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A Study of Internal Structures of Fine-Grained Clastic Rocks by X-Radiography*

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ABSTRACT.—An analysis by x-ray radiography of more than one hundred samples of fine-grained clastic sedimentary rocks has been conducted to determine what types of internal sedimentary structures were present. Four general classes of internal structures were recognized in the siltstones and shales used in this study: I. Regular Layering, II. Disturbed Structures, III. Mottled Sediments, IV. Structureless. These structural types occurred singly or in combination with others within any one specimen. Micro-cross-laminations of various kinds were the most common structures encountered, thus indicating that the sedimentary processes of lateral and vertical accretion operate at very low energy levels.

Siltstones and shales can be as structurally complex as the coarser-grained sediments. Internal structure is usually masked by coloration, fine textures, and weathering characteristics. Completely structureless or homogeneous specimens were rare among the collected rocks. An integration of the "unit stratum" and "sedimentation unit" concepts provides a layer-by-layer approach to be taken in interpretative work.

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TEXT

*A thesis submitted to the faculty of the Department of Geology, Brigham Young University, in partial fulfillment of the requirements for the degree Master of Science.

INTRODUCTION

Fine-grained clastic sedimentary rocks, referred to as siltstone, shale, or mudstone, represent between 42% and 56% of all sediments exposed at the earth's surface. Several authors of texts dealing with sedimentary rocks admit that while "shales" are very abundant, our knowledge of their depositional environment is not as detailed as that of the coarser sediments (Dunbar and Rogers, 1957; Pettijohn, 1957). It would seem that this limited knowledge is due to the difficulties encountered in gleaning information from shales at the outcrop. Studies of the shale record are usually hampered by the inherent characteristics found in fine-grained clastic rocks. The fine-grained nature of shales obscures the structural framework and minute textural differences that usually are present in mechanically laid sediments. The shales weather rapidly and deeply in the outcrop, which makes fresh samples difficult to obtain. Coloring is commonly so varied or contrasting that false impressions of internal structures are mistakenly formed. Postdepositional deformation may easily affect the incompetent shale to such an extent that the primary structural components of the rock are "smeared," displaced, or are otherwise not recognizable. Burrowing organisms, or other benthonic life forms, commonly disrupt or obliterate structural details. Microscopic studies are limited because resolution of the spatial relationships of very fine particles are not easily obtainable, and vertical and lateral relationships of sedimentary structures are not easily studied in thin-section due to a restricted field of view. Another factor indirectly related to the shale problem is that much of the research during the last 15 years has concerned clay mineral identification and genesis rather than mechanical differentiation of the particles themselves.

All of these complicating factors have possibly led many to pass lightly over, or even ignore, the internal structure of shales. Too often they are interpreted as low-energy or quiet-water deposits without much more than a cursory inspection.

This study was undertaken first, to determine if shales are of such nature that x-radiographic studies would be applicable and of significance; second, to study the kinds of primary and secondary sedimentary structures preserved in shales and to classify these structures and compare them with structures in coarser sediments and higher energy regimes; and third, to make preliminary interpretations as to the environmental significance of these structures, such as paleoenvironments and ecology, paleocurrents and energy levels, and sedimentation rates.

Previous Work

The use of x-radiography by geologists dates back to 1896, just a few months after X rays were discovered by Wilhelm Konrad Roentgen in 1895. Since that time, radiographic techniques have been adopted by only a few paleontologists in the study of fossil morphology and orientation. The best illustrated and most recent publications on the use of radiographic techniques by paleontologists have been the contributions of Schmidt (1948 and 1952), Zangerl (1965), and Hamblin (1963).

Reported applications of x-radiography in other fields of geology, especially sedimentology, are relatively few and have been primarily concerned with the coarse-grained sediments, namely, sandstones.

Hamblin (1965) shows that supposed massive or homogeneous sandstones are replete with primary sedimentary structures of various types. The techniques that he developed for his study have been adapted by me to analyze the internal structures of shales.

ACKNOWLEDGMENTS

I wish to express my appreciation and thanks to Dr. W. K. Hamblin for suggesting the problem, directing the initial steps of the project, and for critically reviewing the manuscript; to J. R. Bushman and H. J. Bissell for many helpful discussions during the progress of this work; and for the facilities, advice, and encouragement provided by the faculty and students of the Department of Geology, Brigham Young University. Financial assistance for this research was provided, in part, by a grant to the Geology Department of Brigham Young University and by Marathon Oil Company. Some samples used in this study were supplied by the State Geological Survey of Kansas.

Appreciation is extended to Mrs. Mary Newman, who typed the final manuscript. Judy Jones deserves special recognition and thanks for typing rough drafts and providing encouragement at all times.

METHODS

Sample Distribution and Lithology

All of the samples used in this study could be classified as a variety of siltstone, shale, mudstone, or claystone. The Wentworth scale was used as the guide for the upper limits of clastic size. Only rocks with a particle size of one sixteenth of a millimeter in diameter or smaller were acceptable for the purpose and scope of the project. The samples are classified as either siltstones or shales. More specialized classification seemed superflous, as no definite area or stratigraphic section was involved. The term *siltstone* will be used in reference to those rocks having a dominant proportion of silt-sized particles. Usually these rocks are "massive" in outcrop appearance, weathering to small resistant ledges.

The term *shales* will refer to all other rocks which appear to have a dominating fraction of clay minerals and clay-sized particles. These rocks may or may not be fissile and may or may not weather in resistant layers.

The samples were collected from Kansas, Utah, Arizona, Wyoming, and Texas.

Siltstones and shales were sought in any manner that would yield a suitable sample for study. Collecting in recent roadcuts was generally productive, as the shales were not deeply weathered into the outcrop face. A few diamond cores were acquired as well.

Many different formations were represented, and they gave a broad range of age from Late Paleozoic time through the Mesozoic and Tertiary to Pleistocene. A wide range of probable depositional environments were represented as well. Among these were fluvial, lacustrine, deltaic, marine, lagoonal, paludal, transgressive and regressive sequences, and a possible aeolian siltstone.

Techniques

X-Ray Procedures.—There are many factors which affect the quality of the image on the x-ray negative film: distance from tube to target, thickness of specimen, kilovolts applied to the x-ray tube, milliamps used, length of time the X rays are exposing the film, and lithology of material constituting the specimen under examination. The image on the x-ray negative is the result of differential absorption of the radiation by the constituents of the rock. The degree to which the X rays are absorbed or passed creates light and dark shadings on the film that are rendered as patterns recognizable as sedimentary features. Even minute structures such as micro-cross-bedding and any single bedding plane are readily recognizable. Differences in the packing density of particles and differences in particle size create significant patterns. Cementing agents also are easily differentiated under x-ray exposure. The x-ray source used in this study is provided by a small industrial unit made by Picker X-Ray Corporation. Medical x-ray units that may be available are generally adequate in the absence of an industrial unit.

TABLE 1

Thickness (mm)	KV	MA	Time (sec)	MAS
1	28-30	6	60	360
2	30-32	8	54	432
3	33-34	9	54	432
4	35-38	9	90-120	900
5	38-40	9	90-120	900

TABLE 1.—A generalized exposure guide for fine-grained clastic sedimentary rocks (assumed tube to subject distance of 65 cm.). KV = Kilovolts, MA = Milliamperes, MAS = Milliamps X seconds.

The illustrations in this study were made by making positive prints from the exposed x-ray negative film. The dark or black areas on the resultant positive prints represent layers of high absorption of radiation; the lighter tones reflect little or no absorption of X rays. The x-ray film was Kodak Industrial Film, Type-M.

