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The Environmental Significance of Stratification

by

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STATEMENT OF THE PROBLEM

Stratification, the primary sedimentary feature, has been inadequately studied and is not thoroughly understood. It has been more a puzzle than an aid in stratigraphic interpretation. Various aspects of stratification such as cross bedding and graded bedding, have been given special attention and detailed study. These, however, represent rather restricted ranges of environments. The stratification in easily accessible environments, such as beaches, tidal flats, fluvial, and dune environments, has been studied by several workers. Seaward from the beach very little is known concerning the stratification which is now developing in marine environments. It is obviously difficult to devise techniques for studying such bedding now forming in recent, unlithified, marine sediments.

Stratification develops in response to environmental factors and processes. Therefore, a knowledge of the processes involved must supplement any study of stratification.

Five direct factors--which will be described later--control the nature and pattern of bedding in any aqueous environment. Several indirect factors control stratification by modifying the intensity of the primary factors, or by modifying features that have developed.

Because of its control by direct factors, stratification very accurately reflects the environments of accumulation, possibly even more so than any other indicator. Knowledge of stratification permits rapid and accurate environmental interpretation.

Confusion exists in the literature concerning the terminology of stratification. Terms such as "thick-bedded" and "massive" commonly have several meanings, even as used by the same writer. Most descriptions of stratification are incomplete or inadequate. Apparently the factors which influence thickness determinations have not been adequately explored and defined, nor have workers clearly defined the bases for their estimations of thickness.

Environmentally significant parameters, such as continuity and regularity, are commonly impossible to determine from limited exposures. Knowledge of stratification patterns that develop in response to changing environmental conditions has been gained by observing continuous exposures. Analysis of these patterns can be applied to limited exposures and possibly even to well cores.

PURPOSE AND SCOPE

The purpose has been to study stratification as a manifestation of environmental processes. Bedding becomes a potent tool for stratigraphic analysis, rather than a puzzle, when one understands the agents that control the formation of the various bedding phenomena. Previous studies have been mainly concerned with recent, unlithified sediments. The present study has involved ancient environments represented by lithified sediments. Lithified sediments provide dimensions which cannot be readily utilized in the study of recent sediments. Exposures of lithified sediments permit one to observe environmental changes through time and space.

Emphasis in this study has been on the stratification in marine environments that developed seaward from exposed beaches. Stratification patterns that develop during transgressive and regressive sedimentation, or deepening and shallowing conditions, were given special attention. The study has included stratification in all lithologies. An attempt has been made to relate variation in process intensity, within an environment, to stratification phenomena.

A major purpose has been the establishment of a foundation of principles and a framework of analysis which will aid in interpretation and in the solution of basic stratigraphic problems.

AREAS STUDIED

Selected areas within ten states were studied. Six were in the West and four in the Middle West. Rocks covering a wide range of geologic ages and environments were observed in these areas.

Nevada

A geological section ranging in age from Ordovician to Mississippian, representing a geosynclinal province, was studied in the Pahranagat Range in South Central Nevada in the vicinity of Alamo.

Utah

Triassic and Jurassic exposures were examined in Eastern Utah along highway 160 from Monticello to Moab and in the Arches National Monument outside Moab. Paleozoic, Mesozoic, and Cenozoic sequences were observed in the Uinta Range in the vicinity of Vernal and Dinosaur National Monument.

Arizona

Pennsylvanian exposures were briefly visited in the Salk River Canyon along highway 77. Triassic exposures were photographed along highway 60 in the Winslow-Holbrook area.

New Mexico

Pennsylvanian exposures were analyzed in the Sacramento Mountains with emphasis on the Fresnal Group exposed in Fresnal Canyon.

Colorado

Ordovician, Pennsylvanian, Jurassic, and Cretaceous units were visited in the Canon City area of Central Colorado. Pennsylvanian and Permian exposures were observed near Ouray in Southwestern Colorado. Cretaceous units in Mesa Verde National Park were also observed.

Texas

Interfingering continental and marine Permian units were visited in the Wichita Falls-Archer City-Lake Kemp areas of North Texas. Stratification in Cretaceous units exposed in the vicinity of Austin were analyzed. Cretaceous units, exposed in cuts along highway 90 from Sanderson to Del Rio, and northward from Uvalde to Kerrville along highway 83, were observed.

Arkansas

Ordovician and Early Pennsylvanian formations were visited in the southwestern part of the state along highway 27 from Nashville, through Mt. Ida, and on to Rover. Mississippian and Pennsylvanian exposures were studied in the northwestern part of the state along highway 7 from Ola, through Russellville and Jasper to Harrison. Upper Mississippian units were studied in Northwestern Arkansas in a circuit from Harrison westward along highway 68 to Fayetteville, north to Rogers, and eastward along highway 62 back to Harrison.

Missouri

Cambrian and Ordovician units were studied in Southeastern Missouri in road cuts along highway 67 from Poplar Bluff northward through Mine Lamotte and Flat River to Festus. Ordovician and Mississippian formations were observed in cuts along highway 25 southward from Festus to Ste. Genevieve. Ordovician and Mississippian units were analyzed in East Central Missouri along highway 40 west of St. Louis through Wentzville, Danville, Mineola, and southward through Fulton along highway 54 to Jefferson City. Ordovician units were observed in cuts along highway 66 between Waynesville and Springfield. Mississippian units were visited in Southwestern Missouri in road cuts along highway 65, south of Springfield.

Illinois

The Chester sequence in the vicinity of Chester and Prairie du Rocher was observed in Southwestern Illinois. Silurian inter-reef units were analyzed in quarries in and near Joliet in Northern Illinois. Ordovician units were studied in quarries in and near Ottawa.

Wisconsin

Excellent Late Cambrian and Middle Ordovician sequences were studied in detail in Southern and Southwestern Wisconsin. Late Cambrian units were studied in the Madison area and in the areas to the north and northeast of Madison. Middle Ordovician units were analyzed in areas near

Janesville, New Glarus, Argyle, Blanchardville, Mineral Point, Platteville, Dodgeville, and Fennimore.

METHODS OF STUDY

This study consisted of a library phase and a field phase. The library phase included a literature survey of previous work on stratification and its environmental factors and processes. Photographs included in the stratigraphy of various areas commonly provide valuable information to supplement the field studies. Information concerning environmental process variation and intensity in many areas in various publications has been very useful.

The field phase was directed toward a study of rocks of a wide range of geological ages in the various environments over a broad area to determine whether the basic patterns have remained constant through time in similar situations.

Detailed field notes were taken at each locality. Sketches were drawn to emphasize significant features and relationships. Supplementary forms were prepared which contained a check list of significant observations, measurements, relationships, features, and so forth. One of these forms was filled out for each outcrop visited. Detailed photographs were also taken at each exposure. Most of these were preserved as color slides for more intensive study in the future.

The best and most continuous exposures available in the various areas were studied in detail. Only continuous exposures permitted detailed description of the most significant parameters which are related to primary processes. Well known, classic areas were deliberately chosen because little doubt exists concerning the major ancient sedimentological environments in such areas. Areas where good stratigraphic control had been previously established were emphasized in this study.

A copy of the prepared check list which was filled in at each exposure follows. This illustrates the nature of the data which was gathered.

I. Location

II. Unit (formation)

  Thickness

III. Geologic Setting

  A. Depositional Province - shelf, platform, geosyncline (eu, mio)

  B. Structural Situation

IV. Relations with Subjacent Units

  Relations with Superjacent Units

V. Bedding Observations

  A. Irregular vs Regular (planar or tabular, and so forth)

  B. Sedimentary Structures or Lack of Structure

  C. Continuity

  D. Parallelism

  E. Thickness

F. Nature of Internal Bedding

G. Nature of Bedding or Separation Planes--what influences the thickness determination

H. Operational Procedure applied here

VI. Texture (grain size, sorting, and so forth)

VII. Fauna--nature, preservation, distribution, orientation, concentration, and so forth

VIII. Facies Relations--where determinable

IX. Manner of Deposition and Accumulation--inferred

X. Energy conditions under which material accumulated

XI. Transgressive, regressive, deepening, or shallowing conditions--if determinable

Stratification patterns that resulted from changes in environmental processes were examined from continuous exposures. Certain stratigraphic units such as cyclothemic deposits provide good control for studying stratification patterns that develop in response to deepening and shallowing conditions. Patterns that developed in response to deepening and shallowing conditions were found to be relatively constant, regardless of area, age, or lithology.

Very little sampling was done because the nature of the study and areas covered prohibited extensive sampling. In any case, detailed photographic documentation by means of colored slides probably provides a more potent analytical supplement to field notes.

TERMINOLOGY

Confusion exists in the literature concerning stratification terminology. Accurate description demands a workable terminology. Terms such as "thick-bedded" and "massive" commonly have several meanings. Apparently the factors which influence thickness determinations have not been logically explored and defined.

Some workers have attempted to employ definite thickness terms much as are used in the Wentworth scale. Others have proposed the application of statistics to quantify the thickness variations. It is significant, however, that no one has yet clearly defined the basis for his thickness determinations.

Strata and Bed - Twenhofel (1950) defines a stratum as, "A unit of sediments that separates more or less readily from overlying and underlying units." He further states, "That all strata are lenses of greater or lesser aerial extent, and each thins laterally to disappearance, but there may be passage into some other variety of sediment before a stratum disappears." Twenhofel uses the terms bed and stratum interchangeably. Payne (1942) defines a stratum as, "A layer greater than one centimeter thick that displays continuous variation in lithologic character and is visibly separable from other layers above and below, the separation being determined by a discrete lithologic change, a sharp physical break in lithology, or by both." According to Payne, "A bed is loosely employed but definitely denotes a unit of sedimentary rock of lower rank than a member or formation, composed of two or more strata or laminae that manifest some degree of lithologic unity, and the component layers may be of the same composition and texture, or may consist of two or more related lithologic types." Kelly (1956) attaches the same meaning to both bed and stratum and defines a bed or stratum as, "A single layer bounded by bedding planes or surfaces of abrupt changes in lithology." He further states that these terms have been used collectively for sets of beds or intervals within which there are less marked or less significant surfaces of stratification and lithologic changes. McKee and Weir (1953) define a stratum as, "A single layer of homogeneous or gradational lithology, deposited parallel to the original dip of the formation. It is separated from adjacent strata or cross strata by surfaces of erosion, non-deposition, or abrupt changes in character." According to McKee and Weir (1953), "The term stratum is not synonymous with the terms bed and lamination but includes both." They ascribe definite thickness connotations to each term.

The synonymy of the terms bed and stratum appears to be rather firmly entrenched. The assigning of definite thickness limits to such subjective, qualitative terms seems to be of questionable value.

Units Smaller than Strata or Beds - Next comes the problem of defining terms for units smaller than beds or strata. Twenhofel (1932) states, "That a stratum may be stratified and if the stratum contains thin beds, they are called laminae or laminations, whereas, the thicker units of the stratum may be called stratum layers." Twenhofel defines a lamination as being thinner than one centimeter. Thompson (1937) used laminae for layers as much as 1.2 inches thick. Otto (1938) defines a lamina as the smallest recognizable unit layer of particles of a sediment. He states that the thickness of a lamina may vary from microscopic size for clays to many inches for gravel. According to Geike (1903), the smallest subdivision of the geological record are laminae, a number of which may make a stratum or bed. Payne (1942) defines a lamina as being similar to a stratum but less than one centimeter thick. McKee and Weir (1953) consider a lamination to be between one centimeter and two millimeters thick, and a layer less than two millimeters thick to be "thinly laminated." Most of the writers apparently agree that a lamination is less than one centimeter thick.

The term lamina conveys a degree of thinness which renders it distinct from the synonymous terms bed and stratum. To warrant a separate identity it appears necessary to assign specific limits to this term.

Bedding Plane - Different shades of meaning have been attached to the term bedding plane by different writers, and there has been no adequate standardization of the term. Twenhofel (1950) defines a stratification or bedding plane, "As a plane of separation between laminations or strata; it may represent the contact of lithologically different strata or laminae, without a sharp physical break, or it may represent a physical break resulting from a period of non-deposition or erosion." A bedding plane developed by a sharp physical break could be used in the same sense as a parting plane or a shale break. Payne (1942) defines parting as a lamination occurring between massive strata, different in lithology from the parting itself. Ingram (1954) and Gray (1955) suggest using the term parting in the same sense as mineral parting, rock cleavage, fissility, or shaliness. McKee and Weir (1953) relate parting and splitting properties.

The term bedding plane appears to imply a parting or separation of some sort. It may be a physical separation or a sharp textural or compositional change. Bedding planes separate beds or strata into determinable units. The term used in this sense is almost synonymous with the terms parting and separation plane. The term bedding plane should be restricted to features of depositional origin and any secondary development of such features by weathering, and so forth.

<u>Thickness Terms</u> - Some writers have attempted to standardize or define specific limits for such thickness terms as thick, massive, medium, and thin. Among these are McKee and Weir (1953), Ingram (1954), Gray (1955), Kelly, Silvers, and Caswell (1952). There are considerable differences between the proposed divisions of these workers. Gray (1955) proposed that beds as thin as four inches be called "thick." Ingram (1954) considers beds as thin as twelve inches to be "thickly bedded." McKee and Weir (1953) have included fifty inch beds in the "very thick" category. The "very thick" interval suggested by Ingram begins with beds as thin as forty-two inches. Beds thirty-nine inches and thicker are considered "very thick" by Gray.

Kelly (1956) has observed that the terms thin, medium, and thick, are subjective and relative, relative to one's experience and relative to associated beds. He does not believe that it is advisable or necessary to attach the terms thin, medium, or thick to the thickness categories. He states, "That this subject is of importance to so many geologists and so subjective that no one person should propose a standard. Kelly thinks that it would be more helpful to list the actual thickness ranges in inches and feet.

There seems to be no good reason to standardize these relative terms. A writer could define these terms in a publication as he believes they apply to a specific unit.

If he clearly defines his limits, very little confusion would result. It does seem that greater accuracy would result if the thickness ranges were simply listed in inches and feet.

Massive - Kelly (1956) contributes the following discussion concerning the term massive. "For the purists of English grammar who oppose the use of massive, a bed becomes massive or imposing by its thickness. Most geologists will comment on a big bed in a section and big may mean large or massive at least to a liberalist of English grammar. Massive is also used to mean without internal structure (parting or fissility), as in minerals without fibrous, platy, or cleavable structure, or as- the Bedford shale contains two massive sandstones."

The term massive apparently has two connotations to many geologists, thickness and lack of internal structure or lamination. In this sense a massive layer is thick and has no clearly recognizable internal structure.

McKee and Weir (1953) prefer to use the term massive to describe a splitting property. According to them a massive bed would split into layers greater than four feet thick. Used in this sense, the term connotes thickness only as controlled by splitting properties, with no implications regarding internal features.

The term massive is ambiguous. It might be preferable to eliminate the thickness connotation commonly attributed to the term. The definition would then be restricted to denote a lack of internal structures or layering. An even better suggestion might be to eliminate this term entirely and substitute the term "structureless" which has no thickness implication. The term is so firmly entrenched, however, that its complete eradication would be difficult to accomplish.

Discussion of Terms Which Describe Splitting Properties - McKee and Weir (1953) use the terms "massive," "slabby," "flaggy," "shaly," or "platy," and "papery," in diminishing order, to describe the thickness of units defined by "splitting planes."

The same factors which control splitting properties also control or influence the estimation of thickness. This appears to produce overlap of cause and effect which results in confusion. Splitting properties are apparently controlled by features of depositional origin such as abrupt changes in lithology, texture, erosion surfaces, surfaces of non-deposition, and so on.

The term "splitting" and the concept of "splitting properties" are rather vague and ambiguous. It is not clear whether splitting refers to weathering effects, or to a cleaving which might result from striking the rock with a hammer. There appears to be no good reason to apply such a vague concept as "splitting" to the description of bedding, and it probably should be eliminated.

Terms Which Denote Shape or Configuration - McKee and Weir (1953) suggest the terms "lenticular," "wedge-shaped," "tabular," and "irregular" to describe the shape of stratified units.

Brewer (1928) believes that the term "lenticular," although in common use, is misleading. He states that, "The vertical dimensions of most so called lenticular bodies are so small compared with the horizontal, that they seldom exhibit, in cross section, a true optical lens-like shape, and might be more accurately described as disc shaped."

The term "wedge-shaped" is relatively unambiguous and therefore appears to be quite acceptable.

The term "lenticular" needs further modification. The term implies a shape similar to an optical lens. A lens may have a number of shapes. It may be plano-convex, plano-concave, biconvex, concavo-convex, and so forth.

The term "tabular" is acceptable as it stands. The accuracy, however, could be increased by adding a lateral dimension. Tabular units may be laterally continuous or discontinuous. Some estimate of lateral continuity should modify the term tabular wherever possible.

The term "irregular" also demands further clarification for the sake of accuracy. As used by McKee and Weir (1953), the term is somewhat ambiguous and apparently includes units bounded by surfaces which are not planar or smoothly curving. A wavy or ripple-marked unit is irregular in this sense. Irregular beds may be laterally continuous over long distances or very discontinuous. An irregular bed may have one irregular surface and one planar or gently curving surface. Where the exposure permits, some measurement or estimation of the continuity should be included in the description. A description of the nature of the irregularity would also improve the accuracy. For instance, the irregularity may be wavy, ripple-marked, pitted, grooved, channeled, crinkly, crumpled, convolute, and so forth. Some pattern of symmetry may be apparent, as if one were viewing a cross section through mud cracks, and so forth.

Internal Features of Stratification - The internal features of the stratified unit should be described. The unit may be structureless, internally layered, or laminated, ripple-marked, cross-bedded, irregular, and so on. If irregular, the nature of the irregularities should be described as suggested above.

Cross-Stratification Terminology - McKee and Weir (1953) have proposed a standard definition of cross-stratification terms and a classification of cross-bedding. Their classification is based on physical characteristics rather than on genesis. Interested readers are referred to the publication of McKee and Weir (1953, p. 382-389).

DEFINITIONS OF TERMS USED IN THIS PAPER

Bedding or Separation Plane - This is a plane or surface that separates beds, strata, or laminae into units of determinable thickness. The separation may be a physical break which resembles a joint plane on a weathered surface. The break may be produced by a sharp textural change, a lithologic or compositional change, or a sharp change in color, not involving a physical break. Bedding or separation planes of the physical break variety usually are produced by the secondary development of a primary feature. Differential resistance to weathering, selective removal of cement, orientation of platy minerals, clays, and so forth, are examples of this secondary effect.

Bedding planes influence our interpretation of stratification features. It is important to describe the nature of the bedding planes (physical break, non-physical, and so forth) in any description of stratification.

Bed or Stratum - A bed or stratum is a sedimentary unit separated above and below by a bedding plane. Depending on the nature of the bedding planes, the beds or strata may consist of the same lithology, different lithologies, or different composition. The sedimentary units may be defined by sharp textural changes, color changes, and so forth. A bed or stratum must be one centimeter or greater in thickness.

<u>Lamination or Lamina</u> - A lamination is a sedimentary unit less than one centimeter thick. With the exception of this thickness connotation, the term lamination is synonymous with bed or stratum.

<u>Internal Bedding or Stratification</u> - Lamination or layers within a bed or stratum which are not defined by bedding or separation planes may be called internal bedding. This is especially applicable in describing bedding where the units are separated by bedding planes of the physical break variety. This allows a distinction to be made between units or beds defined by physical breaks and the smaller layered units that may occur within them. These internally layered units may be called stratum layers, internal layers, or internal laminations.

<u>Thickness Terms</u> - Recognizing that these terms are relative, they are used only in the relative sense. The thickness of beds should be listed in feet and inches rather than assign artificial limits to the terms thick, medium, and thin. It is considered neither useful nor practical to ascribe specific limits to relative terms.

<u>Structureless (Massive)</u> - It is considered desirable to replace the term "massive" with "structureless." The term structureless denotes a lack of internal structure or layering and carries no thickness connotation. The writer's experience has shown that many thick, apparently structureless beds actually have internal features which

are recognizable only by careful examination. Internal features can be masked by sorting, cementation, etc.

COMMENTS ON BEDDING DESCRIPTIONS

DISCUSSION OF FACTORS WHICH INFLUENCE THICKNESS DETERMINATIONS

There is a high degree of unity among most workers in defining stratum or bed. In spite of this clear definition, difficulties often arise when one attempts to describe the thickness of such units. When interbedded lithologies or sharp texture changes are involved there is no difficulty in describing thickness. When one deals with subtle gradations and sequences consisting of a single lithology, however, thickness may be more difficult to estimate. There is need for a clear analysis of the factors which influence determination of thickness.

This type of analysis might remove much of the existing terminology confusion and bring about clearly defined and significant descriptions of stratification phenomena. Such a discussion should be included in any description of bedding. The goal of such a procedure is to answer the question, "What influences my thickness estimation in this particular case?" The answer may vary with lithology and is commonly related to genesis.

The interpretation of bedding is rather subjective. In descriptions of stratification, some workers have been influenced by bedding planes of the physical separation variety and many have ignored textural or color changes.

Others may be more strongly influenced by texture, composition, and so forth.

Few if any workers have ever clearly described the factors upon which their determinations of thickness are based. This is unfortunate because two persons might submit different descriptions of the same exposure. Unless a photograph were included, a reader might have difficulty rendering an accurate environmental interpretation from these descriptions. If each person would clearly discuss the factors which influenced his selection of thickness intervals along with the other features which he considered less obvious, then both descriptions would lead a reader to the same interpretation.

The factors which bias interpretations may vary from exposure to exposure even within the same stratigraphic unit. It is important to know whether estimates of thickness are based on physical separations, color changes, texture changes, and so forth.

A review of factors which commonly influence the interpretation and description of bedding follows. This is largely based on field observations made during the present study. The factors vary with lithology and so sandstones, shales, and carbonates are discussed separately.

Sandstones

In weathered exposures of sandstones, interpretations of thickness and other stratification features are commonly related to leaching of cement which in turn is controlled by texture, a primary feature (Figure 4). Textural changes may influence thickness estimation and interpretation of other features even where cement has not been selectively removed. Other lithologies interbedded with sandstones present units which offer varying resistance to weathering and this results in obvious physical breaks. This permits easy thickness determinations. Great care must be exercised when describing stratification in sandstones. Beds may appear thick and structureless because cement has not been selectively leached to reveal or accentuate features which may be present, such as internal layering, cross-bedding, and so forth (Figure 1). Close examination often reveals such features manifest by subtle texture and color changes. Red colored, oxidized zones or bands, possibly related to ground water action, may cut across bedding features and produce a pseudo-stratification which is not related to the true bedding.

Carbonate Rocks

Estimates of thickness from weathered carbonate exposures is usually controlled by physical separations. These breaks often resemble a horizontal joint. In most cases a thinner, less resistant shale layer is removed by weathering to produce a physical break between carbonate units (Figure 3). The differential resistance to weathering may also be related to the percentage of argillaceous

Figure 1. Thinly laminated sandstone which appears as one thick sand unit because of cementation. St. Peter sandstone (Ordovician) near New Glarus, Wisconsin. This unit appears thick and structureless from a distance.

