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Pre-Cincinnatian Paleozoic Cyclic Sediments in the Upper Mississippi Valley: a Discussion

ABSTRACT

Pre-Cincinnatian Paleozoic deposits of the Upper Mississippi Valley area consist of four recurring lithotopes developed in different but related shelf depositional environments. The four lithotopes are: (1) quartzarenite deposited in the energetic near-shore-beach environment; (2) poorly sorted generally coarser grained calcareous arenites which are lithologically transitional with both overlying and underlying lithotopes and which developed seaward of the nearshore environment in a zone which is subject to variable energy and sediment supply and to encroachments by neighboring environments of deposition; (3) shales or argillaceous sandstones deposited in the depositional shelf environment; and (4) carbonates deposited in a shelf-reef environment. These lithotopes accumulated on a mildly unstable craton.

Five successive episodes of submergence and emergence of the shelf are indicated in pre-Cincinnatian deposits. Each episode was caused by the interaction between negative tectonic adjustments in geosyncline and basin areas and positive tectonic adjustment in shelf, dome, and arch areas.

Each environment of deposition was located on a shallow marine shelf and was confined to a zone which occupied a position roughly parallel to the ancient shoreline. In an episode of submergence and emergence each environment migrated first shoreward and then seaward over the shelf producing one cycle of sediments. Deposits of the beach-nearshore environment were the first to be laid down over the submerging land surface and are taken as the basal lithotope of a cycle. Maximum retreat of the sea during any regression coincides roughly with the seaward or southerly limit of deposits of this environment. Deposition in other environmental zones during submergence caused the spreading out of their deposits over those of environmental zones located closer to shore. Thus, beginning at the base of a cycle of sediments, deposits which accumulated in shelf environmental zones located successively farther from the shoreline occur one on top of the other. Reverse ordering of lithotopes may occur with emergence.

The paleoslope of the shelf was to the southeast, and south, and transport of sediments was essentially south and southwest roughly parallel to the shoreline.

INTRODUCTION

Examination of pre-Cincinnatian Paleozoic strata in Wisconsin, as well as in neighboring states, indicates that formational boundaries are inadequately defined and stratigraphic relationships are poorly understood. This is believed in large measure to be due to a lack of understanding of the significance of these deposits in terms of geologic history and development. Only through a broader framework of geologic history and development can stratigraphic relationships be clearly understood. This investigation was undertaken as an initial step toward developing such a framework.

No satisfactory explanation has been advanced to account for the lithologic relationship of these strata except that they have been considered to be cyclic and to have been deposited during successive transgressions and regressions of the sea over a broad and shallow shelf. With the exception of the quartzarenites and the carbonates, no attention has been focused on the similarities between other repetitive elements in the section nor has much attention been given to the significance of these elements in terms of geologic history.

Some recent investigations (Dapples and others, 1948; Krumbein and others, 1949;

Pettijohn, 1957; Pryor, 1960; Wells, 1960) suggest that the vast majority of sedimentary rocks represent repetition or recurring patterns of sedimentation. Pre-Cincinnatian Paleozoic strata of the Upper Mississippi Valley area consist of a series of alternating sandstones and carbonates with subordinate siltstones and shales. This alternation occurs in a broad and regular cyclical pattern spanning the entire sequence. The sequence consists of five regular sets of these alternating strata. Each set consists generally of four lithotopes indicating four depositional environments and is considered to represent a sedimentary cycle. The four lithotopes and their environments of deposition are: (1) quartzarenites deposited in the beach-nearshore environment; (2) poorly sorted generally coarser grained calcareous quartzarenites, transitional with both the overlying and underlying lithotopes, which developed seaward of the beach-nearshore environment in a zone that was subject to variations in energy and sediment supply and to encroachments by neighboring environments of deposition; (3) shales or argillaceous sandstones deposited in the depositional shelf environment; and (4) carbonates deposited in a shelf-reef environment.

The objectives of this paper are to describe the lithotopes, to analyze them in terms of environments of deposition, and to derive from these a broad framework of geologic history which adequately accounts for their pattern of occurrence.

The study is based on examination of approximately 150,000 feet of subsurface well cuttings and numerous outcrops in Wisconsin and neighboring states. In addition, a large amount of literature dealing with these deposits has been reviewed.

Acknowledgments.—This study was undertaken as the initial step in a program designed to re-evaluate the Paleozoic geology of Wisconsin. The author is especially indebted to George F. Hanson, State Geologist, for many discussions of the geology and for editorial assistance.

The author gratefully acknowledges all those investigators whose published works were drawn upon in the preparation of this manuscript. It is not practical to make reference to all of these authors, but where their work is drawn on directly acknowledgment is made.

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LITHOTOPES

The four recurring lithotopes which characterize pre-Cincinnatian deposits of the Upper Mississippi Valley are discussed separately. Discussion of each is limited to its most significant characteristics and to the environment of deposition which it indicates. The names of strata assigned to each lithotope are indicated in the discussions, and the position of these strata with respect to others in the sequence is indicated in the generalized cross section of Figure 1.

Each depositional environment may be transitional with its neighbors because of changes affecting the source area, rate of sediment supply, and efficiency and distribution pattern of marine reworking and dispersing agents. Consequently, a certain amount of intermingling can be expected between lithotopes.

Quartzarenite Lithotope

Formations which belong to the quartzarenite lithotope are the Mt. Simon Sandstone, Galesville Sandstone, Jordan Sandstone, New Richmond Sandstone, and St. Peter Sandstone.

Deposits of this lithotope are essentially monomineralic consisting of rounded quartz sand grains with minor amounts of other constituents (total usually less than 5 percent).

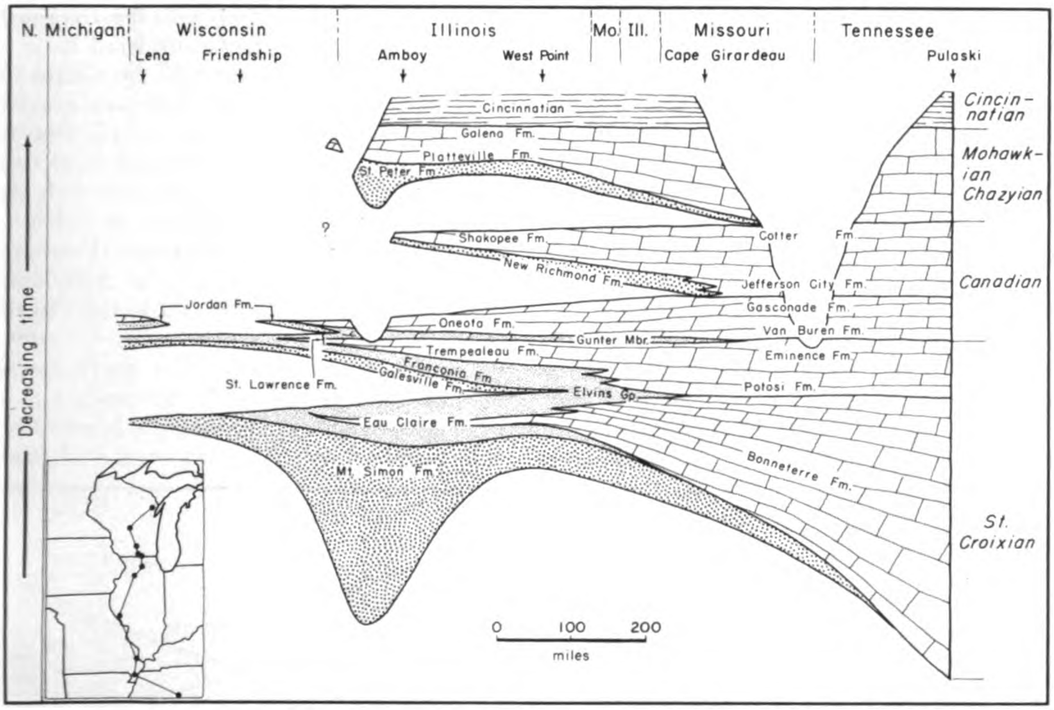

FIGURE 1.—North-south generalized cross section showing relationships of pre-Cincinnatian Paleozoic strata from Lena, Wisconsin, to Pulaski, Tennessee. Vertical scale is much exaggerated and is intended to show relative thickness, inferring a general time relationship. Section is approximately 1200 miles long. Prepared from sample studies of Wisconsin wells and from published logs from Illinois (Workman and Bell, 1948), Missouri (Grohskopf, 1955), and Tennessee (by Freeman, *in* Dott and Murray, 1954).

Impurities are rare and consist generally of noncarbonate materials. The heavy mineral suite is restricted and is dominated by zircon, tourmaline, ilmenite, and leucoxene. Garnet and anatase are minor constituents although garnet is abundant locally.

The texture of the quartzarenites is medium- and fine-grained although locally coarse sand grains and granules are abundant. Clay, silt, and very fine sand are notably rare or absent.

The homogeneous mineralogical and textural character of this lithotope render it indivisible on a regional scale and only partially so on a local scale. Locally a conglomerate may occur in its base as, for example, is the case with the St. Peter and Mt. Simon Sandstones in Wisconsin.

The quartzarenite lithotopes show a general thinning, and are laterally transitional with carbonate deposits, in the direction of the Appalachian geosyncline to the southeast. Areas of thickest sand accumulation coincide with intracratonic basins. Textural and mineralogical characteristics of the sandstones do not change significantly with changes in thickness. Bedding is medium to massive, but may be thin locally.

Directional indicators such as cross-bedding and ripple marks show that sediment was transported from north and northeast to south and southwest, a direction, as will be seen later, that corresponds with the strike of the paleoslope and with the trend of the ancient shorelines.

Fossils are exceedingly rare in the quartzarenites and, where found, consist of small fragments of shells or trails or burrows. Where fragments have been indentified, the forms are generally identified with, or closely related to, those which occur in underlying strata.

Contact of the quartzarenite lithotope with underlying strata may be sharp or transitional. Where sharp it may or may not be considered unconformable. Each of the sandstones is known from at least one outcrop to be unconformable with underlying strata. Examples of unconformable contacts occur at the base of Mt. Simon Sandstone as well as at the bases of the Jordan and St. Peter Sandstones as can be seen from the cross section of Figure 2. Contacts at the bases of the Galesville and New Richmond Sandstones are not so well known. Lee indicates unconformities beneath both of these sandstones in the Ozark area (1943, Fig. 3). Quick (1959) studied a series of cores collected near Troy Grove, in northern Illinois, and concluded that the basal contact of the Galesville is disconformable. Examination of exposures of the Chapel Rock Formation in the Northern Peninsula of Michigan, equated by Hamblin (1958, 1961) with the Dresbach Group of Wisconsin, and considered here to be the lithologic equivalent to the Galesville Formation of Wisconsin, indicates an erosion surface at its base overlain by 15 feet of conglomerate. The New Richmond Sandstone is suspected of being unconformable with the underlying Oneota Formation in the vicinity of a quarry exposure located near Eastman, Wisconsin (Andrews, 1955), at Stillwater, Minnesota (Ulrich, 1924), and in the Ozarks (Lee, 1943).

The quartzarenite lithotopes are believed to have developed from the progradation of a continuous series of coalescing beach-nearshore sands which migrated over a shallow

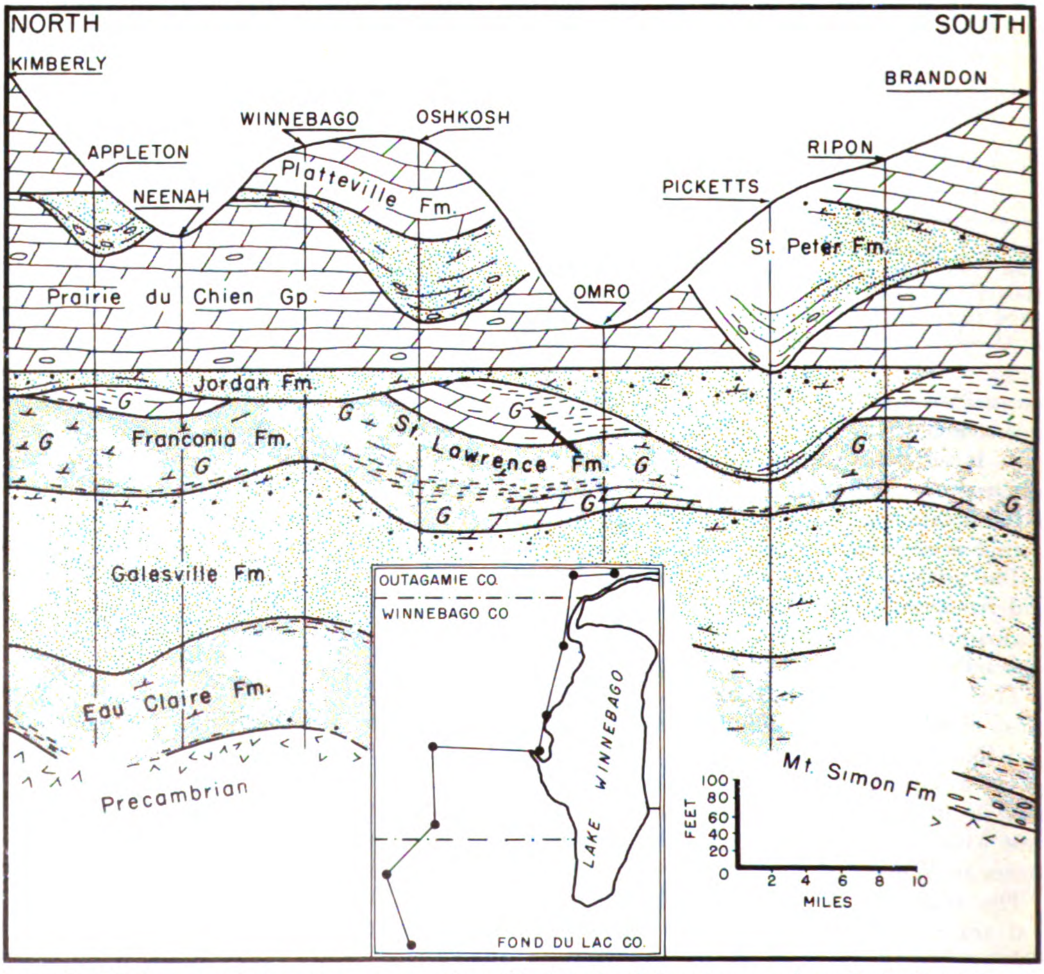

FIGURE 2.—Northeast-southwest cross section of pre-Cincinnatian Paleozoic strata from Kimberly to Brandon in eastern Wisconsin showing variability in thickness and lithology of St. Peter and Jordan Formations. Base of Prairie du Chien Group is used as datum plane. Section covers horizontal distance of approximately 40 miles.

marine shelf during progressive subsidence. Such an origin is suggested for widespread blankets or sheets of sand by Curray (1960), who in an explanation of sedimentation on the Continental Shelf indicates that such sands can be accounted for by the processes of marine transgression with nearshore sand deposition. Both the St. Peter Sandstone (Du Bois, 1945; Dapples, 1955) and Mt. Simon Sandstone (Freeman, 1949; Calvert, 1962) have been attributed to this origin.

Recent studies of shelf deposition and sediments in the northwest Gulf of Mexico indicate that deposits of the littoral zone, a marginal zone comprising ". . . the sediments of the beaches, barriers, and nearshore . . ." shelf area consist of ". . . almost pure fine and medium grained generally well sorted sands" (van Andel and Curray, 1960, p. 352-53). The width of this zone, in a seaward direction, is shown to attain a maximum of about 10 miles by van Andel (1960). This zone is one of high energy and includes the surf zone and the turbulent zone (Parker, 1960) down to a depth of 6 fathoms off the Texas coast (Shepard and Moore, 1955) and to 10 fathoms around the southwestern part of Trinidad (van Andel and Postma, 1954).

Sediment delivered to the sea by rivers, together with sediment eroded from the shore by the transgressing sea, is winnowed and redistributed by waves and currents. The coarser fraction, consisting of sand, is distributed in the beach-nearshore zone by waves and longshore currents (Johnson, 1956) similar to those in the northwest Gulf of Mexico today (Curray, 1960) which parallel the shoreline. Johnson (1956) reports sand is moved parallel to the shore in the longshore drift system out to depths of from 60 to 80 feet.

The direction of maximum inclination of cross beds is interpreted to indicate the current direction involved in the transport and deposition of ancient sediments (Pettijohn, 1957, 1962; McKee, 1957). The predominant direction of sediment transport indicated by cross-bedding in pre-Cincinnatian sandstones deposited in the beach-nearshore zone is to the southwest and south (Potter and Pryor, 1961.)

A study of the St. Peter Sandstone and Simpson Group by Dapples (1955) indicates that the St. Peter Sandstone sheet reached its southerly depositional limit along an indefinite northeast trending line through western Kentucky which represents roughly the zero contour of occurrence of deposits of the beach-nearshore zone and is interpreted to indicate approximately the configuration of the shoreline at that time. Directional properties show that sand of the St. Peter was transported in a direction parallel to this as well as to later hypothetical shorelines (Fig. 3). Similarly, the southerly depositional limits of the other quartzarenites, as constructed from the data of Lee (1943), Cohee (1948), Workman and Bell (1949), and Emrich (1962), and from numerous published well records, indicate roughly the shoreline configuration at the time of their initial stages of deposition, and directional properties indicate that sand was transported generally parallel to this shoreline (Fig. 3). Present northerly limits of the quartzarenites are due to erosion and bear no relationship to the extent of original occurrence.

Deposits of the beach-nearshore zone are characteristically thick to massive bedded, cross-bedded, and are composed of clean and sorted sand.

The finer fraction, consisting of fine sand, silt, and clay, is distributed farther out on the shelf by marine dispersing agents. The distance and direction from their source at which these fines are ultimately deposited depends on the distribution pattern of the dispersing agents (Curray, 1960).

Poorly Sorted Lithotope

Overlying the quartzarenite lithotope there may be a poorly sorted, generally coarser grained, somewhat calcareous, and distinctly bedded lithotope. These two lithotopes are separated because of their marked textural differences. The poorly sorted lithotope is compositionally and texturally transitional with both the overlying and underlying lithotopes, having some of the characteristics of each of them as well as possessing certain unique characteristics. Its contacts may be sharp and well defined or transitional and obscure.

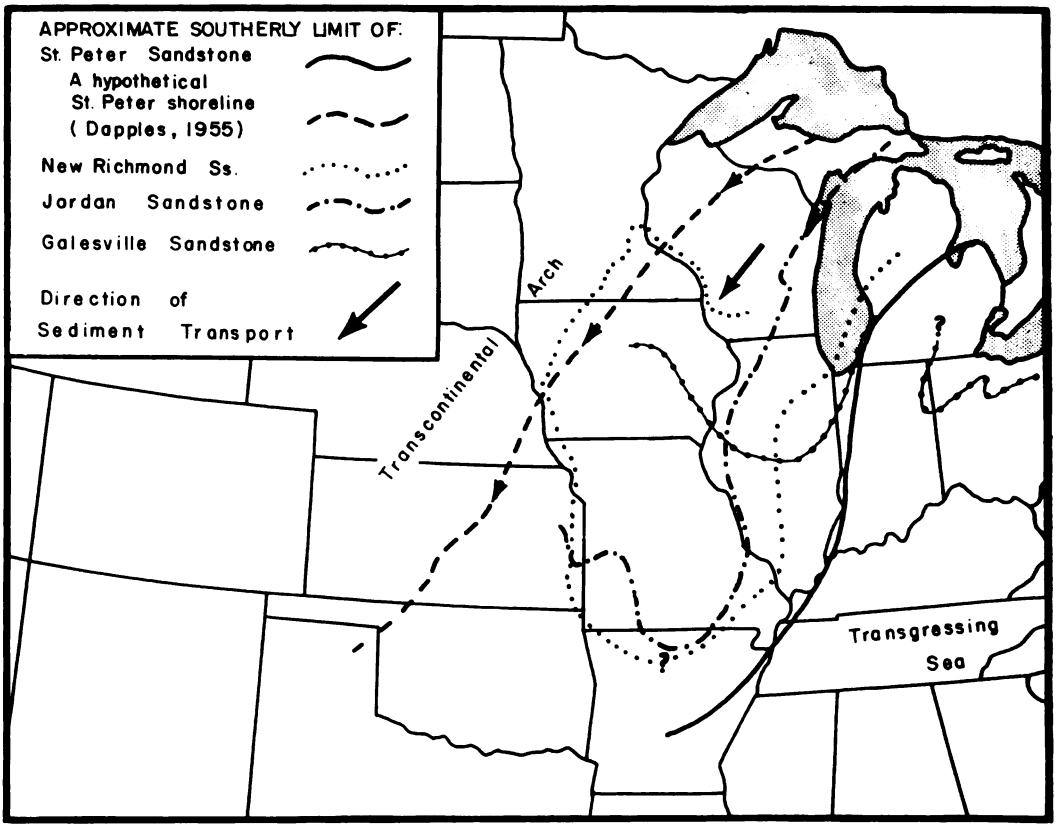

FIGURE 3.—Map indicating approximately southerly limit of occurrence of quartzarenites. Limit is interpreted to indicate approximately shoreline configuration at time of deposition of sands which formed earliest deposits of these formations. Dominant transport directions, as determined from current lineation and cross-bedding measurements, are indicated by arrows. Limits of Galesville, New Richmond, and St. Peter Sandstones modified from Workman and Bell (1948), Emrich (1962), Powers (1935), and Dapples (1955).

Strata which are assigned to the poorly sorted lithotope include the upper part of the Mt. Simon Sandstone, Ironton Sandstone, Madison Sandstone Member near the top of the Jordan Formation, and sandy basal phase of the Glenwood Formation, the Nokomis Member (Templeton and Willman, 1963). This lithotope is not recognized overlying the New Richmond Sandstone.

The poorly sorted lithotope consists of coarse-grained quartzarenites which are commonly interbedded with strata composed of materials ranging in size from silt to granules or with arenaceous carbonate strata. The coarse sandstone beds locally contain thin layers of shale and conglomerate. Some beds are very well sorted. Heavy minerals are essentially the same as those which occur in the underlying quartzarenites, although the garnet content may be higher near its base.

Certain beds in some of the units assigned to the poorly sorted lithotope can be traced over broad areas. For example certain beds in the Ironton Formation are cited as being laterally persistent and as maintaining essentially uniform thickness over distances of up to 100 miles in west-central Wisconsin (Emrich, 1962).

The poorly sorted lithotope thickens in intracratonic basin areas; for example, the Ironton Formation shows an increase of from zero feet in south-central Wisconsin to about 100 feet basinward in northeastern Illinois (Emrich, 1962; Buschbach, 1960).

The coarse-grained beds are commonly cross-bedded. The poorly sorted silty beds are massive and may contain abundant burrows. Mixing of these beds is thought to have been accomplished by the same organisms that produced the burrows. Ripple marks are most common in finer grained beds. Conglomerates are of limited lateral extent and are composed of locally derived materials.

Fossils may be common, especially in the upper part. They are most abundant in the finer grained and poorly sorted beds and consist of the burrows already mentioned and of trails, and less commonly of brachiopod shell fragments and casts and molds of trilobites.

Contact with the underlying quartzarenite may be sharp or transitional. The contact is placed at the base of the lowest bed indicating reworking and is generally based on the change upward to coarser grained sandstone that appears to be better sorted in individual beds, and that may contain materials ranging in size from silt to granules. These strata are generally silty and somewhat calcareous, and they may contain ferruginous cement, fossils, glauconite, pyrite, and beds of shale, dolomite, and conglomerate.

The environment of deposition of the poorly sorted lithotope must account for vertical variability between beds and lateral persistence of individual units. Vertical lithologic variability is interpreted to mean unstable and frequently changing environmental conditions. An area of the shelf in which such conditions exist is located seaward from the beach-nearshore zone, as for example in a large part of the central shelf in the northwest Gulf of Mexico, and is called the nondepositional shelf zone by van Andel (1960; van Andel and Curray, 1960). Neighboring environments of deposition encroach into this zone in response to a variety of conditions and form deposits characteristic of their particular environment. The name "nondepositional" shelf zone is of questionable value because sediment actually is deposited here when sediment supply, available energy, and distributing and dispersing agents change in response to rapid shifts in environment. However, the name is used for drawing comparison between Recent and Pre-Cincinnatian deposits.

In contrast to the environment of deposition of the quartzarenite lithotope, considered to be one of consistently higher energy than those located more seaward, the poorly sorted lithotope is erratic and is subject to extremes of energy conditions. At times of low wave and current energy finer materials normally carried to more remote areas may be deposited, bottom conditions stabilize, animals establish themselves, and neighboring environments of lower energy may encroach on the area. At times of high wave energy bottom sediment is churned up, finer materials are kept in suspension or removed, coarse materials are left behind, animals adapted to low-energy conditions are displaced or destroyed, and neighboring environments of lower energy are encroached upon. It is suggested that periodic storm activity was responsible for much of the modification of bottom sediments in this area.

This environment is, thus, seen to expand, contract, and shift position frequently in response to changing energy conditions causing intricate mingling of deposits characteristic of environments on either its landward or seaward sides which encroach into and retreat from the nondepositional zone.

Shale or Argillaceous Sandstone Lithotope

Strata correlated with the argillaceous lithotope include the Eau Claire Sandstone, Franconia Sandstone, Blue Earth Member in the top of the Jordan Formation, and upper shaly phase of the Glenwood Formation, the Harmony Hill Member. This lithotope is not known to overlie the New Richmond Sandstone.

The argillaceous lithotope is characterized by fine-grained sediments consisting of shale or silty or argillaceous sandstone. Clay may occur as a green coating on sand grains or it may be present in thin shale partings or in shale beds up to 10 or 12 feet thick; it may also occur in the form of abundant glauconite pellets. Carbonate is common as cementing material or as thin beds. The heavy mineral suite is dominated by garnet (up to 90 percent; Driscoll, 1959) with lesser amounts of ilmenite, leucoxene, tourmaline, and zircon.

This lithotope is uniform in composition on a regional scale. Variations are due chiefly to differences in shale-to-sand ratio and locally in carbonate content.

The argillaceous lithotope thins southward and southeastward in the direction of the Appalachian geosyncline and is transitional with carbonate at its seaward edge. In intracratonic basins it may thicken appreciably as do both the Eau Claire and Franconia Formations (Fig. 1). Locally its thickness does not change significantly.

The argillaceous lithotope is commonly thin bedded or shaly which distinguishes it from the underlying lithotopes in which bedding ranges from massive to thin. Cross-bedding may be well developed and is commonly delicate as befits a fine-grained clastic. Ripple marks and current lineations are locally abundant. Intraformational conglomerates are common and are composed of materials derived locally from subjacent beds. Pebbles and cobbles in the conglomerates are commonly sandstone cemented with carbonate. The matrix of the conglomerates is generally calcareous and contains fine sand, silt, and clay.

Fossils, usually consisting of fragments and bits of brachiopod shells, trilobite molds and casts, and abundant burrows and trails, may be common in the argillaceous lithotope.

Contact of the argillaceous lithotope with the underlying lithotope is generally sharp and even. The surface of contact was leveled by waves that reworked bottom sediments at a time when the area was located in shallower water or at times of storm. Selection of the contact is based on the abrupt change from silty medium- and coarse-grained calcareous sandstone to silty fine- and very fine grained calcareous argillaceous and glauconitic sandstone or to shale.

The environment of deposition of the argillaceous lithotope is the depositional shelf located generally seaward from the area of nondepositional shelf environment (van Andel, 1960). The uniformity of texture, composition, and thickness of this lithotope over broad areas is interpreted to indicate a stable environment having an essentially constant energy level and a uniform rate of sediment accumulation. Variations in this uniformity are thought to be due to nearness to neighboring depositional environments or to minor shifts of environmental areas at times of major wave and current activity.

The fine clastics winnowed from the river sediments in the beach-nearshore environment were deposited farther offshore in accordance with the distribution pattern of marine currents. The amount of sediment which accumulated was a function of sediment supply and of local shelf subsidence.

Present-day deposition of fine sediment on the shelf in the northwest Gulf of Mexico is restricted to the area beyond the beach-nearshore zone and occurs primarily in the middle and outer shelf areas. The pattern of dispersion of these sediments appears to be independent of the coarser sand distribution (van Andel, 1960).

Carbonate Lithotope

Formations assigned to the carbonate lithotope include the Bonneterre Dolomite, St. Lawrence Dolomite, Oneota Dolomite, Shakopee Dolomite, and Ottawa Group. The Ottawa includes all the carbonate units between the Glenwood Shale and Maquoketa Shale (Swann and Willman, 1961). A laterally persistent carbonate unit which occurs in Illinois in the upper part of the Eau Claire Formation, and at scattered localities in the Eau Claire of southern Wisconsin, is considered to be the lithostratigraphic equivalent of the Bonneterre Dolomite of Missouri.

The carbonate lithotope is the most readily recognizable of all the lithotopes as it is characterized by carbonate rocks. In the lower part of each carbonate unit sand grains and minor amounts of shale, silt, and glauconite are generally present. Higher in the section these constituents may drop out completely. In other cases beds of shale and sand can be found throughout the unit.

In this lithotope fossils are more diversified than in those of the other three lithotopes. Bedding varies from medium to massive. Biohermal reefs are universally present, but laterally discontinuous, in all carbonates excepting those of the Ottawa Group in which they are rare.

The carbonate lithotope maintains a uniform thickness locally and shows a regional thickening into basin and geosynclinal areas. In the geosynclinal area, carbonate sections appear to be continuous, uninterrupted by intervening beds of sandstone or shale. Exceptions to the local uniformity of thickness occur where erosional unconformity exists between a carbonate and the overlying lithotope or where an irregular reef surface is buried by sediment of a succeeding lithotope.

Where the carbonate is succeeded by a deposit characteristic of a neighboring environment, for example that of the depositional shelf area, the contact is commonly transitional and even. If the carbonate is succeeded by a deposit characteristic of a more remote environment of deposition, for example that of the beach-nearshore area, then the contact is likely to be one of unconformity.

Contact of the carbonate lithotope with the underlying argillaceous lithotope is sharp and even. The regularity of this contact is striking.

The bulk of carbonate deposition today is taking place in reef environments similar to those which occur on the shelf off the east coast of Australia, off the southeast coast of Florida, or in the northwest Gulf of Mexico. Areas of active reef development in the northwest Gulf of Mexico are located in water shallower than 30 fathoms (Parker and Curray, 1955; Stetson, 1953) in the nondepositional shelf zone and in areas of stable but unconsolidated bottom where all other requirements for their development exist. Ladd and Hoffmeister (1936) and Cloud (1952) hold that reefs may develop upward from any stable, but not necessarily solid, pre-existing platform within reach of sea level in areas where all other requirements for their development exist and that they will continue to develop so long as these requirements are not altered. Reefs are not developing in the vicinity of the shoreline in the northwest Gulf of Mexico because nearshore conditions which include unstable bottom and abundant shifting sediment are inhospitable to reef development.

The carbonate lithotopes in Cambrian and Ordovician rocks of the Upper Mississippi Valley are believed to be a geologic manifestation of carbonate depositing environments of the present, namely the shelf-reef environment. The conclusion that these lithotopes probably developed in a reef environment seems logically inescapable (Gilluly, Waters, and Woodford, 1951; Cloud, 1952). Studies of the Oneota Dolomite (Starke, 1949) and of the "Trenton" formations (Du Bois, 1945) in the Upper Mississippi Valley indicate that they were deposited during times of transgression by the sea and that they accumulated in the shelf-reef zone as a series of intermingling carbonate deposits which were spread out as sheetlike bodies shoreward over the shelf by the transgressing sea.

The Shakopee Dolomite in northern Illinois presents a somewhat unique problem to the area in that it consists of interbedded fine-grained dolomite, quartzarenite, shale, and discontinuous thin layers of oolitic chert. Locally the sandstone layers are conglomeratic and contain pebbles and cobbles of dolomite derived from subjacent dolomite layers, otherwise they consist essentially of quartz sand similar to that characteristic of the quartzarenite lithotope. The upper surface of dolomite beds may be ripple marked and cracked. Biohermal reefs also occur at scattered localities. The vertical lithologic variability of the Shakopee indicates changing energy conditions, and the cracks, oolites, and conglomerates signify shallow and agitated waters. The abundance of quartz sand and clay indicates that a source of terrigenous clastics was near.

Deposits having these characteristics are found in shallow-water lagoons. A lagoon receiving, alternately, terrigenous clastics, and carbonate would have to be situated between the mainland at one side and a barrier, for example a reef, at the other. It is postulated that the Shakopee had such an origin.

Lagoonal deposits differ considerably from those of the open shelf, for example banks, which consist almost entirely of carbonate material. Sediment deposited in a lagoon may come from four sources: the mainland, the reef, nonreef skeletal hard parts, and chemical precipitation. The gradation from reef into lagoonal sediments ranges from sharp to indefinite. In a shoreward direction a barrier reef may pass, with indefinite or complexly interfingering relation, into lime sands that surround small patch reefs and eventually into lagoon lime sands, evaporites, or purely clastic sediments (Cloud, 1952). In the Great Barrier Reef lagoon, terrigenous materials are being distributed by strong currents. According to Fairbridge (1950) a limited amount of calcium carbonate is precipitated from the sea water in lagoons and reef-flat pools. However, the work of Illings (1954) indicates that much of the sediment accumulating on the Bahama Banks is authigenic and forms by the physicochemical and biochemical extraction of aragonite from warm shallow sea water saturated or supersaturated with calicum carbonate. Thus, much of the carbonate in ancient deposits may be authigenic.

Sedimentation is described as extremely rapid in the Great Barrier Reef lagoon because of the retaining effects of the outer reef barrier (Fairbridge, 1950). The amount of terrigenous and calcareous materials that accumulate in a lagoon varies in respect to supply and nearness to the main land or the reef. In the area of the Great Barrier Reef, terrigenous material commonly exceeds 90 percent near the mainland. In the reef vicinity calcareous clastic materials and chemically precipitated muds may form 98 percent of the total (Fairbridge, 1950).

PATTERN OF SEDIMENTATION

Locus of Deposition

The locus of deposition of pre-Cincinnatian Paleozoic sediments in the Upper Mississippi Valley was a craton on which were more active intracratonic basins and relatively stable scattered arches and domes. A study of dispersal centers of Paleozoic and later clastics of this and adjacent areas indicated to Potter and Pryor (1961) that the southward direction of sediment movement and slope of the craton have persisted through the Paleozoic to the present. They believe that (p. 1229-30):

> Such uniformity over so long a time and over such a wide area can reflect only major tectonic control. The behavior of basement rocks of the craton provides that control. This underlying tectonic control is the immediate cause of persistent paleoslopes, of recycling, and of the location and orientation of major clastic deposits ultimately derived from distant tectonic lands.

These authors interpreted the dominant southwestward direction of sediment transport to have been toward the continental margin, parallel to their paleoslope and perpendicular to the shoreline. In the present study direction of sediment transport, especially in the beach-nearshore zone, is interpreted to have been parallel to the shoreline, hence sediment transport was parallel to the continental margin, which lay toward the Appalachian geosyncline to the southeast and south, and perpendicular to the paleoslope, a relationship demonstrated for the St. Peter Sandstone by Dapples (1955).

During the Late Cambrian and Early and Middle Ordovician there existed in the Upper Mississippi Valley high areas referred to as the Wisconsin Dome, the North Huron Dome, a connecting link between these two domes called the Northern Michigan Highland, and the Canadian Shield (Fig. 4). The major intracratonic basin of this time was the Illinois-Michigan Basin. The Ozark area is considered to have subsided in Paleozoic pre-St. Peter time and to have risen before the end of the Cincinnatian (Eardley, 1951; Lee, 1943). Deformation during this interval is believed to have resulted in the development of many arches and other structural features on the craton including the Kankakee Arch, which separated the Michigan Basin from the Illinois Basin (Ekblaw, 1938), and the Findlay and Waverly Arches which bordered these basins along their southeastern margin (Woodward, 1961).

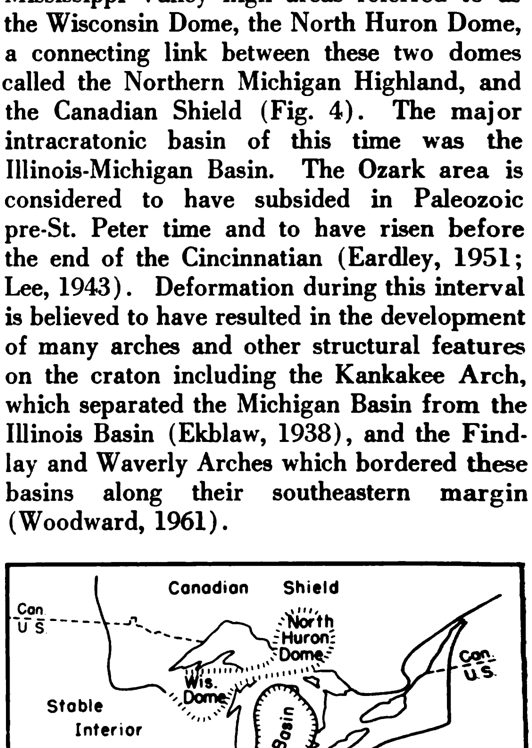

Figure 4.—Map of eastern North America indicating areas of pre-Cincinnatian Paleozoic orogenic activity (adapted in part from Eardley, 1951; King, 1959).

Development of Cycles

Distribution of major environments of deposition over present-day shelf surfaces indicates that they occupy positions roughly parallel to the coastline. Changes in sea level allow each environment to migrate over the shelf. Lowering of sea level relative to the land causes environments to shift seaward; conversely, a relative rise in sea level results in a shoreward shift. Minor sea-level changes, over shallow shelves, may cause broad shifts of the strandline emerging or submerging vast areas and account for many thin, but widespread, units. Major changes in sea level result in the development of complete cycles which should consist ideally of deposits of both transgressive and regressive phases.

In a somewhat irregular pattern seaward from, and roughly parallel with, the coast one can expect to encounter the depositional environments of the beach-nearshore zone, nondepositional shelf zone, depositional shelf zone, and shelf-reef zone (van Andel, 1960; van Andel and Curray, 1960). Migration of each environment over the shelf results in their being deposited in sheetlike bodies over the shelf surface, one on top of the other.

Deposits of the emergent phase are not as well represented as those of the submergent phase. This is especially true of deposits developed in higher energy environments located in the nearshore and inner shelf depositional zones. Regression of the sea exposes these environments and their characteristic deposits to subaerial erosion. Thus, during emergence, deposits of the nearshore-beach environment are continually reworked and removed to the retreating shoreline. For this reason they can be expected to be rare unless they are lowered, by local subsidence, beyond reach of erosion in which case they will be preserved.

A continuous sheet of coalescing nearshore beach sands will be deposited over the erosion surface in the subsequent submergent phase. Deposits of the submergent and emergent phases will be continuous only in the area outlined by the width and breadth of the beach-nearshore environment at the time of maximum emergence which is small in comparison to the aerial extent of the quartzarenite. The erosion surface separating deposits of two cycles may be preserved if it is cut in durable material, or is buried beneath sediment before it can be affected by eroding or reworking agents; otherwise it may be obscured by these agents as the sea advances. In either case the quartzarenite lithotope is taken to indicate renewed submergence, the beginning of a new cycle of deposition, and is the basal unit of a cycle of sediments.

The break between lithotopes of different cycles representing continuous deposition in the same shelf environment from one cycle into the next, as for example continuous carbonate deposition from one cycle into the next in seaward areas of the shelf unaffected by sea-level changes, may be difficult if not impossible to detect. A shift in direction of migration of the strandline over the shelf surface in these areas would be obvious only if marked by a lithologic break such as would be produced by the encroachment of a neighboring environmental zone. A shift to submergent conditions would be reflected in the overlying lithotope by re-appearance of deposits indicating more seaward environments of deposition.

Variations in Cycles

Pre-Cincinnatian Paleozoic sedimentary cycles may be incomplete because of nondeposition or because of erosion subsequent to deposition. A lithotope representing a specific depositional environment will develop only if that environment is present in an area. Thus, deposits of the beach-nearshore zone will not occur seaward beyond the area of maximum regression of this environment nor will they occur shoreward beyond the area of maximum transgression of the environment.

Carbonate lithotopes may be modified if a well-developed shelf-reef area is submerged to a depth greater than that required for reef growth at a rate exceeding the capacity of the reef to develop. This results in death of the reef in seaward areas and new reef development in shallower waters located shoreward. Similar changes have occurred in the northwest Gulf of Mexico and are interpreted to be the result of eustatic changes of sea level during the Pleistocene (Ludwick and Walton, 1957), although they might just as easily have been caused by tectonic adjustment.

Subaerial erosion produces an erosional unconformity with high local relief, as at the base of the St. Peter Sandstone, and abrupt changes in thickness of the overlying lithotope and often complete removal of one or more underlying lithotopes. The unconformity may have low local relief but be of wide areal extent resulting in incomplete removal of the underlying lithotope, or lithotopes, over extensive areas, as for example, at the base of the Jordan Sandstone.

Regressive phases are identified in Cambrian cycles but are unknown in Ordovician cycles. It is suggested that active subsidence of the Illinois-Michigan Basin during shelf emergence, at the close of the Mt. Simon and Galesville cycles, caused regressive deposits to be lowered beyond the reach of subsequent erosion and resulted in their preservation. During succeeding cycles shelf emergence apparently was not accompanied by subsidence of the basin.

The Jordan and New Richmond cycles of the Lower Ordovician differ from other cycles in that their shale or argillaceous sandstone lithotopes, representing the depositional shelf environment, are poorly known. Development of the argillaceous lithotope in the Mt. Simon and Galesville cycles is thought to have been caused by regression of the depositional environment into an actively subsiding basin area which received a large amount of fine clastic debris from a large land area of moderate relief. Regression prior to development of the Jordan and New Richmond cycles was less than during previous cycles and did not extend into basin areas; land areas were low and of low relief and provided only small amounts of clastics, and consequently less sediment accumulated in the depositional shelf environment.

GEOLOGIC HISTORY

As a result of this study, it is possible to formulate a working hypothesis regarding the geologic history and paleogeographic evolution of pre-Cincinnatian Paleozoic rocks in the Upper Mississippi Valley.

Five sedimentary cycles, indicating five successive episodes of shelf submergence and emergence, occur in these rocks. Strata comprising each cycle are indicated in Table 1 and their relationships to each other are shown in Figure 1.

Paleozoic sediments were deposited on an erosion surface cut in Precambrian rocks. The basal Paleozoic deposit in this area is the Mt. Simon Sandstone. The Mt. Simon is a quartzarenite which was deposited on a subsiding shelf in the nearshore-beach environment by a transgressing sea as a sheet of prograding and coalescing sand bodies filled in and mantled the erosion surface. The Mt. Simon, as shown in Figure 1, does not occur south of a point in Tennessee which is believed to mark maximum regression of the sea. Directional indicators in the Mt. Simon show that sediment was transported to the south and southwest parallel to the shoreline.

Seaward from the beach-nearshore environment, in which the Mt. Simon was deposited, was the nondepositional shelf zone. The poorly sorted lithotope, which characterizes this environment, is not known to occur everywhere but may be seen at the type exposure of the Mt. Simon, at Eau Claire, Wisconsin. There, it is represented by a unit about 20 feet thick consisting of alternating layers of silty poorly sorted sandstone containing burrows, thin shale laminae, and small amounts of calcareous cement, and of layers of predominantly coarse-grained quartzarenite.

Deposits of the argillaceous lithotope indicative of the next seaward depositional shelf environment are represented by the Eau Claire Sandstone in which both transgressional and regressional phases are recognized. The two phases of this lithotope are separated, as would be expected, by a carbonate unit developed in the reef environment. In Wisconsin this unit is known only from the subsurface and occurs in southern Wisconsin where it is a thin, previously undifferentiated bed less than 20 feet thick which thickens southward to form the Bonneterre Dolomite of southern Illinois and Missouri (Workman and Bell, 1949; Buschbach, 1960).

The transgressive phase of the Eau Claire, below the Bonneterre, is thin and absent in southeastern Missouri (Fig. 1). Northward in Illinois it thickens, as does the underlying

TABLE 1.—Strata comprising each of five pre-Cincinnatian Paleozoic sedimentary cycles in Upper Mississippi Valley are indicated.

Cycles	Depositional environments			
	Beach-nearshore	Nearshore shelf	Depositional shelf	Reef
5	St. Peter Fm.	Nokomis Mbr.	Harmony Hill Mbr.	Ottawa Group
4	New Richmond Fm.	?	Present, but unnamed	Shakopee Fm.
3	Jordan Fm.	Madison Mbr.	Blue Earth Mbr.	Oneota Fm.
2	Galesville Fm.	Ironton Fm.	Franconia Fm. and Lodi Mbr.	Black Earth Mbr. (Trempealeau Fm.)
1	Mt. Simon Fm.	"U. Mt. Simon"	Eau Claire Fm.	Bonneterre Fm.

Mt. Simon. The increase in thickness is thought to be due to a coincidence of environments of deposition, represented by these two lithotopes, with the subsiding Illinois-Michigan Basin.

Northward from the basin the Eau Claire thins until in eastern Wisconsin it is absent (Twenhofel, Raasch, and Thwaites, 1935). In the Northern Peninsula of Michigan, the stratigraphic position of the Eau Claire is marked by an erosion surface mantled by a basal conglomerate of the succeeding cycle. An erosion surface is also described at the top of the Eau Claire from cores taken near Troy Grove in north-central Illinois (Quick, 1959). This surface is interpreted as having formed in newly exposed land areas as a result of the same emergence that produced the regressive phase of the Eau Claire. Preservation in the Illinois-Michigan Basin of the regressive phase of the Eau Claire is interpreted to indicate that basin subsidence, contemporaneous with shelf emergence, lowered these deposits beyond reach of erosion.

Maximum regression of the strandline is marked approximately by the southerly limit of deposits of the nearshore-beach environment which accumulated during the subsequent cycle, namely the Galesville Sandstone. The Galesville is not known to occur south of a line which intersects the cross section of Figure 1 (*see*, Fig. 3) at about West Point, Hancock County, in west-central Illinois, and which extends eastward through central Illinois and then northeastward through north-central Indiana toward northeastern Indiana (Emrich, 1960). South of this area deposits of more seaward environments were laid down.

The Galesville is succeeded by the Ironton Formation which is generally poorly sorted over-all and consists of alternating beds of well-sorted coarse- and medium-grained sand and poorly sorted silty and calcareous beds containing abundant burrows. It is typical of the lithotope developed in the nondepositional environment. In western Wisconsin successive alternating strata in the Ironton Formation can be traced laterally over distances of up to 100 miles (Emrich, 1962).

Seaward from this zone was the depositional shelf environment. Deposits of the argillaceous lithotope, which developed in this environment, are represented by the Franconia Sandstone and in the northern part of the area by the Franconia and the overlying Lodi Siltstone, an argillaceous and calcareous member of the St. Lawrence Formation, in which both a transgressive and regressive phase are recognized (Nelson, 1956). The transgressive Franconia is lithologically inseparable from the underlying regressive phase of the Eau Claire south of the area of Galesville occurrence and within the area of maximum regression of the depositional shelf environment (Fig. 1, 3) represented by the Elvins Group. The transgressive and regressive phases of the Franconia and overlying Lodi are separated in southern Wisconsin by the Black Earth Dolomite Member of the St. Lawrence Formation, a northward pinching wedge representing the carbonate environment. To the north this carbonate is absent. Southward it increases in thickness and is correlated with the Trempealeau Formation of Illinois and the Eminence and Potosi Formations of Missouri.

The maximum northward transgression of the sea at this time is unknown. Subsequent emergence resulted in subaerial erosion in northerly areas and removal of these deposits (Nelson, 1956). This erosion surface is poorly known, but evidence for its development exists in eastern Wisconsin (Fig. 1) and as far south as Rochelle, in north-central Illinois (Willman and Templeton, 1952).

Beach-nearshore quartzarenite deposits of the subsequent cycle, characterized by thick deposits of Jordan Sandstone, are not known to occur southeast of an indefinite line extending approximately along the eastern border of Wisconsin, then around the western border of Illinois to east-central Missouri, and finally westward where the boundary is lost (Fig. 3).

The Jordan Sandstone is succeeded by deposits developed in the nondepositional shelf environment represented by the Madison Member. The Madison is poorly sorted and consists of alternating beds of sandstone, silty sandstone, sandy dolomite, dolomite, and, to the south, shale (Workman and Bell, 1949). Seaward from this zone was the area of depositional shelf environment. Deposits of the depositional shelf in the Jordan cycle are thin or obscure and poorly known and are represented by a blue-green calcareous, argillaceous and silty zone in Minnesota, the Blue Earth Siltstone Member (Stauffer and Thiel, 1941), and by a greenish argillaceous, silty and sandy zone in Wisconsin. The lack of an extensive shale deposit at this position is interpreted to mean that the depositional shelf environment did not regress southward far enough to coincide with the subsiding basin, that the exposed land area was less and lower than at previous times of emergence, and consequently that only a small amount of clay was delivered to the sea. Deposits of the reef environment developed seaward from the depositional shelf zone and are manifest in the Oneota Dolomite. In northerly areas the Oneota is lost to erosion (Fig. 1), thus its northward extent must be inferred. The erosion surface which developed during subsequent emergence is only poorly known but has been described from exposures near Eastman, western Wisconsin (Andrews, 1955), near Minneapolis, Minnesota (Ulrich, 1930), and in the Ozark area in Missouri (Lee, 1943). Maximum retreat of the sea during the emergence which produced this erosion surface coincides approximately with the southern limit of deposits of quartzarenite (Fig. 3), the New Richmond Sandstone, which occurs along a line trending southwestward from about Danville, in east-central Illinois, toward Cape Girardeau, Missouri (Workman and Bell, 1949).

The New Richmond developed in the nearshore-beach zone during the succeeding cycle. It is succeeded by poorly known deposits of the nondepositional and depositional shelf environments for the same reasons given to account for the poor development of the argillaceous lithotope of the preceeding Jordan cycle, which is overlain by deposits of the reef environment, the Shakopee Dolomite, developed further seaward. In more seaward areas the Shakopee Dolomite is continuous with the Oneota Dolomite of the preceeding Jordan cycle and consists almost entirely of carbonate. Northward, as for example near Utica in north-central Illinois, the Shakopee overlies the New Richmond and has a variable lithology which consists of dolomite containing layers of quartzarenite, shale, and discontinuous thin beds of oolitic chert. The dolomite beds range up to 10 feet in thickness, are seldom more than 3 feet thick, and are commonly very fine grained, and their upper surfaces may be ripple marked and mud cracked. The sandstone beds may be cross-bedded and commonly contain pebbles and cobbles derived from the underlying dolomite bed in their lower part. Beds of shale reach a known maximum thickness of 6 inches. The variable lithologic character of the Shakopee in this area is interpreted to indicate frequent environmental changes and ". . . fluctuation of conditions of sedimentation characteristic of shallow water deposition" (Cady, 1919). It is postulated that the Shakopee Formation accumulated in a very shallow environment situated shoreward from an area of major reef development. This environment is considered to have been a broad, flat, and shallow lagoon or back-reef area subjected to the influence of the land on one side and the reef on the other, while at the same time being influenced by factors affecting carbonate deposition.

The Shakopee Dolomite was removed by erosion in northerly areas during subsequent regression to an indefinite northeast-trending zone through western Kentucky (Dapples, 1955). The surface produced by this erosion is one of prominent relief in Wisconsin and northern Illinois. This emergence coincided approximately with the development of many new intracratonic structural features as, for example, the Kankakee Arch (Ekblaw, 1938) and Ozark Dome (Lee, 1943; Dapples, 1955).

The St. Peter Sandstone was deposited on this erosion surface during the transgressive phase of the subsequent cycle. It is representative of the beach-nearshore depositional environment. Seaward from this zone deposits of the nondepositional shelf zone developed. The poorly sorted lithotope that characterizes this environment is manifest in the lower part of the Glenwood Formation, Nokomis Member, which consists of poorly sorted silty sandstone which may be interbedded with coarse-grained orthoquartzitic sandstone or with shaly dolomite ranging from 0 to 100 feet in thickness. Deposits of the argillaceous lithotope which characterize the depositional shelf zone are represented by the upper part of the Glenwood, Harmony Hill Member, which consists predominantly of green shale ranging from 0 to 30 feet in thickness. In more seaward areas carbonate was deposited in the reef environment and is represented by a sequence of overlapping carbonates which include, in ascending order beginning in southern Illinois, the Dutchtown, Joachim, Platteville, Decorah, and Galena Formations referred to en masse as the "Trenton" formations (Du Bois, 1945) or as the Ottawa Limestone Megagroup (Swann and Willman, 1961).*

Deposition of Cincinnatian clays and carbonates marked the end of cyclic sedimentation characterized by the quartzarenite-carbonate association in the Upper Mississippi Valley. Although the alternating occurrence of clastics and carbonates continued, the clastics of succeeding cycles were derived in large measure from the newly emergent eugeosynclinal area of the Appalachian province (Woodward, 1961; Potter and Pryor, 1961).

SUMMARY AND CONCLUSIONS

Upper Cambrian and Lower and Middle Ordovician deposits of the Upper Mississippi Valley consist of four recurring lithotopes comprising five sedimentary cycles. The lithotopes and their environments of deposition are: (1) quartzarenites deposited in the nearshore-beach environment; (2) poorly sorted generally coarse-grained dolomitic arenites, transitional with overlying and underlying lithotopes; the arenites developed in the nearshore-shelf zone in response to encroachments by neighboring environments of deposition that resulted from frequent energy changes and variations in sediment supply and the pattern of reworking and distributing agents; (3) shales or argillaceous sandstones deposited in the depositional shelf environment; and (4) carbonates deposited in the shelf-reef environment.

The environment in which each lithotope developed occupied a position that was roughly parallel to the shoreline and that migrated over the shelf landward in response to submergence and seaward in response to emergence. Each cycle has in its base a quartzarenite which marks the environment of the beach-nearshore depositional zone. These are overlain, in turn, by deposits developed successively farther out to sea, namely those of the nondepositional shelf environment, depositional shelf environment, and shelf-reef environment. Deposition during emergence resulted in reversed order of occurrence.

* In compliance with recommendations of the Code of Stratigraphic Nomenclature, the designation "Megagroup" is avoided in favor of "Supergroup" or "Group."

Formations which comprise the five cycles of sediments, in ascending order, are the: (1) Mt. Simon Sandstone, Eau Claire Sandstone, Bonneterre Dolomite; (2) Galesville Sandstone, Ironton Formation, Franconia Sandstone, St. Lawrence Formation; (3) Jordan Sandstone, Madison Member, Blue Earth Siltstone, Oneota Dolomite; (4) New Richmond Sandstone, Shakopee Dolomite; and (5) St. Peter Sandstone, Glenwood Formation, and Ottawa Group.

The relationships of factors affecting pre-Cincinnatian Paleozoic sedimentation in the Upper Mississippi Valley are summarized in Figure 5. The locus of deposition of Cambrian and Lower and Middle Ordovician sediments was the craton situated northwest of the Appalachian geosyncline, on which were located more rapidly subsiding intracratonic basins and essentially stable arches and domes. Cycles resulted from repeated emergence, which was caused by rejuvenation of tectonically positive portions of the craton, and submergence, which resulted from subsidence of the geosyncline and of the neighboring shelf area of the craton.

The paleoslope of the area remained constant throughout the time of deposition of these sediments and had a dip to the southeast in the direction of the geosyncline. The dominant direction of sediment transport was to the south and southwest roughly parallel to ancient shorelines.

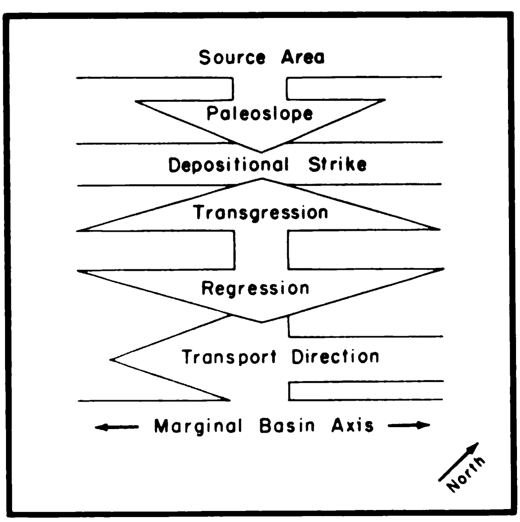

FIGURE 5.—Model summarizing relationships of factors which affected pre-Cincinnatian Paleozoic sedimentation in the Upper Mississippi Valley area.

Regressive phases are identified in Cambrian cycles but are unknown in Ordovician cycles. It is suggested that active subsidence of the Illinois-Michigan Basin during shelf emergence at the close of the Cambrian Mt. Simon and Galesville cycles allowed deposits developed during regression to be lowered beyond the reach of subsequent erosion.

The Jordan and New Richmond cycles of the Lower Ordovician differ from previous cycles, and from the succeeding St. Peter cycle, in that their shale or argillaceous sandstone lithotopes, representing the depositional shelf environment, are poorly developed. Development of this lithotope in the other cycles is thought to have been caused by coincidence of the depositional shelf environment with the actively subsiding basin area which received large amounts of clastic sediment from a land area of moderate relief during regression. Poor development of the argillaceous lithotope in the Jordan and New Richmond cycles is interpreted to mean that the depositional shelf environment did not regress as far south as the subsiding basin, thus could not have coincided with it, that the land area exposed to erosion was lower and less extensive than at previous times of regression, and consequently, that less sediment was delivered to the shelf.

The results of this study present what is believed to be a working hypothesis for interpreting problems of Cambrian and Ordovician stratigraphy and sedimentation in the Upper Mississippi Valley. It is not meant to infer that conclusions drawn from this study are final. However, using the cyclical and environmental concept it is possible to rationalize stratigraphic relationships which have hitherto been poorly known on the local and regional scale, as well as to define geologic problems for additional investigation.

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Finding the Ideal Cyclothem

ABSTRACT

Rock sequences can be translated into numerical sequences by associating with each recognized lithology an integer (1 to 5) according to a fixed classification scheme. Finite numerical sequences, corresponding to actual measured sections, can then be compared to infinite numerical sequences, corresponding to ideal cyclothemic repetitions. If an actual sequence is considered to be a fragmentary ideal, with some lithologies missing owing either to nondeposition or subsequent removal, the deviation of the actual from the ideal can be measured by a *discordance index* defined as the minimum value of the number of missing lithologies. The ideal sequence which best explains the over-all characteristics of a sample of finite sequences is the ideal for which the average value of the discordance index is least.

In this manner, the "best" ideal cyclothem for an area and stratigraphic interval of interest can be determined from arithmetic operations on a sample of actual rock sequences derived from measured sections within the area and interval. The method is developed, and application is made to measured sections from the Missourian-Wolfcampian (Upper Pennsylvanian-Lower Permian) interval of northeastern Kansas.

Of particular interest is the ideal sequence which corresponds to the ideal cyclothem proposed by R. C. Moore for this region. Results indicate that the best ideal cyclothem for the area-interval considered would be similar to that proposed by Moore. However, the classification used was clearly inadequate and some deficiencies of the classification are discussed briefly.

INTRODUCTION

The general repetitive nature of Pennsylvanian and Permian rock sequences is well known and is particularly striking in parts of the Midcontinent region. It seems that the concept of cyclic sedimentation is well established, at least within this region and stratigraphic interval.

Throughout geologic history epicontinental seas have repeatedly inundated the present land masses. In virtually every locality where a sedimentary sequence exists, it contains a record of the transgressions and regressions of such seas. It is natural to equate depositional cycles with marine oscillations. However, the large number of oscillations seemingly required for deposition of the Pennsylvanian cyclothems has led to speculation that physical transgression and regression may not have been involved in each individual "cycle." The terms transgression and regression as used here should be understood to stand symbolically for whatever mechanism may actually have been operative.

A portion of the investigation (Pearn, 1964) was designed to question the *existence* of underlying mechanisms governing the nature of repetitive sedimentary sequences. It may be assumed with confidence that such mechanisms exist. Speculation concerning the nature of these mechanisms is interesting, but conclusions are difficult if not impossible to prove. More practical questions concern the nature of the repetitive record itself. For instance, in a given region and within a given stratigraphic interval, what lithologic units constitute the *ideal cyclothem?* What sequence, if any, is repeatedly though imperfectly represented by actual rock sequences?

A well-known ideal cyclothem, which seems to be applicable to Pennsylvanian rocks in Kansas, is that proposed by R. C. Moore (1936). Recognition of an ideal cyclothem has been possible only after the study of large numbers of actual rock sequences. The process is inductive. From an essentially infinite number of possible ideals one is selected which seems to fit the observational data at least as well as any other.

If the selected ideal cyclothem implies a reasonable transgressive-regressive mechanism, as is certainly true of the Moore ideal, then the over-all concept takes on additional weight as a unifying hypothesis. A recognized ideal cyclothem has the attributes of a "natural law" in the sense that it helps to organize diverse observational data in terms of a single, simple, and reasonable hypothesis. An ideal cyclothem is not only scientifically useful but intellectually satisfying.

The purpose of this investigation was to provide the operational mechanics of an objective procedure for making the necessary inductive step in the recognition of an ideal cyclothem. The methods used were specifically designed to answer certain questions about cyclothems in Kansas. Some of the procedural details, especially of classification and sampling, were dictated by expedience and tailored to use available data. Refinements and improvements will be necessary. It is hoped, however, that the general approach used here will prove useful in future studies and other areas.

Acknowledgments.—The author wishes to thank Dr. Leslie Marcus, Department of Statistics, Kansas State University, for help and advice; Dr. E. J. Zeller, Department of Geology, The University of Kansas, for the suggestion that questions about cyclothems might be handled by considering numerical sequences; and Dr. D. F. Merriam, Kansas Geological Survey, for invaluable service both in supplying the data and in making available computer facilities.

Appreciation is expressed to the Computation Centers at both Kansas State University, where the IBM 1620 and IBM 1410 computers were utilized, and The University of Kansas, where the IBM 1620 was used.

SIMPLIFYING THE MOORE IDEAL CYCLOTHEM

How well does the Moore ideal cyclothem describe rock sequences within the stratigraphic range for which it was intended? With this general question in mind, the first step was to formulate the Moore ideal as a numerical sequence. Moore's original numerical designations were easily adapted (*see*, Table 1).

The reason for combining the shales .1 and .2 into a single lithologic unit, 2, was merely that the first criterion in classification was to be gross lithology. It was desirable, in so far as possible, to restrict the application of other criteria such as fossil content and the presence or absence of coal. Similarly, the regressive units, .6, .7, .8, .9, would have been difficult to distinguish from their transgressive counterparts, .1, .2, .3, .4, except on the basis of relatively subtle distinctions. For that reason, corresponding transgressive and regressive units were considered equivalent. With these modifications the Moore ideal cyclothem is expressible as: . . . 1 2 3 4 5 4 3 2 1 2 3 4 5 4 3 2 1 2 3 4 5 4 3 . . . an infinite sequence consisting of adjacent transgressive (1 2 3 4 5) and regressive (5 4 3 2 1) hemicycles. The units 1 and 5 are at once both transgressive and regressive and will here be called *pivotal lithologies.*

Moore (1936, p. 26) anticipated the consideration of such an infinite sequence when he remarked:

> The entire cyclothem thus records a single marine pulsation. . . . This nearly symmetrical or har-

TABLE 1.—Revised designations for cyclothem units (*after* Moore, 1936, p. 24-25).

Original description	Designation: Original	Designation: Revised
Sandstone	.0	1
Shale (and coal)	.9	2
Shale, typically with molluscan fauna	.8	
Limestone, algal, molluscan, or with mixed molluscan and molluscoid fauna	.7	3
Shale, molluscoids dominant	.6	4
Limestone, contains fusulinids, associated commonly with molluscoids	.5	5
Shale, molluscoids dominant	.4	4
Limestone, molluscan, or with mixed molluscan and molluscoid fauna	.3	3
Shale, typically with molluscan fauna	.2	2
Shale, (and coal) may contain land plants	.1	
Sandstone	.0	1

monic sort of rhythm might be expressed numerically by the sequence 0-1-2-3-4-5-4-3-2-1-0.

In order to complete the classification, it was necessary to consider additional criteria. Specifically, it was necessary to distinguish between the shales, 2 and 4, and between the limestones, 3 and 5. The scheme shown in Table 2 was adopted. The primary criteria correspond to Moore's original descriptions.

If the chief purpose of this investigation were to establish, once and for all, the "best" ideal cyclothem for the area considered, the classification of Table 2 would have to be considered inadequate. The investigation purports to be objective, yet the classification contains many subjective elements. Still worse, the ultimate appeal to "position" when decision seems hopeless *assumes* the underlying Moore ideal, and to answer questions about the Moore ideal on this basis is decidedly circular.

Classification, however, may be considered a separate problem. The purpose of this investigation is not to arrive at unshakeable conclusions, but rather to indicate a line of attack which should lead to objective conclusions, given a better classification, more detailed data, and so forth.

THE DISCORDANCE INDEX, G

The second step in the procedure was to define a numerical statistic to serve as a measure of the amount of deviation of any actual rock sequence from the Moore (or some other) ideal sequence. For this purpose, the discordance index G was defined as follows:

(1) Observe the first lithologic unit, a_1 ($a_1 = 1, \ldots, 5$) of the finite sequence of interest.

(2) Consider a portion of the ideal sequence beginning with a_1 and such that a_1 occurs within a *transgressive* hemicycle.

(3) Sum the number of lithologic units which would have to be inserted to convert the observed sequence of (1) to the ideal sequence of (2). Call this sum G_1.

(4) Consider a portion of the ideal sequence beginning with a_1 and such that a_1 occurs within a *regressive* hemicycle.

(5) Sum as in (3), but comparing the observed sequence of (1) with the ideal sequence of (4). Call this sum G_2.

(6) The statistic G, characteristic of the observed sequence of interest and the ideal being considered, is the minimum of G_1 and G_2.

$$G = \min (G_1, G_2)$$

This definition will, perhaps, be clarified by an example. Consider a seven-unit actual sequence as follows:

actual sequence, 2 3 2 5 3 2 1
ideal (transgressive), . . . *2 3* 4 5 4 *3 2 1* 2 3 4 *5 4 3 2 1* . . .
sum of omitted units, $4 + 4 + 1 = 9 = G_1$
ideal (regressive), . . . *2* 1 2 *3* 4 5 4 3 2 1 2 3 4 *5 4 3 2 1* . . .
sum of omitted units, $2 + 4 + 4 + 1 = 11 = G_2$

$$G = \min (G_1, G_2) = G_1 = 9.$$

The statistic G is called the discordance index because it represents the number of omissions from the observed sequence if the ideal is really applicable. The larger the value of G, the less likely it seems that the observed sequence actually resulted from the transgressive-regressive repetitions implied by the ideal. Because equivalent lithologies in the transgressive and regressive hemicycles are considered indistinguishable, it is logical to characterize the observed sequence by the choice of initial transgression or regression which minimizes G. In this way, the ideal sequence being considered is given the "benefit of the doubt."

Clearly, the discordance index so defined was not the only possible choice for a measure of observed deviation from ideal sequences. The investigation reported here rests on the assumption that G was a natural and interesting choice. The methods used, however, would be adaptable to other statistics, and this is a possible direction for future investigation.

FORMULATING THE QUESTIONS

The general question which guided the translation of the Moore ideal into a numerical sequence and the definition of the discordance index must be made more specific. It can be rephrased in the following alternative forms:

QUESTION A.

1. How well does the Moore ideal cyclothem describe the rock sequences summarized as the composite section of the Kansas rock column?

2. Would some other ideal sequence describe these "facts" better?

TABLE 2.—Criteria for the distinction between nonsandstones.

	If shale 2	If shale 4	If limestone 3	If limestone 5
Fauna	Plant remains (pos. ident.) or mixed fauna. Pelecypods, inarticulate brachiopods, gastropods, ostracodes indicative— especially in the absence of (4) indicators.	Fusulinids (pos. ident.) *or* a relatively abundant mixed fauna. Crinoids, corals, bryozoans diagnostic; articulate brachiopods indicative.	Unfossiliferous *or* a variable assemblage, but without fusulinids.	Fusulinids required may be more or less abundant and occur with or without an assemblage like (4).
	But both may be unfossiliferous.			
Color, Purity, Texture	Black fissile shale or coal (pos. ident.). Black, nonfissile reds, greens, maroons, indicative.	Ordinarily gray or buff. Beds with (4) fossils often described as poorly bedded, clayey or highly calcareous.	Impure, highly ferruginous or sandy *or* may be pure. Thin bedding and poor consolidation indicative, but may be massive.	Relatively pure and massive, but these criteria not diagnostic.
	Yellow, argillaceous, (others?) generally nonindicative.			
Position	If and only if other criteria fail, assign the lithologic identification most concordant. On this basis alone, for instance, a shale between limestones of types 3 and 5 may be considered type 4. Nondescript limestones in association with types 1 and 2 are to be considered type 3.			

QUESTION B.

1. How well does the Moore ideal cyclothem describe actual rock sequences observed in outcrops reported from Kansas localities?
2. Would some other ideal sequence describe actual rock sequences better?
3. Is there adequate reason to believe that actual rock sequences are not random?

GENERATING THE POPULATION OF SEVEN-UNIT SEQUENCES

In order to answer the above questions, it was necessary to restrict the length of the actual sequences which would serve as data units. In particular, question B3 required that the distribution of G in a population of finite sequences be known. If the population of all possible sequences of length L were generated, the distribution of G in that population could be determined. On the assumption of equal likelihood among the sequences, the probability of occurrence of any particular G-value could also be found. The following information was desired:

(1) All permutations of L lithologies chosen from the five recognized lithologic types such that identical lithologies do not occur in adjacent positions in sequence. This restriction was necessary because the actual sequence 1223454, for instance, would probably be reported as 123454.

(2) The values of G which result from comparing each sequence of the population with the Moore ideal.

It can easily be shown that the number of sequences in such a population is given by:

$$N = n(n-1)^{L-1}$$

where n is the number of distinct lithologies recognized, five in this case, and L is the length of the sequences to be generated.

To see this, we may visualize the filling of L positions in sequence by n distinct kinds of items. Let $a_1, a_2, \ldots a_L$ be the items to be chosen. There are n choices for a_1, and for each of these there are n—1 choices for a_2. The single restriction is $a_1 \neq a_2$. For given a_1, a_2 there are n—1 choices for a_3, and so forth. In general,

position	1	2	3..........	L
item	a_1	a_2	a_3..........	a_L
choices	n	n—1	n—1.......	n—1

$a_i \neq a_{i+1}$ from which the above result is clear.

It was desirable to fix L in such a way that the population would be of a manageable size, while the length of actual sequences used would be sufficient to test the hypotheses of interest. Intuitively, it would not have been wise to use actual sequences of length 2, for example, to test hypotheses concerning an ideal sequence with hemicycle length 5. After preliminary considerations of this kind, L was chosen as 7 and the population consisting of

$$N = 5(4)^6 = 20{,}480$$

sequences was generated. At the same time each G was calculated.

Table 3 shows the distribution of G in this population. If the sequences of the population are equally likely to occur in nature, then each possible value of G (0, 1, . . ., 18) will have the probability shown in column 3. In other words, Table 3 gives the expected frequencies of occurrence for each possible G-value under the hypothesis of random deviation from the Moore ideal.

A POPULATION OF ALTERNATIVE IDEALS

Would some other ideal sequence describe the facts better? It was necessary to ask in turn, what other ideal sequences are possible? Any sequence which contains each of the recognized lithologies at least once could be taken as an ideal hemicycle. Some sequences such as 1 2 3 2 3 2 3 4 3 2 3 2 3 2 3 2 3 2 3 4 5 4 do not seem reasonable in terms of the complexity of the transgressive-regressive mechanism implied if such a sequence were to be considered a *hemicycle*. Nevertheless, there is no limit to the number of sequences which might improve upon the Moore ideal cyclothem. In order to search systematically for the "best" ideal sequence, it was necessary to restrict the universe of ideals in some manner.

Because the population of seven-unit sequences was already available, it was convenient to consider a set of ideal hemicycles obtained by examining each sequence of the larger population to see whether either the 5th or 6th positions could be considered pivotal. The procedure was:

(1) Designate the lithologies in each sequence as $a_1, a_2, \ldots, a_7$ where the subscripts indicate the position in sequence. Then $a_i = k$ ($i = 1 \ldots 7$; and $k = 1 \ldots 5$).

(2) If the set consisting of $a_1, a_2, \ldots, a_5$ contains each integer (1, 2, . . ., 5) exactly once, i. e.

the first five lithologies are all different, then the sequence is a potential ideal generator subject to satisfaction of the restriction in (3).

If the set consisting of $a_1, a_2, \ldots, a_6$ contains each integer (1, 2, . . ., 5) at least once, i. e. exactly one lithology is repeated among the first six, then the sequence is a potential ideal generator subject to satisfaction of the restriction of (4).

(3) If $a_4 = a_6$ and $a_3 = a_7$, then the sequence is pivotal around a_5 and the hemicycle length is 5.

(4) If $a_5 = a_7$, then the sequence is pivotal around a_6 and the hemicycle length is 6.

For example, consider the sequence 3 2 4 1 5 3 5. Among the first five lithologies, all are represented. However, $a_4 \neq a_6$ $(1 \neq 3)$, so that the sequence is not pivotal around a_5. Among the first six lithologies, exactly one lithology (3) is repeated, and $a_5 = a_7 = 5$. The sequence is pivotal around a_6, and $a_1, a_2, \ldots, a_6$ constitute an ideal hemicycle.

The population of hemicycles obtained in this manner has 1200 members. From these hemicycles 660 distinct ideal sequences can be generated. Consider the original seven-unit sequences 3 2 4 1 5 3 5 and 3 5 1 4 2 3 2. Both will contribute six-unit hemicycles to the 1200-member population, but these will be merely transgressive and regressive, (obverse and reverse) hemicycles of the same sequence: . . . 3 2 4 1 5 3 5 1 4 2 3 2 4 1 5 3 5 1 4 2 3 2 . . . . However, the original sequences 2 3 4 1 5 1 4 and 1 5 1 4 3 2 3 generate distinct ideals even though the first six positions satisfy the obverse-reverse relationship. The first sequence is pivotal around a_5 and yields the ideal . . . 2 3 4 1 5 1 4 3 2 3 4 . . . while the second is pivotal around a_6 and yields the ideal . . . 1 5 1 4 3 2 3 4 1 5 1 5 1 4 3 2 3 . . . .

It must be emphasized that the population of 660 ideals generated in this way is by no means exhaustive; however, it is exhaustive of symmetric ideals having five- and six-unit hemicycles. A *symmetric* ideal is defined as one in which adjacent hemicycles are obverse and reverse, as opposed to sequences like . . . 1 2 3 4 5 1 2 3 4 5 1 2 3 4 5 . . ., which might be called *simply repetitive* ideals. It should be mentioned here that simply repetitive ideals may best describe actual rock sequences in some areas. Moore (1936) and others have noted that the typical Illinois cyclothem is probably of the simply repetitive type.

Any symmetric ideal which might conceivably constitute an improvement upon the Moore ideal either (1) belongs to the 660-member population described above, or (2) has hemicycle length at least seven. The latter possibility is by no means unthinkable. The ideals to be considered were restricted in the particular manner described only because the next larger population, including seven-unit hemicycles, would have been too large to have been exhaustively analysed in the time available. Either faster computers or a continuing program of study could allow for expanding the present investigation in the direction of a larger population of ideals.

TABLE 3.—Distribution of G in the population of seven-unit sequences based on the Moore ideal.

G	No. of	Pr(G)|H₀	Cum. prob.(%)
0	15	.000732	0.073
1	37	.001807	0.254
2	101	.004932	0.747
3	209	.010205	1.768
4	389	.018994	3.667
5	621	.030322	6.699
6	895	.043701	11.069
7	1148	.056055	16.675
8	1638	.079981	24.673
9	1967	.096045	34.277
10	2061	.100635	44.341
11	1833	.089502	53.291
12	2273	.110986	64.390
13	2245	.109619	75.352
14	1770	.086426	83.995
15	904	.044141	88.409
16	1019	.049756	93.385
17	863	.042139	97.599
18	492	.024023	100.001
	20480		

VARIATION OF G IN AN IDEALIZED COMPOSITE SECTION

Answers to questions A1 and A2 involved a comparison between one abstraction, the population of ideal sequences, and another abstraction, the idealized composite section of the Kansas rock column. The connection with reality attained later by the use of actual measured sections was here lacking. Accordingly, the answers obtained should be considered relatively nonpertinent. This part of the investigation was designed to illustrate how the necessary restriction in sequence length could be overcome if it became desirable to analyse data pertaining to long sequences of *actual* rock units (perhaps from continuous coring operations).

