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The energy sources that result in sediment particle associations, reorientation, and disaggregation are presented in terms of processes and mechanisms. Based on electron microscopy observations and theoretical considerations, the observed and modeled microfabric forms and signatures are associated with processes and mechanisms operating in various micro- and macroenvironments. The interplay of geological, chemical, and biological processes and mechanisms during transport, deposition, and burial of particulate material largely controls and ultimately determines the physical nature, properties, and observable micro- and macrocharacteristics of soft sediments and their indurated equivalents. Discrete events such as suspended sediment transport, flocculation, and slumping may be identified and/or observed in the field or laboratory. More often, the sedimentary material is studied to understand and infer processes and mechanisms responsible for its fundamental properties, origin, significance, and stratigraphic position in the geological record. The particle-to-particle development and ultimate nature of a sedimentary deposit and its variability in time and space depend on multiple processes that include some important mechanisms that occur extremely fast and others that progress over eons. As defined in this study, mechanisms are the specific energy sources that drive microfabric development. Two or more related mechanisms constitute that broader classification termed process. In the continuum of microfabric development, the fundamental processes in which the individual mechanisms operate are described as (1) physicochemical, (2) bioorganic, and (3) burial diagenesis (Fig. 2.1).

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CHAPTER 2

Determinants of Clay and Shale Microfabric Signatures: Processes and Mechanisms

Richard H. Bennett, Neal R. O'Brien, and Matthew H. Hulbert

Introduction

The energy sources that result in sediment particle associations, reorientation, and disaggregation are presented in terms of processes and mechanisms. Based on electron microscopy observations and theoretical considerations, the observed and modeled microfabric forms and signatures are associated with processes and mechanisms operating in various micro- and macroenvironments. The interplay of geological, chemical, and biological processes and mechanisms during transport, deposition, and burial of particulate material largely controls and ultimately determines the physical nature, properties, and observable micro- and macrocharacteristics of soft sediments and their indurated equivalents. Discrete events such as suspended sediment transport, flocculation, and slumping may be identified and/or observed in the field or laboratory. More often, the sedimentary material is studied to understand and infer processes and mechanisms responsible for its fundamental properties, origin, significance, and stratigraphic position in the geological record. The particle-to-particle development and ultimate nature of a sedimentary deposit and its variability in time and space depend on multiple processes that include some important mechanisms that occur extremely fast and others that progress over eons. As defined in this study, mechanisms are the specific energy sources that drive microfabric development. Two or more related mechanisms constitute that broader classification termed process. In the continuum of microfabric development, the fundamental processes in which the individual mechanisms operate are described as (1) physicochemical, (2) bioorganic, and (3) burial diagenesis (Fig. 2.1).

The properties of a sedimentary deposit at the time of initial deposition are determined by (1) particle size, (2) mineralogy, (3) particle sized distribution, and (4) microstructure (fabric and physicochemistry). The sediment particles are derived not only from detrital but also from biogenic sources. Postdepositional authigenic mineralization is important in some environments. The energy regimes characteristic of the particulate transport pathways and postdepositional environments significantly affect the time-dependent development of the microfabric of suspensions and sedimentary deposits. Discriminating analysis and discernment of the developmental stages of sediment microstructure, as a function of processes and mechanisms, are antecedent to gaining a functional understanding of the relationship and importance of microstructure to the developmental history of a deposit.

The microstructure is a crucial fundamental property that largely determines the sediment's physical and mechanical properties and behavior under static and dynamic stresses. Important properties such as porosity, permeability, and stress–strain behavior are intimately tied to the microfabric and the physicochemical characteristics (Bennett et al., 1977, 1989). Improvement in predictive models for science as well as for the solution of practical problems is achieved by continual investigation into the complex interactive processes that influence the fundamental static and dynamic properties of sediments and rocks. Important scientific and technical problems abound in the disciplines of geoacoustics, physical and historical geology, waste disposal, hydrology, agriculture, and the myriad of other activities that depend on and can ultimately utilize a knowledge of the microfabric of sedimentary deposits.

The first objective of this paper is to formulate a rational theme that describes the *major* interactive processes and mechanisms important in microfabric development temporally and spatially. Various sources of energy are intrinsically coupled to the processes and mechanisms that determine clay sediment and shale microfabric signatures. Although some microfabric models are reasonably well known in terms of the processes that determine microfabric signatures, other models that describe

DETERMINANTS OF CLAY AND SHALE MICROFABRIC SIGNATURES:

PROCESSES AND MECHANISMS - A CONTINUUM

PROCESSES

PHYSICO-CHEMICAL	BIO-ORGANIC	BURIAL-DIAGENESIS

MECHANISMS

ELECTRO-CHEMICAL THERMO-MECHANICAL INTERFACE DYNAMICS	BIO-MECHANICAL BIO-PHYSICAL BIO-CHEMICAL	MASS GRAVITY DIAGENESIS-CEMENTATION

Figure 2.1. Diagram depicting the major processes and mechanisms that determine microfabric signatures in the macro and micro geological environments. Processes and mechanisms represent a continuum during the developmental history of clay sediment and shale microstructure.

the history of microfabric development are only in the formative stages of quantitative understanding. This study presents a conceptual framework of the current state of understanding of the processes and mechanisms that drive microfabric development in order to set the stage for future understanding of the complex microstructure processes and the evolution of advanced microfabric models. The second objective is to describe the macro- and microenvironments in which the processes and mechanisms and the particular energy regimes predominate during microfabric development. The third is to describe the time and physical scales over which the various processes and mechanisms prevail. The physical scales vary from submicron and molecular to meters and in some cases particular processes may extend over distances of kilometers. The fourth is to suggest how these processes and mechanisms can be incorporated into descriptive and predictive models that reveal important intrinsic properties and attributes of direct relevance to geology, geophysics, geoacoustics, geotechnique, and interpretation of the geologic record. Present qualitative and semiquantitative understanding of the microstructure of fine-grained sediment permits only rudimentary models of microfabric development. More complex models that include temporal and spatial scales are

required for successful solution of practical problems. The fifth is to reveal the deficiencies in our knowledge of the interacting processes and mechanisms and to suggest future areas of potential research. The main thrust of this study is to present a unified approach to understanding the processes and mechanisms driving microfabric development. An important underpinning of this study is to delimit the macro- and microenvironments where the active energy regimes dominate along the complex and often convoluted sediment transport pathways: from "sediment source-to-sink."

Background

The term clay microstructure refers to two fundamental properties: the fabric and physicochemistry. Early usage and definition of these terms are found in Mitchell (1956), Lambe (1958), and Foster and De (1971). Clay fabric is defined as the orientation and arrangement or spatial distribution of the solid particles and the particle-to-particle relationships. Clay minerals are hydrousaluminum silicates (classified as phyllosilicates) and are generally less than about 4 μm in size as determined by standard tech-

niques (Lambe, 1951; Krumbein and Pettijohn, 1938). The physicochemistry relates to the interparticle forces of the sediment. These forces result from both the physical interactions arising from gravitational forces and the electrical nature of the particle and the surrounding fluids (Bennett et al., 1977). During geological time when sediment experiences increasing overburden with increasing subbottom depth, the gravitational forces dominate electrical forces between particles and burial diagenesis ensues. Often organic material has a significant influence on the strength of interparticle bonds in clay sediments (Pusch, 1973). Because of the ubiquitous nature of organic materials, clay-organic interactions are believed to be significant mechanisms in the developmental history of microfabric (Bennett et al., 1988). Thus knowledge of the fabric and physicochemistry, the fundamental "building blocks," is essential to our understanding of the nature, properties, and large-scale developmental history of sedimentary deposits.

The importance of microfabric in the development of sedimentary deposits was suggested by Sorby (1908). Terzaghi (1925) and Casagrande (1932) proposed primitive fabric models to help explain the bonding and sensitivity of cohesive sediments. During the following 50 years, geologists, soils engineers, and soil scientists proposed numerous simplified models of sediment fabric to account for factors such as the electrolitic environment surrounding the clay particles (Goldschmidt, 1926; Lambe, 1953, 1958; van Ophlen, 1963, 1977; Von Engelhardt and Gaida, 1963; O'Brien, 1970a, 1971), the process of consolidation and compaction (Quigley and Thompson, 1966; Smart, 1967; Ingles, 1968), and soil dynamics and behavior (Pusch, 1970; Yong, 1972). A "quantum jump" in observational techniques was realized with the advent of the transmission electron microscope (TEM) and advanced fabric models emerged (Rosenqvist, 1959); Pusch, 1966; Bowles, 1968; Bowles et al., 1969; Moon, 1972; Collins and McGown, 1974; Bennett et al., 1977). The more recently developed scanning electron microscope (SEM) has provided a means of observing the microfabric of shales and surfaces of clay minerals (Keller, 1976, 1978; O'Brien, 1968, 1970b; O'Brien and Hisatomi, 1978; Weaver, 1984).

Early models of microfabric were developed on the basis of simplified assumptions of the physical chemistry of the fine-grained minerals (single platelets) and the electrolitic chemistry of the fluid suspension. Recent electron microscopy observations (Moon, 1972; Yong and Sheeran, 1973; Collins and McGown, 1974; Bennett, 1976; Bennett et al., 1977, 1981) have revealed the presence of multiplate particles (domains) as the predominant fundamental particle type rather than the thin, single plate particles proposed in early models (Terzaghi, 1925; Casagrande, 1932; Lambe, 1953, 1958). Thus, high-resolution observational evidence has demonstrated that the single clay particle fabric model of sediment is not wholly tenable and the sediment is more completely represented by domain, aggregate, and linking chain particle arrangements (Bennett, 1976; Bennett and Hulbert, 1986). A domain is defined as a multiplate particle

composed of parallel or nearly parallel plates that may be stacked either as sheets in a book or with an offset or stair-step arrangement (Fig. 2.2). Diagrammatic examples of domains were given by Moon (1972), and computer analysis verified that domains are important elements in submarine sediments (Bennett, 1976; Bennett et al., 1977). A domain is considered to have significant structural integrity and to behave in a functional sense as a unit particle for a finite period of time under an applied stress regime. Thus, it is important to note that "a particle" can be defined in terms of its morphology as well as its function. Important microfabric elements of a hypothetical sediment are depicted in Figures 2.2 and 2.3.

Discussion

Throughout the microfabric development of a sediment, beginning with erosion of material from parent sources to the time of deposition and burial, particulate material passes through a wide variety of macro- and microenvironmental conditions. To study and trace the history of microfabric development, the environmental conditions have been organized here into a framework described as a continuum of processes and mechanisms. These sources of energy associated with the processes and mechanisms are the determinants of clay and shale microfabric signatures. The major fundamental processes active in the continuum include (1) physicochemical, (2) bioorganic, and (3) burial diagenesis. Processes include two or more important environmental forcing functions or energy sources defined here as mechanisms (Fig. 2.1). Models depicted in Figure 2.4 reveal simplified graphic examples of their function. The mechanisms are largely responsible for the specific particle-to-particle interactions during a particular time in which a general process is active. Two or more mechanisms (such as electrochemical and interface dynamics) that drive microfabric development may operate contemporaneously but typically only one fundamental process dominates at a specific time.

