Laboratories. This study was part of the In Situ Heat Transfer Experiment (ISHTE)simulation test designed to investigate the thermal, fluid, mechanical, and chemical responses of the sediment to a heater emplaced in the seabed. The clay fabric of the undisturbed core samples was compared with that of the remolded, reconsolidated sediment to investigate the effects of remolding, the mechanical disturbance due to the insertion of probes, and the induced thermal gradients due to heating of the sediment.

No significant difference in the fabric was observed between the undisturbed and remolded sediment. Samples adjacent to the heater probe were subjected to temperatures slightly below 300° Celsius. Slight preferential clay particle alignment developed from shearing stresses during probe insertion. Localized "quasi-expansion" and flow features were observed in the microfabric in the heated zone.

The undisturbed sediment fabric of the control samples, designated RAMA, displayed a random arrangement of particles. The fabric is comprised of a complex assemblage of particles having a matrix consisting predominantly of $\leq 1 \mu m$ domains and small particles. Characteristic microfabric features of this high void ratio sediment are large 2 to $5 \mu m$ illitic domains (fractured during ultra-thin sectioning), stepped face-to-face and end-to-end short chains, various aggregate types including large intra-void and denser aggregates, and channels for fluid transport. Aggregates of finely divided particulate material, having intra-voids, maintain structural integrity in spite of remolding in the laboratory. The surficial illite-rich red

clay is reconstituted easily in the laboratory and thus this remolded sediment appears to be a suitable material for geotechnical laboratory testing simulating in situ conditions for the approximate porosities investigated.

Abst 47

THE GEOTECHNICAL IMPORTANCE OF CLAY FLEXIBILITY

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Flexibility is the geotechnical property of clay and shale to bend plastically without cracking. The property relates to the tensile strength due to flexure when cracking initiates. Clays and shale masses are subjected to differential movements both in the in situ and the remolded or compacted states. The amount of flexure and clay/shale can undergo before cracking is of much importance when the mass is designed as a permeability barrier in such earth structures as earth filled dams, waste disposal landfills and lagoons, levees, dikes and various foundations. Where specified maximum permeabilities are requried, cracks in the clay/shale subsequent to construction amount to a loss of integrity of the masses. This paper will briefly review past studies and current research by the author on developing a laboratory test to evaluate flexibility.

Abst 48

EFFECTS OF HYDROTHERMAL TREATMENT ON THE ENGINEERING PROPERTIES, MICROSTRUCTURE AND COMPOSITION OF OIL WELL CEMENTS

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Portland cements are used in the petroleum industry and elsewhere in borehole completion operations. In some oil recovery procedures and in geothermal power projects the cements are subjected to hydrothermal conditions. At elevated temperatures portland cements show loss of strength and increases in permeability. To combat this deterioration portland cements are commonly blended with silica flour but this causes degradation of engineering properties under ambient conditions. Different forms of silica, and duration and conditions of pre-curing have been used in the present work in an attempt to overcome this drawback. Three types of silica were used: (a) silica flour; (b) silica fume; and (c) silica sand.

A proportion of 40% silica was blended with oilwell cement, API class G, and a constant water/solids ratio of 0.5 was used to facilitate comparison of properties. Cements blended with 40% silica which contained increasing proportions of silica fume and cured in the fog room (22°C, 100% R.H.) showed marked increases in compressive strength. After hydrothermal treatment cement blended only with silica fume showed lower strengths than cement blended only with silica flour. A Cement blended with a combination of silica fume and sand (3:1 ratio), which gave high strengths after fog room curing, also performed well after hydrothermal treatment. The permeability of cements blended with silica fume was generally lower than that of cements blended with silica flour. Typical results are shown in Table 1.

There are significant differences in composition and microstructure between cements blended with silica flour and those blended with silica fume both before and after hydrothermal treatment. Prior to hydrothermal treatment fume-containing cement is dense and granular, apart from a few microcracks, whereas flour - containing cement is more porous, contains platey $Ca(OH)_2$, quartz grains and calcium silicate hydrates with a needle-like morphology. After hydrothermal treatment calcium silicates form which contain less combined water and microcracks seem to be more common in fume-containing blends. Microcracking may occur because dehydration releases water faster than it escapes through the almost impermeable material. Possibly single phase liquid conditions, and correspondingly high pressures, develop within micropores in the cement-silica fume blends. This may account for strength decreases after hydrothermal treatment.