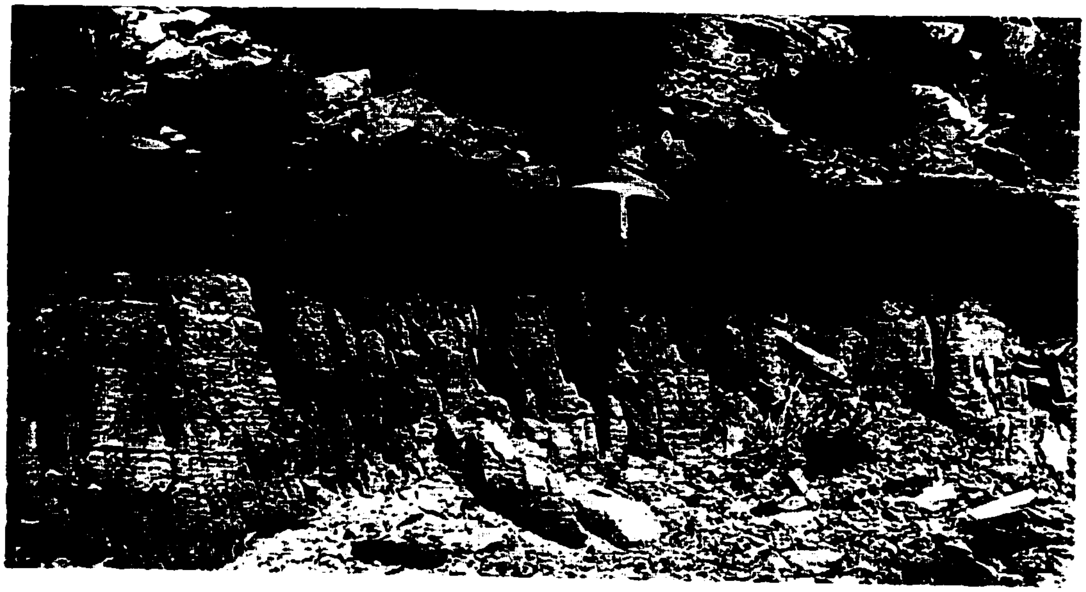

Figure 2. Thickness estimation in this carbonate unit is influenced by a sharp color change. Simonson formation (Devonian) of the Pahranagat Range in Nevada.

Figure 3. Limestone beds separated by bedding planes of the physical break variety. This separation results from the selective removal of thin, less resistant shale partings. Kankakee formation (Silurian) in Romeo quarry near Joliet, Illinois.

material or percentage of dolomite vs. calcite.

In limestone-dolomite sequences, the dolomite layers commonly weather to a buff color due to oxidation of the ferrous iron that is characteristic of dolomites. The limestones generally retain their gray or black coloration. In such cases thickness determinations are influenced by color changes which, in turn, are related to compositional changes. No physical separation may be involved.

Textural changes may influence interpretation of stratification in carbonates. These may be secondary recrystallization phenomena. If so, it is still possible that this is related to a depositional feature.

Interpretation of carbonates may also be influenced by sharp variation in color or shade of color (generally grays) which is related to organic content, sulphides, and so forth (Figure 3).

Where carbonates are interbedded with other lithologies, determination of thickness presents no problems.

Shales

Physical separations, produced by differential resistance to erosion, commonly control determinations of thickness in weathered shale exposures. The variation in resistance to weathering is commonly related to the percentage and distribution of carbonate and organic matter, or the amount of compaction. Orientation of platy minerals may be related to deposition. Compaction may reorient platy minerals and clay minerals parallel to surfaces of deposition. This may produce a separation when the material is weathered. Percentage of organic matter and carbonate, type of clay mineral, oxidation, and so forth, may simply cause color changes in layers which influence the consideration of thickness (Figures 5 and 6). In shale sequences textural changes apparently exert little, if any, control on thickness. Where shales are interbedded with other lithologies no difficulty arises.

Ingram (1953) has discussed the role of cement in producing "flaky-fissile" and "flaggy-fissile" shales. Thicker, structureless shale units may be related to a random orientation of the clay minerals which crystallize from a gel. Intense weathering may produce thick, structureless clay-shales because of disruption of the orientation pattern of the clay minerals (Ingram, 1953).

Figure 4. Beach laminations accentuated by selective removal of cement. La Motte sandstone (Cambrian) one and one half miles north of Mine La Motte, Missouri, on Highway 67.

Figure 5. Bedding in this shale unit is caused by color changes and slightly varying resistance to weathering which may be related to cementation, compaction, and so on. Green River formation (Eocene) near Duchesne, Utah.

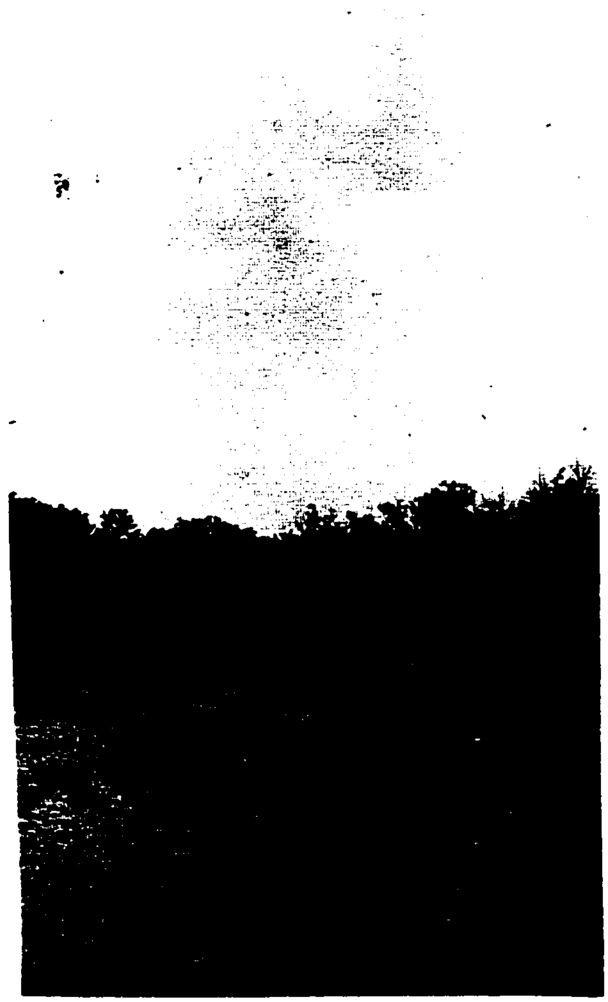

Figure 6. Bedding in this shale is also related to slight color changes and differential weathering. Navarro formation (Cretaceous) exposed at Onion Creek near Austin, Texas.

EXAMPLES OF BEDDING DESCRIPTIONS

A carbonate exposure may be stratified in the following manner. Carbonate units varying in thickness from four to six feet are separated by shale laminae or partings less than one-eighth of an inch thick. On the weathered surface material from these less resistant shale layers has been selectively removed. The four to six foot thick carbonate units, however, contain alternating light and dark layers which range in thickness from six inches to one foot. These layers are not physically separated.

One person might describe the bedding as consisting of carbonate beds which range in thickness from four to six feet. If he did so, he was obviously influenced by the shale breaks. He might not even have included the thinner light and dark layers in his description.

Another person might say that the same sequence consists of beds which range from six inches to one foot in thickness. He would have been influenced by the light and dark layers only, or by both these and the shale breaks.

If the first observer had carefully analyzed the factors that controlled his determinations, his description would have been more meaningful. From his point of view (influenced more strongly by the shale breaks), the following description should have been made. "Carbonate beds, four to six feet thick, are separated by shale partings. These carbonate beds contain dark and light internal layers which range from six inches to one foot thick." If the second person had carefully analyzed the factors which led to his interpretation, he would have rendered the following description of the same sequence. "Carbonate beds consisting of six inch to one foot thick light and dark layers are interrupted at four to six foot intervals by physical separations resulting from shale breaks." Each person was influenced more strongly by different factors and this resulted in two somewhat different descriptions of the same exposure. Both descriptions would, however, lead a reader to the same interpretation.

SUMMARY OF PREVIOUS WORK

This is an abbreviated report on the present status of knowledge concerning the origin and development of stratification in the various dominantly water lain deposits which have been studied in some detail.

Summary of E. D. McKee's Work

McKee has contributed much significant information concerning stratification features that characterize certain modern, accessible deposits. He has described primary structures that are diagnostic of modern beaches, tidal flats, dunes, alluvial fans, and lagoons. McKee also has contributed to the terminology of stratification. McKee and Weir (1953) have published a classification of stratification and a standard terminology.

Summary of McKee's Description of Primary Structures in Modern Beaches

McKee (1957) has examined beach structures on recent beaches on the coasts of Texas, California, and Mexico. He has found that the stratification and structures are similar to those which Thompson (1937) has recorded from his study of beaches near Balboa, California. McKee examined deposits of upper foreshore, and backshore beaches. Upper foreshore deposits were found to consist of flat laminae, sets of which dip toward the sea with relatively low angles of slightly varying degree. These seaward dips range from 5-12 degrees. Dips which exceed 6 degrees, however, are very rare. Backshore deposits studied by McKee are characterized by flat, even laminae of gentle landward dip and by irregular bedding, filled channels, and intraformational conglomerates. Minor structures occurring on beaches include cusps, rill marks, swash marks, and ripple marks.

Summary of McKee's Description of Lagoon Deposits

McKee states that stratification in lagoonal deposits may be expected to consist dominantly of horizontal beds and laminae, since most of the sediments are accumulated under conditions of quiet water. He considers that currents and wave activity are relatively unimportant in most lagoons. McKee believes that in the interpretation of ancient rocks of lagoonal environment, recognition must be based more on composition and texture than on any distinctive type of structure. He points out that the relationship of the lagoonal deposits to those of adjacent environments, especially of barriers--most of which do have characteristic structures--is of major importance.

Lagoons at Corpus Christi, Texas, and Sonora, Mexico, were observed by McKee. The deposits which were examined exhibited weakly defined, horizontal beds, in some cases, and non-stratified or structureless clays and muds, in other cases. Local features and structures included ripple marks, mud cracks, clay balls, and organic trails and burrows. McKee points out that no detailed, comprehensive study of primary structures in the lagoons of the Texas coast has been attempted. Apparently the same thing can be said for lagoons in other areas. If such studies have been made, they have not been published in widely circulated publications.

Summary of McKee's Description of a Recent Tidal Flat (1957)

McKee examined a tidal flat on the Sonoran coast of Mexico to obtain data on the character of the stratification and primary structures. The stratification, exposed in test pits, appeared as crude layers and lenses which were essentially horizontal and non-persistent. Ripple marks of the parallel and cusp types were the most conspicuous and characteristic primary structures which McKee observed. Other primary structures present were curving trails of animals and drag marks where kelp and other material was washed back and forth. Miniature deltas occur where water drains off the flats into the channels.

McKee has also examined primary structures in dunes and alluvial fans. Because continental sedimentary structures, such as dunes and fans, are beyond the scope of this study, descriptions of these deposits are not summarized.

Summary of W. O. Thompson's Work

W. O. Thompson (1937) has described the bedding and original structures of modern beaches, bars, and dunes. Thompson (1949 and 1959) has compared the features and structures from parts of the Lyons formation in Colorado with those of recent beaches on the California coast. He has also studied the rate of accumulation of laminae on a California beach (1937).

Summary of Thompson's Description of Stratification and Structures in Upper Foreshore Beach Deposits of the California Coast (1937)

Thompson defines the upper foreshore as that part of the foreshore extending seaward from the crest of the beach to the zone of permanent saturation. Upper foreshore deposits are commonly laminated. "Some laminae are dominated by light minerals of moderately low specific gravity, such as quartz and feldspar, whereas others are dominated by dark colored heavy minerals, such as magnetite and hornblende." The laminae occur in sheaves or sets which dip gently seaward at slightly varying angles when viewed in cross sections perpendicular to the shoreline. These structures appear as cross-laminated zones. Such zones vary from a few feet long and a few inches thick to 150-200 feet long and 8-10 feet thick. In cross sections parallel to the shore, individual laminae may be traced as far as 100 feet. In sections normal to the shoreline, laminae can rarely be traced over 25 feet. Thompson discusses the processes which produce these structures in detail (1937, p. 733).

Cusped beaches and their intervening scoop-like embayments reveal a more complex structure than the approximately plane surfaces of uncusped beaches. Occasional storms destroy the cusps leaving the beach a smooth surface that slopes gently seaward. The position of axes of cusps and embayments that redevelop after storm erosion usually does not conform to that of the former ones. Thus, laminae of new embayments rest unconformably on laminae of remnants of old embayments. This results in a cross-laminated structure when viewed in cross sections parallel to the shoreline.

Thompson describes other structures occurring on upper foreshore beaches, such as buried wave-cut scarps; buried channels which extend perpendicular to the shore; unlaminated interjacent lenses of sand; backwash marks, which resemble ganoid scales of fish; swirl structures; and ripple marks.

<u>Summary of Thompson's Description of Cross Lamination in Lower Foreshore Beaches</u>

Thompson defines the lower foreshore beach as that part of the beach that is permanently saturated with water. It occupies the zone along the shore between the seaward edge of the upper foreshore and the minimum low-tide shoreline. The lower foreshore structures could not be observed in cross section because the saturation of the sand does not permit excavation. He has, therefore, drawn inferences as to the structure of lower foreshore deposits from his knowledge of surface forms and the processes which produced them. The surface features, such as tidal pools, flat topped bars, and so forth, are described in detail along with the processes which form them (1937, p. 738-739). Thompson (1937, p. 739) draws the following inferences as to the probable structures of lower foreshore beaches. "Deposits on the lower foreshore are intricately cross laminated. Discontinuous, nearly horizontal layers of short, sandy, foreset laminae are interstratified with evenly laminated layers of fine micaceous sand, which conform to irregularly shaped depressions. The short foreset laminae dip in all directions with an angle of dip that approaches 30 degrees. There is no correspondence in direction of dip between the nearly horizontal micaceous laminae and the foreset laminae. The size of these structures is much smaller than that of structures of the upper foreshore beach."

Summary of Thompson's Description of Structures in Offshore Bars, Bars and Spits (1937)

Because the seaward side of an offshore bar is the functional equivalent of a beach, its structures should correspond to those of a beach. Thompson's investigations of bars and spits in California indicate that the structure of the seaward side of a marine bar, or of a spit, is the same as that of a foreshore beach. "The structure of the bayward side of an offshore bar, bar, or spit, which resembles that of a backshore beach, consists of layers of short steeply inclined foreset laminae dipping bayward, interstratified with layers of long, gently inclined topset laminae, which also dip bayward." "Because the crest of a marine bar or spit migrates either landward or seaward, the crests of superjacent, normally partly truncated anticlines of deposition, which characterize the structure of a spit or bar, are staggered unevenly in vertical section." "The seaward limb, composed of gently dipping, seawardly inclined, cross-laminated laminae, is opposed by the somewhat steeper, bayward limb of the baywardly inclined, topset laminae, which limit layers of interstratified, short, steeply dipping, foreset laminae."

Thompson thinks that, "It is probably impossible to distinguish between littoral sandy deposits formed as bars or spits, especially after each has become a part of the stratified marine record, because the structures of each and the processes forming these structures, are almost alike."

Summary of W. Hantzschel's Description of the Stratification, Features, and Processes That Characterize a Recent Tidal Flat Deposit of the North Sea (1955)

Hantzschel (1955) has examined tidal flat deposits at Wilhelmshaven, Germany. "The deposits are stratified in fine laminae." "This delicate bedding is caused by the interlamination of thin layers of fine sandy material in the more argillaceous basic substance." Hantzschel has shown that the bedding is rarely strictly parallel. It is generally streaky and lenticular. The alternating sand and clay layers wedge out in short distances and their thicknesses are not uniform. Hantzschel thinks that this type of bedding indicates frequent reworking of the sediments under the influence of currents of varying strength and direction, which are caused not only by tides but also by meteorological factors, especially the wind. Cross bedding is widely distributed in tidal areas and is also an indicator of rapidly changing currents and agitated waters.

Observations in tidal flat areas have shown that reworking and restratification of the sediments proceed so rapidly that burrowing animals have no time to destroy the existing and newly forming bedding. Hantzschel has found that in some places blocks consisting of several laminations are found transported as a unit and deposited in alien surroundings. The mud, when partially dried, may form flakes or pebbles that may be transported by currents into other places such as sand areas. Such deposits are flat pebble conglomerates. Hantzschel also discusses the origin of the material deposited on the flats and the conditions under which the material is deposited.

Summary of W. H. Bucher's Analysis of Work Done at The Institute for Study of Modern Sediments (1938)

Bucher (1938) has summarized work done by several workers on tidal flat deposits. The work was done at the Institute, Senchenberg-am-Meer, on the shore of the North Sea at Wilhelmshaven. He discusses the formation of flat-pebble or intra-formational conglomerates. Lateral erosion along some of the tidal channels commonly uncovers older beds which break away in more or less angular pieces of unconsolidated sediment. These are rather perfect modern models of intraformational conglomerates, some as typical flat-pebble conglomerates, and others consisting of well rounded pebbles.

Ripple marks which occur on the tidal flat surfaces are also briefly discussed (p. 735-736). Oscillation ripples with broadly rounded crests are commonly found. Where a thin film of water remains covering the ripples, the surface drift caused by wind may change them into irregular lines of rounded flat-topped blobs. These have a morphology similar to that of tar creeping on a sloping surface. Rhomboid ripples and giant ripples ("meta-ripples" or "para-ripples") are also described.

Ice crystals, mud cracks, honeycombed patterns of wave foam, and swish marks are characteristic inorganic markings on the surfaces of tidal flats.

Thin, angular patches of clay-silt, and clay galls are commonly deposited onto sand along the beach. These result from contemporaneous erosion of older layers of tidal flat deposits. Bucher also describes paper-like "skins" which form when films of diatoms dry and are rolled into oblong bodies several inches long. These pile up on occasions in large numbers in wave-born shore drift. Fossil occurrences of these could be mistaken for remains of larger organisms.

Summary of R. N. Ginsburg's Work

Ginsburg (1957) has described surface features that occur on interior mud flats of certain Florida Keys. Ginsburg has shown that sun dried, semi-lithified carbonate mud is sufficiently resistant to wave action that it can be rounded into boulders, cobbles, and pebbles. The surfaces of the mud flats are commonly covered by a thin rubbery mat composed of algae, and the underlying sediments consist of alternating algal and sediment laminae of varying thickness. These laminated structures provide planes along which the sediments may separate into desiccation units. These usually develop in the form of discrete polygons.. "When the surface algal mat is thick or the topmost laminae contain very little sediment, intense desiccation tends to separate the top fraction of an inch into discrete, sheetlike units up to a few feet in diameter." With further drying these sheets of algae are folded and crenulated, until finally highly contorted discrete units only a fraction of the size of the original sheets are formed.

Ginsburg (1953) describes examples of beach rock that forms in the intertidal zone. The rock is composed of thin beds of calcarenaceous sediment that dip seaward at less than 10 degrees.

Summary of W. A. Johnston's Investigation of the Fraser River Delta

Johnston (1922) analyzed stratification of sediment in the Fraser River Delta from sectioned cores. Stratification in the top-set beds differed in different parts of the vertical section. Below mean low-tide level the top-set beds are composed of sand. These are for the most part horizontally bedded, but in places are cross-bedded and current ripple marked. "In places there are thick and thin lenses or beds of silt and clay which show no definite lamination." Bedding in the sandy beds is accentuated in places by thin partings of silt and clay.

"Stratification of the beds in the intertidal zone is marked, the characteristic feature being a very thin tidal lamination." These tidal laminae average 15 or 20 to the inch. Johnston also recognizes what he terms "seasonal layers" composed of darker sandy and lighter silty layers. He believes that the seasonal character of these beds is indicated in places by layers of vegetable matter. It is also indicated in another way by the different character of the laminae formed during the freshet stage of the river (silt), from those formed during the low water stage (sand). These "seasonal layers" average 5 or 6 to the foot.

"The foreset beds are composed of a mixture of fine sand, silt, and clay. They are, for the most part, thinly laminated." "In places the lamination is even, in other places it is markedly irregular, and cross-bedding as well as inclined bedding occurs." Johnston attributes the production of this bedding to the combined effects of flocculation in sea water, river and tidal currents, and slack water.

A marked feature of the bottom samples from the fine-grained bottom-set beds is the absence of any trace of lamination, either in the beds composed of silt with a mixture of very fine sand, or in beds composed largely of clay. He attributes this lack of lamination to the effects of flocculation in sea water, which causes the fine silt and clay particles in suspension to settle to the bottom together when flocculation takes place as a result of the mixing of the two waters. Thus, in the case of fine-grained materials deposited in sea water, there is a lack of sorting and lamination. Johnston concludes that such beds are thick and massive.

Johnston compares the bedding in the topset, bottomset, and foreset deposits of the Fraser Delta with that in a fresh water lake farther up the river which is effected by tides. He has found that the character of the stratification of the deposits formed in the tidal fresh water lake differs in several ways from that of the deposits formed in salt water. Laminae are shown to some extent in all samples from the lake. They are much finer than those formed in the salt water delta. In places they number as many as 100 to the inch. The bedding in the foreset beds is much more even than that of the foreset beds of the Fraser Delta. Apparently, this results from the absence of tidal currents along the front of the delta. A sample from the bottomset deposits of the lake is composed of silt and clay. It differs markedly in the character of its stratification from the fine-grained samples from the bottomset beds of the Fraser River Delta in that it is thinly and gradationally laminated. Such lamination probably results from the absence of flocculation of the fine material in suspension in the fresh water. This permits the silt and clay to settle to the bottom at different rates.

Summary of D. G. Moore and P. C. Scruton's Work on Internal Structures

Moore and Scruton (1957) have described the nature and distribution of certain minor internal structures of recent unconsolidated sediments in the Gulf of Mexico. The study included both nearshore and offshore areas. The information was largely obtained from cores. Moore and Scruton have attempted to relate the observed features to fundamental, environmental factors.

Moore and Scruton have subdivided the structures into four basic types depending on their appearance on the flat surface of a cut or of a longitudinally sectioned core. The four basic types are: (1) regular layers, (2) irregular layers, (3) mottles, and (4) homogeneous sediments.

"Regular layers have relatively uniform thickness in core section, and adjacent layers or sets of layers usually are nearly parallel. The layers are horizontal or inclined, and may be slightly curved. Thicknesses of individual layers generally range from a fraction of a millimeter to about 10 centimeters, and the thinnest ones usually lens or pinch out in core section. Regular layers may be relatively homogeneous in texture, but many coarse-grained layers, particularly the thicker ones, are thinly laminated or cross-laminated internally. Regular layers, in general, present a neat, orderly, parallel or sub-parallel appearance, regardless of their thickness."

Irregular layers present a disorganized appearance, in contrast to regular layers. "Thickness of irregular-layered structures is markedly non-uniform in core section, and individual layers or sets of layers may have little parallelism." They usually appear jumbled and disorderly, but they have distinct elongation in a horizontal plane. "They are equally irregular in three dimensions, but are crudely lenticular or tabular. Irregular layers usually are about 1/2-3 cm. thick; they have less range of thickness than regular layers, rarely are either very thin or very thick, and commonly wedge or lens out in core section." Normally irregular layers are relatively coarse in a finer matrix, but they may be fine in a coarser matrix. They seldom have internal laminations.

"Mottled structures, or mottles, consist of peculiar, irregularly shaped lumps, lenses, pockets, tubes, or pods of sediment randomly enclosed in a matrix of contrasting texture. Color contrast alone, by this terminology, does not constitute a mottled structure. Distributions of these bodies, as well as their shapes, are highly irregular, thereby imparting a mottled appearance to core sections." "Textures of individual structures range from clean sand in a fine matrix to poorly sorted sand in a matrix of silty clayey sand and from clay in a clean sand to sandy clay in poorly sorted sand." "There is no tendency toward horizontal alignment of typical mottles." In fact, ordinarily there appears to be a preferred vertical orientation. "Mottled structures become indistinguishable from irregular layers where there is some horizontal alignment and an increase in regularity." "Two types of mottled structures have been recognized: (a) those with distinct boundaries, and (b) those with indistinct boundaries." This difference is based on the amount of textural gradation between lumps and matrix. "There is no precise division between these types, and in places they constitute a continuous series. Sediments with indistinct mottling in turn grade into homogeneous sediments with further decrease in sharpness of contact and textural contrast between lumps and matrix."