Physicochemical processes play a major role in microfabric development during fluvial and aeolian transport stages of particulates and on their contact with a depositional interface. The fundamental mechanisms operating on particulate materials in the physicochemical process include thermomechanical, electrochemical, and interface dynamics. Bioorganic processes are important in marine and coastal environments, during transport and sedimentation of particulates in organic-rich waters, in areas of high productivity, at the depositional interface, and in surficial sediments. The mechanisms that are important in the bioorganic regime include biophysical, biomechanical, and biochemical. Processes of burial diagenesis drive microfabric development when overburden or tectonic stresses dominate physicochemical and bioorganic bonding energies. Mass gravity effects (slumping, sliding, creep, and consolidation) and diagenesis-cementation are important postdepositional/mechanogravity mechanisms in the
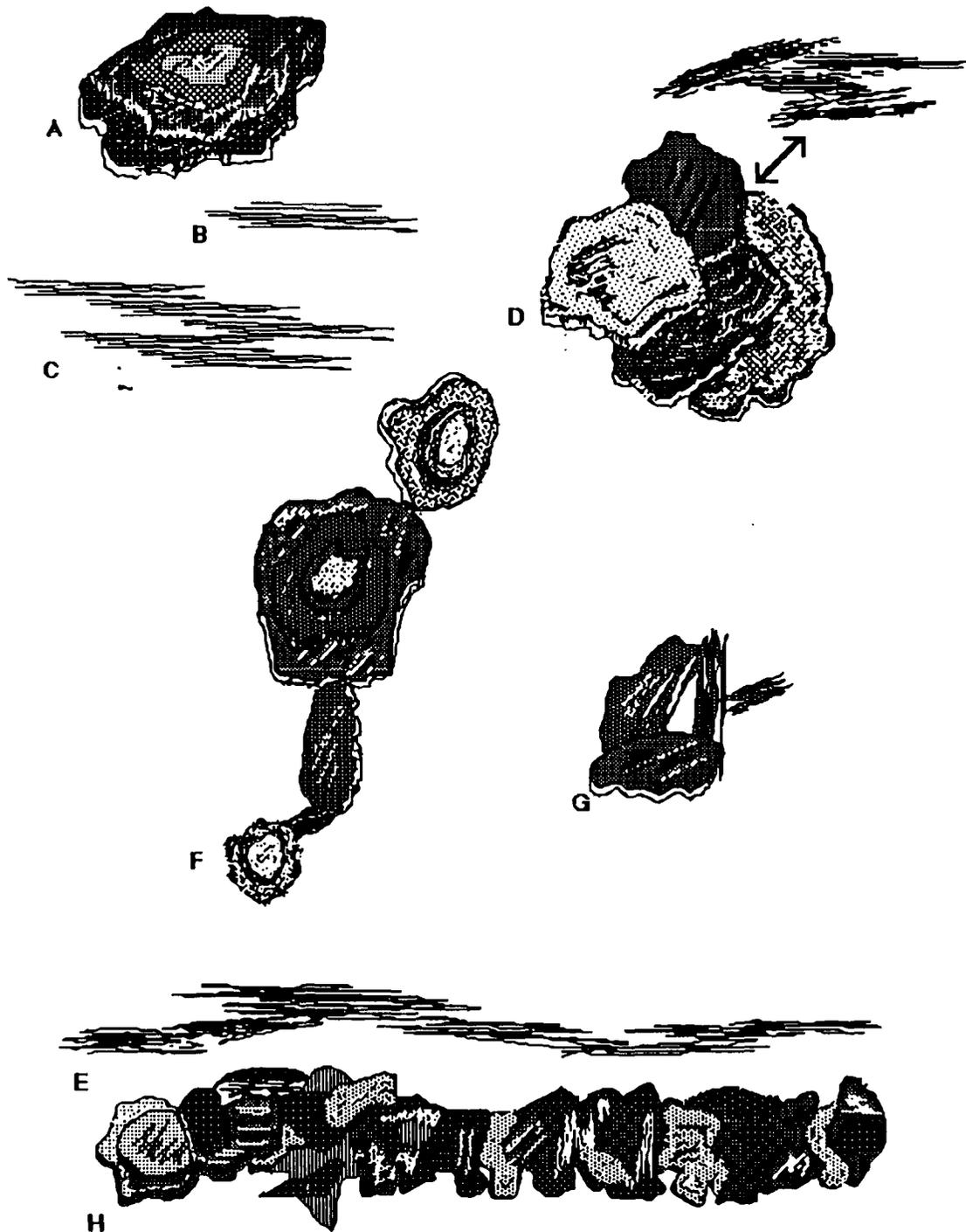
Figure 2.2. Diagram of the fundamental particle units called domains that comprise the "building blocks" of clay microfabric in sediments and rocks (single particles are rare; stipple indicates individual clay layer). (A) neatly stacked multiplate particle called the domain seen in plane view. (B) Cross-sectional view of a neatly stacked domain as would be observed in an ultrathin section prepared for TEM. (C) A cross-sectional view of a domain but showing the frequent offset arrangement of plates. (D) Plane and cross-sectional views of the possible shingle type arrangements of a domain with offset plates. (E) Linkages of domains in stepped face-to-face arrangement that form long chains (cross-sectional view). (F) Plane view of edge-to-edge contacts of domains that also form long chains. Note the difference in the potential strength of the domain formed chains in E and F. (G) Cross-sectional view of edge-to-face domains that are commonly found in marine environments; the microfabric develops large void space between domains. (H) Plane view of a chain of clay plates formed by stepped face-to-face arrangements.

process of burial diagenesis. Cementation at particle contacts may alter fabric morphology and inhibit particle reorientations within a deposit during burial or when the sediments are subjected to tectonic stresses.

The microfabric signatures resulting from the various processes and mechanisms are often recorded in the sediments and rock and are revealed by direct electron microscopy observation. Some of the signatures are difficult to capture in the undisturbed state and thus they are difficult to evaluate and still remain to be studied in detail. In addition, some mechanisms produce very fragile and delicate microfabrics that stretch technology beyond present observational and measurement limits. Thus simplified models, such as depicted in Figures 2.2, 2.3, and 2.4 are a great asset in developing a conceptual understanding of particle-to-particle interactions and resulting microfabrics. The remainder of this chapter presents examples of the microfabric signatures of sediment and argillaceous rock revealed by electron microscopy observations. Simplified microfabric models are presented for those particulate materials and sediments where direct observations have not yet been made. Verification of these models await future technological developments.

Physicochemical Processes

As particles are transported through water and air and become incorporated into the sediment, physical and chemical processes operate to bring them together into aggregates, to hold them together, to break aggregates apart, and to reorient particles within aggregates and the sediment mass. The resultant fabric of the sediment depends on the balance between the mechanisms operating to bring and hold particles together and those tending to disrupt particle-to-particle contacts. Energy mechanisms included in these processes include electrostatic interaction and chemical bonding (electrochemical mechanisms), thermally driven movement of particles (thermomechanical mechanisms), and interactions occurring at the surfaces of contact between the various materials and phases (interface dynamics mechanisms).

Electrochemical Mechanisms

The same forces responsible for the chemical bonding that holds particles together internally also bind particles to one another. These forces are included in the mechanism termed electrochemical. At a point of contact between two particles of the same material, the bonding is similar to and possibly even indistinguishable from that within the bulk material, i.e., covalent and ionic bonds. London–van der Waal's attraction, and extremely short-range Born repulsion (Bennett and Hulbert, 1986).

For particles in near contact (separation distances ranging from atomic diameters to dimensions of clay particles), the electrochemical forces of greatest importance are electrostatic
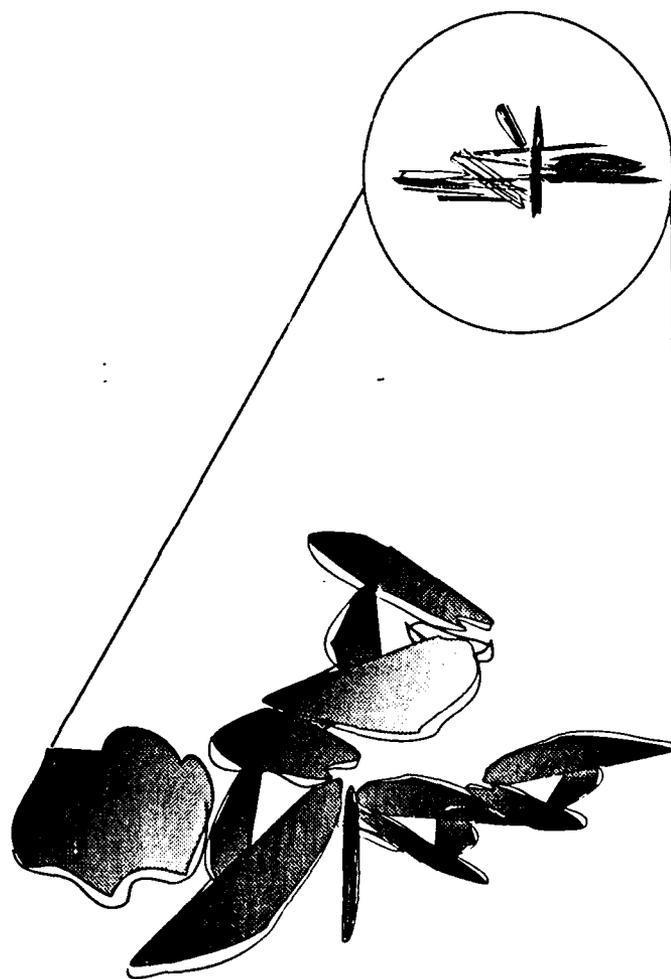
Figure 2.3. Plane and cross-sectional views of the microfabric of a hypothetical sediment constructed of numerous domains in "random" arrangement.

interactions and van der Waal's attraction. The van der Waal's attraction (force) exists between all particles. The force between two particles increases as the particles are moved closer together and as their area of overlap increases. Electrostatic interactions exist between electrically charged particles; particles of opposite charge attract each other and those of the same charge repel. The greater the electrical charge and the closer the particles approach each other, the stronger the electrostatic interaction.

In an aqueous medium, the electrochemical interactions become complex. Almost all materials develop an electrical charge on their surfaces when immersed in water. The magnitude and even the sign of the electrical charge on a particle in water may be quite sensitive to the pH and E_h of the system and on the types and concentrations of dissolved salts (Stumm and Morgan, 1981). This sensitivity to the composition of the surrounding aqueous medium results from the sorption of ions from water onto the particle surface and the release of ions from the particle to water. Hydrogen ions and hydroxide ions are often of
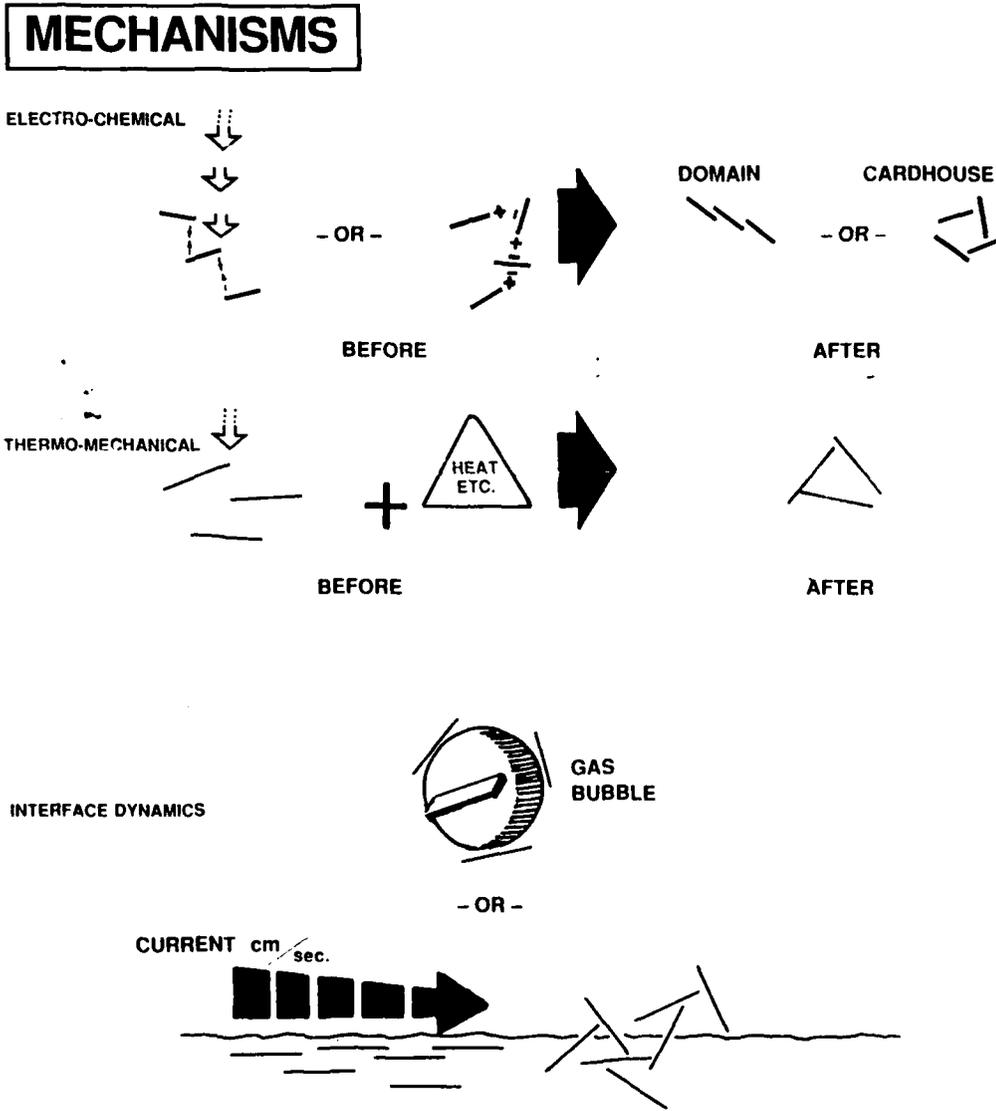
Figure 2.4. Determinants of clay sediment and shale microfabric signatures: processes and mechanisms – a continuum. Diagrams depict the major processes and mechanisms that influence the microfabric signatures in the macro- and microgeological environments. (A) Physicochemical processes. (B) Bioorganic processes. (C) Burial-diagenesis processes.