TABLE 1

Cement + 40% (a), (b) or (c)	Fog Room (56 days) Strength (MPa)	Fog Room (56 days) Perm. (mD)	Hydrothermal (56 days total*) Strength (MPa)	Hydrothermal (56 days total*) Perm (mD)
(a) Silica Flour	25	3×10^{-4}	34	2×10^{-2}
(b) Silica Fume	68	10^{-5}	18	7×10^{-3}
(c) Fume:Sand (3:1)	60	8×10^{-3}	34	8×10^{-3}

* 56 days total = 49 days fog-room + 7 days 230°C; 2.75 MPa Saturated steam pressure

Abst 49

THE MICROFABRIC OF SOME HONG KONG MARINE SOILS

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In Hong Kong where land is scarce, many areas of the holocene marine deposits in the surrounding coastal waters are now being reclaimed. Samples from several locations including some from beneath a trial embankment have been studied. X-Ray diffraction techniques were used to ascertain the mineralogy, while fabric observations were made in a scanning electron microscope on carefully freeze dried specimens. Energy dispersive analytical techniques were also used to identify features seen in the micrographs. Many of the samples close to the present sea bed level have an open honeycomb structure consistent with the high (>1) liquidity indices of those samples. The area under the trial embankment had one of the most open fabrics and showed little signs of consolidation consistent with the high residual pore pressures remaining even after several years of loading. At depth, the fabric was more dense, but once again there was little qualitative evidence of preferred orientation.

Selected micrographs were digitized and quantitatively analyzed for orientation patterns using the digital intensity gradient technique. Little evidence of regional orientation was evident, although local features associated with the flow of the clay matrix during consolidation was seen in samples from depth.

Abst 50

INFLUENCES ON THE RHEOLOGY OF MARINE SEDIMENTS COMPOSED OF LOW-ACTIVITY MINERALS

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The factors controlling the yield stress of fine-grained marine clays deposited in the post-glacial Champlain Sea have been investigated using a coaxial viscometer. The influences of salinity, ion saturation, textural variation, oxide removal and clay mineral removal were investigated on soil from the site of the South Nation River landslide of 1971.

For these low activity materials (with other factors being held constant) it was found that: yield stress decreased with decreasing pore water salinity, for natural material and also regardless of which of the other pretreatments were applied; the yield stress was lower with monovalent than with divalent ion saturation; yield stress increased with increasing clay content; yield stress decreased when oxide minerals were removed and increased when more were added; and yield stress decreased when the clay minerals were destroyed. The relative importance of these factors is as yet undetermined.

The yield stress is an important determinant of the post-failure behavior. The resistance to flow of materials already in motion, at a range of flow rates, can be obtained. This information is useful in estimating runout distances for quick clay landslides and for submarine failures. With appropriate correction, it can also be used to determine the sensitivity of soils with remoulded strengths too low to be measured by conventional means.

Abst 51

ACOUSTIC AND ELECTRICAL PROPERTIES OF MARINE SEDIMENTS: ROLES OF PORE GEOMETRY AND PREFERRED ORIENTATION IN ANISOTROPIC BEHAVIOR

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Laboratory measurements of physical, acoustic, and electrical properties of clay-bearing and carbonate sediments from Deep Sea Drilling Project (DSDP) sites in the Pacific Ocean are systematized in light of their depositional environment, depth of burial, age, and diagenetic stage as interpreted from sediment chemistry and mineralogy. The properties of interest are: bulk density ρ, porosity ϕ, compressional and shear velocities (V_p, V_s) and attenuation (Q_p^{-1} and Q_s^{-1}), and electrical resistivity R_o. Depth-property profiles generally reflect the effects of compaction and loss of porosity accompanying burial; anomalous gradients and reversals are caused by lithological and mineralogical changes (e.g., clay/quartz ratio) and other factors. In contrast to findings in carbonate sediments, pore geometry does not contribute significantly to velocity and attenuation anisotropy behavior in clay-bearing sediments. Rather, preferred orientation of clay platelets controls the anisotropic behavior. For both types of sediments, there is a correlation between V_p and R_o, and between A_p and resistivity anisotropy A_R through porosity.