"Homogeneous sediments have no visible internal structures. These sediments are massive, and their relatively uniform texture may be fine-grained, coarse-grained, or any intermediate texture."

Duplicate and multiple cores were taken within small areas to determine the amount of lateral continuity in layered structures. "It has been found that regular-layered structures may extend laterally for several feet, irregular layers generally are of small lateral extent (a few inches at most), and mottles have essentially no lateral continuity. Groups of these structures form zones which are traceable much farther than individual structures."

The distribution of these minor structures was investigated in the Mississippi Delta area and Texas coastal areas. "Different areas of the sea and sound floors were found to contain different minor sedimentary structures." These structures were found to be arranged in an order that was persistent within each study area and also between study areas where comparison was possible. A definite succession of sedimentary structures was observed in a northerly direction from the Cubits Gap distributary system of the delta. In shallow water around the delta there is a zone of complicated regular-layered structures. These become less abundant and more poorly developed seaward in deeper water. "Farther offshore is a belt of irregular-layered structures that grades outward into mottles. These mottled structures in turn become indistinctly mottled farther seaward and grade outward into coarse homogeneous sediments." In a profile eastward from the delta onto the continental shelf, the outward succession consists of a zone of regular-layered structures, a broad area of homogeneous clays, and an irregular layered band. Southward in the deep water of the Gulf only fine-grained homogeneous clays were found.

Seaward from the Texas barrier islands there is a zone of homogeneous sands, followed by a zone of irregular-layered sediments. This irregular zone gradually gives way to a mottled zone. In deeper water farther offshore is an area of fine-grained homogeneous sediments. In the bays of the central Texas coast, the sequence of structures outward from the barrier island shore is similar to that of the open Gulf. Coarse, homogeneous sediments in shallowest water near shore grade outward into irregularly layered and mottled sediments in deeper water. The deepest parts of the bays contain fine-grained homogeneous sediments.

Origin

Minor sedimentary structures may be either primary or secondary in origin. According to Moore and Scruton, "Primary minor structures are formed at the time of initial deposition by variations in amount and kinds of sediments from a single source or by alternating deposition of contrasting sediments from two or more sources." They have found that sediments with primary regular layers and primary homogeneous sediments are common, but primary irregular layers or mottles are apparently uncommon and form only under specialized conditions.

Moore and Scruton define secondary structures "as those which are produced after initial deposition but before the sediment is buried beyond the reach of physical processes active on and just beneath the sea floor." They are formed by partial or complete destruction of previously formed primary features and by resorting or unmixing of homogeneous sediments. Secondary structures of all kinds are commonly found.

Primary Structures

"Primary regular layers in the two areas studied develop principally from fluctuations either in competence of transporting agent or in type of material off one major source of sediment." "Primary regular layers are also produced in environments which have more than one major sediment source." They form as a result of interrupted transportation from these sources.

"Primary irregular layers apparently have much the same origin as do the regular layers, but they apparently form only if the surface of deposition is one of minor irregularities such as one covered with small ripple marks or the tracks of crawling organisms." These primary irregular layers seem to form only in environments which have intermittent periods of deposition. "Intervening periods of non-deposition must be sufficient to allow the bottom surface to be roughened by currents, bottom organisms, or plants, so that the subsequent layer of sediment is discontinuous and irregular."

"Primary mottles may form in environments having one or more major sediment source." Apparently primary origin of mottles is very uncommon. The most common origin of primary mottles is by filling of open animal burrows and borings with contrasting material after a period of non-deposition and reworking. These mottles may also form from mud pebbles or balls dislodged from the banks of stream channels. "Desiccation of layers of mud on tidal flats or natural levees forms mud curls or cylinders, which at higher water may be carried seaward and deposited as chips or rounded pebbles in a sediment of contrasting texture."

"Structureless, homogeneous deposits often are primary." In the areas that they studied, Moore and Scruton have found that they are products either of a very high rate of deposition which reduces the time available for secondary alteration or of a moderate depositional rate where source materials do not vary in texture or composition.

Secondary Structures

Secondary regular layers form chiefly by current action which resuspends and sorts existing deposits. By this means poorly sorted sediments may be unmixed and the different particle sizes separated. Regular layers are vulnerable to destruction and are most likely to be preserved in environments which have rapid deposition or only few bottom living organisms. In the study areas, formation of both irregular layers and mottles was found to be almost entirely the work of bottom living and feeding animals. It has been shown that the numbers of these structures increase directly with the numbers of mud-feeding, crawling, and burrowing animals and inversely with the rate of deposition. "In order to test these field observations, the effects of burrowing organisms on artificial sediments were studied in the laboratory." These observations proved conclusively that irregular layers may result from animal activity. The same process forms most distinct and indistinct mottles, but the disturbing action of the organisms is more nearly complete than in sediments with irregular layers. A regular layered deposit attacked by bottom dwellers can be converted first into irregular layers. With continuing disturbance these are converted into distinct mottles, indistinct mottles, and finally into homogeneous deposits. In contrast, if the deposit is initially homogeneous and contains mixed particle sizes, burrowers can form irregular layers, distinct or indistinct mottles, or complete the cycle to homogeneous deposits. "The extent to which these processes are carried out depends on the numbers of organisms and the rate of deposition in the environment."

Relations of Minor Internal Structures to Sedimentary Environments

Moore and Scruton have isolated three fundamental factors which relate minor internal structures to their environments of formation. These are: (1) sources of sediment, the control of composition, texture, and quantity; (2) processes of primary sedimentation, and secondary alteration of deposits, together with their activities or intensities; and (3) rate of deposition, the time control on all processes of the water sediment interface.

Off the Mississippi River the tremendous volume of sediment introduced and locally distributed illustrates the importance of rate of deposition as a basic factor in environmental control. North of the delta mottled deposits change shoreward into irregular layers as the deposition rate increases near the delta. These grade into regular layered beds or homogeneous beds of mixed sediments in the areas of fast deposition close to shore. This demonstrates the decrease in effect of burrowing organisms with increasing depositional rate. Near those distributary mouths where sediments are deposited faster than 2-3 feet per year, Moore and Scruton have concluded that wave and current effects are negligible, even though the water is shallow and waves and currents are very active. The sediments in these places contain no laminae or other secondary structures, and are essentially homogeneous.

Moore and Scruton believe that their study has shown: (1) that the very existence of minor structures depends on the sediment sources, (2) that the types which form are a function of the processes, and (3) that the extent to which they develop is determined largely by depositional rate and process intensity. They think that similar sequences of ancient structures may reflect similar environmental changes.

Minor Structures in Ancient Rocks

Moore and Scruton point out that regular-layered structures (layers, laminae, corss-lamination, and so forth) and homogeneous (massive) beds are very commonly mentioned in descriptions of sedimentary rocks. They conclude that mottles and irregular layers also have been described or figured from many different rocks but under a variety of names.

The authors believe that minor structures in ancient rocks can be studied particularly well in thin section.

Summary of J. L. Rich's Work on Three Critical Environments of Deposition, and Criteria for Recognition of Rocks Deposited in Each of Them

Rich (1951) was one of the first workers to consider stratification seaward from the shore zone. In a monumental paper Rich described stratification and textures which he has inferred to be characteristic of three critical environments, the undathem, clinothem, and fondothem. These correspond to the shelf, slope, and basin, respectively.

Processes at Work in the Unda, Clino, and Fondo Environments

Unda Environment

The dominant process of the unda environment is repeated agitation of the water by waves and currents. Wave action frequently suspends the finer material. "Currents then readily remove it, and ultimately most of it is carried out to settle permanently in deep water. This gradual elimination of the finer particles causes a concentration of the coarser particles of the sediment load on the floor of the undathem." "Tidal currents on an undaform facing an open ocean must be important agents in redistributing the coarser material and in working it out toward the edge into deeper water." "Undertow produced by on-shore winds also tends to move material toward the outer edge of the undaform." Any major ocean current which happened to flow over the undaform would aid in moving material temporarily suspended by the waves, even if it were not strong enough to lift material off the bottom.

"Exceptions to the prevailing coarseness of unda sediments occur where subsidence is relatively rapid in regions near the mouths of large rivers bringing in great quantities of sand, clay, and silt. Under these conditions the time available for reworking by waves on the undaform may not be great enough to permit the winnowing out and removal of all the fine material."

"On a stable, maturely graded undaform, little permanent deposition would occur, and the supply of sediment would be used mainly in building forward the undaform and clinoform units." "On a sinking undaform, subsiding slowly enough so that the sediment supplied always kept the surface of the undaform within the range of wave action, great thicknesses of sediment could accumulate, all having unda characteristics."

"If sinking is more rapid than grading of the undaform to its profile of equilibrium, and if only a slight difference in depth exists between the surface of the undaform and that of the fondoform, a peculiar interbedding of unda and fondo sediments, such as is found in the Cincinnatian rocks of the Cincinnati region, might develop."

Clino Environment

The clino environment comprises the slope from wave base down to the floor of the water body. "The most distinctive features of the clino environment are the inclination of the surface of the clinoform and the freedom from wave-caused disturbances of the water. Secondary features are prevailing muddiness, great and oft-repeated variations in sediment supply, deposition dominantly from suspension, density currents periodically flowing down the slope, and gravity sliding and/or intra or interstratal flowage." "Preponderance of coarse sediment tends to produce steep slopes; preponderance of fine sediment tends to produce gentle slopes."

"Oversteepening of the upper part of the clinoform by the coarse sediment may proceed until imbalance is sufficient to cause the overloaded part to slide bodily down the slope as a subaqueous landslip."

"The actual gradients of clino slopes should vary from that of the subaqueous angle of repose for gravel to those so low that the beds might not readily be recognized as having been laid down in a clino environment, and so low as to preclude even the sliding of soft muds and the intrastratal flowage of silts."

"Material of silt and clay sizes in suspension spreads far before complete settling. It produces very even and uniform bedding. Single beds persist for great distances with little variation in thickness." Because deposition is dominantly from suspension, cross bedding and ripple marks should be uncommon.

"After every great storm a considerable quantity of silt and clay-sized material in suspension is carried off the undaform and settles widely over the clinoform and adjacent fondoform." "As each storm subsides, the finer constituents of the suspended load settle over the first deposited coarser silts. During periods between storms only clay-sized material is laid down. In this way, accumulations are built up consisting of alternating beds of silt and clay or of lime-silt and calcareous ooze."

Fondo Environment

The fondo environment represents the generally flat floor of the water body. "The water is generally quiet, though locally and temporarily it may be moved by general currents and by waning density currents descending from the clinoform." Deposition on the fondoform must be mainly from suspension, but bottom dwelling organisms probably contribute a minor part. "The sediment settling from suspension consists mainly of fine terrigenous material and of the remains of pelagic organisms living mostly in the surface water." "This sediment is rarely, if ever, rearranged or sorted after it once reaches the bottom."

"Remote from the base of the clinoform, thick, massive bedding should be expected because of the uniformity of sediment supply and of depositional conditions. Whatever its thickness, fondo bedding is very even." "Deposition in the fondo environment should ordinarily be slow, and a long time would generally be represented by only a small thickness of sediment."

Criteria for Recognition of Sedimentary Rocks as of Unda, Clino, or Fondo Origin

Rocks of Unda Origin

Rocks formed from sediments which accumulated in an unda environment are generally relatively coarse. The grains range in size from that of gravel through sand to coarse silt. Conglomerate, sandstone, coarse siltstone, fragmental limestone (shell hash), oolite, and coquenite are the dominant rock types.

"Bedding--Moderately thin-bedded with a peculiar type of waviness; cross-bedding; flow and plunge structure; individual beds not persistent, lenticular, and prevailingly cut out within short distances; bedding apparently even when viewed from a distance too great to reveal the small-scale irregularities; ripple marks common and of either oscillation or current type."

Rocks of Clino Origin

Rocks originating in the clino environment generally consist of material fine enough to have been carried in suspension, mainly clay or silt. Silt or siltstone, clay or shale, and their calcareous equivalents are the dominant rock types.

"Bedding--Regular alternations of silt-sized and clay-sized material; bedding relatively thin--siltstones half an inch to 10 inches as a rule, but locally thicker; shales commonly half an inch to several feet; bedding remarkably even and persistent; laminations within the siltstone beds even and regular, without evidence of tractional movement except rarely near the tops of the beds; lack of bedding features produced by waves; general absence of cross-bedding and ripple marks."

Rocks of Fondo Origin

"Texture--Universally fine, except for remains of bottom-dwelling organisms and of pelagic forms; fossil remains generally scattered through the rock without having been sorted by water movement though, as lag concentrates, fossil shells may have been concentrated locally as a result of contemporaneous non-deposition of the finer sediments in which they would normally have been bedded; limestones mainly either fine-textured oozes or lithographic limestone types."

"Composition--Generally clay, shale, or calcareous or siliceous oozes composed of fine detrital lime flour, of precipitated lime, or of foraminiferal, diatomaceous, or radiolarian accumulations, all mixed with clay in various proportions; locally interbedded clay and silt; less commonly, bituminous muds or shales or calcareous organic rocks."

"Bedding--Even, generally tending toward massive; may be even and thin bedded; locally (near the base of the clinothem) interbedding of clays and shales with thin, evenly bedded layers of silt without flutings or striations; bedding commonly inconspicuous, but generally revealed in a large exposure by vague color banding or weathering."

Effects of Changes in Relative Level of Land and Sea: The Building of a Continental Shelf

Rich makes the following inferences concerning the influence of relative sea level changes on the building of a continental shelf. "If we start with a broad continental shelf whose floor is a graded undaform extending all the way out to its edge, a rise in sea level will cause a rise of wave base and will start the grading of a new undaform at a higher level. Meanwhile, on the outer part of the shelf, which will now be below wave base, sediments of fondo type will be deposited over those of the former undaform surface. As the new undaform is built seaward, clino beds, and above them unda beds, will be laid down over the new fondo sediments on the outer part of the shelf."

If these processes were repeated many times while the entire region were sinking slowly, most of the products of these fluctuations would be preserved. A great continental shelf could develop, thousands of feet thick and composed of individual undathems, clinothems, and fondothems of various thicknesses superimposed on each other. The history could be complicated somewhat by beveling of former deposits whenever sea level temporarily dropped especially low.

Paleogeographic Applications

Rich has shown that the foregoing criteria can be successfully applied to the interpretation of the geological history of paleogeography of sedimentary rock sequences. He gives a few examples of such interpretations involving rocks of Devonian and Ordovician ages. He has inferred changes in relative level of land and sea from interbedding of unda, clino, and fondo deposits.

Remarks Concerning Rich's Work

Rich assumed that the entire undathem or shelf surface was within the realm of wave base. This assumption should be seriously questioned and probably is not valid for all undathems or shelves. The same types of stratification that Rich considers to be distinctive of clino and fondo environments could also be found on a shelf or undathem whose entire bottom was not agitated by waves. Rich's framework is based partly on inference and partly on data furnished from recent sediment studies. Most of these data concern processes and depositional conditions that obtain in the oceans off the continental margins. Hence, Rich's framework cannot be indiscriminantly applied to all aqueous or marine bodies that receive sediments. In some aqueous bodies there may be no sharp delineation of shelf, slope, and basin. In some bodies of water there may be no clino or slope development. Apparently Rich's terms are not widely used or accepted.

From this study it has been possible to conceive a different analytical framework that overcomes many of the deficiencies inherent in Rich's treatment. This is discussed in detail in a following chapter.

Summary of W. D. Keller's Work

Keller (1936) discusses clay colloids as a cause of bedding in sedimentary rocks. He relates the development of laminated shales to flocculation of platy aggregates, which were originally organically stabilized colloids. Keller believes that thin, disconnected, patchy, undulatory clay partings and clay films in carbonate rocks may be the result of local flocculation on the sea floor. Keller (1953) speculates that laminations in shale arise from parallel packing of particles favored by clay flocculated into platelets before it settles to the bottom in quiet water. He attributes massiveness to randomly oriented crystals which crystallize from a gel, or to rapid deposition of particles which settle from highly viscuous or muddy water.

Summary of V. C. Kelly's Work

Kelly (1956) gives a review of efforts to standardize bed thickness terms. He seriously questions the advisability of standardizing the meanings of such general terms as bed, stratum, and lamina or such relative terms as thick and thin. Most of the proposed recent divisions are based on metric measurements. Kelly considers it neither practical nor conducive to easy acceptance to set up thickness standards based on the metric system. He does not believe that it is necessary or advisable to attach the terms thin, medium, or thick to the thickness categories. He states that this subject is of importance to so many geologists and so subjective that no one person should propose a standard. He thinks that it would be more helpful simply to list the actual thickness ranges in inches and feet.

Kelly states that some sort of partitioning of bed thicknesses is necessary for quantitative studies of beddedness, but care should be exercised in standardizing units for pigeon-holing of bed thicknesses and assignment of standard values for "laminae," "thin-bedded," and "thick-bedded." Statistical analysis of thickness frequencies and establishment of some type of stratification index for regional studies of source, transportation, and deposition of sediment appears to be desirable, according to Kelly. If such quantitative methods are adopted, he believes that in time, as numerical and frequency-curve data accumulate, some unexpected and useful facts concerning stratification of sedimentary rocks may be revealed.

Kelly believes that quantitative study of stratification may be useful in recognition of certain formations that are lithologically rather similar. "The careful determination of stratification indices for a single formation may enhance facies studies. Stratification facies (phyllofacies) as well as biofacies or lithofacies may exist within a formation."

Summary of J. Bokman's Work

Bokman (1957) has attempted to apply statistical methods to describe thickness and lithologic variation. He suggests describing the stratification in terms of the mean and standard deviation. He believes that these statistics summarize the important properties of the distributions. He outlines a procedure which could be followed for such a treatment based on an example from the Atoka formation.

Summary of R. L. Ingram's Paper Concerning the Fissility of Mudrocks

Ingram (1953) has attempted to determine the origin of fissility and nonfissility in nonlaminated mudrocks. He defines fissile as possessing the property of splitting along approximately parallel planes. Massiveness is defined as nonfissile. Mudrock is defined as a sedimentary rock of which at least 50% is silt and clay, with no connotation as to the relative percentage of silt and clay and as to the breaking characteristics.

Three dominant breaking characteristics were observed: massive, flaggy-fissile, and flaky-fissile. "Massive mudrocks have no preferred direction of cleaving or breaking. Most of the fragments are blocky." "Flaggy shales split into fragments of varying thicknesses but with the width and the length many times greater than the thickness and with the two essentially flat sides approximately parallel. Most of the fragments in the flaggy shales have the length and width at least 50 times greater than the thickness." "Flaky shales split along irregular surfaces parallel to the bedding into uneven flakes, thin chips, and wedgelike fragments, whose length seldom exceeds 3 inches."

"Attempts to correlate color with the type of fissility yielded the following observations: (1) those with a flaggy structure are predominantly black or dark gray, (2) those with a flaky structure are predominantly gray or gray black and, in general, are not so dark as the flaggy ones, (3) those with a massive structure have a predominance of colors other than gray black or black--i.e., gray, white, yellow, and red, (4) some exceptions exist to the above trends, the most notable being the occurrence of predominantly flaggy red mudrocks."

Mechanical analyses were run on fifty samples.

"Each sample was split into four size groups: sand and gravel, silt, coarse clay, and fine clay." "No correlation exists between the results of the mechanical analyses and the type of fissility." This is apparently to be expected because it has been shown that only a small amount of clay is necessary to control the behavior of a sediment.

Fifty samples were analyzed for calcium carbonate content. No correlation exists between the amount of calcium carbonate and the type of fissility.

The organic content of the mudrocks was estimated. "The organic content is high for flaggy shales, moderate for flaky shales, and low for most massive mudrocks."

The clay minerals in the samples were identified by x-ray diffraction methods. It was found that no correlation exists between the presence of amount of any clay mineral and the type of fissility in the 50 samples studied. "The clay minerals identified are distributed among all the types of fissility." Ingram points out that several other workers have expressed the idea that the type of clay mineral determines whether or not a mudrock will be fissile. He does not believe that his studies have eliminated the possibility that clay minerals influence fissility.

Experimental work has shown that, "Gravity settling or evaporation of a dispersed clay results in a parallel arrangement of the flaky clay particles." Experimental evidence shows, "Coagulation of a dispersed clay be the addition of an electrolyte results in the formation of a gel or a gelatinous precipitate with the clay particles coalescing in a random manner. This gives a loose packing and a high porosity." Because of the high porosity of flocculated clays, it is probable that compaction or drying will result in the flaky particles being oriented parallel to the bottom of the container. "Experiments with dispersed clay and organic matter obtained from black shales show that either gravity settling or flocculation gives a parallel orientation of the clay particles." Apparently organic matter increases the tendency for parallel arrangement of the clay particles. "The flaggy shales contain by far the largest amount of organic matter." "Of the mudrocks studied none of the massive ones had even a moderate amount of organic matter." Humus is adsorbed by clay. The resulting cementing action enables the shale to break into large sheets without falling apart, thus developing a flaggy-fissility. "Flocculation of clay and $Fe(OH)_3$ together, and flocculation of clay with powdered Fe_2O_3 all produce a random orientation of the clay particles." The influence of aluminum on the structure of mudrocks was found to be similar to that of iron. "The only difference is that a flocculated $Al(OH)_3$-clay system gave a parallel orientation of the clay." "Flocculation of an Al_2O_3 system gave a random orientation similar to the Fe_2O_3 system."

"The drying of a silica gel in which clay had been dispersed produced a hard, chertlike mass in which much of the clay had been expelled to the bottom where the orientation was parallel to the bottom. Apparently silica gel exerts a force which tends to clear it of impurities as it dries." Powdered amorphous SiO_2 in a clay suspension produces the same random orientation as iron and aluminum oxides.

"Flocculated clays can hold up to 85-90% water by volume. Hedberg's work on the compaction of clay showed that a mechanical rearrangement of the clay particles to a parallel position takes place early during compaction and is usually complete in the top 5-10 cm. of a mud deposit."

Keller has offered a probable explanation of some massive mudstones as originating by the random growth of clay minerals in a gel.

"Weller suggested that repeated stirring of bottom muds by wave action may explain some thick-bedded, structureless mudstones." In Ingram's flocculation experiments, repeated stirrings of the flocculated clays produced no effects on the final structure.

"The weathering of mudrocks determines to a large degree the way a potential fissility will be expressed. In general, weathering of a given shale increases the platiness of fracture fragments." "Mudrocks with a parallel arrangement of the clay particles have a potential fissility which may not be realized until weathering has weakened the cementing materials." "Moderate weathering increases the fissility of a shale by the partial removal of the cementing agents along planes parallel to the bedding or by expansion caused by hydration of the clay particles." Intense weathering produces a soft massive clay because of disruption of the orientation pattern.

Summary of a Study by H. N. Fisk, et al. Concerning the Sedimentary Framework of the Mississippi Delta

Characteristics of sedimentary facies in the several main depositional environments of the Mississippi Delta were studied. These characteristics were determined from grain-size analyses, from examination of bedding and other structures seen in cores, and from identification of associated fauna. Examples taken from the bedding descriptions follow.

Bar Facies (p. 86)

"Sands of the bar facies are massive and locally cross-bedded near the top of the section. At depth they consist of alternate thin layers of very fine silty clay with occasional dark organic rich laminae."

Pro Delta Facies (p. 86-87)

"The silty clay deposits of the inner zone are dark colored and well-bedded. In the section which is transitional to the bar sands, layers of sandy silt and silty clays alternate."

"The clays of the outer zone are homogeneous and well-bedded."

In Fisk's study of the Mississippi Delta, grain size and faunal analyses have been emphasized. The bedding is described in rather vague, generalized terms. The descriptions are not sufficiently accurate to warrant further comment in this summary.