MECHANISMS

BIO-MECHANICAL

BIO-PHYSICAL ORGANIC
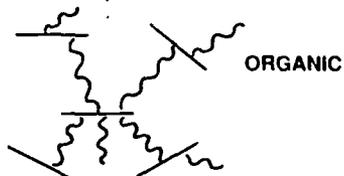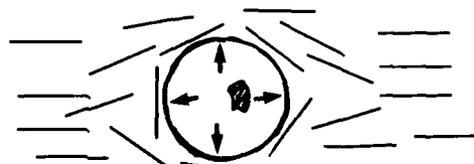
BIO-CHEMICAL

H_2S BUBBLE OR BACTERIA COLONY B

Figure 2.4B

MECHANISMS

MASS GRAVITY

DIAGENESIS-CEMENTATION

H_2O

SILT

SILT   AUTHIGENIC
        CLAY

C   BEFORE   AFTER
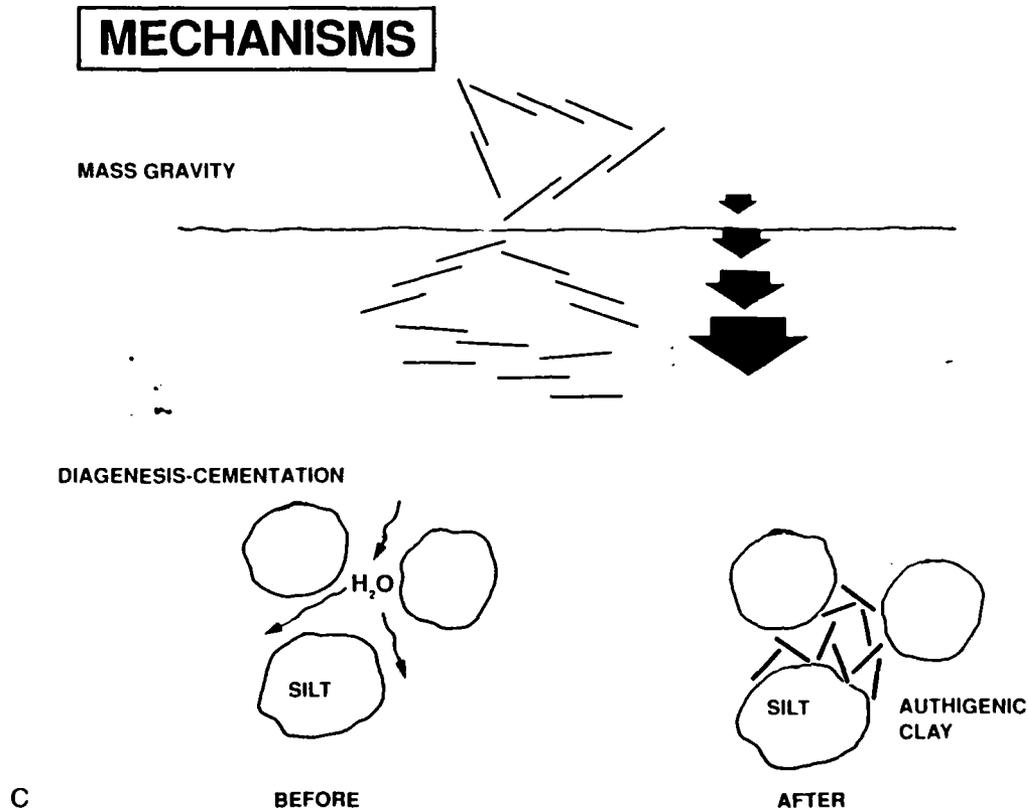
Figure 2.4C

particular importance in establishing a charge. The electrical charge on the surface of a particle in a given aqueous solution will depend not only on the chemical identity of the particle, but may even be of opposite sign on different crystallographic surfaces of a single particle.

Clay minerals in natural waters typically have a net surface charge of negative sign (van Olphen, 1963; Grim, 1968). The distribution of charge on the surface of a clay particle is expected to be patchy rather than homogeneous, and regions of positive charge may develop at edges, at defects, and at sites of sorption of positive ions. The surface charge of the particles is balanced by the net charge of the mobile ions surrounding it in the aqueous medium. In the water nearby there is a net surplus of ions with charge opposite to the particle charge and of total charge equal to the particle charge. These excess positive ions surround the negative particle in a diffuse cloud of charge. As two clay particles in water approach one another, the repulsive interaction between the two clouds of positive charge tends to prevent the particles approaching one another sufficiently closely so that shorter range van der Waal's attraction may pull them together.

As the salt content of the water increases, the effective distance of separation of the positive charges from the particle surfaces decreases, and the effective reach of the electrostatic repulsion decreases along with an increase in the potential of van der Waal's attraction. Now the particles have a greater probability of approaching sufficiently close to permit aggregation. Graphic examples of the above clay particle interactions in saline environments are given by Bennett and Hulbert (1986).

Initial aggregation tends to be edge-to-face, probably controlled by differences in charge density on the different portions of the particle exterior (Figs. 2.5–2.7). The resulting aggregates are open with a high water content and the areas of particle contact and of particle overlap are minimal. In the absence of strong bonding at the point of contact, reorientation to a face-to-face configuration with a resulting increase in van der Waal's attraction may be expected (Fig. 2.8). Rotation about the line of contact between particles will result in an offset shingle-type fabric. Once such a fabric with a relatively large area of particle overlap is created, a much larger amount of energy would be required to convert it to a neatly stacked book-type fabric.

→ NUMEROUS CHAINS-"BRIDGING"
↘ E-F CONTACT

⇦ F-F CONTACT
↯ E-E CONTACT
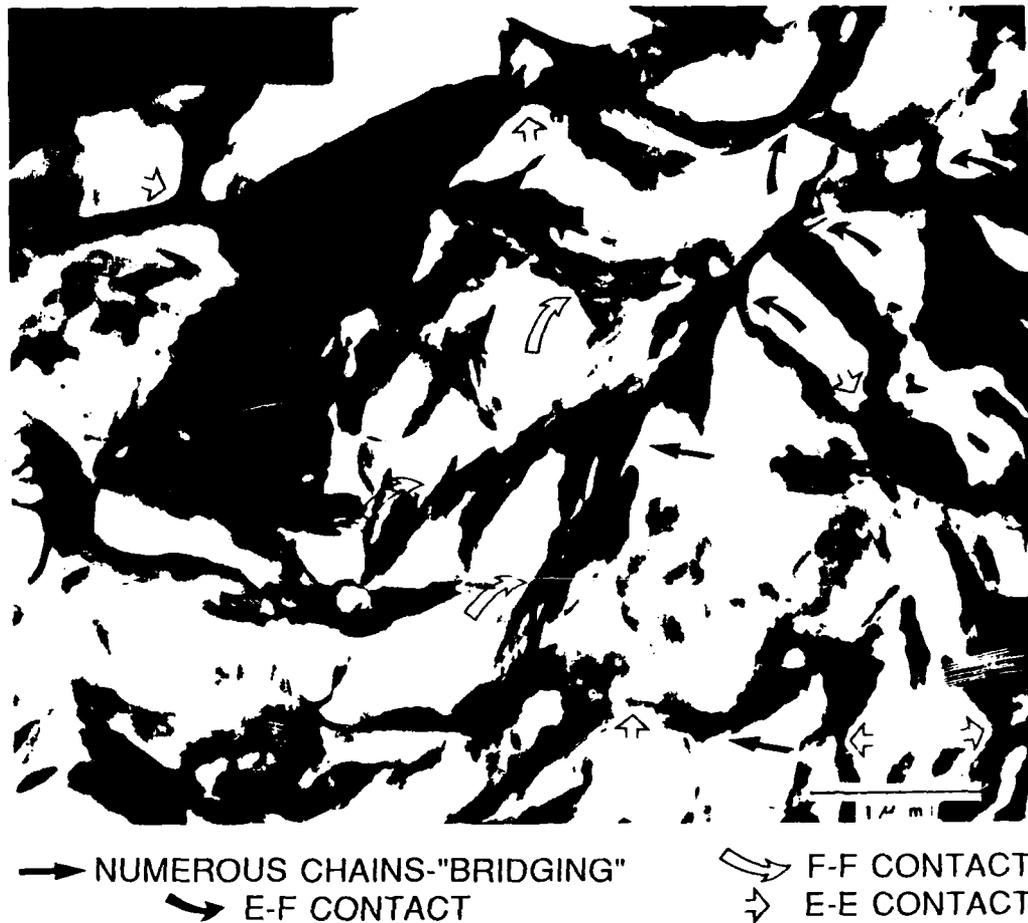
Figure 2.5. Transmission electron microscope (TEM) photomicrograph of clay fabric characteristic of the smectite-illite-rich Mississippi Delta submarine sediments. Note the delicate "bridging" between particles (domains), the chains, and the various modes of particle association, E-E, E-F, and stepped F-F and some E-E contacts.

Thermomechanical Mechanisms

The motion of particles that results in their initial approach and their reorientation after contact is one result of the mechanism termed thermomechanical (Fig. 2.9A). At ordinary environmental temperatures, the thermal energy of water is observable in the Brownian motion it imparts to suspended particles smaller than about 10 μm in diameter (Feynman et al., 1963). The kinetic energy of small particles is significant relative to repulsion forces at typical temperatures of the marine environment and becomes greater in high-temperature regions such as those near hydrothermal vents (Fig. 2.9A).

Another thermomechanical mechanism is the modification of sediment fabric by the freezing of interstitial water. Particles are excluded as water freezes and may be squeezed together if they happen to be trapped between two approaching freezing fronts or between a freezing front and a barrier (Fig. 2.9B). The resulting sediment microfabric may be characterized by relatively dense sediment units surrounding large voids filled with ice (Fig. 2.9A,

B). When the ice melts the sediment tends to retain the modified fabric while salts excluded by the freezing process are redissolved (see for example Fig. 4.1 of Bennett and Hulbert, 1986).

Temperature differences between adjacent water masses leads to microscale laminar flow and turbulence at the boundaries. Shear from this microturbulence may disrupt suspended aggregates or reorient particles within aggregates (Gibbs, 1981). Clearly the scale of the turbulence is critical—turbulence on a dimensional scale much greater than the size of the aggregate will merely translate it through space. A much less probable result of microturbulence is to bring suspended particles into effective contact to form larger particles (Koh, 1984).

Interface Dynamics Mechanisms

Microturbulence also may be considered more generally as an aspect of mass and energy transfer at boundaries between contacting water masses or contacting particles and the surrounding

Figure 2.6. Typical microfabric of surficial submarine sediment from the Mississippi Delta SEM depicts example of a single floccule composed of domains (D) arranged edge to face (E-F) in surrounding material of randomly arranged domains.
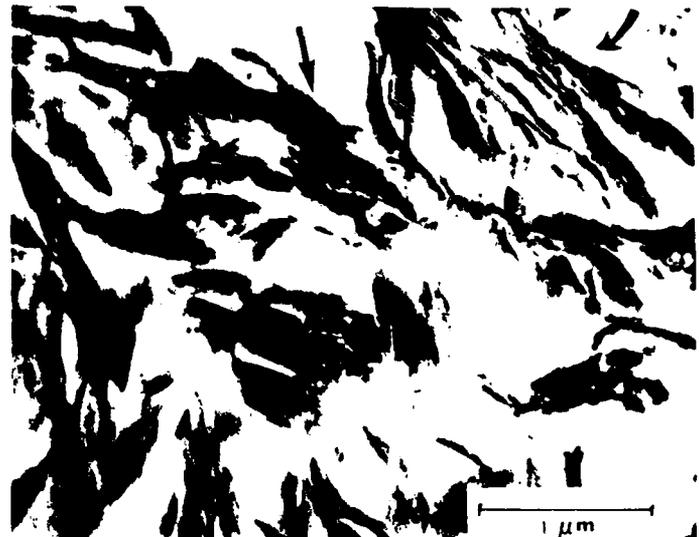
Figure 2.8. TEM showing clear examples of domains typical of the microfabric of Mississippi Delta sediment. Arrows point to face-to-face (F-F) orientation of domains.

fluid. This mechanism is termed interface dynamics. Energy sources include mass fluid flow driven by wave, current, and gravity forces and gravitational settling of particles (Fig. 2.10). In general, mass fluid flow has its greatest impact on microfabric when it impinges on the surface of the sediment. It may serve to reorient particles attached to the surface or it may drive suspended particles onto the surface. In the vicinity of a surface of significant area, the perpendicular component of fluid motion

Figure 2.7. SEM of Mississippi Delta Sample depicting some edge-to-edge (E-E) and face-to-face (F-F) particle contacts. Note large domain in upper center of figure and the large and randomly shaped voids.

approaches zero. Therefore shear forces overcome interparticle binding forces and gravity forces only in regions of relatively rapid flow. For unconsolidated clay-size particles the minimum flow for particle entrainment is about 2.0 cm/sec (Boggs, 1987); a range of flow rates (0.6–3.0 cm/sec) was suggested recently by Li and Bennett (this volume). An important factor not considered above and often omitted from discussions of fabric development under dynamic conditions is that, although individual grains may be of clay size, the kinetic unit is often a multigrain aggregate. Thus, consolidated clay sediments may resist erosion under flow rates of 1 m/sec (Boggs, 1987); and, conversely, multigrain particles (chains, Fig. 2.2) may protrude many single grain diameters above the plane of the sediment surface, and be quite subject to disturbance at even minimal flow.