The Kansas rock column (Moore and others, 1951) was consulted, and the stratigraphic interval to be used was chosen. The interval conformed to that covered by available measured sections used later; it extended from the Pleasanton Group (Hepler Sandstone, Missourian) below into the Council Grove Group (Roca Shale, Wolfcampian) above. By studying the descriptions of each formation and member, the number and classification of recognized lithologies within the interval were determined. The chief problems of classification at this stage were:

(1) deciding what sequence of lithologies to use when it happened that a formation or member was described as being differently represented at different Kansas localities, and

(2) deciding upon the number of distinct lithologies to be included when a formation or member was described as "alternating shales and limestones" or the like.

The unavoidable subjectivity of these decisions was not critical in this phase of the study, since the purpose of the undertaking was primarily illustrative. A total of 278 lithologies were recognized and classified within the interval. This information was subjected to the following steps in analysis:

(1) The 278 lithologies were considered in seven-unit subsequences from bottom to top. The first seven lithologies constituted the first subsequence, lithologies two through eight constituted the second subsequence, and so forth, making a total of 272 subsequences in all.

(2) For the Moore ideal cyclothem, a member of population of ideals, G was computed for each individual subsequence. The values of G were combined in a five-point moving average, and the variation of G through the interval was graphically displayed (*see*, Figure 1).

(3) The average value of G over the interval was determined for the Moore ideal.

(4) For all distinct remaining members of the population of ideals the average values of G over the interval were also obtained.

A detailed discussion of the features of Figure 1 will not be undertaken because the connection with reality is at best problematic. However, the following feature of Figure 1 is perhaps sufficiently general to be considered "real":

Levels of G are noticably higher in the Kansas City Group and below as well as in the Admire Group and above. Clearly, the interpretation is that the Moore ideal is more descriptive of the "facts" within the middle Missourian through Virgilian of Kansas than elsewhere in the interval considered.

Two points demand mention in connection with the analysis described above.

First, because the input lithologies were visualized as representing a continuous sequence, freedom of choice as to the starting point (transgressive or regressive) could not be allowed for *each* subsequence. Rather, the distinct values of G_i resulting from different starting points were first accumulated and averaged over the entire interval and then minimized to obtain the final G. Each G_i represented a single initial choice of transgression or regression (for the first subsequence). Compared to the procedure for calculating G in a single seven-unit sequence, the distinction here is summarized in the statement that reported values were minimized average G (hereafter called MAG) values over the interval.

Secondly, when ideals with six-unit hemicycles are considered there may be as many as four starting points which will yield distinct G_i, rather than two. In such cases, the reported MAG was the minimum of the averaged G_i, where $i = 1,2$ *or* $1,2,3$ *or* $1,2,3,4$ depending on certain characteristics of the ideal under consideration.

Analysis of the complete population of ideals showed that no member had MAG less than that of the Moore ideal. For explaining the composite section of the Kansas rock column on the basis of the least-G criterion, the Moore ideal is the best possible sequence among all symmetric ideals with five- or six-unit hemicycles. No basic significance is claimed for this result because, as has been previously mentioned, the data from the Kansas rock column was pre-synthesized and correspondingly unreal. In addition, bias may well have been introduced by the writer during translation of descriptions into numerical sequences.

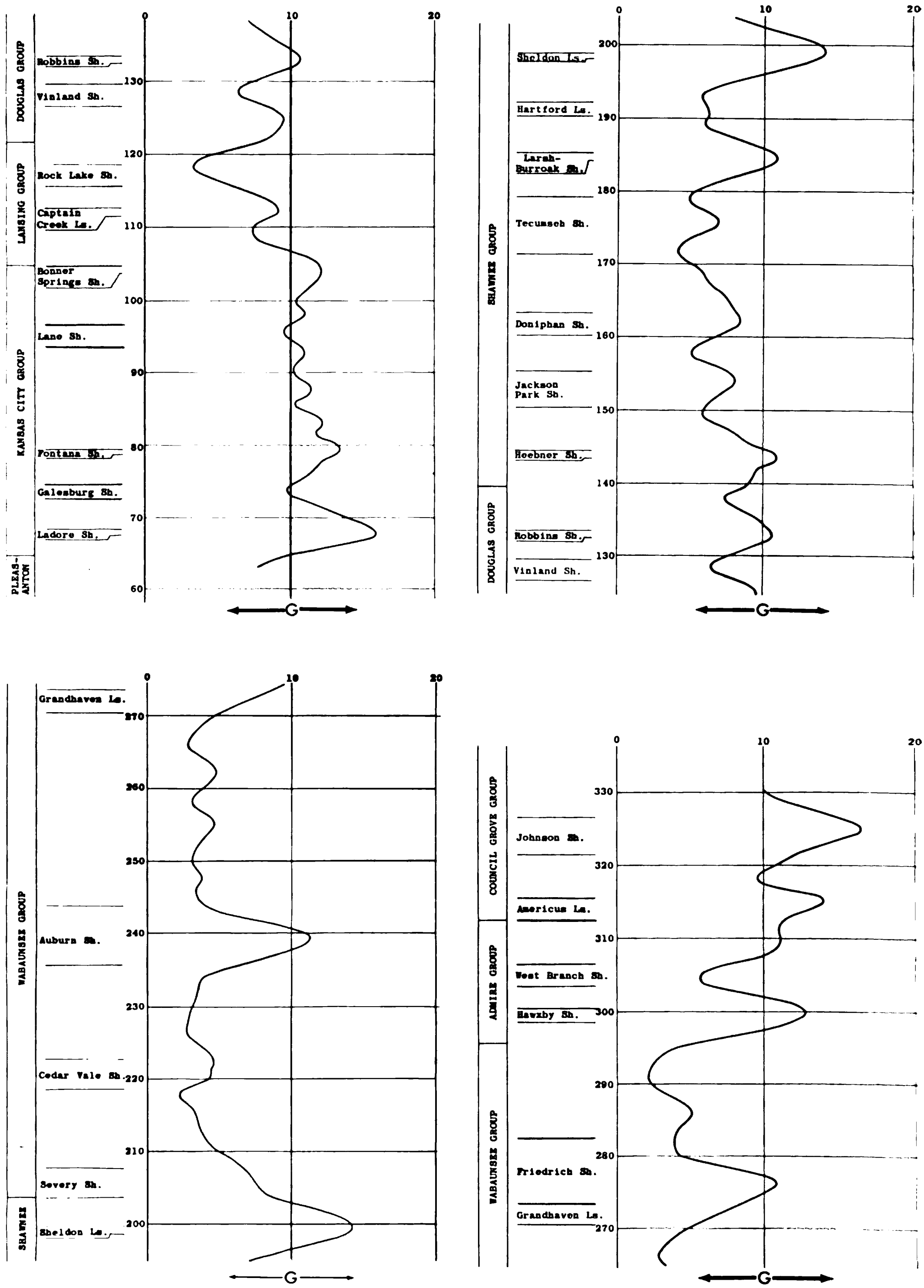

FIGURE 1.—Variation of G through the idealized composite section (five-point moving average).

DISTRIBUTION OF G IN A SAMPLE OF ROCK SEQUENCES

Answers to questions B1, B2, and B3 were obtained from a sample of actual seven-unit rock sequences drawn from available measured sections within the region shown in Figure 2.

The Sample

The State Geological Survey of Kansas kindly made available a file of measured sections and provided a map of locations for an initial selection of about 400 sections. This selection included all available sections which happened to display at least seven lithologic units within the interval from Hepler Sandstone to Roca Shale. The preliminary set of 400 sections was subjected to a sampling procedure as follows:

(1) A grid was superimposed upon the map showing the location of, and stratigraphic group(s) represented in each available section.

(2) The number of available sections per group was tabulated for each grid subdivision.

(3) The total number of sections to be retained was set provisionally at 250, and it was decided that group representation should be proportional to the "size" of the group.

(4) The percent of the total interval actually occupied by each stratigraphic group had been previously estimated by

$$P_i = \frac{n_i}{N} (100)$$

where P_i = percent of interval represented by the ith group.
n_i = number of recognized lithologies within the ith group, estimated from the Kansas rock column.
N = estimated total number of recognized lithologies in the interval studied.

(5) These considerations dictated that the group representation in the final sample should be as follows:

Group represented	*% of sample* ($= P_i$)
Council Grove	8
Admire	6
Wabaunsee	33
Shawnee	23
Douglas	6
Pedee	1
Lansing	6
Kansas City	14
Pleasanton	3

(6) Where a group was originally represented to excess, sections were discarded from those grid subdivisions containing the most representatives of the group in question. The particular sections to be discarded were randomly chosen. In this way 250 sections were chosen from the available 400.

(7) Locations of the desired 250 sections were then communicated to Dr. D. F. Merriam, who provided Xerox copies of the measured sections and descriptions. To this point the writer was unaware of the detailed characteristics of the sections to be used.

(8) On each section containing more than seven lithologic units, according to the classification system of Table 2, a starting point was randomly chosen. Upward from this starting point, seven successive units were defined and classified as 1, 2, 3, 4, 5.

(9) For several different reasons, mainly because of difficulty in interpreting descriptions, 15 sections were considered unsuitable and were discarded. The final sample consisted of 235 seven-unit sequences.

(10) To check the percentage of group representation each sequence in the final sample was classified to group. In cases of overlap, the section was counted twice. Compare the break-down below with that of (4).

Group represented	*% of sample*
Council Grove	8.1
Admire	7.0
Wabaunsee	31.4
Shawnee	20.3
Douglas	7.0
Pedee	1.1
Lansing	6.2
Kansas City	16.2
Pleasanton	2.6

The chief purpose of this procedure was to insure that the final sample of seven-unit sequences would be spread over the geographic area and the stratigraphic interval of interest. The writer feels that this kind of "representativeness" is a desirable feature of geologic sampling, in which true randomness is usually not at issue. In the present case, certainly, it was not a matter of choosing between the kind of sample obtained and a truly random sample. Ideally, a random sample would have had both locality and stratigraphic interval (group) randomly predetermined. It would have been necessary to be able to go to any locality and there observe a section within any stratigraphic group. The obvious difficulty is that when one is restricted to surface measurements, he is also restricted by the fact that outcrops are where you find them. In addition, it was necessary for this study to consider only those sections already measured

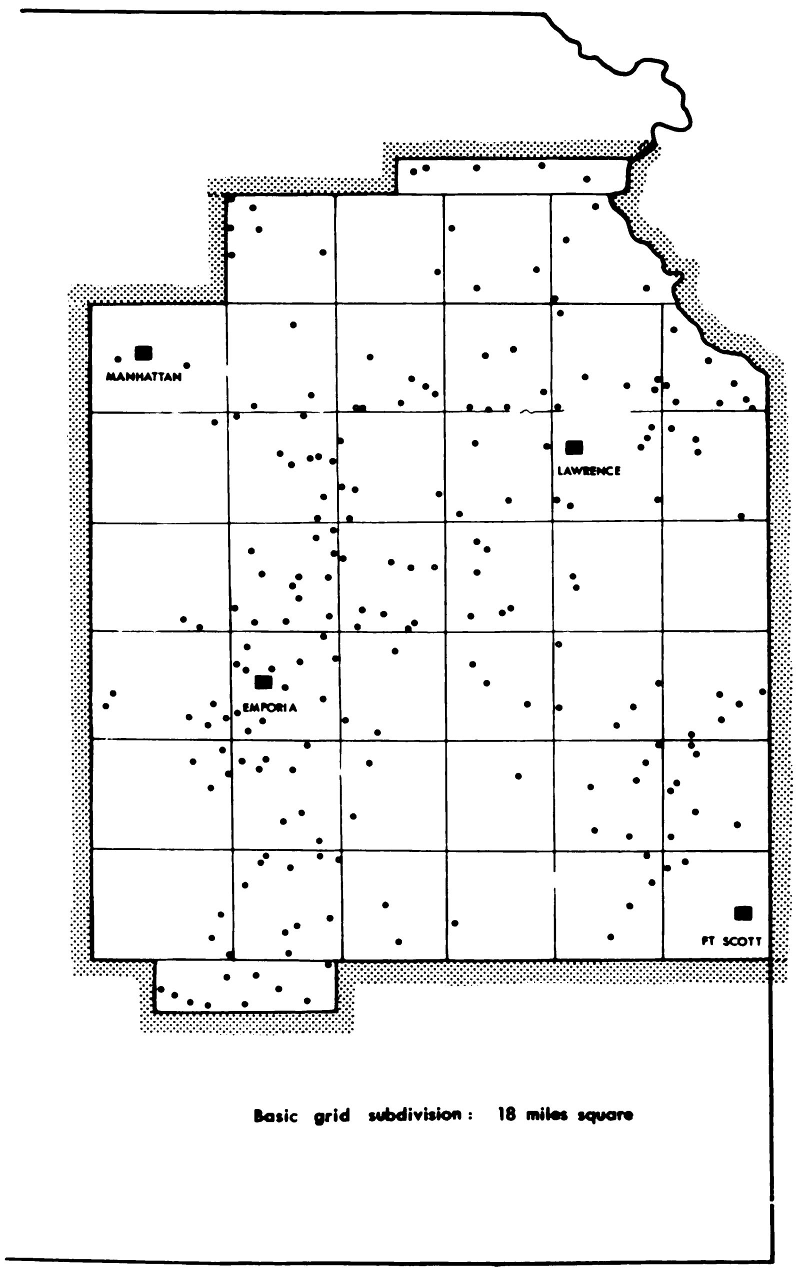

FIGURE 2.—Distribution of sample localities.

and recorded. No sample of the available sections could have been considered a random sample of the population to which inference was to be made, i. e. seven-unit sequences in the three-dimensional area-interval of interest. That the sample actually used was a reasonable approximation to that goal is, at this point, simply assumed.

A Test for Randomness

The sample was analysed in a manner similar to that already described for the composite section. Differences were as follows:

(1) The 235 sections were separate entities and the choice of a minimizing starting point was left open for *each* seven-unit sequence.

(2) The average values of G were determined *after* the 235 separate minimumizations, hence were average minimum G (AMG) values, rather than MAG values as before.

The G-values corresponding to each observed sequence, with reference to the Moore ideal, formed the basis of a simple test in answer to the question B3. Consider the null hypothesis, H_0:

The sample of observed sequences was drawn from a population described in Table 3, i. e. every conceivable seven-unit sequence had equal opportunity to appear in the sample because the sequences occur randomly in nature.

For the sake of brevity, call this H_0 the randomness hypothesis. The alternative hypothesis, then, is a nonrandomness or the simple negation of H_0.

Table 5 shows the observed number of occurrences for the various G-values, the expected number according to the distribution under H_0 (from Table 3), and calculated quantities necessary for a chi-square test of H_0, where

G = a value of the discordance index.

O_G = the number of times (out of 235) the particular G was observed.

E_G = the number of times the particular G would be expected to have occurred under H_0 (= 235 × column three of Table 3).

Groupings at the extremes of the observed distribution were made in order to satisfy the chi-square requirement that min G (E_G) = 7. The procedure is to calculate the statistic:

$$X^2 = \sum_G \frac{(O_G - E_G)^2}{E_G} = 69.71$$

and to note that in large samples X^2 is approximately chi-square distributed under H_0. Reference to tabled chi-square with 13 degrees of freedom (m—1, where m = no. cells used) reveals that under H_0 the probability of observing a X^2 this large or larger is much less than 0.00001. The randomness hypothesis is most decidely to be rejected. It may be desirable to emphasize the assumptions under which the above chi-square test is a valid rejection of the randomness hypothesis. We assume:

(1) That if the recognized lithologies actually occurred in random sequences in nature, then any sequence would be as likely to occur as any other.

(2) That the population distribution of G under the randomness hypothesis would be the same as the distribution derived by generating all possible sequences and *assigning* them equal probabilities.

(3) That we have a random sample from the population of interest, namely the population of all seven-unit sequences, within the defined three-dimensional area-interval.

(4) That the dependence of the theoretical G-distribution on the ideal sequence of reference (the Moore ideal) does not affect the test of randomness.

Assumptions (1) and (2) would appear to be justified. Assumption (3) as we have already seen, is invalid but should be approximately true. Assumption (4) is reasonable because the alternative to randomness is unspecific. The particular kind of order we visualize in order to be able to calculate G has no direct bearing on the question, "Does *any* order exist?". In other words, the test would be expected to reject with any choice of reference sequence.

TABLE 5.—Data for the chi-square answer to B3.

G	O_G	E_G	O_G-E_G	$(O_G-E_G)^2/E_G$
0	2			
1	0			
2	3 } 23	8.62	14.38	23.99
3	6			
4	12			
5	12	7.13	4.87	3.33
6	17	10.27	6.73	4.41
7	9	13.17	4.17	1.32
8	29	18.80	10.20	5.53
9	12	22.57	10.57	4.95
10	26	23.65	2.35	0.23
11	15	21.03	6.03	1.73
12	27	26.08	0.92	0.03
13	14	25.76	11.76	5.37
14	26	20.31	5.69	1.59
15	3	10.37	7.37	5.24
16	18	11.69	6.31	3.41
17	2 } 4	15.55	11.55	8.58
18	2			

G-VALUES OF ALTERNATIVE IDEALS

The AMG values obtained from the analysis of the entire population of 660 distinct ideals will allow no simple interpretation. Of the ideals tested 78 yielded AMG less than that of the Moore ideal. The twenty smallest AMG are listed in Table 6.

Among this surprisingly large number of "improvements" over the Moore ideal, the best is . . . 1 2 3 4 5 2 5 4 3. . . . The chief difference between this and the Moore

TABLE 6.—Value and rank of twenty smallest AMG.

Ideal hemicycle	AMG	Rank
1 2 3 4 5 2	7.4596	1
1 2 5 4 3 2	7.5106	2
2 1 3 4 5 2	7.7702	3
2 1 5 4 3 2	7.8468	4
2 3 1 4 5 2	7.8979	5
1 2 3 4 2 5	8.0043	6
2 3 4 1 5 2	8.0383	7
2 1 3 4 2 5	8.0894	8
2 1 3 2 4 5	8.1021	9
1 2 3 2 4 5	8.1489	10
1 3 2 5 4 3	8.2213	11
2 3 1 4 2 5	8.2596	12
1 3 2 5 3 4	8.2638	13
2 3 1 2 4 5	8.2723	14
3 1 2 5 4 3	8.3191	15
2 1 3 2 5 4	8.3404	16
3 1 2 5 3 4	8.3447	17
1 2 3 2 5 4	8.3872	18
2 3 4 1 2 5	8.3957	19
1 3 2 3 4 5	8.4085	20
1 2 3 4 5 (Moore)	9.9319	79

ideal is the extra unit-2 per hemicycle. Table 7 shows another set of the hemicycles which generate ideals with relatively low AMG. The grouping is intended to illustrate some of the reasons for the results obtained. Note first that all ideals shown have six-unit hemicycles, and the unit repeated in the hemicycle is either 2 or 3. Both of the observations hold for all 78 "improvements."

TABLE 7.—Selected AMG showing relationships: * indicates reverse of a previously listed hemicycle.

Ideal hemicycle	AMG	Rank
1 2 3 4 5 2	7.4596	1
2 1 3 4 5 2	7.7702	3
2 3 1 4 5 2	7.8979	5
2 3 4 1 5 2	8.0383	7
1 2 5 4 3 2	7.5106	2
2 1 5 4 3 2	7.8468	4
*2 5 1 4 3 2	8.0383	7
*2 5 4 1 3 2	7.8979	5
1 2 3 4 2 5	8.0043	6
2 1 3 4 2 5	8.0894	8
2 3 1 4 2 5	8.2596	12
2 3 4 1 2 5	8.3957	19
1 2 3 2 4 5	8.1489	10
2 1 3 2 4 5	8.1021	9
2 3 1 2 4 5	8.2723	14
2 3 4 1 4 5	9.6468	68

Table 8 shows the distribution and frequency of the recognized units among the positions (a_i) of the sample sequences. The high proportions of units 2 and 3 would seem to account for the fact that ideals with extra units 2 or 3 have low AMG, other factors remaining constant. Note also the low proportion of unit-1 in the sample. Table 7 shows that the position unit-1 occupies has relatively little effect on the value of AMG. In the first group of four ideal hemicycles, for instance, the change in position of unit-1 from a_1 to a_4 caused the change in AMG rank from 1 to 7.

In summary, the relative proportions in the sample of the units 1-5 interact with the ordering of these units in the ideal and AMG is a complex function of both. This should have been obvious at the outset. Are all 78 ideals with low AMG to be considered improvements over the Moore ideal? If the classification of lithologies were entirely objective and unambiguous, the answer would be an unqualified yes.

TABLE 8.—Distribution and frequency of recognized lithologic units in the sample of seven-unit sequences.

Position	Unit 1	2	3	4	5
1	26	79	71	22	37
2	24	92	62	28	29
3	14	76	81	32	32
4	17	85	68	33	32
5	13	80	82	28	32
6	7	93	57	38	40
7	15	65	86	27	42
Total	116	570	507	208	244
Percent	7.05	34.65	30.82	12.65	14.83

PROBLEMS OF CLASSIFICATION

The classification used here is deficient. It has already been mentioned that the tie-breaking "position" criterion begs the question. In a sense, the use of such a criterion is the most serious deficiency of this study. In another sense, it is largely irrelevant. Given criteria adequate to assign every lithology in the chosen area-interval to one of the recognized *a priori* classes, the need for tie-breaking would have been automatically removed. This study has been chiefly concerned with the mechanical procedures whereby useful conclusions would be reached, given, as a point of departure, just such an objective and unambiguous classification of cyclothemic units.

The following brief discussion is intended as the barest food for thought concerning the difficulties to be encountered in any future attack on problems of classification. The discussion is in terms of the specific questions asked here. but the implications are more general.

Fusulinid Requirement

In the Moore ideal, the type-5 unit is pivotal between the hemicycles in such a way that if physical transgression and regression is visualized, then unit 5 represents maximum transgression or the so-called "deep-water" limestone. It may be true that the presence of fusulinids is one of the best criteria for recognizing such a unit. Still, the type-5 unit which contains fusulinids at one locality may be physically continuous with a limestone which is type-3 at another locality because fusulinids are lacking. If a true facies change is so indicated, such a situation need not concern us too much. On the other hand, if other faunal elements remain the same we may legimately wonder whether presence of fusulinids is that important. With special regard to the present study, it is probable that fusulinids may be lacking in the descriptions of some measured sections though present at the outcrop.

Inclusiveness of Unit 3

The limestones encountered in the sections used for this investigation are fusulinid-bearing, fossiliferous (no fusulinids), or unfossiliferous; massive to thin bedded and often wavy bedded; hard and dense to soft, argillaceous or "punky"; pure to ferruginous or otherwise impure; and so forth. Almost any combination of such adjectives describes some limestone in the interval considered. In what sense can all nonfusulinid limestones be considered equivalent? In particular it seems likely that the many impure and thin-bedded limestones interbedded with shales and not distinguished as members should be separated from other type-3 units.

Inclusiveness of Unit 2

A similar objection can be made concerning the criteria for recognizing unit 2. As a general rule, the shales of the interval considered tend to be less fossiliferous than adjacent limestones. This alone accounts for the scarcity of positively identifiable type-4 units, and the majority of shales became type-2 by default as it were. Unit 2 may be marine or nonmarine, fossiliferous or unfossiliferous, and any color at all.

Degree of Clasticity for Unit 1

An attempt to use the classification of Table 2 on descriptions of measured sections is especially difficult when the terms siltstone, mudstone, and conglomerate are encountered. Is siltstone to be called sandstone or shale? Is mudstone to be considered shale, or, if calcareous, impure limestone? What about conglomeratic limestones? The relative scarcity of type-1 units in the sample is probably "real" regardless of classification difficulties, but we may wonder whether the presence of sandstone is really an environmental measure. The sandstone environment, whatever it may be, could have been present at many points in time which did not happen to coincide with a supply of coarse clastics.

Thickness

Thickness is a criterion whether it should be or not. For this investigation, all lithologic units less than 0.3-feet thick were ignored. Clearly there must be some such arbitrary cut-off point. Is it then reasonable to assign equal weight to all limestones, for instance, from 0.3 to 20 feet in thickness?

Generalizations and Directions

We may distinguish at least three types of troublesome questions stated or implied in the above discussion:

(1) How many lithologies should be recognized?

(2) What combination of criteria will effect the assignment of actual rock units to the n recognized categories without ambiguity?

(3) Given an appropriate set of criteria, how should they be weighed, i. e what is the order of their relative importance?

There exists no set procedures to tell us *which* criteria may be of importance, but intuitively we may conclude that it will be necessary to consider many types of criteria. Surely an objective synthesis should draw information from many fields. Paleontology, mineralogy, petrology, sedimentology, geochemistry, all may be called upon to contribute to the store of measurable variables from which a set of criteria appropriate for the purpose at hand may somehow be chosen. A subjective guiding principal for preliminary selection of criteria would include an evaluation, in terms of current geologic thought, of the "amount of information" about ancient environment contained in any particular variable.

Various types of cluster and factor analysis exist which could be applied to such preliminary criterion matrices, and in theory at least, useful answers to questions like (1) and (2) would eventually result. For an interesting example of factor analysis applied to a geologic problem see Imbrie and Purdy (1962). Question (3) could then be approached in a relatively straightforward manner through the use of discriminant functions.

Development of a fully objective classification designed specifically for an investigation such as this would be a long and arduous task. By side-stepping the difficult job and anticipating some of the potential returns on such an investment of effort, this study may serve as some small motivation.

CONCLUSIONS

It is easy to see, in restrospect, that the classification used here was such that the preponderance of units 2 and 3 in the sample was inevitable. Any change in the classification which tended to equalize the proportions of the recognized units would probably tend to reduce the number of improvements on the Moore ideal. Of course, this is not to be considered a goal, i. e. justification of the appropriate criteria must be based on independent evidence.

The purpose of this investigation will have been served if any motivation has been provided toward the development of an objective classification based on geochemical and lithologic indicators of environment. In addition it is hoped that the distinction is fully grasped between what is reasonable and what is demonstrable. In the opinion of the writer, there is some degree of evidence here that the Moore ideal cyclothem is, after all, the truth behind the complexity of the observable quantities. But opinion is relatively worthless. Refinement of the criteria for classification may ultimately render the truth susceptible to demonstration by methods similar to those developed here.

In the meantime, geology as a scientific discipline needs more and better attempts to demonstrate the truth of its reasonable hypotheses. If nothing else, such attempts will often demonstrate that our basic methods of observation, measurement, and classification are inadequate to deal systematically with the larger problems. We need to become increasingly aware that the only slightly exaggerated formulation, "How do you feel about cyclothems?", is simply not a scientifically meaningful question. We need to become increasingly willing to focus our attentions on hypotheses at least potentially susceptible to proof and on methods oriented toward the realization of that potential.

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Fourier Series Characterization of Cyclic Sediments for Stratigraphic Correlation

INTRODUCTION

It is the purpose of this paper to present some preliminary studies indicating how the methods of Fourier analysis might be used to identify and classify formations based on their electrical characteristics.

Periodicity is one of the fundamental phenomena recorded by observant man. Cycles associated with astronomical events were among the first natural phenomena described with sufficient precision and generality that such events could be predicted for the future. Even for primitive societies, one measure of their level of scientific understanding is the accuracy of their calendars.

Explanations of sound, tone, and harmonics were among the first elements of modern physical science. This early success in description and prediction of periodic astronomical events together with an understanding of periodicity related to vibration in the production of sounds led scientists to seek periodicities elsewhere in the natural world. Today the list is extensive for phenomena in which cycles have been studied. It includes sunspot activity, tides and ocean waves, earth tides, music, human speech, tree-ring growth, animal population changes, brain waves, heart rhythm, chemical bonding forces, climatic activity, economic growth, light and other electromagnetic wave phenomena, and geological events. The geological phenomena include varve growth and gross sedimentation trends in the sense of A. B. Vistelius (1961) as well as the more generalized cyclothems and megacyclothems of R. C. Moore (1936).

A common feature of the study of periodicity in natural phenomena is the search for the more important cycle periods or cycle frequencies. An attempt then is made to explain the cycles in terms of more fundamental phenomena.

The classic method of harmonic analysis involving Fourier series, has been used to determine these cycles. No general method exists for relating the detected cycles to other phenomena. Thus, although cycles seem to be apparent in the varve thickness sequences studied by Anderson and Koopmans (1963), no immediately obvious connection exists between these observed cycles and other cyclic phenomena, although such a relation undoubtedly exists.

Recently, a new approach has been taken to the study of oscillatory phenomena in which concepts of statistics have been applied to generalized harmonic analysis theory, allowing periodicities to be detected in the presence of noise. Noise is defined here as oscillation of the value of a variable without any periodicity. Thus, one may speak of the random variation of a variable. Where periodicities as well as the random variation are present in a variable, the cyclic component may be obscured unless some means is used to separate or filter out the "noise."

Figure 1 indicates the three types of variation (a) periodic, (b) random, and (c) com-

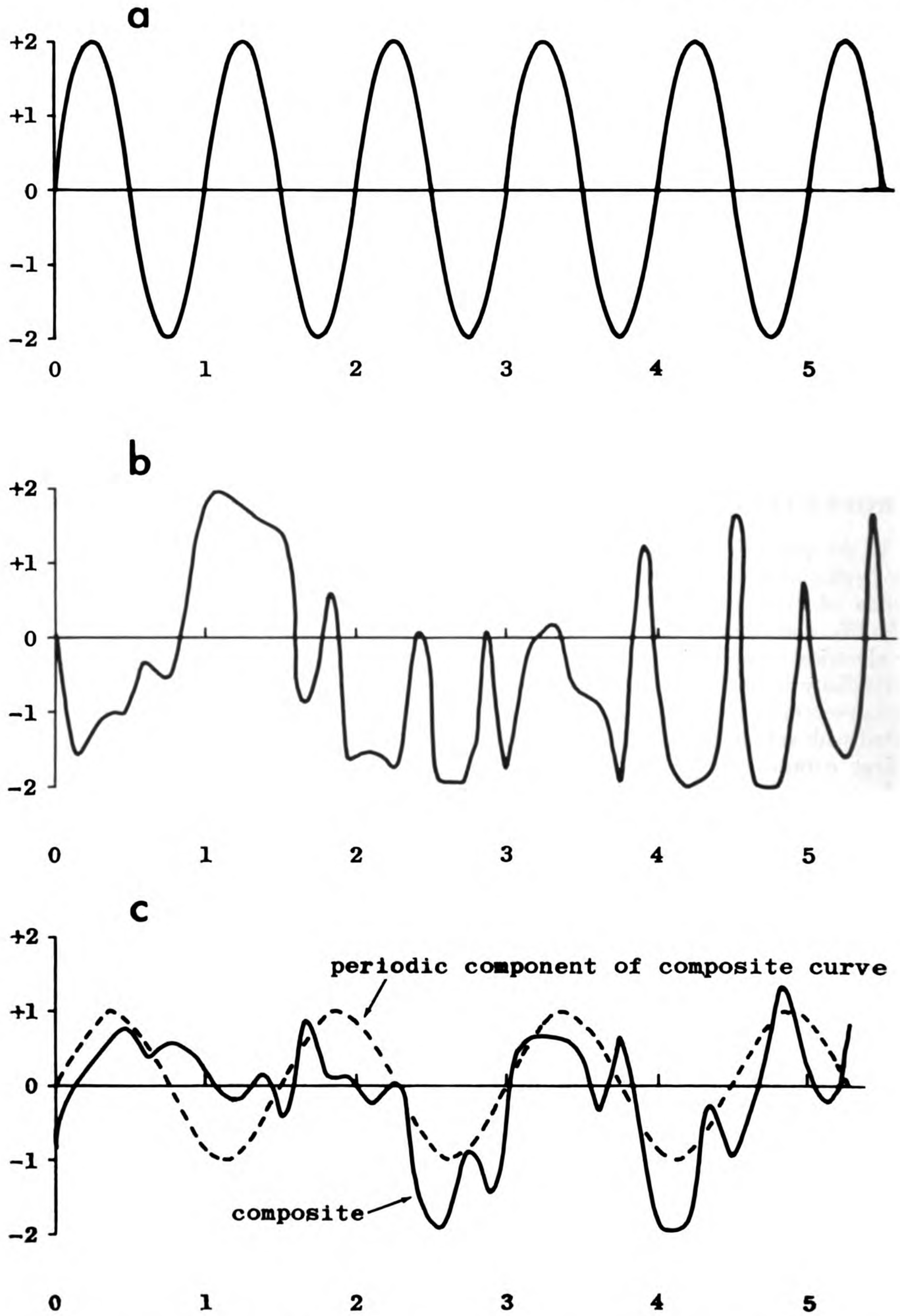

FIGURE 1.—Types of oscillatory behavior: (a) periodic oscillation, (b) random oscillation devoid of periodic component, and (c) composite oscillation, containing periodic and random fluctuation.

bined periodic and random. The variable on the vertical scale might represent, for example, tree-ring width, varve thickness, an economic index such as gross national product, an electronic signal, or height of water in a basin subject to wave action.

Most phenomena that are observed to be oscillatory seem to possess both random (noisy) and periodic components. Methods for separating noise from periodic signals are now reasonably developed within the field of electrical communication. Much of the theory is directly applicable in other disciplines. Even with the application of these new methods, it is not always possible to completely separate the desired periodic portion from the noise. However, the generalized theory of harmonic analysis makes it possible to quantitatively represent a particular sample of a composite periodic signal and the noise to any desired degree of accuracy. This combined oscillatory signal represents only the observed portion of the phenomenon and not the totality of the separate periodic and random components. In a sense, one may say that this sample of the combined signal contains all the available information on the phenomenon, assuming no other samples are available. What is desired is some minimal set of numbers to represent this signal sample. The set of numbers should be minimal in the sense that it takes fewer of them to represent the signal than the original signal contained. It will be shown that through Fourier analysis such a set of numbers is extractable for a given signal and that under the proper circumstances, this set of numbers is an appropriate descriptor of the phenomenon; that is, the number set can be used to distinguish members of one class from those in another class (Henderson, 1962).

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FOURIER SERIES REPRESENTATION OF ELECTRIC LOGS

One may consider an electric log to represent resistivity or some other electrical property averaged over a short distance. A common feature of these logs is their oscillatory character. Although gross changes in pattern can be correlated with known changes in lithology, all too frequently, the detail of the oscillatory signal in the resistivity log in a long undifferentiated shale sequence, for example, contains more information than can be used in a simple stratigraphic classification. Furthermore, a simple picture matching will frequently indicate a lack of correspondence on a detailed scale between logs in adjacent wells penetrating this undifferentiated sequence. Sections of this type are most frequently identified by abrupt and easily recognizable changes that mark their upper and lower boundaries rather than by any characteristic of their interior region. It is believed that Fourier series may represent a means for characterizing sections of logs that have a rather complex logged structure and yet are relatively featureless when viewed by conventional "picture matching" methods.

The Fourier series is given by

$$y = \frac{a_o}{2} + \sum_{n=1}^{n=\infty} \left(a_n \cos \frac{\pi n z}{L} + b_n \sin \frac{\pi n z}{L} \right) \qquad (1)$$

where L = half of the basic or fundamental period; in applications where this is not known, it may be taken as half the length over which a signal is sampled

z = the independent variable of length along the well bore, wherein $-L \leqslant z \leqslant L$

a_o = the zeroth coefficient of a

a_n = the maximum value (or amplitude) of the cosine term $\cos \frac{(\pi n z)}{L}$

b_n = the maximum value (or amplitude) of the sine term $\sin \frac{(\pi n z)}{L}$

y = the dependent variable, such as resistivity, taken to be a function of length or distance z, along the well b re

Equation (1) represents a summing of a large number (in the limit this is infinite) of individual pure sine and pure cosine waves, each with its own period, (2L/n), and amplitude (a_n for cosines and b_n for sines). If appropriate values for the amplitudes (also called coefficients) are chosen, then, with certain exceptions which we shall not consider here, one may represent a large class of oscillatory and some nonoscillatory curves to any desired accuracy.

Because one does not know the mathematical equation of the electric log signal, to represent electric logs as a series of sine and cosine terms, one must use a finite and usually small number of terms (less than 30) in the series (Table 1). Thus, one may represent a resistivity or other log to any desired accuracy by equation (1) assuming a sufficiently large number of points and terms is chosen for the series.

For the case in which the mathematical equation of the "signal" is not available, the method for determining the set of coefficients a_n and b_n is known as harmonic analysis and is described in standard texts on Fourier series (Scarborough, 1962; Lanczos, 1961; Gaskell, 1958). The coefficients are determined from the following equations:

$$a_o = \frac{1}{k} \sum_{j=-k}^{j=k-1} y_j \tag{2}$$

$$a_n = \frac{1}{k} \sum_{j=-k}^{j=k-1} y_j \cos \frac{\pi n z_j}{L} \tag{3}$$

$$b_n = \frac{1}{k} \sum_{j=-k}^{j=k-1} y_j \sin \frac{\pi n z_j}{L} \tag{4}$$

$$o < n < k$$

where y_j = the measured resistivity or other logged property at the point j in the interval from —L to +L

j = an index denoting the j'th value of y; an odd number, 2k + 1, of equally spaced points is chosen in the interval —L to +L. The points are numbered from —k to +k at intervals of 1

k = the number of equal width panels in the interval O to L.

It can be shown that the coefficients obtained by equations (2), (3), and (4) satisfy the least-squares criterion, in that the sum of the squares of the deviations of the predicted values, equation (1), from the observed values is a minimum. Thus, harmonic analysis can be considered to be a special case of polynomial regression or polynomial curve fitting, using a periodic function as the polynomial.

It may be shown (Wylie, 1951) that c_n defined as

$$c_n^2 = a_n^2 + b_n^2 \tag{5}$$

is a measure of the contribution made by the n'th harmonic to the total function, equation (1). The group of numbers, c_1^2, c_2^2, c_3^2, . . . , c_n^2, constitutes a discrete "spectrum" or set and, by analogy to the concept of electrical power in alternating circuits theory, is called the power discrete spectrum of the function given by equation (1). More important, whereas the values of a_n and b_n are dependent upon the location of the section in a continuous oscillating signal from which the length —L to +L is chosen, the values of c_n are independent of this location, assuming 2L is the fundamental period of the signal. Thus,

Table 1.—Observed and computed resistivities for O. A. Sutton No. 1 Gish well. Refer to Figure 1 for location.

Point no.	Index	Observed resistivity, ohm-meter	Computed resistivity, ohm-meters
1	-12	9.10	16.34
2	-11	28.80	28.98
3	-10	54.80	53.94
4	- 9	58.50	58.68
5	- 8	61.00	60.14
6	- 7	66.00	66.18
7	- 6	15.65	14.79
8	- 5	28.90	29.08
9	- 4	57.00	56.14
10	- 3	81.00	81.18
11	- 2	81.00	80.14
12	- 1	14.00	14.18
13	0	54.00	53.14
14	1	65.00	65.18
15	2	57.50	56.64
16	3	65.00	65.18
17	4	33.00	32.14
18	5	31.00	31.18
19	6	32.40	31.54
20	7	37.45	37.63
21	8	17.60	16.74
22	9	15.80	15.98
23	10	24.10	23.24
24	11	26.30	26.48
25	12	17.20	16.34

TABLE 2.—Harmonic coefficients for Fourier-series analysis of resistivity log for O. A. Sutton No. 1 Gish well.

Harmonic n	Cosine term a_n	Sine term b_n	c_n
0	42.28750		
1	13.05240	−10.26861	16.60751
2	1.85156	7.65094	7.87180
3	1.86623	−4.95496	5.29476
4	−12.11042	0.76860	12.13148
5	−7.97458	10.79408	13.42035
6	−2.13750	4.78750	5.24300
7	6.45539	2.79072	7.03280
8	−0.18124	2.52952	2.53600
9	2.36709	6.87004	7.26639
10	6.07344	3.81156	7.17039
11	2.63346	1.18475	2.88769
12	−1.04167	0.00000	1.04167

although the sets of coefficients, a_n and b_n could be used to characterize an otherwise undifferentiated section, it was considered that the set c_n would generally be more amenable to correlation from well to well.

For this study, the Lansing Group, consisting of alternating limestone and shale beds in eight wells in Butler and Cowley Counties, Kansas, was studied by harmonic analysis. After picking the top and bottom of the group, the record of the logged section was enlarged photographically and the interval was divided into 24 panels by a set of 25 equally spaced points. The fundamental period was arbitrarily taken as 24, and the coefficients a_n, b_n, and c_n were determined for the first twelve harmonics, i. e. $n = 12$ (Table 2). The resistivity (short normal) log profiles in this area are shown in Figure 2, and the corresponding power spectra are given in Figure 3. These line spectra can be considered as a type of transformed resistivity log. Adjacent wells can be compared for similarity by comparing their power spectra, similarity of resistivity logs being synonymous with similarity of power spectra. Wells 6 and 7 penetrate a marine limestone bank and are noticeably different, particularly as regards their c_1 and c_2 components.

A similar power-spectrum analysis was made of alternating limestone and shale beds in the Lansing Group in four wells in Phillips County, Kansas. A fifth well (Fig. 4, well 5) was used as a control wherein an interval in the Kansas City Group similar to the Lansing interval was purposely used for the power-spectrum analysis. Logs are shown in Figure 4 and power spectra in Figure 5.

Although several types of differences may be distinguished in the five power spectra of Figure 5, a basic difference between the spectra of wells 1 through 4 and that of well 5 is the reversal in the relative magnitudes of the c_1 and c_2 components. This apparent uniqueness of the spectrum of well 5 was also confirmed by the discriminant-function analysis.

DISCRIMINANT FUNCTION

Although it is valuable to have a means of condensing and representing resistivity measurements of logs in a transformed mode, the primary utility of harmonic analysis is that it yields a set of numerical coefficients which can be considered as a multidimensional description of the original log, allowing analysis by conventional statistical methods. One such method employs the discriminant function. In instances in which classification has been previously established, this technique is useful for identifying an unknown individual record as being from one particular class.

An early reference (Barnard, 1935) concerning the discriminant function deals with an analysis of variations in skull characteristics. It seems that R. A. Fisher conceived the technique and suggested it to Barnard. Explanations of the method and suggestions for practical use may be found in Kendall (1946), Keeping (1962), and Bennett and Franklin (1954).

The use of the discriminant function may be illustrated as follows: Suppose that n individuals are known to be from one population and m individuals are known to be from another population. For each of these individuals we observe a number of characteristics $x_1, x_2, \ldots, x_k$. What linear combination of these k characteristics,

$$X = a_1x_1 + a_2x_2 + \ldots + a_kx_k \tag{6}$$

will best reflect the difference between the two populations? The term X, defined to characterize this difference, is the discriminant function.

It is assumed that for each population, the k characteristics have a multivariate normal distribution, with different means but common variances and covariances. The effect of departure from the assumption of common variances and covariances is not discussed in the literature. Fisher and others do not test for, or mention the effect of, the assumption.

From n observations on k characteristics of the first population, the means for each characteristics, $\bar{x}_{1,1}$, $\bar{x}_{1,2}$, . . . $\bar{x}_{1,k}$, and the matrix of the sums of squares and cross products of deviations from the mean may be found:

$$\begin{matrix} S_1(x_1^2) & S_1(x_1x_2) & \ldots & S_1(x_1x_k) \\ & S_1(x_2^2) & \ldots & S_1(x_2x_k) \\ & & \ddots & \vdots \\ & & & S_1(x_k^2) \end{matrix}$$

where

$$S_1(x_j^2) = \sum_{i=1}^{n} (x_{1,i,j} - \bar{x}_{1,j})^2, \text{ for } j = 1,2,\ldots,k \quad (7)$$

and

$$S_1(x_jx_m) = \sum_{i=1}^{n} (x_{1,i,j} - \bar{x}_{1,j})(x_{1,i,m} - \bar{x}_{1,m}), \text{ for } j \text{ and } m = 1,2,\ldots,k. \quad (8)$$

The means and the matrix for the k characteristics of the m individuals in the second population may be found in a similar fashion. From the k means of the characteristics from the two populations one may obtain the estimate of their differences

$$d_i = \bar{x}_{1,i} - \bar{x}_{2,i}, \text{ for } i = 1,2,\ldots,k. \quad (9)$$

The matrix of the joint estimates of the common variances and covariances,

$$\begin{matrix} s_{1,1} & s_{1,2} & \ldots & s_{1,k} \\ & s_{2,2} & \ldots & s_{2,k} \\ & & \ddots & \vdots \\ & & & s_{k,k} \end{matrix}$$

may be found using

$$s_{i,j} = \frac{S_1(x_ix_j) + S_2(x_ix_j)}{(n+m-2)} = \frac{S(x_ix_j)}{(n+m-2)} \quad (10)$$

The difference, D, of the means of X for the two populations can be found from

$$D = a_1d_1 + a_2d_2 + \ldots + a_kd_k \quad (11)$$

1. Saturn No. 1 Stone - NW NW NE sec. 23, T. 24 S., R. 7 E.
2. Sutton No. 1 Gish - NW NW SE sec. 12, T. 25 S., R. 7 E.
3. Kewanee No. 1 Ferry - NE NE SW sec. 12, T. 26 S., R. 7 E.
4. Gross No. 7 Seward - C E2 E2 SW SW sec. 12, T. 27 S., R. 7 E.
5. Holley No. 27 Ferrell - NW NE SE sec. 21, T. 28 S., R. 8 E.
6. Gralapp & Everly No. 1 Ellis - SW SW SW sec. 35, T. 29 S., R. 7 E.
7. Marts No. 1 "A" Smith - C E2 NW SW sec. 28, T. 30 S., R. 7 E.
8. Royal No. 1 Fox - SW SW SE sec. 15, T. 31 S., R. 7 E.

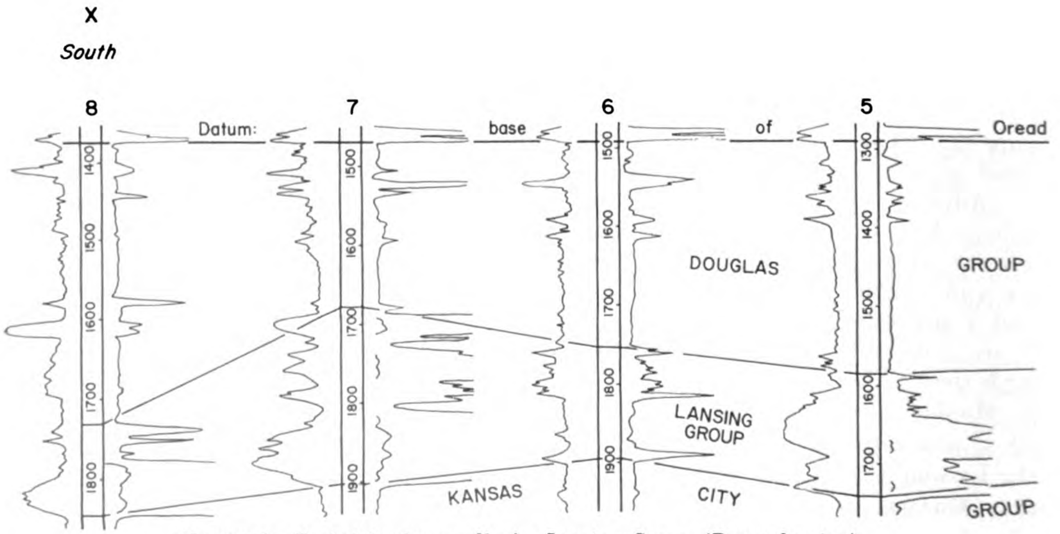


FIGURE 2.—Resistivity log profile for Lansing Group (Pennsylvanian)

The variance of X based on the variations within the two populations can be estimated from

$$S^2_x = \sum_{i,j=1}^{i,j=k} a_i a_j s_{i,j} \tag{12}$$

In the usual test for the difference in the means of two populations, we use the "t" statistic

$$t = \frac{\bar{x}_1 - \bar{x}_2}{S_x \sqrt{\frac{1}{n} + \frac{1}{m}}} \tag{13}$$

and reject the hypothesis that the means are the same if "t" is sufficiently large. It therefore seems reasonable to choose the coefficients of the discriminant function $a_1, a_2, \ldots, a_k$ so that the ratio,

$$t = \frac{\bar{x}_1 - \bar{x}_2}{S_x \sqrt{\frac{1}{n} + \frac{1}{m}}} = \frac{D}{S_x \sqrt{\frac{1}{n} + \frac{1}{m}}} \tag{14}$$

has the maximum absolute value. This is the same as choosing X in such a manner as to make the differences in the populations most likely to be significant. It can be shown that the solutions $a_1, a_2, \ldots, a_k$ to the equations

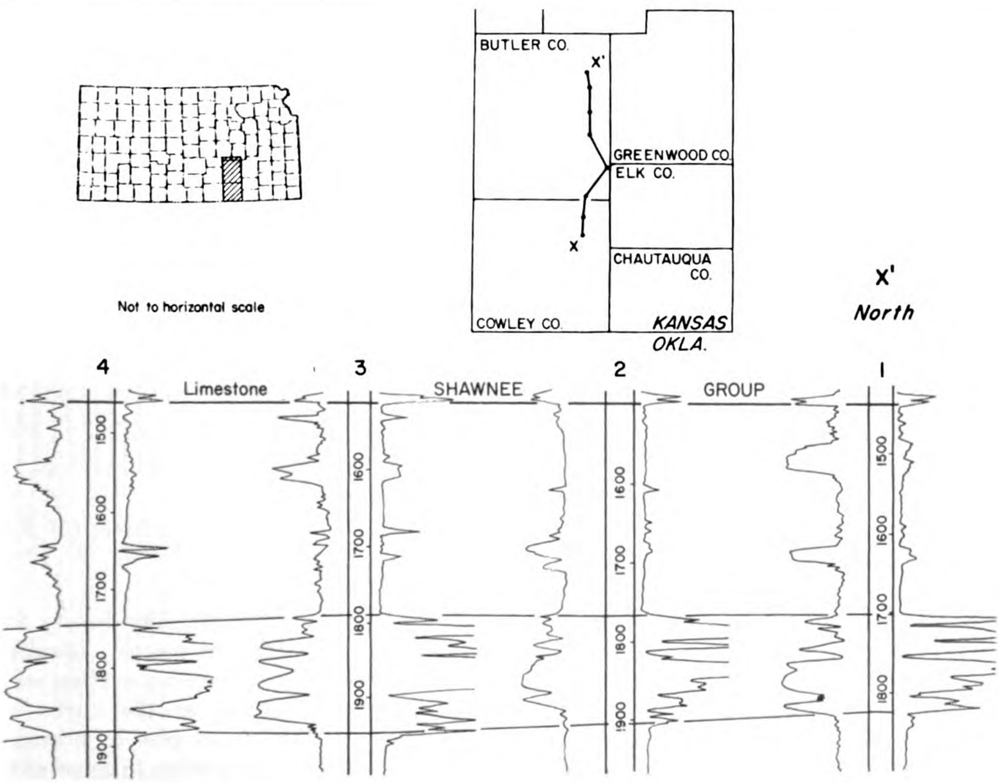
$$\begin{aligned} a_1 S(x_1^2) + a_2 S(x_1 x_2) + \ldots + a_k S(x_1 x_k) &= d_1 \\ a_1 S(x_2 x_1) + a_2 S(x_2^2) + \ldots + a_k S(x_2 x_k) &= d_2 \\ \vdots \qquad\qquad \vdots \qquad\qquad & \vdots \\ a_1 S(x_k x_1) + a_2 S(x_k x_2) + \ldots + a_k S(x_k^2) &= d_k \end{aligned} \tag{15}$$

accomplish this purpose.

Criterion for Assigning Sample to Parent Population

Because the problem is to assign a sample of unknown origin to one of the two parent populations (or to neither), the "t" test on the value from equation (14) is of no value.

Recalling from equation (12) that S_x represents an estimate of the standard deviation



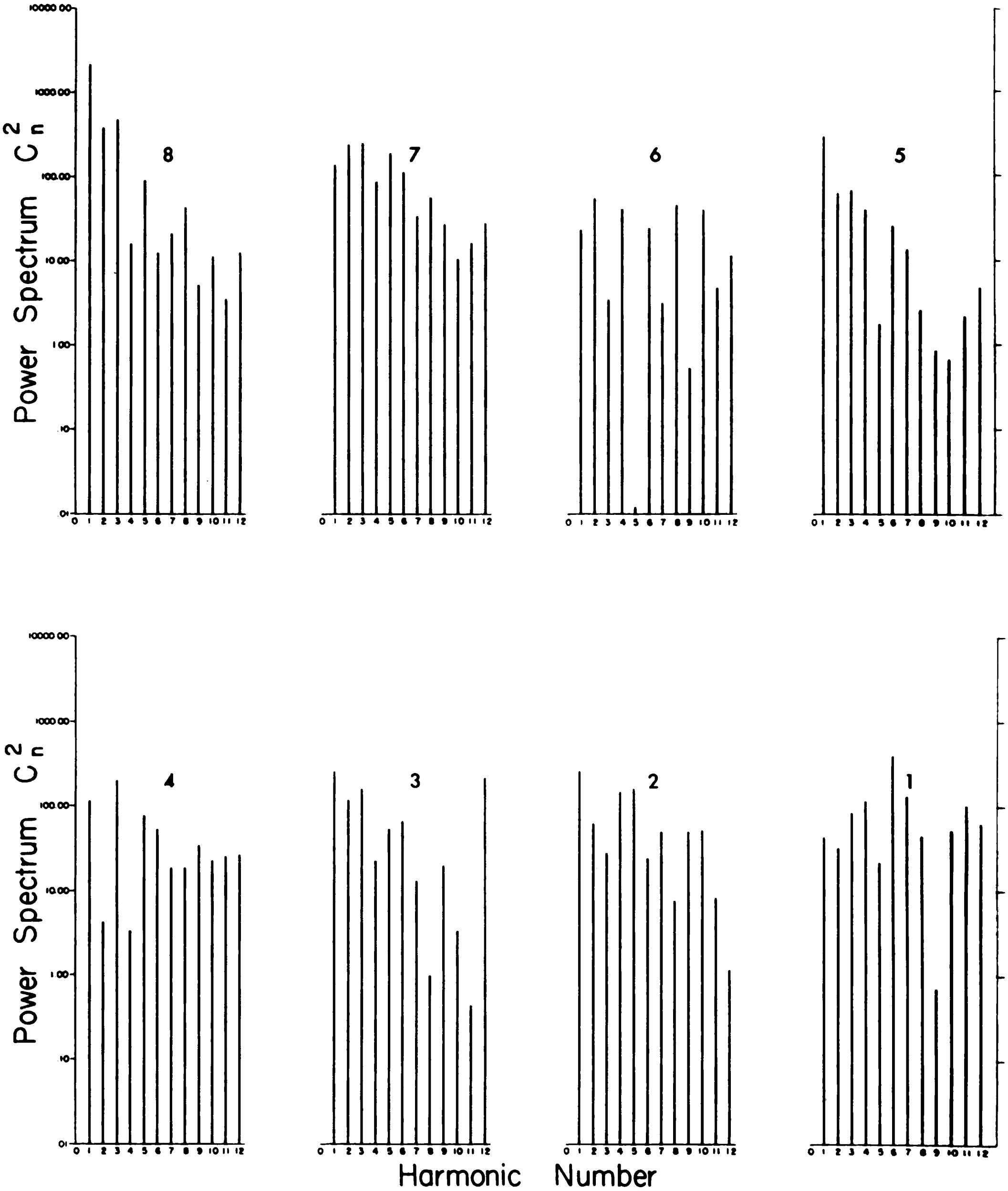


FIGURE 3.—Power spectra for Lansing Group wells shown in Figure 2: (1) Saturn No. 1 Stone; (2) Sutton No. 1 Gish; (3) Kewanee No. 1 Ferry; (4) Gross No. 7 Seward; (5) Holley No. 27 Ferrell; (6) Gralapp & Everly No. 1 Ellis; (7) Marts No. 1 "A" Smith; (8) Royal No. 1 Fox.

of the X's, one can measure the strength of the discriminant function. The value of D/S_x gives the number of standard deviations separating the means of the X's for the two populations. As the X's are assumed to be normally distributed, random variables with the same standard deviations, they can be represented by identical probability density function curves with different means. Ideally, it would be desirable to have no overlap of the two curves. However, as the curves are asymptotic as X tends to plus or minus infinity, they will always overlap to some extent. One can consider the discriminant function

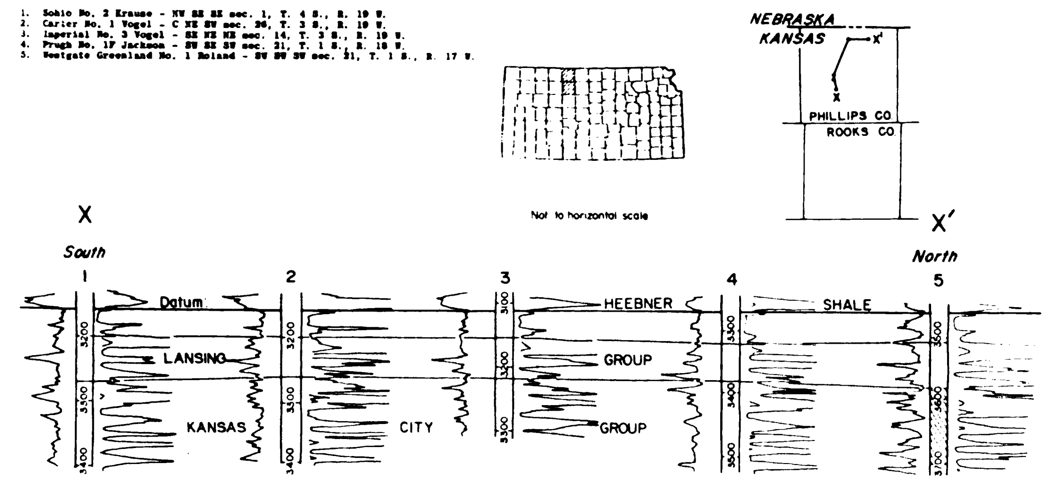


Figure 4.—Resistivity log profile for Lansing Group in north-central Kansas.

a good one if this area of overlap is very small. As an example, if the two probability density function curves have means which are $6S_x$ apart, they will intersect at $-3S_x$ on the curve for the population with the greater mean and $+3S_x$ for the other. The area under the standard normal curve from $3S_x$ to infinity is .0013. Therefore, the probability of assigning a sample to the first population when it belongs in the second is .0013, and *vice versa*.

To assign the sample to the proper parent population, the limits $\bar{x} \pm bS_x$ are chosen so that bS_x is less than the distance from the mean, $\bar{x}$, to the area of overlap for each population. Thus, if the value of X for the sample falls within the limits $\bar{x} \pm bS_x$ for one of the populations, the sample is assigned to that population. If it falls outside these limits, the sample probably did not come from either population. If it falls within the area of overlap, no safe decision can be made.

Use of Discriminant Function With Harmonic Coefficients

In this analysis, the coefficients, c_n, obtained by harmonic analysis were taken as the measurements $x_1, x_2, x_3, \ldots, x_k$. The first four logs of the Lansing Group of Figure 4 and the

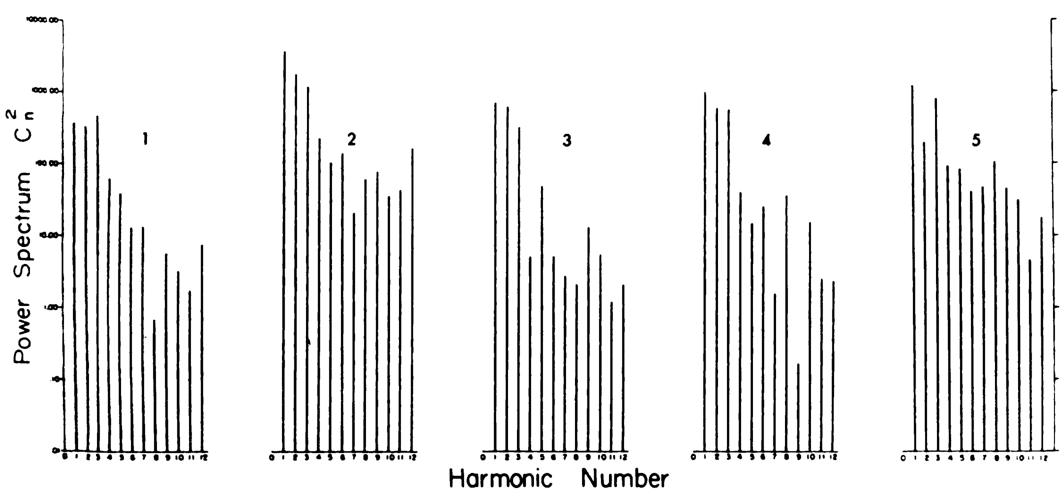


Figure 5.—Power spectra for logs of Figure 4: (1) Sohio No. 2 Krause; (2) Carter No. 1 Vogel; (3) Imperial No. 3 Vogel; (4) Prugh No. 1F Jackson; (5) Westgate Greenland No. 1 Roland.

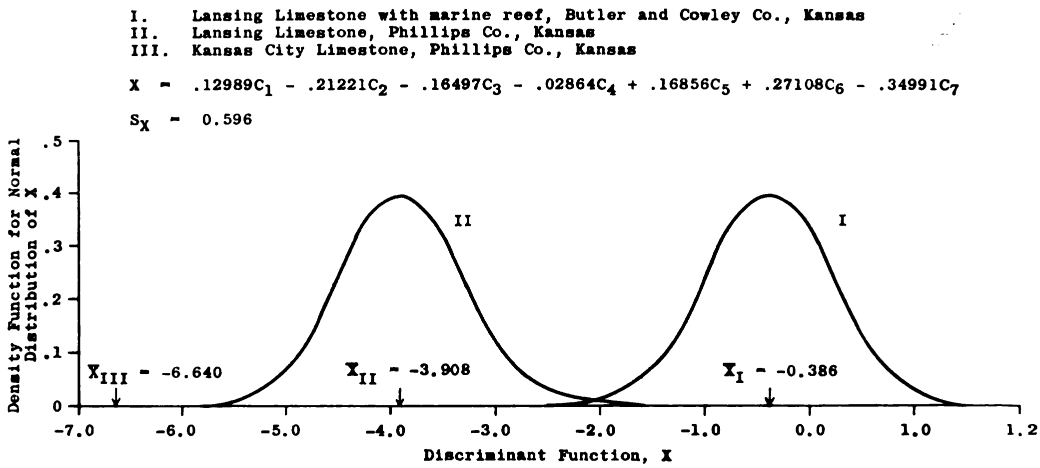


FIGURE 6.—Probability density functions for discriminant X when used to distinguish Lansing Group in two different regions.

eight Lansing Group sections shown in Figure 2 were taken as populations 1 and 2 respectively. The first seven elements of the spectral series, c_n, for each population were chosen as the characteristic measurements, x_1, x_2, x_3, . . . , x_k. The discriminant function for these two populations was:

$$X = .12989c_1 - .21221c_2 - .16497c_3 - .02864c_4 + .16856c_5 + .27108c_6 - .34991c_7 \quad (16)$$

Using the average values of c_n for each population, one obtains $\bar{X}_1 = .386$ and $\bar{X}_2 = -3.908$ with $S_x = .596$.

The strength of the discriminant function may be found from

$$D = \bar{X}_1 - \bar{X}_1 = 3.522 \quad (17)$$
$$D/S_x = 3.522/.596 = 5.909 \quad (18)$$
$$(1/2)\, D/S_x = 2.95 \quad (19)$$

Thus, the probability density functions for the two populations will overlap at $\bar{X}_1 - 2.95\, S_x$ and $\bar{X}_2 + 2.95\, S_x$. The area under the curve at a distance of 2.95 S_x from the mean is .0016. The probability of classifying the unknown well in one population when it should be in the other is therefore .0016. In other words, there are 9,984 chances out of 10,000 that the proper classification will be made.

With such a powerful discriminant function, one can conservatively choose the limits $\bar{X} \pm bS_x$ at $\bar{X} \pm 2.5S_x$. Using these limits, one may say that if the value $\bar{X}$ calculated from equation (16) using the c_i from an unknown sample falls in the range —5.398 to —2.418 the well is more nearly similar to the Lansing Group of cross section B than of cross section A. If it falls in the range —1.876 to +1.104, the reverse is more likely to be true.

To indicate how this classification process might be applied in a specific instance, the Kansas City Group (hatched section) of well 5 in Figure 5 was used as an unknown. The first seven members of the spectral series, c_n, were obtained and using the values for c_n in equation (16), X was computed as —6.640. This value is shown in Figure 6 with the probability density function for the two mean values of X corresponding to populations 1 and 2. In this specific instance, as was to be expected, the formation did not fall into either classification.

DISCUSSION

Preliminary studies presented herein indicate that Fourier analysis can be used to develop a set of numerical parameters that give a reasonably accurate representation of the electric log of a formation and that these parameters may be studied for periodicities. They also may become input data for statistical methods of formation correlation. A new use of Fourier analysis is herein proposed, namely the statistical, numerical characterization of a formation from its electric log and also assignment of a sample of unknown origin to one (or neither) of two parent populations based upon the derived numerical parameters. Methods for determining the strength of the discriminant function and the criterion for making the assignment were also outlined.

An example showing the use of the discriminant function to determine whether or not electric log data came from one of two known formations was presented. This example illustrated use of the methods for obtaining coefficients of the function and application of the decision criterion.

Additional applications of the discriminant function in the petroleum industry include: (1) drawing inferences as to the productive capacity of a well or reservoir based upon the known capacity of another well or reservoir to which it is similar, and (2) aid in reaching decisions concerning the relative effectiveness of various well stimulation processes.

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Transgressive-Regressive Cycle in Croixan Sediments (Upper Cambrian), Wisconsin

ABSTRACT

A preliminary and minimal mechanical analysis study of the marine arenaceous succession comprising the Upper Cambrian (Croixan) strata in the Upper Mississippi Valley strongly suggests the presence of a number of depositional cycles. The initial deposits of the cycles are characterized usually by relatively coarse sands and a histogram with a wide range in grain size, a marked dextral skewness, and a bimodal pattern. In some cycles, however, initial deposits are fine grained and sinistrally skewed. The cycle, where the sequence is not erosionally truncated, terminates as very clean sand with a high sorting coefficient, producing a "pillar" histogram in which over 75 percent of the grains are confined to two adjacent screen sizes. Between the transgressive-regressive extremes, despite considerable variety of histogrammic expression, there is an overall progression in the direction of higher sorting coefficients and coarser average texture.

Cyclical boundaries coincide with nonsequences in the biostratigraphic record, whereas within the cycles the biostratigraphic succession is an undisturbed sequence.

Duration, or "hiatal value," of the nonsequences between cycles is evaluated on faunal grounds. Although the "hiatal value" of the breaks was found to range as high as 10, there seems to be no relation between the physical characteristics of the initial deposits and the duration value of the underlying hiatus.

INTRODUCTION

Extensive sequences of arenaceous marine strata are uncommon in the North American Paleozoic. The most extensive, however, is perhaps that of the type Croixan, or Upper Cambrian, outcropping in the Upper Mississippi Valley region of Wisconsin-Minnesota-Iowa. Because of the nearly unbroken sandstone succession, the section has not yielded readily to the grosser techniques of lithologic subdivision in vogue where contrasting categories of sedimentary rocks comprise the sequence.

This fact confronted the senior author as early as the 1920's in the course of mapping, under the sponsorship of the Wisconsin Geological and Natural History Survey and the Milwaukee Public Museum, of certain quadrangles in central and western Wisconsin. In the virtual absence of units of contrasting lithology (i. e. sandstone, limestone, and shale), the technique of stratigraphic subdivision was based primarily on two factors: establishment (1) of datum horizons through the discrimination of faunal assemblages with lateral distribution but limited vertical extent, and (2) of nonsequences by a combination of faunal and sedimentational criteria. By these means, a series of sequences and nonsequences was determinable which gave consistent results, not only in particular quadrangles, but, as determined through continued studies in the ensuing decades, over the region as a whole.

Whereas the faunal criteria were readily communicable by means of faunal lists and range charts, the sedimentational, based to a large extent on visual inspection of grain size and sorting characteristics, were conspicuously less so. In an effort to document these latter characteristics, the authors, in the early 1950's engaged in sampling the exposed succession in Wisconsin.

The purpose of this paper is to present sedimentational characteristics of a marine environment, expressed as transgressive-regressive cycles; therefore, considerations of stratigraphic breakdown and nomenclature are secondary. Nevertheless, it is necessary to consider the stratigraphic nomenclature and faunal zonation in the interest of supplying a time-stratigraphic frame of reference.

Acknowledgments.—The writers wish to express their appreciation to the Illinois State Geological Survey, Urbana, for use of equipment and assistance in drafting, and to Shell Canada Ltd., Calgary, Alberta, for releasing pertinent western Canadian field and faunal data.

STRATIGRAPHIC SUBDIVISION

The stratigraphic breakdown employed herein is essentially that of Twenhofel, Raasch, and Thwaites (1935) and of Raasch (1935, 1952a). However, the formations of those authors are elevated to groups and their members to formations.

Whether this classification satisfies the requirements of the American Commission on Stratigraphic Nomenclature may be, and has been argued, (Nelson, 1953; Berg. 1954; Bell, Berg, and Nelson, 1956). The "formations" and "members" of Twenhofel, Raasch, and Thwaites and of Raasch certainly satisfy the requirements of time-stratigraphic divisions, stages, and substages. Yet all of them are bounded, at top and base, by recognizable physical criteria, and separated by discontinuities, which, at least on a regional scale, constitute disconformities. Whether, on this basis, they are to be regarded also as proper rock-stratigraphic divisions may be a matter of interpretation, and is not particularly relevant to the present purpose.

The following, then, is the stratigraphic subdivision employed.

- ORDOVICIAN SYSTEM
  - Canadian Series
    - Prairie du Chien Group
      - Oneota Formation (Stage)
        - Hickory Ridge Member (base only sampled)
- CAMBRIAN SYSTEM
  - St. Croix Series
    - Trempealeau Group (Stage)
      - Sunset Point Formation (Substage)
      - Jordan Formation (Substage)
        - Van Oser Member
        - Norwalk Member
      - Lodi Formation (Substage) (not sampled)
      - St. Lawrence Formation (Substage) (not sampled)
      - Arcadia Formation (Substage) (not sampled)
    - Franconia Group (Stage)
      - Bad Axe Formation (Substage)
      - Hudson Formation (Substage)
      - Goodenough Formation (Substage)
      - Ironton Formation (Substage)
    - Dresbach Group (Stage)
      - Galesville Formation (Facies)
      - Eau Claire Formation (Facies)
      - Mt. Simon Formation (not fully sampled)
- PRECAMBRIAN SYSTEMS
  - Crystalline complex

The stratigraphic succession is graphically presented in Figure 1, which also carries a brief lithologic description of the units.

BIOSTRATIGRAPHIC SUBDIVISION

In order to express discontinuities relative to the transgressive-regressive cycles, recourse must be had to the faunal succession. This has been presented in a more or less generalized fashion by Twenhofel, Raasch, and Thwaites (1935) and in greater detail by Raasch (1939, p. 114; 1952b, p. 148). Most current workers in other regions of North America (e. g. Lochman and Wilson, 1958) recognize the seven major zones of the Upper Mississippi Valley Croixan. These are, in ascending order, the *Cedaria*, *Crepicephalus*, *Aphelaspis*, *Elvinia*, *Conaspis*, *Ptychaspis-Prosaukia*, and *Saukia* Zones. These zones, based primarily on the range of assemblages of trilobite genera, are recognizable over much of the continent, and maintain the same succession as in the type region, except that one or more additional zones intervene between the *Aphelaspis* and *Elvinia* Zones—that is, in the sub-Franconian hiatus, in parts of southwestern United States.

In the type region each of the seven genera-zones, with the exception of the *Cedaria* and

System / Series	Group	Formation	Lithologic Character	Fauna
ORDOVICIAN	PRAIRIE DUCHIEN	ONEOTA	Dolomites.	Hystricurus
ORDOVICIAN	PRAIRIE DUCHIEN	HICKORY RIDGE MEMB.	Dol, sandy and ss with cgl, oolite, glauc beds, and cryptozoa. Basal beds cgl or v poorly std. ss.	Symphisurina
(ST. CROIX SERIES)	TREMPEALEAU GROUP	SUNSET POINT	Ss dolc, thin bedded, mainly fn, fucoidal. Base v. poorly std.	Saukia
(ST. CROIX SERIES)	TREMPEALEAU GROUP	JORDAN	TOP: Ss v crse, clean, highly cross-bedded in regular foresets. (VanOser Beds.) MIDDLE: Ss, finer, with intersecting foresets; locally dolc. (Norwalk Beds) LOWER: Dol sandy, shale calc, buff, cgl in dol matrix. Carbonate disappears eastward.	
(ST. CROIX SERIES)	TREMPEALEAU GROUP	LODI	Shale and siltstone, calc, and ss fine. Ss to East.	
(ST. CROIX SERIES)	TREMPEALEAU GROUP	ST. LAWRENCE	Dol, sandy, glauc locally; reefy; locally v conglomeratic.	
(ST. CROIX SERIES)	TREMPEALEAU GROUP	ARCADIA	Siltstone fissile, ss v fn, dol, and cgl.	
(ST. CROIX SERIES)	FRANCONIA GROUP	BAD AXE	Gnsd, with num thin intraf cgl bands in western area.	
(ST. CROIX SERIES)	FRANCONIA GROUP	HUDSON	West: gnsd; east: white to yel ss, fn, v well sorted, thick-bedded, some beds dolc. Borings abund both facies.	Prosaukia-Ptychaspis
(ST. CROIX SERIES)	FRANCONIA GROUP	GOODENOUGH	UPPER: West-gnsd. East-ss yel, fn. LOWER: Ss, v fn, mic, and sh, mic. BASE: Commonly thin clay glauc band	Conaspis
(ST. CROIX SERIES)	FRANCONIA GROUP	IRONTON	Ss, mainly crse; gnsd bed at top on well std ss; v poor sorting toward base. Boring activity thruout.	Elvinia
CAMBRIAN SYSTEM	DRESBACH GROUP	GALESVILLE	Ss, med grained, well std, weak, massive to banded.	○
CAMBRIAN SYSTEM	DRESBACH GROUP	EAU CLAIRE	UPPER: Ss, fn, thin-bedded, mic, yel. Passes to Galesville lithology eastward.	Aphelaspis
			MIDDLE: Ss, fn, thin-bedded, gray, glauc, argill on ss, v fn, wh to buff, non-glauc, thick to thin beds. Passes to Galesville lithology eastward.	Crepicephalus
			LOWER: Ss, mod fn, thin-bedded, much interbedded shale, no glauc. Passes to Galesville lithology eastward.	Cedaria
CAMBRIAN SYSTEM	DRESBACH GROUP	MT. SIMON	Ss, like Galesville, med grained, massive, cliff forming.	○
				Climactichnites
			Like above interbedded with crse, poorly sorted sand.	○
			Interbedded crse grits and shales, gn, red, gray.	
PRE-CAMBRIAN		CRYSTALLINE COMPLEX	Igneous and metamorphic rocks.	○

FIGURE. 1.—Croixan succession in the type region.

Aphelaspis, may readily be divided into a number of species-zones. Thus, four species-zones comprise the *Crepicephalus* Zone, three the *Elvinia* Zone, ten the *Conaspis* Zone, eight the *Ptychaspis-Prosaukia* Zone and fourteen the *Saukia* Zone. Many of these species-zones, based on the biochrons of species-assemblages, maintain their identity as far as Oklahoma, Texas, and the Canadian Cordillera.