CARBONATE MICROFABRICS

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Geotechnical properties (consolidation and permeability) are a function of a number of factors such as the particular constituents comprising the sediment, the mineralogy, structure (grain vs. matrix), cementation, spatial distribution and orientation of particles, as well as a function of depth or overburden pressure. It is further known that fabric is altered by application of pressure. Microfabric is defined as 1) grain to grain relationships (shapes, orientations, nature of grain to grain contacts), 2) grain to matrix relationships (grain supported vs. matrix supported sediment), and 3) matrix component particle relationships (shapes, sizes, orientations, nature of particle to particle contacts). Grains are particles at least 10 times the diameter of matrix particles. Other features that should be noted include lamination, nature of void spaces, crushing of grains and matrix particles, presence or absence of cements, and nature of cements if present.

Our objective is to study the effects of mechanical consolidation (including reduction of permeability) on carbonate sediment fabric. Thirty-two samples from Northern Little Bahama Bank and Exuma Sound were selected as being representative of shallow marine carbonate sediment environments. Shown here are two samples from Site 6P from the lower slope of Exuma Sound. Samples were examined by Scanning Electron Microscope before and after consolidation to $44 kg/cm^2$ using standard techniques.

Early results indicate a decrease in permeability and a reduction in size and width/length ratios of pores accompanied by a sample height reduction between 21.4 and 25.2% during consolidation. Approximately 10% of the known porosity was identified and analyzed using the LeMont image analyzer. The remaining porosity is intraparticle porosity or falls outside the arbitrary limits of 0.5 and 5 μm prescribed for the analyzer. Particle crushing and cementation were not observed at these pressures.

Abst 53

BURIAL TRANSFORMATION OF CLAY FABRIC AT OCEAN DRILLING PROGRAM LEG 117 DRILL SITES

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Leg 117 of the Ocean Drilling Program drilled 12 sites in the northwestern Arabian Sea from August to October 1987. Sedimentation in this part of the northern Indian Ocean is strongly influenced by seasonal coastal upwelling associated with the southwest monsoons. Three areas were drilled during Leg 117: (1) the Oman Margin; (2) the Owen Ridge; and (3) the Indus Fan. Sediments from the Oman Margin are predominantly nanofossil oozes with varying abundance of organic matter and clay that provide a record of the onset and variability of monsoonal upwelling. The sediment section recovered at the Owen Ridge consists of a lower interval of fine-grained turbidites that predate development of the ridge and upper intervals of siliceous and nannofossil ooze that postdate ridge uplift. The Indus Fan site consists of rapidly deposited, Pleistocene terrigenous sediments from the interchannel region of the middle fan.

Samples from five sites (Sites 720, 722, 723, 728 and 731) were chosen for fabric analysis by scanning electron microscopy. Variation in sediment fabric at the five sites reflects the influence of lithology and burial depth. Near surface pelagic sediments at Sites 722, 723, and 728 display high porosity and random arrangement of microfossils. As overburden pressure increases, porosity decreases but remains relatively high because of the resistance of microfossils to compaction. Buried intervals rich in diatoms and radiolarians have higher porosity than present seafloor sediment. Terrigenous sediments at Sites 720, 722, and 731 have variable concentrations of clay-size particles, ranging from 19% to 69%. Illite is the dominant clay mineral, with concentrations ranging from 30% to 67%, followed by palygorskite, 0 to 51% (present only in siliceous-rich sediments and nannofossil oozes); smectite, 9% to 39%; chlorite, 0 to 23%; and minor amounts of kaolinite. Clay fabric initially consists of flocculated domains, with a very porous, random arrangement. With increasing depth, domains become larger and sediments develop lineation, which becomes apparent at Site 720 at a depth of 194 meters below the seafloor (mbsf). Lineation is well developed at 450 mbsf (Site 731). At low magnifications (1000x to 4000x) lineation is visible; at higher magnifications (8000x to 12,000x) parallel alignment is less evident and the fabric is characterized by a flocculated structure. Long, linked chains