Other Contributions

The environment of the turbidity current has attracted a large number of workers. The popularization of the turbidity current mechanism by Kuenen and Migliorini has perhaps been largely responsible for this. Concentrated effort has led to the publishing of many thorough, detailed studies of graded bedding and the other numerous sedimentary structures that characterize slope deposition. Experimental work has increased our understanding of the environmental factors and processes that produce the structures that are found in these deposits. Kuenen, Rich, Heezen, Migliorini, Carozzi, Menard, Emery, Walton, Kelling, Prentice, Cummings, and others have made significant contributions to this body of knowledge. Because of the vast amount of work that has already been done on this subject, turbidity current environments are not included in this dissertation.

In addition to McKee, Kelly, and Ingram, Gray, Payne, Twenhofel, Shrock, Otto, and others have published opinions and discussions concerning the terminology of stratification.

Stratification in Continental Environments

Stratification in continental environments, of course, has some bearing on the study of bedding in marine deposits, but an analysis of bedding in continental sediments is beyond the scope of this dissertation. To date, however, no detailed, comprehensive study has been undertaken with the goal of establishing principles and criteria for recognition of continental deposits and of distinguishing between these and marine deposits. Various writers have published descriptions of the stratification and structures in certain continental deposits, and brief reference is therefore made to work which has been done.

McKee, Reiche, Kiersch, Knight, Shotton, and others have described the stratification and structures which are developed in recent sand dunes. Recent dunes have been compared with dunes which have been preserved in ancient lithified rocks. The structures and bedding that develop in dunes are well understood and need no further comment.

McKee, Knight, Siever, Potter, Brett, Schwarzacher, and many others have studied fluvial cross-bedding both experimentally and in the field. This has increased the knowledge of processes which have produced certain types of cross-bedding.

Siever and Potter (1958) have used cross-bedding trends measured from surface exposures to predict the trends of subsurface sand bodies.

Pelletier (1958) and others have utilized textural gradients, cross-bedding directions, and other directional features to delineate ancient sedimentary bodies and to reconstruct paleogeography.

Bradley (1929 and 1931) has studied in detail the bedding and features of the Eocene Green River lake deposits, and Picard (1957) has outlined criteria used for distinguishing lacustrine and fluvial sediments in Tertiary beds of the Uinta Basin.

McKee (1939) has described structures and bedding in fluvial deposits of the subaerial portion of the Colorado River Delta, and McKee, Blissenbach, and Eckis have listed features that characterize alluvial fan deposits and the formative processes.

Opdyke, Runcorn, and others have used sand dune deposits in ancient rocks to determine the prevailing wind directions.

DISCUSSION OF PREVIOUS WORK

Rich (1951) states that, "Most geologists have tended to overlook the fact that rocks formed in each environment must retain features of composition and bedding so distinctive that when the criteria are adequately worked out it should be possible to examine any sedimentary rock and determine with a high degree of certainty in which environment it was deposited." Although it seems that considerable work has been done with bedding, criteria have not been sufficiently developed to the point where one can examine <u>any</u> sedimentary rock exposure and determine its depositional environment with a high degree of certainty.

Tidal flats, beaches, reefs, and turbidity current deposits have been studied by many workers in widely scattered areas. Detailed work in many areas has shown that the stratification and structures that develop in these environments are constant regardless of textural and lithologic differences in various areas. This is because the processes that produce them are so similar. Rocks deposited in these environments have features which are so distinctive that they can be recognized very easily. Knowledge of stratification and structures in other marine environments has not reached this level of application.

Stratification that develops in lagoons has not been sufficiently studied. Recognition of lagoonal deposits depends upon the inferred presence of a barrier reef or bar.

Processes that characterize delta environments are well understood. Stratification in subaqueous delta deposits, however, has been studied only from core samples of recent deltas. Such studies leave much to be desired and do not form a firm enough foundation for the development of adequate criteria. With the existing state of knowledge, it is dubious that deltaic deposits in ancient rocks could be recognized from the bedding and structures.

Except for turbidity current deposits, Rich's work represents the only attempt to infer stratification in offshore deposits of ancient rocks and to relate its development to formative processes. It has been pointed out above that Rich's criteria cannot be indiscriminately applied.

Moore and Scruton's study represents a significant investigation of features forming in offshore environments. Their analysis of bedding, however, is based on bore sample study and is, therefore, inadequate for the development of applicable criteria. Bedding is not as well developed in recent unconsolidated sediments as it is in ancient lithified rocks.

The relation of bedding thickness and other features in various environments to physical and chemical processes has not been adequately discussed in previous publications.

Prior to this study, no one has attempted to incorporate criteria and isolated fragments of knowledge concerning bedding into an analytical framework which can be applied to the detailed interpretation of stratigraphic history from examination of rock exposures.

THE DEVELOPMENT OF STRATIFICATION AND ITS RELATION TO ENVIRONMENTAL FACTORS

Stratification As An Environmental Indicator

Stratification very accurately reflects the environment of accumulation, perhaps even more so than texture, paleontology, or other indicators. Stratification is omnipresent. Wherever there are sediments there is stratification. Bedding even manages to survive in environments which are hostile to organisms and heavy minerals. The interrelated environmental factors which control stratification have not changed or evolved through time as have organisms and their adaptions.

It may be ehlpful to devise an oversimplified scheme for the purpose of analyzing the processes which produce the various bedding phenomena. Certain factors which exist within a depositional framework directly control deposition. Other factors, some of much greater magnitude, exert a more indirect control on stratification by influencing the direct agents or by modifying primary features.

FIVE FACTORS THAT DIRECTLY CONTROL THE NATURE AND PATTERNS OF STRATIFICATION IN MARINE ENVIRONMENTS

1. Currents--bottom currents, surface currents, tidal currents, turbidity currents, and so forth.
2. Waves and Wave Base.
3. Gradient of Shelf or Slope-Depth Relations, configuration of the basin, bottom topography.
4. Supply-Accumulation (nature of material, source, amount, and rate of supply).
5. Base Levels of Deposition and Erosion.

These five factors are all interrelated. When there is a change in intensity or degree of control exerted by one agent, there are usually complementary changes in the others as well.

FACTORS THAT INDIRECTLY INFLUENCE SEDIMENTATION AND THE DEVELOPMENT OF BEDDING

1. Meteorology (climate, weather, temperature, wind direction, and so forth).
2. Organisms--physical and chemical effects.
3. Chemical Effects--inorganic.
4. Tectonism (orogeny, epeirogeny, and so forth) and Eustatic Sea Level Changes.
5. Compaction and Subsidence.
6. Structure, Topography, and Nature of the Material

of the Coastal and Adjacent Inland Area (drainage, vegetation, and so forth).

These factors are designated as indirect only for the purpose of developing a simple analytical framework. This designation does not reflect the magnitude or importance of these factors.

DISCUSSION OF DIRECT ENVIRONMENTAL FACTORS AND PROCESSES

1. Currents - This includes bottom currents, non-bottom currents, density or turbidity currents, and tidal currents. Variation in competency caused by velocity variation produces bedding, and features such as sorting, size and shape modification of particles, orientation of particles, and so forth. Fine material transported by surface currents may settle out into quiet or deeper water. Structures such as ripple marks, cross-bedding, scour and fill, and so forth, are produced by currents that transport material along the bottom. Convolute bedding, flute casts, flow casts, groove casts, flame structures, graded bedding, and so forth, are developed by turbidity currents. Bottom currents produce layers which are bounded by bedding planes which are laterally discontinuous, and planar or smoothly curving, or arcuate. These bedding planes converge or diverge at relatively low angles to form elongate wedge-shaped, lens-shaped, disc-shaped, or

pod-shaped units.

Currents are related to bottom topography, wind strength and direction, temperature, salinity, turbidity, and so forth. One very important, but commonly underestimated, function of currents is that of preventing accumulation. Kuenen (1950) states that, "Without doubt the main geological activity of currents is merely the transportation of particles loosened and raised by wave action." Prevention of deposition is very important and may allow preservation of features associated with an earlier set of conditions.

2. Waves and Wave Base - Waves may produce currents. Within the realm of wave base the bottom is subjected to agitation. Material is thrown into suspension to be transported by currents. Waves duplicate many of the features produced by bottom currents such as sorting, rounding, shape alteration, concentration and orientation of fossils and grains, and so forth. Waves breaking and spilling on an upper foreshore beach produce laminations which mimick those produced by suspension settling in certain respects. Waves also produce ripple marked and roughened surfaces which later may be translated into wavy, discontinuous beds.

Wave base is the lowest level of agitation produced by waves. It is controlled by the direction, strength, duration, and fetch of winds, and by slope-depth relations of the environment, bottom topography, and so forth. Diagnostic textures, lithologies, and stratification develop within this realm which may be interpreted from ancient rock exposures.

3. Slope-Depth Relations, configuration of the basin, bottom topography - These factors are combined because of their intimate relationship. This combination of factors is related to the first three agents to a variable extent. Therefore, it exerts a control on the nature and pattern of accumulation of material distributed in the environment, and on the resulting stratification. Some estimate of the role played by this combination of factors may be interpreted from the pattern of the stratification in ancient sediments.

4. Supply-Accumulation, nature and rate - The interpretation of ancient environments depends upon knowledge of the agents which operate within them, and of how these influence sedimentation. Material supplied to an environment is acted upon by the various processes and the stratification which results records the impressions of this activity.

The nature and rate of supply are related to a complex combination of factors. The structure, topography and nature of the material (composition, lithified, unlithified, and so forth) of the coastal area are important factors. The nature of the adjacent inland area (vegetation, drainage pattern, structure, topography, and type of material) is an important consideration. Meteorological aspects must not be forgotten. Processes such as orogeny, epeirogeny (tectonics), and eustatic changes of sea level also influence the supply indirectly.

The source of the material supplied is always important in paleogeographic reconstruction. Often it is exceedingly difficult to distinguish between ultimate, intermediate, and immediate sources. The concepts of textural and compositional gradients as applied to source delineation have in many instances led to confusion.

The nature and rate of supply and accumulation may modify the influence of the other primary factors. Moore and Scruton (1957) have concluded that the rate of deposition is the time control on all processes of the water-sediment interface. Therefore, the supply exerts a control on the nature of the stratification which develops. Supply-accumulation characteristics can, to some extent, be interpreted from ancient sediments. Supply features are superimposed upon and translated by environmental agents into stratification.

5. Base Levels of Deposition and Erosion - The base level of deposition is the highest level to which a deposit can be built in a given environment without

being eroded. The base level of erosion is just the opposite.

Waves, currents, bottom configuration, and supply-accumulation are tangible entities which physically interact. Base level is a hypothetical surface which is related in a rather vague way to the wave and current energy, bottom configuration, and supply. Therefore, to consider base level as a direct factor points to the over-simplification of this scheme.

Base level exerts some influence on the accumulation of material which is distributed by the environmental agents. The base level concept provides a simplified framework for analyzing environmental process variation.

In any aqueous environment, the five direct factors listed above ultimately control the deposition, reworking, and accumulation of the material supplied to the environment,

DISCUSSION OF INDIRECT FACTORS AND PROCESSES

1. <u>Meteorology (climate, weather, prevailing winds, and so forth)</u> - These factors strongly influence wave and current strength. Climate and weather influence sedimentation in marine environments mainly through modification of the direct agents. Weathering, erosion, and transportation of materials supplied to environments are related to meteorology.

2. Organisms - In some cases organisms obviously exert a direct control on deposition (reefs, bioherms, and so on). To consider them as indirect agents in this scheme of analysis is, therefore, rather arbitrary.

Organisms influence sedimentation by contributing their bodies to the material supplied to the environment. This material is then influenced by the other primary agents. Organisms may modify or obliterate stratification and sedimentary features, texture, and so forth, produced by primary agents. Organisms such as kelp and reef building organisms may retard or modify wave and current strength and thus influence deposition and accumulation, serve as sediment binders and traps, and so forth.

Some workers, such as Twenhofel, have implied or stated that almost all bottom material has passed through the intestinal tracts of mud ingesting organisms. The present writer's work appears to show clearly that the ability of organisms to destroy or obliterate stratification has been greatly overestimated. Kuenen (1950) contributes the following discussion in this regard. "Some investigators are of the opinion that all sedimentary matter on the shelf is thus passed through the intestines of mud-feeding animals, a large part of it several times. But this opinion doubtless greatly exaggerates the importance of reworking. There are certainly very many exceptions, for instance where accumulation is abnormally swift, or where ecological conditions are unfavorable to benthonic life. It may be observed that even our most richly fossiliferous formations show excellent stratification although deposited in an environment swarming with life." He further points out that, "The widespread occurrence of bedding and even of fine lamination in fossil sediments and recent deposits shows that this action has been of limited importance."

Organisms influence the chemistry of the environment. Life function and decay products influence pH, Eh, and so forth. Some organisms precipitate material directly and influence sedimentation materially. Organisms may aid in cementation, lithification, and so forth.

3. <u>Chemical Effects--inorganic</u> - Chemical agents influence sedimentation by contributing material to the supply by precipitation. Chemical processes may also produce secondary compositional, structural, and textural modifications. In some cases, depositional features may be changed or obliterated by chemical action.

Chemical processes include syngenetic, penecontemporaneous, diagenetic, authigenic, and surface weathering processes. Precipitation, solution, reprecipitation, replacement, permineralization, recrystallization, oxidation, reduction, and so forth, produce the secondary changes mentioned above. Cementation and lithification are related to chemical processes.

4. Tectonism (orogeny, epeirogeny, and so forth) and Eustatic Sea Level Changes - Tectonism and eustatic sea level fluctuations may alter the entire network of environments and depositional provinces, locally, regionally, or (in the case of eustatic changes) the influence may be world-wide. The impressions generated by tectonism and eustatic rises and falls of sea level are received by the direct agents which in turn translate these impressions into changing patterns of stratification.

5. Compaction and Subsidence - These factors influence sedimentation by modifying the base levels and the topography of the bottom to some extent. Thus, the thickness of accumulation may be affected. Primary features may be modified by compaction. Compaction may serve as a vehicle for certain chemical processes by establishing hydraulic gradients, and so forth. Compaction is influenced by the rate and nature of supply and accumulation. Cementation, lithification, and compaction may be interrelated. Features such as cone in cone, stylolites, salt plugs, sedimentary boudinage, and so forth, may be related to compaction.

6. Topography, Structure, Nature of the Material and Configuration of the Coast and Adjacent Land Area, Interior Drainage, Vegetation, and so forth - This group of variables influences the rate and nature of supply

to a rather large extent. Current patterns and wave characteristics are influenced to some extent by this combination. Bottom topography may be closely related to these factors.

ENERGY CONSIDERATIONS

We must now consider the concept of high, low, and intermediate energy levels which in a much over simplified and generalized form is very helpful in environmental interpretation of offshore deposits. As suggested below, this concept of "energy" refers mainly to wave energy in offshore environments (seaward from the low tide shoreline). The processes and factors that influence bedding in the three energy zones will be discussed in more detail in the section entitled "Stratification in Sedimentary Environments." A generalized treatment is inserted at this point to introduce the concept which is essential to the theoretical development presented in the present study.

<u>High Energy Zone</u> - This zone is loosely defined as the region wherein wave agitation continuously stirs the bottom like an elutriation mill. It extends seaward from the low tide shoreline to the outer limit of continuous wave agitation of the bottom.

<u>Low Energy Zone</u> - The low energy zone lies below the influence of wave agitation, but it may or may not be swept

by currents. This includes the slope-basin (turbidity current) environment, if it exists.

Intermediate Energy Zone - This zone ordinarily lies below wave base, but periodically the action of storm waves reaches the bottom. Currents may or may not be present part or all of the time.

Concept of Energy Belt Width as Related to Shelf Gradient, Wave-Wind Relations

The width of an energy belt is, of course, related to slope-depth, wind-wave relations. The gentler the gradient of a shelf, the wider will be the width of the high energy belt generated by a given wind effort. Conversely, the steeper the gradient, the narrower the width of the high energy belt. The same is true for the intermediate zone. Apparently deposits of the intermediate zone do not develop to any extent in areas with relatively high shelf gradients, or in areas with strong bottom currents. Environments with steeper shelf or slope gradients are apparently characterized by interbedded high and low energy deposits. This alternation of high and low energy deposits may be related to strong seasonal variation in wind, wave, and current strength. This combined with higher gradients might allow more rapid deposition and accumulation of finer material which settles from suspension during quiet periods, and coarser material deposited during increased wave and current activity.

(Such an alternation could also be produced by turbidity currents.) The California coast with its strong seasonal variation in wind, wave, and current activity may be an example of this.

Shelves and platform with very low gradients may display high, low, and intermediate deposits. Thus, intermediate deposits may be indicative of broad shelf development. Prevailing offshore winds, or weak onshore winds could inhibit or prevent development of intermediate deposits even on shelves with very low gradients.

Factors and Features Which Characterize Deposits of the Three Energy Levels

In each of these three energy zones, characteristic types of bedding are produced by the direct processes.

High Energy Deposits (Figures 7, 31, 32)

Factors - waves and current turbulence, discontinuous accumulation, reworking, and so forth

Features - discontinuous, planar and gently curving bedding planes; scour and fill, cross-bedding; lens-shaped, wedge-shaped, disc-shaped, pod-shaped units; bedding thickness commonly related to cementation

Intermediate Energy Deposits (Figures 8, 9, 33, 34, 35, 36, 37)

Factors - intermittent wave agitation, continuous or discontinuous, weak bottom currents, quiet periods, rather slow or intermittent accumulation of material, gentle shelf gradient

<u>Features</u> - discontinuous, wavy, undulatory, thin beds which are commonly separated by shaly partings, bedding planes are commonly of the physical separation variety

<u>Low Energy Deposits</u> (Figures 5, 10, 11, 38, 39, 40, 41, 42)

<u>Factors</u> - little or no wave agitation; continuous, discontinuous, currents, or none; accumulation of material which settles from suspension under quiet conditions; possible turbidity current deposition

<u>Features</u> - tabular, laterally continuous beds and laminae; beds thick or thin depending on the supply; bedding planes may or may not be of the physical break variety; also, all features and structures produced by turbidity currents.

Figure 7. High energy deposit in the Franconia sandstone (Cambrian) just north of Middleton, Wisconsin, on Highway 14. Note the complex internal structure (scour and fill, cross-bedding, and so forth).

Figure 8. Intermediate carbonate deposit in the Platteville formation (Ordovician) near Janesville, Wisconsin. Thin, irregularly wavy, discontinuous carbonate beds are separated by shale partings.

Figure 9. Intermediate deposit in the Fresnal Group (Pennsylvanian) of the Sacramento Mountains, New Mexico. Layers of limestone with concentrated shell material are separated by shaly partings.

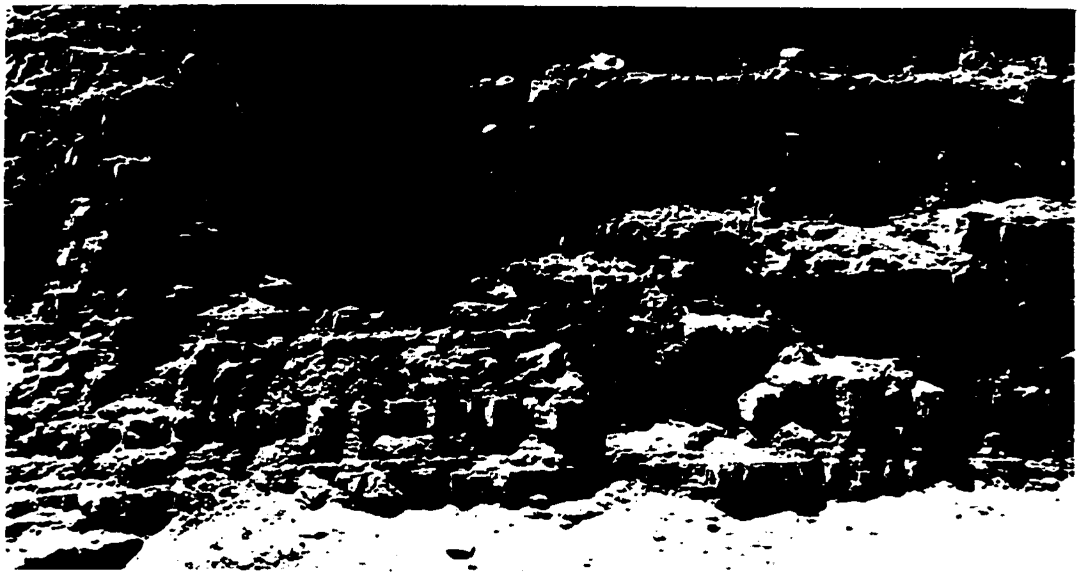

Figure 10. Low agitation deposit consisting of alternating layers of limestone and shale. Beds are markedly continuous and tabular. Pennsylvanian unit exposed in the Salt River Canyon, 4 miles north of the Salt River on Highway 77 in Arizona.

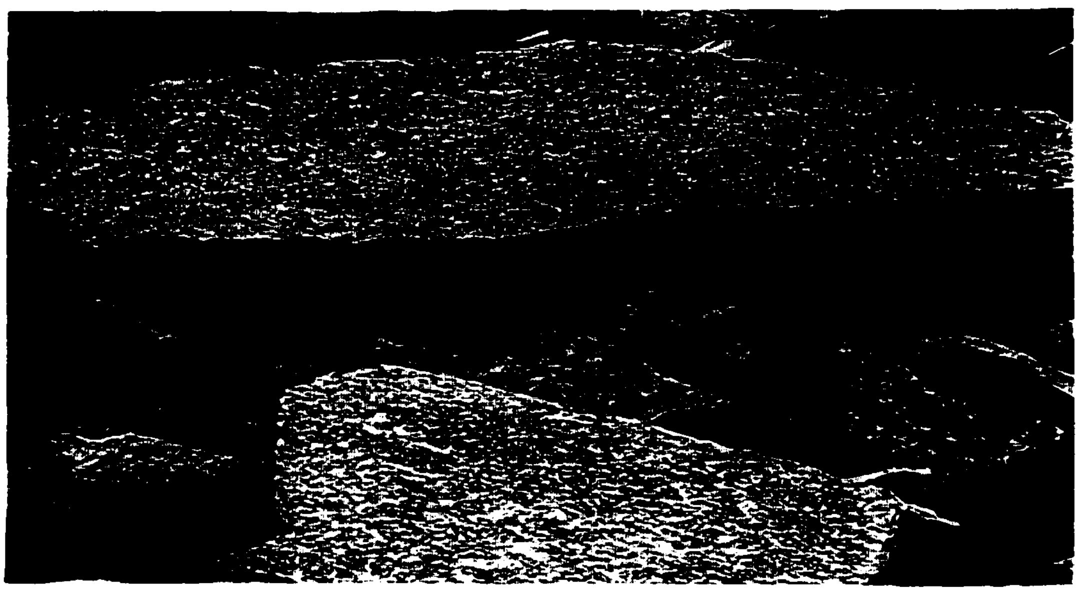

Figure 11. Low agitation limestone bedding. Tabular, continuous limestone beds are separated by thinner shale layers. Kankakee limestone (Silurian) in Romeo Quarry near Joliet, Illinois.

THICKNESS CONSIDERATIONS

Primary Control

Bedding thickness is primarily controlled by direct factors and processes. The position of the depositional interface with respect to the base level factor influences the thickness of accumulation. It might be a safe generalization to assume that the depositional interface and the base level of deposition diverge in a seaward direction and converge in a landward direction. Generally, it should be expected that the divergence would be greater in environments with steeper shelf or slope gradients.