The species-zone succession within the confines of the type area does not seem to be radically different from that outside, with two exceptions. The first of these relates to the *Cedaria* Zone. In Alberta, for example, the

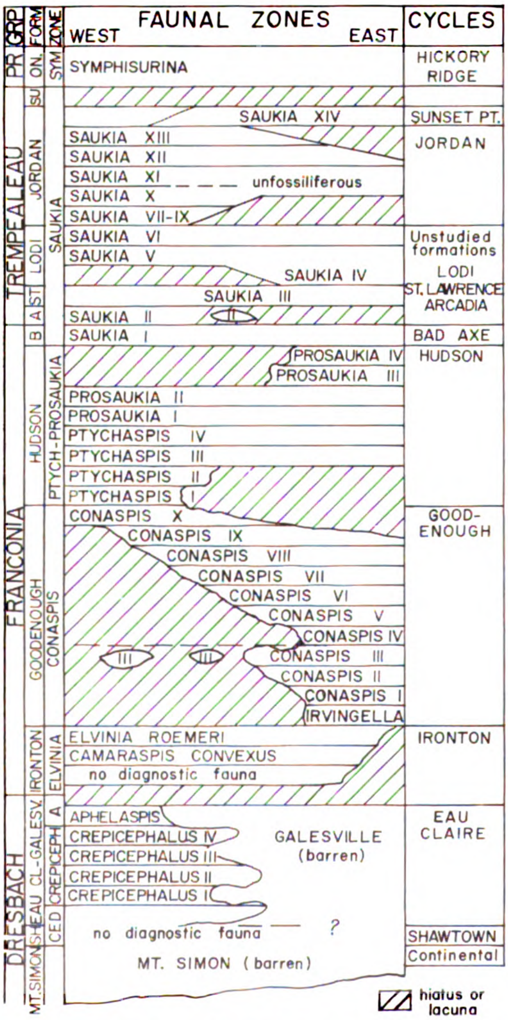

FIGURE 2.—Relation of Croixan faunal zones and sedimentary cycles.

"*Cedaria*" *woosteri* species-zone, of the Upper Mississippi Valley is underlain by at least two additional species-zones, which may be correlated with fauna described by Lochman and Duncan (1944) from central Montana. The absence of the earlier *Cedaria* fauna in the Mississippi Valley appears logically to have been a result of the later arrival of the Dresbachian marine transgression here.

The other horizon at which fauna known from other regions is absent in the Mississippi Valley corresponds to the Dresbachian-Franconian hiatus. This gap in the type Croixan record is filled in certain other areas by (1) several younger species-faunae of the *Aphelaspis* Zone, followed by (2) an additional major or genera-zone (*Dunderbergia* Zone), and finally (3) by several species-zones of *Elvinia* older than those in Wisconsin.

The 41 successive species-zones discriminable within some 500 feet of strata in the Croixan type succession in the Mississippi Valley (Fig. 2) are relevant to the problem of sedimentation and sedimentary cycles in that they establish the position of significant nonsequences and also furnish a basis for evaluation of the duration of the hiatus. The fact that these significant hiatuses are also identifiable on the basis of physical, sedimentational evidence is, of course, the theme of the present discussion.

SEDIMENTATIONAL CHARACTERISTICS AT NONSEQUENCES

The horizons in the Croixan succession at which nonsequences are most generally conceded to exist lie (1) at its base (Precambrian crystallines—Mt. Simon), (2) at its top (Sunset Point—Oneota), and (3) at the Dresbachian (Galesville)—Franconian (Ironton) contact. Because we are concerned primarily with marine arenaceous sediments, the first of the above is not germane, as it represents a thick nonmarine sequence resting on a crystalline basement.

CAMBRIAN-ORDOVICIAN CONTACT

The Cambrian-Ordovician contact was sampled at two localities; Glovers Bluff, Marquette County, Wisconsin, and Stoddard, Vernon

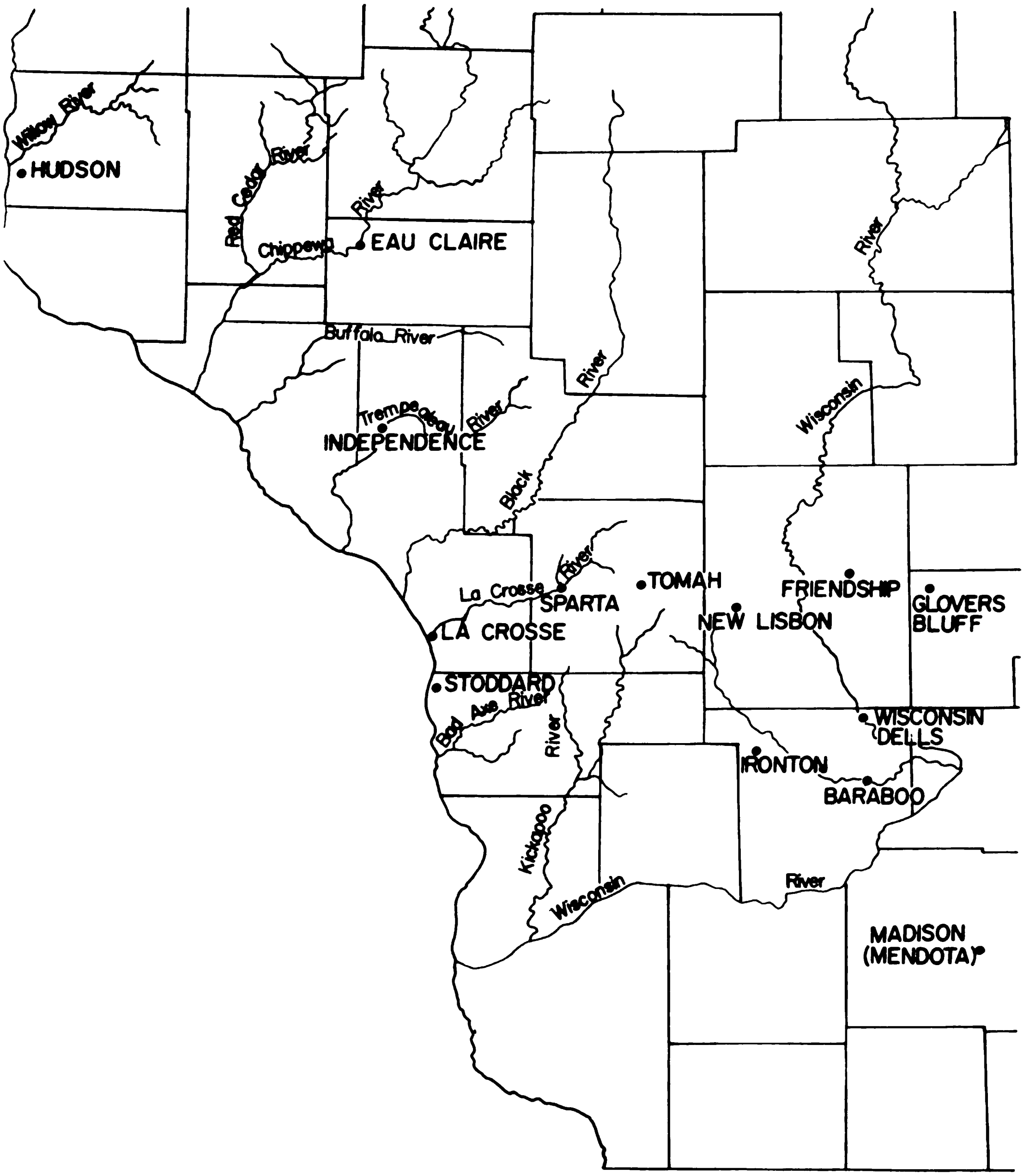

Figure 3.—Southwestern Wisconsin showing location of important sections.

County, Wisconsin, separated by about 80 miles in an east-west direction (Fig. 3). Figure 4 illustrates the sedimentational characteristics at the contact.

It is to be noted that the initial deposit above the contact, i. e. the basal Oneota sand, yields a histogram distinguished by a wide range in grain size, a marked skewing to the right, and a moderately bimodal character. In addition, the upper sand is notably coarser than the lower. A high precentage of carbonate was removed by solution in acid in the Oneota sample from Stoddard, whereas the Glovers Bluff sample of friable sand was untreated, indicating the negligible effect of carbonate content relative to sand characteristics.

The considerable similarity of the histo-

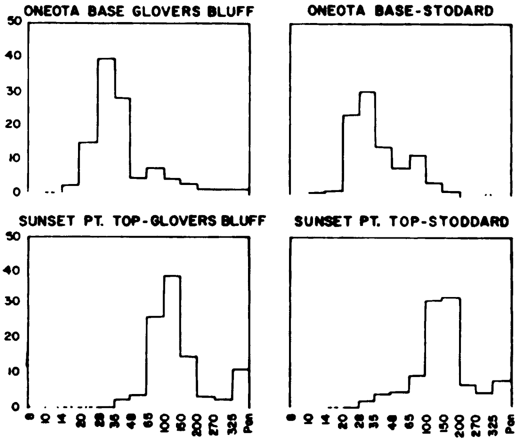

FIGURE 4.—Cambrian-Ordovician contact at two Wisconsin localities.

grams of the two Sunset Point samples from below the contact is also notable.

Dresbachian-Franconian Contact

The Dresbachian-Franconian contact, representing an important nonsequence now recognized as extending over much of the continent, involves the relation between the Galesville Sandstone below and the Ironton Sandstone above. The Ironton increases in thickness westward from a zero line on the Wisconsin Arch to a maximum of about 65 feet. A detailed study of sedimentational characteristics strongly suggests that the underlying Galesville sand is correspondingly truncated in a westerly direction. Figure 5 illustrates the sedimentational characteristics at the Galesville-Ironton contact at three Wisconsin localities: Friendship Mound, Adams County; Wood Hill, southwest of New Lisbon, Juneau County, and a roadcut on Wisconsin Highway 71 about 7 miles north of Sparta, Monroe County. Some 50 miles, on an east-west axis, separates the Friendship and Sparta localities.

In Figure 5, it can be seen that the histogram pattern for the Ironton base at the Friendship and Wood Hill localities is strikingly similar to that for the Oneota base at the two localities shown in Figure 4. That is, the sorting is poor and the histogram is bimodal and skewed to the right. At the Sparta locality, the characteristics are somewhat subdued, in that sorting is less poor and the bimodal character is lacking. The Ironton depositional cycle here, where it is 42 feet thick, is complex in contrast to the simple cycles at the other two localities, where the formation is appreciably thinner. However, the contrast in average coarseness between the Ironton and Galesville sands at all three localities is to be noted. Also the Galesville is appreciably less well sorted at the Sparta locality, where the Ironton base lies deeper in the truncated Galesville sedimentational cycle.

Jordan-Sunset Point Contact

Having demonstrated and compared the sedimentational characteristics on opposite sides of generally acknowledged sequential breaks (i. e. Dresbachian-Franconian and Croixan-Canadian), there remains to be inspected the arenaceous marine sequence for further possible "breaks" of a similar nature. One of these, long recognized and employed by the senior author in field studies, lies between the Jordan and Sunset Point (Madison) Formations of the Trempealeau Group. Unlike the two preceding cyclical breaks, the Jordan-Sunset Point break does not coincide with a major (genera-zone) faunal break. Nevertheless, detailed but unpublished studies of the Trempealeauan succession indicate that the Jordan strata beneath the Sunset Point are appreciably truncated in the region of the Wisconsin Arch, where the total Jordan succession is not only notably thinner, but the upper, or Van Oser Member is missing. Hence a significant nonsequence within the *Saukia* Zone faunal succession coincides with physical contact between the Jordan and Sunset Point Formations.

The histogrammic relationships of the uppermost Jordan to the basal Sunset Point sand are illustrated in Figure 6, which compares two localities separated by some 90 miles along a west-northwest and east-southeast axis. As previously discussed, the sands may be differentiated and the contacts located by inspection on the outcrop. Although the Sunset Point Formation seldom exceeds 35 feet in thickness and is generally much thinner, it is widespread over the region but apparently absent in the northwestern part (St. Croix Valley, etc.), and may be locally absent else-

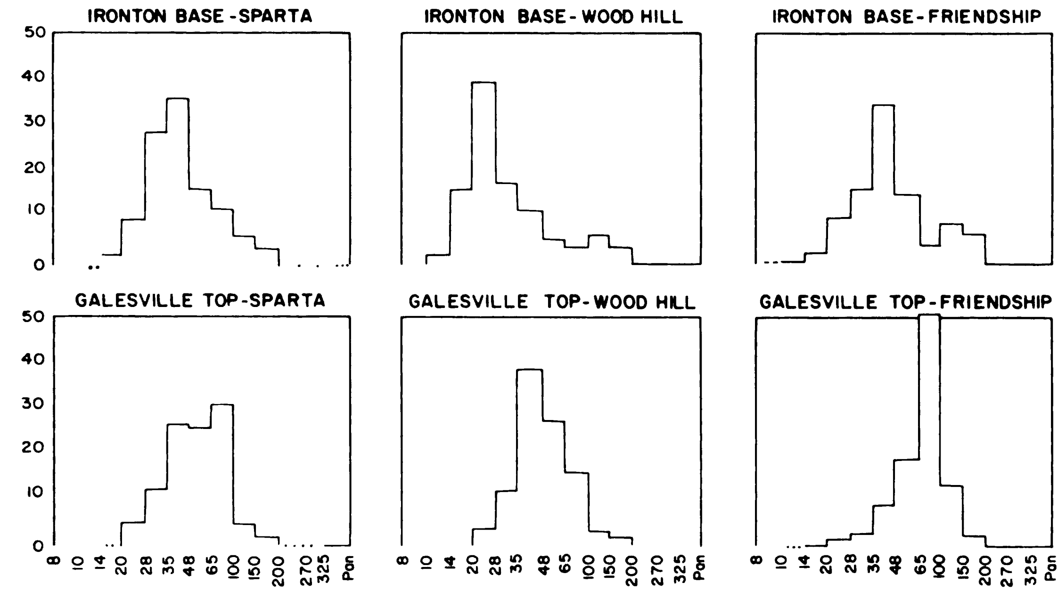

FIGURE 5.—Dresbachian-Franconian contact at three Wisconsin localities.

where, presumably as a consequence of the irregularities of pre-Oneota erosion.

An interesting corollary to the cyclical independence of the Sunset Point is its heavy mineral character, it being garnet free in contrast to the high garnet ratio in both the underlying Jordan and the overlying Oneota Formations (Ockerman's 1930 paper would seemingly refute this, but a re-examination of his outcrops revealed that no sample of "Madison" (= Sunset Point) sandstone was analyzed).

From an examination of Figure 6, it is readily apparent that the basal sands of the Sunset Point Formation possess the same histogrammic characteristics as those of the Ironton and Oneota, namely, relatively poor sorting, a skewing to the right, and a weakly bimodal character. Moreover, the underlying sand is remarkably well sorted, about 60 percent being accounted for by two adjacent screen sizes. The fact that only 64 percent is so confined in the Mendota sample and 84 percent in the Stoddard sample is a consequence of the pre-Sunset Point removal of the closing or Van Oser phase deposits at Mendota in contrast to their preservation at Stoddard.

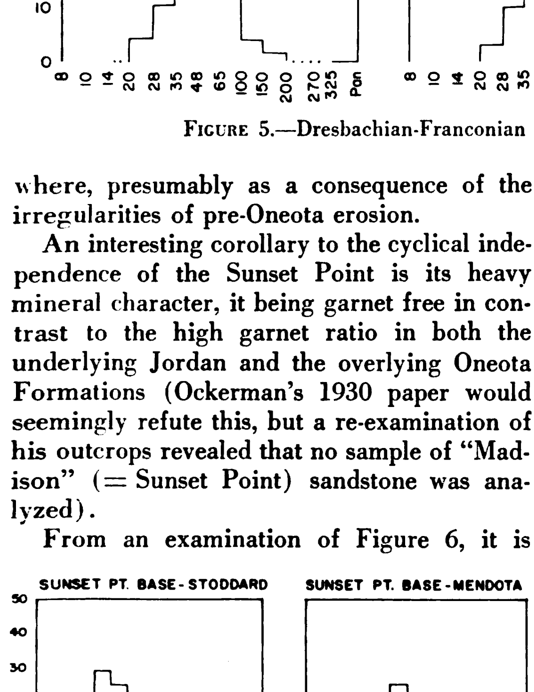

FIGURE 6.—Jordan-Sunset Point contact at two Wisconsin localities.

ADDITIONAL CYCLICAL BREAKS

The above three examples represent situations where the type of cyclical breaks or separations described were expected on the basis of lithological distinctions amenable to visual inspection. An interesting consequence of the application of the mechanical-analysis technique was the apparent revelation of additional and hitherto unsuspected discontinuities, and particularly, the significant location of these breaks relative to major faunal zones. Nevertheless, at this highly preliminary stage in the investigation, it must be kept in mind that significant as these appear, they as yet are based on single observations and still require the substantiation of multiple control.

The additional horizons at which the dextrally skewed histogram significant of cyclical breaks was recorded are three in number and lie, in descending order, as follows: (1) base of Bad Axe Formation, Franconia Group; (2) base of Hudson Member, Franconia Group; and (3) base of the "Upper Mt. Simon" ("Sooty Zone") in the Dresbach Group. Significantly, each of these lies at a horizon corresponding with the base of a major faunal zone.

Intra-Franconian Breaks

The upper three formations of the Franconia Group were analyzed from a single locality, Maynard Pass on US Highway 16 near Tomah, Monroe County, Wisconsin (Fig. 7). Although the formational contacts were drawn here on physical characteristics other than those of sorting and grain size, the results of mechanical analysis showed, to the authors' considerable surprise, the same histogramic patterns as those developed from the more obvious horizons of sedimentational continuity discussed above. In the analysis of the basal Hudson, sample (L) from 6 feet above the contact better illustrates the triple characteristics of poor sorting, dextral skewness, and bimodal character than does the sample (K) 3 feet above the contact. It seems probable that a closer method of sampling, perhaps channel sampling would have eliminated this slight apparent anomaly.

Relative to the sample from the Bad Axe base, it may be noted that it maintains the typical characteristics of a transgressive phase histogram, despite the fact that it is a conglomerate. These "sandstone conglomerates" consist of virtually or totally unconsolidated pebbles in an unconsolidated matrix. Whether conglomeratic or not, the total sample apparently maintains about the same proportions of old (i. e. reworked) and new (i. e. transported or regolithic) sand.

"Late Mt. Simon" Break

The Mt. Simon Formation is traditionally regarded as that portion of the Croixan arenaceous succession which underlies the oldest marine strata, the Eau Claire Formation, and overlies the Precambrian crystallines. This interpretation accords a highly varied thickness to the Mt. Simon in harmony with the irregularities on the surface of the Precambrian crystalline basement.

With respect to the overlying Eau Claire Formation, relations have been interpreted as

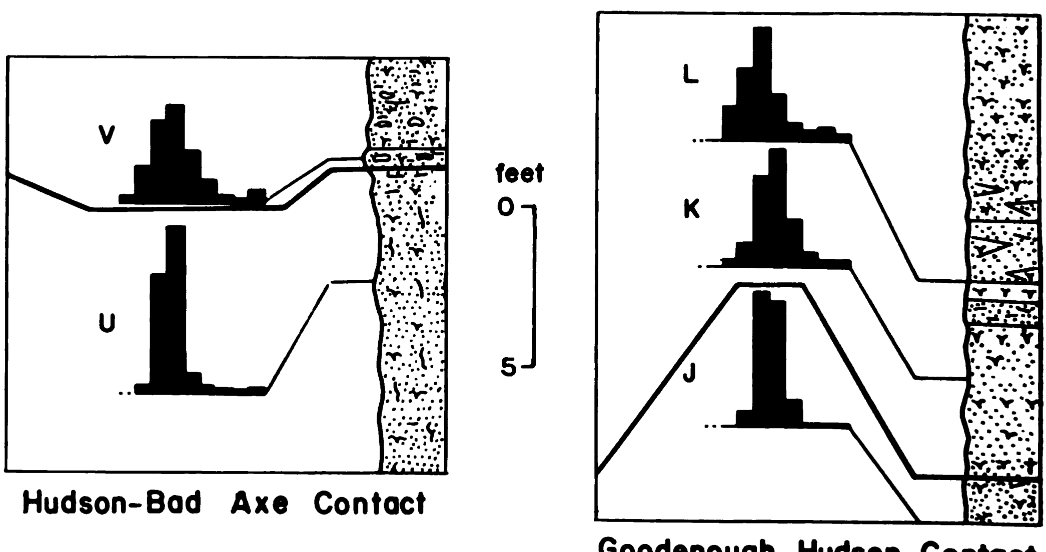

Figure 7.—Cyclical boundaries in the Franconia Group near Tomah, Monroe County, Wisconsin.

transitional, at least in a gross sense. In most localities for example, some tens of feet below the base of Eau Claire lithology, worm borings appear in the Mt. Simon type sands, followed by beds with a high percentage of comminuted oboloid brachiopods and finally by the fine sands and shales of Eau Claire type with fully marine faunas of trilobites, brachiopods, and pteropods. Accordingly, it has remained somewhat of an arbitrary decision whether to draw the base of the Eau Claire Formation at the first appearance of marine criteria or to draw it at the line of change in gross lithology from the coarser and more thickly bedded sands of Mt. Simon type to the more thinly bedded fine sands and shales of Eau Claire type.

Examination of the mechanical analyses from this portion of the sequence from Mt. Simon Peak and Mt. Washington Bluff, in the suburbs of Eau Claire, Wisconsin, suggests a resolution of this nomenclatural problem.

There, the base of the sand which bears the worm borings indicative of the approach of marine waters yielded histograms similar to those marking such known transgressions as those at the base of the Franconian (Ironton) and of the Canadian (Hickory Ridge). Moreover, the coarse beds with oboloids immediately beneath strata of Eau Claire lithology yielded histograms closely comparable with those from the top of the Ironton. Finally, the basal Eau Claire and basal Goodenough, which overlie the "Mt. Simon" and Ironton respectively, also yielded closely comparable histograms (Fig. 8).

Thus, it would appear that the "upper" or "marine" Mt. Simon unit and the Ironton Formation are remarkably similar in physical character, in presence of worm borings and oboloid fragments, in stratigraphic relations, and, therefore, in genetic significance. Both comprise the initial deposition of regionally widespread transgressions and bear a similar relationship to the nonmarine, probably freshwater sediments which underlie them. Both, moreover, ought therefore to merit equal nomenclatural status.

Accordingly it is tentatively proposed to designate the "Upper" or marine Mt. Simon as the Shawtown Formation, after that district of the City of Eau Claire in which Mt.

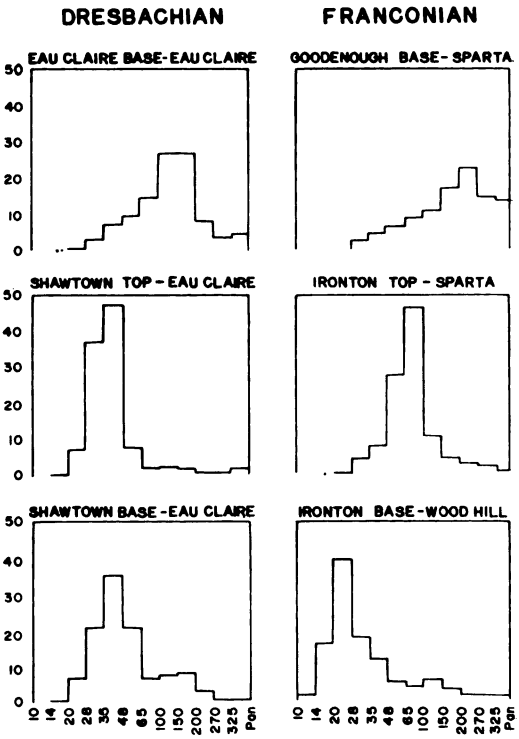

FIGURE 8.—Comparison of early phases of Dresbachian and Franconian sequences.

Washington (the Eau Claire type locality) is situated.*

"PILLAR" HISTOGRAMS

Each of the Cambrian cycles which begins with the dextrally skewed histogram closes, where erosional truncation has not removed their terminal phases, with histograms indicating very well-sorted sands. For convenience in designation, these may be referred to, in consequence of their shape, as "pillar" histograms. Such histograms represent terminal deposits of the Shawtown, Ironton, Hudson, Bad Axe, and Sunset Point cycles. In

* "Shawtown" is a new name proposed herein for the basal member of the Eau Claire Formation. The name is taken from the district of the city of Eau Claire, Wisconsin, which lies at the foot of Mt. Washington Bluff on west side of the Chippewa River. Because the basal contact of the unit is better exposed in Mt. Simon Bluff, in the north part of the city, that locality is selected as the type, however, with Mt. Washington a supplementary type.

At Mt. Simon the unit is 13 feet thick, and underlies 10 feet of *Obolus*-bearing Eau Claire sandstone which forms the peak of the bluff. The histogrammic character, lithology, and stratigraphic relations are shown in Figure 9. Fauna consists of "worm" borings and comminuted fragments of phosphatic brachiopods. In addition, grains under a lens show a sooty coating as in the sands which underlie the Eau Claire Formation in Illinois, where they are known to subsurface investigators as the "Sooty Zone" (*see*, Templeton, J. S., 1950).

addition to these five cycles, however, there are three others which close with similar histograms, but which do not begin with the dextrally skewed histogram.

SINISTRALLY SKEWED HISTOGRAMS

In each of the three seemingly anomalous cycles, the sequence begins with a histogram characterized by a pronounced sinistral skewness plus very fine grain size. This is true of the Eau Claire-Galesville cycle in the Dresbachian, Goodenough cycle in the Franconian, and Jordan cycle in the Trempealeauan. In terms of sequential relationships, the Dresbachian is difficult to evaluate, because the preceding cycle is without diagnostic fauna (long-ranging oboloid brachiopods only). In the Franconian, however, a significant nonsequence exists in most areas between the Goodenough (Tomah lithofacies) and the underlying Ironton. At Maynard Pass, for example, six species-zones, present elsewhere in the region, are missing in the Ironton-Goodenough hiatus, while seven are missing in the Sparta section. In the Trempealeauan, the hiatal significance is not readily apparent, as the basal beds of the Jordan, being conglomeratic dolomites, were not analyzed.

ENVIRONMENTAL INTERPRETATIONS

In several of the cycles beginning with dextrally-skewed histograms, it is possible to demonstrate that the underlying strata had been truncated on a regional scale, and it is probable that some degree of truncation was involved with most, if not all of them. Where cycles begin with sinistral skewness, on the other hand, it seems probable that there was no erosion of the underlying beds, and the hiatal condition is a result of transgressive onlap. The coarseness of the dextrally skewed initial deposits is suggestive of a high-energy environment, in contrast to the low-energy environment in which the fine-grained, sinistrally skewed deposits were laid down. Some, but not necessarily all, of the erosion of the subcrop may have been concomitant with the high-energy conditions prevailing during the transgressive phase of the high-energy cycles.

Fossil remains, or any traces of organic habitation, are highly exceptional in the coarse, high-energy sediments of the dextrally skewed cyclothem, but these sediments grade rapidly upward into sediments with abundant traces of organic habitation (borings, trails, and organic reworking of the sands) and also identifiable fossils.

The sinistrally skewed histograms occur where rich marine faunas commonly pack the fine sands immediately above the contact, and glauconite is typically present. "Mudcracks" and "current" ripples are common. Shallow-marine waters seem to be clearly indicated.

The terminal histograms, on the other hand, indicate a greater variety of environments, on criteria other than those of mechanical analyses. In the Shawtown and Ironton cycles, the terminal beds are the most richly fossiliferous and bear most of the identifiable organic remains. In the Goodenough and Hudson cycles, marine conditions continue throughout, but there tends to be an overall reduction in faunal abundance upward; but the Sunset Point is sparingly fossiliferous throughout. The Jordan cycle, where fully developed, closes with steeply dipping foreset beds of fairly constant inclination which the writers interpret as beach deposits building seaward under a static profile of equilibrium. Except at one locality (Van Oser Creek, Minnesota; Stauffer, 1940), the beds lack fossils and show little evidence of organic habitation. Finally, the terminal phase of the Galesville, with thin and regular bedding, variously oriented "wave" ripple marks, and total absence of any evidence of organic habitation points toward a fresh water, possibly lacustrine environment.

Despite the considerable variety of indicated environments, the terminal phases of the seven cycles possess in common a histogram type in which over 75 percent of the sediment is confined to two adjacent screen sizes and less than 3 percent passes the 150-mesh screen. The terminal phase of the cycle seems to represent a concentration of the coarser fractions, and an elimination by extraction of the finer fractions. This suggests no change in the character of the sediments received, but a passing on of the fines, due to energy increase, so that only the coarser fractions remain. Wave action under regressive conditions resulting from the progressive filling of the basin to the profile of equilibrium is postulated.

SUCCESSION WITHIN THE CYCLE

To this point, it has been possible to generalize with respect to the position of the dextrally or sinistrally skewed histograms at the base of the cycles and of the pillar histograms at the top of the cycle. That these are not random in their occurrence is indicated by the fact that the pillar histogram is succeeded *without transition* by a skewed histogram. Both physical and faunal criteria indicate that the separation between pillar and overlying skewed cycle corresponds with a significant hiatus and time-break.

The succession within any particular cycle is not so amenable to generalization, because each may embrace a considerable variety of environments, and not all of these occur within every cycle. A much more impressive quantity of data needs to be gathered before any significant degree of generalization, let alone interpretation, can be made. In general, however, it is apparent that there is an overall upward progression in the direction of better sorting and coarser average texture.

RELATION OF FAUNAL ZONES AND SEDIMENTARY CYCLES

From the foregoing it can be seen that, whereas seven major faunal zones are present in the Croixan succession of the type region, eight sedimentational cycles were discriminated in the course of this study, to which the unstudied portion of the lower Trempealeau (Arcadia-St. Lawrence-Lodi) might, on the basis of visual inspection, add several more. Thus, it is obvious that an equivalency between major faunal zones and sedimentary cycles cannot be expected (*see,* Fig. 2).

More specifically, the Eau Claire-Galesville cycle embraces the *Cedaria, Crepicephalus,* and *Aphelaspis* zones, although the Shawtown cycle probably also falls within the time-span of the *Cedaria* Zone. On the other hand, the *Saukia* Zone embraces three demonstrable cycles (Bad Axe, Jordan, and Sunset Point) plus those represented by the unstudied formations in the lower Trempealeau. Thus, while the breaks between the seven faunal zones are remarkably sharp, not only in this region but over the continent as a whole, not all of them, and possibly none of them, can be attributed primarily to sedimentary hiatus, although the two may coincide locally or regionally.

Cyclical boundaries in the Croixan region which do correspond with faunal boundaries are those between (1) the *Aphelaspis* and *Elvinia* faunas, (2) *Elvinia* and *Conaspis,* (3) *Conaspis* and *Ptychaspis-Prosaukia,* (4) *Ptychaspis-Prosaukia* and *Saukia,* and (5) *Saukia* and *Symphisurina.* Studies within the region or beyond it reveal that a portion of the faunal record may be absent in a position corresponding to the cyclical boundary. This is determinable on the basis of the minor, but equally discrete, species-zones which comprise the respective major or genera-zones. If the total known species-zones for the continent as a whole are considered, and each species-zone is given a value of 1, the magnitude of the faunal break at a hiatus at a particular locality may be expressed integrally in terms of the number of missing zones. This might be termed the *hiatal value* of the nonsequence.

If we consider the five faunal hiatuses mentioned above, the first or Eau Claire, Galesville-Ironton (i. e. *Aphelaspis-Elvinia*) hiatus proves to have the highest value. As yet, the intervening beds and faunal succession, as expressed in parts of New Mexico and Texas, have not been closely zoned, but a consideration of Palmer's 1960 paper on the sequence in New Mexico suggests a hiatal value of at least 5.

The faunal succession involving the *Elvinia* and *Conaspis* zones is very well known both locally and in other regions. On this basis it is possible to state that in a very small area of the type region (the area surrounding Wisconsin Dells in central Wisconsin), the succession is complete; in other words, the hiatal value is zero. Elsewhere, the hiatus increases in magnitude, and in some parts of the St. Croix Valley may be as high as 10.

Nevertheless, the mechanical-analysis characteristics at the break between the Ironton

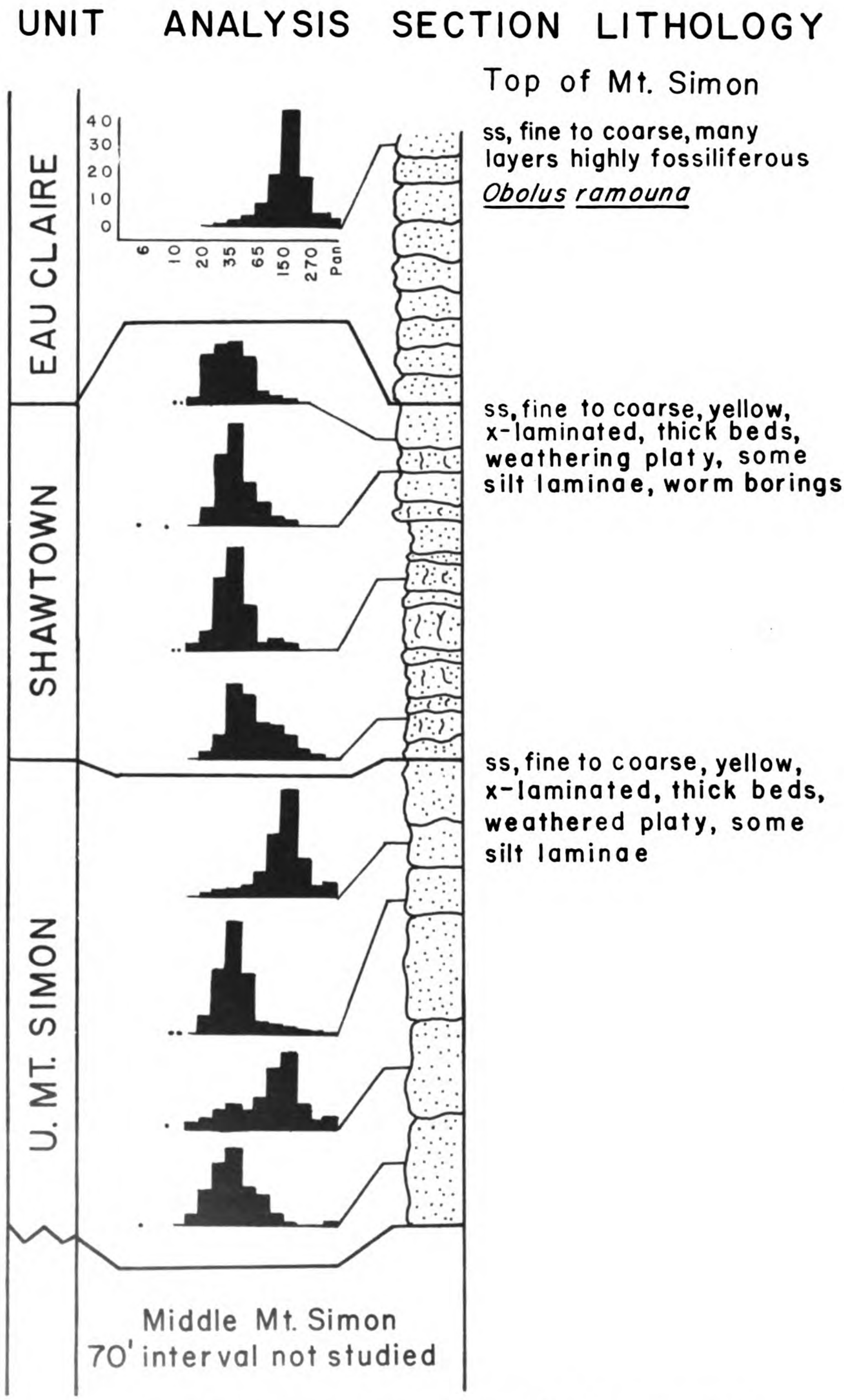

FIGURE 9.—Shawtown type section, Mt. Simon, Eau Claire, Wisconsin.

and Goodenough cycles are the same, regardless of whether the hiatal value be 0 or 10. A further anomaly—where the succession is complete, the highest fauna of the *Elvinia* Zone (*Irvingella major*) is physically not a part of the Ironton cycle, as one might logically expect, but of the Goodenough cycle. Thus, even where the succession is complete, faunal and physical boundaries do not coincide, although there is no transition, either faunally or physically. The same relationship seems to exist in other areas, notably Oklahoma and the Canadian Rocky Mountains, where the *Irvingella* beds, though faunally related to the underlying, are physically inseparable from the overlying strata.

The break between the Goodenough and Hudson cycles, and the corresponding break between the *Conaspis* and *Ptychaspis-Prosaukia* groups of faunas has, over most of the type region, a hiatal value of 3; but in the St. Croix Valley, the succession, on the basis of phyllogenetic studies, is complete, i. e. has a zero value. Here, on visual inspection, it seems probable that the boundary between the two sedimentary cycles also disappears, but this has not yet been documented by mechanical-analysis techniques.

The faunal assemblage which characterizes the Bad Axe cycle (the species-zone of *Saukiella minor*) appears to be extremely widespread, as it has recently been discovered in virtually identical assemblages in the Canadian Rockies. With respect to the underlying Hudson cycle, the hiatus in the type region seems to have a value of from 2 to 3 over most of the region. Where this decreases to zero, in the Baraboo Region, mechanical analyses have yet to be made.

The break between the Jordan and Sunset Point cycles, involving the sporadically occurring species-zones of *Saukia*, is difficult to evaluate. Where the terminal or Van Oser beds of the Jordan are fossiliferous, the Sunset Point is, unfortunately, absent. It is also not known whether the Van Oser and Sunset Point faunas are directly time successive. On mainly physical grounds, it may be estimated that the hiatal value of this nonsequence is nowhere higher than about 3, and may be zero in some areas, as along the Mississippi River south of La Crosse. The cyclical boundary is everywhere maintained.

Finally, with respect to the Sunset Point-Oneota (Hickory Ridge) boundary, an estimate of the hiatal value is facilitated by the discovery, in the Richardson Mountains of Yukon Territory, of a pre-*Symphysurina* fauna, characterized by a species-assemblage including *Pareuloma brachymetopa* Rasetti. Comparison with an underlying *Saukia* fauna in this section suggests that the *Saukia-Symphysurina* faunal break at the Cambrian-Ordovician boundary is not great, and might have a hiatal value of no more than 1. Where the Oneota strata, in the absence of the Sunset Point, locally rest directly on some portion of the Jordan Formation, this hiatal value would, of course, be correspondingly increased.

Thus, in summary, the nonsequence of greatest duration in the Croixan type succession would appear to be that between the Eau Claire-Galesville and Ironton cycles, whereas that between the Cambrian and the Ordovician (Sunset Point-Oneota) is considerably less. There seems to be no obvious relationship between the magnitude of the breaks and the physical characteristics of the basal beds of overlying cycles.

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Stratigraphic Sequences in the Pennsylvanian of Nebraska and Their Relationships to Cyclic Sedimentation

INTRODUCTION

This discussion is limited to the rocks of Late Pennsylvanian age in Nebraska. Older Pennsylvanian rocks do not outcrop in the state, although they are present at depth. Upper Pennsylvanian rocks outcrop in southeastern Nebraska (Fig. 1) and have been studied by many stratigraphers and paleontologists through the years.

Early Stratigraphic Studies in Nebraska

The earliest detailed studies were those of Condra and Bengtson in 1915 which recognized certain sequences and established a beginning in detailed correlation. Condra continued his interest in the Pennsylvanian of Nebraska and published a more detailed report in 1927 which included revisions in classification and many detailed measured sections. He continued his interest in Pennsylvanian stratigraphy throughout his life and published many additions and revisions with his co-workers and participated in joint studies with geologists of adjoining states through the years. He was most persistent in pursuing these studies and contributed more than any other person to establishing the geologic framework of Nebraska's Pennsylvanian and correlations with similar sequences in other states in the northern Midcontinent region. The task of studying Pennsylvanian rocks in Nebraska has been a difficult one because of the lack of exposure continuity and the presence of a thick Pleistocene mantle that obscures this sequence in many localities. The paleontologic studies of the fusulinids and brachiopods by Carl O. Dunbar (Dunbar and Condra, 1927; Condra and Dunbar, 1932) have been outstanding contributions to the correlation of Nebraska's Pennsylvanian rocks. In 1959, Condra and Reed published a revised classification of the geological section of Nebraska.

Graphic Representation of Stratigraphic Sequences

The stratigraphic sequence of the Upper Pennsylvanian in the outcrop area of Nebraska is shown graphically in Figures 2 and 3 and comprises about 810 feet of sediments. The general lithologic and paleontologic character of all formations and members is illustrated and the percentages of acid soluble material in each zone are shown, these being determined from lithologic collections made at the indicated locations. In addition, all limestones are classified according to their general characteristics as related to probable depositional environment.

CYCLOTHEMIC CLASSIFICATION OF MOORE

The cyclothemic and megacyclothemic classification of the Upper Pennsylvanian limestones as developed by R. C. Moore has been

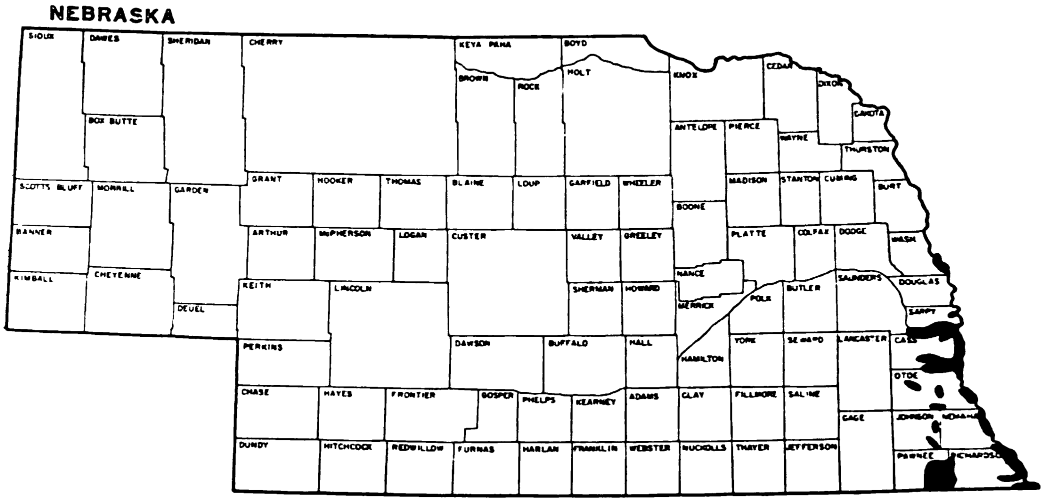


FIGURE 1.—Location map showing outcrops of Pennsylvanian rocks in Nebraska.

very helpful in understanding the environmental conditions during deposition of these sediments and has been a considerable aid in precise correlations, but it also leaves something to be desired in a complete understanding of all varying and variable conditions. Moore's classification also has resulted in some errors in correlation where all parts of a typical megacyclothem are not represented. Regional studies indicate that there is strong tendency to "lose" lower or upper parts of some megacyclothems in a few localities. Significant changes in upper beds of some megacyclothems reflect different conditions of deposition than are represented in other stratigraphic sequences.

The most persistent and reliable lithology in the Upper Pennsylvanian of the northern Midcontinent region is Moore's "middle limestone," a thin, comparatively pure limestone usually with a fusuline fauna overlain by a zone of black fissile shale carrying *Orbiculoidea* and *Lingula*. Overlying the black shale is Moore's "upper limestone" which tends to be comparatively thick and which includes fossils indicative of marine sediment deposited under initially disturbed conditions with progressive quieting and clearing of the sea. The sequence often ends with a lithology suggestive of quiet, shallow-sea conditions.

"Lower limestones" of Moore's typical Shawnee megacyclothems appear to be faunally and lithologically similar to his "upper limestone" except that they are not underlain by black fissile shale and "middle limestone" and typically are of intermediate thickness. Limestones classed as "super limestones" are variable in nature. Typically, they are thin to moderately thick and contain a molluscan fauna indicative of marginal marine to brackish conditions; but some of the "super limestones," at least in Nebraska, are more like thinner "upper limestones" with a good marine fauna. This description is true of the South Bend, Avoca, and Kereford Limestones. Other "super limestones" are oolitic or "*Osagea*"-bearing, suggestive of deposition in quiet, shallow seas. The Farley Limestone and the upper part of the South Bend Limestone, in the Lansing-Kansas City Groups, are examples of this lithology, and the Sheldon Limestone, in the middle part of the Topeka Formation, Shawnee Group, has a similar lithology.

There are strongly developed oolitic or "*Osagea*"-bearing zones at the top of many of the "upper limestones," although occasionally this oolitic rock is separated from the main mass of the "upper limestone" by shale thus becoming a "super limestone." Locally there may be oolitic developments at the tops of some "lower limestones" of the megacyclothems, further evidence that "lower" and "upper" limestones are similar except for thickness and absence of black fissile shales and thin limestones below the "lower lime-

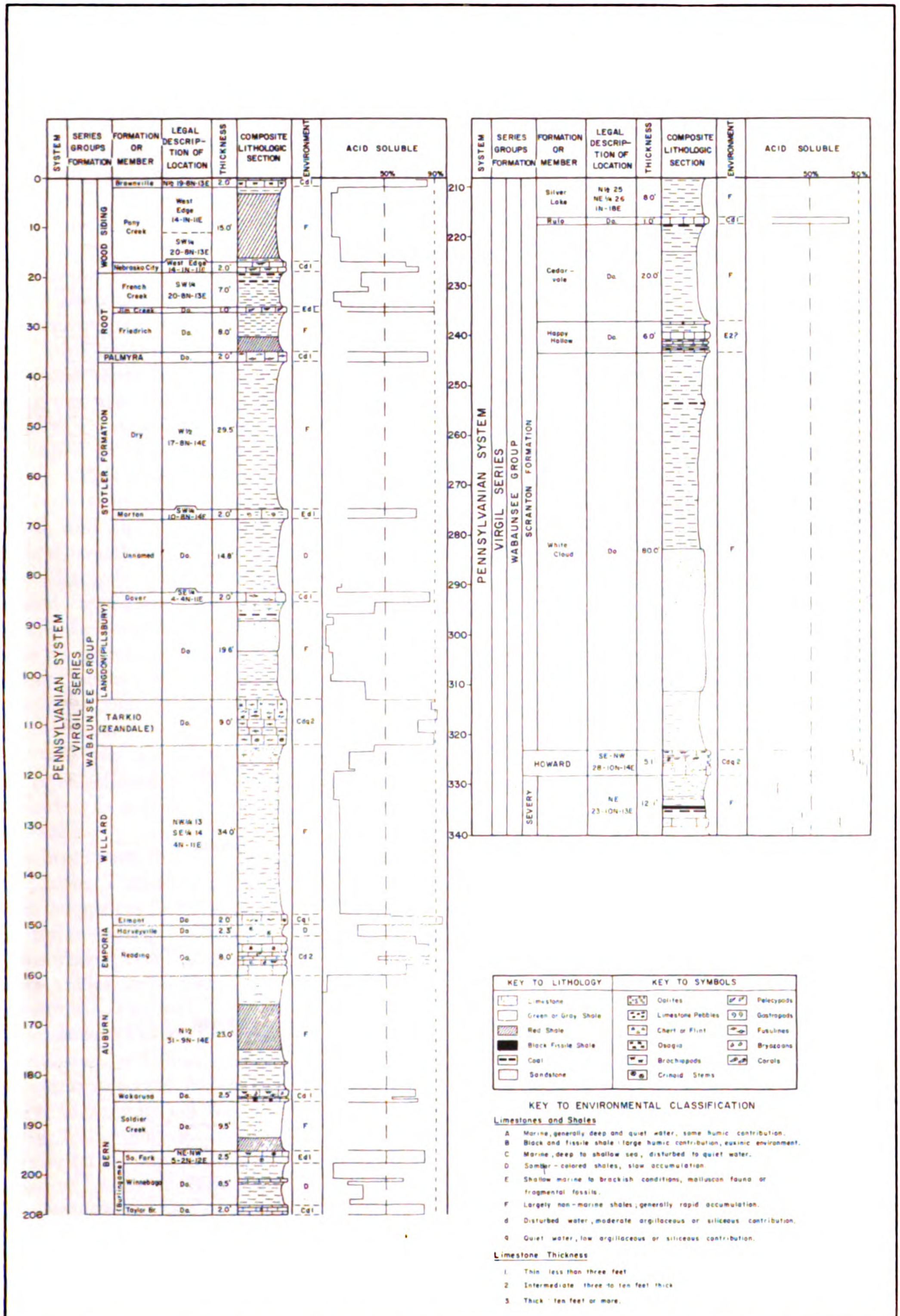
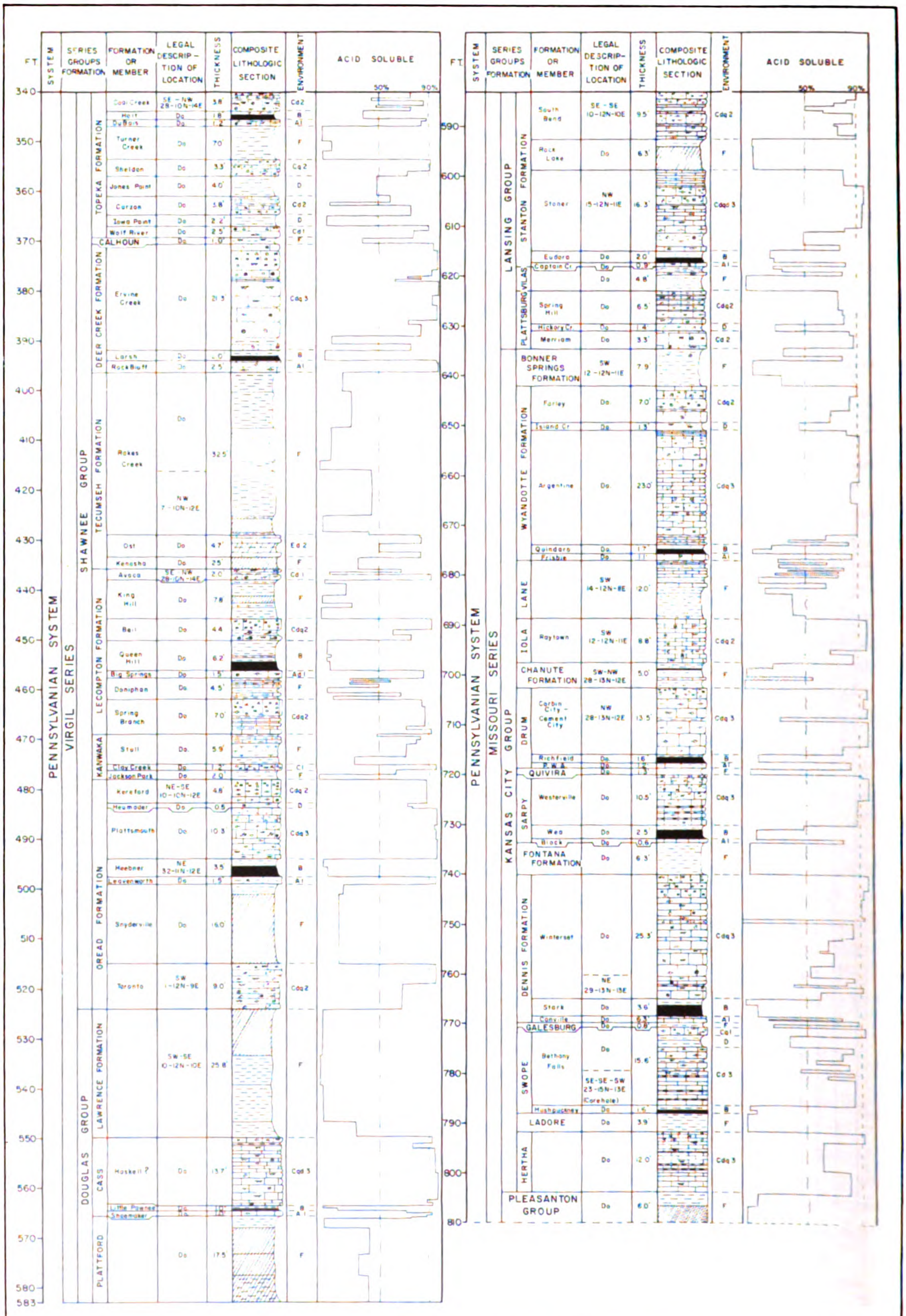


FIGURE 2.—Stratigraphic chart of Wabaunsee Group in Nebraska.


FT.
SYSTEM
SERIES GROUPS FORMATION
FORMATION OR MEMBER
LEGAL DESCRIPTION OF LOCATION
THICKNESS
COMPOSITE LITHOLOGIC SECTION
ENVIRONMENT
ACID SOLUBLE
50%
90%
PENNSYLVANIAN SYSTEM
VIRGIL SERIES
SHAWNEE GROUP
DOUGLAS GROUP
TOPEKA FORMATION
CALHOUN
DEER CREEK FORMATION
TECUMSEH FORMATION
LECOMPTON FORMATION
KANWAKA
OREAD FORMATION
LAWRENCE FORMATION
CASS
PLATTFORD
Coal Creek
Holt
DuBois
Turner Creek
Sheldon
Jones Point
Curzon
Iowa Point
Wolf River
Ervine Creek
Larsh
Rock Bluff
Rakes Creek
Ost
Kenosha
Avoca
King Hill
Beil
Queen Hill
Big Springs
Doniphan
Spring Branch
Stull
Clay Creek
Jackson Park
Kereford
Heumader
Plattsmouth
Heebner
Leavenworth
Snyderville
Toronto
Haskell ?
Little Pawnee
Shoemaker
MISSOURI SERIES
LANSING GROUP
KANSAS CITY GROUP
STANTON FORMATION
PLATTSBURG
VILAS
BONNER SPRINGS FORMATION
WYANDOTTE FORMATION
LANE
IOLA
CHANUTE FORMATION
DRUM
QUIVIRA
SARPY
FONTANA FORMATION
DENNIS FORMATION
GALESBURG
SWOPE
LADORE
HERTHA
PLEASANTON GROUP
South Bend
Rock Lake
Stoner
Eudora
Captain Cr.
Spring Hill
Hickory Cr.
Merriam
Farley
Island Cr.
Argentine
Quindaro
Frisbie
Raytown
Corbin City - Cement City
Richfield
Westerville
Wea
Block
Winterset
Stark
Canville
Bethany Falls
Hushpuckney

stones." These are some of the problems that arise in the use of megacyclothem classification.

In general, the Kansas City Group consists of repeated sequences of the "middle-upper" limestone succession of Moore's megacyclothems with absence of "lower" and "super" limestones. The Lansing Group, in its entirety, is more similar to the Shawnee megacyclothems.

The Douglas Group is typified by shales in its outcrop area in Nebraska with the persistent Cass Limestone, a "middle" and "upper" limestone separated by a black fissile shale, occurring near the middle part of the group. Locally, a lower limestone, the Nehawka, is developed in the lower part of the Douglas Group. This limestone, at its type locality, is relatively nonfossiliferous, appears to be brecciated, and has a thin-bedded appearance on vertical, weathered faces. In other areas the Nehawka is a coquina with, again, a thin-bedded appearance on weathered, vertical faces. In some places, the Nehawka Limestone is represented by a concretionary zone in the Plattford Shale. Local names for these two limestones in the Douglas Group have been preserved because their precise correlation with the Kansas section is in question, but it is believed that the Haskell Limestone of Kansas is a part of the Cass Limestone of Nebraska.

In large part, the Shawnee Group is typified by "lower"-"middle"-"upper"-"super" limestone sequences with some complications in the upper parts, as mentioned above. The Wabaunsee Group consists of major shales, sandy shales, or sandstones separated by thin limestones. The middle limestones, and black fissile shales of older Pennsylvanian sequences are missing, and limestones generally are thin and occur in pairs, at least in Nebraska. Generally, these pairs consist of marine limestone of thin to medium thickness below, and a thin, fragmental to impure limestone above. This sequence seems to be abbreviated "upper"-type limestones below separated from thin "super" limestones above. There is a tendency to "lose" the upper "super" limestones locally, and many of these "super" beds apparently are absent farther south in Kansas. These absences complicate correlation of these units. Typical pairs of this type are the Tarkio-false Maple Hill,* the Dover-Morton, the Palmyra-Jim Creek, and the Nebraska City-Greyhorse.

ENVIRONMENTAL CLASSIFICATION OF INTERVALS

Some of the limestone beds of megacyclothems differ from others mainly in thickness but not in features that suggest greatly different environments. Therefore, it is proposed to use subnumbers for these limestones indicative of thickness only. The subnumber 1 applies to all limestones 3 feet or less in thickness; subnumber 2 is applied to limestones more than 3 feet and less than 10 feet in thickness; and subnumber 3 is used to designate limestones with thicknesses of 10 feet or more. Thickness, in itself, is only a measure of time involved without radical changes in environment of deposition.

Capital letters A to F are applied to limestones, depending upon probable depositional environments irrespective of thickness, and significant thicknesses of shale, within the general limestone sequence, are also assigned capital letters based on probable depositional environments. In addition, subletters are applied to limestones depending upon the disturbed (d) or quiet (q) sea conditions during deposition.

PROBLEMS INVOLVED IN USE OF CYCLOTHEMIC CLASSIFICATION

An examination of all sequential relationships in the Upper Pennsylvanian of Nebraska indicates that the ideal megacyclothemic relationships, as typified by Moore's Shawnee megacyclothem, may be part of an interrupted and incomplete sequence at the base, overlain by a more complete, normal sequence. There seems to be considerable evidence that Moore's "lower" limestones are somewhat thinner equivalents to his "upper" limestones, and

* A thin fragmental limestone is present in some exposures and occurs just above the Tarkio. Condra erroneously correlated this limestone with the Maple Hill of Kansas.

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FIGURE 3.—Stratigraphic chart of Shawnee, Douglas, Lansing, and Kansas City Groups in Nebraska (*see*, Figure 2 for key to lithology and environment).

that the normal expectancy would be a sequence starting with the "middle" limestone followed by the "upper" and "super" limestones with possibility of losing parts of this sequence from either end. Therefore, we designate Moore's middle limestone as the "A" zone, the black fissile shale as the "B" zone, the "upper" limestone as the "C" zone, the upper somber-colored shale as the "D" zone, and the "super" limestone as the "E" zone, providing that it is truly a "super" limestone with a molluscan fauna or fragmental in nature. Nonmarine shales that are red in some localities, indicating more rapid accumulation, are designated as "F" zones. Some nonmarine shales are equivalent to sandy shale or sandstone zones at other localities and some include true coals in their sequences.

It would be helpful if we could apply consistently some designation to limestones indicating probable depth of sea, but this presents some real problems. It is generally agreed that fusulines and many brachiopods indicate comparatively deep water and that oolites are deposited in shallow, quiet seas; but there are some limestones in which these elements are commingled and about all that can be said with assurance is that the sea was quiet and generally free from significant contributions from land areas.

ACID INSOLUBLE RESIDUES AS AN AID IN STRATIGRAPHIC STUDIES

The use of insoluble residue studies in the Upper Pennsylvanian rocks of Nebraska has been helpful in many ways. These studies were started in the 1930's by A. C. Hornady of the Nebraska Geological Survey, continued by the senior author, and supplemented by recent work of the junior author. Complete data for all parts of the Wabaunsee Group are not now available because of poorly exposed sequences. A knowledge of the percents of acid insoluble material in the various zones contributes to more impersonal description of lithologies, and occasionally types of residues are helpful in correlating outcrops. However, residue studies carried out without determination of percentages of residue are of limited use because of the tendency for repetition of residue types.

CALCIUM CARBONATE PERCENTAGES AS A MEASURE OF GEOLOGIC TIME

An examination of residue percentages of many of the thicker limestones suggests that the amount of noncarbonate materials, both argillaceous and siliceous, probably derived from the erosion of land areas, progressively decreases upward. This fact suggests that the percent of carbonate may be some comparative measure of geologic time and it also suggests that Upper Pennsylvanian rocks might have been a complete limestone sequence had it not been for the periodic influx of siliceous and argillaceous impurities. An excellent example of this exists in the Weeping Water, Nebraska, area where the Plattsmouth-Kereford interval is approximately 24 feet of uninterrupted limestone, opposed to a normal limestone thickness of 15 feet. It is believed that the Weeping Water locality was protected from the normal influx of siliceous and argillaceous impurities, giving rise to continuous carbonate deposition and resulting in an overthickening of the Plattsmouth-Kereford limestone.

If we are to assume that percentages of residue are some measure of geologic time it would appear that the Lansing-Kansas City Groups represent 41 percent, Douglas Group about 5½ percent, Shawnee Group about 26 percent, and Wabaunsee Group about 27½ percent of Upper Pennsylvanian time. This, of course, would be assuming that deposition was essentially continuous.

IDEAL SEQUENTIAL RELATIONSHIPS

An ideal sequential relationship, represented by the A-B-C-D-E-F sequence of beds, may be interpreted as beginning with a sudden marine invasion under conditions of quiet seas and comparatively deep water. Inland swamps developed and expanded in the nearshore land areas as A bed was deposited. Headward erosion of valleys rather precipitously opened the swamps and caused draining of the swamps into the sea. Great contribution of humic material under conditions of poor circulation and sudden, quite complete cessation of carbonate deposition formed the B (black fissile shale) zones. This deposition was followed by progressive clearing of sea water as thicker C beds were formed, climaxed by quiet sea conditions with little or no contribution from the land surface and possibly with a shallowing of the sea, as evidenced by the deposition of oolitic limestone. Carbonate deposition of the C horizons was generally abruptly interrupted by the influx of argillaceous and siliceous impurities from the land, resulting in the deposition of the D shales under conditions of comparatively slow accumulation. This accumulation was followed by a progressive shallowing of the seas resulting in a more brackish environment with small to moderate contribution from the land areas as the E limestones were formed. These limestones were followed by progressively more rapid deposition of argillaceous and siliceous material under progressively more nonmarine conditions climaxed by the progressive reduction of nearshore land areas and culminated by development of swamps in which coals were formed. This sequence of events seems to be typical of much of Late Pennsylvanian time.

CRITICAL LEVEL CONDITIONS SUGGESTED BY SEQUENCES

Much of the Upper Pennsylvanian deposition, as evidenced in Nebraska, appears to have taken place at critical levels where small changes resulted in signficant differences in depositional environment. Also, the geologic column appears to represent a number of incomplete ideal sequences where certain conditions persisted locally or were interrupted sooner than in other localities. This results in "losing" parts of the ideal sequence from both the base and top of the sequence. There seems to have been a tendency to "lose" the upper parts of the ideal sequence during much of Lansing-Kansas City time and a strong tendency to lose the lower parts of the ideal sequences during Wabaunsee time.

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Tectonic Cycles of the North American Craton

ABSTRACT

The stratigraphic record on the North American craton from late Precambrian to present is divisible into six sequences which reflect changing patterns of tectonic behavior. Investigation of the distribution of lithologic associations in the successive sequences reveals no systematic repetition suggestive of cyclicity. However, interpretation of the sequences in tectonic terms permits recognition of two models. Four sequences are referable to an epeirogenic model comprising five tectonic stages. Two sequences are relegated to an orogenic model characterized by an apparent lack of order and system in the succession of tectonic events. No relationship is evident between tectonic events in adjoining mobile belts and the North American craton.

INTRODUCTION

This paper considers patterns of tectonic behavior of the North American craton from late Precambrian to the present. Discussion of this topic is impossible without reference to a nomenclature of tectonic elements and tectonic activity, and this nomenclature remains in a state of flux such that clarity demands definitions of the writer's terminology.

Figure 1 illustrates a portion of a model continent characterized by a mobile belt (eugeosyncline) at the left and a continental craton to the right. The craton is dominated by stable shelf areas bearing a thin veneer of sediments. Toward the continental interior, the shelf passes without significant break into broad areas of exposed basement crystallines, a typical shield. Elsewhere, the shelf is interrupted by gently positive (or slightly less negative) elements termed epeirogenic uplifts. These elements may bear exposures of basement rocks as do the Ozark Dome and Llano Uplift, or they may be characterized by slower rates of sedimentation and more frequent episodes of erosion without basement exposure in the manner of the Cincinnati and Sweetgrass Arches. Interspersed with epeirogenic uplifts are ovate areas, the interior basins, of dominant negative tectonic behavior.

These cratonic elements, shelves and shields, epeirogenic uplifts and interior basins, have individual histories of great longevity, extending over hundreds or multiples of hundreds of millions of years. In striking contrast are the cratonic orogenic uplifts and their complementary yoked basins. Cratonic orogeny is relatively rare and is characterized by a dominance of vertical uplift, commonly involving high-angle faulting; discordant and concordant plutonic activity is a common accompaniment of cratonic orogeny but is rarely important volumetrically. Extrusive activity ranges over a wide petrologic variety and may be an important factor in the fill of yoked basins or may be insignificant or lacking. Individual orogenic uplifts and yoked basins have relatively short periods of duration measured in tens of millions of years or less. The uplifts and adjoining basins are typically in the range of one hundred miles in length and may have their long dimensions oriented in apparent random fashion, *en echelon*, or in interrupted linear chains (such as the Laramie-Front Range-Sangre de Cristo) with as much

NOTE: Since the submittal of the above contribution in 1963 a significant and pertinent paper by H. E. Wheeler has been published ("Post-Sauk and pre-Absaroka Paleozoic stratigraphic patterns in North America," Am. Assoc. Petroleum Geologists Bull., v. 47, p. 1197-1526, 1963. See also discussion, *ibid.*, v. 48, p. 122-124, 1964).

It is Wheeler's thesis that the writer's Tippecanoe and Kaskaskia sequence should each be divided into two sequences. The additional sequence-bounding unconformities are recognized by Wheeler below Early Silurian and latest Devonian strata, respectively. These are the positions of Stage 3 of the epeirogenic sequence model noted above. It is the present writer's contention that Wheeler is confusing temporary stabilization of the craton and consequent local and trivial unconformity with the uplift and accompanying cratonwide erosion between sequences.

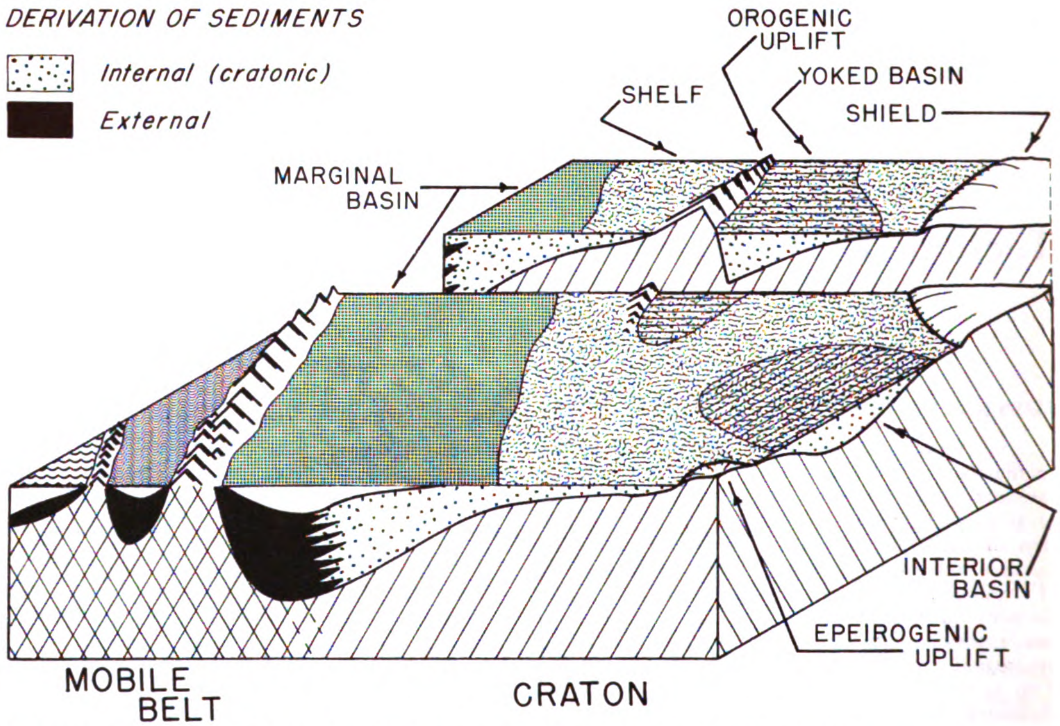

FIGURE 1.—Portion of model continent showing relationships of depositional sites to tectonic framework (Sloss, 1962).

as five hundred miles of continuity of direction.

Topographically similar but genetically remote from cratonic uplifts are the orogenic elements of the extracratonic mobile belt. Here the emphasis is on compression and regional metamorphism; granite emplacement, both magmatic and metasomatic reaches enormous volumes. Mobile belt trends are long in comparison to cratonic uplifts, extending over thousands and multiples of thousands of miles. Although tectonic activity in mobile belts is virtually continuous, it is subject to intense episodes of regional metamorphism, emplacement of granitoid masses, and pronounced vertical uplift. Where uplift produces large volumes of rock above base level, mobile-belt troughs and adjoining areas are the sites of accumulation of very large volumes of immature sediments and volcanics.

Between the mobile belt and the craton lies a transition zone commonly called the miogeosyncline. The writer avoids this term and its connotations for a number of reasons. During much of the history of such zones they are the depositional sites of sediments indistinguishable from those of cratonic interior basins. The rates of subsidence are of the same order of magnitude and their tectonic behavior during sediment accumulation is typically cratonic in habit. Further, during times of relative quiescence in the adjoining mobile belt, much of the sedimentary clastic fill of the so-called miogeosyncline is of interior derivation, that is, it is derived from erosion on, and transportation across, the craton. The term miogeosyncline carries with it an implication that it is half of a couple which, with the eugeosyncline, constitutes the orthogeosyncline. This concept evokes a picture of a continous miogeosynclinal trend everywhere parallel to the eugeosyncline and linked closely to it. In actuality, the subsiding portions of this trend form noncontinuous chains of basins more closely related to, and more difficult to distinguish from, elements of the craton than to the strikingly different tectonic habit of the eugeosyncline. For example, the Arkoma, Ardmore, and Anadarko Basins were a single tectonic province in Ordovician time.

The basin in question extended from southeastern Colorado, surrounded by hundreds of miles of cratonic shelf, to southeastern Oklahoma, where it approached the mobile belt of the Ouachita trend and where it would be considered part of the miogeosyncline. If the concept of the miogeosyncline is adhered to, the Permian of West Texas-New Mexico and the Mississippian of Montana offer similar terminologic problems. Reference to subsiding elements in the transition zone between mobile belts and continental cratons as marginal basins avoids these philosophical questions.

The Allegheny and Warrior Basins of the Appalachian trend are examples of relatively narrow marginal basins with histories strongly affected by behavior of the adjoining mobile belt. Each significant pulse of orogenic activity in the mobile belt is marked by the spread of clastic wedges of externally derived material across much of the width of the marginal basin. In such narrow basins, diastrophic activity of the mobile belt is commonly exerted laterally as far as the basin axis to form parallel folds and thrust faults affecting the sedimentary fill. In Nevada and Utah the Oquirrh Basin, which existed from late Precambrian to mid-Jurassic, is an example of a marginal basin of mainly cratonic habit tectonically unaffected by orogenic events of the Cordilleran trend and almost free from adulteration by externally derived sediment. For hundreds of millions of years this basin behaved as a cratonic element. Ultimately, in Late Jurassic time, it was overwhelmed by externally derived clastic wedges and by mid-Cretaceous time became involved in diastrophism related to the spreading mobile belt. Much of the Gulf Coast Basin, from Late Jurassic to present, provides an example of a marginal basin completely unaffected by mobile-belt tectonics, either as a sediment source or by compressional diastrophism.

This brief discourse of the writer's views on continental tectonics has a dual purpose. First, it attempts to provide a terminology of tectonic elements with which it is possible to consider the periodicity of tectonic behavior and resulting sedimentary patterns on the craton. Secondly and more importantly, the point is made that although orogenesis and resulting sediment supply may occur in mobile belts and on cratons, there is a fundamental distinction in tectonic habit, and no necessary relationship exists in time or space between these two very different patterns of diastrophic activity. In many other respects cratons are independent of mobile belts; however, investigation of the craton is not complete without consideration of the marginal basins. Here, the interplay of cratonic and extracratonic influences is manifested and requires analysis.

STRATIGRAPHIC SEQUENCES

The writer (1963) has recently reiterated the thesis that the stratigraphic record of the North American craton (late Precambrian to the present) is punctuated by six interregional, cratonwide unconformities. The unconformities are recognizable surfaces which subdivide the cratonic stratigraphic column into six vertically successive groupings of rocks, each identified by a geographic term in the manner of other lithostratigraphic units. These units are defined and described in the aforementioned paper, and their time-stratigraphic limits are indicated in Figure 2. The illustration is a time-length diagram. That is, the horizontal dimension is a length (roughly extending from the axis of the Cordilleran marginal basin at the left to the axis of the Appalachian marginal basin at the right), while the vertical dimension is geologic time. Applying the terminology of Wheeler (1958), the white and stippled areas of the diagram are depositional holosomes representing the distribution in time and space of sedimentary accumulation. The black portions of the figure are hiatal holosomes representing the distribution patterns of nondeposition. Transgressions of depositional regimes over the interior of the craton are marked by projections of the white or stippled areas toward the middle of the diagram, while regressions leading to nondeposition, commonly accompanied by erosion, are shown by black tongues projecting toward the borders of the diagram.

Thus, the diagram (Fig. 2) charts the approximate shifting of base-level position on the North American craton during the past six hundred million years or so of geologic

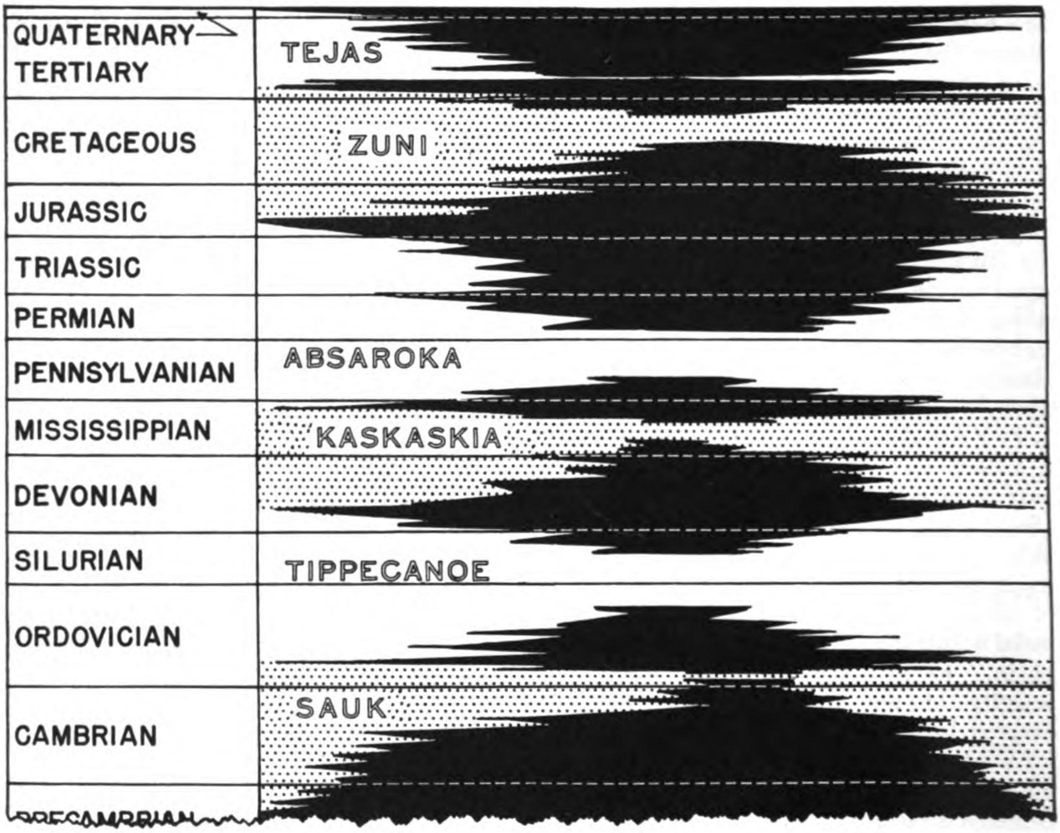

FIGURE 2.—Time-stratigraphic relationships of sequences in North American craton. Black areas represent nondepositional hiatuses; white and stippled areas represent deposition. (Sloss, 1963).

time. It can be seen that the marginal basins tended to remain below base level and were the sites of accumulation of sediment for the greater part of this time span. The interior of the craton shows a centripetal tendency toward persistence above base level, remaining for long periods in a nondepositional regime, and the least negative areas are only occasionally the loci of sedimentary accumulation.