Particles may be brought into contact by any of a number of mechanisms that result in differential rates of particle movement (Montgomery, 1985). Such a differential may arise under gravitational settling between particles of different sizes or densities, for example, and is particularly characteristic of dynamic effects at interfaces. In the vicinity of a static boundary, the velocity of flow of water or air becomes less the nearer the boundary is approached. Particles swept along in the fluid attain a similar velocity gradient and the rate with which they collide is approximately proportional to their concentration and to the velocity gradient (Swift and Friedlander, 1964). Attachment of particles to gas bubbles in water, which may be greatly enhanced by the presence of organic matter, results in the particles being moved in the direction opposite to the general gravitational settling and may be moderately effective in bringing particles into contact (Leja, 1982). These particle-to-particle contacts occur both during bubble movement through the water and on the accumulation of bubbles at the surface. Differential motion of particles attached to a

WATER MOLECULES
IN THERMO-DYNAMIC
MOTION

Na^+

ICE CRYSTAL

a   CLAY PARTICLES   CLAY PARTICLES
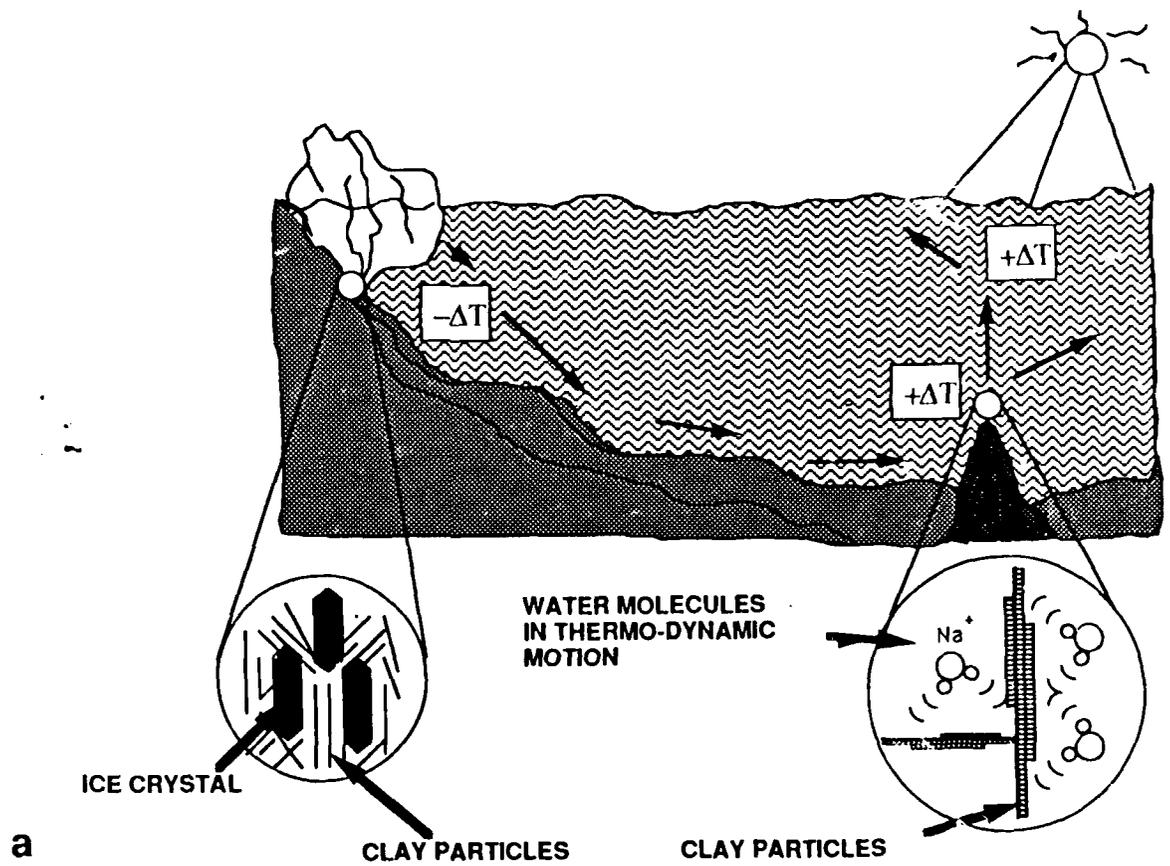
BEFORE

CLAY   LIQUID WATER

GRAIN

AFTER

ICE

GRAIN
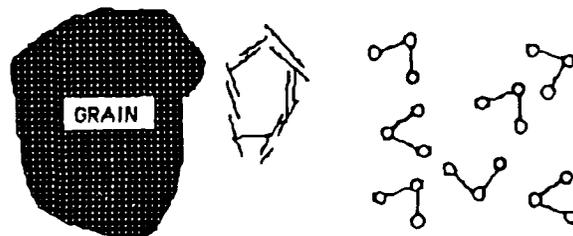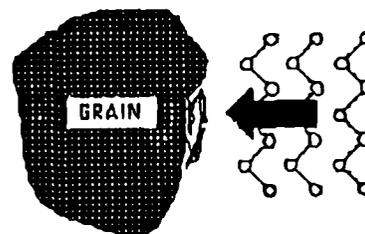
Figure 2.9. (a) Fabric modification by thermomechanical mechanism. Thermally driven mass flow (solar and hydro-thermal heating and atmospheric cooling). Arrows depict relative motion of the water mass; crystallization of ice in sediment; Brownian motion of water molecules and suspended particles. (b) The effects of freezing (surrounding water) on the reorientation of clay particles as the ice crystals press the particles against a large solid such as a quartz grain or pebble.

b
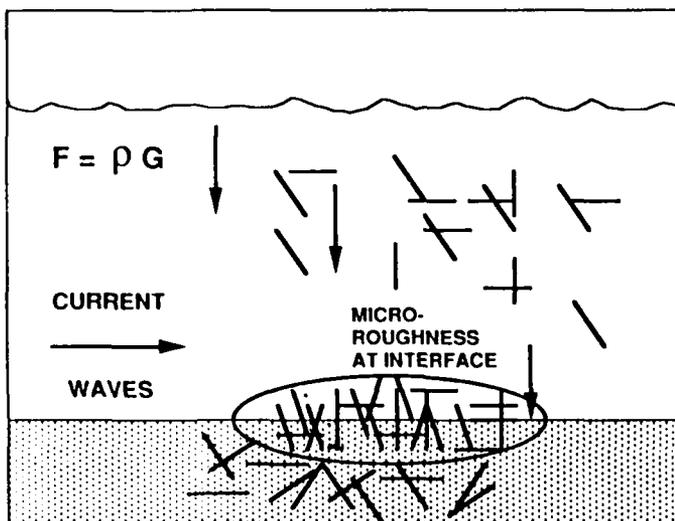
Figure 2.10. Diagram depicting some modes of fabric modification by interface dynamics mechanisms: differential motion of settling particles under the influence of gravity, differential flow of water masses of differing density, impact of particles on sediment interface, and flow at interface (note the importance of microroughness on particle orientation)

single bubble becomes even more pronounced as the water film surrounding the bubble thins when it rises to the water surface or as the gas of the submerged bubble dissolves.

Bioorganic Processes

Bioorganic processes represent direct effects of living organisms on sediment properties and indirect effects mediated by the chemicals (organic materials) they produce. The term bioorganic is constructed from *bio* meaning living and *organic* meaning the chemical products of the life process (Morrison and Boyd, 1983). The mechanical alterations of sediment fabric by activities of organisms are classified as biomechanical. Included are activities that take place in the sediment such as bioturbation and activities that take place in the water column such as ingestion and reorientation of particles and clusters of particles by filter feeders. In the latter case, biophysical mechanisms such as the binding of particles together by organic matter also may be important. Biophysical mechanisms include the adherence of particles to sticky organic mucus and particle binding by polymer bridging. Biochemical influences on sediment microstructure result from changes in the microenvironment brought about by the metabolic activities of organisms. These include the breakdown of materials such as the polymers, which are important in polymer bridging and the production of biogenic materials such as cementing precipitates of pyrite. Biogenic gases, including methane and carbon dioxide, can have a locally important impact on the chemical environment surrounding

sediment particles and, in shallow-water settings, can disrupt sediment by bouyant release (see Wartel et al., this volume).

Biomechanical Mechanisms

Bioturbation, "the churning and stirring of a sediment by organisms" (Bates and Jackson, 1987), is a significant mechanism responsible for producing the particle orientation in a sediment and ultimately in a rock. This biomechanical mechanism produces a clay microfabric that possesses a randomness similar to the primary fabric of a flocculated (edge-to-face) clay, however, it is mainly characterized by randomly oriented individual particles (seen in SEM) rather than the random domains common in flocculated clays formed by other processes. Another distinguishing feature observed by the second author, especially apparent in bioturbated shales and mudstones, is the abundance of silt grains mixed in with the bioturbated clayey material.

In bioturbated sediment, the randomly oriented fabric of individual platelets is a result of mixing by organisms. Mixing disturbs the original primary flocculated fabric. Rhodes and Boyer (1982) indicate that "to facilitate burrowing and feeding, some metazoa, especially bivalves, also liquify the sediment by injecting water anteriorly into the bottom . . . this causes an instantaneous local increase in pore water pressure and the liquid limit of the sediment is temporarily exceeded." At this point the primary flocculated fabric is not only disrupted but silt size grains are mobilized and mixed in with the liquified clayey sediment. On burial and lithification the bioturbated sediment often retains its random fabric. Preservation of randomness in extensively bioturbated sediment is attributed to binding of particles by mucus secreted by burrowing organisms (Rhodes and Boyer, 1982; O'Brien, 1987).

Figure 2.11 illustrates typical microfabric produced by the biomechanical mechanism. Hand sample and X-ray radiographic viewing was first done on each of these poorly fissile gray shales or mudstones to demonstrate that they had been extensively bioturbated. In radiographs all samples show burrows or other evidence of sediment mixing. It should be stressed that to be certain of positive identification of a bioturbated fabric one should combine radiography or thin-section analysis with SEM viewing. Body fossils are not common in the samples, however, various types of trace fossils are apparent. The two important features which characterize this microfabric are (1) a randomness of individual clay flakes, and (2) silt size grains (quartz?) mixed in with the clay matrix.