Specimen Preparation

The absorption of X rays is determined to a great extent by the thickness of the specimen being x-rayed; thus it is critical to prepare the slabs properly. Initial experiments showed that slabs of the specimens could not be sliced to a thickness exceeding five millimeters and expect to get a definitive high-quality exposure. Three millimeters appeared to be the optimum thickness. One problem, which was anticipated, was the poor consolidation of many of the specimens, which, when cut with a large self-feeding diamond saw, broke up extensively. Water proved to be inadequate as a cutting fluid, as it caused the rock to swell, sluff, and generally decompose. Kerosene used as the cutting fluid did not cause any specimen to exhibit any of these characteristics; and even though the slabs generally absorbed the kerosene, the X rays were not affected.

Many specimens were badly fractured or poorly indurated so that a penetrating fluid of "Gelva" cut with acetone was used to cement the specimen before the final slab was cut. Another problem in cutting was that of maintaining an even thickness over the whole slab. Any deviation in thickness due to wedging, saw marks, etc., created corresponding light and dark areas on the x-radiograph.

CLASSIFICATION OF SEDIMENTARY STRUCTURES

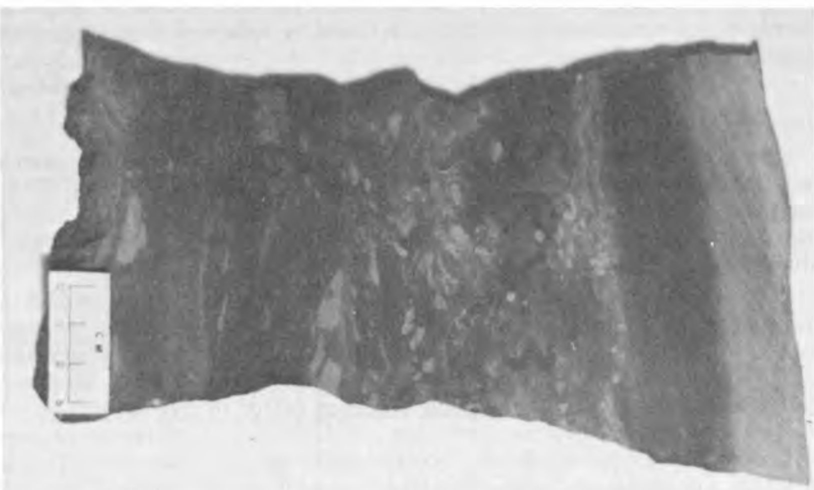
The x-radiographic technique, as used in this study, generally revealed the hidden internal structural framework of siltstones and shales with a great deal of clarity (Text-fig. 1). Thus it is possible to make a preliminary classification of these sedimentary structures. Virtually all major types of sedimentary structures are easily differentiated in the x-radiographs.

The sedimentary structures found in the fine-grained rocks studied are directly correlative with those structures found in coarser clastic sediments. Horizontal layers, cross-stratification, cut-and-fill channeling, ripple-lamination, and differential compaction all exist in the finer sediments—but on a much smaller scale. Within a short vertical sequence (three to five inches), several different sedimentary structures reflecting different levels of energy of deposition, sediment supply rates, etc., occur together one over another (Text-fig. 2). This intermixing of structural types, as well as the common distortion of normal bedding features, has prompted the development of the following generalized classification.

Structural Types

The sedimentary features in the fine-grained rocks, as recorded on radiographs in this study, may be classified into four major categories. The categories I propose are somewhat correlative to those defined by Moore and Scruton (1957, p. 2725-2727) in their study of recent sediments of the Gulf Coast. Their findings suggested the placement of all sedimentary features

1a



1b

TEXT-FIGURE 1.—Photograph (Fig. 1b) and x-radiographic positive print (Fig. 1a) of shale collected from the Moenkopi Formation, Emery Co., Utah. Contrast the structural details of the radiograph with those of the photograph. Note the undisturbed cross-bedding features at the top of the sample, which overlie the highly disturbed unit below.

2a

2b

TEXT-FIGURE 2.—Photograph (Fig. 2b) and x-radiographic positive print (Fig. 2a) showing intermixture of structural types. See Plate 3 and text for details. Moenkopi Formation (Triassic), Emery Co., Utah.

into one of four groupings: (I) regular layers, (II) irregular layers, (III) mottles, and (IV) homogeneous sediments.

For the purposes of this study, the Moore and Scruton classification of internal sedimentary structures will be used in an amended fashion. The classification of internal structures of fine-grained sedimentary rocks, as revealed by x-radiography, is as follows:

I. Regular Layers
   A. Horizontal laminations
   B. Cross-laminations, all types
   C. Micro-cross-laminations, all types
   D. Diastems

II. Disturbed Structures
  A. All primary sedimentary structures are recognizable, but have been contorted or disturbed by postdepositional effects.
  B. Faults, slump structures, differential compaction features, mud cracks
  C. Burrows, plant and animal
  D. Other diagenetic features

III. Mottled Sediments
  A. Pods, lenses, concretions, lumps, pockets, and other undescribed features in an otherwise structureless rock

IV. Structureless
  A. Primary homogeneity
  B. Secondary homogeneity

THE SEDIMENTATION UNIT AND UNIT-STRATUM CONCEPTS

In each vertical section of rock that is properly prepared and x-rayed, a sequence of events is represented by the succession of sedimentary structures. An approach to the interpretation of these internal structures in relationship to their depositional environment involves the integration of several concepts; namely, "cosets of strata" (McKee and Wier, 1953), "sedimentation unit" (Otto, 1938), and "unit stratum" (Hamblin, 1965).

The "building block" of any sedimentary rock is the "unit stratum" (Hamblin, 1965). In theory, a "unit stratum" may be only one grain thick and would represent a layer of clastic particles which are deposited over the depositional interface at approximately the same time. A series of "unit strata," which together reflect the same physical conditions of deposition, are grouped as the "sedimentation unit" as defined by Otto (1938). The "set of strata" of McKee and Wier (1953) would be analogous to Otto's sedimentation unit in this case. The highest rank given to a group of layers used in this study is the "coset of strata" as defined by McKee and Wier (1953). The term *coset of strata* or *coset* refers to the grouping of two or more "sedimentation units" or "sets" of strata.