If it is assumed that a depositional interface is well below a theoretical base level of deposition, then the thickness will be directly controlled by the nature and continuity of supply and accumulation. Wave base does not necessarily coincide with the base level of deposition or erosion. Discontinuous wave activity in an intermediate zone produces thin beds. Even a continuous supply of material accumulating well below base level will not necessarily produce thick bedding. If the nature of the material being continuously supplied should fluctuate, then thinner bedding would develop. Thick bedding and thick total accumulation are often mutually inclusive, but not necessarily so. Thick bedding can develop in places where a relatively thin sedimentary sequence has accumulated. Thin bedding can also be found in thick sedimentary sequences.

Cross-bedded structure commonly results in thick bedded units, especially after cementation. Sandstone units with complex cross-bedded, scour and fill structure commonly assume the identity of a single thick bed (Figures 7 and 31). With thorough cementation and a high degree of sorting the bed may even appear to be structureless.

Secondary Control

Secondary factors and processes may also influence the thickness of bedding. In high energy deposits, thickness is commonly related to cementation. Weathering processes may selectively remove cement and reveal the true nature of the bedding. Burrowing of mud ingesting organisms may obliterate bedding planes and internal features and thus secondarily increase the thickness.

Recrystallization may destroy or mask original features and cause apparent increases in thickness. Reorientation and recrystallization related to compaction may produce the fissility or platiness characteristic of many shales (Weller, 1959), (Ingram, 1955). It is possible that some thin clay or shale partings that separate carbonate beds are related to pressure-solution, associated with compaction (Weller, 1959). Other chemical processes, such as oxidation and reduction, may produce color or compositional changes which control apparent thickness.

LATERAL CONTINUITY OF BEDDING PLANES AND BEDS

This is an important parameter which is seldom included in descriptions. Wave agitation and bottom currents produce units which are laterally discontinuous. The discontinuous nature may be apparent even in very limited exposures.

Accumulation under relatively quiet conditions generally produces layers with great lateral extent. Fine particles require very low energy which is available over wide areas for suspension transport (Potter and Siever, 1955). Thus, lateral continuity may offer some measure of the environmental energy or process intensity.

Organisms may produce discontinuous bedding. Burrowing or scavenging organisms may disrupt lateral continuity by destroying bedding planes or by creating discontinuous surface features (Moore and Scruton, 1957).

DISCUSSION OF WAVE BASE AS A DATUM

The wave base concept provides a datum to which fossils and containing deposits can be related. It can generally be determined whether a deposit formed within or below wave base regardless of the actual depth to which wave base extended. The variation in depth of wave agitation depends on variation wind strength, fetch, and direction, slope-depth and basin configuration. It may be difficult if not impossible to ascribe an actual quantitative estimate of the depth to which wave base extended. This inability to determine its exact depth does not minimize the importance of wave base as a reference.

Dott (1958) states that the question arises as to whether deep water currents or shallow water waves produced the observed effects of agitation. It is possible that the nature of the stratification and textures may provide clues that might settle this question in many instances.

Bottoms that are subjected to continuous strong wave agitation are generally always swept by continuous currents (although the current pattern may be complex). It has been pointed out above that diagnostic stratification, textures, and lithologies develop in such continuously agitated environments (high energy zones). Bottoms traversed by strong currents, however, may or may not be agitated by waves. In other words, where waves continuously stir a bottom currents are also present, but currents flowing along a bottom may exist alone without waves.

Where both waves and currents continuously agitate a bottom, current structures are apparently selectively preserved at the expense of wave features. This is probably because the continuous wave turbulence mainly suspends the sand grains which are actually transported and deposited by currents (Kuenen, 1950), (Arlman, Santema, and

Svasek, 1958), (Handin, 1951). It is possible that the strongest and most turbulent bottom currents are generated by wind, waves, and tides in the same shallower waters which are subjected to continuous wave action.

Strong bottom currents generally could exist alone only in nearshore areas protected from wave activity (lagoons, bays, estuaries, and so forth), and in offshore areas below the level of normal wave agitation (open shelf or deeper ocean currents). Kuenen (1950) points out that turbulence in marine currents apparently is too weak, except for some strong tidal currents (and turbidity currents), to keep sand in suspension. He has shown that even strong tidal currents in the North Sea are insufficient to remove much sand. He states that, "Over vast areas of shelves bottom currents are extremely weak, and, at most, are able to retain clay in suspension."

Johnson (1956) contributes the following discussion in this regards. "Although oceanic currents in some localities may be of sufficient strength to transport sand along the sea bottom, the primary mechanism of sediment transport in deep water appears to be the result of turbulence resulting from the oscillatory motion of the sea bed by surface waves. Sediment placed into temporary suspension then may be transported along the bottom by (a) oceanic currents, or (b) when the forward velocity of the water under the wave crest exceeds the backward velocity under the wave trough, a net transport occurs in the direction of wave travel." He further states that at localities where oceanic and littoral currents opposed, the wave-induced littoral current is stronger.

A bottom subjected to discontinuous wave agitation (intermediate zone) may also be marked by continuous or discontinuous currents. Under such conditions the currents may not be strong enough to obliterate the wave features. Kuenen (1950) contributes the following discussion which seems pertinent to this consideration. "A further general conclusion is warranted that on the open shelf currents are too sluggish to transport sand in the absence of waves. The turbulent action of waves must intervene, and it is just this combination of moderate current velocities and intensive wave action that results in the transport of the sand fraction on the continental shelf." Thus, a deeper bottom subjected to discontinuous current activity only would probably not be as severely agitated as it would if it were subjected to wave turbulence (except in the case of turbidity currents).

Dott (1958) states that coquinites may indicate lowering of wave base resulting in the reworking of slightly earlier deposits, concentrating shells as residual, intraformational lag conglomerates. He further states that in this manner moderately fossiliferous muds could be transformed into thinner, fossil rich, coquinites and calcarenites. In fact, this is probably one of the chief processes that characterize the intermediate zone and its stratification. In between agitations, mud can accumulate in this zone. Discontinuous bottom currents by themselves would probably not be turbulent enough to differentiate the material, concentrate the fossils, and produce the type of stratification that is commonly associated with this zone. Discontinuous wave agitation could accomplish this. Current activity might accompany the intermittent wave activity but would probably not destroy the wave formed features. A bottom photograph taken on Osborn bank off the coast of Southern California at a depth of 190 feet may illustrate this (Emery, 1953, p. 203). It was taken at the end of a summer characterized by small waves and shows large ripple marks made by the previous winter's storm waves subsequently somewhat smoothed by burrowing animals, probably chiefly worms.

With the exception of turbidity currents and slide deposits, most of the effects of agitation which are observed in sedimentary rocks must be attributed to wave turbulence, or to this plus shallower water current agitation, rather than to deep water currents. It is probable that the maximum bottom current turbulence occurs in environments where continuous wave action prevails. If currents are present and sufficiently strong to transport and deposit material suspended by waves, high energy deposits will develop in which current features predominate. Scour and fill structures, cross-bedding, and diagnostic shapes of bedding units will be produced in such a zone. Where a bottom is discontinuously stirred by waves, currents are generally not strong enough to impress their characteristics on the material and wave features may be preserved. Thin, discontinuous, ripple marked, wavy, undulatory bedding is commonly formed. Shell concentrations, coquinites, and so forth, may be formed in finer grained deposits.

STRATIFICATION PATTERNS

The stratification pattern concept is proposed to provide a simple device which might aid in observing the stratigraphic positions of various types of bedding. A stratification pattern may be visualized as a sedimentary sequence in which bedding characteristic of two or more environments is represented; it may also reflect changes in process intensity within an environment. Cyclic Pennsylvanian units commonly exhibit patterns of bedding which formed during gradual deepening or shallowing conditions. A pattern may, in some cases, be illustrated by an exposure which is only a few feet thick. Cconversely, an exposure hundreds of feet thick may exhibit only one variety of stratification and would not be considered a pattern. Some patterns may consist of several interbedded lithologies, and others of only one lithology.

In shorezone deposits the bedding patterns represent specific environments, such as tidal flat, beach (lower and upper foreshore and backshore deposits), lagoon, swamp, and so forth. Stratification patterns that reflect offshore sequences are composed of high, intermediate, or low energy deposits.

Environments which exist side by side during a given period of time are represented by vertical alternations of lithology and type of bedding as these entities shift laterally and vertically through time and space. Thus, lateral changes may be inferred from vertical exposures. This principle is applied in using patterns of stratification to interpret depositional cycles.

Observations have been made on the bedding patterns that developed during transgressions, regressions, or during deepening and shallowing conditions. Deepening conditions are inferred from vertical or lateral changes in bedding that indicate accumulation under quieter or lower energy conditions. Shallowing conditions may be deduced from changes in bedding that are related to progressively higher energy, or to an increase in process intensity. One cannot equate quiet with deeper, or higher energy with shallower conditions and be correct one hundred per cent of the time. Nevertheless, this is generally a rather safe assumption.

Stratification Patterns That Reflect Deepening and Shallowing Conditions (or Transgression, Regression, or Subsidence)

In a deepening pattern lower energy deposits successively overlie higher energy deposits in a vertical section (Figures 12, 13, 14). Higher energy deposits grade upward into lower energy deposits. An ideal deepening pattern might be represented by a high energy deposit which in turn is overlain by a low energy deposit. Shorezone deposits may, in some cases, combine with offshore deposits to form a deepening pattern.

Shallowing patterns record vertical progressions from lower to higher energy (Figure 15). The bedding should reflect a vertical or lateral increase in process intensity. In offshore sedimentary sequences, an ideal deepening (or regressive) pattern might be represented by a vertical or lateral change from low to intermediate to high energy deposits. Shorezone deposits may combine with those of offshore zones to form patterns which indicate shallowing conditions. For instance, a surf zone deposit might be overlain by that of a lower foreshore beach, and this in turn may be succeeded by an upper foreshore beach deposit.

Typical intermediate energy deposits may or may not appear between high and low energy deposits in deepening or shallowing patterns. As pointed out above, formation of intermediate deposits may depend on the shelf or slope gradient, the configuration of the bottom, strength and fetch of winds and their effect on waves and currents.

Two or more deepening and shallowing patterns may occur within a formation. Conversely, two or more formations may form a single pattern. Cyclic Pennsylvanian units commonly contain two or more deepening and shallowing patterns. In the Pahranagat Range of Nevada the West Range formation (Devonian carbonate unit) represents an intermediate deposit. The West Range is overlain by the thinly bedded calcareous shale of the Pilot formation which is a low energy deposit. These two formations form a deepening pattern. The Pilot grades vertically into another intermediate carbonate deposit in the lower part of the Joana formation (a Mississippian carbonate). This indicates a shallowing pattern.

It may be impossible to associate deepening conditions with transgression or shallowing conditions with regression from a single exposure without onlap-offlap relationships. Subsidence may or may not reflect a transgression.

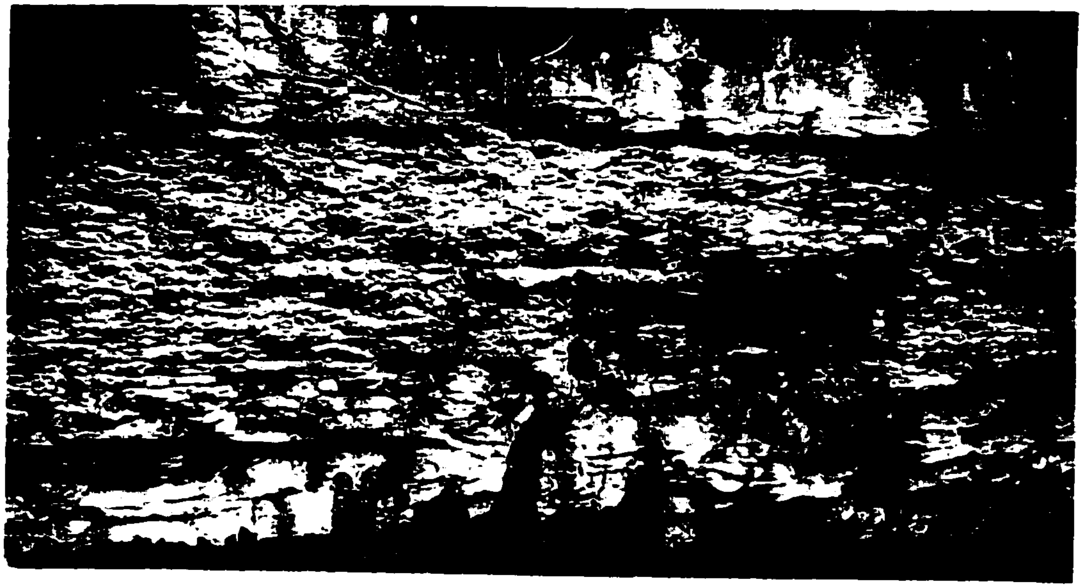

Figure 12. Stratification pattern showing change from high energy at the bottom, to intermediate energy in the middle, to low energy at the top. This apparently reflects a deepening cycle. Ste. Genevieve limestone (Mississippian) approximately 1.5 miles south of Ste. Genevieve, Missouri, on Highway 61.

Figure 13. Stratification pattern in the St. Joe limestone (Mississippian) 3 miles west of Wentzville, Missouri, on Highway 40. From bottom to top this sequence represents a change from high to intermediate to low energy. Only a small portion of the low energy deposit at the top can be seen. This apparently reflects a deepening cycle.

Figure 14. Stratification pattern illustrating a change from intermediate (near bottom) to low energy deposit. This may represent a minor deepening cycle. Limestone unit in the Fresnal Group (Pennsylvanian) in the Sacramento Mountains of New Mexico.

Figure 15. Stratification pattern representing change from low energy deposit at the bottom to high energy deposit at the top. This probably reflects a shallowing cycle. Ste. Genevieve limestone (Mississippian) approximately 3 miles south of Ste. Genevieve, Missouri, on Highway 61.

Remarks Concerning Preservation of Beach Deposits

Thompson (1937), Martens (1955), and others have stated or implied that beaches are most likely to be preserved during a transgression. Martens states that gradual sinking of the land resulting in transgression of the sea over land of low relief is the most favorable condition for extensive geologic preservation of beaches. Data gathered by the writer appear to cast doubt on this generalization. Several transgressive units were observed and no beach stratification or structures could be detected in any of these. Several beach deposits were observed during the study. Apparently all of these were associated with regressions or shallowing conditions. Apparently transgressive situations are not the most favorable for preservation of beach deposits. Possibly the transgressing surf zone obliterates the beach bedding and features.

McKee (1957) has independently arrived at this same conclusion (that beach deposits are not preserved during transgressions). McKee (1957, p. 1745) states that most beach deposits should be recognized because they occur as parts of a typical sequence consisting of marine beds, foreshore beach, backshore beach, and lagoon, swamp, or dune resulting from regression of the sea. He further states that, "Beach sands are not known to be preserved in original form under conditions of transgression."

Apparently beaches are not commonly preserved during transgressions, but the writer would be unwilling to admit that this would be impossible. It does seem that beaches are more commonly preserved during regressions. If a withdrawl of the sea were caused by severe orogeny, it would be improbable that the regressive beaches would be preserved.

During regression over a relatively flat shelf or platform, backshore and dune deposits may cover the beach with a protective blanket of sand and silt. The dune forms and structures may be obliterated during the succeeding transgression. Beach features which were covered by such a protective mat might very well be preserved.

It is possible that beaches on the landward side of bays, inlets, lagoons, and so forth, may be more easily preserved during transgression. Such beaches may be protected from excavation by the surf zone. Perhaps beaches at the maximum extent of a transgression would be preserved because they would not be destroyed by the surf zone.

STRATIFICATION IN SEDIMENTARY ENVIRONMENTS

SHOREZONE ENVIRONMENTS

Upper Foreshore Beach Deposits

The foreshore has been defined as the zone between the crest of the beach and the low tide shoreline. The upper foreshore is that part of the foreshore extending seaward from the crest of the beach to the zone of permanent saturation.

Factors responsible for beach stratification, the manner in which it is formed, and the time represented by individual laminae have been intensively studied by W. O. Thompson (1937). E. D. McKee (1957) has studied bedding and structures in several recent beaches. McKee has found that the stratification features in the beaches he studied were the same as those described in other beaches by Thompson. Because Thompson has done such thorough work, the descriptions of the upper foreshore deposits are summarized from his study.

Review of W. O. Thompson's Description of Stratification and Structures That Characterize Upper Foreshore Beach Deposits (Thompson, 1937)

Upper foreshore deposits are commonly laminated. "Some laminae are dominated by light minerals of moderately low specific gravity, such as quartz and feldspar, whereas others are dominated by dark colored heavy minerals, such as magnetite and hornblende." The laminae occur in sheaves or sets which dip gently seaward at slightly varying angles when viewed in cross sections perpendicular to the shoreline. These structures appear as cross laminated zones in cross sections. Such zones vary from a few feet long and a few inches thick to 150-200 feet long and 8-10 feet thick. In cross sections parallel to the shoreline individual laminae may be traced as far as 100 feet. In sections normal to the shoreline, laminae can rarely be traced over 25 feet.

Cusped beaches and their intervening scoop-like embayments reveal a more complex internal structure than the smoother surfaces of uncusped beaches. Storms may destroy the cusps leaving the beach a smooth surface that slopes gently seaward. The position of axes of cusps and embayments that redevelop after storm erosion usually does not conform to that of the former ones. Thus, laminae of new embayments rest unconformably on laminae of remnants of old embayments. This results in a cross laminated structure when viewed in cross sections parallel to the shoreline.

"No definite relation was found between the number of laminae and the thickness of daily accumulation. Lamination is apparently the result of deposition by an unknown number of waves whose carrying power varies from time to time, and with each change begins the deposition of a new lamina." "It is concluded that the interval of time represented by a group of beach laminae indicates no exact interval of time, because such a group includes intervals of non-deposition and erosion. Furthermore, a group of beach laminae is the result of deposition of irregularly recurrent variations in carrying power of waves. A few laminae may represent the deposit of a single day. But even if each lamination represented one day's deposition, the successive laminations in a thick section would not necessarily represent days, but perhaps only those occasional days whose contributions escaped erosion."

Thompson describes other structures occurring on upper foreshore beaches, such as buried wave-cut scarps; buried channels which extend perpendicular to the shore; unlaminated interjacent lenses of sand; backwash marks, which resemble ganoid scales of fish; swirl structures; and ripple marks.

Illustrations of Upper Foreshore Deposits

Figures 16 and 17 show upper foreshore beach laminations in the St. Peter sandstone (Ordovician) of southern Wisconsin. The laminae are tabular in shape but laterally discontinuous. The laminated nature of the bedding has been accentuated by the removal of cement on the weathered surfaces.

Another laminated upper foreshore beach deposit in

Figure 16. Upper foreshore beach deposit in the St. Peter sandstone (Ordovician) on Highway 81, approximately 2 miles south of Blanchardville, Wisconsin. Note the gently dipping sets of tabular, discontinuous laminae.

Figure 17. Upper foreshore beach deposit in St. Peter sandstone, approximately 1 mile south of Argyle, Wisconsin, on Highway 81.

the La Motte sandstone (Cambrian) of southeastern Missouri is shown in Figures 4 and 18.

Upper foreshore laminae in the Dakota sandstone (Cretaceous) near Canon City, Colorado, are shown in Figures 20 and 21. This deposit is strikingly similar to the beach deposits in the St. Peter and La Motte sandstones.

Another ancient beach deposit has been described by Thompson (1949) in the Lyons formation of Colorado.

Lower Foreshore Beach Deposits

The lower foreshore beach is defined as that part of the beach that is permanently saturated with water. It occupies the zone along the shore between the seaward edge of the upper foreshore and the minimum low-tide shoreline.

Thompson (1937) points out that the bedding and structures in lower foreshore beaches cannot be observed in cross-section because saturation of the sand causes immediate cave in following excavation. Therefore, characteristics of lower foreshore bedding must be inferred from a knowledge of the surface forms and the formative processes. Thompson is the only one who has done this and so the following discussion is taken from inferences which he has drawn.

Figure 18. Upper foreshore beach deposit in the La Motte sandstone (Cambrian) exposed in road cut on Highway 67 about 1.5 miles north of Mine La Motte, Missouri.

Figure 19. Upper foreshore beach deposit overlain by thin backshore beach deposit which is truncated above by an apparent surf zone deposit. (Same locality as above.)

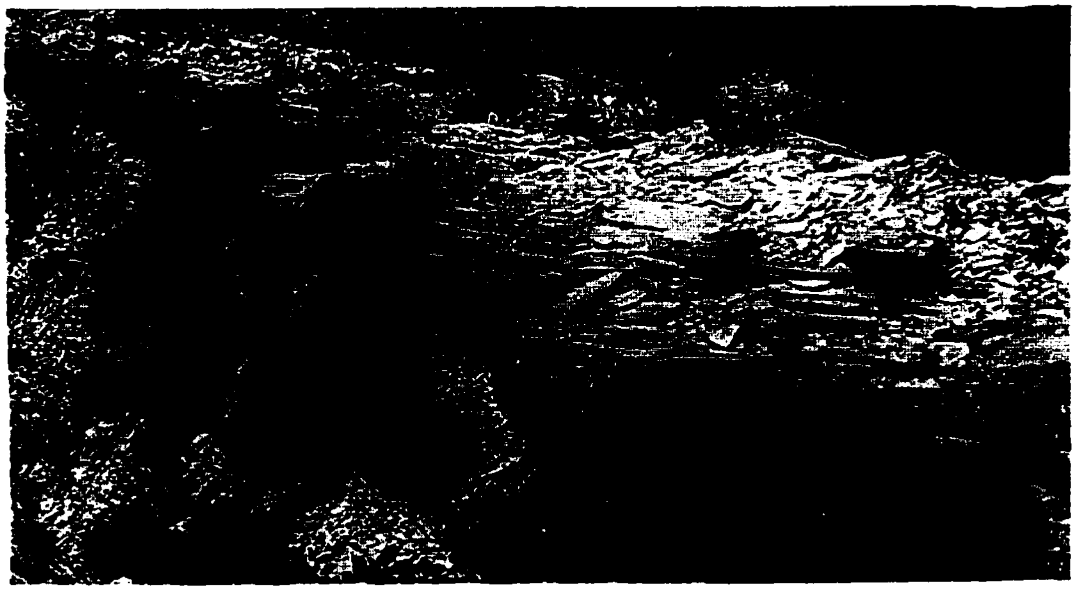

Figure 20. Upper foreshore beach deposit in the Dakota sandstone (Cretaceous) on Skyline Drive, Canon City, Colorado. The laminae are accentuated by selective removal of cement.

Figure 21. Portion of same beach zone shown above, also exposed on Skyline Drive.

Review of W. O. Thompson's Description of Lower Foreshore Beaches and Inferences as to Probable Bedding and Structures (1937)

"Commonly, the most prominent topographic feature of lower foreshore beaches is a broad, low ridge, separated from the seaward slope of the upper foreshore beach by a wide, shallow trough, whose axis is parallel to the shoreline. Part of the time, however, this trough is filled with beach sediment, so that a continuous slope is formed from the upper foreshore to the lowest limit of shore exposure. The declivity of this slope decreases seaward."

"Numerous small basins and shallow embayments interrupt the continuity of the ridge and trough of the lower foreshore. Irregularly shaped, plateau-like sand bars, with lobate, steep sides, project into these depressions. Some depressions have a surface area of a few square feet; others, hundreds of square feet. The depth in the central part of the depression is ordinarily 2 to 3 feet."

"The currents that wash the lower foreshore are extremely complex. Added to the swash and backwash of normal wave activity are the littoral currents, resulting from tides and from waves that strike the shore at an angle."

"Furthermore, seepage water from the upper foreshore forms rills, which transport beach sediment to tidal pools. In many places, these minute drainage systems build small deltas in the tidal pools."