Fecal pellets leave another fabric signature representing a biomechanical mechanism of sediment aggregation. An SEM study by Syvitski and Lewis (1980) revealed the characteristics of marine zooplankton fecal pellets. The ingestion of sediment and its expulsion by organisms as fecal pellets are common. Pryor (1975) studied the feeding activities and excretory products of the marine decapod *Callianassa major* and the
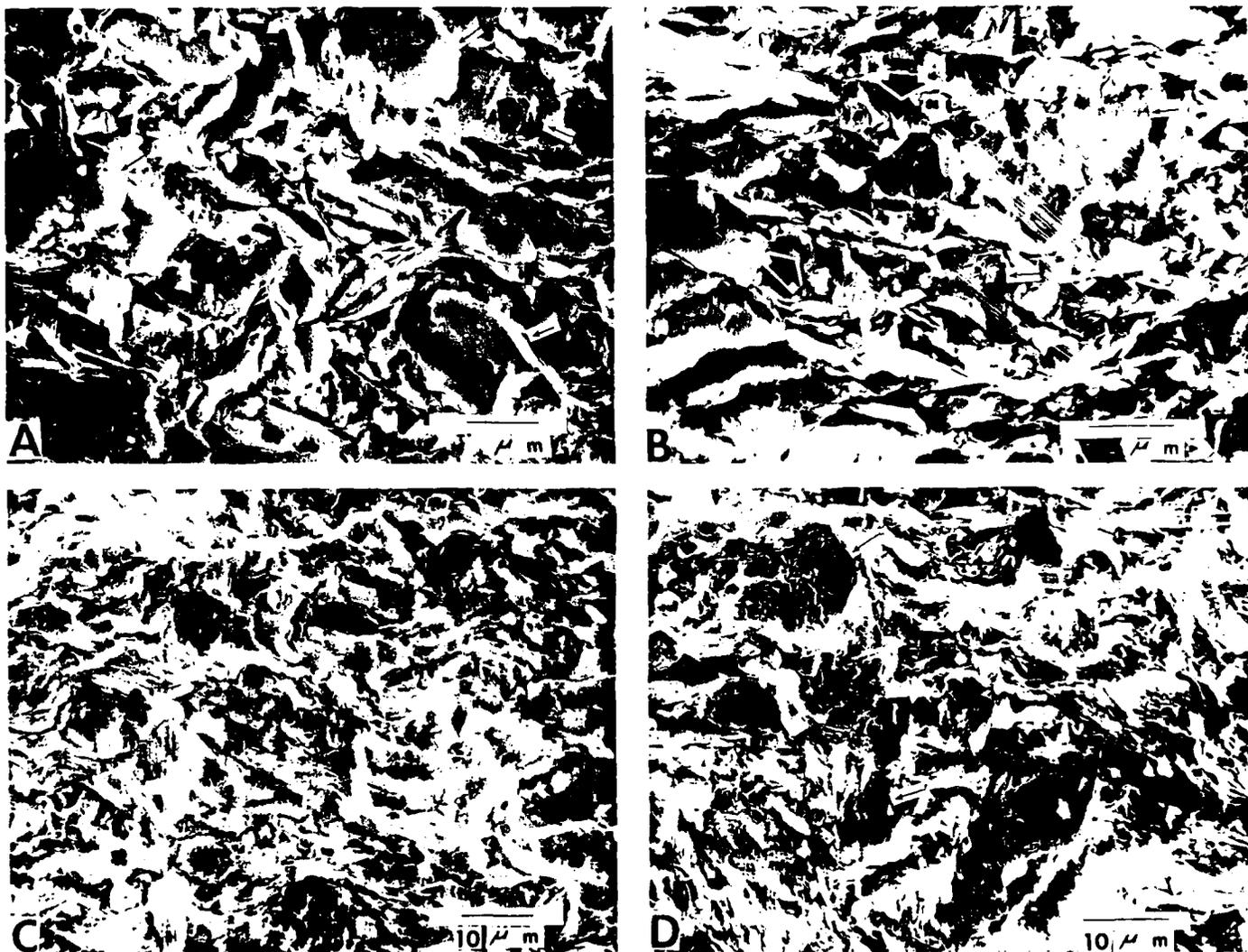
Figure 2.11. SEM photomicrographs of particle association produced by the biomechanical (bioturbation) mechanisms. (A) Silt grains (small arrows) mixed with individual platy clay flakes; Cashaqua shale (Devonian, Wyoming County, NY). Scale = 10 μm. (B) Individual randomly oriented flakes (large arrows) mixed with silt grains (small arrows) in the bioturbated Huron shale (Devonian, Mason County, WV). Scale = 10 μm. (C) Bioturbated mudstone fabric. Notice swirled nature of platy flakes. Penn Yan shale (Devonian, Livingston County, NY). Scale = 10 μm. (D) Typical bioturbated fabric (arrows show silt grains or cavities formerly occupied by grains dislodged during preparation) (Jurassic, gray shale, Yorkshire, England).

marine annelid *Onuphis microcephala* and found that in some areas they removed argillaceous particles from suspension, and deposited layers of fecal mud as thick as 4.5 mm/year, producing as much as "12 metric tons (dry weight) of pelleted mud per square kilometer per year."

The fabric of densely packed randomly oriented fine particles in a well-defined ellipsoidal pellet is easily recognized at low magnification in an SEM. Both recent (Fig. 2.12A, B), and ancient fecal pellets (Figs. 2.13A, B, 2.14A, B) reveal biogenic and lithogenic particles. However, when viewed at magnification greater than ×1000 it is often difficult to distinguish fecal pellet fabric from that produced by physicochemical processes (Fig. 2.13B). At lower magnification the sharp border of the pellet

is easily identified and the fabric difference between pellet and enclosing rock becomes obvious (Fig. 2.14A). Figure 2.14A and B-2 show the typical fossil fecal pellet microfabric characterized by dense packing of randomly oriented nonplaty material that is in contrast to the preferred orientation of platy minerals composing the surrounding shale (see arrows in Fig. 2.14A, B-2).

Biophysical Mechanisms

Clusters of randomly oriented particles are preserved in some organic-rich argillaceous rocks. Here the term biosediment aggregate refers to clusters that are believed to have formed
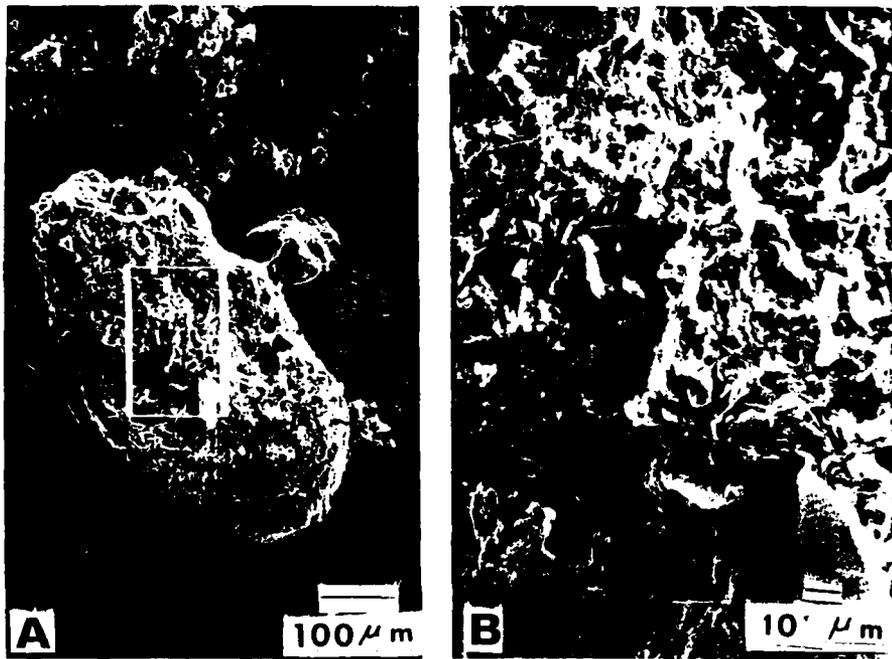
Figure 2.12. Fabric of a recent fecal pellet. (A) Recent fecal pellet (organism unknown) found in marine sediment, Dixon Entrance, Queen Charlotte Is., British Columbia. Scale = 100 μm. (B) Close-up view of pellet area shown in box outlined in A. Notice the random mix of biogenic (diatom fragments) and lithogenic (clay?) matter. Scale = 10 μm.

when lithogenic sedimentary material adhered to sticky organic mucus nets and/or formed by a clay–polymer bridge interaction. Hence, they represent another mechanism by which sediment may aggregate and settle through the water column.

Our investigation of certain organic-rich marine shales reveals the presence of numerous aggregates scattered randomly throughout a matrix of predominantly preferred platy matter. Their presence should not be surprising since McCave (1984) stated that fine-grained marine sediment settles as aggregates produced by biochemical bonding or electrostatic attractions. There is abundant evidence supporting the role of organisms and organic matter in promoting recent sediment aggregation (see for example, Riley, 1963; Kane, 1967; MacLean and Smart, 1978; Silver et al., 1978; Trent et al., 1978; Mullins, 1980; Shanks and Trent, 1980; Syvitski and Murray, 1981). The interaction between organic and inorganic matter is considered responsible for biosediment aggregate formation described here. Examples of their microfabric are shown in Figure 2.15A and B.

Biosediment aggregates found in this study occur only in non-bioturbated rocks that are well laminated, thus eliminating post-depositional biogenic mixing as a mechanism responsible for their formation. They are relics of the original sediment fabric. Because of their association with highly organic sedimentary rock [all shales in which they occur have a total organic content (TOC) of >3%] it is concluded that they record the complex organic–clay interaction which took place during sediment deposition. Modern analogs of this interaction are numerous.

Coccolithophoroid mucus is reported to play a major role in formation of aggregates of particles in recent sediment (Honjo, 1982). Pierce and Siegel (1979) observed that the major portion of suspended solids in estuarine and organic water is composed of aggregates of mineral grains, soft organic matter, biogenic debris, and phytoplankton, all bound by a matrix of organic matter. Alldredge (1986) has shown how the planktonic gelatinous zooplankton *Appendicularia* (Chordata, Tunicata) produces an external mucus structure that becomes clogged with sediment and is eventually discarded. Fungal mycelia and filamentous bacteria in Lake Tahoe, Nevada, were found aggregated with detrital particles (Pearl, 1973).

The work of Avnimelech et al. (1982) is very significant to our study in illustrating the morphology of what we interpret as recent biosediment aggregates (Fig. 2.16). They found that aggregation of clay was promoted by algae that secrete large amounts of polysaccharides and other polymers that produce sticky surfaces, which in turn promote aggregation of clay on algal surfaces. Notice, in Figure 2.16, that the platy clay flakes appear caught on the fine algal filaments much like a fly trapped in a spider's web. The sticky algal surfaces that bind the clay contain polymers that act as bridges via cations or anions to the clay particles. Avnimelech and Menzel (1984) and Reed (personal communication) have used this aggregation mechanism to clarify muddy ponds simply by stimulating algal growth by adding fertilizer to the water, which causes sedimentation of algal–clay clusters. Cyanobacterially induced flocs have been produced in clarifying suspensions of finely divided mineral wastes from phosphate ore beneficiation (Leslie et al., 1984).