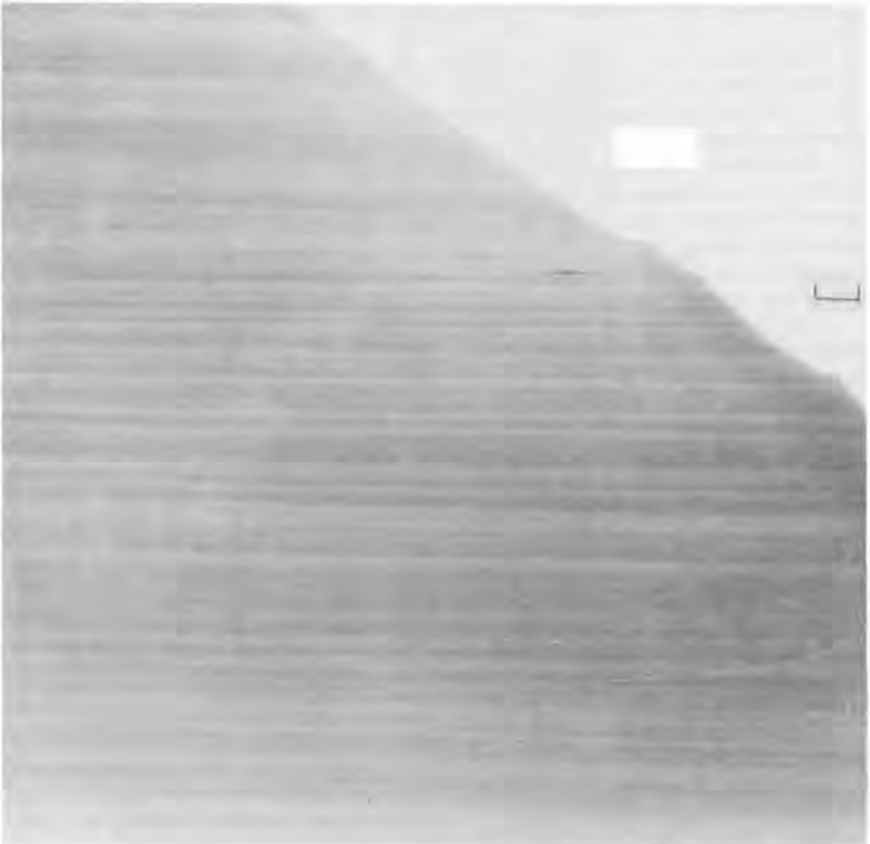
PRIMARY STRUCTURES

Regular Layers

The term *regular bedded* refers to primary sedimentation features which developed in response to the sedimentary environment and have been preserved in the rocks, not being altered by the agents of lithification or diagenesis. The category of the regularly bedded structures has proven to be more complex than originally expected.

A full range of primary sedimentary structures has been observed in the shales and siltstones collected in this study, even though the specimens were collected without bias. Regular structures include horizontal laminae and varieties of cross-strata. Many of these structures can be classed as microstructures as their dimensions are, in many cases, less than one centimeter.

Horizontal Laminations.—Several of the rocks x-radiographed were sediments built up by a sequence of horizontal layers, in which each discernible



TEXT-FIGURE 3.—X-radiographic positive print of sample from the Moenkopi Formation (Triassic), Emery Co., Utah. Alternating light and dark layers are persistent laterally. Dark layers are generally thicker than light layers. The rhythmic alternation of layers may represent storm activities or other disturbances causing sediment influx not necessarily related to seasonal changes. Scale line equals 1 cm.

sedimentation unit had a thickness of less than one millimeter to four and five millimeters (Text-fig. 3). Text-figure 3 shows an eight-inch vertical section of very fine laminar bedding. The laminae alternate between light and dark shades on the x-radiograph. The dark layers have absorbed more radiation than the light layers. A change in the percentage content of minerals, both primary and diagenetic, and organic matter might cause the differential absorption of radiation among the layers. A change in grain size and packing densities are also factors in differential absorption of X rays.

The contact between layers is poorly expressed in the hand specimen. The radiographs show that the light and dark laminae alternate in a rhythmic pattern. In some cases, there is evidence of a cyclic sequence. The contacts between the laminae are gradational for the most part. Either upper or lower boundaries may grade from light to dark or from dark to light. Upon close inspection, a few boundaries can be found to exhibit a sharp, definable surface.

The layers often appear to thicken and thin along their length. Thus the contacts have an undulatory pattern. Some of the very small microlaminae pinch out or are truncated by very gradual, low-angle cross-bedding in the overlying layers.

Horizontal laminations were found to occur in both the shales and siltstones, no preference as to grain size being noted. The radiographs show a general rhythmic alternation of light and dark strata. The light bands are generally deposits of texturally coarser material than the dark bands. In some cases the dark bands may vary mineralogically from the light bands, thus creating the pattern on the radiograph.

The laminations vary in thickness, ranging from 3 per centimeter to 11 or more per centimeter. Normally the dark laminae are thicker than the light laminae among the rocks studied. This is in contrast to the finding of Hamblin (1965, 1964), in which he showed that in sandstones the light laminae were thicker. Hamblin's findings parallel those of Bradley, in which the rhythmic alternations of Bradley's "varves" (1929, Pl. 2) showed that the light layers were thicker than the dark layers.

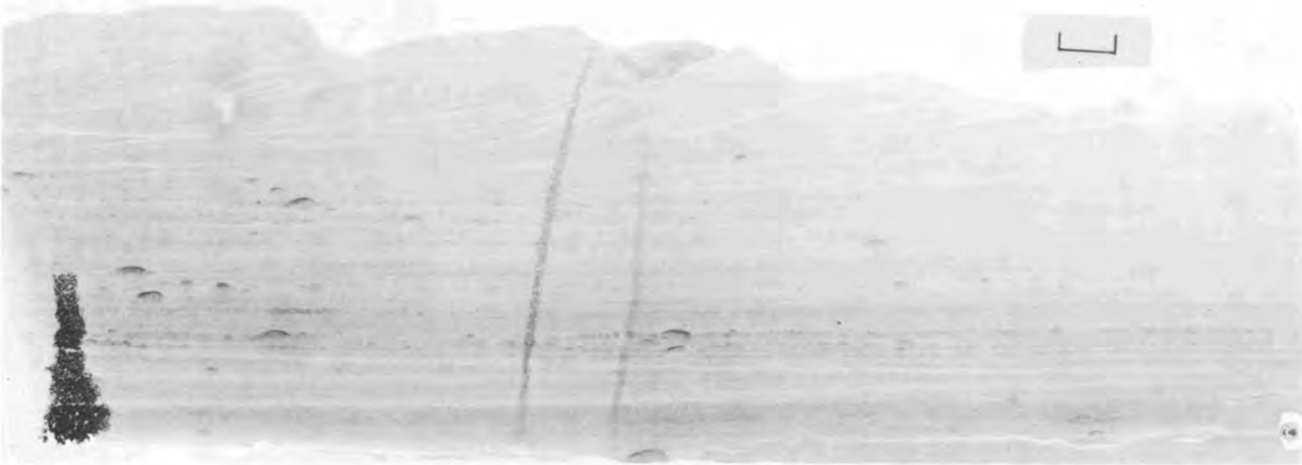
Text-figure 3 thus illustrates the alternating light and dark horizontal laminations typical of those found in this study. The vertical distance of the radiograph is eight inches. The dark laminae are generally two to three times thicker than the light laminae. The top portion of the x-radiograph shows that the light layers are made up of very thin (less than one millimeter) dark laminae alternating with slightly thicker light laminae. Whether this is true for all of the light bands, especially the thinner ones, is undeterminable in this sample.

Assuming that the rhythmic alternations in Text-figure 3 are caused by textural differences, the question arises as to what operating mechanisms or factors created the distinctive laminations. The fact that most of the contacts between laminae are gradational may have a bearing on the problem. A more extensive study of the horizon, from which this specimen was collected would be in order to justify any interpretation of the processes of deposition.

In one x-radiograph a siltstone has a coset of horizontal laminae directly overlain by apparent tabular cross-strata (Text-fig. 4). The slabbed rock does not show any change in texture, nor is there any evidence of internal structure beyond some obscure horizontal lineations. An increase in the energy of the depositing medium is quite obvious. Note the vertical fractures healed by deposition of calcite from groundwater (Text-fig. 4).

Cross-laminated Structures.—Perhaps the most significant result of this study was the discovery of the wide range of types of cross laminae. Major types recognized are tabular, trough (or festoon), oscillation ripples, climbing ripples, "starved" ripples, fill structures, regular current ripples, and microstructures of many of the above types.

Not infrequently, a single, slabbed specimen exhibits horizontal laminations overlain by some type of cross- or current-bedded structure. In most of these cases, there is no observable bedding plane break, nor a tendency for the rock to separate along the plane between the structural differences. In some shales, bedding plane fractures were observed to undulate, paralleling the ripple laminae structures (Text-fig. 5).



TEXT-FIGURE 4.—X-radiographic positive print of sample collected from the Moenkopi Formation (Triassic), Emery Co., Utah. Cross-strata overlies horizontal laminae. Dark vertical features are calcite-filled fractures. Scale line equals 1 cm.