"The various currents which wash the lower foreshore during tidal advance and retreat wash sand from the top of the flat-topped sand bars and add steeply inclined laminae to their sides. Waves swashing across depressions adjust sediment to the depression floors so that the least possible resistance is offered to wave currents."

"It is inferred from the conditions of deposition that: (1) deposits of the lower foreshore are intricately cross-laminated; (2) discontinuous, nearly horizontal layers of short, sandy, foreset laminae are interstratified with evenly laminated layers of fine micaceous sand, which conform to irregularly shaped depressions; (3) the short foreset laminae dip in all directions with an angle of dip that approaches 30 degrees; and (4) there is no correspondence in direction of dip between the nearly horizontal micaceous laminae and the foreset laminae. The size of these structures is much smaller than that of the structures of the upper foreshore beach."

Backshore Beach Deposits

Thompson (1937) defines the backshore as that part of the shore lying between the foreshore and the coastline, covered by water only during exceptional storms or tides. Backshore beach deposits are formed of sand deposited by sheet flood from waves spilling over the beach crest at high tide, by storm waves, and by wind. Channel scour and fill and even lagoonal deposits may be interbedded.

Review of E. D. McKee's Description of Backshore Beach Deposits (1957)

Backshore deposits have been examined by McKee (1957) along the Texas and California coasts. "Irregularities are characteristic of backshore deposits. In many places strata consist of thin, even, gently dipping laminae like those of the upper foreshore, but most of them dip away from the sea; elsewhere they are developed in channels or troughs and consist of steeply dipping and curving laminae or of shells and detritus that settled as horizontal beds in the depressions. Backshore deposits commonly merge into those of lagoons or of dunes."

Troughs and channels, most of which are parallel to the coast, are characteristic features. Marked irregularities of erosion surfaces commonly separate sets of laminae. Clay beds are found deposited among the sands.

Intraformational conglomerates are found among backshore deposits.. "Some beds of this are composed of unoriented chunks of laminated sand, broken from a parent deposit of unconsolidated sediment and redeposited nearby, in a matrix of similar sand. Locally, concentrations of large shells or of charcoal and other unsorted debris are characteristic."

Illustration of Ancient Backshore Deposits

Only one possible backshore beach deposit has been observed during the present study. This appears in a 1-2 foot thick zone exposed in a 10-12 foot thick road cut through the La Motte sandstone (Cambrian) on highway 67, one and a half miles north of Mine La Motte, in southeastern Missouri (Figure 19). This backbeach zone overlies the beach deposit shown in Figures 4 and 18, and is truncated above by an apparent surf zone deposit. The material in this thin zone consists of poorly cemented, friable, poorly sorted material. Coarse, medium and fine sand are mixed with clay and silt. The irregular scour and fill structure and cross bedding are poorly defined because of the friable nature of the material. The sand in the beach deposit below and the surf zone deposit above is very well sorted and firmly cemented.

This vertical succession of beach, backbeach and surfzone deposits may record a minor oscillation of the La Motte shoreline.

Tidal Flat Deposits

Review of E. D. McKee's Description of Stratification in a Tidal Flat Deposit (1957)

Tidal flat stratification examined by McKee (1957) appeared as crude layers and lenses which were essentially horizontal and non-persistent. Primary structures include parallel and cusp type ripple marks, curving tracks and trails of animals, dragmarks where kelp and other material was washed back and forth. Miniature deltas occur where water drained off the flats into the channels.

Review of W. Hantzschel's Description of Stratification in a Modern Tidal Flat Deposit of the North Sea (1955)

Hantzschel reports that, "The deposits are stratified in fine laminae." "This delicate bedding is caused by the interlamination of thin layers of fine sandy material in the more argillaceous basic substance." Rarely is the bedding strictly parallel. It is generally streaky and lenticular. The alternating sand and clay layers wedge out in short distances and their thickness is not uniform. Cross-bedding is widely distributed in tidal areas.

Observations have shown that reworking and restratification of the sediments proceed so rapidly that burrowing animals have no time to destroy the existing and newly forming bedding. In some places blocks consisting of several laminae are found transported as a unit and deposited in alien surroundings. The mud, when partially dried, may form flakes and pebbles that may be transported by currents into other areas such as sand areas.

Description of Tidal Channels, Taken From a Summary of L.M.J.U. van Straaten's Work in Dunbar and Rodgers (1957)

Meandering tidal channels are normally incised on the otherwise smooth surfaces of tidal flats. "The sides of the main tidal channels are scored with many gullies that help to bring the water onto and drain it off the main flats with each tide. Channels and gullies tend to shift laterally, and sediment is deposited relatively rapidly in the abandoned portions or along banks from which the channel or gully is receding. This sediment is generally fine grained and none too well sorted, but distinctly laminated, with alternating commonly thinly lenticular laminae of silty clay and silty sand; because of the rapid deposition, the lamination is not destroyed by burrowing worms."

W. H. Bucher's Summary of Work Done at The Institute For Study of Modern Sediments on Tidal Flat Deposits (1938)

Bucher contributes the following discussion of the formation of flat-pebble or intra-formational conglomerates. Lateral erosion along some of the tidal channels commonly uncovers older beds which break away in more or less angular pieces of unconsolidated sediment. These are rather perfect models of intra-formational conglomerates, some as typical flat-pebble conglomerates, others consisting of well rounded pebbles.

Bucher briefly discusses the types of ripple marks which occur on tidal flat surfaces. Oscillation ripples with broadly rounded crests are commonly found. Where a thin film of water remains covering the ripples, the surface drift caused by wind may change them into irregular lines of rounded, flat-topped blobs. Rhomboid ripples and giant ripples ("meta-ripples" or "para-ripples") are also described.

<u>Examples of Ancient Tidal Flat Deposits Encountered in This Investigation</u>

Cambrian of Southeastern Missouri

Several ancient deposits have been observed which appear to have accumulated in tidal flat environments. A portion of the Davis-Derby, Doerun sequence is exposed in a new road cut on highway 67 in southeastern Missouri, 2 miles south of Bonne Terre. This unit is late Cambrian in age. The deposit has all the features which have been described from modern tidal flat deposits. The deposit consists of interbedded fine sand, silty and shaly material.

On the weathered surface the bedding planes are of the physical break variety. The physical breaks are clearly related to the varying resistance which sandy, silty and shaly layers offer to weathering. The beds range in thickness from two feet to a fraction of an inch. The thickest layers are composed of flat-pebble conglomerates (Figure 25). Some of these layers may represent tidal channels. The layers are essentially horizontal but laterally discontinuous. The beds generally assume the shapes of thin, elongate wedges, discs, lenses, and pods. Some might even be described as spindle shaped.

The bedding may appear to be tabular and laterally persistent from a distance, but closer examination reveals the delicate lenticularity and discontinuity (Figures 22, 23, 24).

Thicker flat-pebble conglomerate layers are interbedded with the thinner units. The flat-pebbles are composed of fragments and angular pieces of the underlying, thin bedded shale, silty and sandy layers (Figure 25).

Channels filled with silt and clay (mud at the time of deposition) can be seen (Figure 26). These channels are commonly cut into layers of coarser material and filled with fine material.

Where bedding surfaces could be examined, tracks and trails of organisms were seen (Figure 27). Blocks composed of several laminae, which were dislodged and transported, commonly project above the bedding surface (Figure 28). Surfaces with well developed ripple marks were not observed, but the bedding surfaces which could be examined were limited to a few isolated blocks which have been blasted free.

The nature of the stratification, internal structures, surface features and lithologies exposed in this cut are strikingly similar to descriptions of modern tidal flat deposits.

Figure 22. Tidal flat deposit in the Davis, Derby, Doe Run sequence (Cambrian) on Highway 67 just south of Bonne Terre, Missouri. Thin, discontinuous, lenticular beds of fine sandy, silty, and shaly material are interbedded with thicker beds composed of sand and flat-pebble conglomerate.

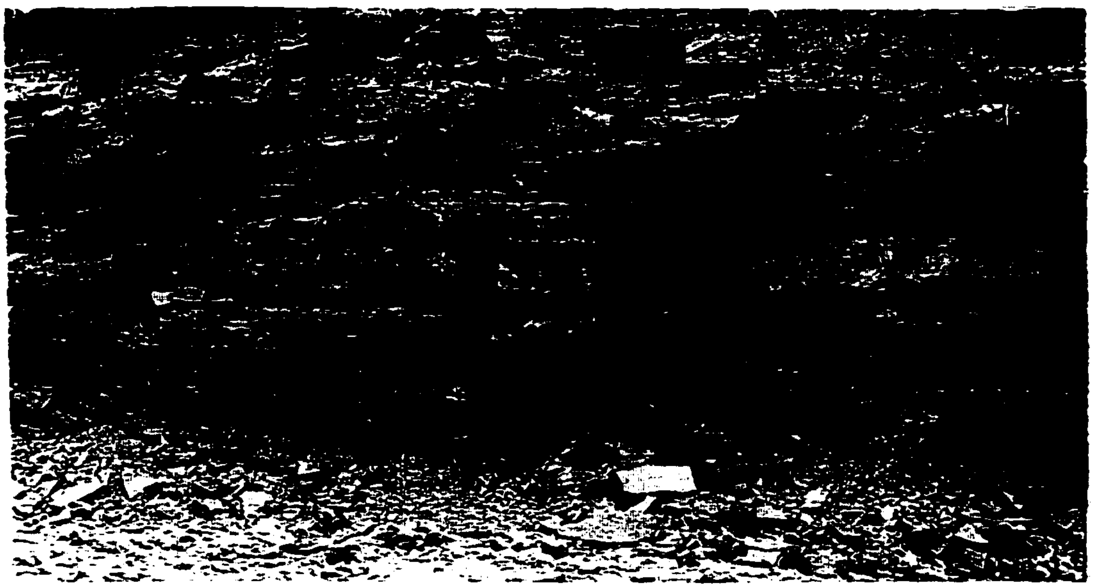

Figure 23. Tidal flat deposit from same road cut as shown above.

Figure 24. Tidal flat deposit from the same locality as Figure 22.

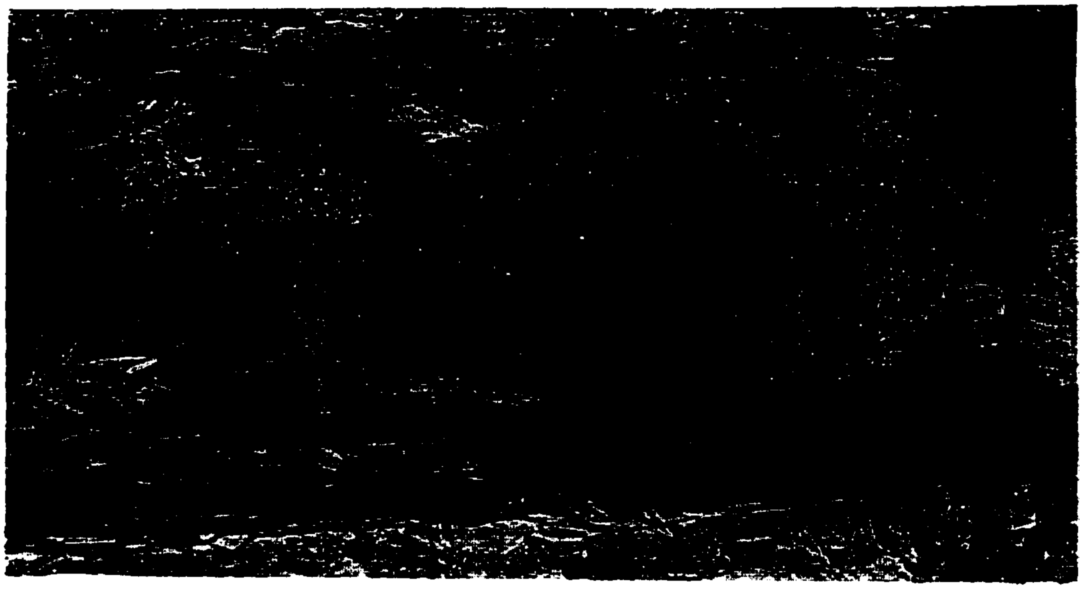

Figure 25. Flat-pebble conglomerate in same tidal flat deposit shown in Figure 22. Material consists of angular blocks and pieces eroded from the delicately lenticular sandy, silty, and shaly material which is interbedded with the conglomerate.

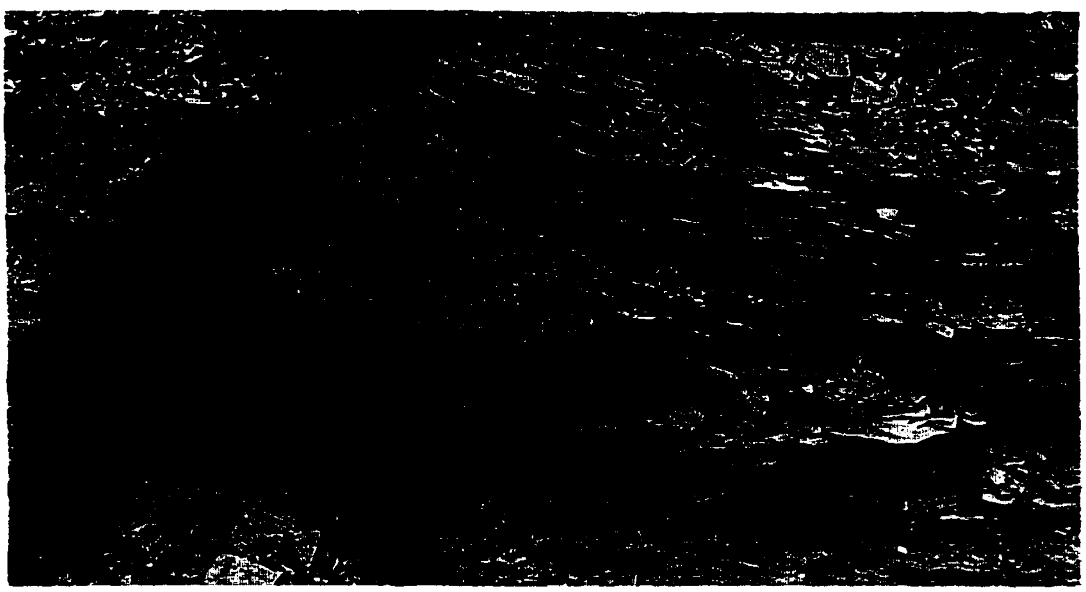

Figure 26. Tidal channel filled with shale and silty material. The channel had cut into one of the thicker conglomerate layers. Same exposure as shown in Figure 22.

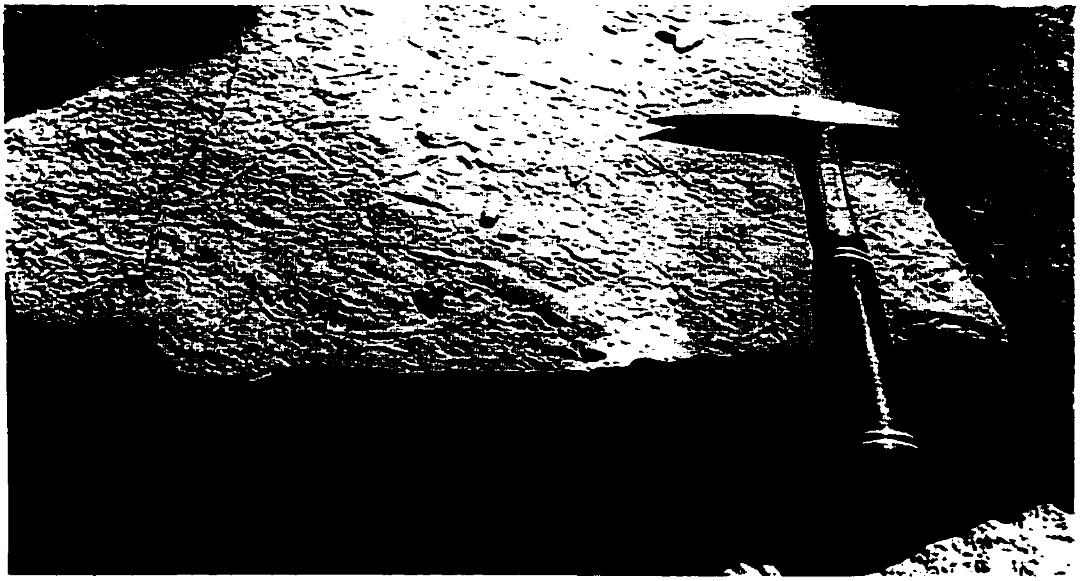

Figure 27. Trails and burrows seen on bedding surface of the tidal flat deposit shown in Figures 22-24.

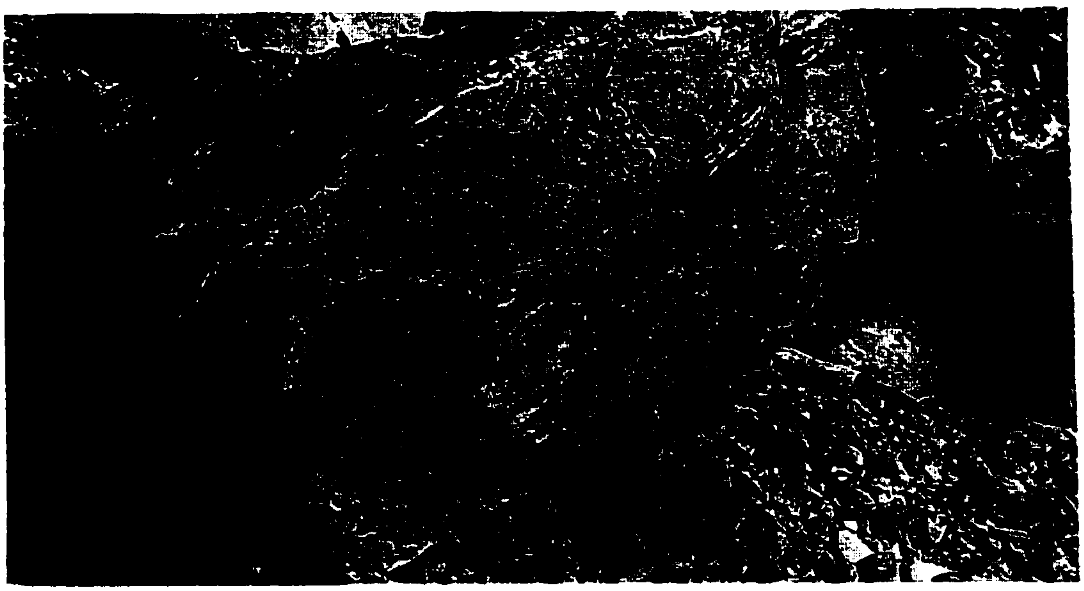

Figure 28. Portion of angular block, composed of laminated shale and silt, projects above bedding surface of tidal flat deposit shown in the last group of figures.

Cretaceous of Southwestern Texas

A sequence exposed in road cuts along highway 90 from one to six miles east of Langtry, Texas, exhibits the same bedding features which characterize modern tidal flat deposits. These cuts ecpose from 10-15 feet of section. Bedding surfaces could not be examined.

Thin layers and laminae of fine sand, silty and shaly material are interbedded (Figures 29 and 30). The layers range in thickness from one foot to fractions of an inch. The layers are laterally discontinuous. A single bed can rarely be traced over 20 feet laterally. In cross section the beds are shaped like thin, elongate, irregular wedges, lenses, discs, pods, and spindles. The bedding is essentially horizontal and the individual layers may appear to be more continuous than they actually are when observed from a distance.

No flat-pebble conglomerates were observed in this sequence, but only 10-15 feet of strata are exposed in these road cuts. Some of the sandy and silty layers appear ripple marked in cross section views. No bedding surfaces were examined, however.

It can easily be seen that the stratification exhibited in Figures 29 and 30 from the Cretaceous of Texas very closely resembles that shown in Figures 22, 23, and 24 from the Cambrian of Missouri.

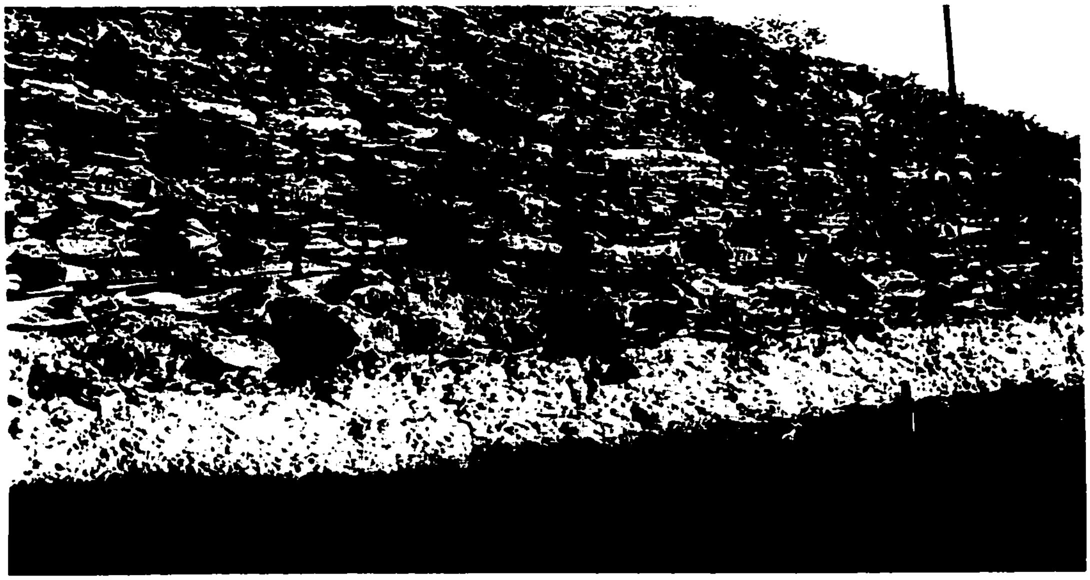

Figure 29. Tidal flat deposit in Cretaceous unit about 1 mile east of Langtry, Texas, on Highway 90. Thin, discontinuous, elongate lens-shaped and disc-shaped units consist of alternating beds of fine sandy, silty, and shaly material.

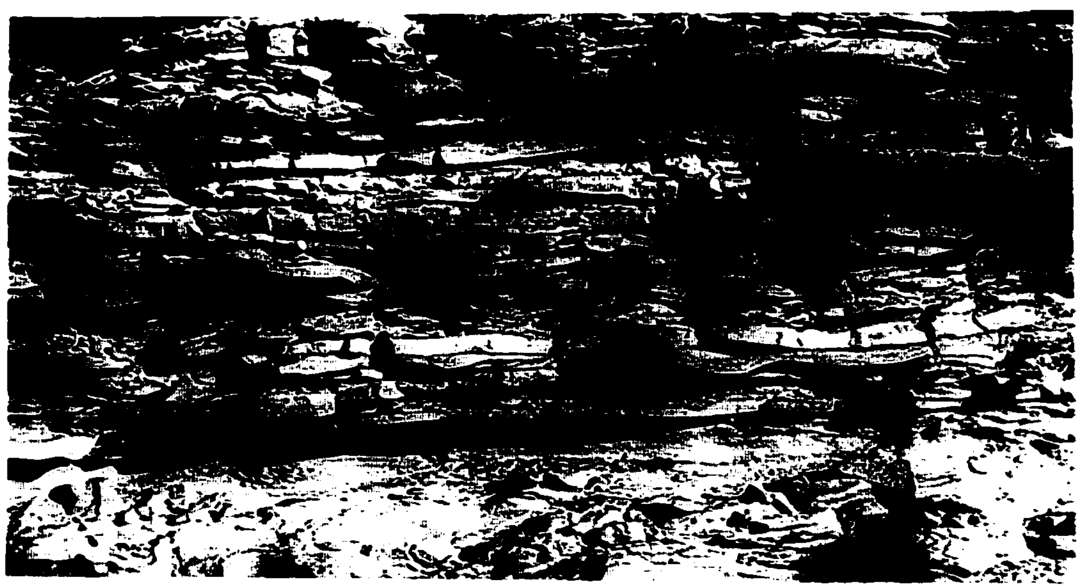

Figure 30. Closeup of same tidal flat deposit shown above. Compare this with Figures 22-24.