Figure 2.13. Comparison of the microfabric of a recent and Jurassic fecal pellet. (A) Magnified view of the microfabric of recent fecal pellet in marine sediment, Emerald Basin, off Nova Scotia. Note the random particle reorientation. Scale = 10 μm. (B) Magnified view of fossil fecal pellet fabric, Bituminous Shale (Jurassic) Yorkshire, England. Note the random particle orientation and dense packing. Coccolith fragments are scattered throughout. Scale = 10 μm.
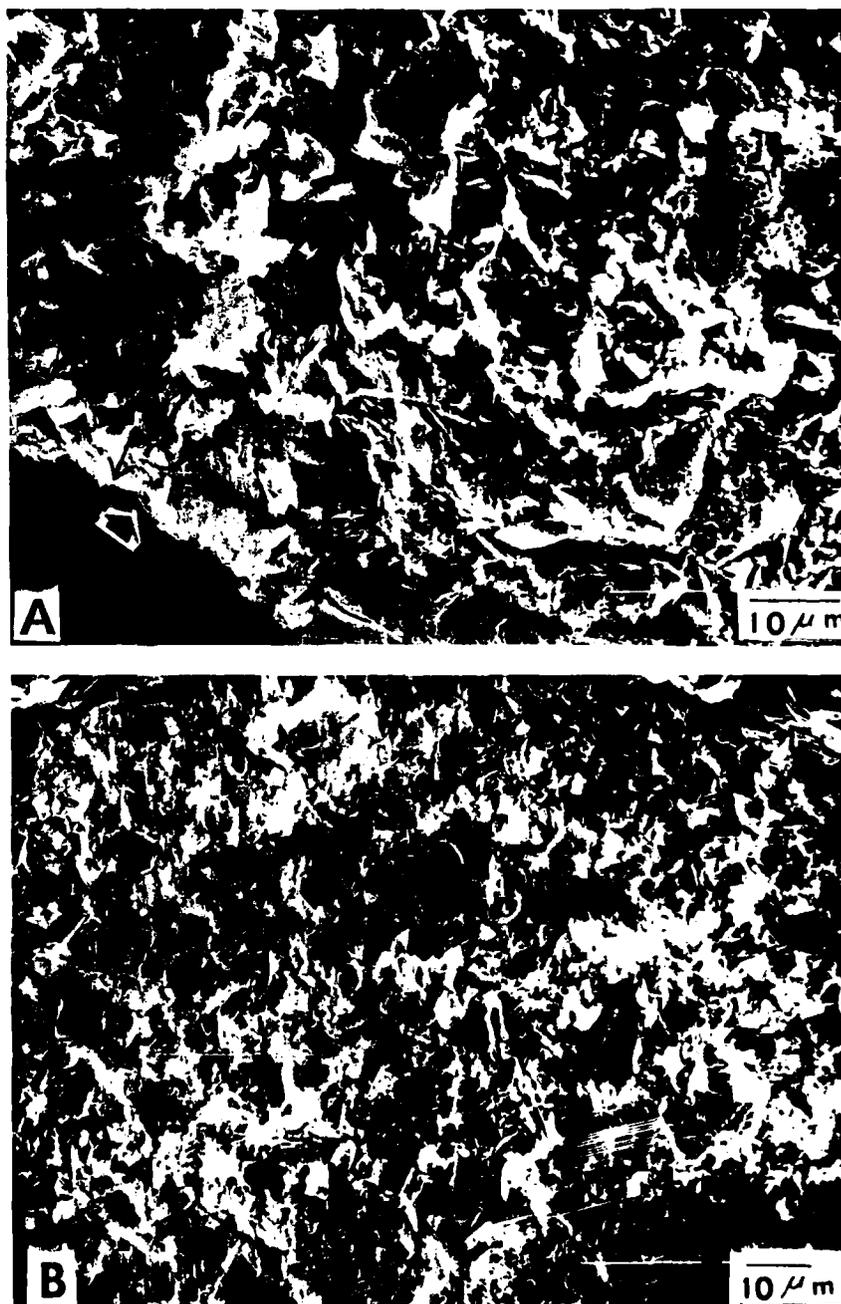
Organic polyelectrolytes have also been reported by numerous investigators to destabilize colloidal suspensions by a "polymer bridging mechanism" (Ruehrwein and Ward, 1952; Lamer and Healey, 1963; Black et al., 1965; Stumn and Morgan, 1981). The bridge forms when part of the polymer chain attaches to a solid particle surface (at an adsorption site) whereas other sections of the chain may extend out into the solution and become attached to a free site on a second particle (Fig. 2.17). This mechanism produces an aggregate of particles and polymers (see also Syvitski, this volume). Rashid (1985) described this mechanism as it applies to the sedimentation of floccules of clay and organic complexes in the marine environment and stressed the role of saline water in promoting flocculation. It is significant that our observations show aggregates in marine organic-rich argillaceous rocks.

We propose that large masses of sediment could aggregate and settle out in an organic-rich environment by the biophysical (sediment aggregate) mechanism. Initially large macromolecules
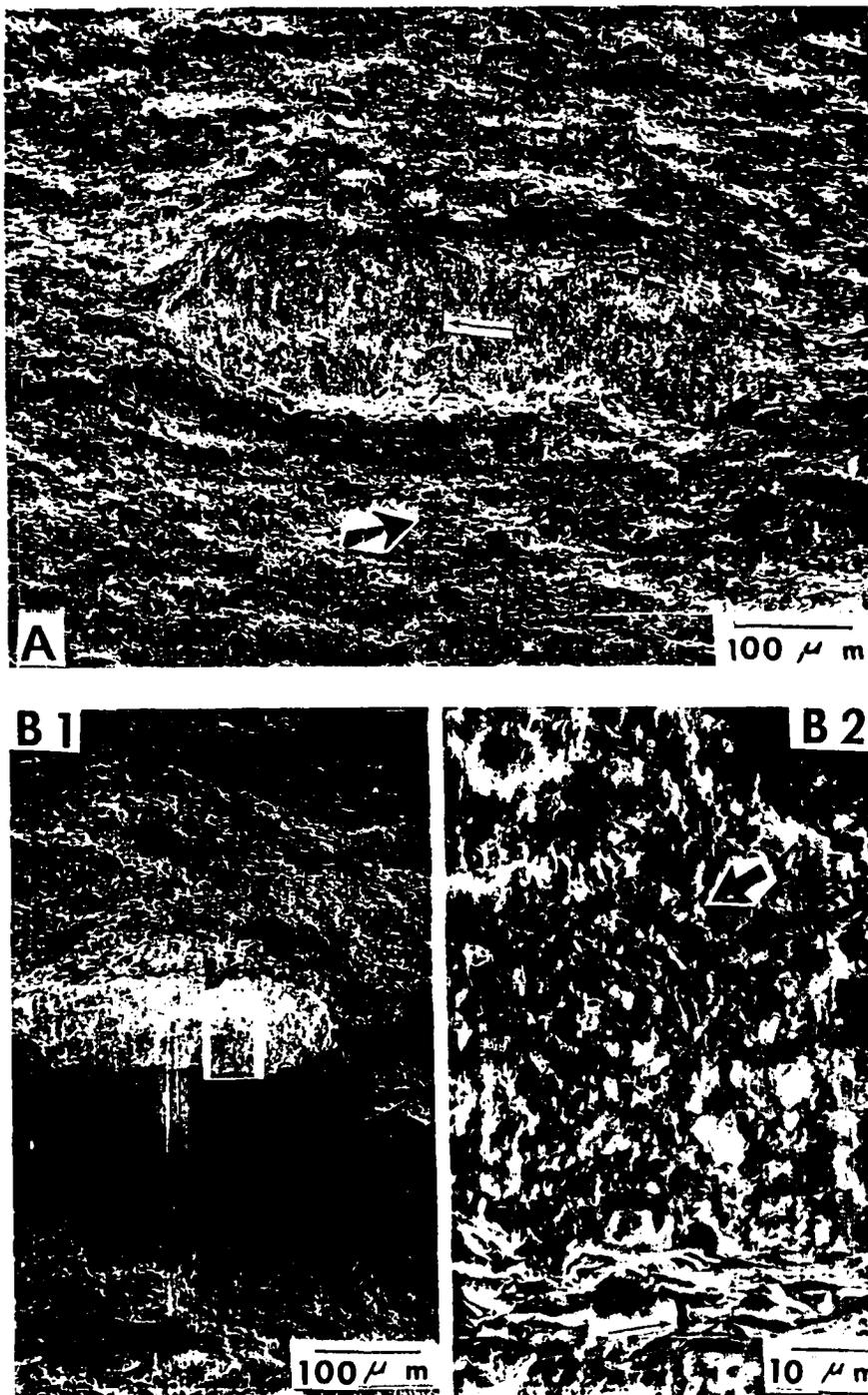
Figure 2.14. Microfabric of fossil fecal pellets. (A) View of fossil fecal pellet at low magnification. Note contrasting fabrics of pellet (small arrow) and surrounding shale matrix (large arrow). Scale = 100 μm. (B-1) Fossil fecal pellet in Bituminous Shale (Jurassic) Yorkshire, England. Scale = 100 μm. (B-2) Close-up view of area shown in outlined box in B-1. Note fabric difference between pellet (large arrow) and preferred orientation in the surrounding shale (small arrow). Scale = 10 μm.

and organic mucus strings suspended in ocean water act as substrates onto which clay, silt, and other detritus aggregates (Fig. 2.17). As this mass settles, other suspended particles are swept up by being caught in the sticky mucus web. The actual aggregation mechanism consists of an organic–sediment interaction (i.e., polymer bridging) as polymer chains link particles into a lacy network of organic and inorganic detritus. Once incorporated within the bottom sediment, the degree to which a biosediment-aggregate resists compaction and particle reorientation relates to the amount of polymer bridges, which in turn relates to the original organic concentration (and organic type?) in the seawater. One has to explain the numerous aggregates scattered

Figure 2.15. Typical examples of biosediment aggregates. (A) Loose packing of randomly oriented platy particles in an organic rich biosediment aggregate shale, Swope Fm. (Pennsylvanian, Adair County, Iowa). Scale = 1 μm. (B) Biosediment aggregate microfabric characterized by an open texture of randomly oriented particles. Note the authigenic framboids (lower right) in the surrounding shale. (Jurassic, Ravenscar, England). Scale = 1 μm.
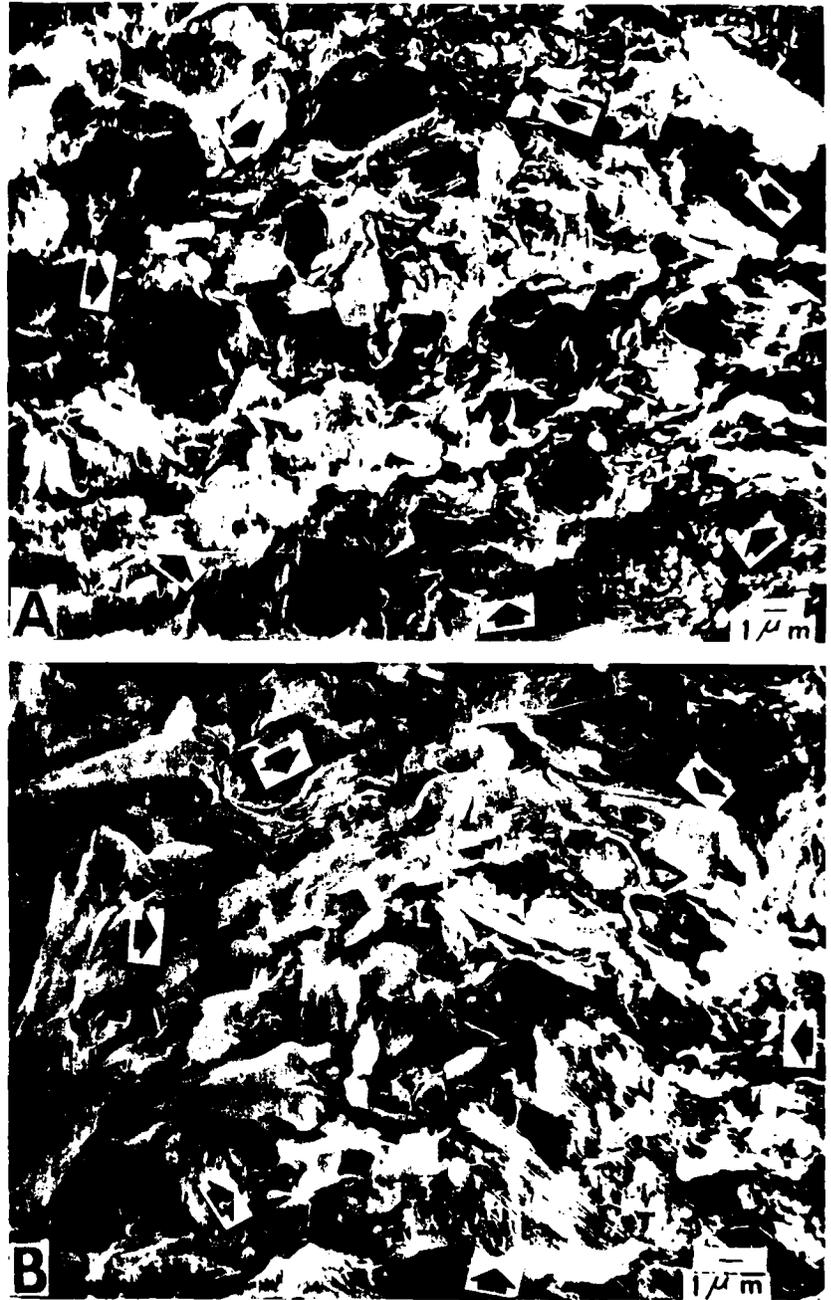
throughout a shale with dominantly preferred particle orientation. The preferred orientation may represent totally collapsed aggregates whereas the clumps of random particles represent some aggregates whose gel strength allowed them to resist reorientation. The concentration of organics is important. A small concentration of polymers in suspension could produce aggregates composed of only a limited number of weakly formed bridges. Black et al. (1965) found, for example, that if too few sites are occupied, the bridging will be too weak even to withstand shearing forces by agitation. Thus, in a sedimentary environment that is anoxic but contains a low content of organic matter, the stress exerted by bottom flowing currents or sediment overburden could be a factor in disturbing the stability of most weakly bridged aggregates and thus produce a dominantly preferred particle fabric surrounding those few clumps of the original biosediment aggregates which resisted deformation.