The record as interpreted on the time-length diagram is not, of course, preserved in anything like this form. Each of the nondepositional episodes was accompanied by extensive erosion introducing a severe loss to the preserved record, thus requiring a very considerable degree of interpretation and reconstruction. Therefore, readers may well find grounds to dispute a number of the details of the writer's reconstruction. However, the gross form of cratonic history from the late Precambrian is clear. The times of maximum transgression of the cratonic interior are approximately those indicated and the episodes of maximum regression, nondeposition, and erosion cannot depart widely from the pattern as presented. In other words, let us not here argue the validity of the sequence concept, but, rather, proceed to a consideration of the alternation between depositional and nondepositional episodes of the craton and the significance of these events. Are the successive episodes repetitions of the same behavior? If differences exist, is there a systematic pattern of recurrence? What relationship, if any, appears to exist between cratonic events and those occurring in neighboring mobile belts?

SEDIMENTARY PETROLOGY AND GEOMETRY OF SEQUENCES

Each of the six stratigraphic sequences may be analyzed in terms of the major sedimentary associations by which they are characterized. Such an analysis is shown on Figure 3; by varying the size of the black circles, the relative prominence of a number of sedimentary associations are shown as they appear in each sequence. The sedimentary associations are those defined by Krumbein and Sloss (1963), and the majority of the terms used are self-explanatory. However, a few words will aid the reader over less familiar parts of the terminology employed.

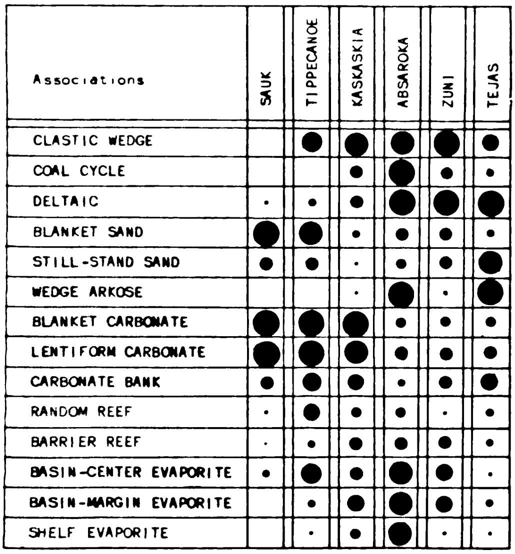

FIGURE 3.—Distribution of lithologic associations. Size of circles indicates relative prominence of associations in each sequence.

The term clastic-wedge association, following the usage of Pettijohn (1957) and King (1959), is applied to wedge-shaped accumulations of sediment derived from extracratonic mobile belts. The Queenston "delta" and Alpine molasse are familiar examples. Coal-cycle associations are those characterized by a repetitive complex of depositional types and environments involving both marine and nonmarine deposition. Coal-cycle associations are dominated by sediment of cratonic interior derivation and are difficult to recognize among older sediments, if lacking land plants to clearly identify them as nonmarine members of the association. The deltaic association includes masses of cratonic interior derivation which, in contrast to clastic wedges, thicken in the direction of sediment transport and direction of reduction of average particle size. The still-stand sand association has much the same geometry but is characterized by mature sandstones representing reworking along strand lines, while the deltaic association preserves the record of the complex of environments observed on many modern delta systems.

Among carbonate-evaporite associations only the lentiform carbonates require explanation. These, the carbonate fills of subsiding basins, conform to the geometry of the basins which they occupy, and thus form lens-shaped masses of broad regional extent.

Returning to Figure 3, the available data on the several successive sequences, when organized in this fashion, do not reveal an order or a system to suggest a cyclical or repetitive pattern. The earlier three sequences, for example, have much in common but differ in important details. All are dominated by blanket, lentiform, and carbonate bank associations, but reef and evaporite associations are important only in the Tippecanoe and Kaskaskia. Blanket sands of high maturity are characteristic of the Sauk and Tippecanoe but occupy little of the total volume of the Kaskaskia. Clastic wedges are virtually absent from the Sauk assemblages but are important in the marginal basin accumulations of the Tippecanoe and Kaskaskia. The three later sequences are dominated by clastic sediments, including clastic wedges in the Absaroka and Zuni and an abundance of wedge-arkose associations in the Absaroka and Tejas. Thus, although the observed sedimentary associations of the several sequences serve to illustrate their similarities and differences, there is no readily detectable orderly succession in the occurrence of major associations. If a systematic pattern exists, it is not made evident by this analytic approach to the cratonic record of the past 600-odd million years.

TECTONIC INTERPRETATION OF THE SEQUENCES

Inasmuch as simple observation of the geometric form and petrology of the several sequences fails to reveal a systematic pattern or trend, it is worth considering interpretations of these observations in terms of shifts in tectonic habit through the span of geologic time represented. The horizontal dimension of Figure 4 is geologic time before-the-present with the period boundaries suggested by Kulp (1961) from radiometric dating. The approximate positions in time of the sequence boundaries are indicated. Four types of tectonic interpretation are illustrated, three referring to cratonic behavior and a fourth which shows the influence of mobile-belt tectonics on cratonic patterns.

The Craton and Baselevel

The lower plot of Figure 4 attempts to chart the movement of a point in the cratonic interior (such as central Iowa, for example) with respect to the equilibrium surface of base level. Where the curve rises above base level, the time spans involved were occupied by nondeposition and erosion; departure of the line below base level indicates times of subsidence and sedimentary accumulation. Tectonic stability is indicated where the line approaches horizontality, and conversely, instability and high rates of change are represented by steepening of the plot.

The Sauk sequence presents a simple pattern. It is assumed that the late Precambrian subsidence of the marginal basins in the Cordilleran and Appalachian regions was accompanied by parallel, though markedly less extreme, subsidence of the continental interior. The continuity of supply of coarse clastic detritus from the cratonic interior indicates that this subsidence did not approach base level, and the relatively slow transgression of the seas in Early and Middle Cambrian time over the cratonic margins suggests an approach to tectonic stability at supra-base level positions in the interior. The rapid advance of Late Cambrian sedimentation over the cratonic interior is clear evidence of renewed subsidence extending below base level and climaxing in very widespread seaways in the Early Ordovician. Relatively abrupt uplift above base level is marked by the sub-Tippecanoe unconformity, but the comparatively low volume of Sauk sediments removed indicates that pre-Tippecanoe uplift was not extreme.

In general form, then, the broad pattern of cratonic-interior behavior during Sauk deposition may be characterized by the following stages:

(1) Slow subsidence of tectonically undifferentiated craton, starting with supra-base level elevation of entire craton and marginal basins, proceeding to submergence of marginal basins and adjacent cratonic border below base level.

(2) Acceleration of cratonic subsidence marked by expansion of sub-base level areas toward interior of craton.

(3) A check in the rate of subsidence during the middle part of the time span of the sequence with an approach to near tectonic stability.

(4) Renewed rapid subsidence with maximal submergence (at any point and in terms of area involved) of craton below base level.

(5) Rapid supra-base level emergence of entire craton, extending to marginal basins, terminating cratonic deposition and creating conditions for widespread nondeposition and erosion in advance of the next cycle.

Three other sequences, Tippecanoe, Kaskaskia, and Zuni, reproduce these five stages with minor variations imposed by mean elevation of the cratonic interior with respect to base level. The Zuni sequence, because of the relatively high mean elevation of the craton, comes closest to mirroring the behavior of the Sauk. The introduction of stage 1 is made manifest by the geographic scope of the sub-Zuni unconformity, the limited extent of early Zuni (early Middle Jurassic) deposition, and the general stability indicated by overstepping sediments such as Carmel and Entrada. Stage 2 is represented by the spread of later Middle Jurassic and Upper Jurassic deposition from marginal basins in the Gulf and Cordilleran areas toward the cratonic interior. Stage 3 is evidenced by latest Jurassic and Early Cretaceous blanket deposits of wide extent and low rates of change in thickness and facies. Stage 4 is introduced by a marked renewal of submergence and transgression in early Upper Cretaceous time, while stage 5 is identified in the latest Cretaceous—Early Paleocene marine withdrawal, leading to development of the sub-Tejas unconformity.

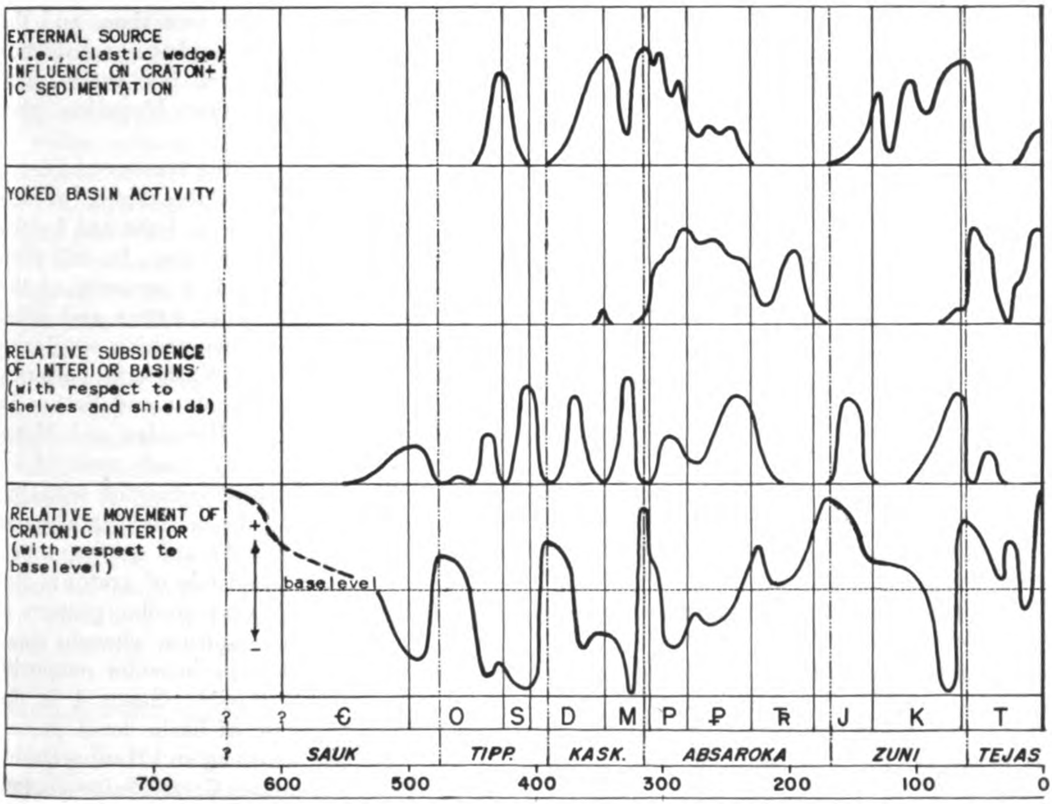

FIGURE 4.—Tectonic activity of adjoining mobile belts (upper plot) as indicated by spread of clastic wedges to cratonic margins, and tectonic activity of interior of craton (lower three plots) in terms of yoked basins, interior basins, and relative position with respect to base level.

Parallel behavior during deposition of Tippecanoe and Kaskaskia sediments is less obvious because the cratonic interior tended to reach sub-base level positions earlier and remain there longer than during Sauk and Zuni accumulation. Nevertheless, broadly similar relative movements can be discerned. Stage 1 is obvious in both Tippecanoe and Kaskaskia episodes. Stage 2 is represented by the transgression of Chazy and Trenton sediments of the Tippecanoe and by parallel onlap of Middle and Upper Devonian Kaskaskia strata. Stage 3, the stable phase, is characterized by the sheetlike geometry of deposits of latest Ordovician-Early Silurian (Tippecanoe) and latest Devonian-Early Mississippian (Kaskaskia) age. There is evidence of minor uplift above base level during this stage in both sequences. It is possible that such positive movement is typical of the stage but, it is difficult to identify in the less complete Sauk and Zuni records. Stage 4, the climax of cratonic subsidence, is indicated by the wide distribution of Middle and Upper Silurian sediments without evidence of littoral deposition except under the influence of mobile-belt sources, and in the Kaskaskia, by the extraordinarily wide distribution of mid-Mississippian carbonates. Again, the evidence for emergence in Stage 5 is undeniable.

The interpretation of the record of the Absaroka sequence stands in decided contrast to those described above. Although much of the Absaroka sequence has been removed or deeply eroded by the severity of pre-Zuni erosion, it seems clear that no simple five stage phenomenon is indicated. Rather, if consideration is directed toward those areas not affected by cratonic orogeny, and thus comparable to the tectonic states of the previously described sequences, it seems clear that the most significant negative movement of the cratonic interior was climaxed very early in the history of the sequence before the close of Pennsylvanian time and in the first one-fourth of the time span of the sequence. For over one hundred million years thereafter the record indicates innumerable minor positive and negative fluctuations whose algebraic sum is a persistent positive trend leading to slow regression. If the sequence were to follow the pattern of the Sauk, Tippecanoe, Kaskaskia, and Zuni, the maximum subsidence and transgression of the cratonic interior should be within the Triassic Period. Although preservation of the Triassic System is limited, the areas of preservation demonstrate a lesser degree of subsidence and transgression than in the Pennsylvanian and Permian.

The record of the Tejas sequence may be clear when it can be seen in the proper time perspective. So far as behavior of the cratonic interior can be interpreted, the pattern seems to be much like that of the Absaroka and distinct from the pattern of the other sequences. Again, there is evidence of early subsidence leading to long-continued emergence with numerous minor oscillations and at least one major positive episode in the Miocene.

Differentiation of the Cratonic Interior

The continental craton reveals a history of episodes during which it and its margins behaved as a single rigid block without significant difference in behavior between shelf areas and areas of previous or later basinal tendency. Such episodes are marked by the sequence-bounding unconformities which extend as unbroken surfaces across the axes of earlier basins. Additional episodes of widespread stability are indicated by sedimentary units which exhibit uniform low rates of thickness and facies change in apparent disregard of previously established tectonic patterns. In contrast to these times of craton-wide stability there are other episodes with records which clearly indicate a marked tectonic differentiation of the craton into epeirogenic uplifts, shelves, and interior basins. The most obvious criteria are the increased thicknesses deposited per unit time, and the marked facies response to basin subsidence (basin-center evaporites, euxinic shales, barrier-reef trends and other hingeline phenomena).

The second plot from the bottom of Figure 4 is an interpretation of the degree of differentiation of the craton as indicated by the development of interior basins. In this plot, the height of the curve is a measure of the degree of differentiation of basins and adjacent shelf areas. Note the striking similarity of the Tippecanoe and Kaskaskia patterns. Each has two peaks, Trenton and Salina in the Tippecanoe, Middle Devonian and Meramecian in the Kaskaskia. Each peak of interior basin development coincides with the time of subsidence of the cratonic interior as a whole (stages 2 and 4) and are separated by the mid-sequence episode of cratonic stability (stage 3). A very similar pattern is apparent in the Zuni sequence wherein stage 2 is the time of major basin-center evaporite deposition of the Jurassic. Stage 4 is the Late Cretaceous phase of basin development, as in the Denver-Julesburg and Hanna Basins of the Rocky Mountains-Great Plains region.

The possible affinity of the Sauk sequence with this pattern of cratonic differentiation is less clear. The lack of significant cratonic-interior Sauk record for anything except the Late Cambrian and Early Ordovician precludes observational data of stage 2, which might be expected to occupy a position in time immediately preceeding the beginning of the Cambrian Period. Great thicknesses of youngest Precambrian sediments in the marginal basin areas of Nevada, British Columbia, and Tennessee strongly suggest rapid subsidence and differentiation representing a marginal basin counterpart of stage 2 interior basin development. However, if there were a concurrent development of basins within the cratonic interior, there is no decipherable record within middle North America. Nevertheless, the writer feels that the numerous points of similarity between the Sauk and the other five sequences demands placement of the Sauk in the same tectonic frame.

Cratonic Orogenic Activity

Orogenesis in the cratonic interior is best evidenced by the sedimentary fill of the complementary yoked basins. Here, accumulation of wedge arkoses clearly identifies the time and position of mountainous blocks developed along high-angle fault systems. The second plot from the top of Figure 4 indicates relative prominence of yoked basins and wedge-arkose associations on the North American craton. The concentration of this unique type of tectonic activity during the spans of the Absaroka and Tejas sequences is noteworthy and serves further to intensify the unique character of these two sequences. Fault block mountains have appeared at other times, as in the latest Devonian of Utah and eastern Montana and the Late Cretaceous of Colorado, but these and similar events are orders of magnitude removed from the extent, duration, and influence of Absaroka and Tejas cratonic orogenesis.

Extracratonic Orogeny

Many North American geologists tend to agree that diastrophism within mobile belts approaches a steady state with shifts in the foci of activity along the axes of the mobile trends. Even though mobile-belt activity may be relatively continuous, the influence on cratonic sedimentation tends to be discontinuous and episodic. The upper plot of Figure 4 shows the timing and degree of cratonic sedimentation which can be shown to represent extensions of clastic wedges spreading from mobile belts across marginal basins. No clastic wedges are recognizable among the sediments assigned to the Sauk sequence. The Queenston wedge of Late Ordovician and Early Silurian age is the first invasion of extracratonic detritus onto the North American craton during the time considered here. Although absent in latest Silurian and Early Devonian, clastic wedges from the four mobile belts surrounding the North American craton are shown as major adulterants of normal cratonic sedimentation from mid-Devonian through Permian. Most of the Triassic and Early Jurassic was relatively free of external-source sediment, but later a renewed clastic-wedge development reached the craton by Late Jurassic time and continued at least until the Eocene in the Cordilleran area.

The timing of major clastic wedges and the maxima of mobile-belt activity which they represent appear to have no correlation with other tectonic events of the Sauk, Tippecanoe, Kaskaskia, and Zuni sequences. Rather, externally derived sediment in these sequences appears as an addition or intrusion into quite unrelated circumstances. Thus, the development of the Queenston wedge coincides with parts of stages 2, 3, and 4 of the Tippecanoe sequence; the Catskill wedge overlaps stages 1, 2, and 3 of the Kaskaskia sequence; and the Blairmore-Frontier-Mesaverde wedges span most of the time of the Zuni sequence.

A vague relationship is seen between mobile belt and cratonic orogenic episodes. In each case, cratonic orogenesis is initiated some hundred million years after the extension of clastic wedges to the cratonic border. However, even in geologic terms a hundred million years is very long for the maintenance of a control and response relationship. Furthermore, the discrepancy in the timing of the maxima and minima of activity is such as to suggest to the writer that no genuine interrelationship exists except, possibly, that the 450 million years which include times of both extracratonic and cratonic orogenesis may represent a phase of a very much longer cycle of tectonic activity in the crust and mantle.

Sequence Models

In tectonic interpretations of the sequences, two distinct tectonic habits are identifiable and may be referred to an epeirogenic model and an orogenic model.

The Epeirogenic Model

The five tectonic stages identified earlier in this paper, in terms of the responses observed in the Sauk sequence, can now be slightly recast as a more general statement of the epeirogenic sequence model as presented in Table 1. The model is best exemplified by the Tippecanoe and Kaskaskia sequences, is recognizable in the Zuni sequence, and by reconstruction of the hiatal record, admits reference of the Sauk sequence. The tectonic elements of the epeirogenic model are typically long-

TABLE 1.—Stages in the cycle of the epeirogenic sequence model.

Stage	Tectonic state	Stratigraphic response	Examples			
			Sauk	Tippecanoe	Kaskaskia	Zuni
1	Slight tectonic differentiation of craton; slow subsidence from supra-base level condition at close of preceding cycle.	Widespread nondeposition and erosion of cratonic interior; blanket sands and carbonates in marginal basins, onlapping to adjacent shelves.	Tapeats Brigham	St. Peter Eureka	Dutch Creek Oriskany	Entrada Sawtooth
2	Accelerated subsidence of entire craton; differentiation of interior basins and positives.	Broad transgression of cratonic interior; lentiform carbonates, basinal evaporites and euxinic shales.	Meagher (?) Gros Ventre (?)	Lower Red River Viola	Elk Point Detroit River	Arapien Sundance
3	Return to stability and lesser differentiation; brief elevation of more positive elements above base level.	Blanket sands, shales, carbonates; minor nondeposition and erosion.	Reagan Mt. Simon	Maquoketa Sylvan	Chattanooga Woodford	Morrison Norphlet
4	Renewed subsidence with extreme development and differentiation of interior basins.	Maximum transgression of craton; maximum facies differentiation of basins with emphasis on restricted deposits, including basin-center evaporites.	Arbuckle Ellenburger	Salina	Charles Salem	Bearpaw Lewis
5	Return to undifferentiated craton; elevation, eventually bringing axes of marginal basins to supra-base level positions at close of cycle; reinitiation of nondeposition and erosion.	Regression and offlap; blanket clastics where preserved.	Swan Peak Roubidoux		Big Snowy Elvira	Hell Creek Animas

lived features prominent in the framework of earlier and younger sequences. Externally derived clastic wedges may intrude upon the normal cratonic sedimentary succession, but the external sediment is deposited under tectonic states dictated by a cratonic pattern and there is a lack of evidence to suggest external control of cratonic tectonic behavior.

The epeirogenic model exhibits a reasonably well defined cyclical pattern of tectonic states and stratigraphic responses. Invasions of extracratonic sediment, variations in physical environment, and the nature and abundance of sediment-contributing organisms introduce a number of significant modulations of the observable stratigraphic response. Yet, the five-fold tectonic cycle remains apparent where the preserved record is adequately complete.

The Orogenic Model

The orogenic sequence model, exemplified by the Absaroka and Tejas sequences, does not conform to any discernable cycle of tectonic events and responses. In tectonic terms, the characteristic feature is the abrupt appearance of orogenic positive elements and complementary yoked basins; some are accelerations or exaggerations of the tectonic habits of pre-existing elements and some are new elements unheralded by earlier patterns of behavior. From time to time during the span of the orogenic model, there is, at least locally, a cessation of violent uplift and downwarp, and the yoked basins take on the tectonic habit and sedimentary responses of normal interior basins. However, there is no evidence of cratonwide synchronism and no suggestion of conformance with the epeirogenic model during times of reduced orogenic activity. Therefore, no orderly systematic pattern of tectonic events and stratigraphic responses is apparent. Perhaps, if there were available for study more than a single complete orogenic sequence and part of a second, a more systematic picture could be developed.

SUMMARY AND CONCLUSIONS

The writer concludes that the history of the North American craton for the past 600-700 million years includes six major episodes of changing tectonic behavior. Of these, two are referable to an orogenic model and exhibit no detectable systematic or cyclical pattern; four episodes, here related to an epeirogenic model, appear to reflect a five-phase cycle of successive tectonic stages.

The cyclical nature of the North American sequences has been recognized for some years (*see*, Sloss, 1950, p. 450). Other contemporary approaches to the definition of cratonic tectonic cycles of the same order of magnitude have developed out of efforts toward improved tectonic maps of major continental areas. The tectonic maps of Mexico (de Cserna, 1961, reviewed by King, 1962) and the U. S. S. R. (explanatory notes by Shatzki and Bogdanoff, 1957) are examples. A similar approach has been adopted in current projects leading to tectonic maps of Canada (Neale, Beland, Potter, and Poole, 1961) and of Europe (Bogdanoff, 1962). The most complete presentation of the European and Soviet point of view is given by Bogdanoff (1962), and a number of contrasts with the writer's thesis can be noted.

Bogdanoff recognizes a hierarchy of tectonic units which may be summarized as follows:

First order units: *Megacomplexes.* Cratonic crystalline basement is considered as one megacomplex; all sediments above, the "cratonic cover," form another.

Second-order units: *Fold complexes.* These are major tectonic subdivisions in time and space, each characterized by definable areas of occurrence, by typical orientation of fold and fault systems, and by a particular structural habit or style. Examples are Caledonian and Variscan complexes; the same terms are applied to both ancient mobile belts and cratons.

Third-order units: *Structural stages.* The stages are described as components of fold complexes, encompassing the rocks of a single geologic system or parts of two systems. Typically, three stages (phases of a tectonic cycle) are recognized within each fold complex in mobile belts and their structurally related margins. Difficulties appear to be encountered in identification of fold-belt stages on cratons.

The writer's sequences are most closely related to Bogdanoff's second-order units, the fold complexes. It is implicit however, in the latter taxonomy that cratonic history is controlled by events in the adjacent mobile belts; there appears to be little confirmation of this thesis in an investigation of the North American craton.

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Rhythmic-bedded Eugeosynclinal Deposits of the Tyee Formation, Oregon Coast Range[1]

ABSTRACT

The middle Eocene Tyee Formation, a thick repetitious sequence of rhythmic-bedded units of graded sandstone and siltstone, has a wide areal distribution in the southern and central parts of the Coast Range of Oregon. The formation consists principally of arkosic, lithic and feldspathic wacke with lesser amounts of volcanic wacke. Petrographic studies and new chemical analyses indicate that the sandstone is rather uniform in composition throughout the outcrop area. X-ray diffraction studies of the silt and clay, which constitute about 30 percent of the wackes, show that montmorillonite and mixed-layer montmorillonite predominate.

The soles of individual graded units are sharply defined and usually contain the casts of sedimentary structures. Groove casts and flute casts are the most common types. Analysis of more than 500 directional readings made on these sedimentary structures indicates that the detritus that comprises the Tyee Formation was transported northward in an early Tertiary geosyncline. The source area for the Tyee sediments is believed to be a metamorphic, igneous, and sedimentary terrane in the area of the ancestral Klamath Mountains that lay south of the geosyncline. Active andesitic volcanism immediately east of the geosyncline also contributed pyroclastic and epiclastic debris to the streams that drained into the basin of deposition.

It is speculated that streams draining these two principal source areas constructed large deltas where they reached the coast along the southern part of the geosyncline. Periodic slumping at steep delta fronts moved large masses of water-saturated deltaic material basinward. These mass movements are believed to have been transformed into turbidity currents that transported the debris northward along the axial parts of the trough for a distance of more than 150 miles. These turbidity currents would have been deflected around volcanic highs that existed in places near the axis of the trough.

Near the close of middle Eocene time the geosyncline was nearly filled with turbidity current deposits to a thickness of approximately 10,000 feet along the axis of the trough. The Klamath source area was eroded to a region of moderate relief and furnished only minor amounts of clastic debris to the marine environment. Silt and clay became the dominant lithology deposited in the geosyncline.

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INTRODUCTION

The middle Eocene Tyee Formation of the Oregon Coast Range consists of many hundreds of thick rhythmic-bedded units (Fig. 1) in which the sole markings show a preferred orientation. This repetitious sequence of graded sandstone and siltstone is interpreted as sediments laid down by turbidity currents that flowed northward along the axis of a eugeosyncline that occupied the present site of the Oregon Coast Range. The sedimentology of the Tyee is being investigated as a topical phase of a program of detailed regional mapping in the west-central part of the Coast Range, and although much work remains to be done before many of the details of the depositional history of the formation are fully understood, reconnaissance studies have shed new light on this history. The information presented here also is intended to call to the attention of others concerned with cyclic sedimentation a few of the interesting problems available for study in the flyschlike rocks of

FIGURE 1.—Tyee Formation showing graded units that range from medium-grained arkosic wacke in lower part to siltstone in upper part. Exposed along Siletz River about 9 miles north of Siletz, Oregon.

the Tyee Formation that crop out over much of the southern half of the Oregon Coast Range (Fig. 2).

The writers wish to acknowledge assistance in the field by F. A. Schilling, Jr., A. M. Johnson, and C. H. Nelson in the summers of 1960, 1961, and 1962, respectively. Patsy Still aided in the compilation of data and preparation of illustrations. The manuscript was improved by the constructive criticism of Dallas L. Peck and David L. Durham.

GEOLOGIC SETTING

The Tyee Formation was first described by Diller in 1898 from exposures at Tyee Mountain in the southeastern part of the Oregon Coast Range (Fig. 2). Regional geologic mapping, principally by Baldwin, Snavely, and Vokes (Baldwin, 1947, 1955, 1956, 1961; Vokes and others, 1949, 1951, 1954; Snavely and Vokes, 1949) extended the use of the formational name throughout the southern and central parts of the Oregon Coast Range, and established the continuity of the Tyee Formation northward to include a correlative sandstone sequence designated the Burpee Formation by Schenck (1927) from outcrops east of Newport (Fig. 2). Strata previously assigned to the Burpee Formation are herein relegated to the Tyee Formation and the name Burpee Formation is abandoned.

In the southern part of the Oregon Coast Range the Tyee Formation overlies the Umpqua Formation (Diller, 1898), a sequence of lower to middle Eocene marine siltstone and graywacke beds and associated submarine volcanic rocks. In the central part of the range the Tyee overlies volcanic rocks and tuffaceous marine sedimentary rocks of the lower to middle Eocene Siletz River Volcanic Series (Snavely and Baldwin, 1948). Baldwin (1963) suggests that in the southern part of the Coast Range a regional angular unconformity is present between the Tyee Formation and the Umpqua Formation. In the central part of the range, however, unconformities between the Tyee Formation and the Siletz River Volcanic Series are of local extent. The writers believe that these local unconformities occur in areas where Tyee beds lap onto topographic highs formed by thick accumulations of submarine volcanic rocks.

The lack of distinctive stratigraphic horizon markers within the repetitious Tyee Formation precludes detailed analysis of the structure and makes accurate thickness measurement difficult. The thickness of the Tyee, however, is estimated as more than 6,000 feet, and perhaps as much as 10,000 feet where it is thickest along the axis of the basin of deposition. The upper part of the Tyee is missing in many areas where a major regional unconformity occurs at the base of the overlying uppermost Eocene strata. Where the upper part of the Tyee is exposed, the sandstone of the Tyee is interbedded with fossiliferous dark-gray mudstone and siltstone of latest middle Eocene age. This transition zone between the arenaceous rocks, typical of the Tyee Formation, and the overlying argillaceous strata is several hundreds of feet thick at some localities. These transitional beds were named the Elkton Siltstone Member of the Tyee Formation by Baldwin (1961).

In the area generally north of latitude 45°, the Tyee Formation interfingers northward with well-indurated dark-gray tuffaceous siltstones that in places contain interbeds of water-laid pyroclastic material. These siltstones include strata referred to as middle? Eocene shale by Warren and others (1945) in the Yamhill quadrangle, and part of the sequence mapped as undifferentiated volcanic and sedimentary rocks by Baldwin and Roberts (1952) in the Spirit Mountain quadrangle. In the central part of the Coast Range, the Tyee Formation probably also grades laterally into finer grained clastics both east and west of its outcrop area, but these facies relations are concealed on the eastern margin of the basin of deposition by volcanic rocks of the Cascade Range and on the western margin by the Pacific Ocean.

Fossils are rare in the Tyee Formation and are found only in the uppermost part. Despite its great thickness, the Tyee represents little time, for it is underlain and overlain by marine strata of middle Eocene age. The underlying siltstone strata in the upper part of the Umpqua Formation contain a foraminiferal fauna correlative with Laiming's (1940) B-1 zone and Mallory's (1959) Ulatisian Stage of

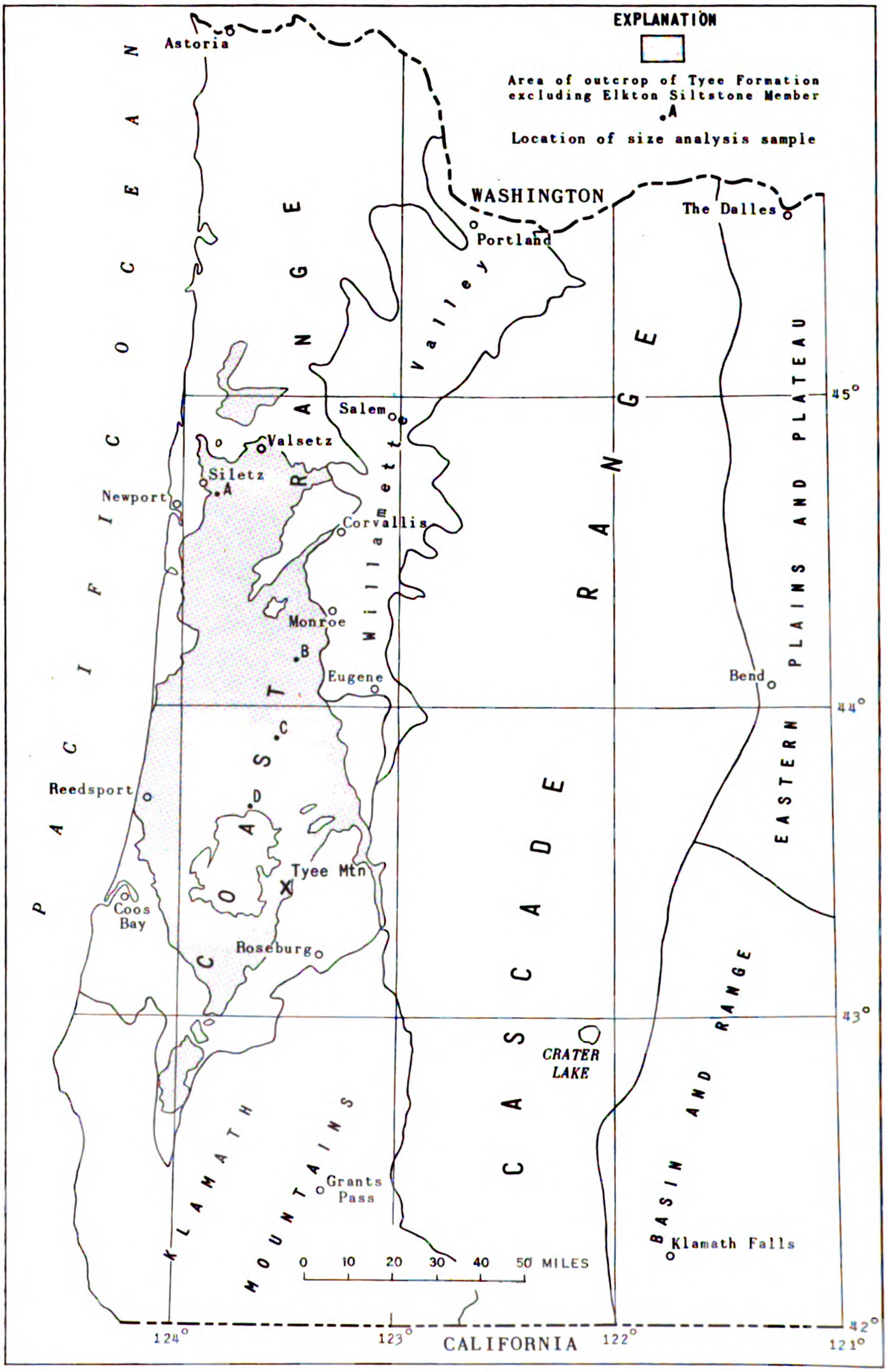

FIGURE 2.—Index map of western Oregon showing area of outcrop of Tyee Formation and its relation to major geomorphic provinces.

the middle Eocene of California (W. W. Rau, written communication, 1963). The overlying mudstone strata near the town of Siletz contain in the lower part a foraminiferal assemblage correlative with faunas found in Laiming's B-1 and B-1A zones and Mallory's upper Ulatisian (middle Eocene) or lower Narizian (late middle Eocene) Stages (W. W. Rau, written communication, 1963). Within the Tyee Formation, a foraminiferal fauna, in a siltstone interbed about 300 feet stratigraphically below its upper contact near the town of Siletz, contains forms indicative of the middle Eocene B-1 zone of Laiming and the Ulatisian Stage of Mallory (W. W. Rau, written communication, 1963). Molluscan faunas collected from the Elkton Siltstone Member in the uppermost part of the Tyee Formation indicate a correlation with the middle Eocene Domengine Stage of the standard West Coast Eocene (Weaver and others, 1944).

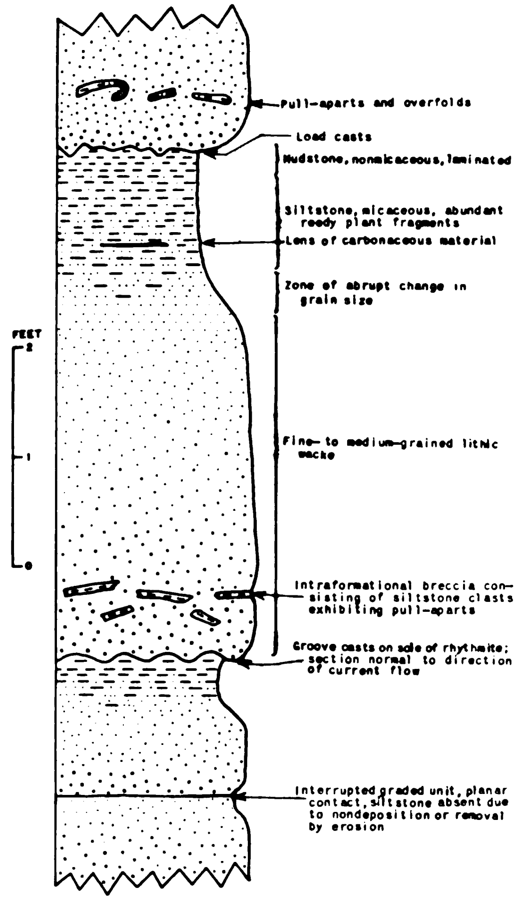

FIGURE 3.—Typical graded units measured in Tyee Formation, near Pioneer Summit, about 10 miles east of Newport, Oregon.

FIELD CHARACTERISTICS

The Tyee Formation exhibits many features that are commonly interpreted as characteristic of sediments deposited by turbidity currents (Kuenen, 1951, 1953; Kuenen and Carozzi, 1953; Crowell, 1955; Dzulynski and others, 1959; Allen, 1960; Bouma, 1962; and others). These include: rhythmic-bedded units of graded sandstone and siltstone, lateral continuity of these units, poor sorting of individual graded beds, sharp soles containing directional features with preferred orientations (such as groove casts and flute casts), tabular siltstone clasts with pull-aparts, slump structures and convolute bedding, uniformity in lithologic composition, and general lack of marine fossils.

The Tyee Formation consists of graded units (rhythmites of Sander, 1951, p. 135) that commonly range in thickness from 2 to 10 feet and average 3 to 5 feet (Fig. 3). In the southern part of the outcrop area, where individual graded units are generally thickest, beds of massive sandstone 10 to 20 feet thick are common. North of the latitude of Newport the graded units are thinner, and the sequence contains a higher percentage of siltstone. The graded units consist of sandstone in the lower part and grade upward into siltstone and mudstone. The sandstone is generally medium greenish gray and bluish gray, and fine to medium grained; the siltstone and mudstone are dark greenish gray and carbonaceous. The predominantly silty upper part of the units, although missing in places, usually represents less than one-quarter of the total thickness, and the boundary between the siltstone and sandstone is abrupt (Fig. 4). The sandstone of the graded units is more resistant to erosion than the siltstone so that in most exposures the sandstone stands in relief and gives the outcrop a banded appearance (Fig. 1). The rhythmites persist along the strike, and a single bed can be traced for the entire length of its outcrop (as much as one-quarter of a mile) with no apparent thinning.

Figure 4.—Graded units (rhythmites) in Tyee Formation, along Siletz River about 9 miles north of Siletz, Oregon. Rather abrupt transition from sand-size to silt-size material takes place near middle of hammer handle. Hammer rests on 8-inch calcareous concretion.

Granule and pebble-size materials are uncommon in the Tyee Formation, but in places in the southern part of the outcrop area rudely imbricated elongate pebbles, chiefly of andesite, occur in some thick sandstone units. In the northern part of the outcrop area, however, no relation is apparent between bed thickness and maximum grain size. Hoover (1963, p. 24) also observed the lack of relationship between bed thickness and grain size in the east-central part of the Tyee outcrop area. In the southernmost part of the outcrop area, lenticular conglomerate and conglomeratic mudstone are interbedded with the thick sandstone units of the Tyee.

The lower part of individual graded units consists of massive-appearing sandstone in which the grading generally is indistinct. Sedimentary structures rarely occur within this part of the units, but poorly developed, small-scale cross-stratification is present in a few places. Brown-weathering calcareous concretions, as much as 1 foot in diameter, and calcite cemented sandstone beds occur locally. Intraformational breccia, containing tabular clasts of siltstone as long as 1 foot, commonly occurs within the sandstone portion of the rhythmite. The clasts are imbricated in a few places and many have pull-apart structures with serrated, unabraded ends. In places large strips of siltstone have been deformed into overfolds similar to those figured by Crowell (1957, p. 1000) and into irregular-shaped bodies. In a few outcrops siltstone clasts constitute as much as 25 percent of the sandstone portion of the rhythmite.

The upper part of each rhythmic unit is generally dark greenish-gray tuffaceous, micaceous siltstone and less abundant mudstone. Fragments of reedy plants are common in the very fine grained sandstone and siltstone portions of the graded units, and carbonaceous material along bedding planes commonly imparts an indistinct parallel lamination. In places carbonaceous material is concentrated in sufficient quantity to form impure coal. Commonly, rectangular carbonaceous fragments have a preferred orientation. In most exposures the siltstone portion of the rhythmite is indistinctly graded and appears structureless on the outcrop, but in several places the uppermost part of the graded units contains thin-bedded to laminated very fine grained sandstone and siltstone that show

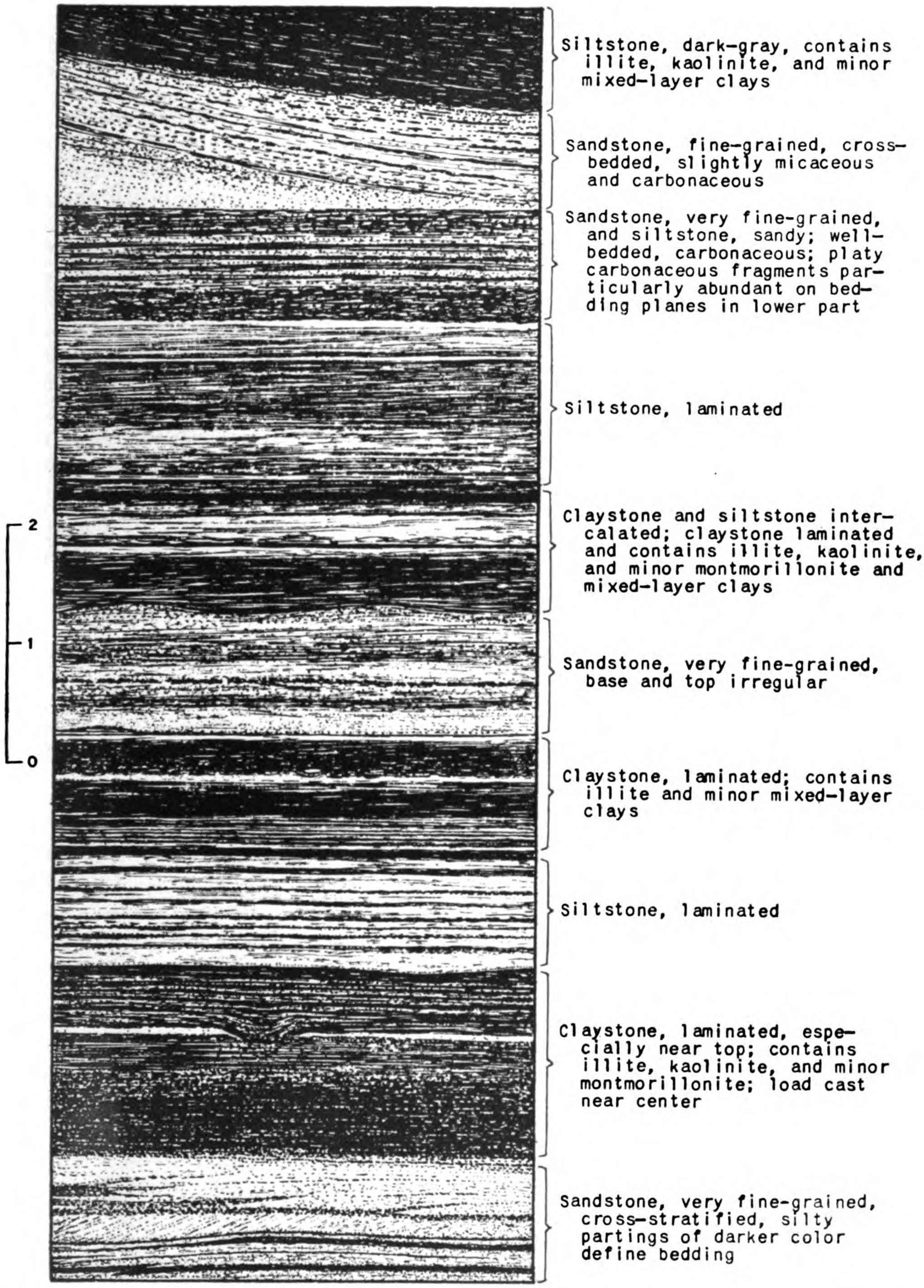

FIGURE 5.—Thin-bedded and laminated fine-grained sandstone, siltstone, and claystone in uppermost part of graded unit of Tyee Formation, about 7 miles southwest of Monroe, Oregon. Drawn by Meade Norman from photograph. (Scale is in inches.)

fine cross laminations, parallel laminations, and current ripple laminations (Fig. 5). Sufficiently detailed studies have not yet been made in these more easily weathered upper parts of the rhythmites to determine the frequency of such features, or to determine whether the Tyee rhythmites have a distinctive sequence of sedimentary structures similar to those described by Bouma (1962, p. 48-66) from the Peira-Cava area of southern France.

The siltstone portion of many graded units is absent, due either to nondeposition or to erosion by the turbidity current that transported the material in the overlying bed. The common occurrence of rectangular siltstone clasts within the rhythmites suggests that these fragments were ripped from the top of the underlying rhythmite by the turbidity current. In a few places, thin-bedded to laminated siltstone units, as much as 8 feet thick, occur between the rhythmites.

LITHOLOGY

Sandstone of the Tyee Formation consists mainly of arkosic, lithic, or feldspathic wacke, and less commonly volcanic wacke.* The sandstone is composed of 60 to 90 percent clastic material and 10 to 50 percent argillaceous matrix. Although modal analyses of Tyee sandstone show some variation in the percentage of clastic constituents (Fig. 6), the sandstone is generally uniform in composition throughout the outcrop area and in most cases is readily distinguished from sandstones in older or younger formations. The few chemical analyses available for Tyee sandstone also reflect the general compositional uniformity (Table 1). The high percentage of matrix in the sandstone, which averages about 30 percent, results in a "tight" sand.†

* Classification of sandstone is that of Gilbert, *in* Williams and others (1954, p. 290-310).

† Porosity and permeability determinations made on 17 representative samples showed that the effective porosity of the Tyee ranged from 4.8 to 20.9 percent and averaged 14.0; the permeability ranged from 0.2 to 4.5 millidarcies and averaged 2.7.

TABLE 1.—Chemical and spectrographic analyses of sandstone and siltstone of the Tyee Formation.

(Major oxide analyses using rapid rock analysis procedures done by P. S. D. Elmore, S. D. Botts, and G. Chloe. Powder density obtained by air pycnometer. Semiquantitative spectrographic analyses by I. H. Barlowe; results are reported in percent to the nearest number in the series 1, 0.7, 0.3, 0.2, 0.15, 0.1, etc.; which represent approximate midpoints on a geometric scale. The assigned group for semiquantitative results will include the quantitative value about 30% of the time.)

	1	2	3	4
SiO_2	64.8	62.4	65.8	61.8
Al_2O_3	15.1	16.1	14.8	15.2
Fe_2O_3	2.4	2.0	2.1	2.2
FeO	2.7	3.4	2.9	2.2
MgO	2.7	3.0	2.5	1.9
CaO	3.2	3.1	2.4	2.2
Na_2O	3.0	2.8	2.9	2.4
K_2O	2.3	2.1	2.5	3.4
H_2O^+	2.2	3.0	2.4	3.7
H_2O^-	1.4	1.8	1.2	2.8
TiO_2	.68	.68	.64	.63
P_2O_5	.18	.20	.18	.14
MnO	.06	.03	.04	.04
CO_2	<.05	<.05	<.05	<.05
Sum	100	100	100	99
Powder Density	2.69	2.68	2.68	2.56
Lab. No.	159003	159004	159001	159002
Field No.	SR57-25	SR58-7	SR61-72	JT61-82

	1	2	3	4
Ag	<.00007	<.00007	<.00007	<.00007
B	0	<.003	<.003	<.003
Ba	.05	.05	.07	.07
Be	<.0001	<.0001	<.0001	.0002
Ce	.01	0	0	0
Co	.001	.001	.001	.001
Cr	.015	.005	.005	.007
Cu	.0005	.0005	.0007	.0015
Ga	.001	.001	.001	.001
La	0	.003	0	0
Mo	.0003	.0005	.0003	.0003
Nb	.0007	.0003	.0007	.0007
Ni	.002	.002	.003	.003
Pb	.0005	.0007	.0005	.0007
Sc	.001	.0007	.0007	.0007
Sr	.05	.05	.05	.07
V	.007	.005	.005	.007
Y	.001	.001	.0015	.001
Yb	.0001	.0001	.0002	.0001
Zn	.03	.02	.01	.01
Zr	.015	.007	.015	.015

1. Lithic wacke, center, SW sec. 32, T. 20 S., R. 10 W., Goodwin Peak quad., Oregon.
2. Arkosic wacke, NW NW sec. 14, T. 12 S., R. 10 W., Toledo quad., Oregon.
3. Lithic wacke, center, sec. 1, T. 22 S., R. 11 W., Scottsburg quad., Oregon.
4. Siltstone, NE NW sec. 18, T. 14 S., R. 9 W., Tidewater quad., Oregon.

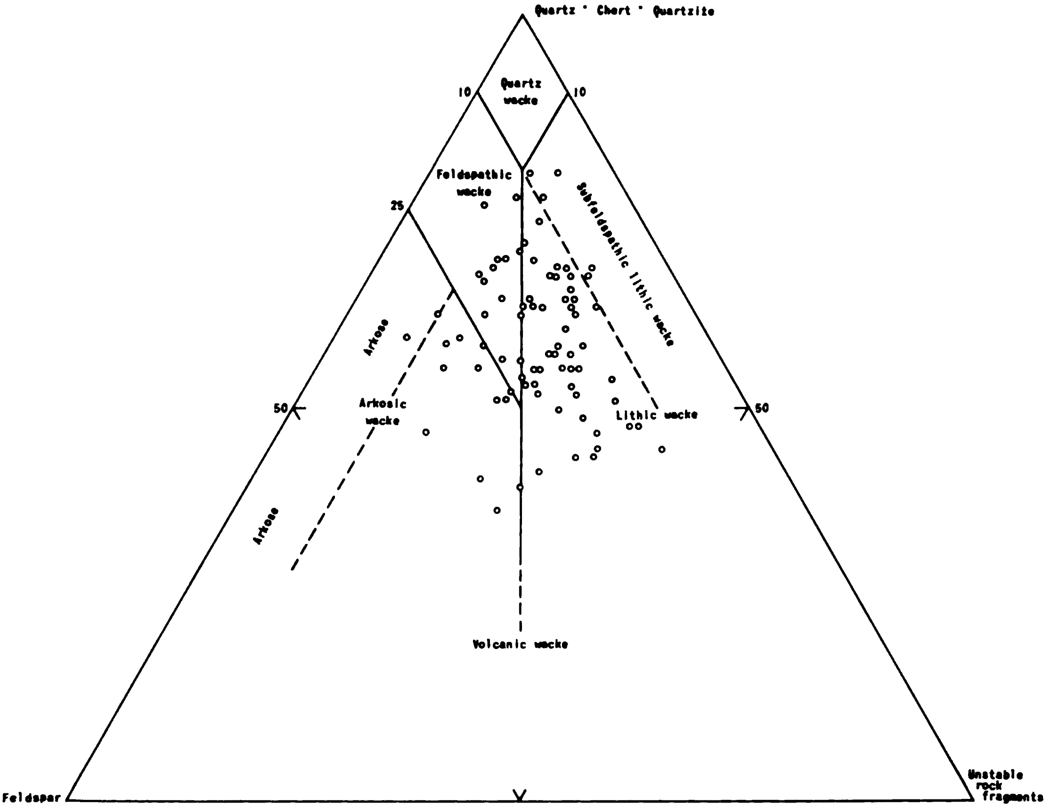

FIGURE 6.—Ternary diagram showing relative proportions of mineral and lithic grains in arenaceous rocks of Tyee Formation (classification after Williams and others, 1954, p. 292).

Thin section studies of 75 sandstone samples show that the Tyee is composed primarily of quartz, unstable lithic fragments, and feldspar, with lesser amounts of mica, chert, and pelitic fragments. Most of the mineral grains are subangular or subrounded and have an average size of about 0.2 mm (Fig. 7); the largest grains are about 1 mm.

Quartz, which commonly has undulatory extinction, is the dominant detrital mineral in the sandstone and composes 20 to 40 percent of the grains (average 30 percent). The roundness of quartz grains averages about 0.3; the sphericity averages about 0.7.* Plagioclase ranges from euhedral crystals to rounded grains and makes up 3 to 20 percent of the rock (average about 10 percent). Composition of the plagioclase is most commonly andesine or calcic andesine, but ranges from oligoclase to labradorite. Many of the plagioclase grains are euhedral, a shape that is interpreted as evidence of their volcanic origin, probably from feldspathic tuffs. In support of this interpretation, the detrital grains of plagioclase and the plagioclase laths in volcanic lithic fragments are similar in composition, and show a very common and pronounced oscillatory zoning. Also, the sandstones that contain larger proportions of volcanic fragments generally have a greater proportion of plagioclase.

K-feldspar is less common in the sandstone than is plagioclase and generally makes up less than 5 percent of the grains in the thin sections studied. In order of abundance the K-feldspar minerals were identified as orthoclase, sanidine, perthite, and microcline. Because small grains of K-feldspar are difficult to distinguish from quartz, staining techniques using sodium cobaltinitrite (Bailey and Stevens, 1960) were used to determine the quantitative error in the identification of these

* Roundness and sphericity based on visual comparison with the chart of Krumbein and Sloss (1951, p. 81).

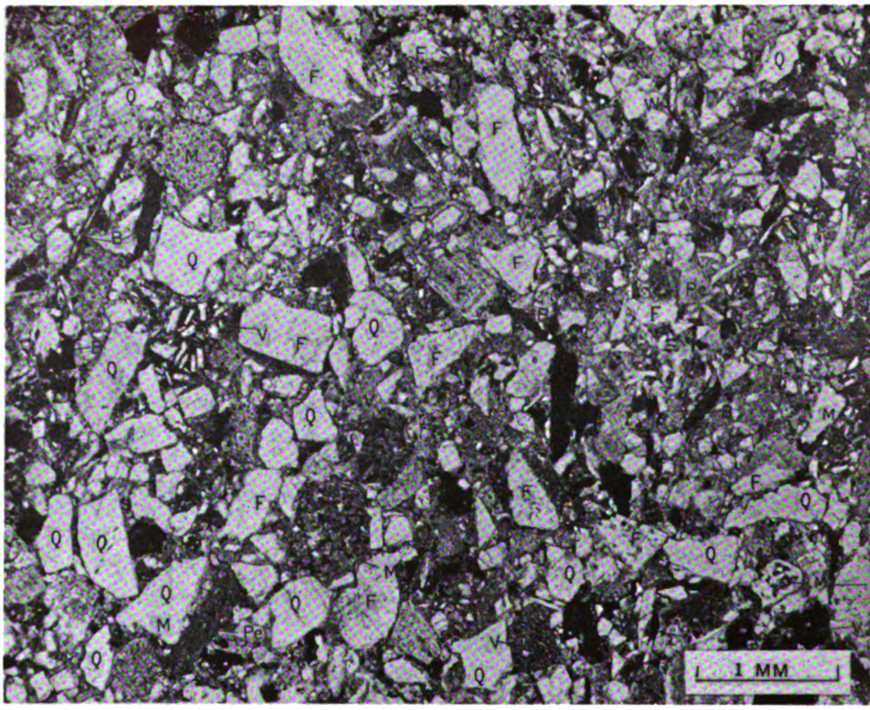

FIGURE 7.—Photomicrograph of sandstone from Tyee Formation. Ordinary light. B—biotite, F—feldspar, M—metamorphic fragment, Pe—pelitic fragment, Q—quartz, V—volcanic fragment, W—white mica.

minerals in unstained thin sections. Modal analyses of several stained rock slabs and thin sections indicate that K-feldspar constitutes a higher percentage of the sandstone grains than is apparent when working with unstained thin sections. The plots of sandstone composition on Figure 6 are based on modal analyses of unstained sections, and presumably most of the individual points would shift slightly towards the feldspar corner of the triangular diagram if stained sections had been analyzed.

The most characteristic feature of Tyee sandstone, both in hand samples and thin sections, is the abundance of large crinkled flakes of muscovite and smaller flakes of biotite. The micas compose 1 to 15 percent of the grains, and average about 5 percent. Muscovite generally predominates over biotite, but the reverse order of abundance is common. The micas are as much as 2 mm in largest dimension and generally are molded around other grains. The muscovite in most thin sections is unaltered, whereas biotite ranges from fresh to completely altered.

Volcanic fragments, which are the most common lithic grains in Tyee sandstone, constitute about 10 percent (range: 1 to 25 percent) of the clastic material. The texture and composition of the fragments vary somewhat, but vitrophyric or pilotaxitic andesite and, less commonly, basalt predominate. The glassy groundmass is almost invariably devitrified, and in many places grain boundaries are obscure where the grains are surrounded by clay matrix. Plagioclase, the only primary mineral in many of the grains, displays pronounced oscillatory zoning and twinning. Very small pyroxene crystals and opaque minerals are commonly scattered through the devitrified groundmass. Silicic volcanic rock fragments are rare, but were observed in several thin sections.

Metamorphic rock fragments, which average about 2 percent, but form as much as 8 percent, of the clastic material are predominantly quartz-muscovite schist or quartz-biotite schist. Quartz-epidote hornfels and hypersthene-plagioclase-quartz hornfels also were identified in thin sections. The small size of most of the lithic fragments and the pervasive alteration of the rock make difficult the identification of the rock type in these fragments.

Fragments composed of interlocking quartz grains (quartzite?), which may be either of plutonic or metamorphic origin, and of cryptocrystalline chert make up about 6 percent (range: 2 to 30 percent) of the grains. Fragments of pelitic rock form approximately 1 percent of the grains, and fragments of carbonaceous material are locally abundant.

In many specimens calcite cement makes up as much as 20 percent of the rock. The calcite is rather dark in thin section, due to included clay minerals, but is easily distinguished, and was noted in quantities greater than 1 percent in approximately one-quarter of the sections studied. Opaque minerals (magnetite and ilmenite) make up 2 percent or less of the grains. Hornblende, garnet, tourmaline, zircon, zoisite, rutile, allanite, sphene, and monazite were identified; of these only hornblende is present in more than trace amounts.

The wackes of the Tyee Formation have a matrix of silt and clay that compose about 30 percent (range: 10 to 50 percent) of the rock. As shown in the grain size percentage diagrams (Fig. 8), the proportions of clay and silt generally increase upward in the rythmites with an abrupt increase near the top of the sand fraction. The diagrams of four graded units, designated A to D from north to south (*see*, Fig. 2), indicate a general decrease in sand and increase in silt northward. In all except the southernmost unit, D, a relative increase in the silt and clay fraction occurs 6 to 12 inches above the base of the rhythmite. X-ray diffraction studies * of the clay indicate that montmorillonite and mixed layer montmorillonite-mica together with illite predominate; kaolinite is present in lesser amounts. In a few samples the upper few inches of individual rhythmites are predominantly illite and kaolinite, with montmorillonite either present in small amounts or absent. A preliminary study of the clay mineralogy of the unnamed mudstone unit that overlies the Tyee near the town of Siletz and of the siltstone interbeds in the upper part of the underlying Umpqua Formation indicates that illite and kaolinite are the predominant clay minerals. Cummings and Beattie (1963, p. 29) suggest that the change in clay mineralogy in the upper part of graded units is principally the result of authigenic enrichment of the sediments in illitic clays, but because a considerable amount of pelagic clay of illitic and kaolinitic composition was deposited both before and after Tyee time, pelagic sediments can reasonably be assumed to have been accumulating in the geosyncline during deposition of the Tyee as well. These pelagic clays would form recognizable beds only if considerable time elapsed between deposition of individual rhythmites.

* X-ray diffraction using nickel-filtered copper radiation and techniques similar to those described by Hathaway (1956).

SOLE MARKINGS

The soles of graded units are sharply defined, and although commonly they contain casts of several kinds of sedimentary structures, some are smooth and planar. Groove casts are by far the most common sole markings and occur in more than one-half of the exposures examined. These groove casts range in size from delicate ridges ⅛-inch across to inverted tunnel shaped features with breadths as much as 8 inches and amplitudes of 6 inches. Most groove casts, however, are 2 to 4 inches in breadth and ½ to 2 inches in amplitude (Fig. 9). They are often uniformly spaced and in cross section have the appearance of oscillation ripple marks, for which they have been mistaken. Grooves exposed in a quarry along the Umpqua River in the southwestern part of the outcrop area probably were formed by the gouging action of plant debris that was swept across the muds on the sea floor. The moving debris also produced small drag folds that curve toward the direction that the material was transported (Fig. 10). The low dip of the strata coupled with poor exposures precludes large exposures of bedding planes. Therefore, the extent of most groove casts cannot be measured. On quarry slabs they extend completely across the block (as much as 10 feet), but many are undoubtedly tens of feet long. The groove casts commonly contain longitudinal ridges or striae, and in a few places pea-sized nodes occur along the crests of the groove casts.

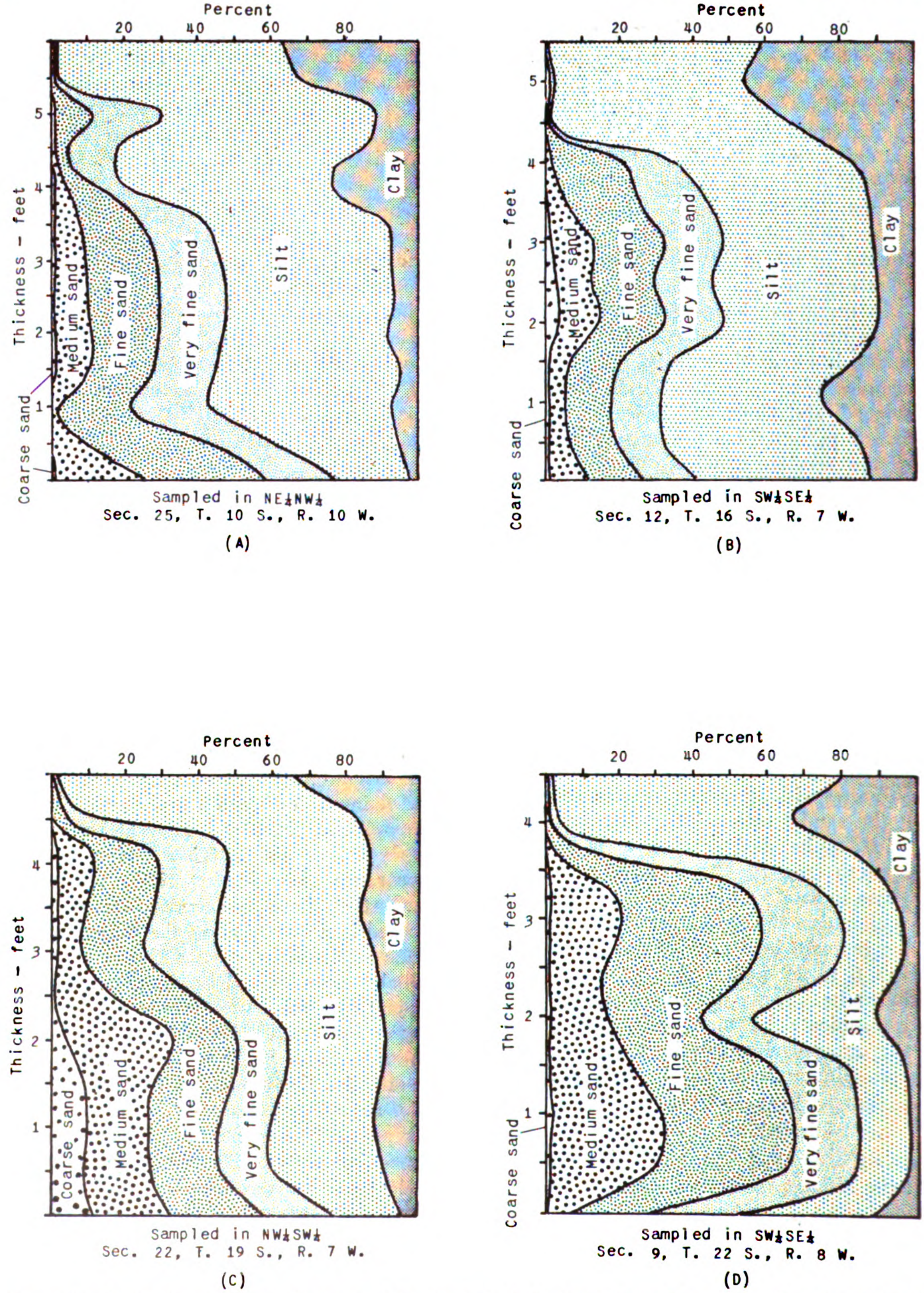

FIGURE 8.—Grain size percentage diagrams of four typical rhythmites in Tyee Formation. Samples analyzed were taken at 6-inch intervals. Pipette and sieve analyses made by James A. Thomas, U. S. Geological Survey.

FIGURE 9.—Deformed groove casts at base of graded sandstone unit in Tyee Formation viewed perpendicular to north-south direction of lineation. Flame casts (F) formed at sandstone-siltstone interface by penecontemporaneous slumping westward from left to right. Photograph taken at Green Mountain about 5 miles south of Valsetz, Oregon.

FIGURE 10.—Groove casts on base of graded unit in Tyee Formation. Small drag features along groove casts indicate that current moved from right to left. Small rectangular casts in upper part of photograph are impressions of plant fragments. Photograph taken in quarry on south side of Umpqua River about 7 miles east of Reedsport, Oregon.

Where both groove casts and striations have been observed together on the sole of a graded unit, the two features usually diverge less than 20 degrees.

Flute casts occur in many outcrops of the Tyee Formation, either as isolated structures or in clusters. Such casts are oblong-shaped, are as much as 6 inches long, have bulbous ends up current (to the south in the mapped area), and tail out down current. The flute casts generally trend parallel to the groove casts, but in some outcrops the trends of the two form an acute angle. Many flute casts have a ropy appearance caused by shallow ridges and striations parallel to their length. Overlapping flute casts appear to be superimposed on groove casts in places (Fig. 11).

DEFORMATIONAL STRUCTURES

Penecontemporaneous slump structures, although not common in the Tyee Formation, occur in thick (6 to 8 feet) siltstone units within the graded sequence. These dark-gray siltstone units contain light-gray, fine-grained sandstone interbeds 1 to 4 inches thick that clearly indicate details of structures produced by submarine gravity sliding. Detached sandstone beds in these units have been deformed into recumbent folds, "jelly-roll" features, and complexly contorted masses. The folds average about 1 to 2 feet in height and width.

The trend of fold axes and the direction of overturning in slump structures, measured in the upper part of the Tyee Formation at four widely separated places in the northern part of its outcrop area, indicate movement toward the west or west-northwest. This suggests that the deepest part of the basin of deposition in the central part of the Coast Range shifted westward with time and that downwarping of the basin produced gradients steep enough to promote slumping normal to its axis. In one outcrop, structures similar to flame casts (Walton, 1956, p. 267-268) are streaked out into the overlying sandstone at right angles to the north-south lineation of the groove casts (Fig. 9). This streaking is directed westward, also indicating a deepening of the basin to the west soon after deposition of these sediments.

ANALYSIS OF CURRENT DIRECTION STRUCTURES

About 500 directional measurements were made on current structures; these strongly indicate northward transport of material in the geosyncline (Fig. 12).* Approximately 90 percent of the measurements were made on groove casts and indicate that the currents flowed either north or south. More than 60 measurements made on flute casts show that the currents moved northward.

A rose diagram of the groove casts (Fig. 13) shows a maximum trend directed N. 5 E. Two secondary trends diverge about 20 degrees east and west of this maximum. The rose diagram for the flute casts (Fig. 14) shows a maximum trend directed N. 10 W. with a secondary maximum trending N. 30 E. A third maximum trends N. 10 E. and coincides approximately with the maximum trend of the groove casts.

The grouping of groove cast lineations around a N. 5 E. direction and the northward current sense indicated by the flute casts are interpreted as reflecting the general northward movement of the turbidity currents responsible for the Tyee Formation, and hence a northward bottom slope of the basin of deposition. Northeast and northwest divergences in current direction readings, 15 to 25 degrees from the N. 5 E. trend, in part probably reflect changes in current flow in response to bottom relief in the basin. Volcanic highs were present in places in the eugeosyncline (Snavely and Wagner, 1963), and such highs probably diverted the turbidity currents away from their general northward flow. A volcanic high undoubtedly existed immediately south of latitude 45°, where interflow soil zones, locally derived mudflow breccias, and subaerial basalt flows in the exposed underlying Siletz River Volcanic Series indicate that these rocks accumulated in sufficient thickness to form an island within the geosyncline. The northeast and northwest divergences of current direction lineations south of this area (Fig. 12) suggest that turbidity currents were deflected around this area of volcanic accumulation. The presence of rhythmites of the

* In particularly good exposures, several current-direction readings were made, and an average of these readings was plotted.

FIGURE 11.—Flute casts, probably superimposed on groove casts, in Tyee Formation. Arrow indicates sense of current. Photograph taken at Green Mountain about 5 miles south of Valsetz, Oregon.

Tyee Formation above the subaerial flows indicates that this volcanic island was eventually buried by the turbidite deposits. The generally higher content of basaltic fragments in sandstone of the Tyee Formation in this area supports the concept that the Siletz River Volcanic Series was subjected to subaerial erosion and supplied detritus to the basin.

SOURCE AREA

The limited number of readings on directional features obtained by the writers in the southernmost part of the outcrop area of the Tyee Formation (Fig. 12) precludes more than speculation as to the sources of sediments in the Tyee. Also, much of the Tyee that would be helpful in determining a specific source area has been removed by erosion. Available directional features suggest that the principal sources of Tyee sediments lay south of the present area of outcrop. The few northeast-trending groove casts in the southwestern part of the outcrop area and in places in a belt that extends diagonally northeast across the Coast Range between Coos Bay and Eugene (Fig. 12) are interpreted as caused by turbidity currents that flowed down the flanks of a northwest-trending pre-Tertiary highland that may have existed west of Coos Bay (Snavely and Wagner, 1963). Therefore, divergences of current direction readings in the southern part of the outcrop area may reflect the overlapping of turbidites originating in two source areas, one in the southern part and the other in the southwestern part of the geosyncline. As the preponderance of measurements on sedimentary structures is northward, the principal source area probably was to the south.

The lithologic character of the Tyee Formation is consistent with the interpretation that the sediments were derived from the south, as much of the material consists of debris eroded from a metamorphic, igneous, and sedimentary terrane similar to that of the Klamath Mountains. For example, grains of quartz-muscovite schist and abundant muscovite in the Tyee could have been derived from some of the metamorphic rocks of pre-Tertiary age

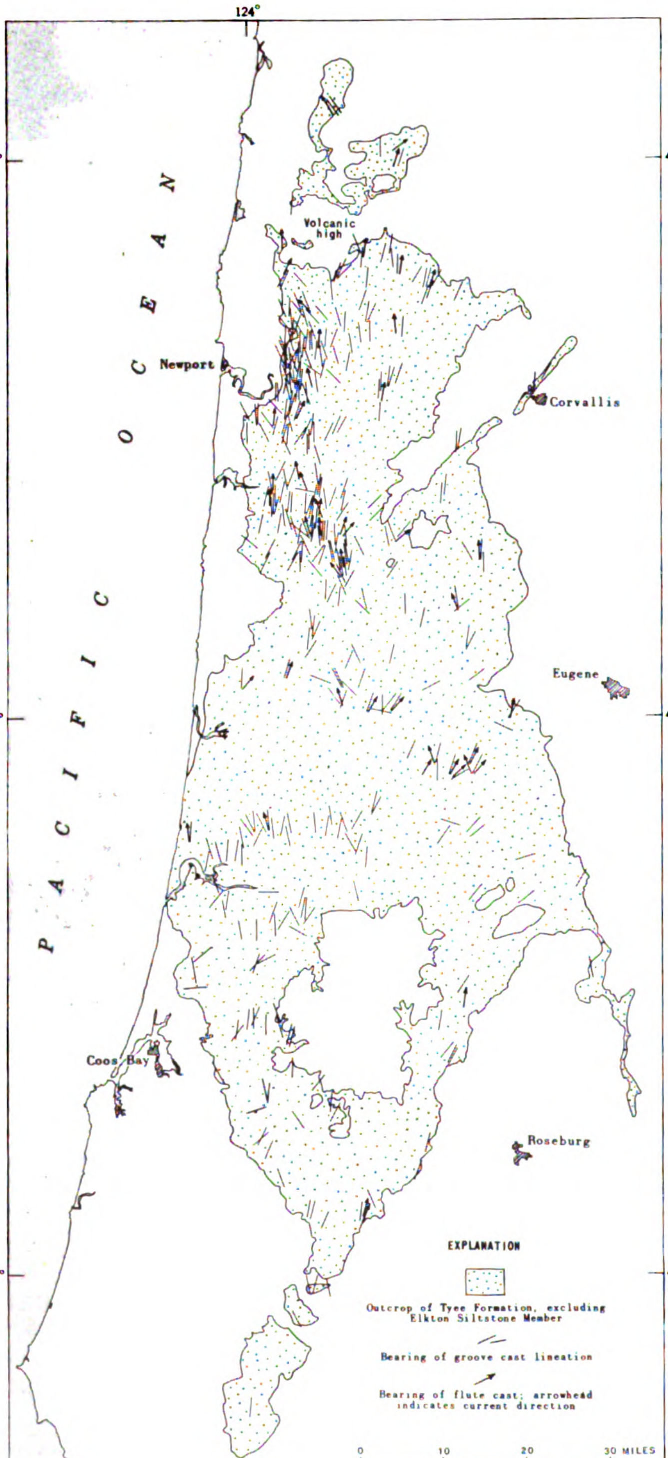

FIGURE 12.—Trends of groove casts and flute casts in Tyee Formation, Oregon Coast Range.

that are assigned to the Abrams Mica Schist by Irwin (W. P. Irwin, oral communication, 1963), Grouse Ridge Formation by Davis and Lippman (1962), and Colebrooke Schist of Diller (1903). Much of the quartz, biotite, and K-feldspar could have been derived from fine- to coarse-grained granitoid rocks, such as the biotite granites, granodiorites, and trondjemite mapped in the Klamath Mountains by Wells (1955) and Davis (1963). Clasts of hornfels in the Tyee Formation could have been derived from rocks in the extensive contact aureoles around the granitic bodies (W. P. Irwin, oral communication, 1963; Davis, 1963). The heavy minerals in the Tyee Formation, including clinopyroxenes, epidote, tourmaline, zircon, hornblende, sphene, and garnet, are common in gneisses and schists that crop out throughout the Klamath province (Wells and Walker, 1953). Sedimentary rocks, mainly shelf-type deposits of Cretaceous age, formerly covered much of southwestern Oregon (Jones, 1960) and unquestionably contributed large quantities of detrital material to the Tyee basin of deposition. Peck and others (1956) report that quartz, feldspar, lithic fragments, and biotite are major constituents of the arkosic wackes in the Upper Cretaceous Hornbrook Formation. Therefore, similar clastic material in

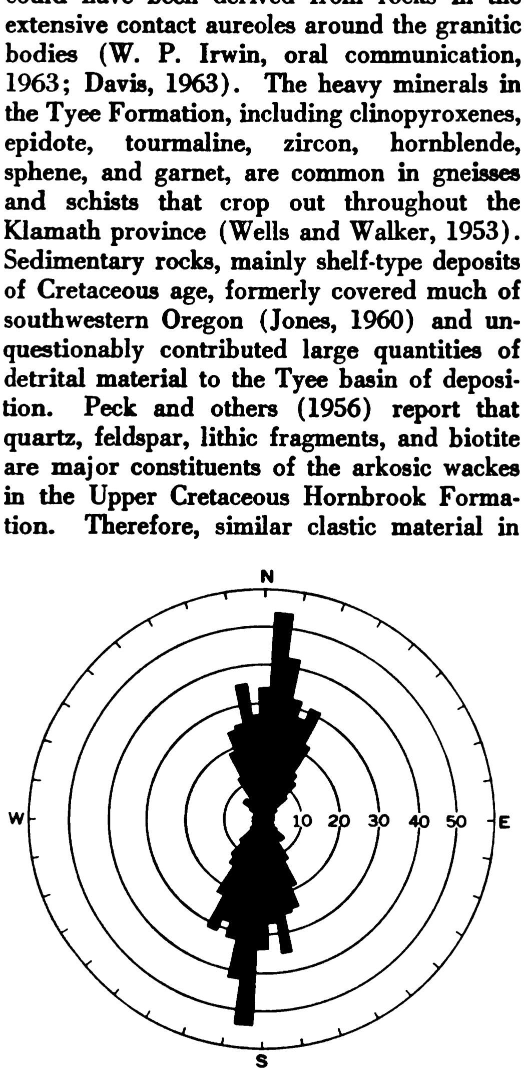

FIGURE 13.—Rose diagram of orientation of approximately 500 groove cast lineations in Tyee Formation, Oregon Coast Range. Bearings of lineations on inclined strata were corrected by rotation to horizontal and plotted to nearest 5 degrees.