TEXT-FIGURE 5.—X-radiographic positive print of a sample from the Carmel Formation (Jurassic), Emery Co., Utah. The wavy white line that crosses entire slab in lower quarter of the specimen is a natural break on a ripple-marked surface. Three major cosets of strata are seen here (see text). The slab was oriented and cut normal to the ripple axis of the top surface. The origin of the upward branching, "feathery" structures near the middle of the specimen have not been definitely defined. These are postdepositional features as noted by their cross-cutting relationships. A probable cause postulated for these features is the upward migration of light fluids or gases through the unconsolidated sediments. Scale line is 1 cm.

A significant number of the rocks radiographed were totally cross-bedded throughout a vertical distance of 8 to 10 inches. The boundary relationships between sets and cosets of cross-strata are easily determined from the radiographs. The McKee and Weir (1953) classification and terminology of sedimentary structures can be used effectively here as the boundary relationships are observable.

Approximately 50 percent of the radiographs showed some variety of cross-lamination, ripple lamination, or cut-and-fill structure. All of these features are primary internal structures of sediments that reflect the sum total of the environmental factors and processes existing at the time of deposition. Many controlled experiments and detailed observations have been made concerning the formation of cross-strata in the modern sedimentary environment (Moore and Scruton, 1957; McKee, 1965; Harms and Fahnestock, 1965; Coleman and Gagliano, 1965; Potter and Pettijohn, 1963). This information has been used to interpret the dimensions of the sedimentary processes that deposited ancient cross-bedded rocks. Some general relationships can be used, however, by applying the general principles developed in the above works to the structures seen in the fine-grained rocks of this study.

Micro-cross-laminations.—Text-figure 5 is a vertical section from the Jurassic Carmel Formation. The lower two and one-half inches of the radiograph show a complex of trough cross-strata. Each set of cross-strata has a concave lower boundary indicating that it is an erosional contact. The thickness of the sets of cross-strata ranges from two millimeters to more than six millimeters. The width of the sets varies from less than two centimeters to about four centimeters. These cosets of trough cross-strata are classified as microstructures.

Next above the coset of micro-trough cross-strata is a two-and-one-half inch thick sequence of larger cross-strata. The structures are an intimate mixture of trough cross-strata and ripple laminae. The top and bottom surfaces of this slab are ripple marked.

The third coset of cross-strata in this sequence is the top two and one-fourth inches. The structures are basically the same as in the middle coset, except that the trough cross-strata sets are smaller in their dimensions.

Structures of special note are the two ripple-marked features. One is expressed by the rhythmically undulating pattern of the physical break near the bottom. The bedding plane break is apparently controlled by a ripple-marked surface. The other structure is the series of ripples near the top of the middle coset. The crest of each ripple appears to be composed of coarser fragments of quartz than the surrounding material. Note that the ripple crests pinch out at their margins, with the intervening trough showing no presence of the coarser clasts. The ripple crests appear to be slightly asymmetric, with a gentle lee slope on the right. These nearly isolated ripples are analogous to the "frozen" ripples described by Coleman and Gagliano (1965, p. 136).

A sequence of events can be postulated from the structural details as seen in Text-figure 5, by identifying and dealing with each coset of strata in turn.

The first coset to be deposited is made up of the micro-trough cross-laminae. This specimen is a shaly-siltstone, appearing to be very evenly textured throughout. The structures described above are undiscernible in the hand specimen. Due to the fineness of the clasts and minuteness of the troughs themselves, current velocities would appear to be lowermost in the flow regime. The microtroughs are linear structures and indicate a unidirectional depositing current. The thickness and the continuity of the coset indicate a steady rate of sediment movement with little or no fluctuation.

The second or middle coset and the top coset are composed of larger trough cross-laminae. The average grain size appears to be larger now. Again, this textural difference is not seen in the hand specimen. The current velocities have increased over those of the bottom coset. Sediment supply seems to be more erratic, as witnessed by the "frozen" ripples near the top of the middle coset. This particular situation appears to come about in a starved sediment supply condition. A small amount of coarse clastic detritus is flushed into the environment and these particles are stabilized into ripples with the trough areas swept clean by the current. The ripples are preserved by rapid burial when a large supply of finer particles is introduced with no increase in current velocity.

The smaller structures in the top coset indicate a decrease in current strength over those of the middle coset.

The relationship of small-scale trough cross-strata with ripple laminae has been noted by Harms and Fahnestock (1965) and Hamblin (1961).

Many other cross-strata and ripple laminae types are illustrated in plates 1 and 2. One interesting type of ripple laminae is pictured in Text-figure 6. These ripple laminae structures appear to be similar to the "climbing ripples" discussed by McKee (1965) in his "Experiments on Ripple Lamination." McKee notes that "climbing ripples" evolve when detrital clasts are fed into the current system in excess of that required to form a rippled surface. In Text-figure 6, note the tangential form of the "unit strata" in their terminal contacts. The bounding surfaces between sets of laminae are curved upward at their crest and dip to the left. The apparent current direction is to the right. The upstream or stoss slope of each set of ripple laminae is erosional and the lee slopes are depositional. The black dots, large and small, are diagenetic mineral growths, probably iron sulfides.

Diastems.—One other current-indicating structure observed in a few radiographs was a plane of truncation (Text-fig. 4). This plane divides two nearly parallel, horizontally laminated cosets. The truncating surface represents an erosional, degrading current system. The period of time involved is not estimated, but on the scale being dealt with in these radiographs, the hiatus must be relatively small. The x-radiograph in Text-figure 4 shows two sequences of deposition separated by a surface that parallels the upper, younger strata. The truncation of the lower laminae indicates a period of degradation by currents with no accompanying influx of sediment. An alternative situation postulated is a sediment bypass condition.

POSTDEPOSITIONAL STRUCTURES

The sedimentary structural categories delineated as II. Disrupted Structures, III. Mottles, and IV. Structureless are, for the most part, postdepositional modifications of primary structures or features that develop after deposition, but before lithification. Commonly, various structures will occur together within the same slab. Some radiographs show that the rock slabs contain regular bedding features, mottles, and disturbed structures within a six- to 8-inch thickness (Text-figs. 1, 2).

TEXT-FIGURE 6.—X-radiographic positive print of Kiabab (Permian) siltstone, collected in Emery Co., Utah. Climbing ripples are the prominent structures comprising the internal framework of this rock. Note the tangential contacts made by each of the "unit strata," seen as the dark lines in the radiograph. Black dots scattered throughout the specimen are diagenetic minerals. Scale line equals 1 cm.

PLATE 1.—X-radiographic positive prints of cross-stratified structures, in the Regular Layer category. Silty shales collected from different horizons of the Moenkopi Formation (Triassic), Washington Co., Utah. Scale line equals 1 cm.