1 μm
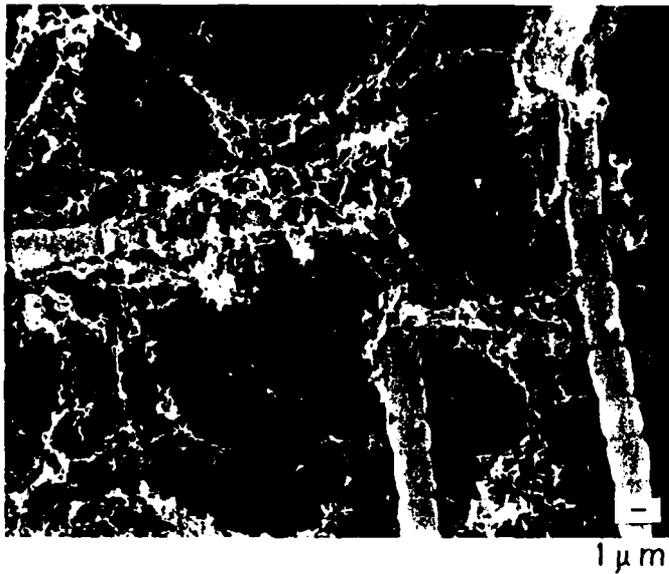
Figure 2.16. A biosediment/algae-clay aggregate from Avnimeleck et al. (1982). Note the fine algal filaments and large (white) particle possibly some clay particle and/or skeletal debris and the overall morphology of the aggregate. Scale = 1 μm. (Reprinted with permission from Y. Avnumelech et al., 1982. Fig. 2a, 216, p. 63-65, 2 April. Science, Mutual flocculation of algae and clay: evidence and implication. Copyright Science, 1982 by the AAAS.)

Although the exact understanding of their preservation is not clear, aggregates of randomly oriented particles observed in this study are in organic-rich rocks in the geologic record and presumably the biosediment aggregates occur also in some modern sediments. It is suggested that biosediment aggregates may be a result of a polymer bridging mechanism.

Figure 2.17. Steps in the formation of biosediment aggregates. (A) Large clumps of organic mucus sweep up suspended detritus during settling. (B) The actual contact between organics and sediment is a result of particle linking by polymer bridges. Notice linkage of clay flakes by polymers. (C-D) Orientation of biosediment aggregates in loosely consolidated sediment.

Biochemical Mechanisms

Organisms alter their environments by the production and destruction of many chemical entities. The impacts on sediment microstructure that these chemical alterations cause are included in the term biochemical mechanisms. Some of the simpler chemical conversions of interest are illustrated (Fig. 2.18). Not only are sugars, proteins, oils, and the rest of the complex array of biomolecules made by organisms, but also these compounds are decomposed and result in a variety of changes in inorganic constituents. The decay of polysaccharides and other polymers responsible for polymer bridging discussed above, for example, may allow particles in aggregates to be more easily moved apart or reoriented after sedimentation.

Gases produced by organisms in sediment masses also may alter sediment microstructure as they are released. A spectacular example of macroscale disruption of deep-sea sediment by presumed gas release was reported recently (Prior et al., 1989). In

this case, about 2 million cubic meters of sediment was excavated and redeposited about the resulting blowout crater. The measured crater depth was 58 m, and the total amount of sediment excavated corresponded to a sedimentation time of about 200,000 years. Much less spectacular but much more common venting of biologically derived gases such as CO_2 and CH_4 in shallow water churns and resuspends sediments.

An example of a biochemical mechanism reflected through inorganic species is the formation of authigenic pyrite by the combination of ferrous ions and disulfide ions generated metabolically in anaerobic environments (Lynch, 1983). The formation of authigenic pyrite framboids in fine-grained sediment also influences clay fabric. Although framboid growth does not produce sediment aggregates, it does exert a significant influence on microfabric by causing particle reorientation in specific areas of the sediment. The individual framboid (composed of iron sulfide) found in shale is spheroidal (Fig. 2.19). The spheroidicity

Figure 2.19. Pyrite framboid in Bedford shale formation (Mississippian. Ohio). Notice doming of platy particles (arrow) around framboid and well developed preferred orientation in surrounding shale. Scale = 10 μm.

Figure 2.18. Diagram depicting simple biochemical conversions of materials, including representation for the formation of authigenic pyrite. Organisms are depicted by stippled form showing uptake of chemical species such as nitrate, which is reduced to nitrite. Nitrite can be processed by an organism expelling the diatomic molecule (N_2). nitrogen gas, and also producing ammonia NH_3.

is attributed to pseudomorphism of a preexisting spherical body – e.g.. immiscible organic globules or infilling of gaseous vacuoles (Rickard, 1970). A biochemical origin for framboid sphericity has been proposed (Kalliokoski, 1974; Jabor and Mountjoy, 1976) and is discussed here. Bacteria or microflora colonies may produce the spheroidal morphology of framboids and also may be responsible for the biochemical reactions leading to their formation in sediment.

The typical framboid found commonly in organic-rich shales displays platy flakes wrapped around the sphere and is associated with a doming of adjacent particles. The adjacent particle orientation is interpreted as indicating that the sphere (be it a gas bubble or bacterial colony) grew in soft, easily deformed, flocculated clay sediment. Such a sediment would exist in the early stage of deposition. Framboids are found today at relatively shallow depth (< 3 m) forming as a feature of early sediment diagenesis (Love, 1967). It is proposed that some framboids found in organic-rich shales originally grew in soft flocculated clay under the reducing conditions existing in the sediment soon after deposition. These conditions favored bacterial growth. As a bacteria

colony enlarged (generating sulfur in the process) the soft flocculated clay sediment was easily deformed adjacent to it causing clay flakes immediately adjacent to the colony to wrap around its surface and reorienting and doming the sediment farther away in response to the growing sphere (Fig. 2.19). Subsequent sediment loading due to deeper burial reoriented the surrounding flocculated clay into the typical preferred fabric of shale. During early diagenesis, iron diffusion from the organic-rich anoxic sediment into the bacterial cavity resulted in iron sulfide precipitation.

This is only one possible explanation for the origin of pyrite framboids in clayey sediment. What is important is that this example illustrates they may form by a biochemical mechanism that in turn exerts an influence on the final clay or shale microfabric.

Burial Diagenesis Processes

Postdepositional alteration of microfabric during the process of burial diagenesis is driven largely by two mechanisms: mass gravity and diagenesis-cementation. Both mechanisms may proceed simultaneously. However, mass gravity stresses within a deposit are ever present regardless of the degree of chemical activity and mineralogical alterations and often mass gravity acts independently without influence of significant chemical activity associated with diagenesis-cementation. Burst (1976)

Figure 2.20. Microfabric typical of the surficial submarine sediment (1.3 m subbottom) of the Mississippi Delta observed by TEM. Note random arrangement of domains and large, irregular-shaped, voids. Scale = 1 µm.

Figure 2.21. Microfabric of Mississippi Delta sediments (30 cm subbottom) observed by SEM. Compare with TEM in Figure 20. Note domains, large voids, and short chains. Scale = 1 µm.

suggests that gravity is the dominant consolidation–compaction mechanism during dewatering of argillaceous sediment in the upper 914 m, but he contends that mineral diagenesis of clays, and osmotic and aquathermal pressuring are significant contributing mechanisms at burial depth.

Mass gravity mechanisms are used here to include not only consolidation and compaction, but also the dynamics of slumping, creep, orbital bed motion and deformation, and seismic shock. For this study, diagenesis–cementation mechanisms include mineral alterations, interstitial fluid transport, cementation and leaching, and organic-clay and gas interactions. A very limited number of studies have addressed the significance of these various mechanisms on microfabric development. The most popular topics have included study of fissility versus depth of burial (Hedberg, 1936; Weller, 1959; White, 1961; Gillott, 1969; Rieke and Chilingarian, 1974) and the association of organic material with the development of preferred particle orientation in shales (Gipson, 1965; Odom, 1967; O'Brien, 1968, 1989).

Mass Gravity Mechanisms

Limited but revealing sediment microfabric signatures that developed as a function of post depositional/mechanogravity mechanisms have been observed in electron micrographs. The depositional microfabric of high porosity sediment characterized by randomly oriented domains (Figs. 2.20, 2.21) was observed to have responded to overburden stress by mechanical rearrangement of particles normal to the direction of stress

(Figs. 2.22, 2.23). Initial depositional porosities of 70-75% contrasted sharply with consolidated sediment porosities of approximately 50% at burial depths of only 90-150 m (overburden stresses of 6-12 kPa). Reorientation of particles is observed for both field and laboratory consolidation (Bowles et al., 1969; Bennett et al., 1977, 1981). Hedberg (1936) recognized the importance of mechanical rearrangement of particles during the early stages of compaction and his observations appear to have been well documented by later studies (Bowles et al., 1969; Bennett et al., 1977, 1981; Faas and Crocket, 1983).

The consolidation process involves volume reduction as a result of sediment dewatering under an imposed load. The geologist often refers to this process as compaction. The importance of the mechanisms involved in sediment dewatering was recognized as early as 1908 by Sorby. He observed significant reductions in porosity as a function of compaction. As noted above, volume reduction on compaction also is associated with platy particle reorientation. Randomness in the original flocculated clayey sediment changes to more preferred orientation with depth. This volume reduction and particle reorientation are important early burial diagenesis processes that influence the final microfabric of resultant rocks. White (1961), Gipson (1965, 1966), and Gillott (1969) concluded that the high degree of clay mineral preferred particle orientation was associated with fissile shales and that random orientation of particles was characteristic of the more massive argillaceous rocks. Scanning electron microscopy observations of shales by O'Brien (1968, 1970b) revealed strong preferred particle orientation in a fissile Pennsylvanian black shale (Fig. 2.14A) and random particle orientation in nonfissile argillaceous rocks (Fig. 2.11A).

Figure 2.22. Microfabric of consolidated sediments from the Mississippi Deleta recovered from 120 m subbottom observed by TEM. Note the highly oriented clay plates that lie in a direction normal to the direction of the overburden stress. Larger particles prevent perfect alignment of all the platelets. Voids become long and linear as compared to surficial sediments (see Figs. 2.21 and 2.22).

Figure 2.23. High TEM magnification of consolidated sediment recovered from 150 m subbottom, Mississippi Delta. Note the strong degree of preferred particle orientation. Scale = 1 μm.

The most conclusive evidence to date indicates that fissility is related to preferred particle orientation, but the degree of preferred orientation is not directly related to depth of burial in most cases. Thus the decrease in porosity with depth of burial varies considerably among various sediment types. Evidence from numerous studies of the relation between sediment and shale microfabric and compaction has shown the importance of other factors such as geochemical conditions, environments of deposition, biological activity, and related geological and dynamic factors that set the stage and influence the initial formation of microfabric in suspension and at the depositional interface. The initial depositional microfabric and effects of biological activity most certainly influence the response of the particles in the postdepositional development of microfabric with increasing depth of burial and when the deposit is subjected to external environmental stresses (Bennett, 1976, 1977).

Downslope movement and shearing of sedimentary deposits also have a profound influence on the postdepositional development of microfabric. Massive blocks of sedimentary material can move downslope without significant resuspension of particles (McGregor and Bennett, 1981) and, conversely, slumping can produce massive amounts of resuspended particulates that can travel many kilometers subaerially or on the sea floor as turbidity currents (Middleton and Bouma, 1973).