Abst 54

APPLICATION OF MICROSTRUCTURE CLASSIFICATION OF MARINE SEDIMENT TO ENGINEERING GEOLOGICAL EVALUATION

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The classification system of the microstructures of marine sediment for the purpose of geotechnical engineering is briefly introduced in this paper, which has been published in Scientia Sinica (B series), 1984, No. 9; in American Society for Testing and Material, STP-923, 1986, and given widely attention. In order to verify the feasibility to apply this classification system to engineering geological evaluation, samples of nearshore/offshore sediment which are located in various sea area in China have been tested on their mechanical properties and also studied on their corresponding microstructure features and classification by scanning electron microscope. The correlation of the modulus of compressibility E_s and allowable bearing value R with various types of microstructure has been established, which indicates this system may be effective in engineering geological evaluation for marine sediment. Also given are application a case history.

Abst 55

STRUCTURAL MODEL OF THE CLAY - WATER SYSTEM

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Platey clay particles are arranged parallel in domains, which in random orientation form clusters, these create aggregates which are ordered in a more or less regular aggregate lattice with "vacancies" (macropores) filled with water or water vapor. This aggregation process is stepwise, resulting in macroaggregates visible optically.

Between structural elements, separated by a plane - parallel gap of the given thickness 2<u>d</u> (SEM, XRD), there exist long range interactions, i.e. repulsion R and attraction A, which energy (V_R, V_A) or pressure (P_R, P_A) may be calculated as given functions of <u>d</u> DLVO- theory, see Stepkowska, 1977, 1982.

At equilibrium balance of pressures corresponds to an extremum on the total energy vs, distance curve. The system tends to this equilibrium state by: (1) changing of <u>d</u> by (a) change in total water content (consolidation, swelling) or (b) change in internal redistribution of water (change in particle thickness, vapor bubble formation, syneresis), (2) change in size of structural elements, which influences attraction, (3) distribution of the system into various microstructural phases (parallel, cluster, floc) of local equilibrium.

This structural non-homogeneity and variable particle thickness are the main reasons of variability in the observed clay properties.

Prolonged storage at a high water content of a clay (containing illite-montmorillonite mixed layers) may result in particle delamination. External pressure may have an opposite influence. There is a correlation between water sorption, particle thickness, specific surface, cation exchange capacity and aggregation state (content of fraction less than 2 μm).

At a high water content and good dispersion (Na-clay) the repulsion prevails being accompanied by osmotic pressure (negative pore water pressure). At a low water content (Ca-clays) attraction prevails and contact bonds may form. These interactions as calculated were equal to the measured cohesion in bentonite of various exchangeable cations (<u>d</u> was estimated by water sorption and variable particle thickness assumed). Similar agreement between experiment and theory was obtained in Kuzmice bentonite and in some natural clays.

ANISOTROPY AND NON-HOMOGENEITY IN THE CLAY - WATER SYSTEM

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Except very special cases of the water content corresponding to equilibrium distance between structural elements (see adjoining paper) a clay - water system is non-homogeneous and in situ it is anisotropic.

Anisotropic pressure results in (1) anisotropic particle arrangement perpendicular to action of this pressure and (2) increase of particle thickness. Strength of such a system depends on orientation of the shear stress with respect to particle edges: if perpendicular, it causes particle delamination, thus decrease in interparticle distance and increase in strength (Grimmen clay).

Especially sensitive is the microstructure of young marine clay sediments: their particle thickness increases, whereas their liquid limit, their secondary swelling (also in freezing) decrease with depth. Formation of parallel structure in freezing is accompanied by a dramatic change in weight loss in static heating (800°C). Most valuable informations on microstructure are obtained from SEM, water sorption test, static TG, eventual XRD and rate of drying measurement.

Aging of a clay-water system (bentonite suspension) results in ordering of size, shape and arrangement of its structural elements (SEM). In suitable conditions formation of new phases (feldspar, zeolite) was observed both in suspensions (1) air dried and heated at 800°C, (2) stored for a prolonged time and air dried. This indicates that besides energetic considerations, time factor should be accounted for, as action = energy x time.

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