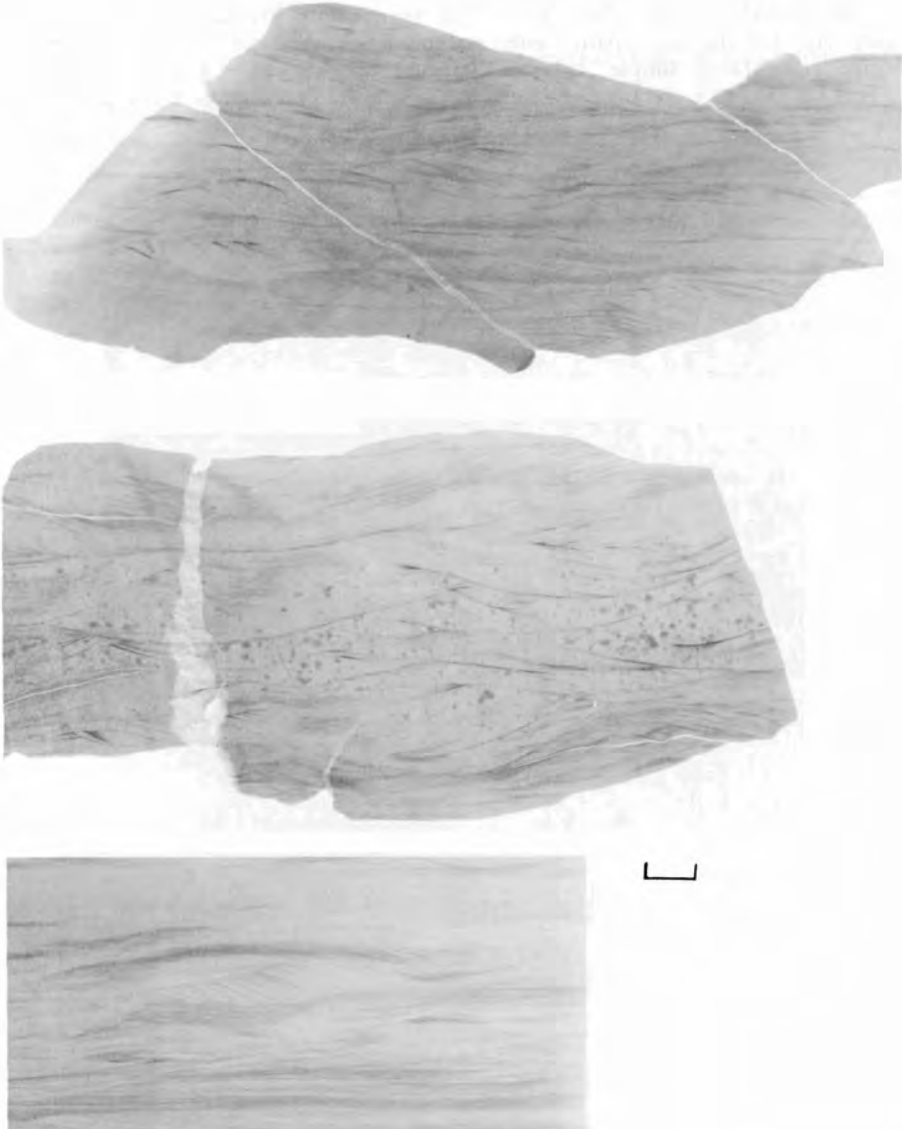


PLATE 2.—X-radiographic positive prints of cross-stratified structures. Samples collected at various horizons within the Moenkopi Formation (Triassic), Washington Co., Utah. Note the calcite-filled fracture in the middle sample. Scale line equals 1 cm.

Disrupted or Disturbed Structures

Recognizable Primary Structures.—The sedimentary structures in this category are, for the most part, penecontemporaneous features. These features range from fairly simple, irregular layering of the pinch and swell type (Text-fig. 7), to a complex of structures as seen in Text-figures 1 and 2.

TEXT-FIGURE 7.—X-radiographic positive print of a section of core cut from an unidentified formation in the Late Paleozoic rocks of west Texas. This shale shows recumbent folding of laminae. This indicates a movement of unconsolidated material, probably due to the compaction effects of burial. Scale line equals 1 cm.

Once clastic material has been deposited within the structural framework of the energy requirements of the environment, many agents and forces continue to act upon the sediment in an attempt to bring about a state of equilibrium, pursuant to the new environmental requirements induced by burial.

The deforming agents appear to be diagenetic mineral growth, activities of burrowing organisms as well as plant and root penetrations, and disturbances created by percolation of gases and other light fluids.

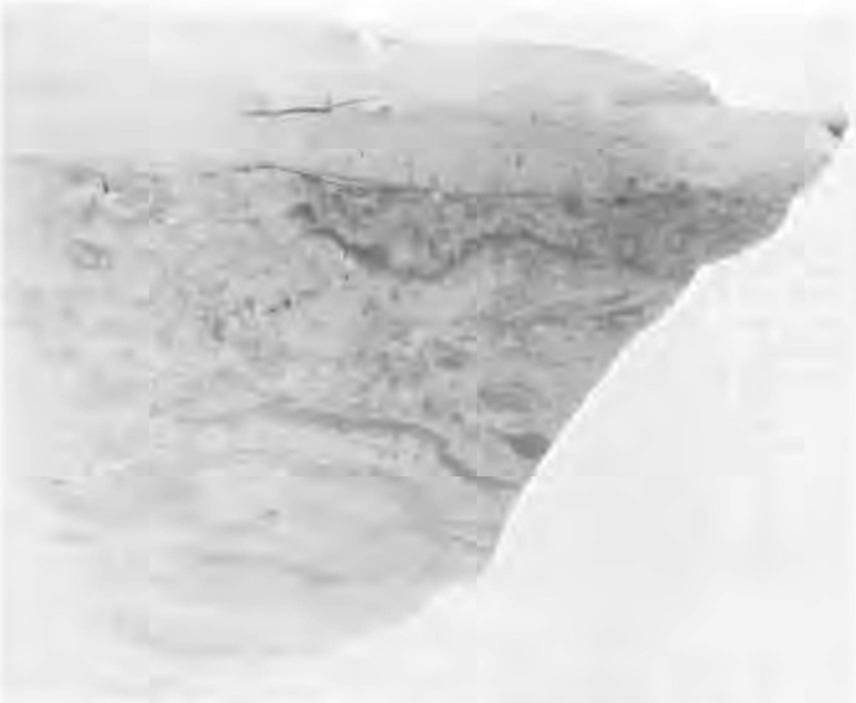
Forces which may cause deformation are from two sources. One set of forces is comprised of those that are regional and have tensional, compressional, and vertical gravitational force vectors. Another set of forces is comprised of those that are created within the sediment itself. Some of these internal forces are gravity motivated, however. Local loading phenomena, the combined swelling and shrinking effects of clay minerals and organic matter, and replacement or growth of minerals contribute to these internal forces.

Compaction Features.—Nearly all of the shales and several siltstones used in the study showed disturbed bedding features that have been described elsewhere by many others (Van Stratten, 1951; Moore and Scruton, 1957; Pettijohn, 1957). Gravity-driven compaction or differential loading structures are commonly found. A rather simple pinch and swell effect with minor convolution of certain laminae, as seen in Text-figure 7, is indicative of the internal adjustments that have taken place within the incompetent siltstones and shales.

Boudinage structures are recognized. As an example, Text-figures 1 and 8 are shales cut at right angles to one another from a Triassic silty shale. The top coset of cross-strata is higher in its silt fraction and relatively undisturbed. The bottom, silty group of laminae also appears to be fairly competent. The middle portion is highly contorted, displaced, and broken. No one sedimentation unit is traceable across this disturbed section. The rounded, somewhat elongated clay lenses or pods were probably once part of a single sedimentation unit. The tensional forces created by downward loading (McCrossan, 1958) have probably been the driving force for the flowage and squeezing effects seen in these radiographs.

An interesting group of "boudinage-type" structures was encountered in a radiograph (Text-fig. 9) of a black shale from Kansas. In the slab, the ground mass or bulk of the rock is black. A few conspicuous, round white bodies are within the black groundmass. The radiograph shows these white objects as nearly circular to oblate bodies. Some are isolated and others have tails. What was once laminar bedding shows as wavy, dark streaks. The centers of some of the larger bodies are cored by material different from the mantling material. The streaks of dark material and the round bodies seem to be the result of compaction forces, squeezing certain incompetent layers into the present configuration (boudinage). Later diagenetic minerals have grown in the centers of these "boudin."