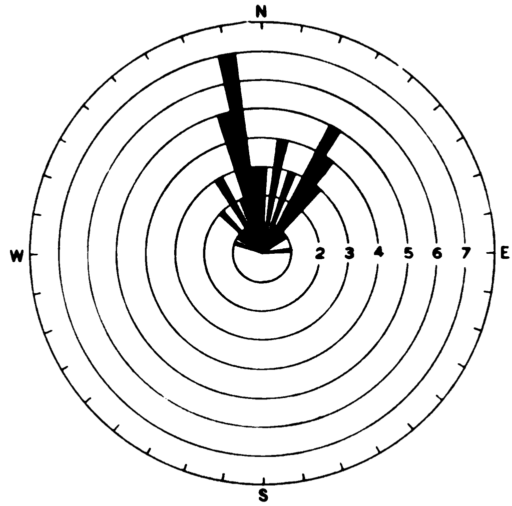

FIGURE 14.—Rose diagram of orientation of approximately 60 flute casts in Tyee Formation, Oregon Coast Range. Bearings plotted to nearest 5 degrees.

the Tyee Formation could have been reworked from Upper Cretaceous sedimentary rocks. Chert, which is present in most of the sandstone of the Tyee, is a common constituent in eugeosynclinal Mesozoic sedimentary rocks, such as those of the Applegate Group and the Dothan Formation (Wells and others, 1949, p. 3-8), that crop out in broad areas in the southeastern part of the Klamath Mountains.

Clasts of andesite and euhedral grains of andesine feldspar are two principal components of Tyee sandstone and are believed to have been derived from contemporaneous volcanism immediately east of the geosyncline, as similar rocks are found in the Eocene volcanic terrane of eastern Oregon. The unstable nature of this andesitic volcanic debris demands rapid deposition and burial in order to preserve it in the Tyee.

A part of the volcanic material in the Tyee Formation could have been derived from the andesite and dacite that are intercalated with Jurassic sedimentary rocks, particularly in the Galice Formation (Wells and others, 1949, p. 4-5) and Rogue Formation (Wells and Walker, 1953). Considerably more detailed petrography needs to be done on the volcanic components of the Tyee and on the products of lower Tertiary and Mesozoic volcanism before the provenance of the volcanic material in the Tyee can be more definitively evaluated.

PALEOGEOLOGIC INTERPRETATIONS

Certain broad interpretations of the depositional history of the Tyee Formation seemingly are warranted on the basis of the field and laboratory data herein presented, particularly where these data are evaluated within the regional geologic framework of western Washington and Oregon (Snavely and Wagner, 1963).

At or near the end of Cretaceous time, downwarping along the Pacific margin produced a linear geosyncline that extended southward from Vancouver Island to the Klamath Mountains, a distance of about 400 miles. The eastern margin was beneath the present Cascade Range, and the western margin was west of the present coast line.

Early in the history of the geosyncline, in the early Eocene, a thick sequence of tholeiitic basalt in the form of pillow lavas and breccia erupted from numerous centers onto the floor of the rapidly subsiding trough. These volcanic rocks intertongued with, and in places were buried by, silts and impure sands that probably were derived from the southern and eastern margins of the geosyncline. Very coarse clastic debris, including cobbles and boulders, was laid down contemporaneously with the sands and silts in the southern part of the geosyncline, reflecting uplift and erosion of a rugged pre-Tertiary terrane in the present Klamath Mountains area. The presence of tuffaceous material and detrital grains of andesite in many of the impure sandstone beds of the Umpqua Formation suggests that part of the detritus was derived from volcanic fields that lay east of the geosyncline. The current structures, the graded nature of many of the graywacke beds, and the high percentage of unstable rock fragments in the Umpqua indicate rapid deposition, probably by turbidity currents that flowed generally northward and westward into the deeper parts of the basin (Snavely and Wagner, 1963, p. 1-6).

In middle Eocene time major uplift and erosion in the Klamath pre-Tertiary terrane south of the geosyncline and contemporaneous volcanic activity east of the geosyncline supplied great quantities of arkosic, lithic, and volcanic debris to the south end of the geosyncline where large deltas may have formed. Periodic slumping at the delta fronts, perhaps triggered by earthquake shocks that accompanied active volcanism east of the geosyncline or by the failure of water-saturated, metastable sediments under gravity load, moved large masses of this mixed sand, silt, and clay basinward. These mass movements of clastic materials northward into the deeper part of the geosyncline are believed to have been transformed into turbidity currents that flowed along the axial part of the trough at least as far north as latitude 45°. The materials thus transported and deposited now form the Tyee Formation. Northeast-trending current directions in a belt extending from Coos Bay to Eugene suggest that the source of some of the detritus was a highland area that may have existed west of the present coast line.

Near the close of middle Eocene time, the geosyncline was nearly filled by turbidity-current deposits to a thickness of approximately 10,000 feet along the axis of the trough. The Klamath source area apparently had been eroded to a region of moderate relief and furnished less debris to the marine environment. At this time coal-bearing continental beds and nearshore bar-type sands were laid down near the southern fringe of the basin, and silt and clay, probably derived from a northeastern source, became the dominant lithology in the geosyncline.

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Periodicity in the Wellington Formation of Kansas and Oklahoma

INTRODUCTION

The Wellington Formation of Kansas and Oklahoma is essentially a shale sequence. The recurrence of thin limestone units, almost invariably argillaceous and overlain and underlain by shales, indicates that at times carbonates were introduced into the generally clay mud bottom. Siltstones in the Midco section of Oklahoma indicate an occasional influx of quartz detritus.

The formation is generally viewed as a unit which was deposited in epeiric seas. However, as the evaporitic sequence (Hutchinson Salt, Annelly Gypsum) indicates, for a period of time Wellington waters were hypersaline. Furthermore, as this paper will show, from base to top of the formation, there is considerable evidence to support an interpretation of an alternation of conditions from limited evaporative to brackish to fresh.

The general picture that has emerged from the research to be discussed is one of a coastal flat with relict puddles, ponds, and even small-scale lakes that gradually freshened as the epeiric sea regressed. Marine encroachments over this coastal area occurred between times of recurrent fresh-water biofacies.

Thickness of the Wellington Formation is about 700 feet. The base of the formation is the contact with the Herington Limestone and can be seen exposed in Cowley County, Kansas (SE NE sec. 21, T. 34 S., R. 3 E.). One can proceed in an almost straight line to the top of the formation, a distance of 23 miles, west of the Cowley County exposure to where the upper member of the Wellington, the Milan Limestone, is exposed in Sumner County (NW NW sec. 23, T. 34 S., R. 2 W.). Along and near this traverse line, as well as south (Kay and Noble Counties, Oklahoma) and north of it (Sedgwick, Harvey, Marion, and Dickinson Counties, Kansas) are numerous but discontinuous exposures.

Field exploration for the past four years and subsequent laboratory study of samples have brought to light new information on the Wellington Formation. Because material is still being studied, however, field notes will be used for sections still to be processed.

Acknowledgments.—Field and laboratory research on the Wellington Formation has been supported by National Science Foundation grants (G-4150, G-7320, G-14141). The Kansas Geological Survey prepared the illustrations for this paper.

GENERAL STATEMENT ON PERIODICITIES

The basal 40 feet of the Wellington may be used as an illustration. The transition from the marine Herington provides some important clues. Overlying the marine, cherty Herington Limestone are some 6 feet of gray-black, blocky shale, in turn, overlain by a 1-foot bed of a silty, calcareous argillite, bearing fossils of the calcareous-phosphatic, inarticulate brachiopod, *Lingula*. Approximately 5 feet of blocky, waxy shale overlies the *Lingula* bed, and the next interval is occupied by a snail-ostracode coquina.

Thus, there is clear evidence of a post-

Herington regressing, epeiric sea. The blocky, waxy shales represent shallow-marine deposits; the *Lingula* bed, a nearshore deposit. With further regression of the sea, a coastal flat bearing relict puddles and ponds remained. The snail-ostracode coquina seemingly accumulated in such relict brackish-water bodies. Thereafter, at this locality (*see*, Table 1), minor oscillations of the sea-cover on and off the coastal flat can account for the subsequent shales and fresh-water biota found in them.

A snail-ostracode coquina, including reptilian fragments, also occurs in Dickinson County, Kansas (Elmo VIII-B; Tasch, 1963a), at the approximate horizon of the "Carlton Insect Beds." Preliminary study shows that the two coquinas appear to have similar species.

Two things are striking about this recurrence of a biofacies: first, the Cowley County occurrence (Table 1) is 12.3 feet above the top of the Herington, whereas the Dickinson County coquina is approximately 250 to 300 feet above that top; second, *Myalina meeki* Dunbar, a brackish-water pelecypod, occurs

TABLE 1.—Basal Wellington in Cowley County, Kansas. Fresh and brackish-water biofacies (SE NE sec. 21, T. 34 S., R. 3 E.).

Height above top of Herington, feet	Lithology	Fauna or faunal element (Macroscopic)[1]
13.8	Gray, waxy shale	Reptilian fragments;[2] snail-ostracode coquina
24.7	Buff-gray argillite	Reptilian fragments (scales, etc.)
30.6	Green, waxy shale	Conchostracans; reptilian fragments
38.7	Green, platy shale	Reptilian fragments; carbonaceous plant fragments
40.3	Massive, reticulated argillaceous limestone	Reptilian fragments; worm burrow?

1. Microscopic floral elements are discussed in the section on "Carbonized wood/plant beds."

2. Objects referred to as reptilian fragments throughout this paper, properly belong under fishes. This correction is important because fish are generally absent in modern conchostracan-bearing ponds in Kansas and Oklahoma, a condition that markedly contrasts with their frequent association with fossil conchostracans in the Wellington Formation (Permian).

in the Dickinson County coquina (Tasch, 1961, 1963a).

Thus, the interpretation derived from study of the transition from the marine Herington to the snail-ostracode coquina in Cowley County is sustained by the appearance of a brackish-water mollusk in the almost identical type of coquina in Dickinson County. It is such evidence taken from different localities in contemporaneous beds and in beds at different elevations above the datum that have led to the environmental interpretations given in this paper.

At the Cowley County section we also are afforded the earliest glimpse of the primary periodicity in the Wellington, i. e. recurrence of fresh-water, brackish-water deposits containing conchostracans, fish remains, and other fossils (Table 1).

Whereas the snail-ostracode coquinas are strictly limited in recurrence, one or another of the biofacies indicated in Table 1 recur intermittently to the top of the Wellington (Milan Member). We thus have unmistakable evidence of periodic fresh- to brackish-water conditions *throughout* Wellington time.

Evaporites (hopper crystals, salt casts, and gypsum), generally in small quantities, are found in recurring conchostracan-bearing beds. These evaporites provide a further criterion that these creatures lived in freshening relict ponds and puddles on a coastal flat. The oldest hopper crystal-bearing bed (Wellington XVIII)* occurs an estimated 50 to 70 feet above the top of the Herington. The youngest occurrence of evaporties was found two-tenths of a foot below the upper Milan Limestone which caps the Wellington Formation (Wellington XI).

A large-scale periodicity in the Wellington is the recently discovered cyclical recurrence of insect beds at approximately 100-foot intervals above the top of the Herington. Exclusive of the fourth 100-foot interval (for which data are lacking), insect beds were found in the first, second, third, fifth, and sixth 100-foot intervals above the top of the Herington (Tasch, 1962, Table 1). Of these insect beds, five contained conchostracans as well as insects, and other fresh-water biota.

* A tabulation of all localities is appended at the end of this paper.

The conchostracan-bearing beds represent the most persistent periodicity in the Wellington. These are found intermittently throughout the formation starting with the basal 40 feet and extending to the Milan Member. Two conchostracan-bearing beds also were found in the interbeds of the Annelly Gypsum, the top of which is an estimated 210 to 260 feet above the Herington.

A brief consideration of the conchostracan-bearing beds is necessary at this point to clarify the way in which a microscale periodicity was deciphered. It has been shown that in Leonardian time conchostracans intermittently occupied the same pond sites (themselves intermittent) in Sedgwick, Harvey, and other counties in Kansas. Such on and off occupancy ranged from 40 to 150 years, and frequently conchostracan occupancy lasted for a single season only. This determination was made for conchostracan-bearing beds 0.12 to 0.45 feet thick (Tasch, 1961).

As an example, we can examine one slab of an argillaceous limestone 0.32 feet thick. Eighteen distinct conchostracan generations were found in this slab. These creatures were and are seasonal animals that still persist in ponds in the same general area as the Wellington outcrop belt (Tasch and Zimmerman, 1961a). The time span calculated as necessary for this thickness to have been deposited was about 106.6 years. Because the slab is lithologically uniform, no periodicity could have been detected if one viewed the entire thickness as the result of a single unchanging depositional event.

However, separating this slab into distinct conchostracan-bearing surfaces, along which it readily parted, revealed a periodicity. The surfaces bearing clam-shrimp fossils represented times when pond conditions permitted clam-shrimp eggs to hatch and pass from naupliid to adult stage in a normal growth cycle covering a few months. By contrast, between these fossiliferous surfaces, the rock was barren of fresh-water biotic elements indicating that pond conditions represented could not sustain clam-shrimp populations. If the barren intervals were thicker, they would represent destruction of a given pond site by a marine influx and subsequent restoration of the pond site at a later time.

Many variations of this type of periodicity were found. Successive events in thin slabs of Wellington shale or limestone might be marked by other fresh- to brackish-water biotic elements such as mollusks, fish fragments, carbonized wood and plants, xiphosura, insects, and occasionally other items in the complete absence of conchostracans. In turn, these permitted the reconstruction of microcycles at a given pond site.

Thus, within the larger context of recurring fresh- to brackish-water conditions during Wellington time, it is necessary to abstract microscale periodicities in thin lithologic units. These permit interpretations of paleolimnological events on a basis heretofore unthinkable for a Paleozoic deposit, that is, a season-by-season account of successive events.

Thus, three major types of periodicities differing in scale are indicated:

Large scale—Insect beds recurring at approximately 100-foot intervals.

Small scale—Recurrent conchostracan beds, and multiple insect beds in 5 to 10-foot intervals, and the usual biotic associates of clam shrimps in beds lacking clam-shrimp fossils.

Microscale—Seasonal events separated by sediment intervals of 0.02 to 0.04 inch within insect and conchostracan-bearing beds.

All three of these periodicities are part of what is here designated as the "paleolimnological cycle," which will be discussed more fully in another section.

Events during Wellington time also include some acyclical deposits, i. e., those that are restricted in the formation. Among these are: the *Lingula* bed (discussed earlier), marine algal reefs, Hutchinson Salt Member * and the Annelly Gypsum, a hystrichsphaerid-dinoflagellate assemblage at a single locality and horizon (Tasch, 1963b), and several alga belonging to the same species at a single locality and single horizon (Wellington II-C, bed 3).

* The well log of the salt at a mine in Hutchinson shows cyclical deposition of salt, anhydrite, and shale. However, relative to the entire Wellington, the evaporite event may be viewed as acyclical. The same holds for the Annelly Gypsum.

SMALL-SCALE PERIODICITY

Sediment Interval

Tables 2, 3, and 4 show the recurrent biofacies with a view of emphasizing the sediment interval between them. Table 2 represents the second to third 100 feet above the Herington; Table 3, the fifth 100 feet; and Table 4, the sixth 100 feet.

The sediment interval between any two successive fossiliferous beds varies between very short intervals of tenths of a foot to short intervals of 3 feet or less, and finally to intervals of greater than 5 feet. Study of these tables indicates that in the Kansas section (Table 2), 83 percent of all sediment intervals are 3 feet or less; in the Noble County section (Table 3), this interval occurs 75 percent of the time, whereas in the Kay County section (Table 4), it occurs 86 percent of the time. Since these three sections represent different portions of Wellington time, it is apparent that the fresh-water, brackish-water biofacies followed a similar rhythm in recurrence.

The basal Wellington, by contrast (Table 1), had only thicker sediment intervals of 5 feet or greater between successive biofacies. At this locality it appears that the epeiric sea covered the coastal area for longer periods of time. Only when this sea retreated from the coastal area were relict brackish- to fresh-water bodies available.

Very short sediment intervals between successive biofacies separated by a few hundredths of an inch are unlikely to be related to marine transgression. Rather, these represent persistent pond conditions through several seasons or years. Approximately 50 percent of all sediment intervals are less than 1 foot in thickness. In most of these intervals decades of time separated any two successive conchostracan-bearing beds.

Environmental Indicators

There are a variety of environmental indicators which provide critical evidence on the sedimentary environment during portions of Wellington time. Some of these indicators are illustrated in Figure 1.

Figure 1A shows a small-scale algal (biscuit) structure. This was secreted by marine algae when the epeiric sea washed over a portion of the coastal area dotted with ponds and puddles in which conchostracans thrived. Insects are found on the flanks of these algal structures suggesting freshening pools as the sea receded.

Figure 1B shows such algal masses and their areal disposition. These structures created a shallow-water topography. Pools that formed between and around such structures freshened and bore conchostracans.

Figure 1C indicates that after the insect-conchostracan bed was deposited, the bottom muds became desiccated (as shown by the mudcrack bed). That, in turn, was followed by a marine transgression as evidenced by the algal bed.

A few tenths of a foot of section is shown

Table 2.—Composite of all clam shrimp-bearing beds and other biotic horizons in a 4-county area (Sedgwick, Harvey, Marion, and Dickinson Counties, Kansas).

Clam shrimp C-horizons	Other faunal horizons	
C_{17}-56.0[1]		
- - - - - - - - - -	10′ cover - - - - - - - - - -	
C_{16}-47.5		
C_{15}-47.4		
C_{14}-45.4		
C_{13}-45.1		
C_{12}-45.0		
- - - - - - - - - -	44.8′ log bed	42′-44′ snail-ostracode coquinas
C_{11}-43.1		
C_{10}-42.1		
- - - - - - - - - -	42.0′ insects[2]	
C_{9}-41.5		
- - - - - - - - - -	41.0′ insects	
C_{8}-40.4		
C_{7}-39.9		
- - - - - - - - - -	37.2′ insects	
C_{6}-28.2		
C_{5}-27.7		
C_{4}-26.0		
- - - - - - - - - -	22.4′-24.2′ plants[3]	
C_{3}-21-22		
- - - - - - - - - -	16.5′ mollusks	
C_{2}-11.5		
C_{1}-10.-11 - - - - - -	insects	
C_{0}- 3.5BG		
C_{00}- 5.78BG		

1. All elevations are in feet above the Annelly Gypsum except C_0 and C_{00} which are given in feet below the top (BG). Total thickness: about 65 feet.

2. The three insect beds constitute the "Carlton Insect Bed" and taken together are one of the large-scale periodicities discussed in this paper.

3. Plants and mollusks are also found in many clam-shrimp beds in addition to the indicated horizons. This also applies to other biotic elements.

TABLE 3.—Fresh-water biofacies in Wellington Formation of Noble County, Oklahoma (Noble I A-D).[1]

Elevation above base of section, feet	Clam-shrimp fossils	Insects	Plants and carbonaceous beds	Fish fragments and xiphosurans
9.2			X	
21.3[2]	X	X		
21.4	X	X	X	X
22.0	X			
22.7[3]		X	X	
22.8			X	
24.1[4]	X	X		
31.4[5]	X	X		
31.5	X			
31.9			X	
32.4	X			
33.8	X			
34.9	X			
37.7	X			
44.6	X			
45.9	X			
46.0	X		X	X
47.0	X			

1. Total thickness of composite section is about 77 feet.
2. 3. 4. Respectively, the lower, middle, and upper insect beds of the Midco.
5. The *Asthenohymen-Delopterum* Insect Bed (Tasch and Zimmerman, 1962).

in Figure 1D that represents a portion of the Milan Member of the Wellington. The ripple-mark surface, which denotes very shallow water, was succeeded by a mudcrack surface that denotes a regression of the sea. A clam shrimp-bearing, argillaceous limestone shows that relict ponds had freshened only to be followed by a period of desiccation (upper mudcrack surface). The sea once again covered the area and deposited a barren limestone.

Ten distinct sets of mudcrack surfaces are shown in Figure 1E; these occur within a thickness of 1.1 foot. There is also a ripple-mark surface in the lower third of this sequence. In and between several mudcrack surfaces, there are four conchostracan generations represented. Two additional conchostracan generations occur on and directly below the ripple-mark surface. The mudcrack surfaces are separated from each other by very thin shale partings. Such surfaces and the recurrent fresh-water fauna clearly represent alternate wetting and drying conditions in the area. A tongue of the sea could wash over the coastal area briefly then retreat during which time the mudflat dried up except for isolated puddles, then the sea could wash over the area again, etc.

The association of conchostracans on and below the ripple-mark surface suggests that they thrived in nearshore puddles, probably brackish, and when current ripples developed in the shallows and the sea retreated again, they thrived in narrow lenses of brackish water in the troughs between ripple crests.

Figure 1F illustrates the type of fresh- to brackish-water, clayey-lime mud deposition. Carbonized plants and conchostracans occur throughout the 0.8 foot of limestone. The upper of the two units contained the brackish-water pelecypod *Myalina meeki* Dunbar. These limestones clearly were deposited in a brackish-water swamp environment which was

TABLE 4.—Fresh-water biofacies in Wellington Formation of Kay County, Oklahoma (Wellington XIX).[1]

Elevation above base of section, feet	Clam-shrimp fossils	Insects	Plants	Xiphosurans?
19.9	X			
21.6	X			
21.7	X			
28.1	X			
28.6	X			
30.0	X			
30.5	X		X	
31.1[2]	X	X		X

1. Total thickness of section is 41.3 feet.
2. This bed has been tentatively designated as the "Youngest Insect Bed" (YIB; Tasch, 1962).

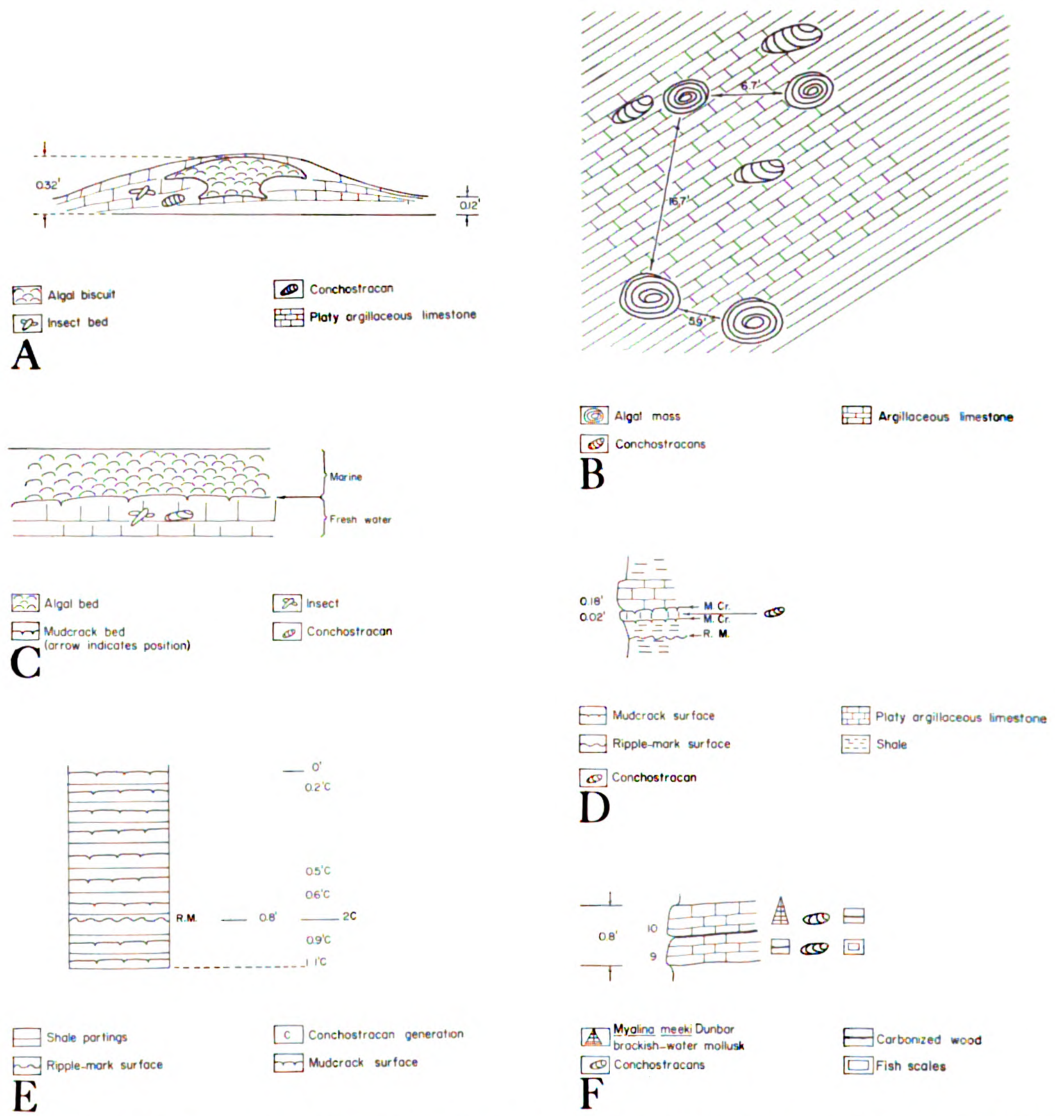


FIGURE 1.—*A*, Small-scale algal (biscuit) structure. *B*, Plan view of algal structures. *C*, Relation of desiccated bottom muds to overlying insect-conchostracan bed. *D*, Milan Member of Wellington Formation. *E*, Ten distinct sets of mudcrack surfaces that occur in 1.1-foot interval. *F*, Relation of fresh- to brackish-water deposits of clayey-lime mud.

marginal to a coast. The presence of conchostracans indicates freshened isolated puddles on this clay-carbonate mud bottom.

Interpretation of the depositional environments throughout Wellington time is derived from evidence of the type discussed above. Multiple examples of the types mentioned and a wide range of other examples lend support to the conclusion that, exclusive of the major evaporitic deposition in the Wellington, the absence of the fresh- to brackish-water biofacies in any portion of the Wellington denotes shallow-marine deposition.

Carbonized Wood/Plant Beds

Elsewhere (Tasch, 1963a, Table 2), it has been shown that carbonized wood/plant beds occur at approximately 10-, 20-, 30-, and 40-foot intervals above the top of the Annelly Gypsum in Harvey, Marion, and Dickinson

Counties, Kansas. The top of the Annelly is approximately 210 to 260 feet above the Herington (Tasch, 1962, Table 1). Thus, the carbonaceous facies occur at 220 to 270, 230 to 280, 240 to 290, and 250 to 300 feet above the Herington Limestone.

Carbonized wood, etc., occurs 38.7 feet (Table 1) above the Herington in Cowley County (Cowley I). A series of slides of all beds of this section processed for spores, pollen, and carbonized debris adds information to this picture. Carbonized material also occurs 6.1 and 36.1 feet above the Herington. At Wellington XVIII carbonized material was found in the insect bed which is an estimated 50 to 70 feet above the top of the Herington Limestone.

Carbonized plant facies occur in the Noble County sections ("Midco Insect Beds" are approximately 550 feet above the Herington) as follows: 538, 551, 567.9 and 575.8 feet; these may be broadly interpreted as filling the 540-, 550-, 560-, and 570-foot intervals above the datum.

In the estimated 595 to 668-foot interval above the Herington there is negligible macroscopic carbonized wood/plant material (Wellington XIX; elevation of the youngest insect bed in the Wellington at this locality is an estimated 630 to 668 feet; *see*, Tasch, 1962, Table 1). Palynological analysis however, shows considerable carbonized wood, spores, and pollen in this interval. These occur at 6 to 9-foot intervals with several tenths of a foot recurrences between some of the larger intervals.

Another bit of evidence may be cited here. Elsewhere (Tasch, 1960), an occurrence of carbonized wood in shale interbedded with Hutchinson Salt in the Carey salt mine at Hutchinson was reported. Since then, the writer has found carbonized floral debris (gymnosperm tracheid cells not unknown in other Wellington beds) in shale in-fills in this mine. The writer's former field assistant, Bernard Shaffer, demonstrated that a microfloral suite of spores and pollen occurred in the salt both at the Hutchinson and Lyons, Kansas, mines (Shaffer, 1961).

If, as Dunbar suggested (1924, p. 194), the upper portions of the Hutchinson Salt lie at or slightly below the level of the "Carlton Insect Beds," then the carbonized wood and microfloral suite found in the salt should correspond to one or another of the recurrent carbonaceous facies in the 220 to 290-foot interval above the Herington.

The picture that emerges at present indicates that small-scale rhythmicity of carbonaceous facies in the Wellington can be demonstrated on the macroscopic level for the following intervals above the Herington: 220 to 290, and 540 to 570 feet. On the microscopic level, comparable rhythmicity can be shown for the 595 to 668-foot interval. The record of the basal one hundred feet as noted, is sparse. This is true even when implemented by palynological study of all exposed beds in the sequence. However, the same type of recurrence of carbonized wood facies is apparent although the sediment interval between any two successive carbonized wood facies in this portion of the column is generally greater than in other sections. With these restrictions in mind, one can also include the 6 to 70-foot interval.

This record might be less spotty if more and better exposures were available for sampling. Nevertheless, it does establish the recurrence of both macroscopic or microscopic carbonaceous facies in the Wellington.

A distinct floral absence * is indicated for the upper 32 feet of the Wellington (above 668 feet), that persisted through all of the overlying Ninnescah Shale.

It has already been suggested (Tasch, 1962) that this floral absence could "reflect some important environmental change." However, whatever change did occur, affected only the insects which are also absent above 668 feet and all through the Ninnescah Shale.**

PALEOLIMNOLOGICAL CYCLE

General Characteristics

A paleolimnological cycle has not heretofore been defined. The Wellington cycle was controlled by small regressions and transgressions of an epeiric sea over a coastal flat or

* Palynological study of the Milan type section and all Ninnescah beds failed to reveal any palynomorphs of any kind. Several Ninnescah samples were rerun as a check also with negative results.

** The striking biotic change that occurs above the 668-foot level, suggests that this level should logically be the top of the Wellington.

marginal swamp. There are many other possible controls for such a cycle: (1) shrinkage of a river's volume leaving isolated pools on a floodplain (Missouri River floodplain, for example) in which conchostracans thrived; (2) relict ponds, hospitable to conchostracans and other fresh-water biota on the emerged portion of a delta or the shallows of estuaries; or (3) the shallow margins of inland lakes. Today, particularly as pertains to conchostracans, such cycles occur in temporary inland bodies of fresh water, seasonally. The control, in this last instance, is the available relief (i. e., the existence of any kind of depression, regardless of size), precipitation, and static dispersal of clam-shrimp eggs by wind or water. In the Wellington outcrop belt of Kansas and Oklahoma, this control applies to the present-day ponds. Twelve percent of these ponds contain living clam shrimps (Tasch and Zimmerman, 1961a, 1961b).

The Wellington paleolimnological cycle has two phases: Phase I—the coming into existence of temporary ponds. Two different periods are associated with this phase, namely, the large-scale period, recurrent, insect beds, and small-scale period, recurrent, conchostracan beds. Phase II—seasonal events in ponds that come into being (recur) in Phase I. Here, the only period is microscale, i. e., events separated by a few millimeters of sediment.

Phase I generally involves a transition from normal marine to brackish- to fresh-water conditions. The step from normal marine to brackish is first achieved by regression of the sea. The step from brackish to fresh is achieved by evaporation that acts to fractionate the brackish zone into isolated ponds and puddles.

Presence of large-size hopper crystals and considerable numbers of salt casts and gypsum in a fresh-water biofacies can be explained by omitting the brackish-water step. The complete absence of evaporites in any quantity suggests that the brackish-water step was a prelude to the fresh-water biofacies.

Thus the two types of events would be:

A: Normal marine → regression → fractionation into relict ponds → evaporation → fresh-water ponds . . .

B: Normal marine → regression → brackish inner margin → evaporation → fresh-water ponds . . .

Where the fresh-water biofacies terminates and is succeeded by nonfossiliferous shales, a slight normal marine transgression over the area is indicated (Fig. 1C).

There are, of course, variants of A and B. During Annelly time, conditions were obviously evaporative, and a cutoff margin of an inland sea gave rise to the gypsiferous deposit. Because conchostracans occur in some shale interbeds of the gypsum, it is apparent that the same evaporatic conditions that caused shrinkage of the Annelly basin also created temporary fresh-water conditions on its margins (with a one-to-two inch cover of water). That would define a modified cycle.

C: Normal marine → cutoff → evaporation leading to evaporitic deposits → marginal fresh-water ponds → marine influx → cutoff → evaporation leading to evaporitic deposits . . .

There is another variant of C that does not generally involve evaporites (Fig. 1E).

D: Evaporation or shrinkage of brackish-water zone → relict puddles on mudcrack surfaces bearing fresh-water biota → brackish-water cover → evaporation or shrinkage, etc.

Seasonal Component of Paleolimnological Cycle: Insect Beds

Phase II of the paleolimnological cycle covers the sequence of seasonal events, i. e., events that transpired during the life of a given pond site. Characteristic of all such sites in the Wellington is that they were varisized depressions intermittently filled with water (Tasch, 1961, 1963a; Tasch and Zimmerman, 1961a).

Figure 2 illustrates the biotic spectra of the insect beds, which, as noted previously, constitute the large-scale periodicity in the Wellington. The recurrent features of these beds are: (1) same faunas (frequently on the species level, although particular insect genera show changes in ratios of abundance); (2) evaporites (salt casts and hopper crystals); and (3) carbonaceous material (wood and plant debris).

The distinctive characteristics of these beds are:

(1) Seasonal differences in biotic components. For example, Figure 2, Elmo IV, the ostracodes, fossil leaves, insects and xiphosura do not recur throughout the given bed, but are restricted to certain sea-

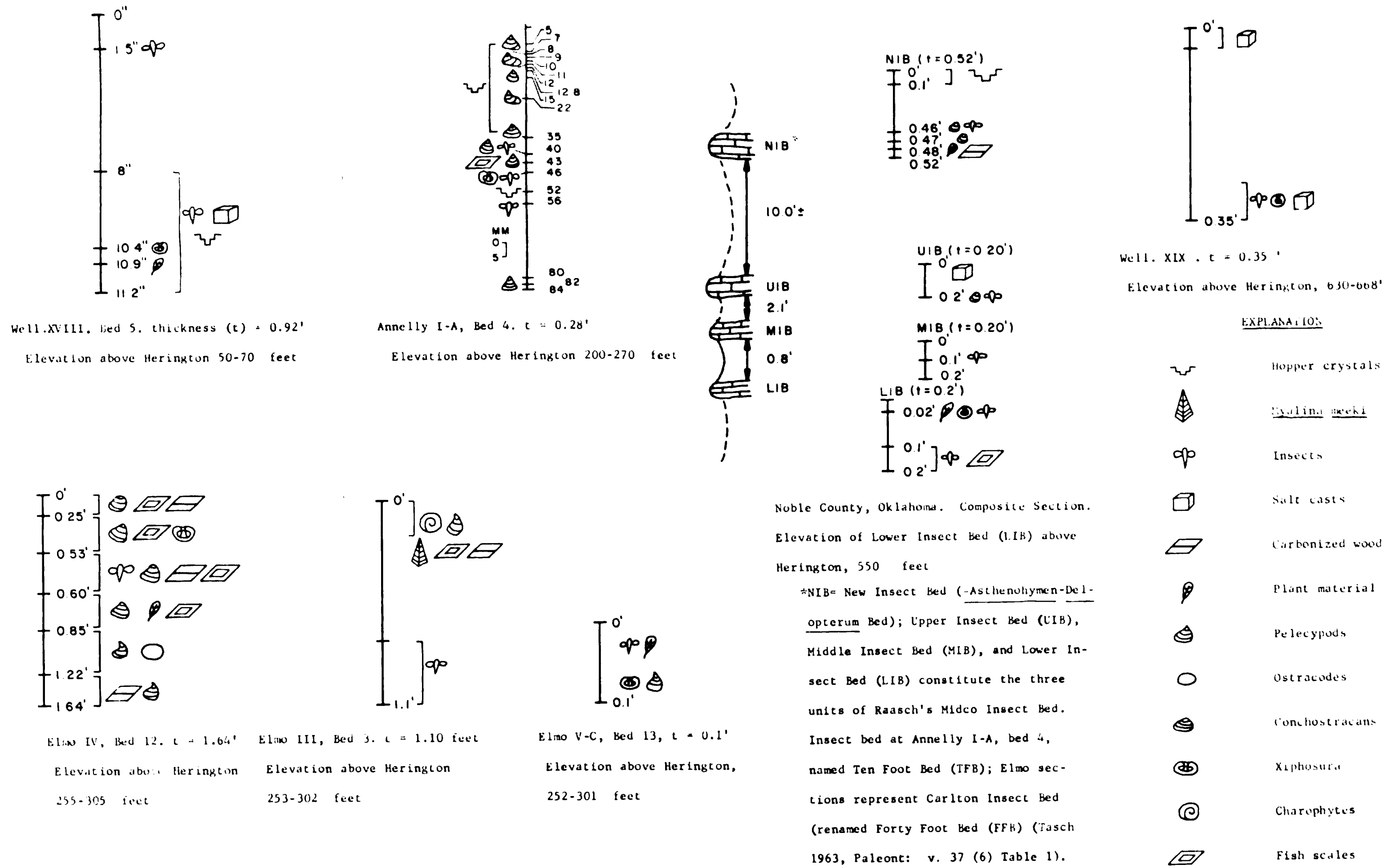


FIGURE 2.—Biotic spectra of insect beds.

sons only. Conchostracans which are also seasonal do recur through such beds.

(2) Brackish-water elements such as the mollusk, *Myalina meeki* D., are restricted to a few of the insect beds.

(3) Where they occur, hopper crystals and salt casts are always restricted to a particular season or successive seasons. Hence, the insect bed in which they occur cannot be viewed as representing a single evaporative event.

(4) The portions of the biotic spectra in Phase II that are nonfossiliferous indicate multiple seasons when the pond represented was barren of fresh-water biota. (We take one season to equal one year of time, although actually it represents a few months).

Seasonal Component of Paleolimnological Cycle: Conchostracan-Bearing Beds

Although conchostracans occur in some of the insect beds, they are found in many interbeds as well. Very small intervals (hundredths of an inch) within such units as the conchostracan-bearing beds may be attributed to the seasonal history of a given pond site. Accordingly, such beds can be evaluated in terms of seasons of time.

Ten feet above the *Asthenohymen-Delopterum* insect bed in Noble County, Oklahoma (Noble II B, bed 3), 25 conchostracan generations were found in a thin, fissile shale 3.2 inches thick. These generations occurred below the top of the bed (in millimeters) as follows: 3.5; 5.0; 10.0; 13.0; 15.0; 21.0; 23.0; 24.0; 25.0; 27.5; 32.5; 33.0; 34.5; 36.5; 38.5; 39.5; 41.0; 46.0; 47.5; 49.5; 51.5; 53.5; 56.5; 58.5; and 62.5 (this is bottom surface).

The smallest sedimentary interval between two conchostracan-bearing surfaces was 0.5 mm (= 0.0192 inch = 0.02 inch; Tasch and Zimmerman, 1961b; Tasch, 1961). The time represented by this one fossiliferous bed (3.2″/0.02″) is about 160 years. If there had been one generation per year, there should have been 160 conchostracan generations. Actually, about one-fifth of maximum was found to have occurred.

Table 5 graphically illustrates the paleolimnological cycle represented by the Noble County sample. The graph shows the variable time value in seasons for successive sediment intervals between clam shrimp-bearing surfaces. The table is to be read as follows: Generation I died out and the pond remained barren for eight successive seasons (years). Generation II lived a season and for the next four seasons the pond site was barren, etc.

The sedimentary cycle in this Leonardian pond appears to have been quite simple:

(1) The bottom cover was composed of gray, silty clay muds subsequently blackened by an influx of carbonaceous debris (plants).

(2) Into this matrix the valves of the given population (generation) settled at death of the individual conchostracans.

(3) As the pond seasonally dried up, silt and clay, suspended in the water, settled as a fine layer over the conchostracan valves. This suspended material had been, in part, added to the water by conchostracan-burrowing and tracking of bottom muds.*

(4) When the pond filled again the next season, clay muds were deposited perhaps by feeder streams. Clam-shrimp eggs that had survived from the previous season in the dried-out bottom muds of this or other pond sites were spread by wind or water. Naupliid conchostracans were hatched from such eggs and began the next conchostracan generation at the given pond site.

As shown by the sediment intervals on Table 5, the given pond site we are discussing was barren of conchostracans and associated fresh-water biota four-fifths of the total time it endured.

A similar, yet more complete, cycle, because a more complex biota occurred in the life of the pond site, was found in Harvey County (Annelly IA; *see*, Tasch, 1961, Fig. 2). This cycle has yet to be evaluated on a seasonal basis but that will be done here (Table 6).

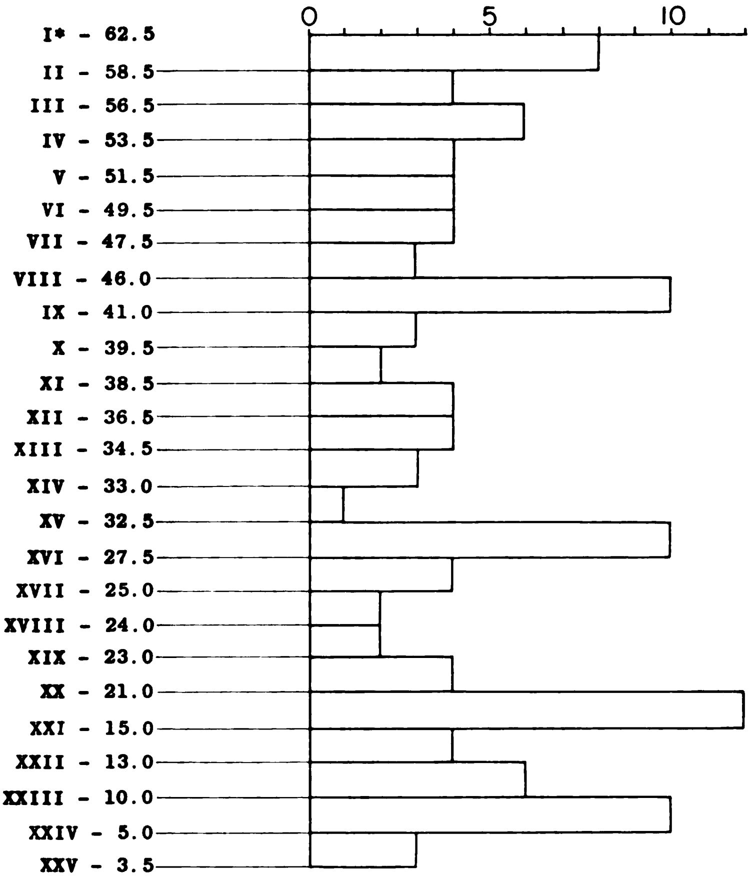
Table 6 indicates the following history during the time represented by 0.28 foot of sediment deposition.

(1) From 84 to 80 mm. Clam shrimp Generation I occupied the pond for a season. The next two seasons the pond was barren. Generation II then occupied the pond and died out at the end of the season. Two seasons then passed in which the pond was bar-

* Since there is nothing in the literature on this subject, observations on living clam shrimps made in the laboratory may be of interest. Conchostracans create microturbidity currents when they burrow in the bottom muds. They also form tracks on occasion. Such tracks are represented in the bottom muds as continuous winding depressions. The depth of the depression, as well as its width, indicates the amount of sediment removed by a given conchostracan responsible for the track. *See*, Kansas Acad. Sci. Trans., 1964, v. 67 (1).

TABLE 5.—The Paleolimnological Cycle, Phase II—Leonardian Wellington of Noble County, Oklahoma (Noble II-B, bed 3, thickness 3.2 inches).

Conchostracan generation number	Depth below top of bed (mm)	Time-value of sediment interval between any two successive conchostracan-bearing beds (in years) (1 season = 1 year)



*Each conchostracan-bearing surface in this rock represents one season (year) with the exception of Generation XIV-XV, which are interpreted to be "same-season" generations. For the total history of the pond-site these seasons must be added to those represented by the sediment intervals between conchostracan-bearing beds

ren. This was before Generation III occupied it.

(2) From 80 to 56 mm. When the clam-shrimp Generation III died out at the end of the given season, the pond site ceased to exist, probably due to an influx of brackish water. (The absence of evaporites suggests brackish instead of normal marine). This condition persisted for approximately 24 consecutive seasons when an insect fauna frequented the margins of the new pond site.

(3) From 56 to 52 mm. Some of the insect fauna died at the end of the particular season. Other individual insects may have migrated from the area. The appearance of hopper crystals suggests that the pond site

may once again have been under a cover of normal marine water.

(4) From 52 to 46 mm. A xiphosuran fauna inhabited and an insect fauna frequented the pond site after a lapse of four barren seasons.

(5) From 46 to 35 mm. After a lapse of three seasons, fishes frequented the pond site and clam shrimps inhabited it. At the end of the given season, the conchostracans died and did not reappear until after the lapse of three more seasons (Generation V). Five seasons then passed with the pond site either under a brackish-water cover or, if still extant, barren of fresh-water biotas. At the end of that time normal pond conditions were restored as Generation VI appeared.

(6) From 35 to 5.0 mm. All during this interval, hopper crystals were being deposited. The sea apparently washed over the pond site area repeatedly and for brief intervals; it then retreated. Pond volume shrinkage by evaporation would then account for the hopper crystals.

Eleven seasons elapsed from Generation VI to the appearance of the pelecypod *Productae dunbaris*. The clay conglomerate associated with this mollusk suggests drying of clay mud and redistribution of enrolled desiccated fragments over the flat. Nine seasons followed that were barren of fresh-water biota. Thus, two decades are indicated between successive conchostracan occupancy of this pond site.

Generation VII then appeared and within the same season, Generation VIII. This is evidenced by the sediment interval which is less than the annual rate of sedimentation in the area. Thereafter, for two successive seasons, while clam shrimps were totally absent, the pond site supported *Productae dunbaris*.

After two more seasons, Generation IX appeared, followed in the next season by Generation X, and two seasons later by Generation XI.

Thus, the intermittent occupancy of the given pond site by fresh-water biotas covers almost a century of time and is now represented in an argillaceous limestone a few tenths of a foot thick.

TABLE 6.—Paleolimnological cycle—Phase II, Harvey County, Kansas (Annelly I-A).[1]

Conchostracan generations (Gen. I, etc.) and other elements	Depth below top of bed (mm)	Time-value of sediment interval between successive pond events, years
Gen. I	84.0	
		2
Gen. II	82.0	
		2
Gen. III	80.0	
		24
Insects	56.0	
		4
Hopper xtals; shale cg.	52.0	
		6
Insects; xiphosura	46.0	
		3
Fishes; Gen. IV	43.0	
		3
Insects; Gen. V	40.0	
		5
Gen. VI	35.0	
		11
Cg. layer;[2] pelecypods	22.0	
		9
Gen. VII	12.8	
		1[3]
Gen. VIII	12.0	
		1
Pelecypods	11.0	
		1
Pelecypods	10.0	
		2
Gen. IX	8.0	
		1
Gen. X	7.0	
		2
Gen. XI	5.0	

1. Total thickness of this bed = 0.28 feet.

2. Conglomerate layer. Hopper crystal deposition occurred from 5 to 35 mm below top of bed.

3. Sediment interval is less than the annual rate of sedimentation and hence Gens. VII and VIII occurred within the same season (year).

WELLINGTON OF KAY COUNTY, OKLAHOMA (SEDIMENTARY HISTORY OF SUCCESSIVE CONCHOSTRACAN BEDS)

At locality Kay I and Kay I-offset, more than 40 successive conchostracan beds were found in some 57.4 feet of section.* Here, then, is an excellent exposure to examine in order to find answers to the following questions: (1) What is the range of lithologies characteristic of multiple clam shrimp-bearing beds at one locality? and (2) What are the sedimentary events that eliminated a given

* This material is still being processed, and the discussion is based on field notes.

pond site for shorter or longer intervals of time?

Fresh-Water Deposits

The successive clam shrimp-bearing beds are generally units of a few tenths of a foot thick which testifies to the relatively short duration of the water bodies they represent. Blocky, platy, laminated waxy shales and argillaceous limestones are the recurrent lithologies in such beds. The color of the thin limestones is generally gray-blue weathering gray-white. These limestones are hard beds and stand out in outcrop since they are more resistant to weathering than overlying or underlying shales. Equivalent beds in Kansas sections have greater than 50 percent carbonate as determined by insoluble residue studies.

The shales are generally some variation of green, black-green, or gray-green. Red shale is rare in the Kay County section.

From study of the lithologies of the 40 plus clam shrimp-bearing beds of Kay County, certain observations emerge:

(1) Small quantities of carbonate (or the complete absence of carbonates) in the bottom muds at any given time had no effect whatsoever on conchostracan growth and reproduction. These forms are as abundant and sometimes more abundant in the shales as in the limestones. Some of the shales, of course, are calcareous.

(2) Despite its thinness, the argillaceous limestone within a given bed frequently shows gradation upward or downward to blocky, platy or laminated shale. That would indicate temporary and limited increase in carbonate in the given water body where the dominant sediment was clay mud.

(3) The top beds of the Kay section are siltstone and sandstone. These are laminated and cross-bedded as well as pelletiferous. Several surfaces contain conchostracan fossils.

Somewhat lower in the section (Fig. 1E), a mudcrack bed composed of argillaceous siltstone showed ripple marks. The lower inch of this bed is a purple orthoquartzite. Five successive conchostracan generations occur in this unit.

The mudcrack surface and ripple marks indicate deposition in the shallowest portion of a brackish-water cover with minor onlap and offlap controlled by slight oscillations of the sea.

(4) Frequently, the fossiliferous argillites are waxy to the touch, suggesting a relationship to the organic content; however, chemical determinations have yet to be made. It should be noted, however, that many waxy shales are barren of fossils.

Observations of ecdysis of living conchostracans in aquaria show that the creatures shed a very thin chitinous duplicature of the entire skeleton. These objects float for a while and then sink to the bottom muds. On the mud, they soon crumple or roll into an indistinguishable mass. Such chitinous material could be reworked by chitin-reducing bacteria although there is no direct evidence of the presence of such forms in Leonardian time. Chitin-reducing enzymes secreted by snails could also reduce such fine duplicatures. However, mollusks were not found in the Kay County sections.

Even explanations of this kind for fossiliferous waxy shales would still leave the barren waxy shales in the Wellington to be explained. Microscopic algae that seasonally cover all or a portion of many extant Kansas ponds may have had Leonardian equivalents. If so, that might account for the waxy shales. A few undetermined yet apparent algal filaments have been found in one or two Wellington sections in Sumner County but not in waxy shales. The only algae that have been found in Kay County, Oklahoma, and Sumner County, Kansas, were carbonate-secreters that formed reeflike and biscuitlike structures. Most of the waxy argillites in Kay County, surprisingly, lack spores or other palynomorphs. Therefore, in most instances, this type of explanation would be inapplicable.

(5) Grading into an argillaceous limestone in one bed of the Kay County section, was a sedimentary conglomerate of clay pebbles. Such objects were probably formed in shallow nearshore depressions that paralleled the shore or in desiccated portions of the mud bottom.

Interbeds and Sedimentary Events Indicated

The second question pertains to the types of sedimentary events that followed a given fresh-water biofacies in the Kay County section. One can take certain relatively closely spaced biotas as an example. The beds range from 62 (older) to 59 (younger). These are field numbers and are reversed for convenience.

Between bed 62 (a hard, argillaceous limestone), that contains insects and conchostracans, and the next overlying conchostracan-bearing bed, there occurs an interval of 0.1 foot of black, waxy shale. In turn, that is overlain by 0.1 foot of a hard, argillaceous limestone bearing conchostracans and xiphosura. That bed is separated from the next higher fossiliferous bed by 0.04 foot of a black, waxy shale. The next three fossiliferous units occur at approximately 0.1-foot intervals of shale or argillaceous limestone. A waxy shale 0.41-foot thick that overlies the upper of these fossiliferous beds is followed by another conchostracan bed.

Measurements indicate that the annual rate of sedimentation is about 0.02 inch for these Leonardian beds. Taking this figure, for the intervals given above that separate conchostracan beds, the time value in years (from older to younger) is: 60, 60, 24, 60, and 240. If the sedimentation rate is doubled, i. e., taken to be 0.04 inch as in the Kansas sections, these rates would be halved.

These intervals should be compared with those given in Table 5 for a single fossiliferous bed with 25 successive conchostracan generations in a sediment thickness of 3.2 inches. If multiple generations had occurred in successive seasons in the *same* pond, they would have been represented by separations between generations of as little as 0.02 inch. Because in actuality at the locality under discussion, they did not recur after such intervals, it is apparent that each of these fossiliferous beds represent a single season. At the end of one season multiple decades elapsed before a new pond site came into being at the same locality.

The most plausible explanation appears to be that the existence of pond sites, as noted earlier, was a fortuitous result of movements of an epeiric sea on and off a coastal flat.

In turn, this last observation may have value as a climatic indicator. If there were temporary ponds that seasonally dried up and contained evaporites during any of the 60-year intervals, such occurrences would denote a more arid weather cycle. In the absence of such evaporites or of evidence of small-scale wetting and drying during the 60-year intervals, a more temperate weather cycle would be indicated.

The point here is that there was a variation in weather during Wellington time; this can be inferred when thin units are studied that represent decades of time instead of millenia. The concept of deciphering, or at least securing a glimpse of "weather cycles" as distinct from overall climate in selected Paleozoic deposits, seems to merit additional study and may have applicability to Pennsylvanian and Permian cyclothems * as well as older Paleozoic evaporite sequences.

In view of these considerations, the question asked earlier can be answered. The pond sites ended after a single summer. Decades to centuries of time separated successive pond sites at the same locality. The control appears to have been the minor fluctuations of an epeiric sea. Influx of occasional carbonized material indicates a vegetal cover in the swampy inland environs, and such debris was probably transported by small nonpersistent feeder streams.

CONCLUDING REMARKS

Raasch (1946, p. 91) interpreted the upper 50 feet of the Midco as a sequence of seven cyclothems. There is no doubt that some kind of periodicity occurred (*see*, Table 3; Fig. 2). The new data, some of which have been reviewed in this paper, suggest that the primary periodicity was a recurrent paleolimnological cycle (Table 5, for example). The difference in these two interpretations may arise from the difference in the scale used as well as in a difference of orientation. The present re-

* It should be noted that conchostracan fossils are present in many Pennsylvanian cyclothems and in such deposits as the Dunkard Group (Permian).

search has shown that the single most persistent recurrence in the Wellington from basal portion to capping limestone is the conchostracan-bearing beds. When one keys his scale to this fact, the paleolimnological cycle emerges as the chief periodicity.

Certain similarities to the Dunkard cyclothem (Beerbower, 1961) were suggested to the writer by the recurrence of carbonaceous beds at approximately 10-foot intervals above the gypsum in the Kansas Wellington sections (Tasch, 1963). Occurrences of conchostracans, fresh-water ostracodes and vertebrates, as well, in the Dunkard and Wellington seemed to strengthen this idea.

However, it remains to be seen by processing of all Wellington and Ninnescah samples on hand, and detailed comparisons to the Dunkard, whether the paleolimnological cycle can be made to fit into a modified Dunkard-type cyclothem. More importantly, it remains to be seen whether any new insights into environments, biotas, and sediments are thereby achieved. It may turn out that the concept of the "paleolimnological cycle" is a more productive approach.

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LIST OF LOCALITIES

COWLEY COUNTY, KANSAS
- Cowley I—SE NE sec. 21, T. 34 S., R. 3 E.

DICKINSON COUNTY, KANSAS
- Elmo VIII-B—SW SW sec. 36, T. 16 S., R. 3 E., and offset.
- Elmo III—C SE sec. 21, T. 10 S., R. 2 E.
- Elmo V-C—NE SE sec. 28, T. 16 S., R. 2 E.

NOBLE COUNTY, OKLAHOMA
- Noble IA-D—SW NE sec. 34, T. 22 N., R. 1 W., and offsets.
- Noble III—SE SW sec. 28, T. 24 N., R. 1 W.
- Noble IV—SW SW sec. 23, T. 24 N., R. 1 W.
- Noble II-A—NW NW sec. 4, T. 23 N., R. 1 W.
- Noble II-A—SW SW sec. 23, T. 24 N., R. 1 W.

KAY COUNTY, OKLAHOMA
- Wellington XIX—SE NW sec. 20, T. 29 N., R. 2 W.
- Kay I—NW SW sec. 21, T. 25 N., R. 1 W.

SUMNER COUNTY, KANSAS
- Wellington II-C—NW NE sec. 18, T. 32 S., R. 1 W., offset.
- Wellington XVIII—NW NE sec. 23, T. 34 S., R. 2 E.
- Wellington III—SE SE sec. 30, T. 32 S., R. 3 W.
- Wellington XI—NW NW sec. 23, T. 34 S., R. 2 W.

HARVEY COUNTY, KANSAS
- Annelly 1-A—NW NE sec. 21, T. 23 S., R. 2 E.

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Cyclic Lacustrine Sedimentation, Upper Triassic Lockatong Formation, Central New Jersey and Adjacent Pennsylvania

ABSTRACT

Upper Triassic Lockatong lacustrine deposits in central New Jersey and adjacent Pennsylvania are arranged in short asymmetrical "detrital" and "chemical" cycles that resulted from expansion and waning of the lake, presumably due to cyclic variation in climate.

Detrital short cycles, averaging 14 to 20 feet thick, comprise several feet of black shale succeeded by platy dark-gray, carbonate-rich mudstone in the lower part and gray, tough, massive calcareous silty mudstone in the upper. The massive mudstone has a small-scale contorted fabric produced largely by crumpled shrinkage cracks and burrows. Thicker, coarser grained detrital cycles contain 2 to 5-foot layers and lenses of thin-bedded, commonly cross-stratified siltstone and very fine grained sandstone, locally with small-scale convoluted bedding.

More common chemical short cycles average 8 to 13 feet thick. Lower beds are alternating dark-gray to black, platy dolomite-rich mudstone and marlstone 1 to 8 cm thick, extensively broken by crumpled shrinkage cracks. Locally initial deposits are crystalline pyrite or calcite as much as 2 cm thick. In the middle, several feet of dark-gray mudstone encloses 2 to 8 cm-thick layers of gray marlstone disrupted by syneresis. The upper part is gray, tough, massive analcime- and carbonate-rich mudstone containing as much as 7 percent soda and as little as 47 percent silica, and a maximum of about 35 to 40 percent analcime. The mudstone is brecciated on a microscopic scale, probably the product of syneresis. Much of the mudstone is also disrupted by slender crumpled shrinkage cracks irregularly filled with crystalline dolomite and analcime.

Some thinner chemical cycles are grayish red, especially in the uppermost part of the formation. These contain layers of greenish-gray weathering mudstone variously disrupted by shrinkage cracking. Thinner beds are broken into mosaic intraformational breccia; thicker ones are disrupted by long intricately crumpled cracks. Small lozenge-shaped pseudomorphs of dolomite and analcime after gypsum? or glauberite? are common in the grayish-red mudstone. Analcime and dolomite are also concentrated in shrinkage cracks and between mosaic flakes in dark dusky-red mudstone.

Varve-counts of black mudstone suggest that short cycles resulted from 21,000-year precession cycles. Bundles of detrital and of chemical short cycles occur in intermediate cycles 70 to 90 feet thick; these in turn occur in long cycles 325 to 350 feet thick. The patterns apparently resulted from alternating wetter and drier phases of intermediate and long climatic cycles, producing through-flowing drainage and a bundle of detrital cycles or a closed lake and a bundle of chemical cycles.

INTRODUCTION

The Upper Triassic Lockatong Formation in central New Jersey and adjacent Pennsylvania (Fig. 1) is a thick lacustrine deposit characterized by abundant analcime, small-scale disturbed bedding, and sedimentary cycles.

The most obvious cycles are asymmetrical ones generally 10 to 20 feet thick (Fig. 2). These short cycles, repeated with almost monotonous uniformity of successive sedimentary features, occur in patterned sequences or bundles of two different orders of magnitude: intermediate ones 70 to 90 feet thick, which are oscillations within long sequences 325 to 350 feet thick (Fig. 2, 19A).

Not only was cyclic sedimentation a dominant process controlling deposition of the formation (Van Houten, 1962), but it was

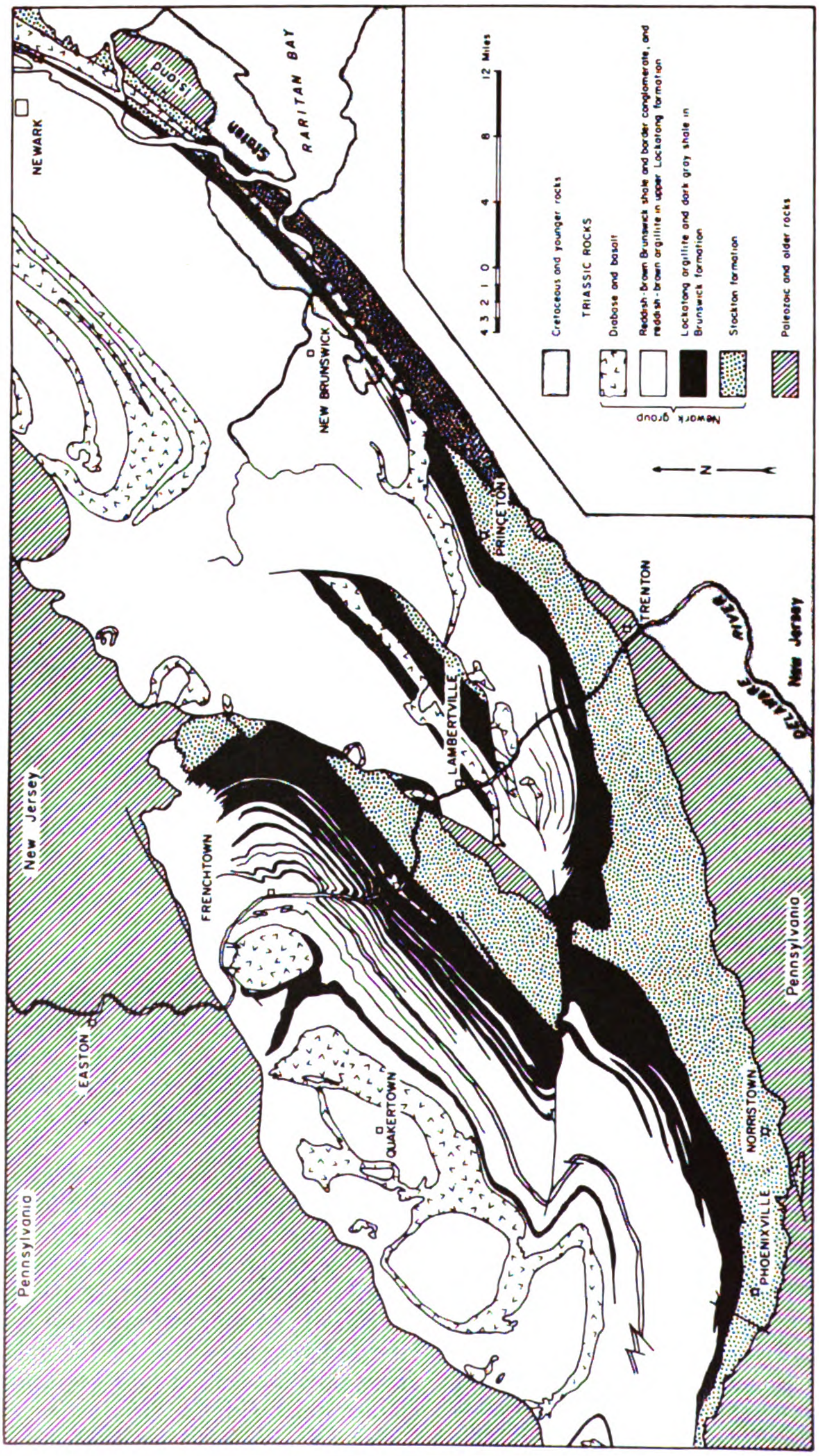


Figure 1.—Geologic map of central New Jersey and adjacent southeastern Pennsylvania. Interfingering Lockatong and Brunswick lithofacies based largely on mapping by McLaughlin (1946, 1959).

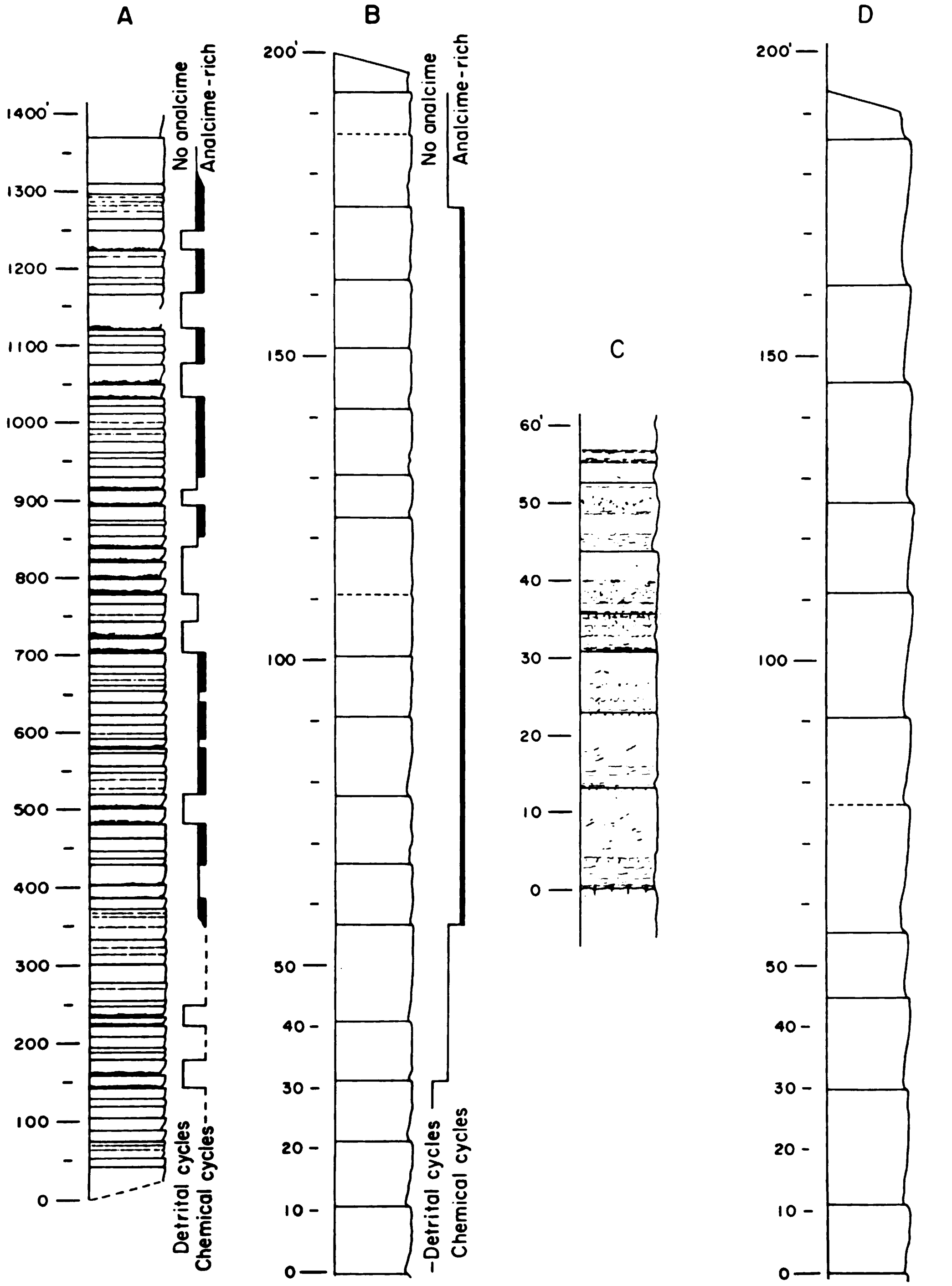


FIGURE 2.—Generalized stratigraphic sections of Lockatong Formation showing detrital and chemical short cycles. *A*, Roadcut along New Jersey Highway 29, 6 to 8 miles south of Frenchtown, N. J. Pattern of intermediate bundles of detrital and chemical cycles indicated along right side of section. *B*, Quarry at Rushland, Pennsylvania, about 13 miles west-northwest of Trenton, N. J. Detrital and chemical cycles indicated along right side of section. *C*, Chemical cycles in quarry along Pennsylvania Highway 32, 7 miles northwest of Trenton, N. J. *D*, Detrital cycles in quarry 2.5 miles west of Warrington and 4 miles southwest of Doylestown, Pennsylvania.

also a basic factor in the concentration of the abundant soda now present in one of the largest-known deposits of nonvolcanic sedimentary analcime.

Detailed variations in structures and textures which reflect changing conditions during the course of a short cycle and disruption during dewatering and compaction of the muddy sediments are described here as a part of a study of the Lockatong Formation that has been supported largely by a grant from the National Science Foundation (grant G-5032).

Several short cycles can be traced for nearly ½ mile in a large quarry west of Warrington, Pennsylvania, and show a lateral variation in thickness of no more than a few inches. But tracing of cycles regionally and reconstruction of the formation are hampered by limited exposures and by fragmentation of the basin into several tilted fault blocks. For this reason the present study relies heavily on analyses of vertical profiles. In the regional aspects of the interpretation, I have had to depend upon probabilities, thus making the conclusions insecure and tentative.

The Lockatong Formation of the Upper Triassic Newark Group is a huge lens a maximum of 3,500 to 3,750 feet thick. It lies conformably on the Stockton arkose and reddish-brown, sandy mudstone (a maximum of 5,000 feet thick) and under the reddish-brown Brunswick Shale (at least 6,000 feet thick; *see*, McLaughlin, 1959, p. 99-102). In general aspect each of these thick formations is an unusually uniform nonmarine lithofacies, pointing to prolonged persistence of established conditions of deposition in the Triassic intermontane basin in New Jersey and eastern Pennsylvania.

The Lockatong Formation grades downward into the Stockton arkose through several hundred feet of tough, well-bedded, very fine grained sandstone, siltstone, and mudstone, and interfingers laterally and upward into the Brunswick mudstone facies.

DISTRIBUTION OF LOCKATONG FORMATION

Lockatong deposits are thickest and most distinctive in the central part of the basin (in the northwestern fault block), wedging out in southeastern Pennsylvania and in northeastern New Jersey.

At its southwest end, 10 miles west of Phoenixville, Pennsylvania, the Lockatong Formation wedges out between the Stockton arkose and a conglomeratic facies of the Brunswick Shale (Hawkins, 1914, p. 148; Bascom, 1938, p. 72). Toward the northeast the southernmost belt of Lockatong rocks is covered by Cretaceous deposits east of New Brunswick, New Jersey, but has been traced in subsurface to Port Reading, 12 miles south-southwest of Newark, where recent drilling has revealed that argillite hornfels is at least 500 feet thick. Twenty miles farther north-northeast along strike, as seen in the old Granton quarry in North Bergen, the Lockatong hornfels facies apparently wedges out into the uppermost Stockton arkose (*see*, Bock, 1959, p. 130), in an area of conglomeratic Newark deposits. Apparently the Lockatong lake occupied a lowland between two major sites of fanglomerate deposition (Fig. 3).

On the basis of available data the Lockatong lacustrine facies is at least 90 miles long and may be as much as 110 miles long. The analcime now present in the central 45 miles of the formation has been traced to within 25 miles of its southwestern end. Toward the northeast analcime must have originally occurred beyond its known limit (just west of New Brunswick), where it was present in rocks which are now albite-rich hornfels.

Along the northwestern margin (in the northwestern fault block) fine-grained Lockatong deposits lie within several miles of the northwest border-fault and may, in fact, interfinger into coarser deposits of the Newark Group (McLaughlin, 1946). These relations indicate that no great influx of detritus spread across the basin from the northwest during Lockatong deposition. This fact, together with the feldspathic composition of Lockatong detrital deposits, points to a major source in crystalline rocks to the east and southeast that also supplied most of the Stockton arkose as well as much of the feldspathic Brunswick mudstone (Sturm, 1956, p. 159) in the central and southeastern part of the basin.

Toward the southeastern border of the basin, the Lockatong Formation thins to about 1,500 feet (Hawkins, 1914, p. 148). Here

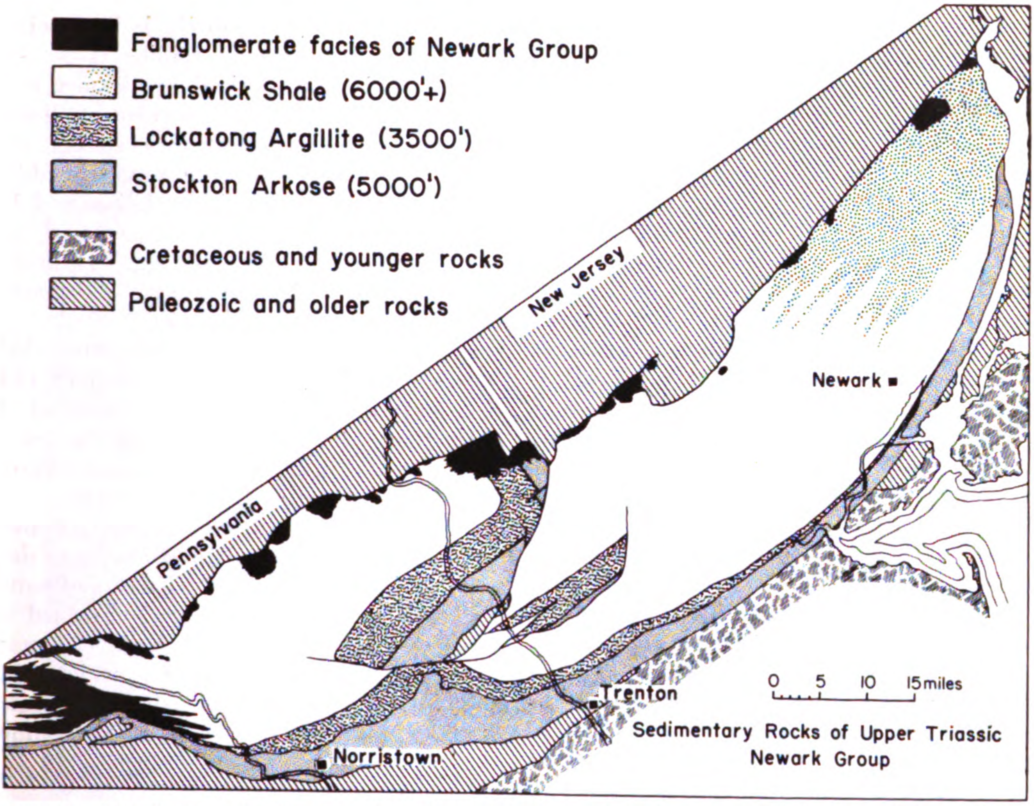


FIGURE 3.—Sketch map of Triassic sedimentary rocks in central New Jersey and adjacent Pennsylvania, showing relation of Lockatong Formation to distribution of fanglomerate facies and conglomeratic deposits of Brunswick Formation.

analcime-rich mudstone within a few tens of feet of the underlying Stockton arkose, as seen in the vicinity of Princeton, New Jersey, suggests that the thinning was accomplished largely by progressive lateral overlap of the upper part of the lacustrine deposits on the fluvial Stockton facies. The presence of abundant analcime along the eroded southeastern margin also suggests that the Lockatong Formation extended several miles farther to the southeast and thus had a total width of at least 25 miles and possibly considerably more. Sanders' (1963, p. 504) recent defense of a broad terrane reconstruction of the Triassic basins proposes a rift valley that was 50 to 70 miles wide.