The Mississippi Delta, a "natural laboratory" for the study of coastal sedimentary processes, is an excellent example of a sedimentary environment experiencing massive downslope movement of fine-grained deposits (Coleman and Garrison, 1977; Coleman and Prior, 1978). "Crust" zones, defined on the

basis of shear strength profiles with depth of burial, typically show a significant strength reduction or "cut back" in shear strength at depths of about 8–14 m subbottom (Doyle et al., 1971; Bea and Arnold, 1973). These zones are related to submarine slumping of soft, high porosity, deltaic sediments and the movement of massive amounts of sediment seaward on gentle slopes. The microfabric of these smectite–illite-rich high porosity sediments above and below the "crusts" is characterized by randomly arranged clay particles and domains (Figs. 2.24–2.26). This type of microfabric is typical of the unconsolidated surficial submarine sediments of the Mississippi Delta (Bowles, 1968; Bennett et al., 1977, 1981). Detailed microfabric studies of the "crusts" zones (Figs. 2.27, 2.28) have revealed a significant difference in the particle arrangements and orientations compared to the fabric above and below the "crusts." The microfabric in the "crusts" zones is characterized by areas of preferred particle alignment but with an overall appearance of remolding (Bennett et al., 1977; Bohlke and Bennett, 1980). As the sediment shears, remolds, and dewaters, the microfabric undergoes particle rearrangement. These microfabric signatures are characteristic of remolded sediment that has been verified by Bennett (1976) and Bennett et al. (1977, 1981). Pusch (1970) studied the effects of sediment shearing on microfabric and showed the distortion of links and chains and reorientation of particles in the direction of the principle shear stress. In shallow coastal environments, energy from surface waves reach the sea floor and produce orbital motion of the sediment (Yamamoto, 1982). These motions reduce the sediment strength and when shearing stresses exceed the sediment shear

Figure 2.24. SEM of surficial sediments recovered from 30 cm subbottom above the "crust" zone of the Mississippi Delta in relatively undisturbed material relative to the sheared characteristic of the "crusts." Note similar microfabric as observed in other subenvironments of the delta (compare Figs. 2.20 and 2.21). Scale = 1 μm.

Figure 2.25. TEM of microfabric characteristic of sediments above the "crust" zone (compare with Fig. 2.24). Note high porosity, large voids, delicate particle-to-particle contacts, and short chains. Scale = 1 μm.

strength the deposit fails and submarine sliding often occurs (Dunlap et al., 1978; Henkel, 1970; Bea, 1971).

Diagenesis-Cementation Mechanisms

Diagenesis of mineral phases and cementation operate over a wide range of thermal regimes that can alter the character of the fabric. The literature is replete with studies of mineral transformations, mud to shale diagenesis, compaction (consolidation) versus depth of burial, and so on, however, meager attention has been given to the relationships of mineral alterations and microfabric. A recent study by Howard (1987) pointed out the importance of microfabric in controlling fluid flow properties; differences in permeability were shown to have a significant influence on the reaction rates of mineral transformation in shales. Reaction rates clearly depend on complex interacting processes and mechanisms that include not only fluid flow properties but also the availability and presence of inorganic chemical species in solution, the mineralogy of the solid particles, and the organic compounds present. The presence of organics in sedimentary sequences was shown to be very significant in burial diagenesis (Johns, 1979). The complexity of the geochemistry in cementation and mineral diagenesis was revealed clearly in the work of Curtis: "Chemical changes within clay mineral assemblages cannot be attributed to reactions among clays alone and indeed all the available evidence suggests other minerals are involved. Clastic sediment sequences include shales, silts, and sands. Shales start life as muds with upward

of 70% pore water and relatively reactive, unstable minerals derived from soil profiles. As well as the clay minerals themselves, amorphous compounds of iron, aluminum, and silicon are important, as is organic matter. Carbonate, reactive silica, and more organic matter may be added from depositional waters" (Curtis, 1985, pp. 91-92).

Dunoyer De Segonzac (1970) pointed out that mineral transformations, neoformation, and recrystallization are accompa-

Figure 2.26. SEM of microfabric characteristic of sediments below the sheared sediments of the "crust" zone. Note similarity with the undisturbed surficial sediments. Scale = 1 μm.
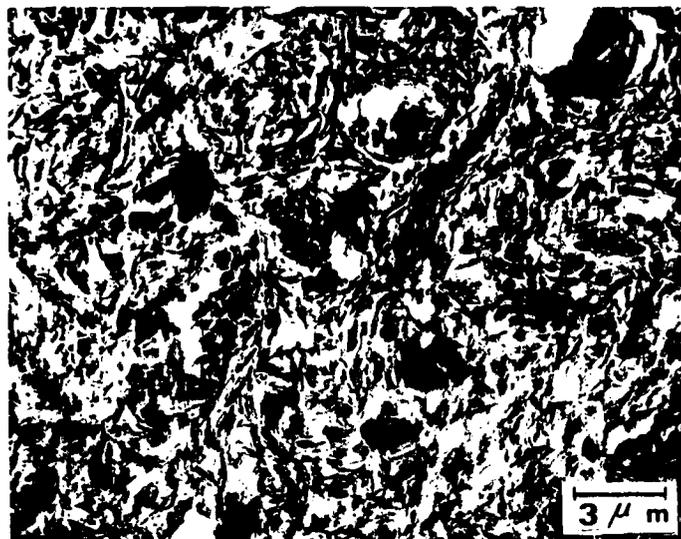
Figure 2.27. Microfabric characteristic of the "crust" zone of the Mississippi Delta as observed by TEM. Note swirled features and localized areas of preferred particle orientation. Clay platelets orient in the form of an "onion" skin around larger particles. The microfabric is typical of remolded clay sediment (Bennett et al., 1977, 1981). Scale = 3 μm.

Figure 2.28. High magnification of remolded sediment characteristic of the "crust" zone depicting a localized area of preferred particle orientation (8 m subbottom). 16.5 mm = 1 μm.

nied by crystalline growth and changes in particle morphology, which translates directly to changes in microfabric. The complex microfabric of "red clays" from the Pacific Ocean Basin was revealed in scanning and transmission electron micrographs (Bryant and Bennett, 1988); authigenic mineralization was shown to have a profound influence on not only the clay microfabric features but also on the physical and mechanical properties of the sediment (Fig. 2.29). The overconsolidation characteristics of the soft clays were attributed to the strong bonding of argillaceous shale clasts and quartz grains by X-ray amorphous and well-developed authigenic smectite (Bryant and Bennett, 1988). Considerably more research is required to develop meaningful microfabric models and to discern microfabric signatures that are directly related to diagenetic mechanisms including authigenic mineralization, mineral transformations, solution and deposition of minerals and cementing agents.

Summary

The microfabric signatures resulting from the various processes and mechanisms are often recorded in the sediments and rock and can be revealed by electron microscopy observations. Based on numerous detailed studies of sediment and shale microstructure and the related environmental factors affecting the development of microfabric, three dominant processes have been identified and studied. The important processes that produce microfabric development of clay sediments and shales

are physicochemical, bioorganic, and burial diagenesis (Figs. 2.1, 2.4).

Mechanisms associated with physicochemical processes include (1) electrochemical mechanisms 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; (2) thermomechanical mechanisms that arise from thermally driven forces in the water column (Fig. 2.4A and from dynamic interaction of particles driven by wave, current, and gravity forces (Fig. 2.10); and (3) interface dynamics mechanisms in which particles impinging on the sediment–water interface are in dynamic motion and collide with other particles in a variety of configurations depending on the microrelief of the bottom. Electrochemical and thermomechanical mechanisms produce high intravoid (edge-to-face) flocs and face-to-face sheet like multiplate particle associations. Domains are common (Fig. 2.2).

Mechanisms associated with bioorganic processes are (1) biomechanical or bioturbation, which produces a random clay microfabric similar to the primary fabric of flocculated (edge-to-face) clay; however, often it is characterized by randomly oriented individual particles (as resolved by SEM) rather than thick domains and/or stepped face-to-face particles; (2) biophysical mechanisms produce biosediment aggregates, which are clusters of randomly oriented clay-silt particles formed when lithogenic matter adheres to sticky organic mucus or is bound together by polymer bridging; and (3) biochemical mechanisms, which cause microfabric changes in sediment due to chemical transformations mediated by organisms.

Figure 2.29. The microfabric of authigenic mineraliza tion in a red clay of the northwest Pacific deep-sea basin (22.5 m subbottom) as observed by TEM. Note the lacy, finely divided crystals that form a very porous network. The mineral "smectite" appears to have developed by expan sion of the crystal network pressing larger crystals of illite and smectite radially outward while reorienting the larger particles in a direction normal to the direction of stress. Note how the electron-dense particles appear to outline the circumference of the authigenic mineral. Sample recovered by DSDP Leg 86, Hole 576 (water depth 6217 m, 32° 21.38'N, 164° 16.52'E) in the basin east of Shatski Rise. Scale = 1 μm.

Burial diagenesis processes involve (1) postdepositional/mechanogravity mechanisms that arise from overburden stress and gravity-driven vertical and downslope forces that modify microfabric during consolidation and shearing; and (2) diagenesis-cementation mechanisms that alter the original character of the microfabric such as the formation of authigenic minerals.

All of the above-mentioned mechanisms produce microfabric signatures. Some signatures may be revealed in sediments and rocks by detailed electron microscopy observations. Recognition of a unique signature coupled with other observed properties (e.g., percent organics, porosity, and geochemistry) and larger scale features such as observed with X-ray radiography thus enables the investigator to determine or infer the dominant processes and mechanisms responsible for the observed microfabric. Collectively, these macro- and microproperties provide a qualitative and quantitative data base for understanding the geological record, and environments of deposition. These properties also provide crucial input properties for predictive modeling of the static and dynamic behavior of sediments and rocks for a wide variety of basic and applied research studies and for solving practical problems.

The processes and mechanisms that determine the microfabric signatures operate over various physical and time scales that are largely specific to a particular mechanism. For example, the

Table 2.1. Summary of processes and of the fabric signatures and physical and temporal scales associated with various mechanisms.

Processes	Mechanisms	Fabric signatures (predominant)*	Scales physical	time	Remarks
Physicochemical	Electrochemical	E-F	Atomic and molecular to ~ 4 μm	μsec to msec	Two particles may rotate F-F
	Thermomechanical	F-F (some E-F)	Molecular to ≤0.2 mm	msec to min	Initial contacts E-F then rotation to F-F; common in selective environments
	Interface dynamics	F-F and E-F	μm to ~ ≤0.5 mm	sec	Some large compound particles may be possible at high concentrations
Bioorganic	Biomechanical	E-F	~0.5 mm to >2.0 mm	sec to min	Some F-F possible during bioturbation
	Biophysical	E-E and F-F	μm to mm	sec to min	Some very large clay organic complexes possible
	Biochemical	Nonunique (unknown)	μm to mm	hr to yr	New chemicals formed, some altered
Burial diagenesis	Mass gravity	F-F localized swirl	cm to km	≥yr	Can operate over large physical scales
	Diagenesis-cementation	Nonunique (unknown)	molecular	≥yr	New minerals formed, some altered, changes in morphology

*F-F, edge-to-face; E-E, edge-to-edge; F-F, face-to-face.

energy regimes driving microfabric development can be important over physical scales that can range in size from atomic dimensions to as large as kilometers and over time scales that are important in the microsecond range or up to periods of years or greater in the geological sense (Table 2.1). Examples of these extremes are found by comparing the electrochemical mechanism, where atomic and molecular dimensions are important over micro- and milliseconds during microfabric development, with the mass gravity mechanism, that occurs over dimensions of centimeters and kilometers for periods of thousands of years.

Examination of Table 2.1 reveals that although the various mechanisms produce predominant fabric signatures, similar particle-to-particle associations are common to different processes (compare physicochemical processes with bioorganic processes). Obviously more than a single criterion is usually required to interpret the processes of microfabric development. Such information may include percent organic carbon, interstitial water chemistry, porosity and/or permeability of the geological material, position in the stratigraphic column, and association with other particulates.

An important factor in understanding the microfabric of sediments and rocks is the aspect of observational scale. This factor can range from large-scale field observations, through the scale of X-ray radiography, to the scale of angstroms revealed by techniques of electron microscopy. Often many levels of observation are required to develop an adequate understanding of the particular problems(s) being addressed whether it be in disciplines of geology, environmental engineering, geotechnical engineering, petroleum exploration, or the recovery of hydrocarbons. Understanding of the processes and mechanisms responsible for microfabric development is an important factor in gaining a

functional understanding of the relationship of microstructure to the developmental history and the bulk physical and mechanical properties of a deposit.

The microstructure is a crucial fundamental property that plays a significant role in determining the sediment and rock physical and mechanical properties and its behavior under static and dynamic loads. Many of the rock and sediment properties, important to a variety of scientific and technical disciplines, are intimately tied to the microfabric characteristics (Bennett et al., 1977, 1989). Delineation of the complex interrelationships among microfabric, processes and mechanisms is significant in terms of (1) understanding the role of specific energy regimes during the stages of microfabric development and sediment diagenesis and (2) development of predictive models (acoustical, mechanical, geological) that depend critically on the nature of the microstructure and basic physical and mechanical properties. Future investigations of the subtle difference in microfabric and its relationship to environmental processes and mechanisms, including detailed geochemical factors (organic and inorganic) and large and small scale features, could add important dimensions to scientific and technical knowledge and the ultimate applications of microstructure to practical problems.

Acknowledgments

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