Upon inspection of the radiograph in Plate 3, several structures stand out. Through the use of the "sedimentation unit" concept, nine sequences are recognized and identified by letters on the line drawing. These sedimentary units are lettered according to superposition from A to I. Layers A and C are dense, relatively competent shales. Bed B is a siltier, less competent sediment than A and C. Boudinage flowage has occurred with the squeezing



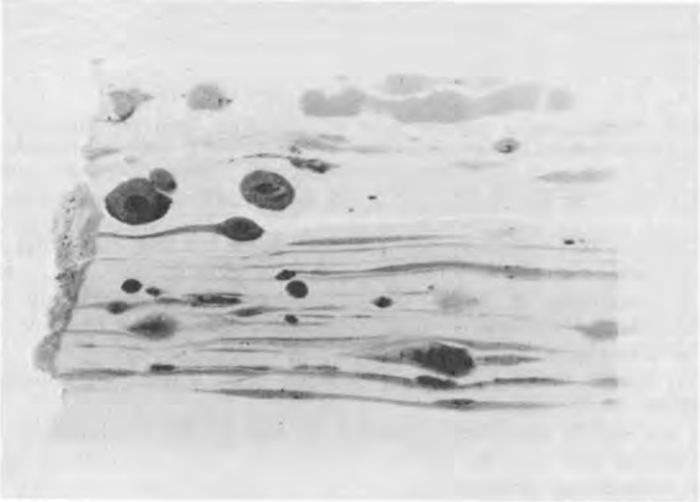
TEXT-FIGURE 8.—X-radiographic positive print of a sample from the Moenkopi Formation, Emery Co., Utah. This slab is cut normal to the slab of Text-figure 1. Compare top coset of cross-strata in each figure. The vertical thickness of this specimen equals the vertical thickness of the specimen in Text-figure 1.

of B into the roll or pod at the left of center. A and C act as the top and bottom boundary layers containing the soft-sediment flow. Note the small piercement feature of B material near the left end. It penetrates through C into D. This cross-cutting relationship indicates that D had at least been deposited before deformation started in B. Note also the trail of B material to the right of the large swell in B. The evidence indicates that units A, B, and C were nearly the same thickness before the deformation.

Unit D is a coset of ripple laminae. The detrital grain size is coarser than in C. Depositing currents were probably becoming slightly more vigorous during this period of time. The contact between C and D was probably originally flat and uniform. Now the contact undulates and near the right side the sediment of D has broken through to lower layers. The upper contact of D is also undulating, but there is some evidence that this might have been a ripple-marked surface.

Layer E appears to be texturally the same as A, C, and I. The thickness of E pinches and swells along its length. What internal sedimentary structure may have been present in units A, C, E, and I is not entirely evident. Traces of possible horizontal laminations exist in A and E.

9a



9b

TEXT-FIGURE 9.—X-radiographic positive print (Fig. 9b) and photograph (9a) of dense, black shale collected in the "Tebo" pit, Crawford Co., Kansas. Note the apparent destruction of laminar bedding units. Remnants of the layers are now rolls and disconnected lenses of material. Black cores in the rolls are diagenetic minerals.

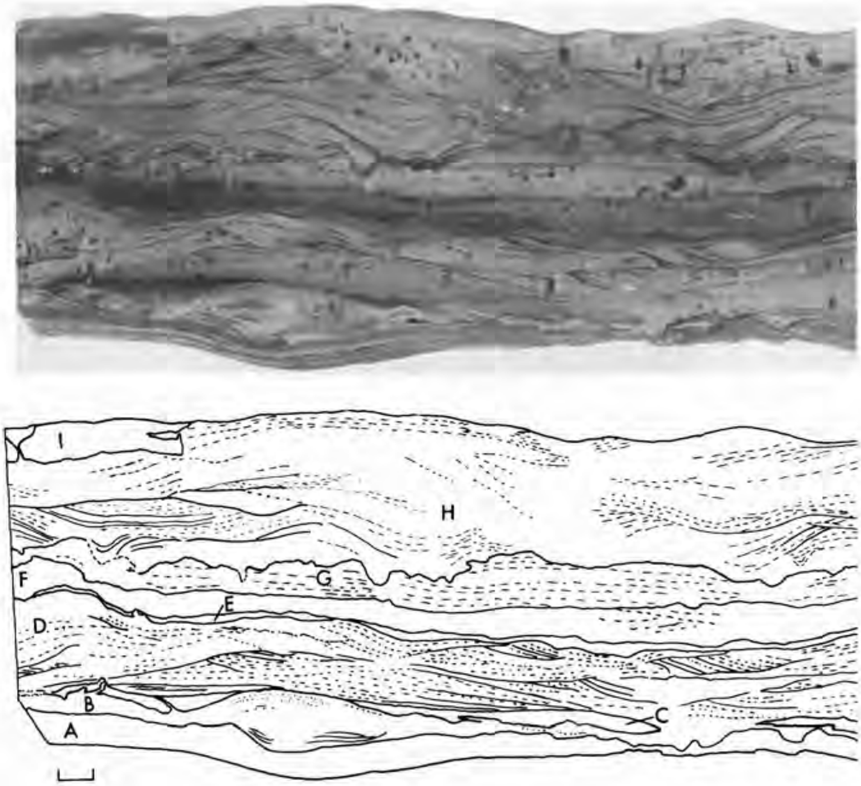


PLATE 3.—Top: X-radiographic positive print of silty shale from the Moenkopi Formation (Triassic), Emery Co., Utah. (See Text-fig. 2 also.) Bottom: Line drawing of the internal structures taken from the x-radiograph. Letters A through I identify cosets of strata discussed in text. Scale line equals 1 cm.

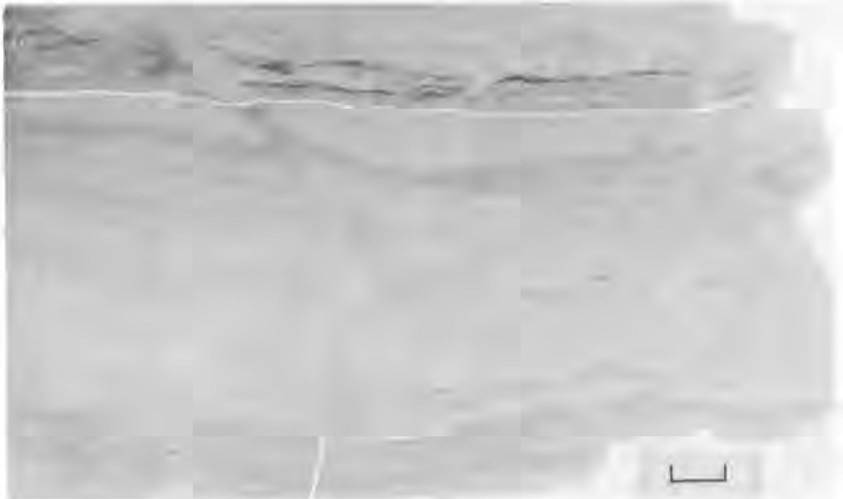
Unit F appears to be coarsely laminated; G above has thin horizontal lamination but is coarser than the very fine-grained units, as in A.

Coset H constitutes a group of sedimentary structures varying from cross-strata to channel-fill types. True relationships are vague in some areas of H due to disturbances.

Unit I is in the upper left corner and has been abruptly terminated by postdepositional displacement.

Overall, the slab is structurally complex, as seen in the x-radiograph. The appearance of the slab or even the rock in outcrop does not indicate such a diversity in sedimentary structure.