ROCK TYPES

(1) Rocks in the southwestern extent of the formation and in the lower 400 to 500 feet of the thick section in the northwestern fault block consist principally of dark grayish-red and greenish-gray tough, micaceous mudstone, siltstone, and minor very fine grained sandstone. These deposits are characterized by small-scale irregular bedding and ripple- and cross-lamination. Moreover, the bedding is extensively disturbed by mudcracks and animal burrows, but bedding planes are seldom distinctly ripple marked.

(2) The characteristic rock type of the formation is tough, massive, homogeneous, very fine grained to aphanitic mudstone (argillite as a field term), most of which is medium to dark gray. Some of it is reddish brown to grayish red. This rock is used for building blocks and crushed stone, and is the type seen most commonly in outcrops.

It comprises two varieties which occur in different kinds of short cycles. Both exhibit extensively disturbed or disrupted fabric on a small scale.

(*a*) One kind which breaks with a hackly or gnarly fracture is a detrital deposit composed of calcareous, feldspathic siltstone and silty mudstone with only a minor amount of quartz. It has indistinct irregular to wispy carbonaceous laminae that are extensively disturbed and generally deformed into a small-scale irregularly contorted fabric (Fig. 4C).

(*b*) The other kind of argillite is chiefly a colloidal-chemical deposit that is more brittle and breaks with a subconchoidal fracture. This rock type is rich in carbonate minerals of which dolomite is the more common. It contains as little as 47 percent silica and as much as 7 percent soda which is concentrated largely in analcime and albite. Analcime-rich argillite predominates in the upper part of the formation where some of it is grayish red. Because of its variation in color, colloidal-chemical argillite is the preferred building stone.

The groundmass generally has a unique brecciated aspect on a microscopic scale, and commonly is speckled with white patches of crystalline analcime and carbonates, producing a fabric similar to that of "birdseye" limestone.

(3) The rock type second in abundance in the Lockatong Formation is platy, very dark-gray to black, laminated, carbonate-rich mudstone and marlstone in which dolomite commonly predominates. Some of these rocks are varved (Van Houten, 1962, Pl. 2A), and many are extensively disrupted by shrinkage cracks (Fig. 15A, 15D, 15E).

(4) Thin-bedded, calcareous, well-sorted feldspathic siltstone with minor very fine grained sandstone occurs in 2 to 5 foot-thick layers and broad lenses in detrital argillite (type 2*a*). Only very rarely is it associated with colloidal-chemical argillite (type 2*b*). This rock is characterized by distinct black micaceous laminae and irregular small-scale ripple-bedding, lenticular cross-bedding, convoluted bedding, and rare graded bedding (Fig. 5A, 5B, 5C). Microstylolites and isolated animal burrow-casts are common, and many of the thin black laminae are broken by slender, indistinct mudcracks and marked by small, indeterminate "tracks."

(5) Laminated black silty, calcareous shale, commonly with sublenticular laminae (Fig. 4A, 4B) constitutes a minor amount of the formation. Reddish-brown shale occurs in the uppermost part of the formation where it interfingers with the Brunswick Shale.

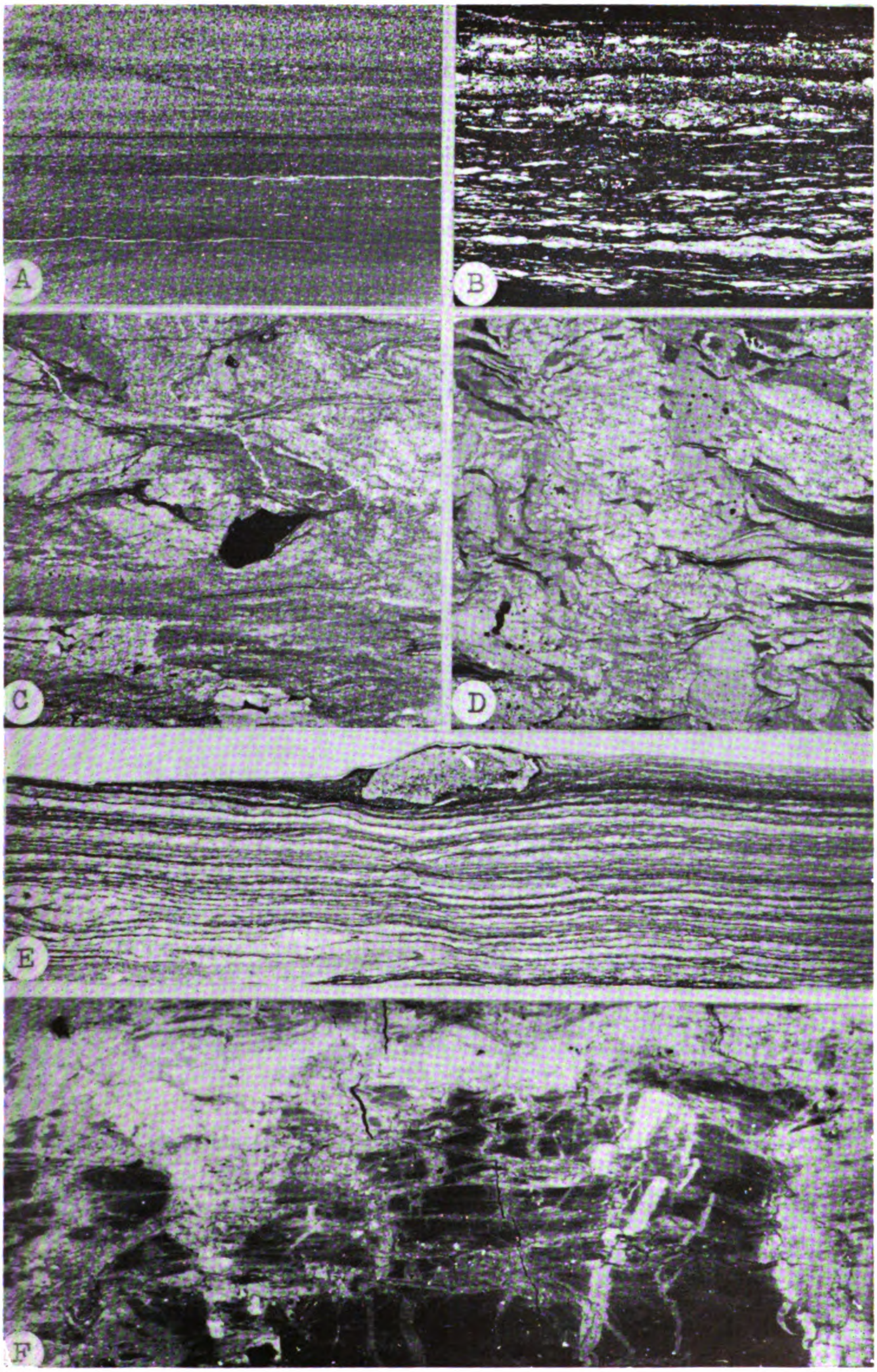
All of these rock types normally contain illite and some chlorite, albite, calcite or dolomite, and scattered pyrite. Quartz and potash feldspars are unusually scarce. Toward the southwest end of the basin, however, quartz is more common. The extent to which albite in the unmetamorphosed colloidal-chemical argillite is authigenic has not been determined.

SHORT CYCLES

General Statement

An orderly asymmetrical repetition of the common rock types, reflected in weathered profiles, is accompanied by a regular vertical variation in color, composition, and sedimentary structures. Approximately 80 short cycles are present in a well-exposed 1,400-foot section of the middle part of the formation in a long road cut on New Jersey Highway 29,

FIGURE 4.—Sedimentary features of detrital short cycles. *A*, Photomicrograph of lower black shale. Lower half composed of undisturbed, commonly discontinuous, black carbonaceous films in silty mudstone. Upper part massive, fine-grained siltstone with scattered pyrite, mottled by indistinct burrow-casts 0.1 to 0.2 mm in diameter. × 4.2. *B*, Photomicrograph of lower black shale with delicately disturbed bedding. Lower two-thirds composed of irregular films and laminae of black, dolomitic mudstone and sublenticular laminae of finely crystalline calcite; bedding apparently disturbed by organisms. Thicker bundles of black films recur about 0.4 to 1 mm apart. Upper third consists of several layers of black dolomitic mudstone with abundant scattered calcite crystals, disturbed by burrowers. Black lens with speckled center probably a coprolite. × 3.9. *C*, Photomicrograph of upper dark-gray, massive, silty mudstone with extensively disturbed fabric. Lighter, silty structure in lower left quarter may be burrow-cast. Black patch near center is pyrite. × 3.1. *D*, Photomicrograph of upper dark-gray, silty mudstone with siltier crumpled burrow-casts, and mottled or bioturbated fabric. Black spots are pyrite. × 3.7. *E*, Lower black shale with delicately disturbed films and laminae of black mudstone (white in directly reflected light) interbedded with very finely crystalline calcite (black in photograph). Thicker bundles of black films recur about 0.5 to 1.5 mm apart. Large black nodules are coprolites. × 1.7. *F*, Upper dark-gray, massive, silty mudstone extensively disrupted by siltier shrinkage crack casts offset by horizontal compaction shearing and by vertical zones of brecciation produced by upward-moving water and fluid mud. Upper part, medium-gray, siltier, and calcareous. White specks in lower part are pyrite, locally in shrinkage cracks and in thin zones of shearing. × 0.62.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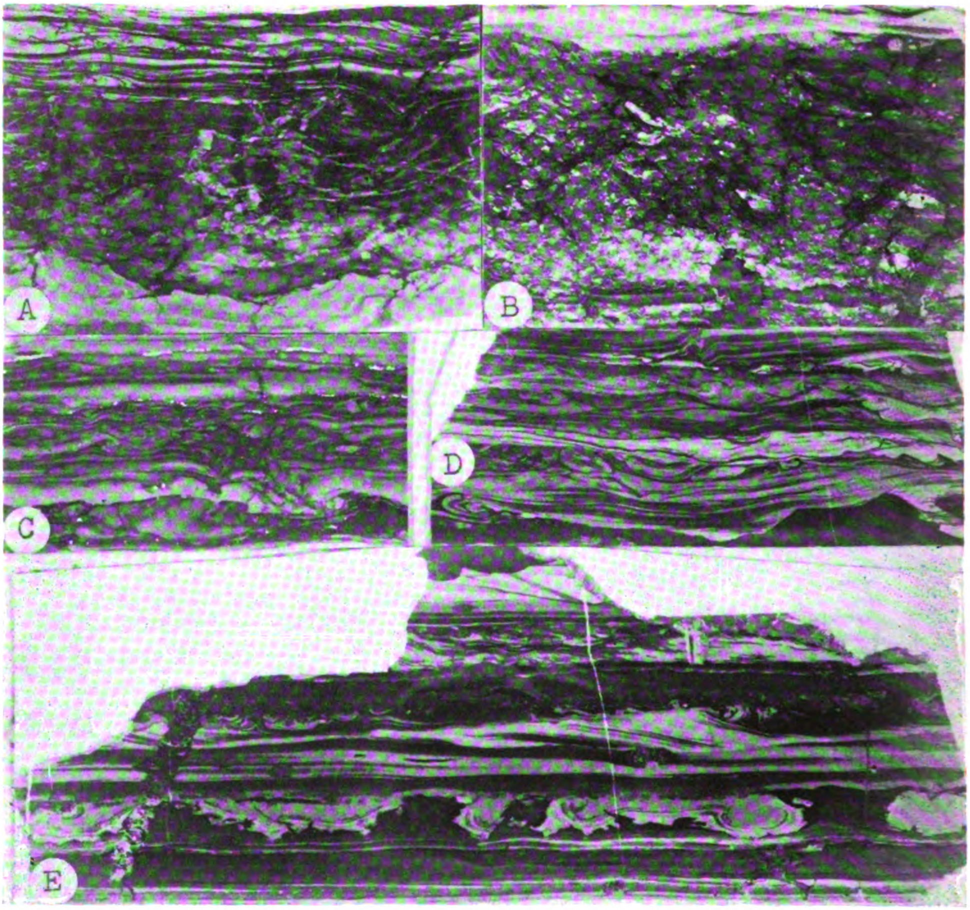


FIGURE 5.—Sedimentary features of detrital short cycles. *A,* Upper massive dark-gray silty mudstone with abundant slender crinkled shrinkage-crack casts; overlain by calcareous, cross-bedded well-sorted siltstone. × 0.54. *B,* Upper massive dark-gray silty mudstone mottled or bioturbated by organic burrowing. Overlain by calcareous ripple- and cross-bedded well-sorted siltstone with scouring and small load casts at base. × 0.54. *C,* Interbedded light-gray well-sorted siltstone and dark-gray mudstone of siltstone unit in upper part of cycle. White spots are pyrite mostly concentrated along base of beds. Contorted bedding in middle may be organic disturbance. × 0.58. *D,* Interbedded light-gray well-sorted siltstone and dark-gray mudstone of siltstone unit in upper part of cycle. Layers with distinct convoluted bedding and streaked-out "ripples." Load cast? in lower right corner and marked scouring of dark-gray mudstone below. × 0.58. *E,* Interbedded light-gray well-sorted siltstone and dark-gray mudstone of siltstone unit in upper part of cycle. Layers of cross-bedding and convoluted bedding with streaked-out "ripples." Several solitary burrow-casts parallel to bedding and a large cast at left rising vertically. × 0.58.

6 to 8 miles south of Frenchtown on the Delaware River (Fig. 2A, 19A). Short sequences of cycles are also well displayed in several large quarries in southeastern Pennsylvania (Fig. 2B, 2C, 2D; Van Houten, 1962, Pl. 1B).

In general form each short cycle consists of lower black shale and platy mudstone and marlstone, and of upper massive mudstone commonly mudcracked on top. There is no evidence of erosion between cycles but the most marked change in rock type occurs between the uppermost argillite and the basal shale or platy mudstone of the succeeding cycle. Observed in detail short cycles are of two rather distinct types, here informally referred to as detrital and chemical varieties (Fig. 6).

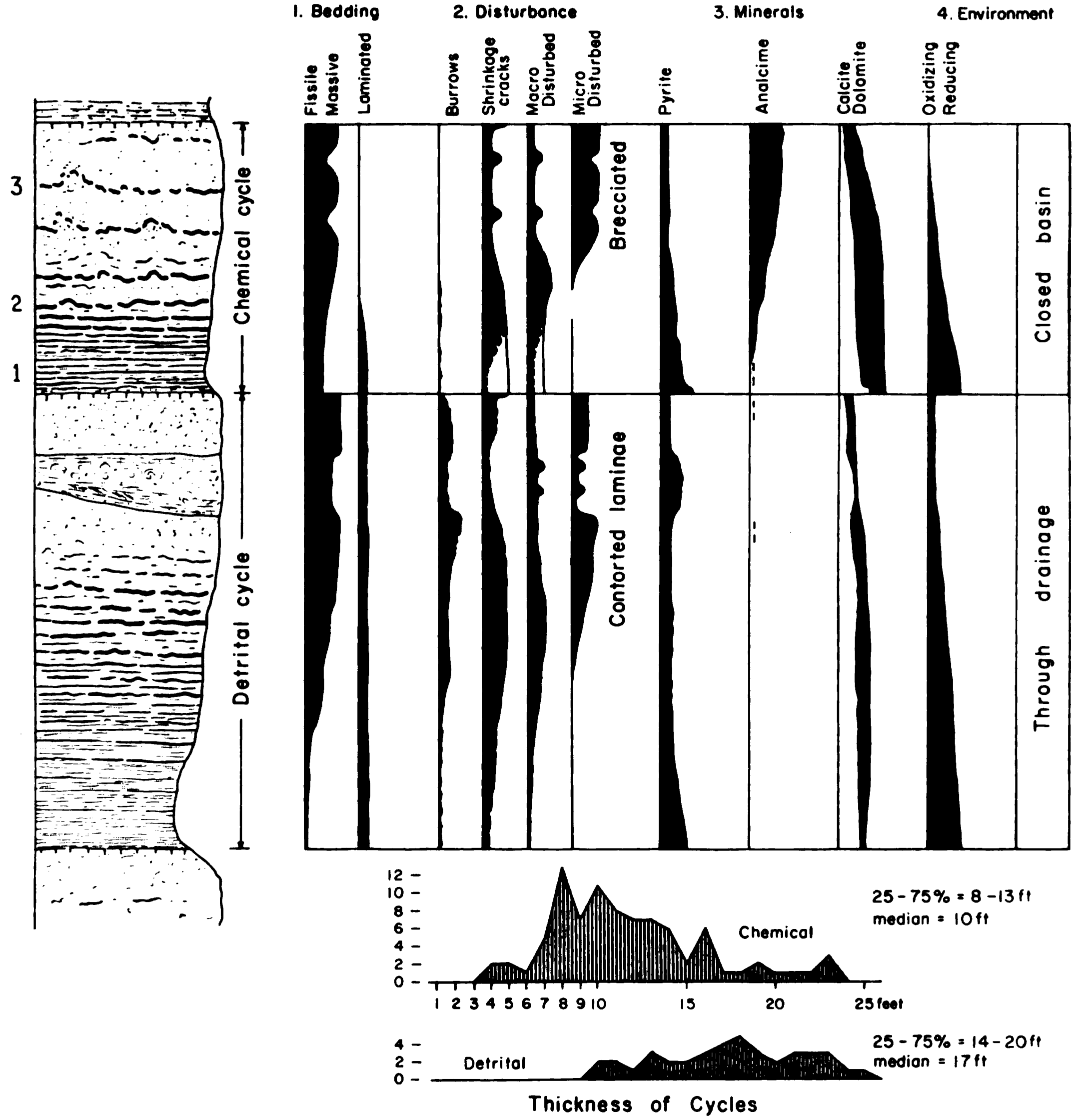


Figure 6.—Model of detrital and chemical short cycles, showing distribution and qualitative estimates of prevalence of sedimentary structures, selected minerals, and sedimentary environments; data on thickness of cycles. Numbers along left side of chemical cycle indicate units referred to in text.

Detrital Variety

The lower several feet of most detrital cycles consists of black shale succeeded by platy black to very dark-gray mudstone (laminae 0.5 to 2 mm thick) and interbedded tan-weathering disrupted, dark-gray, calcitic or dolomitic marlstone (laminae 0.1 to 2 mm thick) in alternating layers 1 to 6 cm thick. The fissile and platy beds normally are marked by rare short burrow-casts, but some thin beds of better-sorted siltstone are mottled by very small burrows (Fig. 4A). The upper part of a cycle is tough, massive dolomitic or calcitic silty mudstone and siltstone with indistinct irregular laminae. Only rarely are there distinct laminae 0.2 to 1 mm thick and some of these are graded. Instead, most of these rocks have been churned up on a small to microscopic scale to produce a contorted and disrupted fabric (Fig. 4C, 4D, 4F, 5A, 5B). In addition they commonly contain a 2 to 5-foot lens of rather well-sorted calcitic, feldspathic, laminated siltstone and rare very fine grained sandstone, much like deposits in the lower 500 feet of the formation (Fig. 5C, 5D, 5E).

Minute specks and larger crystals of pyrite are widespread in detrital cycles. Deep impressions of cubes of pyrite as much as 2 mm wide on surfaces of black laminae both above and below suggest growth of the crystals before complete induration of the mud. Coarsely crystalline patches of pyrite as much as 2 cm long occur in siltstone lenses, presumably as diagenetic concentrations in the more porous deposits.

Detrital cycles generally range from 14 to 20 feet in thickness, comprising the thicker short cycles; but they constitute only about one-fourth of the short cycles in the thickest section of the formation in northwestern New Jersey (Fig. 2A). In contrast, throughout the western third of the formation, west of Montgomeryville, Pennsylvania, only detrital cycles are present and these contain more quartz than occurs in cycles in the central part of the basin.

Chemical Variety

A second, more common type of short cycle differs principally in containing less detrital and more colloidal-chemical sediment. These cycles generally range from 8 to 13 feet in thickness.

The lower part consists of interbedded, commonly disrupted black to very dark-gray, platy, laminated, dolomitic and calcitic mudstone and marlstone (Van Houten, 1962, Pl. 1C) and rare layers and lenses of crystalline carbonate (Fig. 7). The upper part is massive analcime- and carbonate- (predominately dolomite) rich mudstone brecciated on a microscopic scale. Presumably this nonlaminated mudstone resulted from flocculation of a colloidal sediment in the presence of a concentration of cations which produced random orientation of the clay minerals (White, 1961, p. 561). The analcime in these cycles was derived largely from saline water of a closed lake in which the mud itself was laid down. It may have been more nearly diagenetic than syngenetic, having been formed below the surface of the bottom mud, but it was introduced before the rock was lithified or deeply buried.

Many of the platy mudstone layers in the lower part of chemical cycles are composed of regularly alternating black and light-gray, carbonate-rich laminae. These couplets, which range from 0.05 to 0.2 mm in thickness, resemble carbonate- and organic-rich varves in the Eocene Green River lacustrine deposits (Bradley, 1930, p. 95-96). Basal beds of platy gray mudstone in some cycles consist of graded laminae of silt and clay ranging in thickness from 0.2 to 2 mm.

Fossils

Fossils found in the Lockatong Formation record a fauna conspicuously devoid of large aquatic bottom dwellers. It comprises, instead, mostly remains of elasmobranch, coelocanth, and palaeoniscid fishes, estheriids and ostracodes, plant fragments (cycads, equisitales, ferns, and possibly dasycladacean algae), and indeterminate microscopic spines or setae, as well as coprolites as much as 6 cm long and insect larvae faecal pellets about 2 mm long. In addition, there are traces of several kinds of small reptiles, phytosaurs, and large squat amphibians. There are also rare indistinct large footprints, presumably of large phytosaurs and tracks of small dinosaurs, rare small tetrapod tracks and minute indeterminate "tracks and trails."

Most of the fossils were recovered from the shaly and platy beds in the lower part of cycles, but estheriids occur in abundance in the upper part of detrital cycles as well. Plant remains are much more rare than in most lacustrine deposits, and efforts to recover spores or pollen from the mudstone have yielded very little.

Isolated silty casts of animal burrows 1 mm or less in diameter are scattered through the lower shale and platy mudstone. Rarely, irregular laminae of siltstone 1 to 2 mm thick in the black shale consist almost entirely of minute crumpled casts. In detrital cycles crumpled burrow-casts 1 to 3 mm in diameter are abundant in the upper gray muddy siltstone (Fig. 4D; Van Houten, 1962, Pl. 2C) which commonly is indistinctly mottled (*see*, Moore and Scruton, 1957, p. 2725-2731). In associated better-sorted coarser siltstone and very fine grained sandstone burrow-casts are rare, and bioturbation by bottom crawlers is preserved locally. Beds of reddish-brown to grayish-red mudstone and siltstone in the uppermost part of the Stockton Formation, in the lower 500 feet of the Lockatong Formation, and in the Brunswick Formation contain abundant burrow-casts as much as 1 cm in diameter. Locally these strata are mottled.

The fact that the fish faunas from the three formations of the Newark Group differ only in detail (Bock, 1959, p. 130-132) implies that the Lockatong deposits, like the Stockton and Brunswick Formations, are of nonmarine origin (Schaeffer, 1952, p. 58).

Most of the fish, amphibians, and reptiles found in the Lockatong Formation were recovered from its more marginal southwestern and northeastern parts, or from its lowest part near the middle. Although this distribution may have been controlled largely by available outcrops very few vertebrate remains have been found in quarries in the upper part of the formation in western New Jersey. According to these data, fossils occur mainly in detrital cycles and there apparently was a paucity of vertebrate life in the central part of the Lockatong lake.

Interpretation

Of all the distinctive sedimentary features of the Lockatong Formation, crumpled shrinkage-crack casts and bedding disturbed by burrowing or by hydroplastic disruption are the most ubiquitous and varied, and generally point to slow accumulation of mud. In contrast, ripple-marked strata are rare. A greater

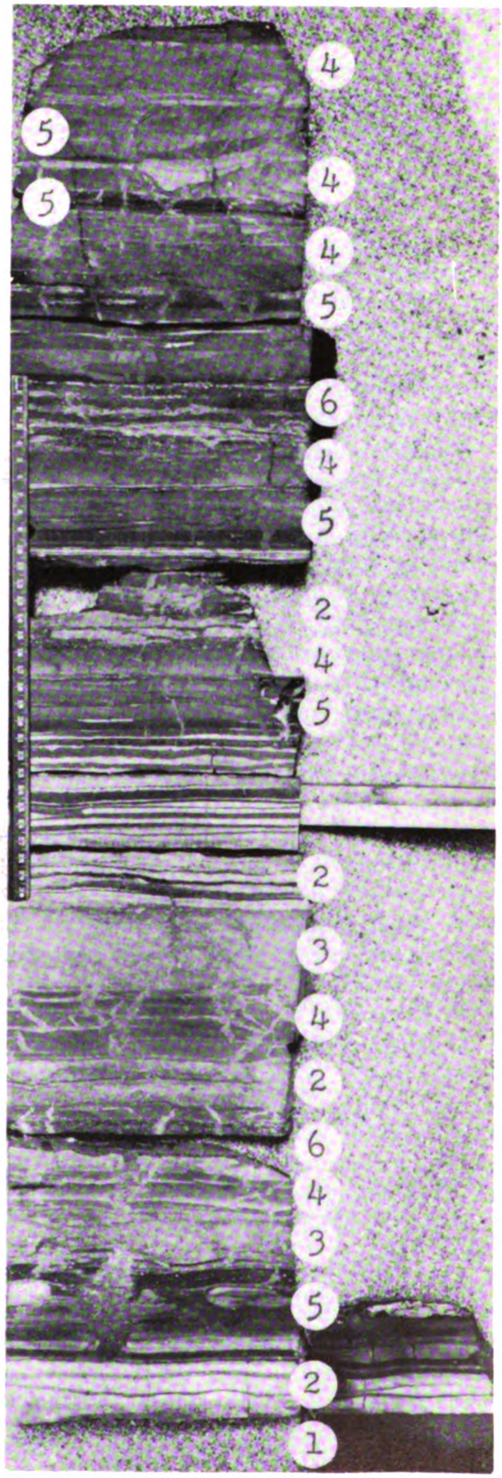


FIGURE 7.—Lower platy black mudstone and gray marlstone of gray chemical short cycle, showing various types of disruption by shrinkage. (1) Very dark-gray analcime-rich mudstone at top of preceding cycle. (2) Very light gray crystalline calcite with layers of dark-gray dolomitic mudstone. (3) Light-gray, extensively disrupted dolomitic marlstone with scattered small patches of calcite. (4) Medium-gray brecciated dolomitic marlstone with shrinkage-crack casts of gray calcitic and dolomitic or of black, dolomitic mudstone, offset laterally by compactional shearing. (5) Very dark gray to black dolomitic mudstone with medium-gray, dolomitic crumpled shrinkage-crack casts. (6) Black dolomitic mudstone with densely scattered crystals of calcite and medium-gray, dolomitic shrinkage-crack casts. Vertical zone of brecciation by upward-moving fluid in lower block. Specimen is 81 cm high.

thickness of most detrital cycles compared with chemical ones reflects a more rapid rate of detrital deposition.

In both lithic features and fauna the Lockatong Formation shares many characters with the mid-Devonian Caithness Flagstone of Scotland (Crampton, 1914), Mississippian Albert Shale of New Brunswick (Greiner, 1962), Permo-Pennsylvanian Dunkard Group in Pennsylvania, West Virginia, and Ohio (Beerbower, 1961), Triassic Blomiden Formation of Nova Scotia and New Brunswick (Klein, 1962a), Triassic Keuper rocks (Bosworth, 1912, p. 51-116; Elliot, 1961), and Eocene Green River Formation (Bradley, 1931), each largely of lacustrine origin.

Detailed comparison of the Lockatong lacustrine deposits with these formations emphasizes the uniqueness of the chemical cycles and the features they share with the distinctive 5 to 10-foot cycles in the Green River Formation. Lockatong detrital cycles, on the other hand, are more like lacustrine and alluvial Dunkard cyclothems and cyclic deposits in the Papigoe beds and Thurso flagstone of the Caithness Flagstone. In addition, detrital cycles share significant features with some deposits of marine tidal lagoons (Van Straaten, 1954). Nevertheless, the lagoonal deposits differ in possessing more numerous small channel and gully lenses pointing to some current action, abundant load casts, wave ripple marks, and ripple bedding (but only minor current ripple marks), a marine fauna, and shell beds, and abundant drifted plant fragments.

Members of the detrital and chemical short cycles record an asymmetrical sequence of events resulting from expansion and waning that recurred relentlessly during the life of the Lockatong lake. Each cycle began with the slow filling of the basin to form swamps and marshy ponds, and then extensive shallow lakes. During this initial stage mud accumulated in a reducing environment noxious to large bottom dwellers and burrowers. Gradually the inflow increased and the redox potential decreased. Then inflow waned and some cycles ended with exposure of the lake bottom; yet no erosion ensued, thus suggesting but little hiatus between cycles.

Reconstruction of an extensive shallow lake in which only slight differences in elevation of the basin floor could cause widespread differences in conditions of deposition implies that members of a cycle may vary from place to place. Moreover, the paucity of bottom scour in these shallow-water sediments requires that there was no single large lake where wind-driven waves could easily have been generated, or that some deterrent, such as aquatic vegetation, restricted wave action.

In their study of two Pennsylvanian black shales Zangerl and Richardson (1963, p. 117-122) have recently explored the problem of accounting for an absence of disturbance of bottom mud below shallow water. As a solution they have elaborated the role of an algal flotant, a mat of floating vegetation as much as 3 feet thick which protected the mud from wave action. The flotant may also have prevented spores and leaves from reaching the bottom (p. 218-219) while it showered abundant microscopic plant debris on the mud. A flotant may have had a similar role in the Lockatong lake, but there is no direct evidence of its presence. In fact, Lockatong mudstone contains no such abundance of decomposition products of plants as occurs in the Pennsylvanian shales (p. 105-106). Moreover, a flotant could not have been present during oxidizing episodes that produced grayish-red chemical cycles.

The present attempt to account for the short cycles assumes that both detrital and chemical varieties had a common control, that the base of each is correctly identified, and that they accumulated in a lake. In its general setting the thick Newark Group accumulated in a continuously sinking basin supplied by a rising source area to the east or southeast as well as to the northwest. Secular fluctuations imposed on this framework produced the distinctive Lockatong cycles. But no obvious interpretation follows. Not only are there several possible causes of cyclic sedimentation but authors disagree as to which one may have been the fundamental control of a particular cyclic deposit (Weller, 1956; Goodlet, 1959; Wells, 1960; Beerbower, 1961).

Cyclic sedimentation has been attributed to continuous subsidence accompanied by *periodic compaction* (Van der Heide, 1950), or by *shifting of the pattern of sedimentation*

(Goodlet, 1959; Duff and Walton, 1962), as well as to a more regional tectonic control, either *periodic subsidence* (Trueman, 1948; Zangerl and Richardson, 1963) or *repeated uplift and submergence* as envisaged by Weller (1956). In contrast, theories of worldwide control have called upon *eustatic rise and fall* of sea level (Ham, 1960) or *cyclic variation in climate* accompanied by compaction in a continuously sinking basin (Brough, 1928; Beerbower, 1961).

My prejudice in favor of climatic control, rather than periodic sinking, stems largely from an assumption that alternations in climate are apt to be more regular and persistent than intermittent subsidence (*see*, Gilbert, 1895, p. 123, 127). Moreover, they account more reasonably for the sequence of members in the Lockatong short cycles. Admittedly, detrital short cycles alone could be attributed to tectonic control, but the chemical ones point, instead, to a climatic control. Significantly, climatic cycles have recently been advocated by Beerbower (1961) as the basic control of alluvial and lacustrine Dunkard cyclothems of Permo-Pennsylvanian age, Wanless (1963) has favored climatic oscillations and glacial episodes as basic causes of late Paleozoic cyclothems, and Elliot (1961) has ascribed cycles in the Triassic Keuper Series to a climatic control.

A tentative estimate of the duration of a short cycle, based on varves in the lower part, gives an average of 22,000 years, which agrees well with the 21,000-year precession cycle. Support for this interpretation is afforded by similar cycles in the Eocene Green River lacustrine deposits of Wyoming and Colorado. Varve-counts of these 5 to 10-foot cycles indicate an average duration of 21,630 years, suggesting control by the precession cycle (Bradley, 1930, p. 105-106).

VARIATIONS IN SHORT CYCLES

The characteristic features of detrital and chemical short cycles vary considerably in detail. Analysis of these variations yields basic data for a paleogeographic reconstruction (*see*, Duff and Walton, 1962).

Detrital Cycles

Thickness

The detrital cycles measured range in thickness from 10 to 25 feet (Fig. 6). The 25 to 75 percent class is 14 to 20 feet thick; the median is 17 feet.

Stratification and grain size

Lamination of the lower fissile, black, pyritic mudstone varies considerably. Some of the mudstone with indistinct black films occurs in beds 0.5 to 3 mm thick (Fig. 4A). Very rarely there are minor scours 5 mm deep with tiny streaked-out "ripples" at the bottom. Distinct lamination 0.02 to 1 mm thick varies from a succession of delicately wrinkled black laminae with scattered silt and minute calcite crystals to wrinkled and delicately disturbed films and bundles of films of black mud with sublenticular laminae of silt or very finely crystalline calcite (Fig. 4B, 4E). Thicker bundles of black films commonly recur about 0.4 to 1.5 mm apart. In some beds the calcite and silt occur as sharply defined layers, stringers, and lenses 0.05 to 0.5 mm thick. Only very locally are laminae of black mud distinctly graded.

The pyritic, black shale in the lower part of detrital cycles apparently accumulated in marshy ponds and lakes as did the thin coaly shale (humulite) overlying the coal of some Pennsylvanian cyclothems of Illinois (Zangerl and Richardson, 1963, p. 69-74, 225-226). In contrast, the humulite contains abundant shells and microscopic flaky plant debris, and it is overlain by a transgressive marine facies of gray to black shale that was deposited in marginal lagoons along a deltaic coastal plain (p. 24, 226-227).

Thicker detrital cycles are consistently siltier in the upper part which contains a distinct 2 to 5-foot unit of gray, laminated (laminae commonly 0.2 to 1 mm thick, rarely 3 mm thick), well-sorted siltstone and fine-grained sandstone. Within each unit some of the siltstone and sandstone has irregularly paralled lamination, some has small-scale, ripple- and cross-lamination (Fig. 5C, 5D, 5F) and rarely some of the coarsest sandstone has crudely graded beds 1 to 2 mm thick. In some cycles the siltstone unit is scoured broadly a few feet into the darker mudstone below and contains very dark-gray intraformational mud clasts 1 to 10 mm long.

These coarse units mark the episode of maximum inflow, producing repeated scour (Fig. 5A, 5B) and spread of relatively well-sorted silt and very fine grained sand. Normally the coarse unit in the upper silty mudstone does not extend to the top of a cycle, suggesting a decrease in transportation energy toward the end of a cycle.

Thinner detrital cycles commonly begin with platy mudcracked mudstone and dolomitic marlstone, and have no distinct upper siltstone unit; the thinnest ones consist only of mudstone in the upper part, approaching chemical cycles in their sedimentary features. In fact, some cycles about 10 feet thick are intermediate in character between detrital and chemical varieties and contain traces of analcime.

Disturbed bedding

Inorganic.—Platy marlstone and mudstone in the lower part of detrital cycles commonly are conspicuously disrupted by shrinkage cracks of several different patterns like those in the platy lower part of chemical cycles.

Silty mudstone in the upper part of detrital cycles is marked by abundant long, slender, crumpled shrinkage-crack casts (Fig. 5A) and very irregular vertical brecciated zones 2 to 5 mm wide that apparently were paths of upward moving water and fluid mud (Fig. 4F). Disrupted bedding surfaces appear "shattered" by a complex of randomly oriented, slender, straight crack-casts rather than by a simple polygonal pattern. Locally, specks of pyrite are more abundant in crack-fillings and vaguely outline a mosaic type of intraformational breccia with all the fragments parallel to bedding. Much of this small-scale shrinkage disruption may have occurred under shallow water (*see,* Van Straaten, 1954, p. 38).

In profile, crumpled casts of silt vary from rare to abundant, and from obvious crack-fillings to obscure structures (Fig. 4C, 4F, 5A). Some may be crumpled siltstone dikes (Shelton, 1962). Some may fill pockets and passageways formed by escaping gas (Cloud, 1960) or water released during compaction. Without adequate evidence, however, they cannot be distinguished from obscure shrinkage-crack casts or from animal burrow-casts.

Commonly, crumpled structures have been offset laterally (in profile) a few millimeters by shearing parallel to bedding on planes 2 to 15 mm apart (Fig. 4F), similar to slip-layers in fine-grained detrital deposits in the Keuper Series (Elliot, 1961, p. 199-202). Presumably the shearing resulted from local lateral flowage during dewatering and compaction. Vertical displacement of offset crumpled casts points to further compaction after shearing.

In a few detrital cycles bedding surfaces in the upper silty mudstone are marked by shrinkage cracks as much as 5 cm wide that outline polygons as much as 35 cm wide, like those "suncracks" in mudstone of the Caithness Flagstone (Crampton, 1914, Pl. VI, 2).

Many of the siltstone and fine-grained sandstone units are marked by layers of conspicuous irregular bedding (Fig. 5C, 5D, 5E), and by deformed load casts of silt protruding into underlying silty mudstone (Fig. 5C). Minor scouring and slumping or flowage over a distance measured in millimeters are common, and delicately convoluted beds with folds about 2 to 5 mm high are associated with streak-out "ripples" of the underlying mudstone (Fig. 5E). These features probably resulted from frictional drag of silt- and sand-laden currents on soft but cohesive mud over which the sediment was spread (Sanders, 1960), and in part, perhaps, from vertical loading (McKee and others, 1962). As pointed out by Sanders (p. 414), convoluted laminae in other deposits, such as the Keuper Series (Elliot, 1961, p. 202-204), are characteristically limited to sediments of silt and very fine grained sand sizes.

Rarely, anastomosing sharp-crested, slightly asymmetrical current ripplemarks with secondary crests are preserved on the surface of 1 to 2 cm-thick beds of well-sorted siltstone that are marked by conspicuous ripple-bedding, intraformational mud-chips, and scouring at the base. The main ripples have wave lengths of about 3 to 3.5 cm and amplitudes of 3 to 4 mm (ripple index = 8 to 12). Secondary crests are displaced somewhat toward the downcurrent side of each ripple.

In a few of the siltstone and sandstone units in the upper part of detrital cycles, as well as in similar rock types in the lowest part of the formation, lamination is disrupted by irregular vertical zones of brecciation as much as 2 cm wide and 8 cm high. At their bases these structures join shrinkage-crack casts, and like smaller ones in the silty mudstone (Fig. 4F), probably resulted from dilatation of sand and silt by gas, water, and fluid mud moving upward along shrinkage cracks during compaction.

The assemblage of structures in the siltstone and sandstone units is remarkably like that in cyclothemic Carboniferous deposits in England (Greensmith, 1956) and the regressive Dakota deposits in North Dakota (Shelton, 1962).

Organic.—Although much of the crumpled fabric of the silty mudstone is the result of inorganic disturbance some irregularly contorted structures are animal burrow-casts 1 to 3 mm in diameter that seldom have septal laminae and can be traced only a few centimeters (Fig. 4C). In siltier mudstone, burrow-casts crumpled by compaction are more abundant (Fig. 4D, 5B), as they are, for example, in the siltier Baggy Beds of the Old Red Sandstone (Goldring, 1962, p. 242, 248). Locally, the siltstone is indistinctly mottled. In many cycles, muddy siltstone with abundant burrowing (bioturbation or mottling) is interbedded with units of parallel- and cross-laminated well-sorted siltstone and fine-grained sandstone that slightly truncate the extensively burrowed beds (Fig. 5B). Apparently the spreading sand sheet killed off the abundant mud-dwelling burrowers, for the well-sorted deposits, in contrast, are penetrated only by solitary burrow-casts as much as 5 mm in diameter and commonly with septal laminae (Fig. 5E). These features record minor variations in scour and sedimentation during accumulation of the coarser units.

Locally, several inches of the laminated siltstone and very fine grained sandstone unit has an irregularly and intricately contorted fabric of very lobate and crumpled folds as much as 1.5 mm high. The complex pattern suggests disturbance by bottom crawlers rather than by an inorganic agent.

As observed in other studies (Van Straaten, 1954, p. 29; Greensmith, 1956, p. 352; Goldring, 1962, p. 248; Middlemiss, 1962) muddy silt to very fine grained sand is the favorable range of sediment size for abundant burrowers in lakes, lagoons, and tidal flats, and extensive bioturbation or mottling points to a relative slow rate of deposition.

Many of the prominent features of the upper part of detrital cycles, and especially those in the coarser siltstone and very fine grained sandstone units, resemble features in the Devonian Psammites du Condroz which Van Straaten (1954, p. 43-44) believes accumulated in a marine lagoon that was covered by water most of the time.

Chemical Cycles

Thickness and grain size

The measured chemical cycles range in thickness from 4.5 to 17 feet. The 25 to 75 percent class is 8 to 13 feet thick, and the median is 10 feet. The basal black shale that aids in demarcating detrital cycles in outcrop is present only in the thicker chemical cycles. Thinner ones begin with platy mudstone and marlstone and are less evident. The thinnest chemical cycles are composed mostly of grayish-red mudstone.

Several analcime-rich sequences between distinct cycle bases range from 18 to 25 feet thick. A vague 6 to 12-inch zone of shrinkage-cracking in the middle of some of these anomalously thick successions suggests that each may comprise two poorly demarcated cycles. If correctly interpreted, these long chemical sequences apparently resulted from relatively little change in conditions of deposition during two successive climatic cycles.

Almost every chemical cycle consists only of silty mudstone and colloidal-chemical sediments. In the upper part of a few, however, there is a 1 to 2-foot unit of delicately laminated (laminae generally 0.3 to 1.5 mm thick) calcareous siltstone with isolated burrow-casts. Locally the thinnest laminae are graded; more commonly all are sublenticular and disturbed. Rarely, part of the siltstone unit is mottled.

Sedimentary features of gray cycles

Inasmuch as chemical cycles are the distinctive ones and reflect more clearly the unique conditions of deposition of the Lockatong Formation, variations within them will be described in detail in a sequence of rather arbitrary units (Fig. 6) of each cycle.

Unit 1.—The lower several feet of a cycle consists of black platy carbonate-bearing mudstone with thin layers, lenses, and scattered patches of coarsely crystalline carbonates and rare short burrow-casts less than 1 mm in diameter. Deep impressions of carbonate and pyrite crystals as much as 3 mm wide on the surface of black mudstone above and below indicate that the crystals grew before complete induration of the mud. Commonly, bedding surfaces are also marked with small indeterminate "tracks and trails."

Bedding is 1 to 10 mm thick, with laminae normally 0.2 to 1 mm thick, but where the lowest beds are undisturbed by shrinkage-cracking they are commonly composed of varves 0.05 to 0.2 mm thick.

In several cycles with undisturbed lower beds, the initial deposit is a 2 to 7 mm-thick layer or lens of coarsely crystalline pyrite overlain by a 2 to 7 mm-thick layer of crystalline calcite and subordinate dolomite with interbedded black dolomitic mudstone containing abundant scattered crystals of dolomite and pyrite. In other cycles pyrite is less common and the initial deposit consists of 0.5 to 2 cm-thick, pinching and swelling layers of coarsely crystalline calcite and subordinate dolomite with a distinct pseudopellet texture which are interbedded with irregular layers of black dolomitic mudstone 2 to 4 mm thick (Fig. 7).

As in detrital cycles, dolomite generally predominates in fine-grained mudstone and aphanitic marlstone. In contrast, the layers and lenses of coarsely crystalline carbonate commonly consist mainly of calcite. Where coarsely crystalline dolomite predominates a minor amount of analcime is present. Moreover, scattered crystalline patches suggestive of minute salt casts contain only dolomite and analcime, and these patches are more common in the upper part of a cycle.

The lower part of many chemical cycles shows a distinct pattern of 1 to 6 cm-thick layers of black to very dark-gray mudstone alternating with 1 to 6 cm-thick layers of tan-weathering gray marlstone and aphanitic dolomite, locally disrupted by "pull-aparts" (Fig. 8). More commonly the alternating layers have been extensively disrupted by shrinkage cracks with distinctly different surface pattern, depth of penetration, and kinds of crumpled casts (Fig. 7). The surfaces of some layers of black mudstone are marked by a delicate tracery of incomplete polygons no more than 1.5 cm wide. Where layers and lenses of crystalline carbonates are common 0.5 to 1 cm-thick layers of black, dolomitic mudstone speckled with calcite patches show distinct shrinkage polygons a maximum of 6 cm wide and outlined by stout dolomitic crack-casts 1 to 4 mm wide (Fig. 7 (6), 9A). Layers of black mudstone only a few millimeters thick between crystalline calcite layers have a more randomly "shattered" pattern of slender cracks (Fig. 7 (2), 9B).

Layers of black mudstone more than 1 cm thick normally have complexly cracked surfaces and shrinkage-crack casts of aphanitic dolomite and marlstone that are thick and crumpled and anastomose downward, as in gray beds in grayish-red cycles (Fig. 17). In contrast, associated layers of brecciated marlstone have slender, slightly crumpled crack-casts of black mudstone or gray dolomite. Some of the abundant cracking in unit 1 probably resulted from subaerial shrinkage. but the fact that the cracks in many layers were filled from above and below suggests that much of the shrinkage resulted from syneresis under shallow water and after burial.

As in detrital cycles, crumpled crack-casts in chemical cycles commonly have been offset a few millimeters by shearing parallel to bedding. Moreover, thicker beds of both mudstone and marlstone in this lower sequence are disrupted by irregular vertical zones of brecciation as much as several centimeters wide which join shrinkage-crack casts at their base (Fig. 7).

In several chemical cycles, the basal few inches contain a 2 to 4 cm-thick layer of black. laminated dolomitic mudstone broken by conspicuous shrinkage cracks 1 to 2.5 cm wide. These outline simple polygons as much as

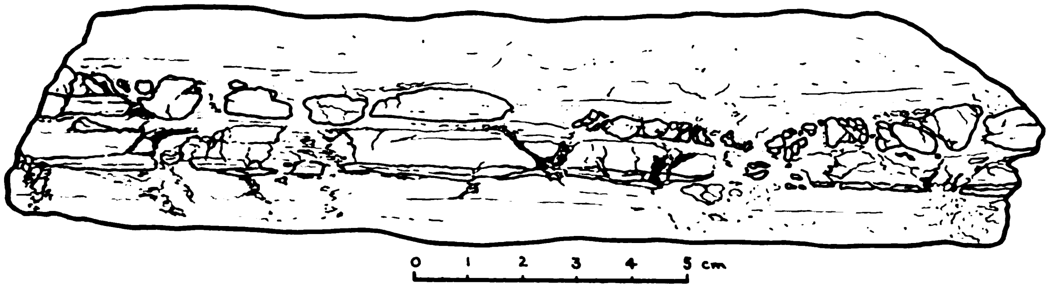


FIGURE 8.—Small-scale pull-aparts in beds of medium-gray, dolomite-rich marlstone and aphanitic dolomite set in matrix of dark-gray, dolomitic mudstone, in upper part of unit 1 of gray chemical cycle. Shrinkage produced by dewatering after burial.

15 cm wide (Fig. 10). The cracks are filled with thick, broken casts of aphanitic dolomite. During compaction the more rigid dolomitic casts were flattened, but they were compressed less than the cracked layer of black mud. Consequently, compaction "folds" developed in the beds above and below the casts. The pattern of the "folds" now reflects the polygonal pattern of the shrinkage cracks in the black mudstone.

A similar feature occurs in the carbonate-rich basal part of a thin, extensively cracked and brecciated cycle in a sequence of grayish-red cycles. Here a layer of dark-gray dolomitic mudstone is broken by wide cracks that outline irregular polygons as much as 15 cm wide (Fig. 11). These cracks are filled with unique flattened casts of aphanitic dolomite about 2.5 cm thick. Each cast is irregularly oval to lobate and shows internal plastic flowage and lateral injection into the enclosing mudstone. Layers of crystalline calcite 1 to 2 cm thick above and below the mudstone and dolomitic lobate casts apparently served as buttresses between which the plastic dolomitic crack-filling was squeezed during compaction of the dark-gray mud.

The preservation of delicate seasonal laminae and of undisturbed dead fish in pyritic black mudstone of unit 1 in some chemical cycles points to accumulation on a stagnant bottom, probably in a warm-climate, thermally stratified lake with cooler bottom water low in oxygen, and with no active benthic fauna, waves, or currents. Although these very features have been cited as evidence of deep water, such an interpretation is not required. Instead, shallow water with deposition below wave-base, as elaborated for other deposits of black shale (Richter, 1931; Engels, 1957; Beerbower, 1960; Conant and Swanson, 1961; Zangerl and Richardson, 1963) accounts satisfactorily for the Lockatong features, thus suggesting a lake with depths measured in a few tens of feet at most, and perhaps similar to shallow alkaline lakes with "bottomless" mud in Kenya (Jenkins, 1932, p. 546-547). As pointed out previously (p. 12-13) this interpretation does introduce the problem of accounting for no bottom stir-up in an extensive shallow lake.

Additional problems concerning unit 1 remain. It is not clear why the Lockatong lake contained such an abundance of calcium and magnesium carbonate at the beginning of a chemical cycle, or why a lake that produced beds of crystalline limestone did not support abundant organic activity that would have yielded deposits rich in organic carbon and calcareous algae. It is reasonable to expect that algae did participate in concentrating the carbonates, but there is no direct evidence that they did.

In the upper part of the platy unit 1, thicker layers of tan-weathering marlstone predominate, and these are extensively broken by slender, irregular shrinkage cracks now filled with dark-gray mudstone that was only slightly crumpled during compaction (Fig. 12A). The small-scale fragmented fabric of some of these thicker layers and their relation to overlying deposits indicates that they were disrupted after burial, during dewatering and compaction.

Only in the most analcime-rich cycles are there traces of analcime in the lower part of unit 1. Locally, minor amounts of crystalline analcime mixed with crystalline dolomite oc-

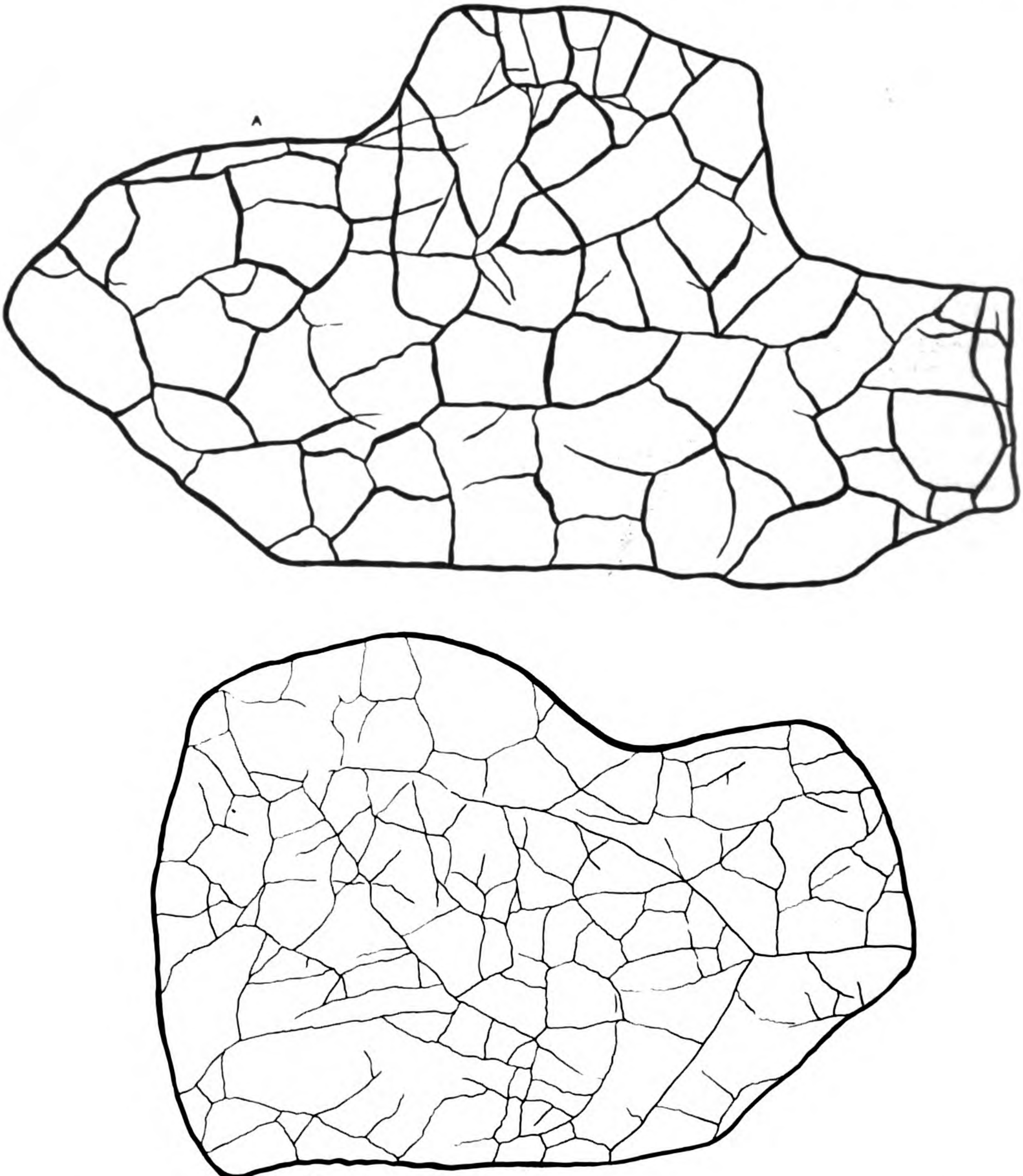


FIGURE 9.—Bedding plane pattern of shrinkage cracks in black dolomitic mudstone in lower few feet of gray chemical cycle. Casts are tan-weathering aphanitic dolomite and marlstone. *A,* Layers 0.5 to 1 cm thick with scattered small patches of calcite. Specimen is 45 cm wide. *B,* Layers 1 to 2 mm thick between layers of crystalline calcite. Specimen is 35 cm wide.

cur in lenses as much as 5 mm thick, and in densely scattered small crystalline patches in black mudstone layers (Fig. 12A).

Unit 2.—Above the distinctly platy, cracked sequence there are several feet of extensively disrupted 2 to 8 cm-thick layers of tan-weathering marlstone (Fig. 12; Van Houten, 1962, Pl. 1C) embedded in very dark-gray analcime-bearing mudstone. The pattern of fragmentation is similar to that of a flow-type, penecontemporaneous breccia developed in mudstone of the Keuper Series (Elliot, 1961, p. 205-

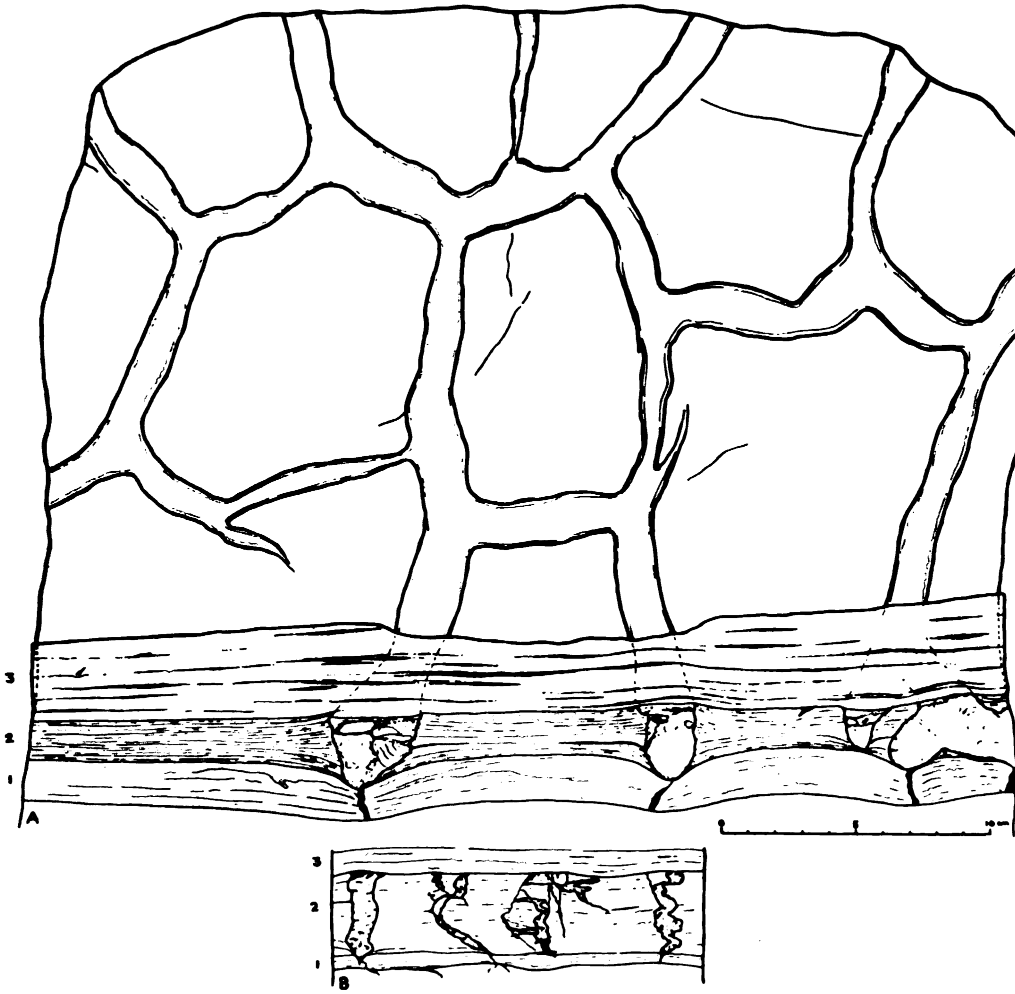


FIGURE 10.—Shrinkage-crack pattern and casts deformed during compaction, in basal part of short cycles. *A*, Surface (above) of platy black mudstone 3 cm above base of chemical cycle, and profile (below) of basal 6 cm of cycle showing thick broken and compressed crack-casts of aphanitic medium-gray dolomite and compaction "folds" developed in beds above and below. Specimen is 35 cm wide. *Bed 1.* Medium-gray dolomitic silty mudstone. *Bed 2.* Black dolomitic mudstone with some analcime, containing broken casts of aphanitic dolomite with trace of analcime. *Bed* 3. Black dolomitic mudstone with stringers of finely crystalline dolomite and analcime. *B*, Profile of basal 4 cm of detrital cycle, showing more slender crumpled crack-casts of aphanitic medium-gray dolomite which was locally injected into surrounding mudstone during compaction. *Bed 1.* Medium-gray, calcitic silty mudstone with trace of dolomite. *Bed 2.* Black mudstone containing crumpled casts of aphanitic dolomite. *Bed 3.* Black, dolomitic mudstone with trace of calcite.

206). These dolomite-rich layers apparently hardened and shrank more rapidly after burial than the surrounding dark-gray colloidal mud (*see*, Boswell, 1961, p. 67). Some of the disruption may have begun as syneresis cracks, then fragmentation by post-burial shrinkage upset the physical system so that the surrounding black colloidal gel reverted thixotropically to a sol. With loss of support the firmer dolomitic fragments drifted apart and colloidal mud in the sol state was forced around the firmer pieces.

This interpretation is consistent with Boswell's (1961, p. 50) report that lime added to clay-rich sediments reduces the thixotropy, that the plasticity of lime-rich mud is low, and that they compact more rapidly and fracture with ease if disturbed in the course of diagensis (p. 86, 98, 102).

In the middle of some chemical cycles frag-

FIGURE 11.—Irregular shrinkage-crack polygons and casts deformed during compaction, in basal part of chemical cycle. Surface (above) of dark-gray mudstone about 4 cm above basal bed of crystalline calcite, and profile (below) showing thick, plastically deformed casts of aphanitic dolomite compressed between layers of coarsely crystalline calcite. Specimen is 35 cm wide. *Bed 1.* Medium-gray, dolomitic marlstone with densely scattered calcite crystals in lower part. *Bed 2.* Coarsely crystalline calcite. *Bed 3.* Dark-gray, dolomitic mudstone with lobate casts of aphanitic dolomite. *Bed 4.* Coarsely crystalline calcite underlain by thin, discontinuous layer of black mudstone.

mented marlstone layers have been widely dispersed, yet a vague continuity of layering may be preserved by an alignment of angular pieces, or the fragments may be scattered upward through the overlying analcime-bearing mudstone in a large-scale "explosive" pattern (Fig. 13A; Van Houten, 1962, Pl. 1D) that suggests forceful disruption of layers of quick-setting dolomite-rich mud by localized upward moving muddy sol and water released during compaction.

The analcime-bearing mudstone in unit 2 commonly is brecciated and disturbed on a small scale as a result of physical disruption of colloidal-chemical mud. A minor part of the fabric may be bioturbation, but no certain

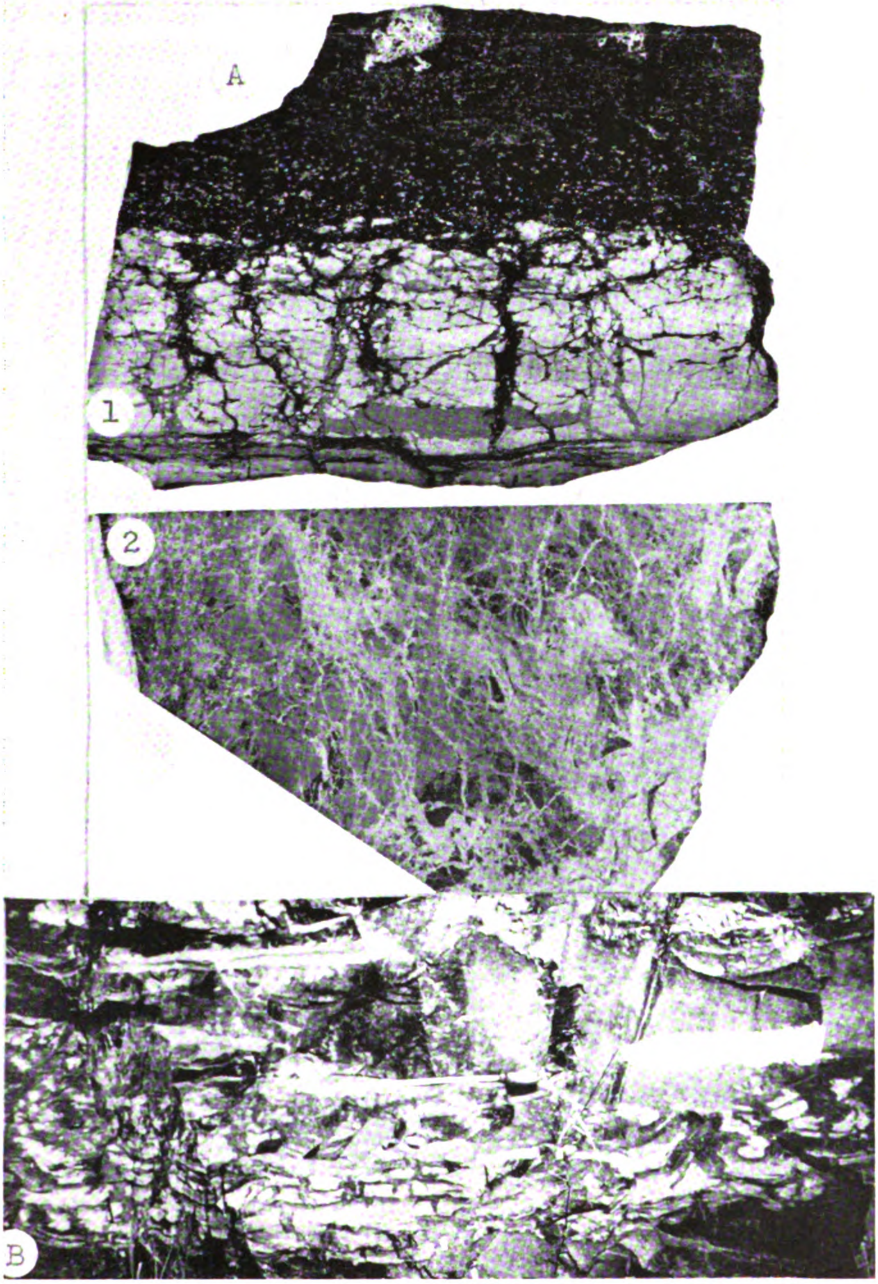


FIGURE 12.—Sedimentary features of middle part of gray chemical short cycle. *A*, Tan-weathering medium-gray marlstone in upper part of unit 1 brecciated by shrinkage cracks. × 0.66. 1. Profile showing shrinkage cracks only slightly crumpled. Overlying dark-gray, dolomitic mudstone speckled with small patches of dolomite and analcime. 2. Bedding surface showing shattered pattern of shrinkage cracking. *B*, Very dark-gray, analcime-bearing dolomitic mudstone with beds of tan-weathering medium-gray dolomitic marlstone in unit 2. Beds of marlstone in lower part of outcrop are fragmented by shrinkage cracks filled with dark-gray mudstone, but fragments are not widely scattered. Lower beds are 4 to 6 cm thick. Tape is 12 inches long.

evidence of burrowing has been found. In a few cycles a fabric of minute shredded and wispy fragments suggests that an intricate churning up of fluid mud with scattered firmer muddy films has occurred. The pattern resembles that of some of the complexly disturbed, indistinctly laminated mudstone in detrital cycles, but has no structures like burrow-casts.

The markedly different fabrics and patterns produced by disrupted layers in the middle of most chemical cycles apparently resulted mainly from differing thicknesses and proportions of firmer, quick-setting dolomite-rich beds and colloidal mud. It is of interest to note that they are *not* dependent upon the presence of montmorillonite which possesses remarkable thixotropic properties.

In the middle and upper part of some chemical cycles there are conspicuous patterns of irregular, white crystalline, crudely lozenge-shaped patches of analcime and dolomite as much as 7 mm long. Smaller patches occur inside indistinctly outlined lozenge-shaped areas of dark-gray mudstone. Some are densely scattered in zones 2 to 4 cm thick parallel to bedding; some occur in crudely radiating patterns as much as 10 cm in diameter. Others are distributed in irregular downward and outward diverging stringers that form sprays in a zone as much as 20 cm thick. The shape and distribution of these large crystalline patches of analcime and dolomite suggest that they may be pseudomorphs after gypsum or glauberite (Hawkins, 1914, p. 163-164; Wherry, 1916; Schaller, 1932, Pl. 1) that grew in soft and drying mud during low-water stages of chemical cycles. Once trapped, the soluble salts presumably were isolated from resolution and the ions migrated downward to places of lower concentration.

In the brecciated, dolomite-rich unit 2 of analcime-rich gray and grayish-red cycles in the upper part of the formation long crinkled shrinkage-crack casts are conspicuously offset or deflected along shear planes or thin laminae of sheared matrix parallel to bedding and about 2 to 5 cm apart (Fig. 13B). In some of these cycles, where seen on a large joint face, the shear planes have been deformed by plastic flow into a secondary structural pattern of broad upward-concaved arches (Fig. 14) ranging from 15 to 30 cm high and with wave lengths of 0.5 to 1 meter. In any one cycle there is only one zone of uparched shear planes and all arches are about the same height.

The arcuate shearing ends abruptly at the base of the structure with a distinctly fragmented horizontal layer bounded by horizontal shear planes along which most of the plastic flow took place. In the lower central part of each structure the crests are lower and the rock in intensely brecciated, suggesting flow of material inward and upward. At the apex of the intersecting arcs the crests are sharp; one limb commonly overrides the other a few centimeters; the overriding is in opposite directions on different crests in a cycle, and the slope of the shear planes is a little steeper on the overridden limb. Above the crest the sheared and brecciated layers are vaguely outlined as the arcuate pattern fades out upward. Because of the limited nature of Lockatong outcrops there is little information about the third dimension of these structures. From available observations they appear to be crudely conical structures. Apparently the cones formed in firm but plastic mud during dewatering and compaction of each cycle by the uparching of horizontal shear planes by inward and upward localized flowage concentrated on the basal planes of shearing.

The following sequence of nearly contemporaneous post-depositional events in analcime-rich cycles is suggested by the observed relationships:

(1) Many long, slender shrinkage cracks developed in carbonate-bearing gray mud by dewatering.

(2) The cracks were filled with more fluid dark-gray or grayish-red mud.

(3) Casts were crumpled as compaction began.

(4) Long, narrow fissures developed very locally and were filled with specular hematite and minor analcime.

(5) As compaction continued horizontal shearing offset and deflected crumpled casts and veins.

(6) Upwelling of differentially compacting mud at local centers arched the horizontally sheared mud into conical structures.

(7) Further compaction flattened the struc-

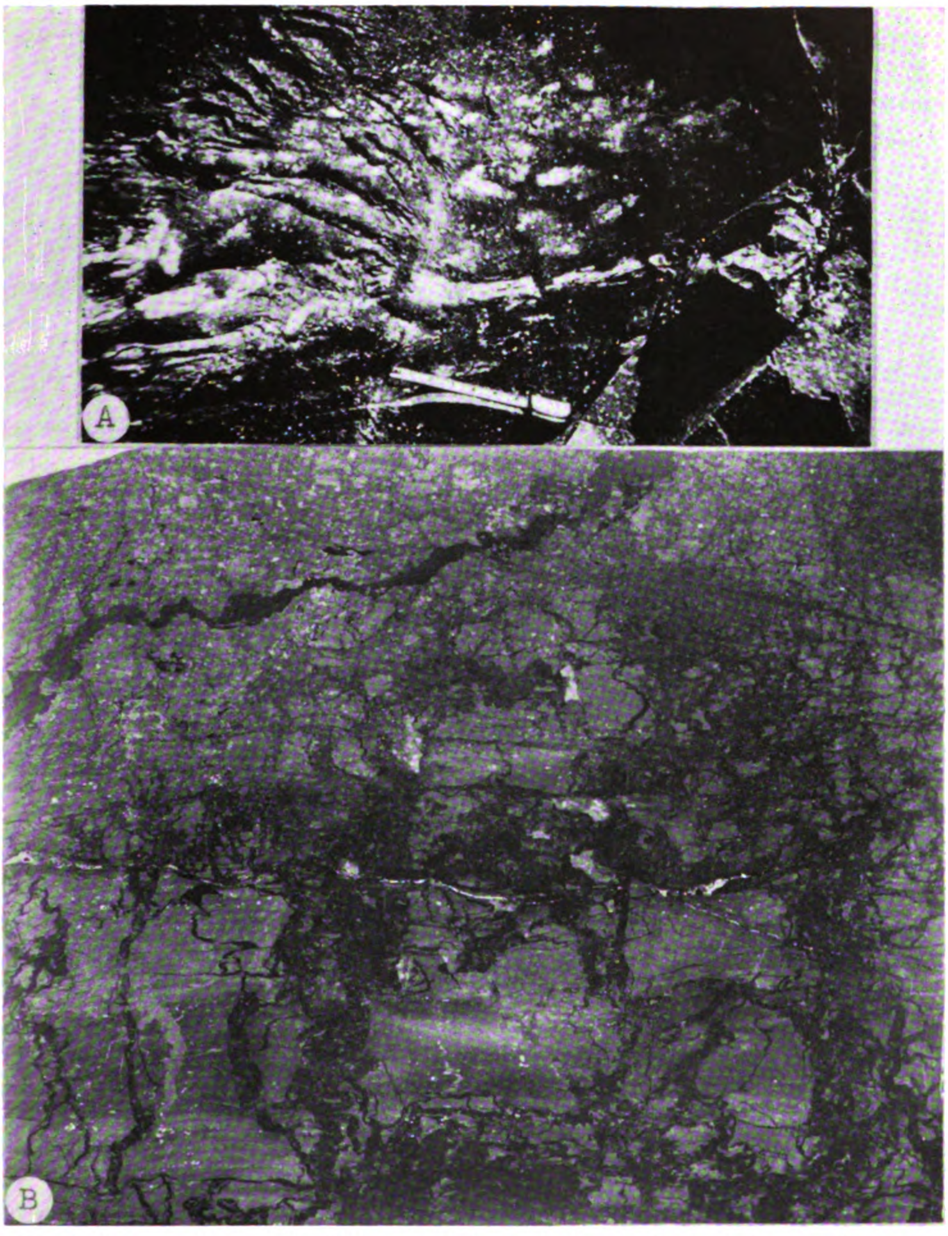


FIGURE 13.—Sedimentary features of middle part of chemical short cycles. *A*, Disrupted tan-weathering medium-gray, dolomitic marlstone layers scattered widely through very dark-gray analcime-bearing mudstone of gray cycle. Pattern of dispersal suggests forceful disruption after burial by upward-moving water and fluid mud. Small fragments of marlstone thinly dispersed through dark-gray mudstone above and below central feature. Tape is 6 inches long. *B*, Greenish-gray weathering, medium-gray mudstone in grayish-red cycle. Upper part extensively brecciated and immersed in grayish-red mudstone. Lower part disrupted by long, slender crinkled and injected shrinkage-crack casts of grayish-red mudstone. Many casts are offset laterally by compaction shearing. Crinkled vein of hematite and analcime in upper left. × 0.7.

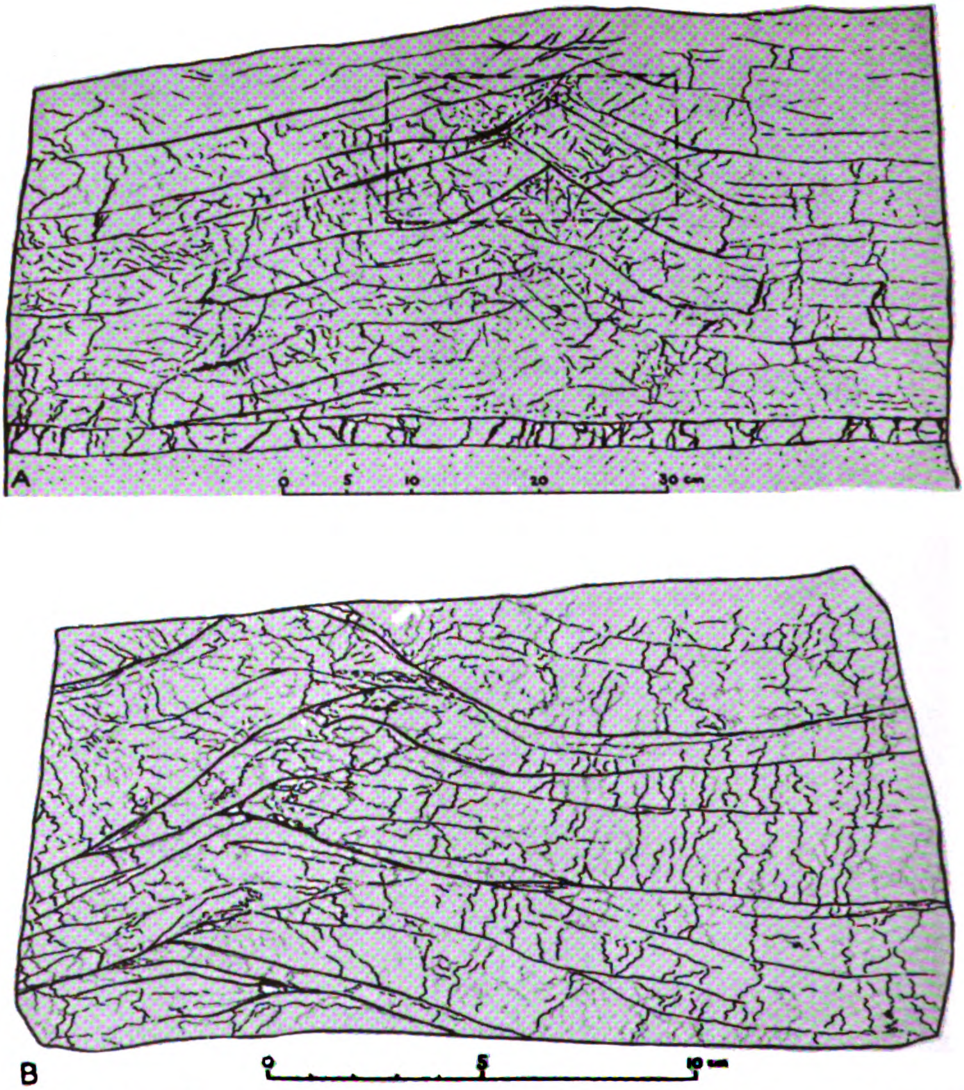


FIGURE 14.—Secondary structural pattern of upward-concaved planes and thin zones of shearing in dolomitic and analcime-bearing mudstone in middle part of chemical cycle. *A*, Complete pattern of arched shear planes showing abundant crumpled shrinkage cracks offset along shear planes, and distinctly brecciated, somewhat more dolomitic basal layer involved in structure. Right limb steeper and overriden. Dashed rectangle encloses area of *B*. *B*, Apex of another arched structure, equivalent to enclosed area of *A*. Right limb steeper and overriden.

tures somewhat so that the sheared layering was overridden at the crest of the cones.