Other Possible Occurrences

Other probable tidal flat deposits were observed during the present study in the Glen Rose formation (Cretaceous, near its type locality), in the Atoka formation (Pennsylvanian, Boston Mountains of Arkansas), in a Permian unit exposed at Lake Kemp in the vicinity of Wichita Falls, Texas, and in the Dakota formation (Cretaceous) near Canon City, Colorado.

Other Reports of Ancient Tidal Flat Deposits

Dunbar and Rodgers (1957, p. 71-72) point out that few ancient tidal flat deposits have actually been reported. They have listed reported occurrences of ancient tidal flat sediments by van Straaten in the Psammites du Condroz (Devonian) of the Belgian Andennes, and by Richter in the Hunsruckschiefer (Devonian) of the Rhineland (Dunbar and Rodgers, 1957). The authors state that, "Possible tidal flat sediments in the United States are the thinly laminated, strongly mudcracked, very clayey limestones of the upper Silurian of the Central Appalachians and New York (parts of the Tonoloway and Manlius limestones), but proof is lacking."

Dunbar and Rodgers have included two photographs in their text which exhibit stratification features that suggest deposition in tidal flat environments. These exposures have apparently not been previously recognized as possible tidal flat sediments. One is the Oswego sandstone (Ordovician) at Salmon River Falls, New York, which is figured on page 98, figure 43. The caption reads as follows. "Irregularly bedded, lenticular sandstone and shale." This so closely resembles Figures 22, 23, and 24 that it looks as if it could have been photographed from the same exposures. The other is in the Trenton limestone (Middle Ordovician) shown on page 118, figure 58. Here the Trenton has been photographed where it non-conformably overlaps on Pre-Cambrian granite at Montmorency Falls, east of Quebec City. Compare this with Figure 30.

Potter and Glass (1958) have suggested a tidal flat origin for certain Pennsylvanian deposits in southern Illinois.

Tanner (1953) has interpreted certain dark blue-gray and gray shales, in the upper Pennsylvanian of Oklahoma, as tidal flat deposits. The material is apparently thinly bedded, but his description is not clear and detailed. He reports ripple marks, leaf imprints, and the presence of carbon films in the shales.

Apparently tidal flat deposits are relatively common but have not been widely recognized.

<u>Summary of Tidal Flat Bedding and Structures</u>

Recent and ancient tidal flat deposits are rather thinly stratified. Discontinuous, streaky beds and laminae generally consist of interlayered sandy, silty, shaly, or carbonate material. In cross sectional views, the shapes of the bedding units resemble thin, elongate, irregular wedges, lenses, discs and spindles (Figures 22, 23, 24). Thicker layers of intraformational or flat-pebble conglomerate, and of sandy material or shell debris, are commonly interbedded with the thinner units (Figure 25). Channels filled with silty, shaly, or sandy material are commonly present (Figure 26). Cross-bedding may be present in these channels. Tracks, trails, and burrows of organisms, drag marks, ripple marks, mud cracks, miniature deltas, and crenulated algal mats are features which may be preserved on bedding surfaces.

Discussion of Tidal Flats

Tidal flats may superficially resemble deposits that accumulate in the intermediate zone. Agitation is intermittent in both environments. Currents, however, dominate in the tidal flat environment and wave turbulence rules the intermediate zone. As a result, current features characterize tidal flat deposits. The beds are discontinuous, more planar, wedge-shaped, lenticular, disc-shaped, spindle-shaped, and pod-shaped. Channels, flat-pebble conglomerates, cross-bedding, and surface features (tracks and trails, drag marks, mud cracks, crenulated algal mats, and so forth) distinguish the tidal flat deposits from those of the intermediate zone.

It has been pointed out that current features predominate over wave features in high energy deposits. Agitation is continuous in the high energy zone but is intermittent and more variable on tidal flats. Therefore, sandy, silty, shaly and calcareous material can accumulate on the tidal flats but only coarser material is deposited in high energy environments. This alternation of texture and lithology on tidal flats results in thinner bedding, because the different materials offer varying resistance to weathering. High energy deposits commonly appear to be thick bedded as a result of cementation.

Apparently tidal flat deposits may occur at the base of transgressive sequences. Widespread tidal flat deposits generally occur only in protected areas such as bays, inlets, estuaries, and so forth. During transgression they might thus be protected from excavation by the surf zone.

Lagoonal Deposits

No detailed descriptions of lagoonal bedding and structures in modern sediments or ancient deposits have been published to the writer's knowledge. Textures, lithologies and faunas that characterize modern lagoonal deposits are relatively well known. No undoubted ancient lagoonal deposits have been studied during this investigation. Bedding and structures must be inferred from a knowledge of processes, structures, and so forth, which are known from other studies of modern lagoons.

Review of E. D. McKee's Description of Lagoonal Deposits (1957)

Lagoons at Corpus Christi, Texas, and Sonora, Mexico, were observed by McKee. McKee states that stratification in lagoonal deposits may be expected to consist dominantly of horizontal beds and laminae, because most of the sediments are accumulated under conditions of quiet water. He considers that wave and current activity are relatively unimportant in most lagoons. Currents may be important locally, where tidal channels occur and near the mouths of streams. McKee believes that in the interpretation of ancient rocks of lagoonal environment, recognition must be based more on texture and composition than on any distinctive types of structure. He states that, "Of major consideration, however, is the relationship of the lagoonal deposits to those of adjacent environments, especially of the barriers most of which have characteristic structures.".

The deposits which were examined exhibited weakly defined, horizontal beds, in some cases, and non-stratified or structureless clays and muds, in other cases. Local features and structures included ripple marks, mud cracks, clay balls, and organic tracks and burrows. In places where the surface is bare, irregular shrinkage cracks can be observed in yellow-brown, gray or black, sticky mud; elsewhere it is covered with mats of vegetable matter. Roots and cracks help destroy the bedding. In and near tidal channels, layers of sand, sandy shell material and coquinas may occur interbedded. Cross-bedding may be found in the channels. Accumulations of sandy clay balls that range from one-half inch to 3 inches in diameter are commonly found in lagoons of the Texas Gulf coast. Flat lying layers of black carbonaceous matter and plant roots are often comspicuous. Holes of burrowing animals may be abundant. Where lagoons are separated from the sea by barrier islands, extensive sand flats may form adjacent to the lagoon on the inner side of the barrier islands. Parallel type ripple marks oriented with crests parallel with the lagoon are common structures on the surfaces of these inner sand flats.

"Sediments in lagoons may be from any of four principal sources or from combinations of these. Most commonly they are introduced from the landward side and consist of detrital materials, clay and silt, or if in an area of marked relief, coarser fragments also. Sediments also may be introduced from the seaward side through tidal currents, exceptionally high waves, or by the wind. Another source of sediment is from dissolved salts which, in areas of poor circulation where evaporation exceeds inflow, may be exceedingly significant. A fourth source is from organisms, either invertebrates that thrive in the quiet muddy waters or that float in, or plants that become extremely abundant in the late stages of lagoon filling when swamp conditions develop."

Inferences as to the Nature of Lagoonal Deposits

Most of the material consists of clay and silt transported from the landward side by streams. This material settles from suspension under quiet conditions. Flocculation may also result in rapid deposition of clay aggregates. Coarser sand and shell material may be transported through tidal channels and be deposited in the lagoon in and near the channels. Sand and silt may also be transported into the lagoons by winds and settle from suspension. Sandy clay balls may be transported into the lagoon from either landward or seaward sides. Burrowing organisms and plant roots may secondarily destroy bedding features. During low tides marginal areas may be subjected to subaerial exposure and desiccation features (mud cracks, irregular shrinkage cracks) may form.

The bottom should be relatively smooth and flat. The surface may be locally scoured by tidal channels. Ripple structures produced by tidal currents may cover the marginal sand flats. Smaller scale, irregularities formed by burrowing animals, mud cracks, and so forth, may be covered with fine material and preserved. Accumulation of sandy mud balls may develop irregular, lumpy, bedding surfaces. Portions of the bottom may be intermittently subjected to wave turbulence and wavy, undulatory, rippled surfaces may be formed and buried by the ensuing accumulation under quiet conditions, and thus preserved.

Wave and current ripples could be preserved in lagoons. Channel scour and fill and cross-bedded structures could form in and near tidal channels. Animal burrows, mud cracks and irregular shrinkage patterns may be locally preserved. Layers of mud ball accumulations may appear as irregular, rounded, lumpy structures.

Thick and thin, structureless layers of homogeneous clay and silty clay should be the main type of bedding (low agitation). These layers could be continuous laterally over great distances. This type of bedding results from material which settles from suspension under quiet conditions. Locally, discontinuous, thick or thin beds of coarser material should occur. These could represent deposition by tidal currents. These units would be shaped like irregular wedges, lenses and discs. Thin zones of wavy, undulatory or rippled beds might record deposition under conditions of intermittent wave turbulence..

Lagoonal deposits may be expected to exhibit great variation in bedding thickness, features and structures within rather thin stratigraphic intervals.

OFFSHORE ENVIRONMENTS

Deposits of the High Energy Zone

The zone of continuous wave agitation (high energy zone) extends from the low tide shoreline to the outer limit of continuous wave agitation of the bottom.

Bedding and structures that form in the zone of continuous agitation have not been described. Nor have any attempts been made to draw inferences regarding the structures of these deposits, to the writer's knowledge. Bedding in these deposits cannot be studied by excavation or other direct observational techniques yet developed. Therefore, inferences regarding stratification and structures must be drawn from a knowledge of the processes and surface forms that characterize this environment.

It may be possible to subdivide the zone of continuous agitation into a surf zone or breaker zone which extends from the low tide shoreline to the outer line of breakers, and a zone which extends beyond the surf zone to the outer limit of wave agitation of the bottom. This outer zone might be called the extra-surf zone. This extra-surf zone would grade seaward into the zone of intermittent wave agitation (intermediate zone). Bedding and structures formed in these two zones might be distinguishable from each other. The stratification should be roughly similar but there would be sharp or gradational differences of degree and scale as a result of the seaward decrease in process intensity.

Surf or Breaker Zone Deposits

Waves and currents both agitate the bottom of the surf zone. The continuous turbulence prevents the accumulation of fine materials. Wave turbulence suspends the material which is then readily transported by the currents. Current patterns may be very complex as work done by the Beach Erosion Board has shown. Currents may shift directions during various times of the day (Arlman, Santema, and Svasek, 1958). Longshore currents, drift currents, rip currents, tidal currents, and eddy currents may all combine to form a very intricate and variable current pattern. Wave and current strength may exhibit great variation with the seasons (Shepard and Inman, 1950), (Shepard, 1950; 1 and 3), (Trask, 1956), (Inman and Rusnak, 1956). Such seasonal variation results in cutting and erosion of the beaches in the winter and filling of the same areas in the summer on the California coast.

Much of the material is transported as suspended load. Material is suspended by breakers and is displaced parallel to the coast by longshore currents (Arlman, Santema, and Svasek, 1958). Transportation in the breaker zone is also accomplished by the orbital movement of water beneath waves. Shepard (1950; 1) has shown that currents inside the breakers are generally stronger than currents outside the breakers. His data show that off the southern California coast current velocities inside the breakers are from 2.5 to 4 times greater than those outside. Johnson (1956) also has found that the strongest littoral currents are inside the breaker zone.

Handin (1951) states that, "Observations by the Beach Erosion Board show that sand in suspension is concentrated at the plunge point, and that only 25 feet seaward of that point the concentration is reduced by a factor of 4. At a point 275 feet seaward of the plunge point, the concentration is only one seventeenth of that within the breaker zone." "At the plunge point the distribution of suspended sand is uniform from bottom to surface, but the sand content near the surface decreases rapidly seaward of the breaker zone, since there is no known force present to keep the sand in suspension beyond the region of turbulence." "The maximum rate of sand movement was found to be in a zone about 10 feet shoreward of the high water plunge point, the rate dropping off rapidly seaward, but remaining fairly constant to the limit of uprush of the waves."

Deposition and accumulation are intermittent in the surf zone. Deposition and reworking may alternate over short periods of time.

The surface of the bottom in the surf zone is generally quite irregular and roughened. Longshore bars and troughs are prominent features (Shepard, 1950; 2). These bars and troughs are closely related to the depth of the breaking waves, wave height, position of breakers, and so forth (Shepard, 1950; 2). Multiple sets of bars and troughs may form in response to strong variation in wind, wave and current characteristics. According to observations made by Kuenen (1950), inside the plunge point of breakers the ripples are not of the oscillation type but are true current-formed ripples. Apparently, these ripples are not commonly preserved.

Bedding and Structures - Irregular scour and fill structures and intricate sets of cross strata oriented in various directions should be expected to develop in the surf zone in response to the strong variation in wave and current strength and direction. Bedding units should be laterally discontinuous and approximately parallel to the surface of deposition. The bedding planes should appear in cross section as planar or gently curving, arcuate lines which converge and diverge at small angles. These form complete or incomplete wedges, disc-shaped, and lens-shaped units depending upon whether and how the lines intersect. Internal laminations other than cross laminae generally should be uncommon or lacking. Bedding planes would be primarily related to texture changes (grain size, shape, sorting, packing) rather than to lithologic changes.

In weathered exposures of lithified sediment, the bedding thickness is commonly related to cementation and selective removal of cement. This in turn is related to primary depositional features such as texture. Surf zone deposits may appear as thick, structureless units where they are well cemented. The internal structure and bedding may be revealed only by detailed examination.

Examples of Surf Zone Deposits - Probable surf zone deposits have been observed during this study in the Glen Rose formation (Cretaceous) of central Texas, the Franconia sandstone (Cambrian) of southern Wisconsin, and the St. Peter sandstone (Ordovician) of southern Wisconsin.

Figure 31 shows a surf zone deposit in a Cretaceous formation near Austin, Texas. Opposed sets of cross strata can be seen. Figure 7 from the Franconia sandstone of southern Wisconsin shows a thick sand unit with internal scour and fill structures and a complex pattern of cross-bedding. Figure 32 shows a surf zone deposit in the St. Peter sandstone of southern Wisconsin. The bedding planes consist of planar and smoothly curving lines. Two prominent biconvex lens-shaped units can be seen.

Extra-Surf Zone Deposits

The extra-surf zone extends seaward from the outer limit of breakers to the outer limit of continuous wave agitation of the bottom.

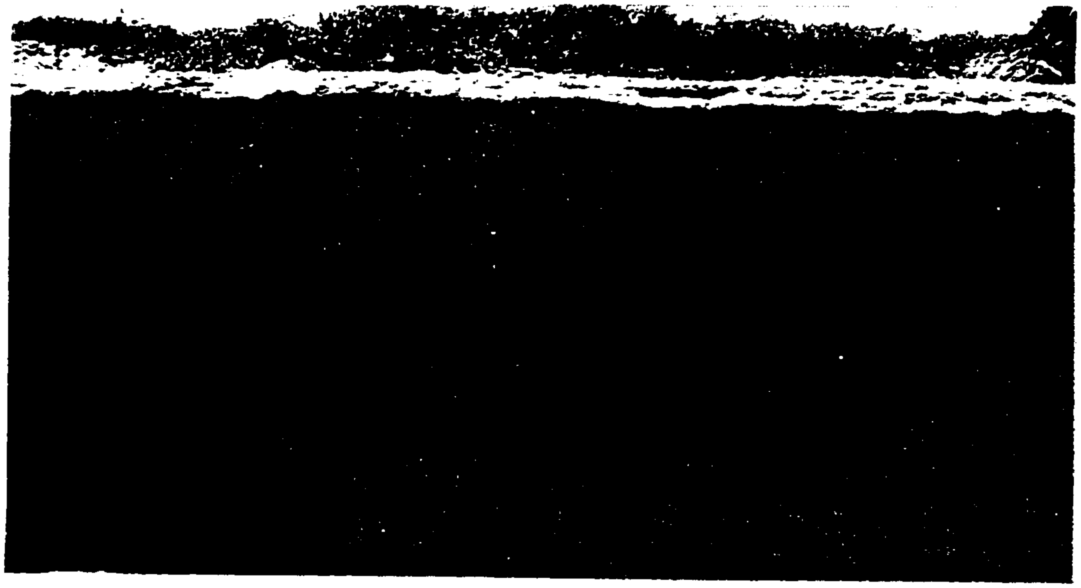

Figure 31. Probable surf zone deposit in a Cretaceous carbonate unit in central Texas. The material is calcarenite. Note the opposed sets of cross strata. Cedar Park quarry, near Austin, Texas.

Figure 32. Apparent surf zone deposit in the St. Peter sandstone (Ordovician), approximately 5 miles south of Blanchardville, Wisconsin, on Highway 81.

Waves and currents operate on the bottom beyond the breaker zone but with less turbulence and decreased intensity. The current patterns in this zone should be somewhat less complex and more stable. The currents outside the breakers should more closely resemble broad, ill-defined sheets of moving water that gently sweep the bottom (Dunbar and Rodgers, 1957). Such currents should be more laminar and less turbulent. Turbulence by waves is sufficiently developed that large portions of the bottom of this zone may be covered with oscillation ripple marks (Trask, 1955). Deposition and accumulation here is intermittent with much shifting about of the material. Rates of supply and deposition may vary with local and seasonal changes in wind strength and direction. Bottom current velocities are generally greater inside the breaker zone than beyond it (Shepard, 1950; 1). Although currents inside the breaker zone are stronger, Johnson (1956) states that turbulent forces are generally great enough seaward of the breaker zone to cause a general alongshore movement of sand out to depths of 60 to 80 feet.

Offshore most of the material transported by bottom currents and waves is carried as bed load (Arlman, Santema, Svasek, 1958). This is probably a result of the general decrease in turbulence.

Although portions of the bottom of this zone are covered with ripple marks, generally the bottom should be smoother and flatter than that inside the breaker zone because of the decreased wave and current turbulence. Strong wind variation may, however, result in smaller scale scour and fill, and other bottom irregularities. These may be alternately excavated and filled. Filling of irregularities may result in the formation of cross-bedding. Larger scale bar and trough structures associated with the breaker zone should not be developed seaward from the breakers.

Bedding and Structures - It appears more probable that oscillation ripples would be preserved in sediments deposited outside of the surf zone than inside it. Cross-bedding probably develops, but it should be on a smaller scale than that which develops inside the breakers. The cross-bedded units should not be so irregular or show the diversity of orientation shown by that which develops in the surf zone. Sets of cross strata with foresets dipping in opposed directions might commonly develop. This could be caused by shifts in current direction related to changes in wind direction and in angle of wave approach.

Bedding planes should resemble those of the surf zone, but would differ in scale and degree. Beds would be laterally discontinuous and roughly parallel to the surface of deposition. Continuity of bedding units should, however, exceed that of those formed in the surf zone by increasing degrees in a seaward direction. In cross sections the bedding planes should appear as planar, smoothly curving or arcuate lines which converge and diverge at small angles. These lines should be less arcuate and diverge at smaller angles than the bedding planes developed in the surf zone. The shapes would be similar to those of beds inside the breakers, and the wedges, lenses, discs, and so forth should be even more elongate. Internal lamination (other than cross laminae) should be more common. Generally speaking, continuity should increase in a seaward direction and the beds should more closely approximate tabularity.

In lithified exposures the bedding planes would be related to primary depositional features like texture rather than to lithologic changes. Interpretation of bedding thickness from weathered exposures would be influenced by cement relations which in turn may be related to the depositional features. Like surf zone sediments, extra-surf zone deposits may appear as thick internally layered units where they are well cemented. They may even appear structureless if hastily examined or if features are marked by sorting.

<u>Discussion of Surf and Extra-Surf Zone Deposits</u> - It has been suggested that bedding and structures of the surf zone would probably differ in degree and scale from those of the extra-surf zone. These differences may be gradational. The differences in degree and scale would be produced by

the general decrease in wave and current process intensity with increasing depth and distance from shore. Therefore, the degree and scale which characterize bedding forms in these two zones may differ markedly in different areas along different coasts and even along the same coastline. It may be easy to distinguish deposits formed in these two zones where they are exposed in vertical or lateral juxtaposition. This distinction might be more difficult to make if only one deposit is exposed. This subdivision might be applied with more certainty to a single sequence than to exposures in different areas.

Both surf zone and extra-surf zone deposits accumulate within the zone of continuous wave agitation (high energy zone), and high energy deposits should be easy to recognize whether or not the distinction between surf and extra-surf deposits can be made.

If these two environments can be distinguished in vertical or lateral juxtaposition, it may be possible to deduce shoreline advance and recession from limited exposures.

<u>Examples of Extra-Surf Deposits</u> - Apparent surf and extra-surf deposits have been observed in the St. Peter sandstone of southern Wisconsin. These features do not photograph well even where clearly observed because of the whiteness of the sand, lack of contrast, cementation, and masking of the features by excellent sorting.

Another probable gradation of surf zone and extra-surf zone deposits was observed in the Harding sandstone (Ordovician) near Canon City, Colorado.

Deposits of the Intermediate Zone

The intermediate zone is that portion of the offshore bottom which is subjected to intermittent wave agitation. This discontinuous wave agitation may be related to local or seasonal wind variation. Longer periods of quiescence generally follow the interrupted lowerings of wave base. The intermediate zone grades shoreward into the extra-surf segment of the high energy zone. It grades seaward into the low energy zone.

Bottom currents may be present but are generally weak (Kuenen, 1950). Somewhat stronger bottom currents may accompany the storm wave activity, but these would generally not be strong enough to obliterate the wave formed features.

Much of the material that accumulates in this zone settles from suspension or is transported by weak bottom currents. Accumulations of shell material may constitute a relatively high percentage of the material. Deposition and accumulation are generally rather slow and discontinuous. The coarser material (commonly shells and shell fragments) is commonly concentrated into layers of coquinite and shell hash by the storm waves. Wavy, irregularly undulatory, or rippled bottom surfaces are produced by the agitation. After the storm subsides and quiet conditions resume, the finer material settles on the roughened surface (Rich, 1951). If the storm agitation is very infrequent, deposition by settling may smooth out the roughened surface during the intervening quiet periods.

Bedding and Structures - The deposits are thinly bedded and commonly range from one-half inch to 4 inches in thickness. In cross section the beds appear wavy, undulatory, or rippled, and are laterally discontinuous. Individual layers can rarely be traced beyond 40-50 feet laterally. Layers of coquinite, calcarenite, or mixtures of carbonate mud and shell hash are commonly separated by very thin clay or shaly layers or laminae which offer very little resistance to weathering. Bedding planes of the physical separation variety are produced when these shaly layers are selectively removed. The bedding thickness is related to the frequency of wave agitation. Cross bedding and scour and fill structures are generally absent.

Examples of Intermediate Deposits - Well developed intermediate deposits are widespread in Ordovician and Mississippian carbonates in the Upper Mississippian and Ohio Valleys where the depositional province was undoubtedly a broad platform or shallow epeiric sea. Figures 8 and 33 show typical intermediate deposits in the Platteville formation (Ordovician) of southern Wisconsin. Deposits of this type have been observed in Ordovician, Devonian, and Mississippian carbonate units in the Pahranagat Range of Nevada. Figure 34 shows an intermediate deposit in the West Range formation (Devonian). The major depositional province in the Pahranagat Range was apparently a miogeosyncline. The intermediate deposits there may indicate broad shelf development.