Burrows.—Borings, tubes, and burrow structures left by marine and freshwater benthonic organisms often fill with detritus of a different nature than the host sediment. When this occurs, the differences are reproduced on the radiographic film. Burrowing structures are seen in Text-figures 4 and 10. This evidence, which may not be readily apparent in the outcrop or slabbed



TEXT-FIGURE 10.—X-radiographic positive print of Kayenta (Jurassic-Triassic) Formation, Washington Co., Utah. The lower cosets of strata are horizontal laminae, which are overlain by a sequence of cross-strata. The activities of burrowing organisms are an apparent and major feature here. The scale line is equal to 1 cm.

specimen, is vital to the paleoecologist and environmental sedimentologist. Presence of ichnofossils tells something of bottom conditions of the water and sediment, and sedimentation rates, etc. (Twenhofel, 1961, p. 626).

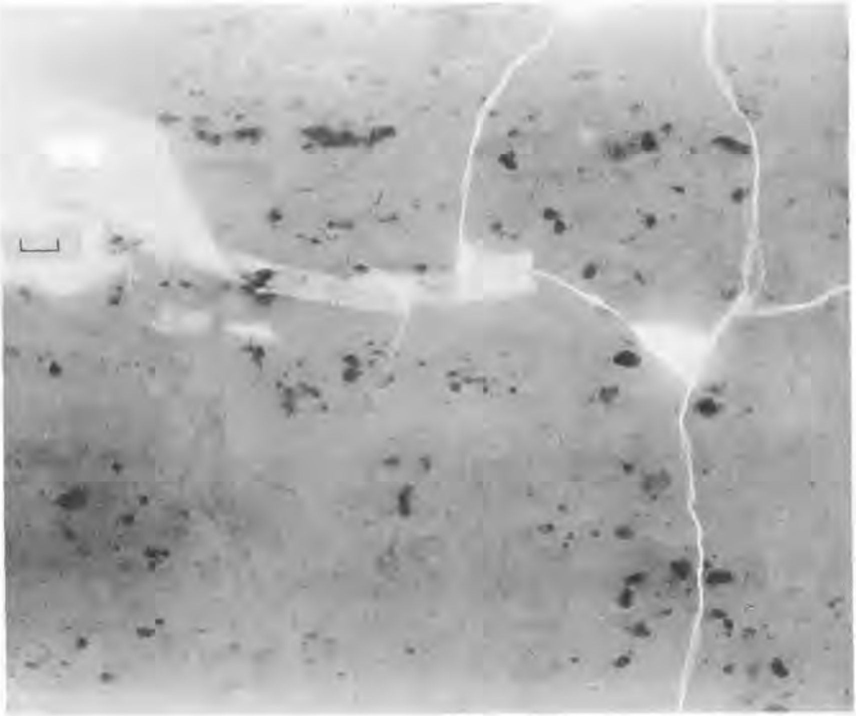
Mottled Sediments

A large number of the rocks collected for this study contained some mottling effect. In most cases, the mottled specimens are void of any other sedimentary structure. That these rocks were stratified in some fashion and the structural framework has been destroyed by the agents producing the mottles is still a moot question. The mottles may, in some instances, be primary features.

The term *mottles* is here used as a general description of any feature not attributable to sedimentary structures, normal or disturbed; fossil hard parts; or ichnofossils. This category, then, includes pods, lenses, lumps, and pockets of light and dark areas differently absorbing X rays, such as disseminated organic material, including roots and rootlets, algal "stromatolitic" structures, and stains or concentrations of diagenetic mineral implacement, replacement, or growths.

In the recent, unconsolidated sediments studied by Moore and Scruton (1957), two distinct types of mottles were recognized: (1) mottles with distinct boundaries and (2) mottles with indistinct, fuzzy, or gradational boundaries. They also recognized intermediate types between the two extremes.

X-radiographs of the ancient fine-grained sediments show that mottled structures are prevalent in the consolidated rocks. These mottles have bound-



TEXT-FIGURE. 11.—X-radiographic positive print of Kayenta (Jurassic-Triassic) Formation, Emery Co., Utah. Mottled appearance of the x-radiograph is not seen in hand specimen. Note lack of any recognizable primary sedimentary structure. Filamentous features scattered sparsely throughout may be roots or rootlets. Scale line equals 1 cm.

ary relationships that range from indistinct to distinct. The density per unit area of the mottles ranged from spotty (Text-fig. 11), to heavy concentrations (Text-fig. 12).

The mottles of others (Moore and Scruton, 1957) include lenses and pockets of sediment that have a different texture than the enclosing sediments. The mottles of this study are restricted to those blotchy, obscure, or filamentous features that occur in some x-radiographs.

The presence of organic material is recognizable in some cases (Text-fig. 12), and the recognizable growth of diagenetic minerals can leave light or dark areas on the x-radiograph (Text-fig. 6). In some cases the mottled effect could be due to the random mixing of the soft sediment by burrowers. The origin of all mottles cannot be ascertained from the radiographs alone.

Structureless

This category is poorly represented in numbers among the samples used in this study. Without doubt, the truly structureless sedimentary rock is an

TEXT-FIGURE 12.—X-radiophic positive print of the North Horn Formation (Tertiary), Price Canyon area, Utah. Heavy concentration of filamentous "organic" material obscures or obliterates any primary structures that may be present. Scale line equals 1 cm.

exceptional case as borne out by results of this study and by Hamblin (1965). Within any vertical sequence more than a foot or two thick, it would seem extremely difficult to have sediment deposited and not have a distinguishable, depositional structural framework present. The absence of any bedding has to reflect several conditions: a constant and rapid sedimentation rate; homogeneous mineralogy; particle size, shape, and color. Water agitation must also be either vigorous or in abeyance.

Other causes of structureless sediments are actually due to postdepositional effects. Burrowing organisms are probably the most common agent for the mixing of newly deposited sediments. Studies have shown that a very rapid and thorough job is done by these organisms. A small number of the specimens x-radiographed in this study were apparently made structureless by the direct effects of burrowing organisms. Burrows show up clearly in the x-radiographs and are generally not discernible in the hand specimen.

The structureless effect in some shales may be due to the destruction of bedding structures by postdepositional forces. Another postdepositional effect, in some sediments, is the bleaching or leaching work of groundwater or other mineralizing fluids which can destroy the more obvious primary sedimentary structures.

There appears to be a trend toward the structureless rock from one which is stratified. The x-radiographs show a transition of rocks within the disturbed category containing minor amounts of the mottling effect, to nearly structureless rocks with a minor degree of mottling, to rocks that are completely structureless.

X-radiographs that pictured the rock as being internally featureless were not common. Only four slabs x-radiographed of over one hundred were classified as structureless. Text-figure 13 is exemplary of the structureless category. This apparent isotropism to radiation is thought to come about by either a primary deposition of homogeneous material or by the combined effects of various postdepositional processes which so mix up the sediment as to leave it structureless and unmottled. One specimen, collected in the northwest corner of Arizona, came from a Pleistocene deposit of silt and is poorly consolidated. This deposit is considered by some (Hamblin, 1969, oral communication) to be aeolian. The x-radiograph of this deposit showed no traces of structural elements, so this would appear to be an example of a primary, homogeneous deposit.

SUMMARY

The x-radiographic techniques used in this study have shown that most fine-grained detrital sedimentary rocks have a definite internal structural framework. The structures are classified in four broad categories: I. Regular Sratification, II. Disturbed Structures, III. Mottled Sediments, and IV. Structureless. In a majority of cases, two or more structural types were present within the 8- to 10-inch thickness of the slabbed samples.