Unit 3.—The upper part of most chemical cycles is characterized by medium-gray to dark brownish-gray, analcime- and carbonate-rich mudstone with abundant tiny rhombs of dolomite and small patches of analcime. On a microscopic scale the rock is extensively disrupted and locally contains very small, thinly dispersed fragments of marlstone (Fig. 13A). Irregularly disrupted layers of tan-weathering marlstone, like that in unit 2, recur about every 3 to 4 feet in the gray, massive mudstone. In a few chemical cycles there is a 1 to 2-foot bed of siltstone with delicately disturbed laminae, some of which are graded, and with only rare small burrow-casts.

The distinctive microscopic fabric of only slightly displaced fragments suggests small-scale brecciation of a flocculated colloidal mud by dewatering after burial. The shape and size of the microbreccia fragments differ in detail from one cycle to another. In a few cycles the fragments are barely discernible; in others they are wispy and shredded or irregularly blocky (Fig. 15A, 15B, 15C). As yet no trend in these differences is apparent, but they probably reflect variations in the colloidal and chemical environment of deposition, such as varying concentrations and kinds of cations present (White, 1961, p. 569).

In addition to its distinctive microbrecciation, the upper massive mudstone has a fabric of indistinct, delicate and discontinuous crinkled cracks partially and irregularly filled with crystalline dolomite (rarely calcite) and analcime forming patches as much as 8 mm long. The pattern of delicate fissure-filling is like that of syneresis cracks in mud where the process of shrinkage continued until little curds or islands of mud formed with cracks on all sides (White, 1961, Pl. 2).

In detail there are several distinctive associations of minerals in the patches. In some cycles minute dolomite rhombs are scattered abundantly throughout the analcime-rich mudstone, and analcime is the principal mineral in large irregular patches with lobate outlines. In other cycles analcime fills numerous thin discontinuous cracks and coarsely crystalline dolomite occurs in large patches. Less commonly small patches of analcime and crystals of dolomite are arranged in vague trends with no discernible fissures. Analcime and dolomite also occur as scattered lozenge-shaped pseudomorphs.

In addition to analcime and dolomite, the following minerals fill patches in unmetamorphosed mudstone: calcite, albite, chlorite, epidote, quartz, and amphibole.

The uppermost 2 to 8 cm of a cycle commonly is very dark-gray above gray mudstone and the top surface is mudcracked. The darker color apparently resulted from downward penetration of strong reducing effects prevailing at the beginning of the succeeding cycle. A similar situation prevailed at the top of Dunkard cycles (Beerbower, 1961, p. 1035).

Sedimentary features of grayish-red cycles

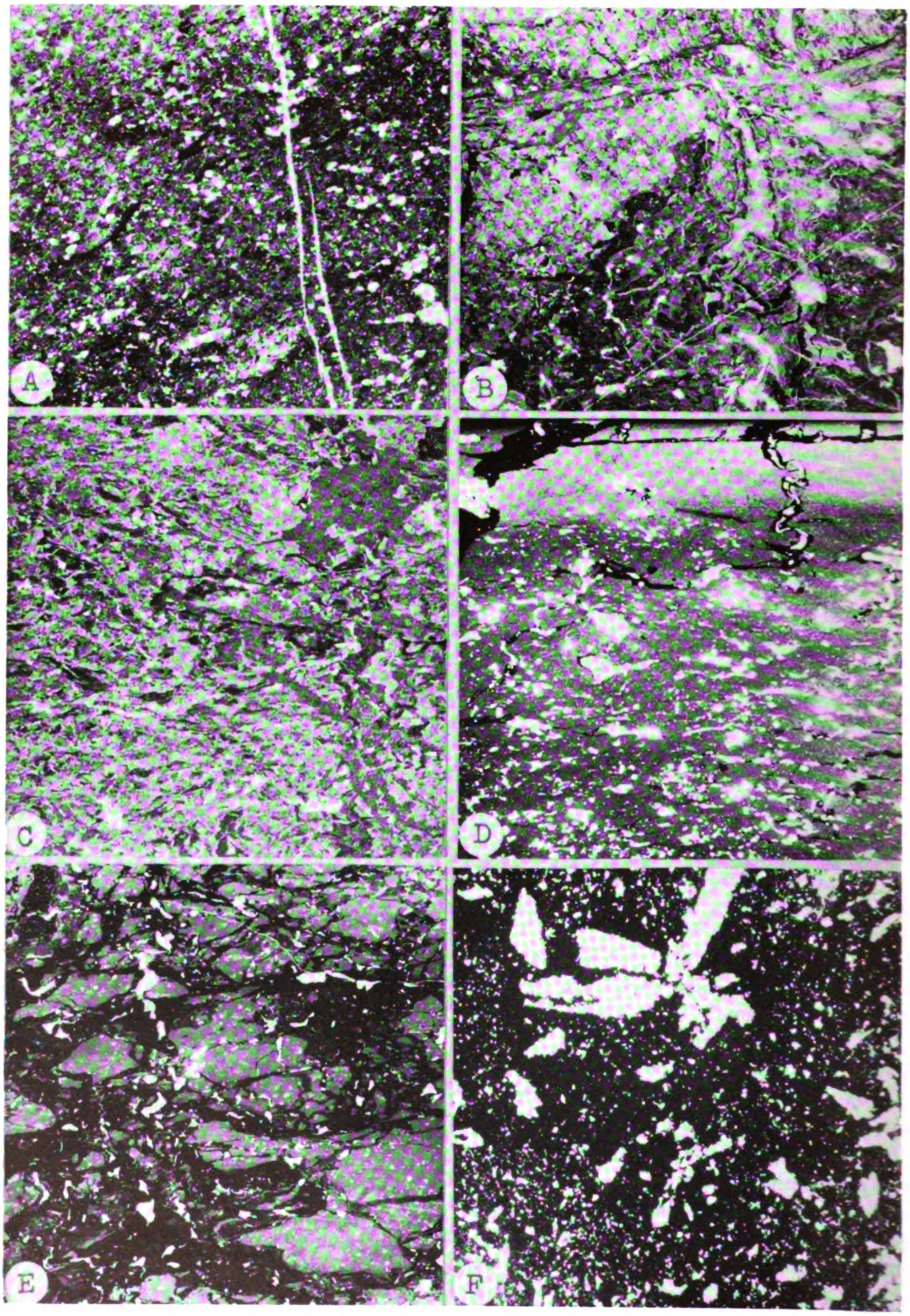
Some of the chemical cycles in the upper part of the Lockatong Formation are grayish-red in the upper part or grayish-red to grayish-red purple throughout. In the succession of cycles these occur in the most analcime-rich intervals (Fig. 2) and apparently grade laterally into tongues of reddish-brown Brunswick mudstone. In the grayish-red cycles, greenish-gray weathering, light- to medium-gray, slightly dolomitic mudstone, normally with considerable analcime, proxies for the variously disrupted tan-weathering dolomitic marlstone in gray cycles. The massive grayish-red mudstone also contains more analcime and less dolomite than massive mudstone in gray cycles.

In cycles that are grayish-red in the upper part only, the color change occurs in the middle extensively brecciated unit where small greenish-gray weathering fragments of mudstone are scattered thinly through dark grayish-red massive mudstone.

As in some analcime-rich gray cycles, an arcuate pattern of shear planes has been imposed on the middle part of grayish-red cycles. It is conspicuously recorded by brecciated greenish-gray weathering beds with crinkled crack-casts cut by arcuate grayish-red zones of shearing 0.5 to 1 mm thick.

In a few cycles veins filled with specular hematite and analcime are as much as 4 feet long and 1 to 4 mm wide, and cut diagonally across the bedding (Fig. 13B). In detail, the veins are crinkled in both vertical and horizontal planes, and in profile are deflected or offset along planes or zones of horizontal shearing.

The upper massive analcime-rich mudstone commonly is grayish-red to dark reddish-brown, shows no disruption by shrinkage cracks, has only a vague fabric of microbrecciation, and contains abundant minute rhombs, clusters, and stringers of dolomite and analcime (Fig. 15F). Some are scattered lozenge-shaped pseudomorphs after gypsum, or glauberite? as much as 4 mm long. Locally, concentrations of analcime and dolomite crystals occur in crudely radiating patterns


A
B
C
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F

through an area about 10 cm in diameter, suggesting replacement of a salt that crystallized in a radiating pattern in soft mud. Similar rosettes of slender lozenge-shaped calcite pseudomorphs as much as 3 cm long occur in the Brunswick mudstone.

The uppermost several centimeters of many of the grayish-red cycles, as in the gray ones, show the effect of reducing conditions imposed by the succeeding cycle, and the top bedding surface is mudcracked (Fig. 16).

Cycles that are entirely grayish-red or grayish-red purple comprise some of the thinnest of the chemical cycles and are only vaguely demarcated in outcrop. Greenish-gray weathering mudstone at the base of some of these cycles occurs in several layers 5 to 10 mm thick. Most of the layers are broken into angular fragments by shrinkage cracks filled with grayish-red mudstone (Fig. 15D), and commonly show a mosaic type of intraformational brecciation with flat, flakelike fragments oriented parallel to bedding.

In the middle and upper part of some thin grayish-red cycles 15 to 25 cm-thick layers of greenish-gray weathering mudstone are extensively brecciated into large fragments immersed in grayish-red mudstone. In other cycles 5 to 15 cm-thick layers of gray mudstone are brecciated on a small scale (Fig. 15E) and disrupted by many long, slender, intricately crumpled and delicately ramifying shrinkage cracks apparently produced by syneresis (Fig. 13B). The crack-filling was locally injected into the matrix and was laterally displaced by horizontal shearing during compaction.

In contrast to the delicately brecciated features, some layers of gray mudstone as much as 8 cm thick are broken by stout cracks as much as 3 cm wide. These outline large irregular polygons (Fig. 17). The unusually thick crack-casts of grayish-red mudstone anastomose downward through brecciated gray mudstone and are joined by short, slender, randomly oriented and crinkled casts that are laterally offset or deflected by compaction shearing. Their bedding-plane traces form a complex pattern of thin cracks within larger polygons.

The fact that cracks in gray beds are filled with grayish-red mudstone but cracks in grayish-red beds are never filled with gray mudstone suggests that the gray beds accumulated subaqueously in a weakly oxidizing or reducing environment and were readily disrupted by syneresis or by shrinkage during exposure on mudflats on which overlying grayish-red mud accumulated. Continued cracking of gray beds after burial permitted squeezing of fluid grayish-red mud into intricate syneresis cracks during compaction.

In thin grayish-red cycles the analcime-rich mudstone commonly is blackish red to very dusky red. Beds conspicuously speckled with large white patches of analcime and dolomite, are interbedded with completely aphanitic layers as much as several millimeters thick that are disrupted by intricate patterns of shrinkage cracks or by mosaic type of intraformational brecciation (Fig. 18). Many of the white patches, which may be as much as 8 mm long, are concentrated in shrinkage cracks or between mosaic flakes.

In contrast to the abundant evidence of post-burial shrinkage and disruption in gray chemical cycles, most of the structures in grayish-red cycles suggest repeated cracking when the mud stood a little above water-level during low stages of the lake. In fact, many of the patterns are suggestive of large playa cracks crossed by later less regular ones

FIGURE 15.—Photomicrographs of massive analcime-rich mudstone of chemical cycles. *A*, Dark-gray mudstone with shredded fabric of microbrecciation and distinctive pattern of short trains of rhombs, lozenges, and ovals of dolomite (mostly 0.2 to 0.4 mm in diameter). Trains and darkest shreds outline vague stratification from upper right to lower left of photograph. Many small irregular patches are analcime. × 3.5. *B*, Dark-gray mudstone with colloform fabric. Large irregular vugs (0.5 to 1 mm long) filled with analcime, dolomite and muscovite?. Slender crumpled shrinkage cracks and very small patches filled mainly with analcime. × 3.5. *C*, Dark-gray mudstone with shredded to blocky fabric of microbrecciation. Irregular vugs (0.5 to 1.4 mm long) filled with analcime, dolomite, and muscovite?. Crumpled fabric near right edge may be gas passageway. × 3.5. *D*, Medium-gray, homogeneous mudstone fragmented by crumpled shrinkage cracks filled with grayish-red mudstone and specular hematite, and analcime and rare dolomite. × 3.5. *E*, Brecciated, medium-gray mudstone immersed in grayish-red mudstone. Crumpled shrinkage cracks are filled with long patches of analcime and dolomite. × 3.5. *F*, Reddish-brown mudstone speckled with minute irregular patches of analcime in discontinuous shrinkage cracks around curds of mudstone. Large lozenge-shaped pseudomorphs of dolomite after gypsum or glauberite. × 3.9.

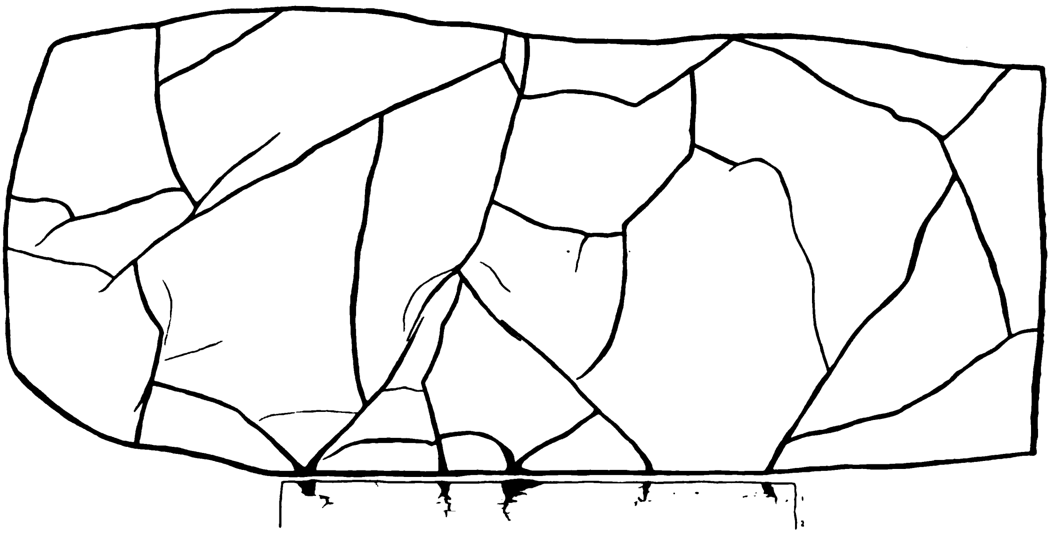


FIGURE 16.—Top surface of grayish-red chemical cycle showing pattern of shrinkage cracks; and profile of uppermost 3.5 cm showing crumpled and horizontally sheared crack-casts. Vaguely brecciated light- to medium-gray, analcime-rich mudstone (1) grading down into massive grayish-red analcime-rich mudstone (2). Gray color produced by downward penetration of reducing conditions imposed by initial stage of succeeding cycle. Casts are dark-gray, dolomitic mudstone. Specimen is 80 cm wide.

(Longwell, 1928, Fig. 6). After burial, crack-filling mud in a very fluid state apparently was squeezed along lateral passageways opened as the casts were crumpled during compaction.

Despite the abundance and variety of subaerial cracking recorded in the grayish-red cycles, they need not have been out of water most of the time. Accumulation of lacustrine mud may have persisted for long intervals, probably measured in hundreds of years, to be interrupted by brief episodes of exposure and deep cracking that may have been but one season long. Accordingly, these subaerial episodes were brief intense reversals in the long sequence of aggradation under water.

SYNTHESIS

(1) In common with other lacustrine deposits the Lockatong Formation is characterized by laterally persistent units, thin-bedding, varving, local graded bedding, disturbed bedding, small-scale cross- and ripple-bedding, subaerial shrinkage cracking, abundant carbonates, and salt casts (Klein, 1962b). Animal burrow-casts are common in the Lockatong detrital cycles; syneresis disruption predominates in chemical cycles where analcime and dolomite are concentrated.

(2) In contrast to other lacustrine deposits, the Lockatong Formation is marked by an unusual abundance of small-scale disturbed bedding as well as a paucity of fossils, algal structures, ripple-marked bedding planes, oolites, and irregular channel lenses. Among minerals there is a notable scarcity of quartz, potash feldspars, and montmorillonite, and no concentration of salts.

(3) Accumulation of the Newark Group took place in a continuously sinking basin surrounded by uplands that supplied a thick wedge of nonmarine sediments. During the course of aggradation of the Triassic basin in New Jersey and eastern Pennsylvania fluvial deposition of the Stockton arkose and mudstone ended with ponding of the longitudinal drainage of the basin. At present there is no direct evidence as to the direction of flow of the main stream or the specific cause of damming. Initial deposits of the developing new environment were ripple- and cross-laminated silt and very fine sand and mud spread across broad flats where they were mudcracked and reworked by abundant burrowers.

With the establishment of a long lake, uniform lacustrine conditions prevailed and these varied only within narrow limits for several million years (Van Houten, 1962, Table 1).

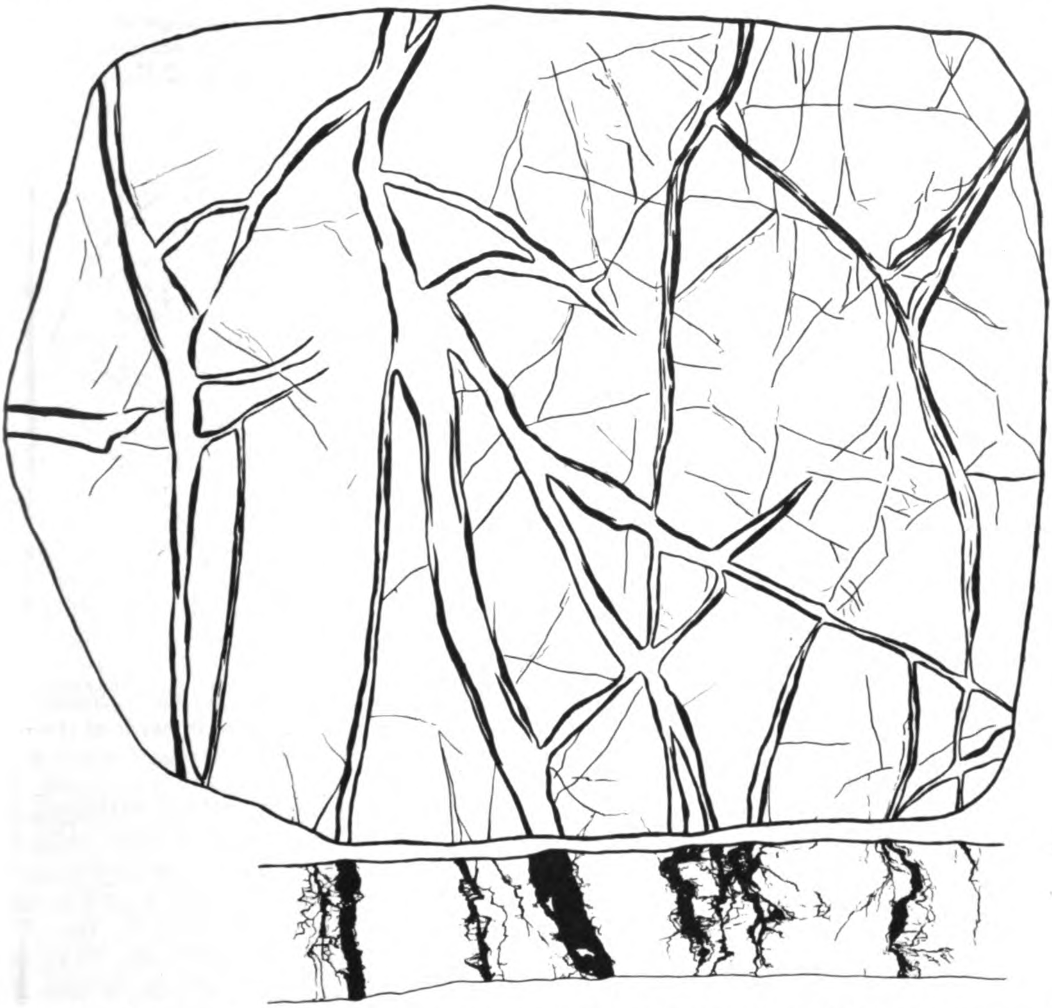


FIGURE 17.—Surface pattern of stout shrinkage-crack casts and profile of 5 to 8 cm-thick layer of gray mudstone at top of thin grayish-red chemical cycle, showing unusually thick and anastomosing casts of grayish-red mudstone that were crumpled, sheared, and injected laterally during compaction. Specimen is 60 cm wide.

Most of the sediment accumulated in shallow, thermally stratified water, below wave base, with no bottom turbulence. Interpretation of these as shallow-water deposits implies that their total thickness provides an approximate measure of the amount of subsidence of the basin.

In this setting cyclic variations in climate exerted a major control on sedimentation. A warm climate, as recorded by floras from Triassic deposits of eastern North America, probably induced deep weathering in the source areas, thus providing abundant free ferric oxide and silica as well as rapid evaporation which aided the concentration of cations in the lake. Assuming that the short cycles were produced by the 21,000-year precession cycle, the following reconstruction is proposed.

Chemical cycles accumulated when the lake had no outlet and chemicals from a deeply weathered source area were concentrated and precipitated in the lake. A cycle began with increasing rainfall and inflow of fresh water. As the lake level rose, laminated carbonate-rich black mud and layers of pure carbonate and pyrite were deposited on the stagnant bottom, but there is no direct evidence of pre-

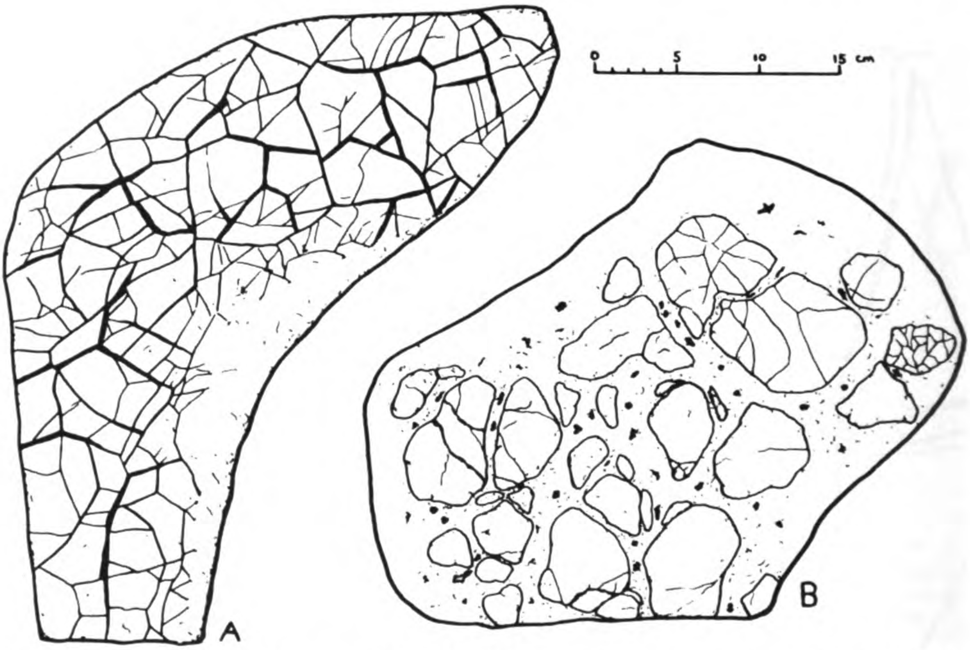


FIGURE 18.—Pattern of shrinkage cracks *A*, and mosaic type intraformational breccia; *B*, in blackish-red to very dusky-red analcime-rich aphanitic mudstone in grayish-red chemical cycle in uppermost part of Lockatong Formation. Patches of analcime and dolomite as much as 8 mm long are concentrated in blackish-red mudstone filling cracks and spaces between mosaic flakes.

cipitation of carbonates by algae. Through the course of a short cycle, rainfall began to wane; the water perhaps became somewhat shallower and less stagnant. Deposition of uniform colloidal clay predominated as the continued precipitation of carbonates left the water enriched in sodium. In this way analcime or its precursor accumulated in the colloidal mud.

In the late dry stage of many of the chemical cycles, and throughout the course of some, grayish-red mud was preserved in a dry oxidizing environment that produced a maximum concentration of sodium. At such time the size of the lake probably was reduced, leaving broad mudflats with pools of noxious brine from which scattered crystals of salt (probably gypsum or glauberite) were precipitated in the mud. In the final stage of minimum rainfall of many chemical cycles, the lake basin was covered by vast swamps, but during drier episodes the lake bottom and mudflat deposits were exposed to suncracking in the final stage and salts crystallized locally in the mudcracks. Once formed, the recently deposited cycle underwent relatively rapid compaction which accentuated lowering of the basin floor by continuous sinking. During early compaction upward-moving water probably transferred some sodium, silica, and carbonates to the upper part of the cycle where they were deposited in shrinkage cracks and salt molds. Such an upward migration apparently occurred before deposition of the analcime-lean basal beds of the overlying cycles that was initiated by renewed inflow of fresh water.

Detrital cycles resulted from a similar cyclic increase and decrease in rainfall, but they accumulated during moister episodes that maintained a through-flowing drainage which carried most of the soluble material to the sea. Only during the stage of maximum inflow were silt and very fine sand spread as a prograding facies across the lake basin, accumulating above wavebase in a setting of repeated gentle scour and fill.

Throughout the history of the Lockatong lake (Fig. 19A) deposition repeatedly reverted to a Stockton-like "deltaic" facies whenever moister phases of long climatic cycles generated through drainage and produced detrital cycles. During drier phases of the long cycles, especially in the later stage of the lake, grayish-red chemical cycles were induced by conditions that anticipated the broad expanse of oxidizing mudflats on which reddish-brown Brunswick mud accumulated.

In this setting chemical cycles developed in two different ways essentially related to the influx of detrital sediments. In an earlier stage of an elongate lake flooding the length of the basin, chemical cycles accumulated as a central basin facies remote from detrital contamination while mud forming detrital cycles accumulated at the periphery and graded marginward into the Stockton arkose. When accumulation of the Stockton facies gave way to the Brunswick mudflat facies at the margin the lake became more equant in shape, less long and spreading marginward to the southeast beyond earlier Lockatong deposits. Now chemical cycles achieved their maximum development as the mudflat facies with relatively little coarse detrital sediment encroached upon the lake.

(4) In their general pattern detrital cycles that accumulated in open lakes possess many of the characteristics of some cyclothems (Beerbower, 1961, p. 1040-1042). Each was controlled by symmetrical climatic cycles that produced an asymmetrical succession of depositional environments; each shows a crudely symmetrical cycle of grain size; each contains siltstone and very fine grained sandstone channel deposits developed as delta distributaries cutting into lacustrine mud accumulated in shallow water; and each records cyclic deposition preserved in a continuously sinking basin.

In contrast, chemical cycles accumulated in closed saline lakes. From comparison with modern closed lakes (Langbein, 1961) the environment was arid to semiarid, and gross evaporation exceeded precipitation of less than 25 inches a year. As in playas, salt crystals apparently grew in the mother liquor in the mud below the drying surface.

(5) With the waning of the Lockatong lake, mudflats or broad floodplains with wandering watercourses and weak external drainage prevailed during deposition of Brunswick mudstone (Fig. 19A). Now expression of the short climatic cycles was diminished again, but long cycles produced episodes of a dry oxidizing environment and thick sequences of reddish-brown mud that alternated with moister periods producing brief returns to reducing conditions and accumulation of thin sequences of dark gray mud.

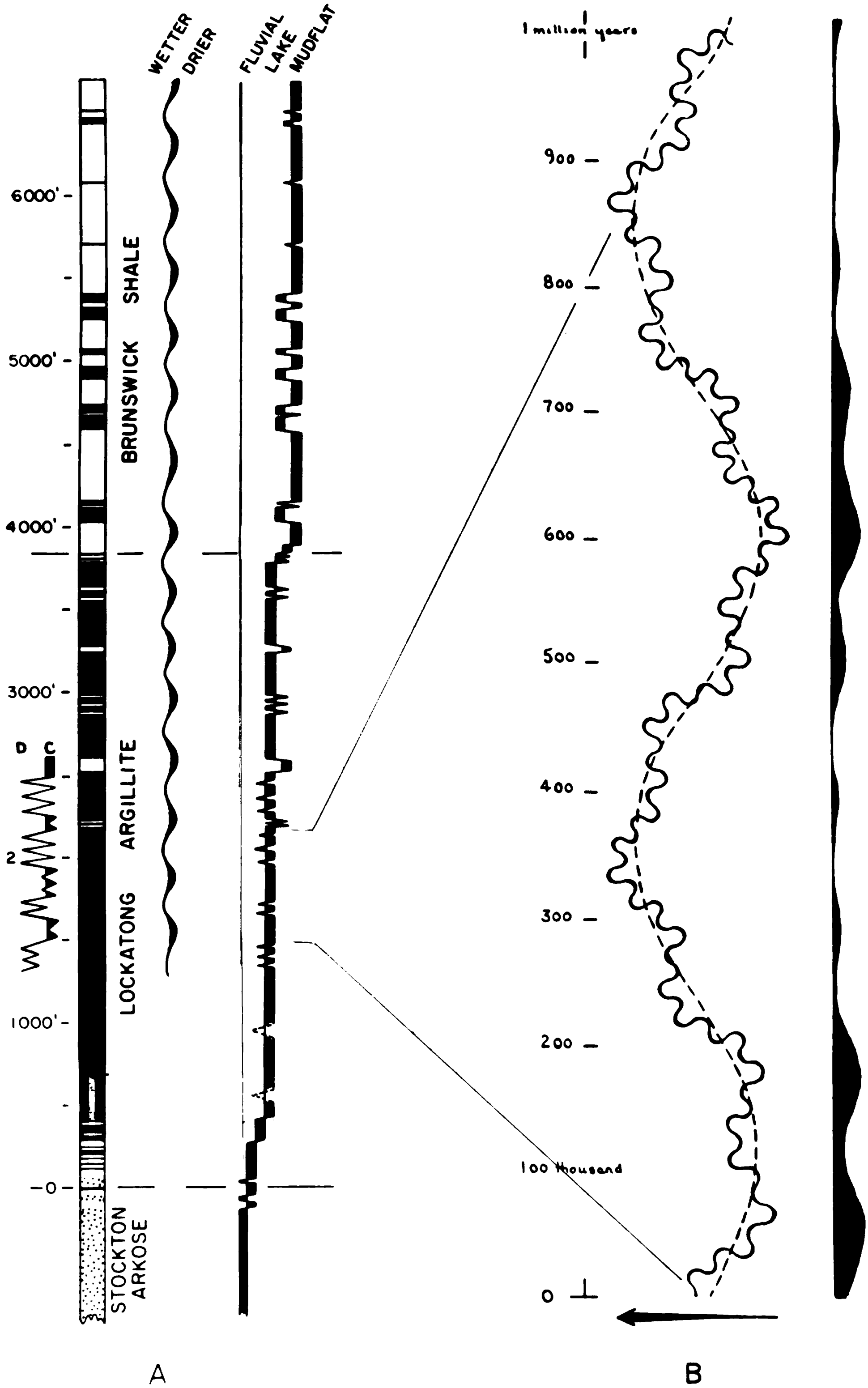
(6) Similarities between Lockatong detrital cycles and Stockton fluvial deposits and between grayish-red chemical cycles and Brunswick mudflat deposits (Table 1), (*a*) suggest that in many ways the Lockatong conditions were transitional between those of the Stockton and the Brunswick lithofacies, and (*b*)

Table 1.—Distribution of selected features in Lockatong Formation and adjacent strata of Newark Group (Fig. 19A).

	S	Lockatong			B
		L	M	U	
Redox potential					
Oxidizing	X	X		x	X
Reducing		x X	X	X	xg
Drainage					
Through	X	Xd	xd	xd	X
Closed		xc	Xc	Xc	
Fauna					
Swimmers		xd	xd	xd	xg
Burrowers	X	Xd	xd	xd	X
Tracks	x	x	x	x	X
Current action					
Channeling	X	x xd	xd	xd	x
Cross-bedding	X	X xd	xd	xd	x
Shrinkage cracks					
Subaerial	x	X x	x	Xc	X
Syneresis		X	X	X	
Grain size					
Medium sand	X				
Fine sand	X	X xd	xd	xd	x
Silt-clay		Xd	Xd	Xd	X
Collochemical		xc	Xc	Xc	
Minerals					
Quartz	X	x			x
Calcite	X	Xd	Xd	Xd	X
Dolomite		x	Xc	Xc	x
Analcime		X	Xc	Xc	
Pyrite	x	x	X	x	xg
Salt casts			xc	Xc	X

X—dominant
x—subordinate
d—detrital short cycle
c—chemical short cycle
g—gray units

S—upper Stockton
L—lower Lockatong
M—middle Lockatong
U—upper Lockatong
B—lower Brunswick


WETTER
DRIER
FLUVIAL
LAKE
MUDFLAT
1 million years
900
800
700
600
500
400
300
200
100 thousand
0
6000'
5000'
4000'
3000'
1000'
0
D
C
2
BRUNSWICK SHALE
LOCKATONG ARGILLITE
STOCKTON ARKOSE
A
B

support the reconstruction of a shallow lacustrine origin for the Lockatong Formation.

(7) The fact that the grayish-red chemical cycles with abundant pseudomorphs of salt accumulated during the driest episodes in Lockatong history implies that Brunswick redbeds were also products of dry phases of the long climatic cycles. In this dry environment halite and glauberite crystallized in soft Brunswick mud (Wherry, 1916; Hawkins, 1928), and concentrated cations in ephemeral lakes on Brunswick mudflats crystallized out as anhydrite and glauberite when local lakes were overrun by lava (Schaller, 1932, p. 8).

(8) On the basis of varve-counts of beds in the lower part of chemical cycles the duration of three different cyclic patterns (Fig. 19B) has been estimated:

(*a*) short cycles: 15 feet thick average; 21,000 years.

(*b*) intermediate bundles of short cycles: 70 to 90 feet thick; 100,000 years.

(*c*) long cycles: 325 to 350 feet thick; 500,000 years.

A similar sequential pattern of cycles of three different orders of magnitude has been identified in the Keuper Series of England (Elliot, 1961, p. 225) and has been portrayed as "composite rhythms" by Barrell (1917, p. 795-797).

(9) The sequence of facies in the Newark Group points to a general progression from fluvial to mudflat environments. Assuming that climate was a basic control, the succession of Stockton, Lockatong, and Brunswick deposits reflects a change from abundant to limited inflow in response to a general trend from moister to drier climate. Granted, this sequence of formations could have been produced by controls other than climate. The possibilities await rigorous testing.

(10) Considered in their regional setting, Lockatong cycles were part of a continuing pattern of cyclic sedimentation recorded in late Paleozoic and Triassic rocks in eastern United States. Mississippian and Pennsylvanian cyclothems of western Pennsylvania were cratonic marine to nonmarine cyclic deposits reasonably accounted for by climatic oscillations (Wanless, 1963). Latest Pennsylvanian and Permian cyclothems of the Dunkard Group are essentially like their predecessors but are wholly nonmarine and partly lacustrine. These, too, have been attributed to climatic control (Beerbower, 1961).

According to this reconstruction, cyclic climatic control of sedimentation during late Paleozoic and Triassic time was accompanied by a progressive withdrawal of the sea that produced a succession of environments from marine to nonmarine. Then a trend toward drier climate produced changes in environment from fluvial to open lakes, then to closed lakes and finally to mudflats.

FIGURE 19.—*A*, Generalized stratigraphic section of uppermost Stockton, Lockatong, and Brunswick Formations. Black—gray units; white—grayish-red to reddish-brown units. Left of column—distribution of short chemical (C) and detrital (D) cycles in pattern of intermediate and long cycles; based on data in Fig. 2A. Long climatic cycles of wetter and drier phases and sequence of alternating geographic environments sketched in columns at right. *B*, Model of two long climatic cycles and associated intermediate and short climatic cycles. Arrow indicates direction of increase in detrital sediment, in moisture, and in rate of deposition. Graph shows relative amount of analcime produced during intermediate and long cycles.

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Depositional Topography in Relation to Cyclic Sedimentation

ABSTRACT

The electric logs of numerous wells drilled in west-central Texas and adjoining West Texas afford an opportunity for more detailed stratigraphic studies than is possible on such an extensive scale with other kinds of subsurface data or with outcrop sections. These studies disclose that the sediments deposited during the regressive part of the major Pennsylvanian-Permian sedimentary cycle assumed a topographic form which, in profile, resembles the classic delta, with topset (unda), foreset (clino), and bottomset (fondo) segments, in sequence toward the southwest. Under stable conditions clay and sand were carried southwestward and deposited in all environments, but principally on the clinoform, shifting it and extending the undaform southwestward at the expense of the fondoform.

True stability was rarely attained, however, because relative sea level often changed, in a few cases by hundreds of feet but usually by some tens of feet. During each rise or transgression, limestone accumulated in a broad belt along the outer "drowned" undaform, occasionally developing a barrier reef behind which evaporites formed. Gradually pre-existing conditions were restored as increasing amounts of clay and sand arrived in the form of a smaller-scale embankment which advanced seaward across the lagoon which had developed over the older "drowned" undaform. When advance continued past the position of the older clinoform, it produced the "complete, normal" sedimentary cycle.

Occasionally regression modified the cycle by promoting deposition of coal or of red clay and evaporite facies on the emergent undaform, or in more extreme cases permitting erosion and channelling of the undaform and extensive deposition of sand and clay on the fondoform.

Much more commonly, however, the cycle was interrupted by renewed transgression long before the lagoon was filled, yielding an incomplete cycle which may not be widely recognizable. Repeated interruptions enabled a few undaform-edge limestone bodies to accumulate to thicknesses of several hundred feet, giving rise to composite cycles.

Each well-developed cycle should be recognizable in all environments; but part of the cycle may be represented by nondeposition in the deeper water environments, and by erosion on the undaform, especially near the sediment source areas. The base of each cycle is that of the bed deposited during the relatively rapid shift of facies that initiated the cycle, or the corresponding hiatus, both of which are practical "time surfaces." This rapid shift of facies was caused by some change in external conditions, ordinarily expressed by a rise in relative sea level, which upset the pre-existing gradational equilibrium. The rest of the cycle is the product of slow migration of contemporaneously adjoining environments past the point of observation as pre-existing conditions were gradually restored.

Cycles were caused, and preserved, by regional subsidence at a fairly uniform rate, upon which were superposed large and small fluctuations in sea level caused by waxing and waning of distant continental glaciers. Smaller cycles resulted, in part, from shifts in the positions of river mouths.

INTRODUCTION

Pennsylvanian and Permian sediments of west-central Texas and adjoining regions record one major transgression of the sea over what briefly had been a land area, with development of an inland sea more than 1,000 feet deep, and subsequent filling of this sea by the southwestward advance of a deltalike coastal plain. Superimposed upon this major sedimentary cycle are many smaller cycles expressed by repetitive lithologic sequences. The present paper is concerned principally with the smaller cycles in the regressive part of the major Pennsylvanian and Permian cycle. Earlier papers by the writer (1957b, 1958) describe the sedimentary framework and patterns.

Numerous wells have been drilled through the Pennsylvanian and Permian sediments and logged electrically. Distinctive successions of responses on the electric logs make it possible to correlate some parts of the section in great detail so that lateral changes in the lithology of thin time-stratigraphic units can be observed on a much more extensive scale than is possible with other kinds of subsurface data or with outcrop sections. Unfortunately, however, intensive studies of such lateral changes in the lithology of restricted time units by use of cuttings and cores from numerous wells seemingly have not been made, or published. Despite this deficiency, certain broad relations are evident from electric logs plus scattered cores, samples, sample logs, and a few published descriptions. This approach brings out the unity of seemingly unlike cycles that formed simultaneously under dissimilar conditions.

THE BASIC CYCLE

Figure 1 illustrates the basic cycle, of which many variants exist. When clay, sand, and even gravel were carried in abundance into the area, the topographic surface assumed a form resembling in cross section the classic delta, with topset (unda), foreset (clino), and bottomset (fondo) beds. The writer uses the parenthetical terms, plus the suffix-*form*, to designate the particular topographic element; and *-them* similarly for the corresponding rocks, as proposed by the late John L. Rich (1951). Depositional topography is a general term used to describe such topographic forms assumed by sediments as a result of depositional processes. The unda-clino-fondo suite seems to be much the most commonly observed manifestation of depositional topography, but sediments are deposited also in many other topographic forms (e. g. organic reefs, "sand bars" of many sorts, etc.); and with initial dips above these as well as over topographic irregularities produced by erosion. Present consideration is restricted to the lithologic cycles in certain unda-clino-fondo sediments.

The "typical" cycle of Figure 1 began with marine transgression which abruptly reversed the pre-existing conditions under which clay and sand had been arriving in sufficient amounts to build out the clinoform and undaform. In the absence of these terrigenous sediments indigenous lime-secreting organisms became the chief source of material deposited on the outer, "drowned," undaform. However, before the limy facies expanded into some localities, and beyond the limits of that facies, dark organic clay was the usual fondo deposit under the new sedimentary regime (where water depths were sufficient). On the deeper fondoform such clays tended to be highly siliceous, thus forming the most satisfactory stratigraphic markers in the deep fondo environment.

This state of affairs—deposition of limestone along the outer drowned undaform and fondo dark clay on both sides—changed as pre-existing conditions were gradually restored by arrival of increasing amounts of clay and sand. These sediments were deposited in the form of a smaller scale embankment, a clinoform-undaform, which advanced seaward (southwestward) across the lagoon which generally had developed over the drowned undaform. At first this advance simply restricted the area of "shallow" fondo deposition on the drowned undaform, then the embankment lapped onto the unda-edge limestone and in some cases completely covered it. If sand and clay continued to be supplied, the embankment built out beyond the pre-existing (drowned) clinoform and thereby restored conditions to those at the beginning of this "typical" cycle.

If no new cycle was started immediately, the clinoform-undaform continued to advance, expanding the coastal plain environments. In west-central Texas the two conspicuous sediment suites formed in such "extended" cycles were characterized by coal, and by red shale, which occasionally extended over much of the earlier limestone facies of the same cycle. Farther landward the coastal plain (as well as sediment source areas) was subject to erosion, which in some places formed a conspicuous unconformity similar to the channelled surfaces described on the outcrop by Lee and others (1938, Pl. 1, 2, 3).

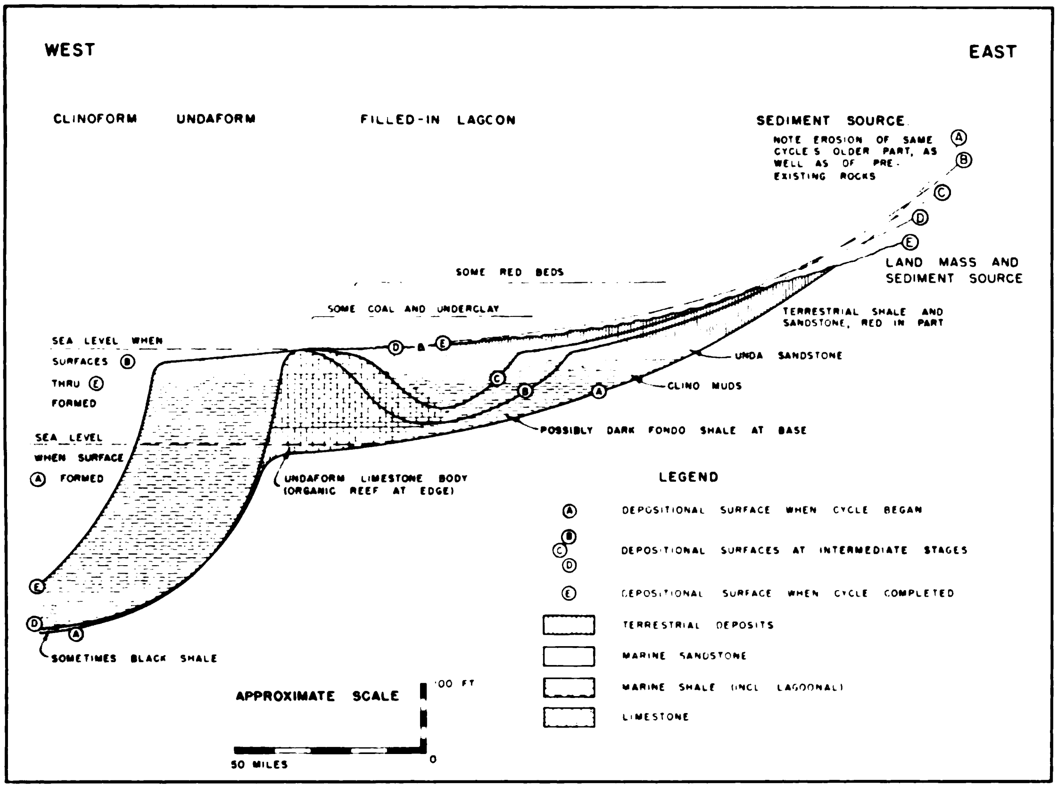

FIGURE 1.—Diagrammatic representation of uninterrupted complete "normal" sedimentary cycle in late Pennsylvanian and early Permian of western and central Texas. Shapes are distorted by thousand-fold vertical exaggeration of sediment body between surfaces A and E.

COMMON VARIANTS OF THE CYCLE

In some cycles evaporites formed when the undaform-edge limestone developed into a continuous barrier reef which impeded circulation of sea water into the lagoon. Perhaps the most widespread effect of restricted circulation was dolomitization of the previously deposited limestone (as described by Adams and Rhodes, 1960). Extensive accumulations of anhydrite, and even halite formed in the lagoon in a few cases (*see*, Mear and Yarbrough, 1961). In some other cases anhydrite beds formed in isolated pools along the landward margin of the lagoon, where the characteristic sediment was red clay.

During accumulation of the first red clay and evaporite section of regional extent, (Valera Anhydrite), the first *fondo* sand of regional extent (Dean Sandstone) was accumulating on the fondoform farther west, as demonstrated by well-log cross sections (Van Siclen, 1958, p. 1900). This association prompted the writer to suggest that extensive evaporite and fondo sand deposits may be the result of a relative drop in sea level which exposed part or all of the undaform. The result is an extreme modification of the basic cycle of Figure 1, with the cycle being terminated "prematurely" over most or all of the undaform while deposition is concentrated on the fondoform in what should perhaps be regarded as a new and different cycle.

However, most cycles were interrupted by marine transgression before the lagoon was filled and the cycle "completed." As a result, the area in which a cycle is expressed may be restricted to belts along each side of the lagoon. Along the seaward (southwest) side there is an alternation of limestone and shale; and along the landward side in the older (generally late Pennsylvanian) cycles alternations of clay and of sand occur, whereas in the younger cycles anhydrite and dolomite alternate with much thicker red shale and siltstone.

Repeated transgressions which kept the lagoon open continuously also enabled the limestone to become hundreds of feet thick over a few of the submerged undaform-edges, because this facies of successive small cycles continued to occupy the same geographic position. Time finally arrived (generally because of lowered sea level) when enough clay and sand were carried into the sea beyond the limestone belt to build the clinoform-undaform to a new position. The alternation of such outer undaform and upper clinoform limestone bodies, hundreds of feet thick, and belts of terrigenous clastic sediments, usually miles wide, gives rise to large-scale or composite cycles (Van Siclen, 1958, p. 1902).

LATERAL DEVELOPMENT OF THE CYCLE, AND SUCCESSIVE CYCLES

Perhaps the chief virtue of the present approach, as illustrated by Figure 1, is to emphasize that every fully developed cycle should be represented in *all* environments, even though recognition may not be practicable in some. On the fondoform and part of the clinoform the cycle may be represented by deposits only a few feet thick made by bottom currents (often designated "turbidity currents"), alternating with long intervals of nondeposition. Near the sediment source areas the same cycle may be expressed by alternating intervals of accelerated erosion (valley cutting) and of widespread accumulation of detritus (valley filling). The latter cycle is observed commonly in Pleistocene beds deposited outside glaciated regions, and has been described in the present area by the writer (1957a). The more varied cyclic deposits developed on the undaform between these extremes.

The cycle began when some change in external conditions occurred, in these instances a rise in relative sea level, which favored certain gradational processes and environments. As a result, these environments developed and expanded rather quickly at the expense of other environments that were affected adversely. However, the pre-existing pattern was gradually restored by the continued action of the same processes. These processes tended to maintain dynamic equilibrium, while the changes in external conditions produced nonequilibrium, the alternation being responsible for cyclicity. Regarded in this manner, the ideal base of each cycle is the base of sediments that reflect the relatively rapid shift away from "equilibrium" under the influence of a change in external conditions (generally marine transgression).

To be recognizable throughout its area of occurrence, an individual cycle must include all sediments formed during an essentially uninterrupted interval, and *only* these. Its boundaries will then be thin zones representing rapid shifts of facies (and perhaps additional changes), or horizons representing fundamental reversals in conditions, which affect all environments and therefore are essentially "time surfaces." Each simple cycle so defined may be expected to vary by the addition of deeper water members at the distal extremity, and by addition of terrestrial members (if preserved) adjoining the source area. The systematic vertical changes in lithology represent principally the migration of a succession of adjoining environments past the locality of the observer.

In west-central Texas and adjoining regions, environments tended to migrate toward the southwest throughout the Pennsylvanian and Permian Periods. As a result, the stratigraphic section preserved at any particular locality displays various parts of many cycles; in the regressive part of the major cycle these generally begin with fondo deposits and end with terrestrial strata. This superposition of different parts of similar cycles in one general area facilitates reconstruction of the "complete, normal" cycle of Figure 1.

CAUSES OF CYCLICITY

The cycles considered here developed and were preserved because *relative* sea level rose, due to regional subsidence accentuated presumably by sediment compaction. Subsidence is inferred from the fact that the region was above sea level near the beginning of Pennsylvanian time, yet Pennsylvanian and Permian marine sediments are several thousand feet thick. Corresponding uplift took place several hundred miles to the east, along what is now the southward subsurface continuation of the Ouachita deformed belt, from middle Pennsylvanian perhaps into Triassic time.

Sediments of the area under consideration are most simply interpreted as having formed under conditions of continuous, fairly uniform absolute subsidence; and continuous, fairly uniform absolute uplift of the terrigenous sediment source areas. Oscillatory uplift of the sediment source areas, or oscillatory subsidence of the depositional areas, is *not* necessary to explain the cycles. However, the occurrence of some such oscillations, and of sea-level changes caused by distant diastrophism, cannot be ruled out from evidence in the area under consideration.

Cyclicity is due largely, or entirely, to repeated drops in sea level caused by expansions of distant continental glaciers, plus local shifts in the position of river mouths, superposed upon the continuous regional subsidence. Evidence of repeated glaciation in the Pennsylvanian and Permian of Australia has been cited by Teichert (1941); this and additional evidence of extensive glaciation in the present Southern Hemisphere and in India was first applied in detail to the present problem by Wanless and Shepard (1936), and most recently by Wanless (1963). The shifts (avulsion) of river mouths is most conspicuously demonstrated by the Recent subdeltas of the Mississippi River, as described by H. N. Fisk (1944). For example, marine regression is resulting today from deposition around the active delta, while the older St. Bernard subdelta is sinking and the transgression has formed Chandeleur Sound.

Net changes in relative sea level associated with the undaform-edge limestone bodies hundreds of feet thick must have been of about the same magnitude—hundreds of feet. Stepdowns of the base of undaform-edge limestone body "X" southward across Kent and Scurry Counties, Texas (as shown by Van Siclen, 1958, p. 1907), from about 670 feet below the base of the Coleman Junction Limestone datum across Kent County to about 1,100 feet below that datum in the southeastern corner of Scurry County and vicinity, demonstrate about 430 feet lowering of sea level; there is no reason to believe that this lowering is close to the total. Sea-level fluctuations of such magnitude, in a region of so little deformation and so little change in general conditions of sedimentation must have external causes. Fluctuations occurred so frequently, and in a sense regularly, that the effects of distant diastrophism must be ruled out as the sole or chief cause. The remaining possible cause, the only one that to the writer seems adequate quantitatively, is distant continental glaciation.

If the sea-level changes were produced principally by waxing and waning of distant continental glaciers, it appears likely that sea level was high most of the time, and that the episodes of lowered level were relatively brief departures from the norm. At first glance this statement seems to invalidate the writer's previous statement that equilibrium conditions existed when mud and sand were arriving in sufficient amounts to build the undaform and clinoform, that transgression upset this equilibrium, and that the cyclic sediments represent gradual restoration of pre-existing equilibrium. The critical factor here is the rate at which equilibrium was attained at each extreme position of sea level, relative to the length of time each extreme existed. The writer's opinion is that erosion of weathered rock and recently deposited sediments, and deposition of the material, under conditions of lowered sea level is much more rapid than the same processes plus biochemical and perhaps chemical sedimentation during elevated sea level, so that equilibrium was much more commonly attained in the west-central Texas area during the lowered sea-level stages. This phenomenon is analagous to the present-day situation in which the continental shelf is adjusted to lowered sea level of a Pleistocene glacial stage, and has not been altered greatly by deposition since the Recent transgressions, except near the mouths of very large rivers and to a much lesser degree along coasts where barrier reefs occupy the drowned Pleistocene undaform-edge (like the Australian Great Barrier reef).

CONCLUSIONS

1. In west-central Texas and adjoining West Texas numerous wells have been drilled through a major sedimentary cycle, and logged electrically. These electric logs allow interpretation of distinctive successions of events, making it possible to carry time-stratigraphic correlations of many thin lithologic units over large areas.

2. Such correlations disclose that the sediments deposited in this part of Texas in the regressive part of the major Pennsylvanian-Permian sedimentary cycle assumed a topographic form which in profile resembles the classic delta, with unda, clino, and fondo segments.

3. The normal situation, in terms of work accomplished if not in length of time, was for considerable clay and moderate amounts of sand from sources to the northeast to be carried across the undaform and deposited principally on the clinoform, extending the undaform (coastal plain) southwestward.

4. Each normal sedimentary cycle began with transgression of the sea, which prevented sand and appreciable clay from being carried onto the outer part of the "drowned" undaform and permitted biochemical limestone to accumulate there instead.

5. Small thicknesses of dark clay often accumulated on both sides of the undaform-edge limestone belt; that on the original fondoform tending to be highly siliceous (providing key beds).

6. Some undaform-edge limestone bodies developed into almost continuous barrier reefs which impeded circulation of sea water into the adjoining lagoon, and led to dolomitization of previously deposited limestone and accumulation of anhydrite and rarely halite.

7. Generally the lagoon that had developed from the drowned undaform was filled principally by clay and sand deposited in the form of a small-scale undaform-clinoform which advanced seaward in adjustment with the "new" higher sea level.

8. As long as conditions remained about the same the "new" undaform-clinoform continued to advance, first over the undaform-edge limestone of the same cycle, then into deep water beyond the former (drowned) clinoform. Such "complete" cycles display considerable seaward extension of terrestrial environments characterized by coal or by red clay.

9. Some cycles were modified by the effects of regression, which in certain instances led to extensive deposition of coal or of anhydrite and red clay on the emergent undaform, to conspicuous channelling, and generally to unusually extensive deposition of sand and clay over the fondoform.

10. More commonly the cycles were modified by renewed transgression even before the lagoon was filled, which greatly restricted the area in which each such cycle was clearly developed, and which enabled limestone bodies several hundred feet thick to accumulate over a few of the drowned undaform-edges, giving rise to large-scale or composite cycles.

11. Every well-developed "normal" cycle can be recognized in all environments (in principle), but part may be represented by nondeposition in the deeper water portion, and by erosion on the undaform, especially near the sediment source areas.

12. The base of each cycle should be defined as that of the bed deposited during the relatively rapid shift of facies that initiated the cycle, or the corresponding hiatus, both of which are practical "time surfaces."

13. This rapid shift of facies was caused by some change in external conditions, ordinarily a rise in relative sea level, which upset the pre-existing gradational equilibrium.

14. The cycle itself simply represents the slow migration of contemporaneous, adjoining environments past a point of observation, as the pre-existing conditions (equilibrium) are restored.

15. The various environments also had a net shift across the region toward the southwest during the Pennsylvanian and Permian Periods, so that at any locality various parts of many cycles are present.

16. The cycles developed, and were preserved, because the region subsided at a fairly uniform rate, and because large and small fluctuations in sea level were superposed on the subsidence.

17. The larger changes in sea level (to at least 400 feet), and many of the smaller ones,

were caused by waxing and waning of continental glaciers in the present Southern Hemisphere and in India.

18. Small cycles resulted, in part, from shifts in the position of river mouths, and possibly from climatic changes.

19. There is no need for oscillatory uplift of sediment source areas, or oscillatory subsidence of the areas receiving sediments, or for sea level changes caused by distant diastrophism, although none of these can be ruled out as a contributing factor on the basis of evidence developed in the region under consideration.

20. Equilibrium was more commonly attained during the glacially lowered sea-level stages, which is analogous to the present-day situation where the continental shelf (a drowned undaform) is adjusted to glacially lowered late Pleistocene sea level. This situation is due principally to accelerated gradation upon lowering of base level and has little bearing on the relative length of the glacial and interglacial stages.

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Origin of Repeated Fossiliferous Concretion Layers in the Fox Hills Formation

ABSTRACT

Successive layers of fossiliferous concretions dominated by great numbers of one or two molluscan species characterize marine parts of the Late Cretaceous Fox Hills Formation in its type area, north-central South Dakota. Individual fossil assemblages appear to have formed simultaneously throughout their extent, the more widespread covering at least 1,500 square miles and containing millions of specimens of the dominant species.

Geographically the assemblages occupied elongate northeast-trending areas in what was apparently a northern embayment of the waning interior Cretaceous sea. Groups of assemblages show progressive southward shift concurrent with encroachment of littoral facies from the northeast. Finer patterns of distribution resulting from local abundances of non-dominant species and from differing local associations of species are characteristic of the individual layers.

The distribution patterns, together with the characteristic dominance of a few species and the fact that dominant associations are repeated in the sequence both locally and regionally, contribute to the marked general resemblance between the fossil assemblages and modern marine bottom communities. The preservation of successive accumulations of shells showing patterned distribution over much the same large area is taken as strong indication that the assemblages resulted from recurrent mass mortalities with relatively little disturbance by current action before burial. The cause of the mortalities is not known. Sparse evidence seems to favor burial under conditions of excessive turbidity and lowered salinity, possibly brought about by repeated influx of sediment-charged fresh water from rivers in flood.

INTRODUCTION

The outcrop of the Fox Hills Formation in Dewey and most of adjacent Ziebach and Corson Counties, northwest-central South Dakota, constitutes its type area (Fig. 1). This considerable expansion beyond the historical locality of Meek and Hayden is necessitated by deficiencies of exposure and of stratigraphic coverage in the restricted area of the historical type (Waage, 1961, p. 230). Unlike equivalent strata in the western plains and Rocky Mountain region, the Fox Hills of the Missouri Valley is predominantly unconsolidated, resembling in this respect the Cretaceous deposits of the Atlantic Coastal Plain.

Studies of the Fox Hills and its fossils in the type and adjacent areas have been in progress for a number of years, supported by National Science Foundation grants G-5657 and G-18674 and the Peabody Museum, Yale University. Detailed presentations of the complex factual data are in preparation; the present paper is largely a summary with parts of the data as examples. Ian Speden, who is preparing a study of the systematics and ecological features of the Fox Hills bivalves, has contributed considerable information and stimulating thought. I have also benefitted greatly from discussions with A. Lee McAlester, Copeland MacClintock, and Gordon Riley, and I am indebted to David Harvey for assistance with the illustrations.

The richly fossiliferous concretion layers in the marine part of the formation have been the most intriguing but also the most perplexing aspect of the work. With the details of the stratigraphy known and a start made on distributional studies of the fossils, the idea that the fossil assemblages resulted from recurrent mass killings grew from an impres-

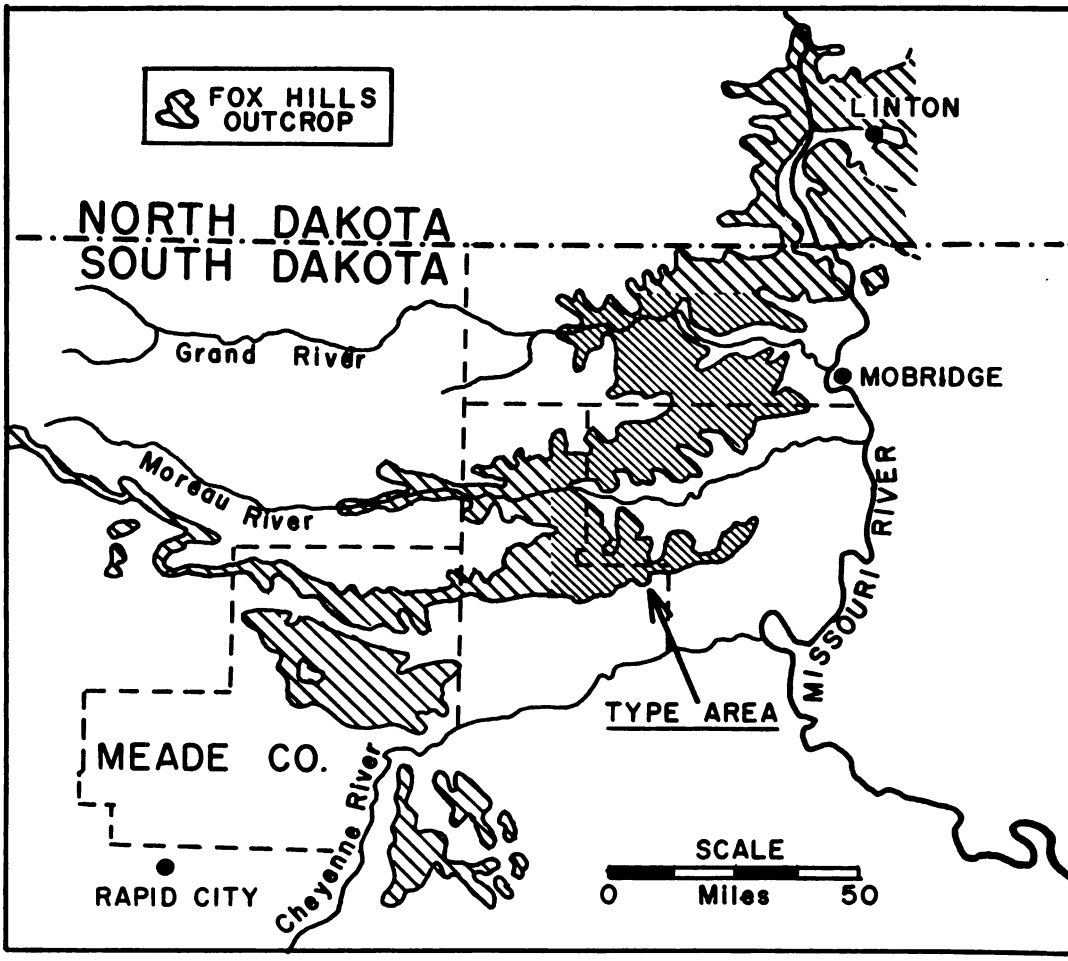

FIGURE 1.—Principal outcrop of Fox Hills Formation in Dakotas showing location of type area.

sion to a strong working hypothesis. This hypothesis permits explanation of distributional peculiarities as vestiges of natural ecological arrangements, and in this context a number of facts make sense that are otherwise exceedingly difficult to explain. The reason for presenting the idea at this stage of the work is to emphasize that it can be substantiated or disproved only by detailed studies on the distributional and ecological aspects of the paleontology of similar interior Cretaceous terrains—an approach still much neglected despite the apparent popularity of paleoecological studies.

STRATIGRAPHIC SETTING

In its type area the Fox Hills Formation consists of 300 to 350 feet of dominantly silty and sandy beds transitional downward into the Pierre Shale and upward into the continental beds of the Hell Creek Formation (Fig. 2). It is subdivided locally into four successive members—lithofacies gradational vertically and to some degree laterally, that represent distinct marginal environments. The lower two are almost entirely marine, the upper two contain mixed marine and brackish-water deposits.

The basal Trail City Member of the Fox Hills averages about 90 feet in thickness and consists chiefly of clayey silt that becomes more sandy upward. Its two most conspicuous characteristics are the general, but not universal, lack of bedding structures and the prominent layers of limestone concretions, many of which are abundantly fossiliferous. Blebs and stringers of silt and clay and bored and contorted laminae indicate post-depositional working of the sediment by organisms; details of the structure are identical to those of recent sediments that have been so worked. The presence of distinctive assemblages of great numbers of fossils in successive layers, or groups of layers, is an outstanding feature of the fossiliferous concretions. The successively different fossiliferous layers, together with certain persistent layers of dominantly barren concretions, thin layers of yellow-weathering jarositic silt, and glauconitic silt or sand layers form a framework of key beds that can be carried throughout the extent of the member and for some distance into equivalent lateral facies.

The Trail City Member becomes increasingly sandy upward and grades into the overlying Timber Lake Member. The latter consists of dominantly fine-grained, dirty, gray to greenish-gray sand that weathers yellowish brown. The sand is locally clayey and is massive to thin-bedded and cross-bedded. The Timber Lake Member also contains limy concretions, but only those in the lower beds of the southern part of the type area are abundantly fossiliferous and distributed in persistent layers similar to the Trail City concretions. The member pinches out southwestward in the western part of the type area but thickens northeastward; commonly it is between 80 and 100 feet thick. A marine fauna is found abundantly throughout the member in the southern part of the type area; but in the northern part, only a few elements of this fauna persist and most of the member is occupied by a biofacies in which the supposed crab burrow *Ophiomorpha* (better known as *Halymenites*) and the pelecypod *Tancredia* are the dominant fossils.

Together the Trail City and Timber Lake Members form a distinctive lower marine part of the Fox Hills Formation. Northeastward

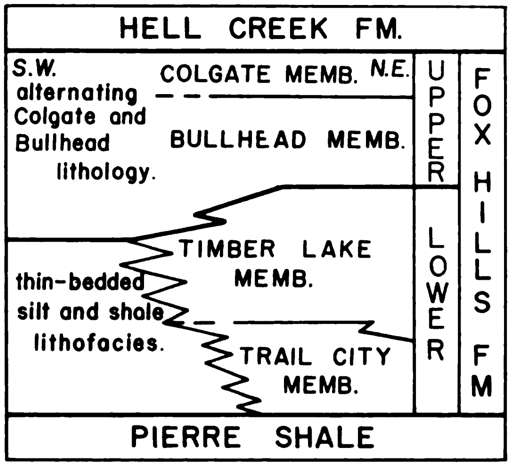

FIGURE 2.—Subdivisions of Fox Hills Formation in type area.

in the Missouri Valley area the sandy lithofacies thickens at the expense of the underlying clayey silt; the contact between the two occurs progressively lower in the section. In the northeasternmost outcrops in North Dakota east of the Missouri River, only a few feet of Trail City lithology remain. Southwestward in the type area both members grade laterally into a succession of sparsely fossiliferous, thin-bedded silty shale and clayey sand and silt. This lithofacies superficially resembles the underlying Pierre Shale, but is considerably more silty.

Succeeding the Timber Lake Member is a conspicuous unit, between 35 and 110 feet thick, of thinly interbedded shale, silt, and sand that was long referred to as the "banded beds," but more recently named the Bullhead Member. A sparse and restricted marine fauna is locally present in the lower part of the member; but higher in the section fossils are rare except for otoliths.

The Colgate Member overlies the Bullhead throughout much of the area. It consists of fine- to medium-grained, dirty, friable sandstone with considerable interstitial white clay. It weathers to characteristic gray-white fluted outcrops. Generally the Colgate is about 20 feet thick, but may be considerably thicker or entirely absent from the sequence. Large spheroidal, brown-weathering concretions of lime-cemented sand are characteristic features. The most common fossils in the member are reefs and coquinas of oysters and a brackish-water fauna dominated by the bivalve *Corbicula.* Locally this fauna contains a few marine elements and, where its usually gradational contact with the Bullhead Member is channeled, there are local accumulations of plant and dinosaur remains.

The Bullhead and Colgate Members form a distinctive upper part of the Fox Hills Formation characterized by restricted marine and brackish-water faunas. The two lithofacies are so closely interrelated that it is not practical to separate them over all of the type area. The upper contact of the Fox Hills with the Hell Creek Formation is arbitrarily taken at the first bed of lignite or lignitic shale. This contact is more or less traditional and generally satisfactory, as it marks the beginning of dominantly continental sediments.

The rich molluscan faunas of the type Fox Hills and equivalent beds in the Missouri Valley area of the central Dakotas are the youngest marine Cretaceous faunas known in the interior region of the United States and Canada. These faunas disappear westward and southwestward within the type area. As the formation is traced along the outcrop to the southwest from the type area, a major change in facies takes place within about 50 miles which completely transforms the Fox Hills into a heterogeneous sequence of dominantly sandy nonmarine beds containing such atypical sediments as lignite beds and variegated silty clays. This complex and little known Fox Hills terrain occupies a large area of outcrop in and south of Meade County, between the type area and the Black Hills (Fig. 1). Here the formation rests about 250 feet lower in the section relative to the top of the range zone of *Baculites clinolobatus* than does the base of the Fox Hills in the type area. Although the details are unknown, the gross relationships indicate that this brackish and continental phase of the Fox Hills was a large delta or series of coalescing deltas formed by major drainage into the Cretaceous sea from the north or northwest. The delta complex was established while Pierre Shale was deposited in the area of the type Fox Hills, and it marks the westward limit of the sea in this part of the interior region during the deposition of the type Fox Hills. There is also evidence of regional shoaling to the north and northeast within the Fox Hills of the Missouri Valley region, and it appears that sediments of the type Fox Hills were deposited in a northern embayment of the Late Cretaceous sea which lay between deltaic areas to the west and east or northeast.

FOSSIL DISTRIBUTION IN LOWER FOX HILLS

Limestone Concretions

Marine fossils in the Fox Hills Formation occur chiefly as accumulations in limestone concretions, a mode of occurrence that is restricted to the lower marine portion of the formation, in particular to the Trail City Member and the marine biofacies of the Timber Lake Member. In the Trail City Member the abundantly fossiliferous concretions are concentrated in the lower 50 feet of the member; both here and elsewhere in the member, fossils are exceedingly rare in the surrounding clayey silt and clayey sand. In the Timber Lake Member abundantly fossiliferous concretions are limited to the lower 60 feet of its marine biofacies, but scattered fossils are not uncommon in the surrounding sandy sediments. Fossils in the *Tancredia-Ophiomorpha* biofacies of the Timber Lake and those of the restricted faunas of the upper part of the Fox Hills rarely occur in limestone concretions.

The concretions are commonly distributed in continuous layers. In some the individual concretions are closely spaced; in others they are widely spaced. Locally concretions are scattered through an interval of several feet which when traced laterally thins to a single concretion layer. The extent of the individual concretion layers ranges greatly. Some persist throughout the fossiliferous Trail City Member and extend many miles beyond it into the relatively barren, thin-bedded lithofacies to the southwest. Other layers are of local extent within a very small part of the area.

Although none of the concretion layers in the lower part of the Fox Hills appears to be completely barren, several are commonly unfossiliferous. Of the layers shown in Figure 3, those indicated as barren A, *Nucula,* and barren B, commonly lack fossils. The *Nucula* layer carries a very sparse but distinctive faunule, but the barren A and barren B layers are even less fossiliferous and have yielded only a very few scattered ammonoids.

Within the highly fossiliferous concretion layers, not all of the individual concretions are fossiliferous, indeed there may be more unfossiliferous than fossiliferous concretions. The two-dimensional nature of most of the outcrop prevents adequate sampling of a single layer over a unit of area, but it is evident from outcrop counts that considerable geographic differences occur not only in the relative abundance of fossiliferous and unfossiliferous concretions within individual zones or layers but also in the relative abundance of the fossiliferous concretions from layer to layer.

The layers of richly fossiliferous limestone concretions in the marine lower Fox Hills sequence of the type area are one of its most conspicuous and interesting features; the same can be said for a number of other Upper Cretaceous terrains in which similar fossiliferous concretions occur. Many geologists have described these layers, collected their fossils, and speculated on the origin of the concretions, but James Todd appears to have been the first of very few to be impressed by the fact that each fossiliferous layer commonly contains a distinctive faunal assemblage. His appreciation of the biological implications of this peculiar distribution is apparent in the following excerpt from his remarks on the origin of the fossiliferous concretions in the type Fox Hills (Todd, 1910, p. 31).

> Very commonly they are crowded with fossils, which in the same concretions are usually only one or two species, as though they had been isolated colonies in the surrounding mud flat. Some of the shallow masses are barely covered with the calcareous rock. In other cases they are very thickly invested. The colony theory seems as probable as any, but why should they have a thickness nearly equal to their breadth? No shells are found in the surrounding clay or sand. The shells do not seem to be horizontally laid as in stratified rocks. Is it possible that some strong currents broke them out of stratified patches and rolled them away? This does not seem likely when we remember the fine character of the material in which they lie; nor does it agree with the uniformity of individuals in the same concretion; nor with the difference of kinds in different concretions. That they have grown by concretion is evident, but the original blocking out and dispersion is the puzzle.

No progress toward the solution of Todd's "puzzle" has been made in the more than half century since these observations. His clear separation of concretion formation from the origin of the fossil accumulations and his implication that the latter is the more significant problem are points that deserve re-emphasis; investigators commonly make speculative remarks about the concretions, but usually take the fossil masses for granted. However, the fossil assemblages and concretions are too closely associated to ignore one completely in discussing the other. A more realistic perspective is to regard concretion formation as a related, post-depositional aspect of the broader problem of the origin and preservation of the fossil accumulations.

This is not the place for a thorough discussion of what is known about the origin of the Fox Hills concretions, but certain aspects of the subject are pertinent to the pattern of fossil distribution. The principal role of the concretions relative to the fossil accumulations has been that of a preserving medium. The fact that fossils do occur, though rarely, in the sediments outside of concretions indicates that the peculiar distribution of the fossils in localized masses or clusters is not merely the result of localized preservation resulting from selective calcification of parts of widespread shell beds. The scattering of fossiliferous concretions among unfossiliferous concretions, which is a pattern prevalent in all layers, supports this contention, as do the rare occurrences of single fossils and small clusters of shells about which no concretion has formed.

Thin sections of the concretions show that they consist of calcium-carbonate cemented sediment preserving structures similar to those in the surrounding sediment. All features point to their formation after the burial of the organisms but before compaction. Fossils in the concretions show no flattening in the horizontal plane, but those extending beyond the concretion and the few that occur entirely outside in the clayey silt are generally crushed.

As there is no way of making a reasonable estimate of the rate of sedimentation, the knowledge that the concretion formed before compaction cannot be used to determine how long it took the concretion to form. Preservation of perishable structures such as the ligaments of bivalves, occasional leaves, and thin carbonaceous aptychi of scaphitid ammonoids suggests that concretion formation took place within a relatively short time after burial. Calcareous concretions in marine sediments of relatively recent origin are of little help in estimating the time involved in concretion formation. In a study, now in progress, of fossiliferous limestone concretions from Pleistocene deposits in Long Island Sound, the radiocarbon age of included scallop shells is 4600 ± 90 years B. P. Although this is, to my knowledge, one of the youngest marine concretions yet dated, the figure probably has little bearing, even as an outside limit, on the rate of formation of concretions of this type. If the precipitation of calcium carbonate is brought about by the products of decomposition of the organisms as is commonly held (Burt, 1932; Weeks, 1953; and others), but as yet incompletely explained, concretion formation must have taken place at most within tens rather than thousands of years.