Intermediate bedding is also found in cyclic Pennsylvanian deposits in the Sacramento Mountains of New Mexico (and elsewhere) where the seas advanced and withdrew over broad, shallow shelves and coastal plains. Figures 9 and 35 show intermediate deposits in the Fresnal group (Pennsylvanian) in the Sacramento Mountains.

Intermediate deposits can be seen in Texas Cretaceous units, such as the Glen Rose and Walnut formations (Figure 37).

<u>Discussion</u> - It has been suggested that intermediate bedding forms on broad, shallow, shelves with very low gradients. In coastal areas with steeper gradients, intermediate bedding may be replaced by interlayered high and low energy deposits. Deposits consisting of coarser, current bedded material might alternate with deposits consisting of continuous, tabular layers of fine material which settled under quiet conditions. Further steepening of gradients might result in turbidity current and slump deposition.

Figure 33. Intermediate carbonate deposit in the Platteville formation (Ordovician) near Janesville, Wisconsin. Notice the thin, wavy, discontinuous carbonate layers separated by thinner shale breaks.

Figure 34. Intermediate carbonate deposit in the West Range limestone (Devonian) of the Pahranagat Range in Nevada.

Figure 35. Intermediate limestone deposit in the Fresnal Group (Pennsylvanian) of the Sacramento Mountains of New Mexico. Thin shaly partings separate the wavy, fossiliferous, limestone beds.

Figure 36. Rippled surface of intermediate limestone covered with thin layer of shale (dark). St. Joe limestone (Mississippian) near Jasper, Arkansas, on Highway 7.

Figure 37. Intermediate carbonate deposit in the Walnut formation (Cretaceous) near Austin, Texas. Shell material is concentrated in the thin, discontinuous, wavy layers.

Deposits of the Low Energy Zone

This offshore zone lies below the influence of wave agitation. This zone may include the slope-basin environments (Clinothem and Fondothem of Rich, 1951). This zone grades shoreward into the zone of intermittent agitation (intermediate zone).

Bottom currents, if present, would generally be weak and resemble broad, ill-defined sheets of moving water that gently sweep the bottom (Dunbar and Rodgers, 1957). Where slope and basin are developed, turbidity currents and slumping may constitute an exception to the above generality. Currents sweeping through narrow straits may be another. Most of the sediment that accumulates here consists of fine material (silt, clay, carbonate mud, and so forth) which may be transported by surface currents or locally precipitated. Most of the material settles from suspension under quiet conditions. Fossil remains of bottom-dwelling or pelagic forms may be generally scattered through the rock. These remains have generally not been sorted and concentrated by water movement. Shells may, however, be concentrated locally as a result of contemporaneous non-deposition of the finer sediments in which they normally would have been bedded.

The bottom surface should generally be smooth and flat. Ripples would be more difficult to develop in the finer material even if the bottom should be infrequently stirred. Small scale, local irregularities could be formed by organic structures or rafted material.

Bedding and Structures - The low energy deposits could be thick or thin bedded. The beds would generally be laterally continuous over great distances (hundred of feet, even miles). In cross section the beds would resemble persistent, tabular or sheet-like forms with parallel upper and lower surfaces. Wedges, lenses, discs, and so forth would be very uncommon or absent entirely. Scour and fill, cross-bedding, and so forth would generally be absent. Undulatory or rippled beds should be absent or exceedingly rare. Thicker units may be internally laminated or layered. These internal laminae would be parallel with the bedding planes. Minor secondary internal structures such as organic burrows may be observed.

Thickness would be closely related to the rate and continuity of supply and accumulation. Discontinuous supply and accumulation would result in thinner bedded or laminated units. Continuous supply and accumulation would result in thicker beds. On weathered surfaces, bedding planes may be expressed as physical or non-physical separations. Physical breaks are related to varying resistance offered to weathering by layers of different lithology (limestone, dolomite, shale, and so forth), variation in cement, compaction, and so forth. Non-physical separations are commonly related to variation in organic matter, carbonate, oxidation, reduction, and other color changes.

Illustrations of Low Energy Deposits - Low energy deposits are commonly found in offshore deposits in almost all depositional provinces. Figures 5, 10, 11, 38, 39, 40, 41, and 42 provide representative illustrations of low energy deposits in rocks of a wide range of geologic ages, formed in several depositional provinces. It can easily be seen that these deposits have very similar features.

Figure 38. Low energy deposit. The bedding is expressed by color changes. Navarro formation (Cretaceous) at Onion Creek, near Austin, Texas.

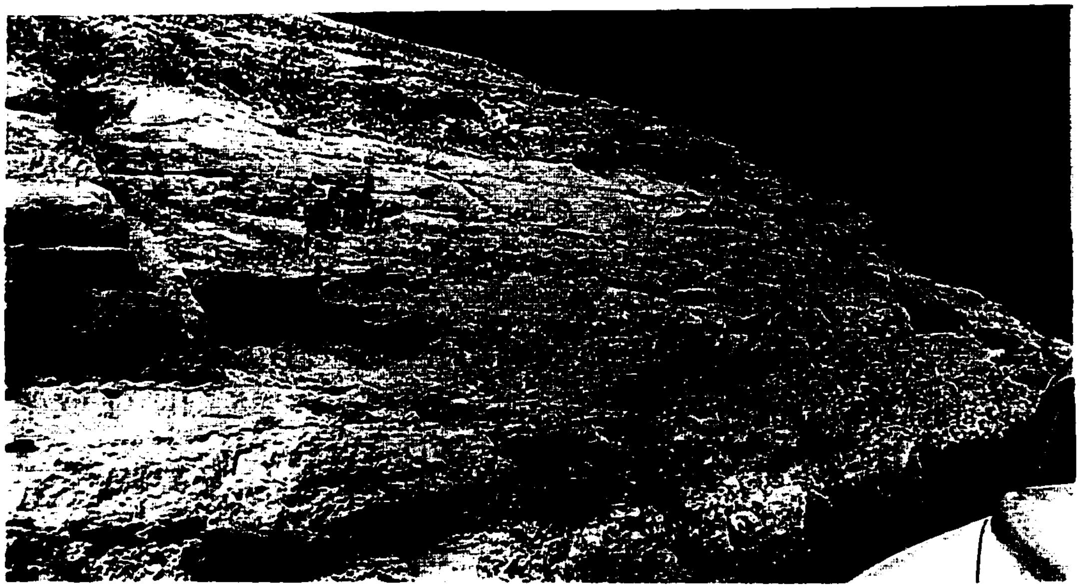

Figure 39. Low energy carbonate deposit which consists of tabular, laterally continuous sheets of carbonate separated by shaly partings. Jefferson City formation (Ordovician) on Highway 54 near Holts Summit, Missouri.

Figure 40. Kankakee formation (Silurian) in quarry in Joliet, Illinois. Splendid example of low energy deposit. Remarkably continuous, tabular, limestone beds are separated by thinner shale layers.

Figure 41. Laminated calcareous shale of the Pilot formation (Devonian) in the Pahranagat Range of Nevada. This is a typical low energy deposit.

Figure 42. Another typical low energy deposit consisting of laminated shale. Womble formation (Ordovician) on Highway 27 south of Washita, Arkansas. The beds are nearly vertical in this outcrop.

POSSIBLE FUTURE APPLICATIONS OF STRATIFICATION STUDIES

APPLICATIONS TO STRATIGRAPHY AND SEDIMENTATION

Discussion of General Problems

An understanding of stratification and its relation to environments and processes should provide a foundation of knowledge and principles which can be applied to stratigraphic interpretation.

Oscillations of sea level with respect to the land may be easily determined in near shore areas where continental and marine deposits appear in the geologic column. Recognizing sea level changes where only offshore deposits are exposed is not so easy a task.

The base level changes which accompany fluctuations of sea level influence the rate, nature, and amount of material supplied to offshore areas. Continuous accumulation may occur in some offshore areas at the same time that deposition and erosion alternate in the zone of strand migration. It might be possible to deduce deepening and shallowing conditions from the bedding patterns which developed in these offshore areas where sedimentation was continuous. Perhaps these offshore cycles could be matched with those containing the shoreline fluctuations.

Deepening and shallowing progressions may not always be associated with transgression or regression. Rise of the land may be accompanied by sinking of the sea floor, especially in geosynclinal regions. In this regard, Kuenen (1950) states that, "A shifting of the strand line need not occur, but rejuvenation of the erosion and a continual creation of space to accomodate the erosional products are the result." Depositional shoaling or subsidence could produce smaller scale changes in process intensity which would also be manifest by stratification patterns. These minor cycles might mimick the patterns associated with transgression or regression. Recognizing these cycles is important even though it may be difficult or impossible, on a local scale, to determine what caused the cycle. In areas where overlap-offlap stratigraphic relations have been obscured or obliterated by erosion, it may be possible to infer transgression or regression.

The accurate interpretation of geologic history has often been clouded or confused by lithologic contacts, formation boundaries, systemic boundaries, and so forth. Such artificial separations superimpose a discrete variable system of analysis on materials and processes which exhibit continuous variation, and thus bias one's reasoning.

Stratigraphic analysis is retarded by promiscuous application of vague, poorly understood concepts. This stems from a lack of knowledge of sedimentary factors and processes. In the literature reference is commonly made to complete intervals or parts of a sequence which are "present" in one area and "missing" in another area. Stratigraphers boldly insert unconformities, disconformities, paraconformities, diastems, and so forth, in their columns. (These are usually represented by wavy lines.) Commonly it is implied that the "missing section" was deposited and then eroded. Where offshore sequences are involved, it is questionable whether much submarine erosion could be accomplished except locally (in narrow straits and submarine canyons). These "missing sections" might, in many instances, be more accurately explained by non-deposition, changes in the rate of deposition, or environmental changes in the different areas. For the sake of accuracy an attempt should be made to distinguish between deposition and erosion, non-deposition, and very slow accumulation. Knowledge of environmental factors should clear up the concept of the "missing section." The observed thickness of contemporaneous units may be resolved by reconstruction of the network of depositional environments.

The concept of unconformity, disconformity, paraconformity, diastem, and so forth, should be reevaluated in terms of processes. An attempt should be made to determine whether an apparent "break" or "gap" resulted from deposition and removal of material or from non-deposition. The apparent unconformity, disconformity, and so forth, may be manifest by an erosion surface. If so, an effort should be made (but rarely, if ever, is) to find whether the erosion surface represents inherited depressions which were carved during a previous cycle and filled during a later cycle, or whether the relief was developed and filled in the same cycle. At any rate, perhaps some other means of depicting time breaks that result from non-deposition should be proposed to replace the wavy line.

Application of the Stratification Pattern Concept to the Interpretation of Sedimentary Cycles

The use of stratification patterns in determining deepening and shallowing trends has been previously discussed. Patterns containing shore zone sediments consist of deposits which reflect accumulation in beaches, tidal flats, lagoons, and so forth. Indications of shoreline advance or retreat may be deduced from exposures where these deposits appear in vertical or lateral juxtaposition. In sequences containing offshore sediments, deepening and shallowing patterns involve high, low, or intermediate energy deposits.

Depositional cycles involve all indications of changes in relative level of land and sea which are recorded in continental, shorezone, and offshore deposits. Such cycles are manifest by patterns of stratification.

Remarks Concerning Carbonate Rocks

Where stratification patterns include several lithologic units (sandstone, shale, limestone), the very nature of the lithology and textural changes may be suggestive of deepening or shallowing cycles. Carbonate sediments, however, accumulate in high, intermediate, and low energy zones. Carbonates may, of course, also accumulate on beaches, tidal flats, lagoons, and so forth. Recrystallization, dolomitization, and so forth, may obscure or destroy original carbonate textures. Field observations appear to indicate that bedding is generally not obliterated by the above processes. Thick carbonate sequences which have been recrystallized, and so forth, may contain records of major and minor cycles which can still be interpreted from the bedding. A carbonate "facies" may consist of material which accumulated in several recognizable environments. Figures 12, 13, 14, and 15 show examples of deepening and shallowing cycles within carbonate units.

Application to the Interpretation of Sheet Sandstone Deposits

Analyses of bedding may shed light on the origin and deposition of widespread sheet sandstone deposits, like the St. Peter, Eureka, Oriskany, and so forth. Segments of such sand bodies must have been deposited in different environments (i.e., beach, surf zone, extra-surf zone, and so forth). Recognition of the stratigraphic positions of the deposits formed in these various environments and their aerial extent should reveal the manner of accumulation of the sheet.

As a result of regression of the sea, sands may be deposited out to the edge of a shelf. During the following transgression, currents may be sufficiently strong to prevent the accumulation of silt and clay for long periods of time (Kuenen, 1950, and Shepard, 1959). Thus, these shelf edge sands may remain uncovered for extended periods.

Bottom currents may be strong enough to transport the loose sandy material or shift it about. Although these sands may have originally accumulated mainly in beach, surf, or extra-surf environments, the upper portions may be subjected to reworking by a different set of processes. The bedding should reflect this change. Depending on the strength, turbulence, and other aspects of these deeper water currents, various bedding features would be formed. Such deeper currents may generally be expected to exhibit less turbulence than shallow water currents. They should not generally be confined by channels to the extent that shallower currents are delimited. The surface of the bottom should, in general, be smoother than that closer to shore where wave turbulence is much greater. Scour and fill structures should not commonly be developed, and are likely to be absent. Cross bedding could be extensively formed by such currents. This cross bedding may be of a different nature than that formed in shallower water. It may be possible to distinguish these types.

The above reasoning is purely hypothetical, but application of such a line of reasoning may greatly increase the accuracy of stratigraphic interpretation. When more is known about the nature of the deeper water currents, then their influence on stratification may be more accurately determined. It may eventually be possible to interpret such situations where features developed in response to a given set of conditions and were preserved with little or no modification when subjected to an entirely different set of conditions for a relatively long interval of time.

Stratigraphic Analysis Applied to Deposits that Represent Only One Energy Level

It is easier to determine deepening or shallowing progressions from outcrops where deposits representing two or more energy levels are exposed than in exposures that reflect only one energy level. If a single energy zone were influenced by gradual deepening or shoaling conditions, process intensity might vary only within narrow limits. These variations may be reflected by subtle, almost imperceptible changes in the stratification features, commonly involving only slight changes in degree and scale.

High Energy Deposits

Influence of Primary Agents on Bedding

1. Waves and currents both operate continuously and most strongly influence the bedding that develops in the high energy zone.
2. Base level almost merges with the surface of the bottom of the high energy zone. Erosion and deposition may alternate with increases and decreases in wave and current activity which are related to wind variation.
3. Slope-Depth, Configuration of the Basin - These factors influence the location and dissipation of wave and current energy. These factors also regulate the width of the energy belts.
4. Supply and Accumulation - Deposition may be rapid but accumulation is slow and intermittent. Accumulation in this zone is not directly related to the rate and amount of material supplied to the environment. Sand, silt, and clay sized material may be supplied, but constant agitation allows only coarser material to accumulate.

Interpreting Deepening and Shallowing Conditions from High Energy Deposits - Look for evidence of vertical or lateral variation in process intensity reflected by the bedding features. Changes from surf zone to extra-surf zone bedding may be recorded by changes in degree and scale of bedding and structures (scour and fill, cross-bedding, shape, and so forth).

Low Energy Deposits

Influence of Primary Agents on Bedding

1. Waves and bottom currents exert little or no control on bedding in low energy zones. Surface currents may transport fine material suspended in high or intermediate zones and allow it to settle from suspension under quiet conditions.
2. Base Level - This zone is generally below the base level. Accumulation may be more permanent and closely related to supply characteristics as a result.
3. Slope-Depth-Bottom Topography - This influences the accumulation by controlling the divergence between the base level of deposition and the depositional interface.
4. Supply-Accumulation - Deposition is commonly slow except in the case of turbidity current and slump deposits. Accumulation is very closely related to supply and may, therefore, be continuous or discontinuous.

Interpreting Deepening and Shallowing Cycles from Low Energy Deposits - Supply-accumulation characteristics exert the strongest control on bedding. Since the material accumulates below base level, the continuity of accumulation depends on the continuity of the supply. Discontinuous supply should result in thinner bedding. Continuous supply should result in thicker bedding.

Deepening conditions are generally accompanied by landward displacement of shorezone and agitation belts as a result of eustatic changes in sea level, orogeny, epeirogeny, and so forth. Base level of streams is generally raised as a result of this change and they supply decreased loads to the seas. A given offshore area becomes progressively farther from sources of material. As a result of the above relationships, the supply should decrease and become more discontinuous. This should result in progressively thinner bedding. Thus, in low agitation deposits, deepening conditions might be inferred from a vertical or lateral progression toward thinner bedding.

Shallowing conditions are generally accompanied by seaward migration of shorezone and agitation belts resulting from eustatic lowering of sea level, epeirogeny or orogeny. The base level of streams is generally lowered and they carry increased loads to the seas. A given offshore area would become progressively closer to the source of material and competent transporting agents. These relationships should result in an increase in the amount of material supplied to offshore areas. The continuity of supply and accumulation should increase. This should result in thicker bedding. Therefore, a progressive vertical or lateral change toward thicker bedding might reflect a lowering in relative level of land and sea.

Intermediate Energy Deposits

Influence of Primary Agents on Bedding

1. Waves are the most important agent in the intermediate zone. Most of the bedding features result from intermittent wave agitation.
2. Currents - Bottom currents are generally weak and cannot eliminate wave formed features. Surface currents may supply finer material which accumulates during quiet periods.
3. Base Level - This zone is generally below base level, but base level is not as important an element in this zone as it is in the high and low agitation zones.
4. Slope-Depth-Bottom Topography - Typical intermediate bedding apparently reflects very gentle shelf gradients. Steeper gradients may result in interlayered high and low energy deposits rather than the characteristic undulatory bedding.

5. Supply-Accumulation - Supply and accumulation are somewhat more difficult to determine. It should generally be expected that accumulation would be rather slow and discontinuous.

Interpreting Deepening and Shallowing Progressions from Intermediate Deposits - Discontinuous wave agitation and intervening quiet periods exert greatest influence on bedding. The general thinness of the beds results from the frequency of intermittent agitation.

Deepening trends might be inferred from progressive increase in thickness of agitated units as a result of less and less frequent agitation. Increases in continuity of beds, and decreases in size of undulations might reflect decreasing agitation and deepening cycles.

Shallowing conditions might be reflected by progressive decrease in thickness as a result of an increase in the frequency of agitation. Progressive increases in wave agitation may also be indicated by decreases in continuity of beds, increases in scale of undulations, and so forth.

Integrated Analysis Applied to Regional and Continental Interpretation and to the Solution of Basic Problems

Stratification studies should offer an analytical approach which can be applied to the interpretation of depositional cycles that develop in response to relative changes in sea level with respect to the land. These relative changes in level are translated into stratification by the primary agents. Reconstruction of depositional cycles should be pursued without concern for formation boundaries, lithologic contacts, systemic boundaries, and so forth. A cycle may consist of several formations, or a single formation may encompass one or more cycles. Perhaps offshore cycles can be related to sequences composed of continental and shorezone deposits. The influence of shoreline advance and retreat on offshore sedimentation might then be determined. It may be possible to more closely delineate the actual extent of transgression and regression.

Continuous accumulation in offshore areas may preserve an unbroken record which accurately reflects the influence of relative changes in level of land and sea. Integrated analysis may suggest possible causes of these oscillations.

Once the scheme of major and minor cycles and their sphere of influence are understood, it may be possible to conclude that a major cycle has been caused mainly by a eustatic sea level change and that minor cycles record contemporaneous tectonic influence (orogeny, epeirogeny, and so forth) superimposed on the major eustatic cycle, or vice versa. This leads to a clear understanding of the principles that govern transgressive and regressive sedimentation.

If the nature and extent of the cycles can be determined, then ultimately a more reliable and meaningful concept of correlation may develop. Units may be correlated with reference to their positions in major and minor cycles, and eustatic cycles may have world-wide influence. Thus, barriers that block accurate interpretation of specific sequences of events (lithologic contacts, formation boundaries, systemic boundaries, and so forth) may be removed, at least figuratively.

An Example of Possible Criteria for Distinguishing Between Tectonic and Eustatic Control of Depositional Cycles

Perhaps it would be helpful to suggest a list of generalized criteria which would aid in interpreting the causes of major depositional cycles. One set of criteria would generally be associated with a cycle which was produced mainly by a eustatic change of sea level. Another set would be more diagnostic of a tectonically controlled cycle than a eustatic cycle.

Generalized Criteria that Might Commonly Reflect a Tectonically Controlled Cycle

1. Position of strand would be relatively stabilized.
2. Indications that the gradient of the shelf or slope increased during deposition.
3. Movements generally would operate in one direction for

longer periods of time and would commonly occur slower.

4. The sphere of influence would generally be local or regional.
5. Cycles might not match on opposite sides of a basin.

Generalized Criteria that Might Indicate that a Depositional Cycle Was Produced Mainly by Eustatic Sea Level Changes

1. The position of the strand would generally be displaced farther landward and seaward.
2. Eustatically controlled cycles would generally have a wider sphere of influence than a tectonic cycle. It may be world-wide.
3. Eustatic cycles might commonly match on opposite sides of a basin.
4. Eustatic changes of sea level generally fluctuate more rapidly and occur with greater rapidity.
5. Indications that the gradient of the shelf or slope decreased during accumulation.

It is obvious that none of the individual criteria listed above is an infallible indicator of either a tectonic or a eustatic cycle. If, however, four or five criteria suggest the same cause, this might constitute rather strong circumstantial evidence. A line of reasoning such as this one might eventually allow the roles of tectonism and eustatic rise and fall of sea level to be differentiated. Many of the criteria could be demonstrated only by integrated regional or interregional analysis.

APPLICATIONS TO PETROLEUM GEOLOGY

Stratification studies should aid in locating stratigraphic traps. Petroleum formation, migration and accumulation is related to specific environments. A shale should not be considered just a shale: it accumulated in a lagoon, bay, swamp, offshore zone, and so forth. The same applies to deposits composed of other lithologies.

Permeability and porosity in reservoir rocks may be controlled by the environment of accumulation. For instance, investigation may reveal that the optimum trends are related to surf zone deposits, beaches, and so forth. Application of this type of analysis should increase exploration efficiency and decrease costs.

OTHER APPLICATIONS

Knowledge of stratification and sedimentary features may eventually permit continental deposits to be easily differentiated from marine sediments.

PRINCIPLES AND CONCLUSIONS

Principles

1. An oversimplified analytical approach is suggested. This scheme isolates five agents which directly control the development of primary features and structures, and a group of factors which indirectly influence bedding.
2. The concept of high, low, and intermediate zones of wave energy is proposed to provide a generalized framework of analysis for interpreting offshore deposits. Criteria for the recognition of each are discussed.
3. The stratification pattern concept is introduced as a simple device for interpreting depositional cycles. Application simply involves observation of the stratigraphic positions of various types of bedding that record accumulation in shorezone or offshore environments.
4. Beach deposits are apparently preserved more commonly during regression than during transgression.

Conclusions

1. The interrelated environmental factors which control stratification have not changed or evolved through time as have organisms and their adaptions.

2. Stratification very accurately reflects the environments of accumulation, permits rapid and accurate environmental reconstruction, and does not require exhaustive, time consuming sieve analyses or the application of statistics.
3. The energy level concept provides a useful framework for analyzing offshore deposits.
4. The stratification pattern concept can be applied to the analysis of limited exposures, and possibly even to the interpretation of well cores.
5. Studies of bedding may solve many existing stratigraphic problems. Application of principles established in this study may eventually lead to the solution of such a basic, perplexing puzzle as determining whether major depositional cycles (as recorded in the sediments) are produced mainly by eustatic rises and falls of sea level, or by tectonism.
6. It appears probable that many major and minor depositional cycles exist which have not been recognized.
7. It is probable that the role of organisms in destroying stratification has been greatly overestimated.

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