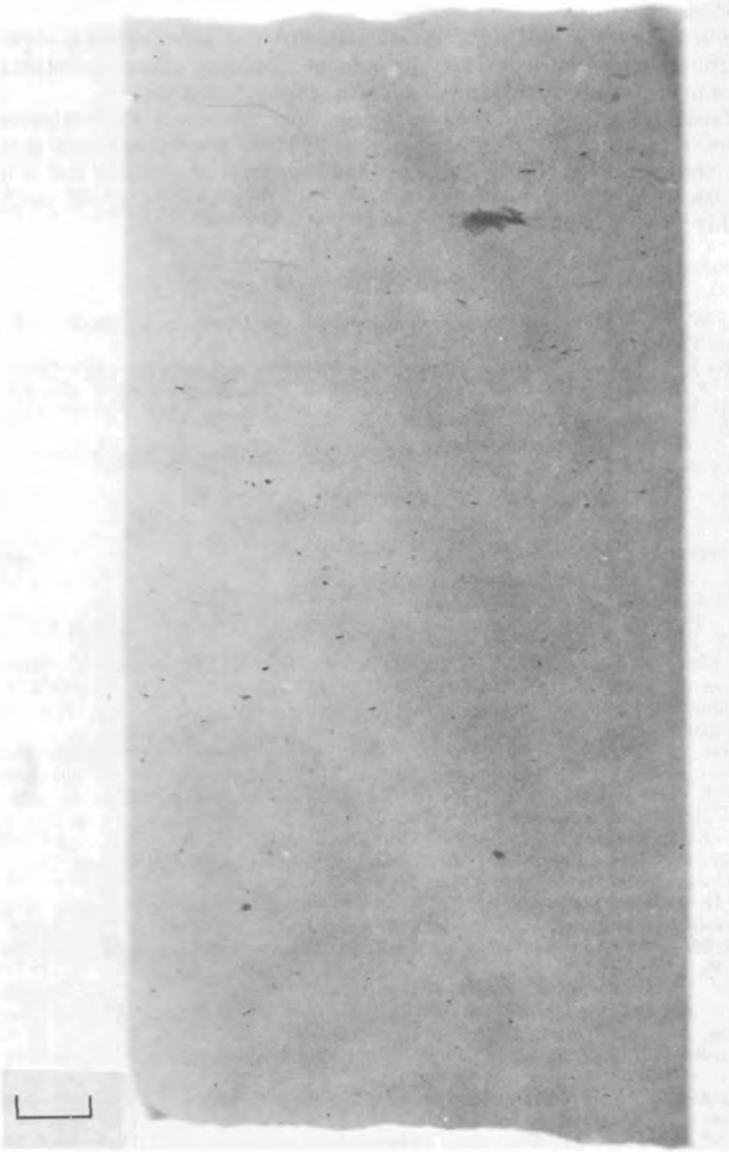
The textural differences in shales and siltstones are so slight that the true stratification is often masked by secondary coloration or other weathering characteristics. The fine particles are apparently moved by very low-energy water motion, thus giving rise to a variety of microstructures.

The use of the "unit stratum" and "sedimentation unit" concepts provided coordination in interpreting depositional sequences.

The use of the term *massive* should be restricted to gross bedding features. It would be improper to summarily refer to any shale or siltstone as "massive" without an X ray of the rock's internal structure to prove homogeneity.

CONCLUSIONS

Most shales and siltstones have a complex internal structure. "Massive" or "homogeneous" fine-grained detrital sediments are the exception. The "internal view" of rocks obtained by x-radiographic techniques provides a reliable, four-part classification for siltstones and shales. This is based on their depositional and postdepositional histories. Identification and classification of primary and secondary structural features known to occur in shales, but not normally observed megascopically, have significance. Correlation of various microhorizontal and cross-strata laminations, with their larger counterparts in



TEXT-FIGURE 13.—X-radiographic positive print of a core cut in the Late Paleozoic of west Texas. This siltstone is completely structureless and nearly homogeneous in mineral content. Scale line equals 1 cm.

medium clastic rocks, can provide meaningful data for paleoenvironmentalists and sedimentologists.

A tendency for the shale or siltstone to split along planes, separating two different structural types, was not evident. Bedding plane separations were more common where a substantial textural change occurred.

"Massive"—appearing siltstones, shales, and mudstones do not necessarily represent deposition in quiet, deep water. Their general internal structural complexity belies that common notion. It is apparent that shales and siltstones accumulate laterally and vertically by the same mechanisms as do sandstones and other detrital sediments.

REFERENCES CITED

Bradley, W. H., 1929, The varves and climate of the Green River epoch: U.S. Geol. Surv. Prof. Paper 158-E, p. 87-110

Coleman, J. M., and Gagliano, S. M., 1965, Sedimentary structures: Mississippi River deltaic plain, *in* Middleton, G. V. (Editor), Primary sedimentary structures and their hydro-dynamic interpretations Soc Econ Paleontologists Mineralogists Spec. Pub 12, p 133-148

Dunbar, C. O, and Rodgers, J, 1957, Principles of stratigraphy: John Wiley and Sons, New York, 356 p

Hamblin, W. K, 1961, Micro-cross-lamination in upper Keweenawan sediments of northern Michigan Jour Sedimentary Petrology, v 31, p 390-401.

...., 1963, Radiography of rock structures. *in* Clark, G L (Editor), Encyclopedia of Xrays and gamma rays Reinhold Publishing Corp, New York, p 940-942

———, 1964, Rhythmic laminations within some seemingly homogeneous sandstones of Kansas and Oklahoma: Kansas Geol Surv. Bull 169, p 183-189.

———, 1965, Internal structures of "homogeneous" sandstones: Kansas Geol Surv Bull 175, pt 1, p. 1-37.

Harms, J. C., and Fahnestock, R K, 1965, Stratification, bed forms and flow phenomena (with an example from the Rio Grande). *in* Middleton, G. V. (Editor), Primary sedimentary structures and their hydro-dynamic interpretation: Soc. Econ Paleontologists Mineralogists Spec Pub 12, p 84-115

McCrossan, R. G, 1958, Sedimentary "boudinage" structures in the Upper Devonian Ireton Formation of Alberta Jour. Sedimentary Petrology, v 28, p 316-320.

McKee, E D., and Weir, G W., 1953, Terminology for stratification and cross-stratification in sedimentary rocks: Geol Soc America Bull., v 64, p 381-389.

———, 1965, Experiments on ripple lamination: *in* Middleton, G V (Editor), Primary sedimentary structures and their hydro-dynamic interpretation: Soc Econ Paleontologists Mineralogists Spec Pub 12, p. 66-83.

Moore, D. G, and Scruton, P C, 1957, Minor internal structures of some recent unconsolidated sediments: Amer. Assoc Petrol. Geol. Bull., v 41, p. 2723-2751.

Otto, G H, 1938, The sedimentation unit and its use in field sampling Jour. Geology, v 46, p 569-582

Pettijohn, F J, 1957, Sedimentary rocks: Harper and Bros., New York, 718 p.

Potter, P. E., and Pettijohn, F J, 1963, Paleocurrents and basin analysis. Academic Press, Inc, New York, 296 p

Schmidt, R. A M, 1948, Radiographic methods in paleontology: Amer Jour. Sci., v 246, p 615-627.

———, 1952, Micro-radiography of microfossils with x-ray diffraction equipment. Science, v 115, p. 94

Twenhofel, W. H., 1932, Treatise on sedimentation. 2d ed The Williams and Williams Co, Baltimore, 926 p

Van Stratten, L M S V, 1951, Texture and genesis of Dutch Wadden Sea sediments: Proc Third International Congress of Sedimentology, Gromingen-Wageningen, Netherlands, p. 225-244

Zangerl, R., 1965, Radiographic techniques: *in* Kummel, B., and Raup, D. (Editors), Handbook of paleontological techniques: W H Freeman and Co, San Francisco, p 305-320