The barren concretions do not necessarily weaken the hypothesis that the decomposition of organic matter created local environments chemically favorable to the formation of calcium carbonate. Shelled molluscs, which make up practically the entire macrofossil content of the fossiliferous concretions, were only a part of the biomass and most likely were appreciably less in aggregate volume than the combined marine plants and soft-bodied animals that lacked easily preservable parts. Throughout the marine portion of the type Fox Hills it is a conspicuous fact that the area of most abundant concretions coincides geographically with the area of most abundant fossils. Only preliminary geochemical work * has been done on the Fox Hills concretions, and although this indicates as strong a concentration of amino acids in the "barren" limestone concretions as in the fossiliferous ones, it is obvious from lateral changes in the physical properties and calcareous content of concretions and from peculiarities in both their stratigraphic and geographic distribution that their mode of origin is far more complex than can be explained by any simple relationship to accumulations of organic matter alone. The point pertinent to this paper, however, is that the original distribution of organic matter apparently had a great deal to do with concretion formation; but concretion formation was subsequent to fossil distribution and did not influence it other than to insure local preservation of the fossils in an uncompacted state.

* As part of a senior project in 1962-63 at Yale University by Edward Gilfillan.

Assemblage Zones

The fossiliferous concretion layers, either individually or in groups of several layers, contain distinctive assemblages of fossils. In the Trail City Member one or two species of pelecypods commonly dominate a given assemblage, locally constituting as much as 95 percent of the total number of specimens in a concretion. Less commonly the dominant species is an ammonoid or a gastropod. The assemblages in the Timber Lake Member are usually characterized by more variety within the individual concretions, but the dominance of one or two species is still marked. For the lower Fox Hills as a whole, the pelecypod fauna is relatively uniform in composition and the majority of species range throughout the sequence. The conspicuous faunal difference from one fossiliferous concretion layer or group of layers to the next results from differences in the abundant species, the majority of which are long-ranging. Accumulations of this type are assemblage zones (Am. Comm. Strat. Nomenclature, 1961, Art. 21) and are named for one or more of the dominant elements in the assemblage.

The sequence of assemblage zones in the lower Fox Hills is shown diagrammatically in Figure 3. Not all of the assemblages shown in this composite illustration are necessarily found at any one place. The lower Trail City assemblages all have approximately the same general pattern of distribution occupying, to somewhat different degrees, a northeast-trending lobate part of the type area that terminates in the vicinity of the Moreau River (Fig. 4, 5, 6, 7). The Timber Lake assemblages overlap those of the Trail City in the eastern part of the Moreau-Grand divide, but they

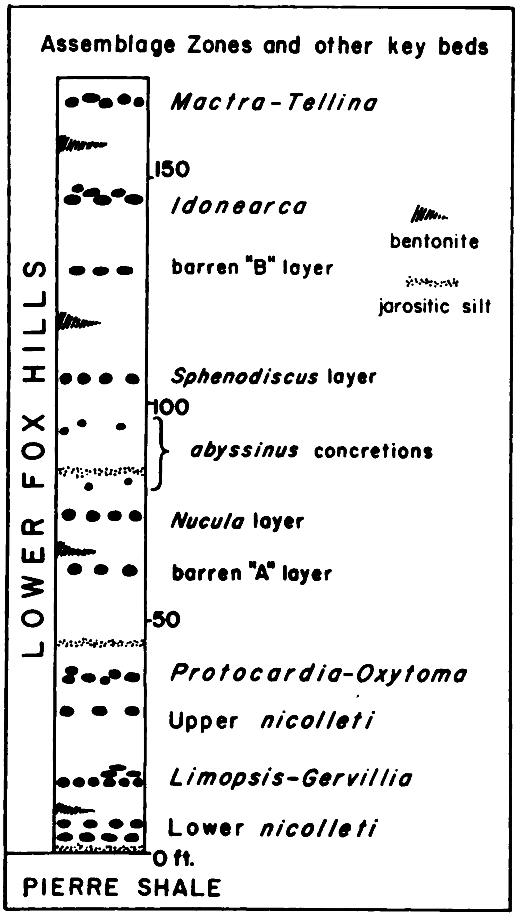

FIGURE 3.—Generalized composite succession of assemblage zones and other key beds in marine biofacies of lower Fox Hills Formation.

extend farther to the south and southwest beyond the limits of the Trail City assemblages (Fig. 4).

The Timber Lake assemblages are so similar in all respects to those of the Trail City that their common mode of origin is not questioned. The few differences that exist between them are (1) different gross pattern of geographic distribution, (2) slightly different faunal composition, and (3) somewhat more breakage of specimens and separation of valves in the Timber Lake assemblages. These all can be attributed to the environmental factors attending the change from Trail City to Timber Lake sedimentation, although the small but significant change in the fauna—particularly the ammonoid fauna, is probably an age factor. The generally higher degree of shell damage and mixing is indicative of stronger current action prior to or during burial. In general the features of the fossil accumulations are best and most extensively displayed in the Trail City Member and for this reason only the Trail City assemblages are described in detail here.

Trail City Assemblages

For some 200 feet beneath the widespread and abundantly fossiliferous succession of assemblage zones in the lower 50 feet of the Trail City Member the drab gray, finely silty Pierre Shale is practically devoid of macrofossils except for scattered linguloid brachiopods and rare ammonoids. The base of the Fox Hills Formation is marked by both an appreciable and fairly abrupt increase in silt and by the appearance of the concretions of the basal assemblage zone.

Within the individual concretions of the Trail City assemblages, the fossils occur in great numbers oriented at random (Fig. 8, 9, 10). Preservation is excellent. Pelecypods commonly are preserved with both valves in position or agape, some retaining ligament, and complete specimens of ammonoids are a commonplace. In fresh concretions the bivalve shells usually show their original luster

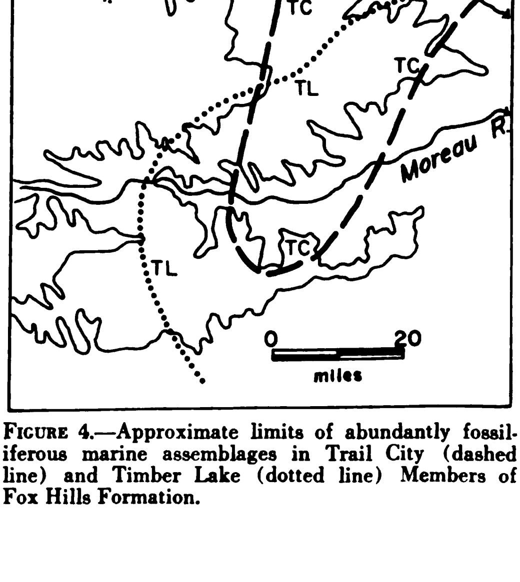

FIGURE 4.—Approximate limits of abundantly fossiliferous marine assemblages in Trail City (dashed line) and Timber Lake (dotted line) Members of Fox Hills Formation.

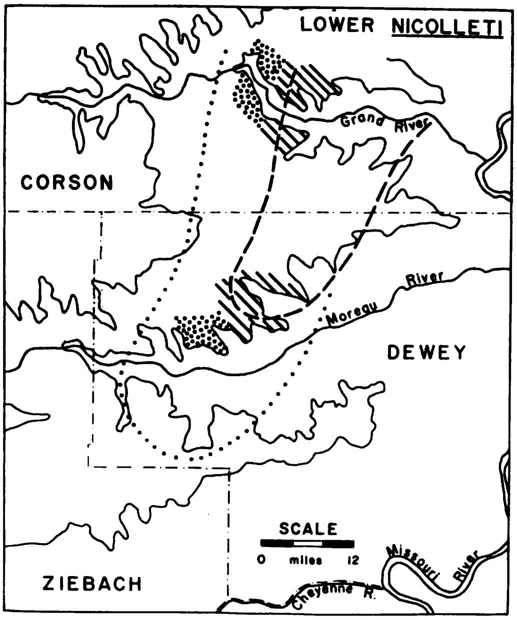

FIGURE 5.—Distribution of Lower *nicolleti* assemblages. Dashed line encloses area of abundant large accumulations of *nicolleti*, dotted line scattered small concretions. Stippled areas indicate *Drepanochilus* accumulations, cross-hatched areas abundant large *Gervillia*.

and the ammonoids a beautiful iridescent coloration.

Lower *nicolleti* Assemblage Zone

Light-gray weathering, ovoid, to flat-ovoid, calcareous concretions consisting of thick, punky jackets of calcareous silt and harder, silty, gray limestone cores up to 18 inches in diameter are characteristic of this zone (Fig. 8). Beginning at or a short distance above the base of the formation, the concretions are distributed in two to five layers spread through an interval that ranges from 2 to 15 feet in thickness. Concretions containing large numbers of the ammonoid *Scaphites* (*Hoploscaphites*) *nicolleti*, and a less conspicuous fauna, chiefly other molluscs, are scattered throughout the concretion layers. The number of concretion layers, concretion density in the layers and relative number of fossiliferous concretions varies from place to place. The fossiliferous concretions are substantially outnumbered by the unfossiliferous, but exposures adequate for counts are too few in relation to the size of the area, and the counts themselves too variable to permit a meaningful estimate of the ratio.

The Lower *nicolleti* zone exhibits two principal phases, a thinner eastern phase characterized by several layers of jacketed concretions, and a thicker western phase characterized by numerous small spherical concretions scattered among some of the larger jacketed kind. The abundantly fossiliferous *nicolleti* concretions disappear westward about where the latter phase begins; *nicolleti* and a few other ammonoids occur rarely as single specimens in the small concretions. Westward beyond this latter phase concretions at the horizon of the Lower *nicolleti* zone are few and barren.

The principal features of faunal distribution in the Lower *nicolleti* zone are shown in Fig. 5. Certain conspicuous local variations indicate a more complex distribution pattern of molluscs other than the ubiquitous *nicolleti*. In the uppermost concretion layer of the zone in restricted areas of outcrop along both the Moreau and Grand Rivers, small concretions dominated by the gastropod *Drepanochilus americanus* occur. Just to the east of both

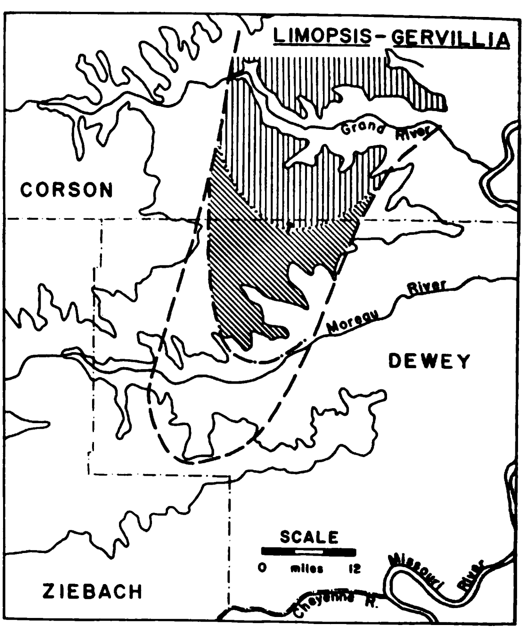

FIGURE 6.—Distribution of *Limopsis-Gervillia* assemblages. Vertical pattern indicates abundant *Limopsis* and *Gervillia* accumulations, slanted pattern abundant *Limopsis* accumulations, blank area sparse *Limopsis* accumulations.

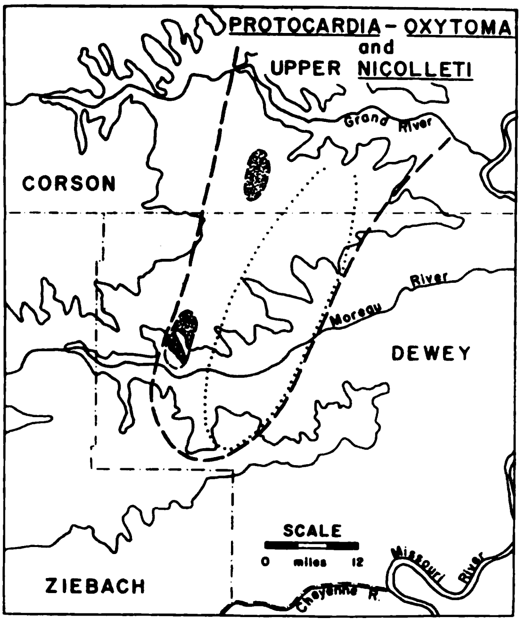

FIGURE 7.—Distribution of *Protocardia-Oxytoma* (within dashed line) and Upper *nicolleti* (within dotted line) assemblages. Stippled areas indicate *Lucina* concentrations in *Protocardia-Oxytoma* zone.

of these areas large specimens of the bivalve *Gervillia* are noticeably more abundant than elsewhere in the zone.

In addition to these more obvious distributional features the dominant bivalves associated with the masses of *nicolleti* in individual concretions differ from place to place. In many concretions the chief bivalve accompanying *nicolleti* is *Inoceramus fibrosus,* which is not very common in the Fox Hills except in association with *nicolleti.* Speden (oral communication) has found that at least four different associations of bivalves occur in the Lower *nicolleti* Assemblage Zone but, as is true of this type of association at all levels, not enough is yet known about the probable life habits of the fossil bivalves to judge the ecological validity of the associations.

The total geographic extent of the abundant Lower *nicolleti* accumulations is unknown, but they have been found as far to the northeast as Linton, North Dakota, 90 miles from their southwesternmost occurrence in the type area of the Fox Hills Formation (Fig. 1). A conservative estimate of the area they cover is 1,500 square miles. Fossiliferous concretions have been calculated to occur locally with a frequency of as high as one in every 100 square feet; this probably approaches maximum local density. There is no quantitative basis for arriving at an average density figure for the entire area. From collecting experience in the type area the frequency of one in every 2,500 square feet would be a conservative estimate. Individual fossiliferous concretions may yield from as few as 10 to as many as 45 specimens of ammonoids. In a count of approximately 1,800 specimens, 14 out of every 15 were the species *nicolleti.* Even using the most conservative figures the number of specimens of *nicolleti* in the area covered by the assemblages is in the tens of millions. In one 20 square-mile area along the Grand River, all outcrops sampled indicate a density of appreciably more than one fossiliferous concretion in every 2,500 square feet, but even taking this figure and an average of 20 *nicolleti* specimens per concretion the estimated number of specimens in the 20 square-mile area is more than 20 million. Consequently, if the buried area between outcrops is as prolific as the outcrops of the Lower *nicolleti* zone, which we must presume is so, the number of ammonoids can be measured in the hundred millions. No matter how one manipulates the figures available, the accumulation is impressive; yet of all the principal assemblage zones, the Lower *nicolleti* zone has the fewer fossiliferous concretions.

Limopsis-Gervillia Assemblage Zone

From as little as two to as much as 13 feet of barren clayey silt lie between the highest concretion layer of the Lower *nicolleti* zone and the basal concretion layer of the *Limopsis-Gervillia* Assemblage Zone. This persistent basal layer is in some places the only concretion layer in the zone, but in other places it is one of several layers in a zone ranging from 3 to 10 feet in thickness.

The basal layer consists of hard, blue-gray, spherical to ovoid concretions that commonly weather a characteristic rusty brown color. Many of these are crowded with the small bivalve, *Limopsis striatopunctata* Evans and Shumard (Fig. 9) and an assortment of less numerous molluscan species the more common

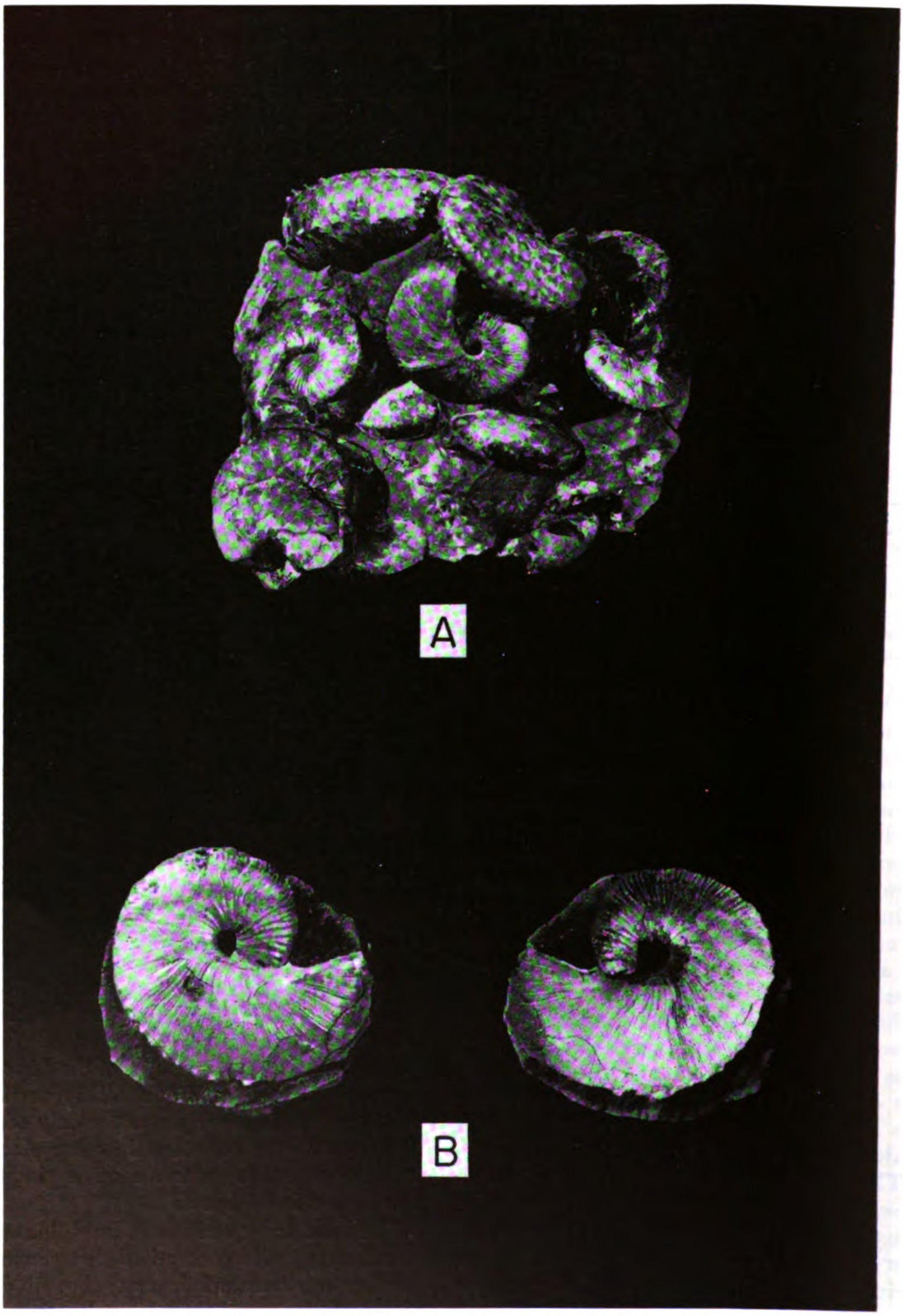

FIGURE 8.—Concretions from Lower *nicolleti* Assemblage Zone. *A,* Partly prepared core of large *nicolleti* concretion (approx. × ⅓); note random orientation. *B,* Split small concretion (approx. × ⅗) from western phase of zone.

of which are *Gervillia recta?* Meek and Hayden and a small bivalve that Meek called *Nemodon sulcatinus.* Ammonoids, though few in number relative to bivalves, are numerous and considerably richer in variety than in the Lower *nicolleti* Assemblage Zone.

Outcrops in the Moreau Valley commonly have only the single concretion layer in the *Limopsis-Gervillia* Assemblage Zone, but in the Grand River Valley from one to three layers of concretions occur above the basal layer and commonly contain masses of the bivalve *Gervillia* (Fig. 9). The *Gervillia*-bearing concretion layers are the only ones in the Fox Hills Formation in which the fossiliferous concretions appear to outnumber the unfossiliferous. The concretions are mostly flat-ovoid, usually lack jackets, and consist of bluish-gray limestone that weathers gray or brownish-gray.

Distributional features of the *Limopsis-Gervillia* Assemblage Zone in the type area of the Fox Hills are shown in Figure 6. It covers approximately the same area as the Lower *nicolleti* zone, although its fossil accumulations disappear several miles beyond the western limit of the large accumulations in the *nicolleti* zone. Outside of the type area it too extends northeastward to the vicinity of Linton, North Dakota.

The number of individual specimens of *Limopsis* in the lower concretion layer throughout its area of extent must number in the billions for there are not only a greater number of fossiliferous concretions per unit area than in the *nicolleti* zone, but also many times the number of individual specimens in a single concretion. The fossiliferous *Gervillia* concretions do not cover as large an area as the *Limopsis* layer, but they are much more heavily concentrated and more numerous than *Limopsis* concretions. At one locality where a layer is exposed at the surface of a small bench about 300 square feet in area, 17 fossiliferous concretions were counted, each of which contained over 100 specimens, counting two valves per specimen. This same concretion density in one layer over 1 square mile would amount to well over a hundred million specimens.

Upper *nicolleti* Assemblage Zone

The interval of beds between the *Limopsis-Gervillia* Assemblage Zone and the next major zone above it—the *Protocardia-Oxytoma* Assemblage Zone—ranges from 5 to 30 feet in thickness. Throughout the western part of the outcrop area of the Fox Hills in the Grand River Valley the interval is less than 15 feet in thickness and lacks persistent concretion layers. Throughout the eastern part of the type area it is over 15 feet thick and contains a rather poorly defined layer of widely spaced, ovoid, hard, dark-blue limestone concretions some of which contain accumulations of *Scaphites* (*Hoploscaphites*) *nicolleti.* These concretions, which make up the Upper *nicolleti* Assemblage Zone vary in position from 2 to 12 feet below the lowest concretions in the *Protocardia-Oxytoma* Assemblage Zone.

As the distribution map indicates (Fig. 7), the Upper *nicolleti* zone is more restricted geographically than the other zones in the succession; it has not been found outside the type area of the Fox Hills. In the southwestern part of the type area it changes laterally into a sparsely fossiliferous zone with small scattered concretions containing a few ammonoids, pelecypods (chiefly *Oxytoma*), and less commonly but in unusual numbers considering their scarcity in the interior Cretaceous, the gladii of coleoids.

The Upper *nicolleti* assemblages contain other ammonoids including representatives of the *Discoscaphites conradi* (s. l.) complex. The most common bivalve is *Inoceramus fibrosus.* Fossiliferous concretions of the Lower and Upper *nicolleti* zones are readily distinguished by their stratigraphic position, marked difference in the lithology of concretions, and absence or presence, respectively, of certain members of the *conradi* complex. Nevertheless, fossils of the two assemblages are remarkably similar and in dealing with weathered concretions in float it can be very difficult to tell them apart. This is particularly true where both zones locally have the *nicolleti-fibrosus* association, and no ammonites other than *nicolleti* are present.

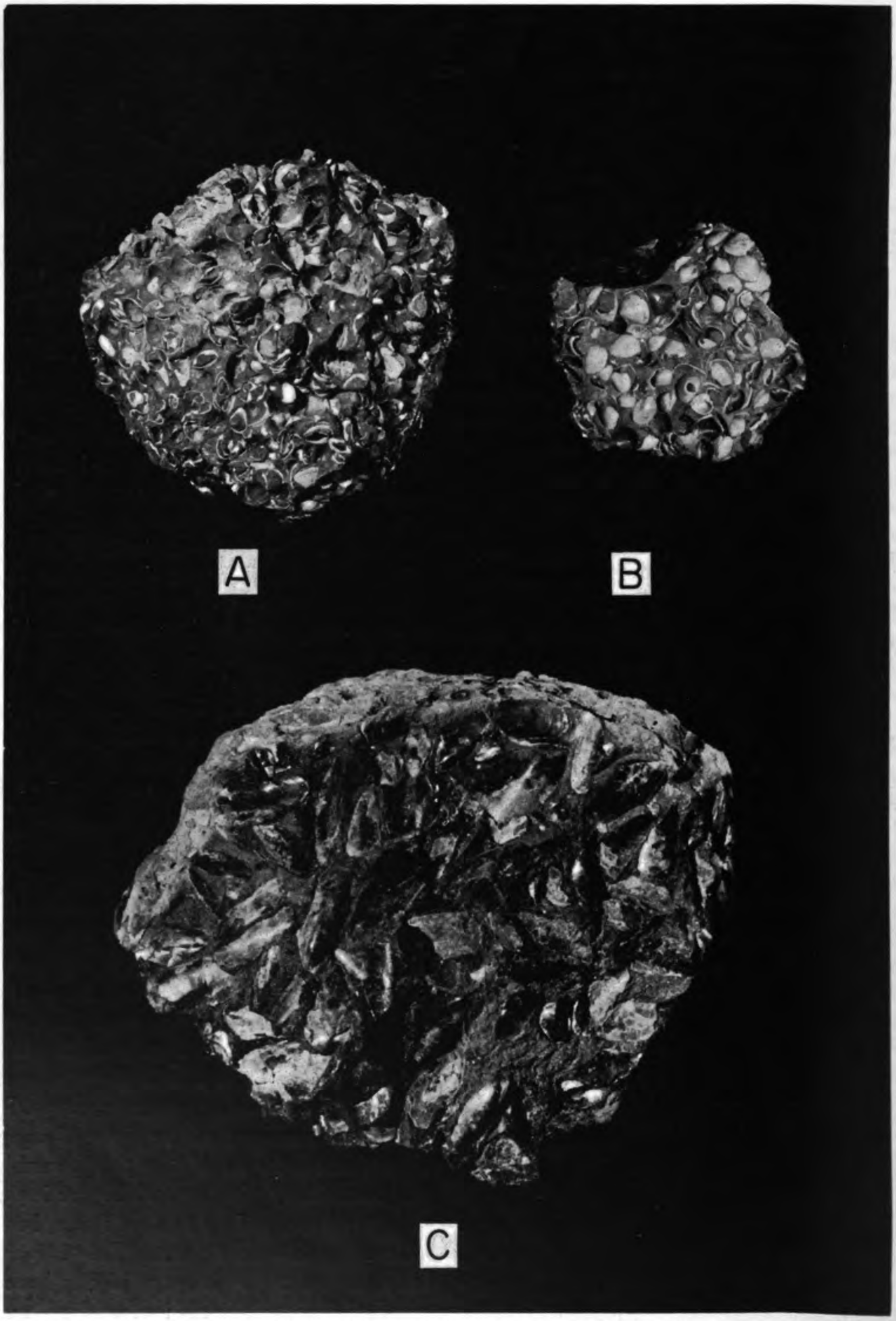

FIGURE 9.—Concretions from *Limopsis-Gervillia* Assemblage Zone. *A*, Weathered core of a *Limopsis* concretion (approx. × ⅓). *B*, Fresh fragment of a *Limopsis* concretion (approx. × ⅔). *C*, Part of a *Gervillia* concretion (approx. × ½) oriented as found in place.

Protocardia-Oxytoma Assemblage Zone

This uppermost zone in the succession of highly fossiliferous assemblage zones in the lower Trail City ranges from a single layer of concretions to an interval locally as much as 10 feet thick, containing scattered concretions. It lies approximately in the middle of the Trail City Member varying locally in position from 30 to 55 feet above its base.

The *Protocardia-Oxytoma* Assemblage Zone is associated with the first appearance of an appreciable amount of fine-grained sand in the Fox Hills Formation. Within the type area the sand thickens to the east and northeast and grades into clayey silt to the south and west, its maximum thickness in the area is about 12 feet. The concretions are hard, dark blue-gray limestone commonly surrounded by semi-indurated rusty-weathering jackets where the matrix is sandy; the cores range from 6 to 15 inches in diameter and are spherical to flat-ovoid in shape.

Two species of bivalves, *Protocardia subquadrata* (Evans and Shumard) and *Oxytoma nebrascensis* (E. and S.) commonly occur in about equal quantity, each far outnumbering individuals of the other species in the varied fauna. (Fig. 10). Their common mode of occurrence is in clusters of one or the other species, and a single concretion may have a mass of *Protocardia* in one part and of *Oxytoma* in another. *Oxytoma,* an epifaunal bivalve, is the more gregarious and commonly monopolizes individual concretions. The fauna of the *Protocardia-Oxytoma* assemblage is the most varied in the succession of assemblage zones; ammonoids are plentiful and concretions in which they are a numerically significant part of the assemblage are not uncommon.

Westward in the type area the concretions of the *Protocardia-Oxytoma* zone become unfossiliferous at approximately the same places as those of the underlying assemblage zones. Locally in the western marginal area of the zone where the characteristic fossils are rare, associations dominated by the bivalve *Lucina* are common (Fig. 7). The extent of the *Protocardia-Oxytoma* assemblage northeastward beyond the type area of the Fox Hills is not known; it is not present in the Linton area of North Dakota, so its lateral extent is less than that of the Lower *nicolleti* and *Limopsis-Gervillia* zones.

Although the *Protocardia-Oxytoma* Assemblage Zone is more abundantly fossiliferous than any other in the sequence, excepting the layers with *Gervillia,* it would be exceedingly difficult to estimate abundances of the dominant species because the fauna is more varied and the dominants do not generally monopolize the fossiliferous concretions.

COMMON FEATURES OF THE ASSEMBLAGE ZONES

The similarities between the successive fossil accumulations in the Trail City Member are more impressive than their differences. The only marked difference is the change in the dominant species from layer to layer. The principal features in common are the dominance of one or two species, the great number of specimens, their excellent state of preservation, their random orientation within the aggregations, the stratigraphic constancy of the layers, and the patterns of geographic distribution—both coarse and fine, within each layer. These features point to a common mode of origin for the successive assemblages. The characteristics of dominance by a few species, numbers, preservation and random orientation have been brought out in the preceding descriptions and illustrated in the photographs; the remaining features warrant additional discussion.

Stratigraphic Constancy

The individual assemblage zones and their component layers hold the same stratigraphic position relative to one another throughout their geographic extent. The observer mindful of ecology is easily persuaded by the faunal distinctiveness of the individual assemblages, their lateral continuity without break, and their relatively limited geographic distribution within the region, that each layer of accumulation was formed simultaneously over its entire area of distribution. The areas of accumulation in both the Trail City and Timber Lake Members appear to follow the environmental strike, and there is no reason to suspect that any of the individual layers might be time-transgressive.

Other key beds in the lower 50 feet of the Trail City conform to the fixed stratigraphic pattern of the assemblage zones. Two persistent jarositic silt layers, one at the base of the Trail City, the other a short distance above the *Protocardia-Oxytoma* Assemblage Zone, maintain their positions relative to the concretion layers, but their relation to time planes cannot be demonstrated as nothing is known about their origin.

Consistent maintenance of position of the assemblage zones relative to bentonite beds would be strong indication of the contemporaneity of individual layers; the evidence of such a relationship is suggestive but incomplete. Although several bentonite layers are present in the Fox Hills, they are preserved chiefly in the relatively unfossiliferous lithofacies of interbedded thin layers of silt and silty clay into which the Trail City and Timber Lake Members grade to the west and southwest. Traced eastward from this thin-bedded lithofacies, the bentonite layers begin to disappear where the thin bedding gives way laterally to predominantly mixed sediment in the marginal parts of the area rich in fossil accumulations. Here, there is abundant evidence that the ash falls were dispersed in the sediment during or soon after deposition by the mixing action of burrowing organisms.

Some overlap of bentonite layers and fossil accumulations exists in areas of gradation between the two lithofacies, and the bentonites consistently hold their position relative to the layers of fossil accumulations. Moreover, within the thin-bedded lithofacies the bentonites lie parallel to layers of barren concretions which can be traced laterally into specific assemblage zones. Together, these parallel relationships can be traced for over 12 miles along the Moreau River, obliquely across the environmental strike of the lower Trail City Member.

The thickness of beds between individual assemblage zones and concretion layers varies within the type area of the Fox Hills. The variations, all of which are very gradual lateral changes, consist of both broad areal trends and more local fluctuations within areas 30 to 40 square miles in extent. For the latter, a vertical difference of 10 feet is about the maximum fluctuation in thickness between any of the layers. The most marked areal trend is a general northwestward thinning of the intervals between all of the lower Trail City assemblage zones. The reduction in thickness of the lower Trail City observed in this trend is about 30 feet, the assemblage zones becoming more closely spaced as the member thins northwestward. The Upper *nicolleti* Assemblage Zone disappears where the interval between the *Limopsis-Gervillia* and *Protocardia-Oxytoma* zones becomes less than 15 feet in thickness. Nowhere in the succession, however, is there any evidence of erosional unconformity or subaerial exposure of the sediments, and the thinning must have resulted from decreased sediment supply or relatively stronger current action.

An apparently unique occurrence of the convergence of two concretion layers is found locally within the *Limopsis-Gervillia* zone in the area of reduced thickness in the western part of the Trail City outcrop along the Grand River. Here large barrel-shaped concretions, with their long axis perpendicular to bedding, contain masses of *Limopsis* in the lower part and *Gervillia* in the upper part. It is evident from the field relationships that the *Limopsis* masses were either still exposed on the sea floor or had been laid bare by currents when the area became inhabited by the *Gervillia* association. The local coincidence of the *Gervillia* masses with *Limopsis* masses, ultimately to form together a single concretion, poses a problem that cannot be reasonably explained by agencies of sedimentation. It seems more likely that at least the initial localization of *Gervillia* masses in areas of *Limopsis* accumulation was controlled by ecology rather than sedimentation—the exposed clusters of *Limopsis* shells affording the best settling place for the epifaunal *Gervillia.*

In summary, the stratigraphic relationships of the fossiliferous concretion layers, in combination with their internal characteristics, indicate that individual accumulations were formed simultaneously. The resultant fossiliferous concretion layers then represent time planes. Relatively level sea bottoms continuously submerged were the site of the successive accumulations.

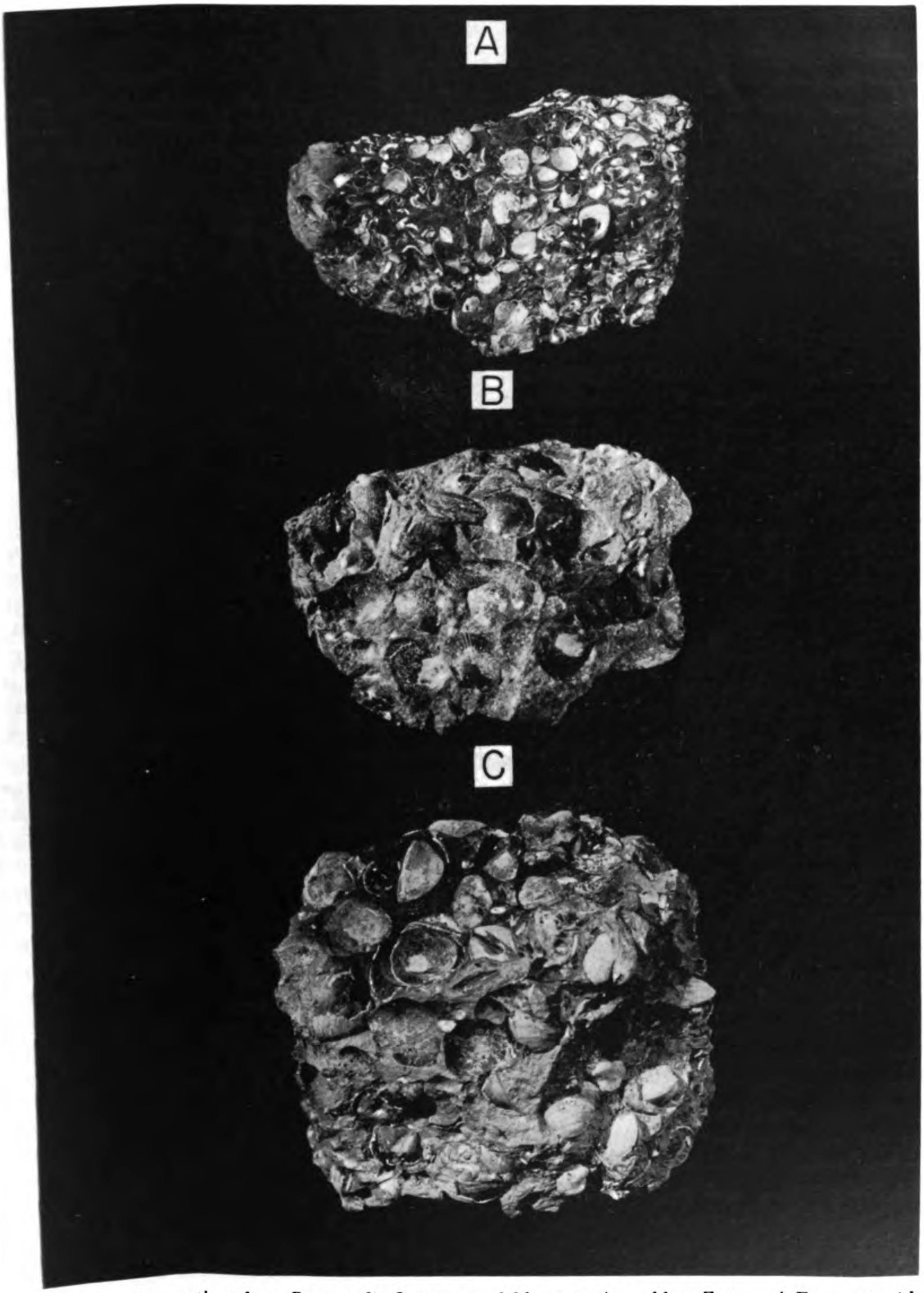

FIGURE 10.—Concretions from *Protocardia-Oxytoma* and *Idonearca* Assemblage Zones. *A*, Fragment with *Protocardia* (approx. × ½). *B*, Fragment with *Oxytoma* (approx. × ¾). *C*, Part of an *Idonearca* concretion (approx. × ½).

Distribution Patterns

Three different kinds of distributional features are encountered in examining the geographical aspects of an assemblage zone: the total distribution of the fossil accumulations, distribution of specific associations of animals within the zone, and distribution of specimens in scattered, dense, clusters. In regard to total distribution, only the western limits of the Fox Hills assemblages are known for certain because of the pattern of outcrop. The southern and eastern limits shown for the Trail City assemblages (Fig. 4, 5, 6, 7) are approximations which will probably need some revision if drought ever lays bare the grassed-over slopes. Enough is known, however, to show that the Trail City assemblages have approximately the same geographic limits within the type area and that they define a lobate area trending, and broadening, northeastward and terminating southwestward within the Cheyenne-Moreau divide. The limits of this area of prolific fossil accumulations do not coincide with any pronounced stratigraphic change.

Distribution of the assemblages outside of the type area has not been studied in detail. It is evident, however, that the Lower *nicolleti* and *Limopsis-Gervillia* assemblages are the most widespread, and as far as is known, coextensive. The Upper *nicolleti* and *Protocardia-Oxytoma* assemblages do not extend as far to the northeast as the preceding, apparently because of the gradual southward encroachment of more marginal environments. The distribution of the assemblages in the lower part of of the Timber Lake Member shows a pronounced southward shift or spread (Fig. 4). At this stratigraphic level the distribution of the rich assemblages appears to coincide with the clayey marginal areas of the Timber Lake sand body, the remainder of which has in some places a sparse marine fauna similar to that in the rich assemblages, but more commonly has the restricted *Tancredia-Ophiomorpha* biofacies.

Total distribution patterns of the Fox Hills assemblage zones show that all the areas of maximum fossil accumulation overlap to some extent, and southward shift took place apparently in response to a southward encroachment of more restricted marginal environments. As recorded in the successive zones of fossil accumulations, this environmental shift appears episodic rather than gradual. Instead of the succeeding assemblage zones showing a progressive southward restriction, three groups of zones indicate three positions at which the environment must have remained stable long enough to permit the accumulation of two or more layers of abundant marine mollusc shells and from 15 to 30 feet of sediment. The Lower *nicolleti* and *Limopsis-Gervillia* zones mark the initial spread of the Fox Hills fauna in the Missouri Valley region; the Upper *nicolleti* and *Protocardia-Oxytoma* zones mark a stage of restriction from the northern part of the original spread; the *abyssinus-mandanensis* and *Idonearca* assemblage zones mark a stage of more radical geographic shift southward, and the *Mactra-Tellina* assemblage represents a much restricted final stage in which the last prolific marine faunas of the type Fox Hills are found.

The second kind of distribution pattern has to do with the occurrence of particular associations of species of fossils within individual assemblage zones. Such associations are present in all of the zones, but they are not commonly conspicuous because of the masking effect of the great numbers of the one or two dominant species. Study of these associations is barely begun but it is evident that they are numerous, that some occur more frequently than others, and that some recur at a number of levels. A few of the more obvious associations such as the large *Gervillia* and the *Drepanochilus* masses noted in the Lower *nicolleti* Assemblage Zone and the *Lucina* in the *Protocardia-Oxytoma* zone, appear to have a preferred distribution (Fig. 5, 7).

These examples have in common the fact that a species other than one of the zonal dominants is locally abundant. Less conspicuous associations involving the sparser elements of the accumulations are also present. A good example of this is the *nicolleti-Inoceramus fibrosus* association noted in both the Upper and Lower *nicolleti* zones. Particularly important to the interpretation of such associations as ecological rather than depositional or chance features is the fact that some

250 feet below the base of the Fox Hills, in the Pierre Shale, an earlier variant of *I. fibrosus* occurs in association with earlier variants of *Scaphites* (*Hoploscaphites*) *nicolleti*. Whether the *nicolleti-fibrosus* and other similar associations have recognizable geographic patterns is not yet known. The impression is that they are patchy, with limited areas of distribution.

The prevalence and diversity of the associations within the individual assemblage zones and the preferential geographic distribution and recurrence of some indicate that each assemblage zone is a complexly structured entity. Just how closely these reflect the original ecological distribution of the species involved is not yet known, but their gross resemblance to marine bottom communities is unmistakable even at this preliminary stage of investigation.

The third kind of distribution pattern, clustering, is found in the individual fossil accumulations, the great majority of which are contained in calcareous concretions. That concretion formation most likely took place subsequent to the accumulation and burial of the masses of shells has already been discussed. Distribution of the fossils in scattered clusters that are roughly ovate in shape and show chiefly random orientation is difficult to attribute entirely to sedimentary processes. This is particularly so when one considers not only the preservation of the specimens, which include many complete pelecypods, but also the preservation of patterns of geographic distribution and intricately structured associations. Current action seems to have had very little sorting or redistributing effect on the assemblages; only rarely and very locally do the clusters exhibit layering of fossils or other evidence of bedding that one would expect if the shells had been swept into heaps or into irregularities on the sea floor by currents.

While no completely satisfactory explanation of the clustering of the shells in the assemblages presents itself at this stage of the investigation, the possibility that the masses of shells represent an incipiently clustered distribution of organisms on the sea floor that was accentuated by some current action at the time of burial finds support in the size distribution of specimens. Speden (oral communication) finds that in the bivalve-dominated concretions of the lower Trail City there is marked conformity in the size of specimens of the abundant species in a single concretion. In an adjacent fossiliferous concretion specimens of the same species may be uniformly of a different size. The spotty distribution of sizes does not suggest current action as the size range for specimens of all the species, not just those of the dominant species, is great. Commonly, clusters of tiny bivalves occur in the same concretion with clusters of larger bivalves of similar shape. This intricate and random pattern of size changes among the shell clusters suggests age grouping of the bivalves. Hallam (1961) interpreted clusters of brachiopods from the Jurassic, which have many features in common with the Fox Hills molluscan clusters, as "life assemblages" and suggested the presence of successive annual broods in the clusters on the basis of size-frequency analyses.

On the other hand, the shape of the clusters is difficult to explain as the result of organic agencies alone, and the general lack of either epifaunal or infaunal elements in living position favors at least some influence by sedimentary agencies. Many concretions are as thick in vertical dimension as they are broad and in the principal assemblages most are between 8 and 12 inches thick. The random orientation of specimens, which include both infaunal and epifaunal bivalves as well as elongate elements such as pieces of wood, belemnites, scaphopods and large cephalopods, precludes the growth of the clusters by gradual increment. If, as it appears, the clusters were buried rapidly, they must have accumulated along with about 8 to 12 inches of loose sediment on the sea bottom.

Resemblance to Modern Communities

Two striking characteristics of the successive fossil assemblages are (1) the relatively uniform faunal composition of the individual assemblage zones throughout their extent, and (2) the numerical dominance in each assemblage of one or two species. These same two characteristics are the conspicuous features of present-day marine bottom communities;

in fact, as Thorson points out (1957, p. 467), Petersen's concept of marine communities grew out of his repeated observance of these features.

Thorson also notes (1957, p. 468) that one of the more convincing indications of the reality of Petersen's communities is ". . . that communities parallel to those described from Danish waters, comprising characteristic animals of the same genera and associated with the same type of substratum, are now known from nearly all parts of the globe." The validity of a natural community thus can be indicated by the recurrence of similar faunally homogeneous associations. Sanders (1960, p. 138), in a recent ecological study of a bottom community, emphasizes this point by using the term community ". . . to mean a group of species that show a high degree of association by tending to reoccur together." In the study of the Fox Hills assemblages the area involved is too small to test the validity of the individual assemblages as natural communities by the criterion of geographic recurrence. But here the dimension of time, the paleoecologists' one advantage over the ecologist, helps out. Similar fossil assemblages do recur stratigraphically in the interior Cretaceous strata. Within the area of the type Fox Hills this is demonstrated by the Lower and Upper *nicolleti* assemblages, and particularly by the recurrence of the *nicolleti-Inoceramus fibrosus* association at these two horizons and in an earlier evolutionary stage in the Pierre Shale some 250 feet lower stratigraphically. Even more convincing evidence comes from preliminary studies of Late Cretaceous (Montanan) assemblages outside the area of the type Fox Hills. The more pertinent recurrent assemblages substantiated to date are the *Protocardia-Oxytoma* assemblage from older beds in both Montana and Wyoming, and the *Limopsis*-dominated assemblage from Montana. Even the more restricted assemblage dominated by the gastropod *Drepanochilus* has been found to recur well down in the Pierre Shale of South Dakota.

In addition to the similarity of the gross features of assemblage zones to those of marine bottom communities, the numerous local faunal associations in the assemblage zones suggest a complex internal structure possibly comparable to the ecological units of varying size and complexity that exist within communities. Any significant comparison of these details must await more complete knowledge of the fossil species, their life habits and their distribution in the assemblages.

In seeking possible explanations for the widespread clustering of fossils within assemblage zones one finds that studies of modern marine bottom populations reveal very little about the finer patterns of animal distribution. This is undoubtedly a consequence of the limitations of the prevalent methods of sampling bottom communities; the dredge does not preserve any evidence of the spatial relations of the recovered animals, and the use of grab and coring devices are generally too spotty to reveal distributional detail. Pratt (1953, p. 62), in a study of the abundance of *Venus* and *Callocardia* in relation to type of bottom sediment, makes the following statement which, enhanced by reverse perspective, neatly sums up the factors limiting our knowledge of distribution patterns.

> Experience of quahog fisherman has shown that the distribution of individuals in a bed is spotty, the numbers often varying greatly from one square yard to the next; hence a large number of grab samples is required to make an adequate census. In the dredge sample this unevenness is averaged out.

A substantial number of scattered references, the majority of which are only brief notations, indicate that clustering is not an uncommon feature in intertidal and sublittoral environments. Observations of clumped distribution of intertidal invertebrates, particularly mussels and oysters, are fairly numerous. Kuenzler (1961, p. 197) in a study of *Modiolus demissus* in a Georgia salt marsh notes that "mussels are usually found in clumps" and suggests that "since large mussels have very limited motility, the clumps probably result from attraction of small mussels to ones already established and, perhaps, from enhanced growth or lessened mortality in the group." Clustering of more motile molluscs has been less frequently observed. Bradley and Cooke (1959, p. 322-323) attribute the bunched pattern of distribution in *Gemma gemma* largely to the modification of grouping, in a reproductive pattern, by waves and currents. Moulton (1962) describes clustering in small circular groups of up to a few thousands of individuals in a population of Australian cerithiid gastropods and concludes (p. 176) that the ". . . clustering is a behavioral adaptation to tropical conditions superimposed perhaps over physiological adaptations . . . ." Loesch (1957), in a study of *Donax*, observes that living concentrations of this bivalve correspond to beach intercusps. Connell (1955), investigating intertidal distribution of *Mya arenaria* and *Petricola pholadiformis* found nothing indicating gregariousness; both random distribution and a tendency to aggregate were evident and he attributed aggregations of the two clams to variations in the substrate.

The examples noted, which are among the few that attempt to explain clustering, serve briefly to suggest the great range and complexity of the modes of clustering, the factors governing it, and the animals involved in it. Beyond indicating that clustering is a fairly common ecological pattern, works on present-day marine communities offer little that is useful in attempting to interpret the fossil clusters of the Fox Hills assemblage zones.

PROBABLE ORIGIN—RECURRENT MASS MORTALITY

From the foregoing description and discussion of the aspects of the Fox Hills fossil assemblages it seems reasonable to infer that in life the individual layers of accumulations were (1) simultaneous throughout their extent, (2) broad sublittoral bottom communities dominated by great numbers of one or two species of molluscs, and (3) divisible into smaller ecologic units by local differences in association of nondominant species and by local concentrations of species other than the dominants. The successive communities conformed fairly closely in their geographic distribution, occurring in elongate, dominantly northeast-trending patches up to 1,500 square miles in area which shifted progressively southward with the gradual encroachment of intertidal environments from the north or northeast. The site, probably an embayment on the northern side of the Cretaceous sea during its last major stand in the interior region, was flanked to the west by a large delta; its eastern or northeastern side is not preserved but littoral facies in that direction suggest another deltaic area.

Continuous deposition of sediment, though undoubtedly at varying local rates, is indicated by the nature of the sedimentary record which features uninterrupted and intricate intergrading of facies marginal to and succeeding the beds with the fossil accumulations. No recognizable evidence of marked hiatus or of subaerial exposure yet has been found in the marine lower Fox Hills in the type area, and considering its marginal locus of deposition and position in a gradational series from marine to continental in an area of active sedimentation, it is not likely that significant breaks in deposition occurred. Moreover, both the general uniformity and distinctive distributional patterns of the individual layers of fossil accumulations, as well as the unusually good preservation of the shells themselves, preclude the possibility that the accumulations were formed gradually during long intervals of nondeposition or slight sedimentation. The marked confinement of accumulations to layers separated by unfossiliferous sediments points to abrupt extermination and burial of the existing community and subsequent fresh resettlement of the area, sometimes by the same association and sometimes by different associations of the same basic fauna.

Repeated mass killings, presumably accompanied by rapid burial and relatively little redistribution of the organisms by current action, seems the most satisfactory explanation of the richly fossiliferous layers in the Fox Hills Formation. In her excellent synoptic paper on mass mortality in the sea, which pertains mostly to vertebrates, Brongersma-Sanders (1957, p. 968) states that:

> Whether the abundance of invertebrates in certain deposits was caused by catastrophic killing has not been convincingly determined.

Ample evidence is given in her paper of both the frequency of mass mortality in the sea and the fact that marine invertebrates are commonly involved in it; consequently, it is reasonable to assume that some accumulations of invertebrate fossils have resulted from such catastrophes, the principal problem is what constitutes convincing evidence.

Abundant vertebrate fossils are so rare in marine sediments that local accumulations are highly suggestive of catastrophe; on the other hand, local abundance of invertebrates is not significant in itself as it could result from a number of causes. But geographically patterned accumulations of abundant invertebrate fossils seem to be convincing evidence of mass mortality, for it is difficult to visualize any alternative way of entombing in marine deposits great numbers of invertebrates that retain both coarse and fine patterns of community structure over sizable areas. The repetition of such patterned accumulations over approximately the same area is strong supplementary indication of mass killing for as Brongersma-Sanders points out (p. 942), certain of the more common phenomena causing mass mortality in the sea are repeated at short intervals.

To what extent the hypothesis of mass mortality can be applied to other interior Cretaceous terrains with similar types of fossil accumulations will have to be determined by detailed study of the individual occurrences in the context of local features of their stratigraphy. Layers of scattered calcareous concretions many of which contain rich associations of fossils dominated by one or two species are a common kind of fossil accumulation in the interior Cretaceous. Two features of these accumulations in particular (1) their apparent preferential occurrence in clayey marine sediments beneath and laterally adjacent to marginal facies of restricted marine or mixed environments, and (2) the repetition in successive layers of particular associations of dominant genera, are, I believe, strong reason to suspect that mass killings of the bottom fauna may have been common occurrences repeated many times in certain environments of the coastal waters of the interior Cretaceous sea.

Possible Causes

A thorough review of the known causes of mass mortality and step by step comparison with the fossil accumulations in question is not warranted here. The range of possibilities is well documented in Brongersma-Sanders paper (1957), which is necessary background for any discussion of the subject. Unfortunately, we do not know enough about the oceanography of epicontinental seas to be able to rely on analogy with mass mortality in modern seas with complete confidence. This is especially true for the interior Cretaceous sea whose faunal peculiarities are well known. Somehow it seems presumptive to speculate about how certain communities of the fauna died when we know so little about how they lived. However, consideration of pertinent features of the assemblages in question may at least provide some idea of the nature of the catastrophes involved.

The repetition of the assemblage zones with similar features over similar areas indicates that the mass killings were recurrent and suggests that the agent was the same for each successive killing. Three causes of modern mass mortality, low temperature, hypersalinity, and noxious waterbloom, recur frequently in local areas (Brongersma-Sanders, 1957, p. 942). For the Cretaceous interior sea, particularly for the shallower restricted phases of it marginal to deltas, reduced salinity might be added to the list. The possibility of recurrent low salinity in coastal areas seems a legitimate assumption considering the great size of the area draining into the sea and the humid warm temperate to subtropical climate indicated by the Late Cretaceous flora (Dorf, 1942, p. 100-103). This does not eliminate the possibility of local or even widespread hypersalinity in the interior sea, although there is no obvious indication of it, and to my knowledge it has been proposed only on theoretical grounds.

The faunal constitution of the Fox Hills assemblages suggests selective killing. Each layer contains the same principal types of animals; infaunal and epifaunal molluscs and ammonoids—chiefly scaphitids. The latter were most likely slow swimmers feeding on or near the bottom. Fish remains, except for scattered scales, are rare; belemnoids are present but not abundant and never found in concentrations. It would appear that the killing, whatever the cause, did not take place rapidly enough to catch the more mobile organisms such as fish and belemnoids. The absence of these more capable swimmers also suggests that the area in which the mortalities took place, though an embayment, was open to the sea.

The floral constitution of the assemblages may be significant. Of the varied vegetable contents of the assemblage zones, wood fragments, commonly infested by the wood-boring bivalve *Martesia*, are the more abundant. Fragmental to complete leaves, conifer cones and foliage, fragments of palm fronds, nut-like bodies, charcoal fragments and slender trunks of *Palmoxylon* up to 8 feet long, have all been found in the assemblage zones. While not in abundance, these plant structures are sufficiently common to attest to the proximity of land and of rivers competent to sweep such debris out to sea in times of flood.

Clustering and concretion formation are both features that have a bearing on the killings. As has been noted, the clusters may have resulted from the accentuation of an original ecological clustering by some sort of mild current action, and it was indicated that from 8 to 12 inches of sediment are involved in the deposition of individual layers. If, as seems likely, concretion formation resulted from the decay of buried organic matter, both clustering and concretions call for either the rapid deposition of up to a foot of sediment or the roiling of the bottom sediment to that depth. Strong sweeping currents are ruled out by lack of sorting, by the cluster pattern itself, and by the random orientation of shells.

The thin bentonites in the Fox Hills bear no direct relation to the fossil assemblages. Although there was appreciable volcanic activity in the Late Cretaceous of the interior region, there is no evidence that the marine faunas suffered directly from it in any way. In fact, the disappearance of the ash in the areas of abundant invertebrates suggests that the sediment feeders literally ate it up.

Bringing together the scanty direct evidence we can say that the fossil assemblages were associated with a recurrent phenomenon, localized in a fairly large but geographically restricted coastal area, which selectively affected the bottom fauna and slow-swimming invertebrates and accomplished the deposition and redeposition of approximately a foot of bottom sediment without the aid of currents strong enough to redistribute and sort the organisms. This suggests that turbidity was an important factor at the time the accumulations were buried, but if the beds in which the accumulations are found were ever graded, the evidence was subsequently destroyed by burrowing organisms. Some small-scale graded bedding is at least locally associated with the thin-bedded silt and silty shale facies into which the fossiliferous sequence grades to the west; its frequency of occurrence is not known.

Recurrent phenomena that could conceivably have caused turbid bottom conditions include severe storms, which could both disturb bottom sediment and bring about the introduction of sediment laden currents from rivers in flood; flooding of rivers in periods of excessive rainfall not associated with severe storms; and stirring of the bottom by tsunamis. Tsunamis cannot be ruled out as a frequently recurrent phenomenon considering that quakes may have been common during the Laramide mountain building then in progress nearby in the interior region, but the effects of such disturbance should be fairly widespread and not restricted to the limited area of fossil accumulation. If evidence for disturbances of the bottom exists lateral to the horizons of fossil accumulations, it is not apparent. It is also questionable whether burial in bottom sediment alone could have destroyed the dominant faunal elements found in the associations. Certainly the ammonoids and epifaunal bivalves could have been killed in this manner, but we do not yet know enough about the life habits of the infaunal bivalves involved to determine whether they are types that would not have been able to re-orient themselves in the sediment and continue to live. If the study of the bivalves in progress indicates that the dominant infaunal species present are exclusively types that could not have readjusted to burial, the selectivity of the mortality will add considerable support to the possibility of smothering.

If turbidity resulted from the discharge of sediment-laden rivers during storms or periods of torrential rainfall, reduction of salinity may have acted together with smothering to cause mortality. In this situation even bivalves that could adjust to burial would have suffered. The chief obstacle to this possibility is that reduction of salinity by freshets usually affects only very shallow bottoms, generally not below 3 meters, as the fresh water being less dense than the salt, tends to remain on the surface. Conceivably, highly turbid fresh water because of its greater density, could affect bottoms to greater depths, but I know of no recent studies offering quantitative data on this subject. The salinity of the interior sea, particularly in coastal areas, is also an important consideration here, and the possibility that it was considerably less than the salinity of normal oceanic waters has yet to be either substantiated or disproven. The scarcity of such common invertebrates as echinoderms, corals, and bryozoa in the interior Cretaceous sea could result from low salinity, excessive turbidity, or even hypersalinity. Whatever the salinity of the sea, the inclusion of plant remains in the marine assemblages points to the recurrent local influx of highly turbid fresh water from rivers in flood.

None of the foregoing speculations are supported by sufficient evidence to rule out other possible causes of mortality. Periodic low temperatures could have occurred, as they do today in the Gulf of Mexico, in the warm temperate to subtropical climate of the Cretaceous. Noxious waterblooms may also have been common. However, the absence of fish in the assemblages, unless explainable in some other way, does not favor either of these common kinds of recurrent mortality. The actual cause or causes of mortality may not be determinable from what evidence is left in the record. Even in some present day mortalities the multiplicity of factors involved obscures the principal causes of killings. In hurricanes, for example, killing may locally result from stranding, hypersalinity in brackish waters, lowered salinity in coastal waters, burial and deoxygenation, as well as other direct physical effects. Possibly the prevailing bottom conditions in much of the Cretaceous sea were inhospitable to life and became the agent of mortality following brief episodes of hospitable conditions brought about by some recurrent environmental factor. If so it is the existence of the benthic faunas rather than their extermination that requires special explanation. But until more is known of the life habits of the species in the peculiarly restricted interior Cretaceous faunas, we are not likely to understand the factors involved in either their great local abundance or their repeated local extermination.

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Pennsylvanian Megacyclothems of Wilson County, Kansas, and Speculations Concerning Their Depositional Environments[1]

ABSTRACT

Sedimentation during Pennsylvanian time in Wilson County was cyclic. Approximately 15 separate but generally incomplete transgressions and regressions of the sea are represented in the limestone, shale, and sandstone strata. Cyclothems recorded in these rocks are parts of six larger cyclic repetitions, megacyclothems. Characteristic environments prevailed during each part of the megacycle and resulted in the formation of sedimentary rocks with clearly different lithologic and faunal attributes. Ten depositional stages composing each megacycle are categorized as follows: A, fluviatile continental; B, continental to marine transitional; C, argillaceous transgressive-regressive marine; D, continental margin; E, rapid-oscillation marine; F, stagnant-water marine; G, normal transgressive-regressive marine; H, nearshore argillaceous marine; I, nearshore clear-water marine; and J, nearshore regressive marine. The sedimentary rocks that formed during these stages are described, and speculations concerning their depositional environments are given.

INTRODUCTION

The Pennsylvanian System in Wilson County contains strata of 5 groups and 13 formations (Fig. 1). The system is characterized by sequences of limestone, shale, sandstone, and coal representing alternating marine and nonmarine depositional environments that were operative during successive advances and retreats of the Pennsylvanian sea. Each transgressive-regressive sequence defines a cycle of deposition, or cyclothem (Wanless and Weller, 1932, p. 1003), and several cyclothems are combined into larger cyclic sequences termed megacyclothems (Moore, 1936, p. 29, 30).

The cyclic deposits of Pennsylvanian age in Kansas were thoroughly discussed by Moore (1936, 1949), who presented typical schemes of cyclic deposition for beds in different parts of the Kansas Pennsylvanian and Permian sequences. Although each distinctive rock type in the Pennsylvanian strata of Wilson County does not precisely fit into Moore's typical megacyclothems (1936, p. 30-34), most of the major rock units are present. Each rock type reflects deposition under different environmental conditions of water movement, water depth, water temperature, light abundance, salinity, hydrogen ion concentration, dissolved carbon dioxide, organic content, nutriment supply, abundance of land-derived matter, and other factors. On the basis of the lithologic and faunal characteristics of the strata exposed in Wilson County, 10 different sequential depositional environments, designated as stages, can be postulated as follows (Fig. 2): A, fluviatile continental; B, continental to marine transitional; C, argillaceous transgressive-regressive marine; D, continental margin; E, rapid-oscillation marine; F, stagnant-water marine; G, normal transgressive-regressive marine; H, nearshore argillaceous marine; I, nearshore clear-water marine; and J, nearshore regressive marine. Most of these 10 stages occur

1. Publication authorized by Director, U. S. Geological Survey. The nomenclature and classification of the geologic units described in this report differ somewhat from the usage adopted by the U. S. Geological Survey.

SERIES	GROUP	SUBGROUP	FORMATION	MEMBER	MEGA-CYCLE
UPPER PENNSYLVANIAN	SHAWNEE		Oread Ls.	Plattsmouth Ls.	MEGA-CYCLOTHEM 6
				Heebner Sh.	
				Leavenworth Ls.	
				Snyderville Sh.	
				Toronto Ls.	
	DOUGLAS		Lawrence Sh.	Unnamed Sh.	
				Amazonia Ls.	
				Ireland Ss.	
			Stranger Fm.	Robbins Sh.	MEGA-CYCLOTHEM 5
				Haskell Ls.	
				Vinland Sh.	
				Westphalia Ls.	
				Tonganoxie Ss.	
	PEDEE		Weston Sh.	----	MEGA-CYCLOTHEM 4
	LANSING		Stanton Ls.	South Bend Ls.	
				Rock Lake Sh.	
				Stoner Ls.	
				Eudora Sh.	
				Captain Creek Ls.	
			Vilas Sh.	----	
			Plattsburg Ls.	Spring Hill Ls.	MEGA-CYCLOTHEM 3
				Hickory Creek Sh.	
				Merriam Ls.	
	KANSAS CITY	ZARAH	Lane-Bonner Springs Sh.	----	
		LINN	Iola Ls.	Raytown Ls.	MEGA-CYCLOTHEM 2
				Muncie Creek Sh.	
				Paola Ls.	
			Chanute Sh.	Cottage Grove Ss.	
				Unnamed Sh.	MEGA-CYCLOTHEM 1
			Drum Ls.	----	
			Cherryvale Sh.	----	
		BRONSON	Dennis Ls.	Winterset Ls.	

FIGURE 1.—Nomenclature of exposed Pennsylvanian rocks of Wilson County.

in each of the 6 megacyclothems into which the Pennsylvanian strata of the county are herein grouped (Fig. 3).

The environmental significance of fossils and lithologies characteristic of the Pennsylvanian rocks of Wilson County are herein briefly discussed, the strata formed in each of the 10 stages are described, and their depositional environments reconstructed. In attempting reconstructions of the environments, a literature survey was made, and it was determined that opinions concerning the signifi-

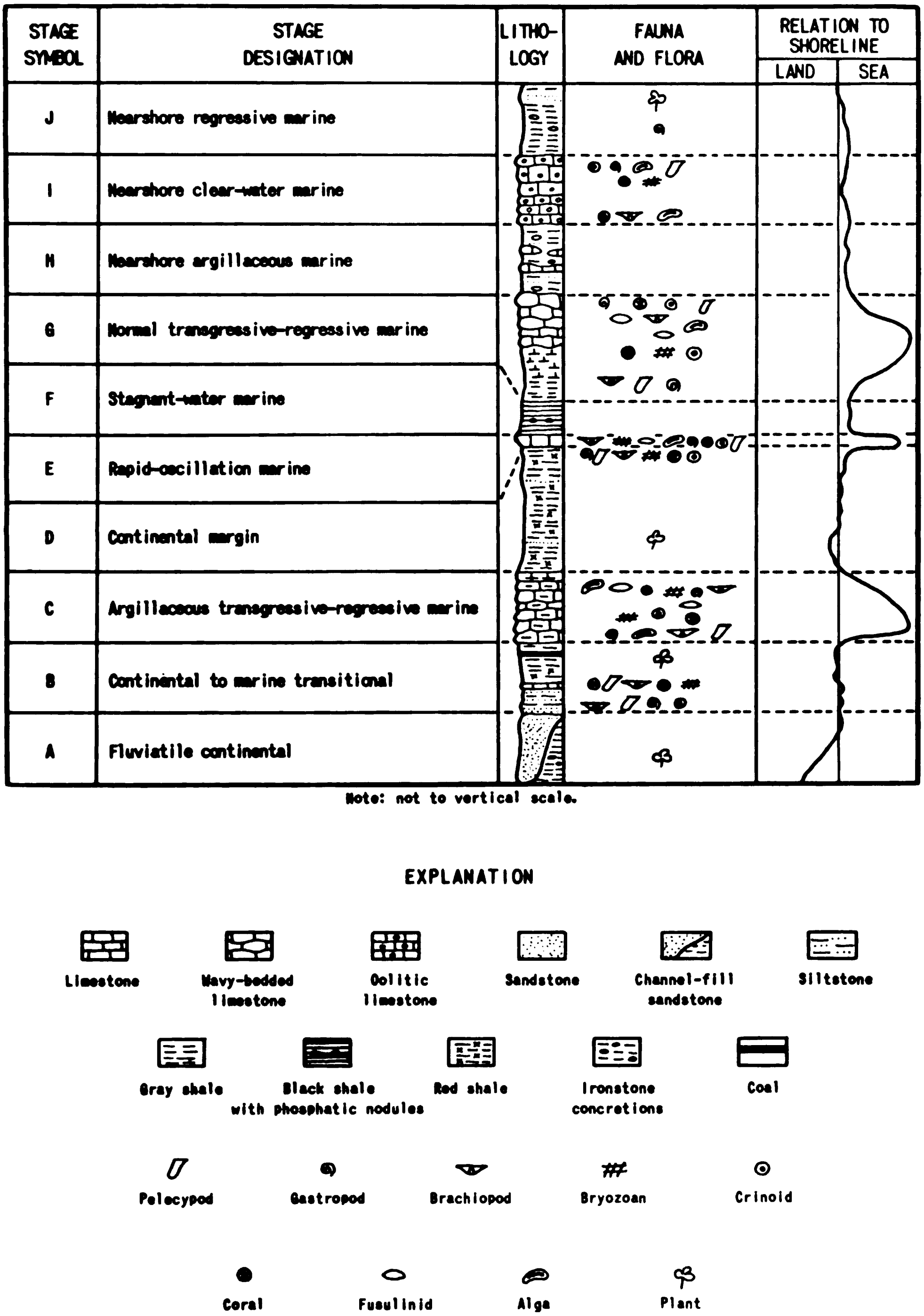

FIGURE 2.—Depositional stages represented in Pennsylvanian megacyclothems of Wilson County.

cance to be attached to faunal and lithologic elements in rocks are many and varied.* Space does not permit a comprehensive summation of these opinions, and I have therefore made an arbitrary selection of the opinions that I feel best account for the faunal and lithologic characteristics displayed in the Pennsylvanian rocks of Wilson County. Because of the emphasis placed on Kansas rocks in his writings, I have drawn heavily on the works of R. C. Moore and his associates.

Sediments of stages A, B, D, and J contain the fossil remains of land plants; those of stage B contain pelecypods, gastropods, brachiopods, bryozoans, crinoids, and corals; and those of stages C, E, and G contain fusulinids and algae in addition to forms enumerated for stage B. Ostracodes and conodonts were found in sediments of many of the stages, but particularly those of stage F. Calcareous sponges are common in stages E, F, and G of megacyclothem 3; and cephalopods are found in stage E of megacyclothem 4.

Pelecypods and gastropods are adapted to many sorts of environments, but the vast majority are bottom dwellers in shallow-marine water (Moore and others, 1952, p. 277, 398). Myalinids and particularly *Myalina* (*Orthomyalina*) are believed to have been sedentary forms, but they were not necessarily attached by a byssus (Mudge and Yochelson, 1962, p. 105). Newell (1942, p. 19) suggested that these myalinids lived in the shallow, turbid waters of the shore zone, and could tolerate an unusually great amount of variation in the salinity of the water. Brachiopods prefer shallow water—many forms prefer very shallow water with solid objects available for attachment, others prefer muddy bottoms, and still others prefer shallow water of subnormal salinity (Moore, 1929, p. 469). Weller (1957, p. 351) suggested that the orbiculoid brachiopods found in the fissile black shale probably were attached to seaweed.

Bryozoans live mostly in shallow clear water, fairly close to shore. Some are found in water constantly agitated by waves and strong currents, and colonies are most numerous on rocky bottoms and in places where shells of other invertebrates afford places for attachment (Moore and others, 1952, p. 156). Elias (1937, p. 418-419) believed that Paleozoic encrusting bryozans lived in both the littoral and sublittoral zones, that fenestrate bryozoans were adapted for life in sublittoral regions where wave and current action were strong, and that ramose types of bryozoans were adapted for life in deep or sheltered water where wave action was absent and currents scarcely active. Concerning bryozoans, Moore (1929, p. 468-469) stated; "The nature of the enclosing sediments, perfection of preservation of delicate structures, and association with numerous crinoids, . . . indicate quiet water. . . . Presence of many shallow-water invertebrates and interdigitation of bryozoan-bearing beds and continental deposits may be interpreted as signifying depths of a very few fathoms rather than several tens of fathoms."

Modern crinoids, throughout life, generally are attached to the sea bottom by a stem, and their occurrence as fossils in Paleozoic rocks suggests a habitat of moderately shallow, quiet marine water (Moore, 1929, p. 470; Moore and others, 1952, p. 604). Crinoids need well-aerated water of relatively high minimum salinity and an abundance of suspended food matter (Clark, 1957, p. 1183). Reef corals are confined to marine water and are most abundant in clear, warm, shallow seas. They live in colonies between sea level and a depth of approximately 250 feet, but active building takes place in water less than 50 feet deep (Moore and others, 1952, p. 117-118; Wells, 1957, p. 1087-1088). Many solitary corals are firmly attached, others are loosely embedded in soft sediment, and some can endure a muddy environment (Moore, 1929, p. 468; Moore and others, 1952, p. 117). Sponges and echinoids indicate warm, clear, shallow seas (Moore, 1929, p. 468, 470).

Fusulinids are not found in direct association with fossil forms of invertebrates of the types that live today in brackish-water or nearshore environments (Thompson, 1948, p. 7); they presumably lived mainly in relatively unagitated water far from shore (Moore, 1929, p. 467-468; Thompson, 1948, p. 7). Occurrences of fusulinids in shale and sandstone

* The writer wishes at this point to express his appreciation for the constructive criticism and suggestions given by T. A. Hendricks and E. E. Glick whereby the manuscript was measurably improved.

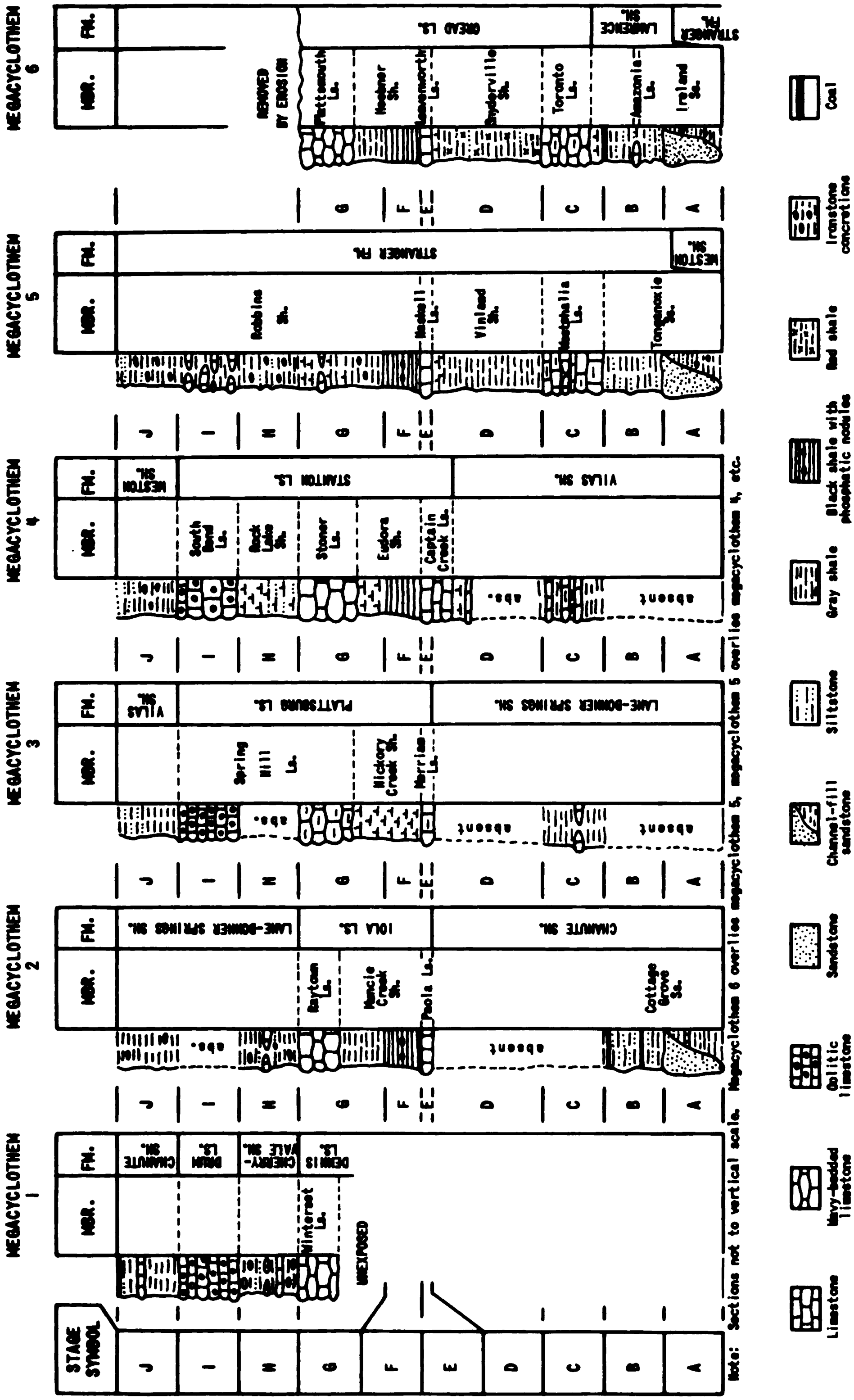

FIGURE 3.—Megacyclothems represented in exposed Pennsylvanian rocks of Wilson County.

suggest that they also lived in clayey and sandy environments, but the possibility should be considered that currents may have flushed the organisms into an unwholesome environment in which they died in great abundance. They were probably bottom dwellers and moved about on feeble pseudopodia; but late forms may have become adapted to a floating habit, the protoplasm in the inflated part of the shell having been distended by gaseous vacuoles (Dunbar, 1963, p. 30, 31, 41). The presence of algal incrustation in conjunction with fusulinids indicates that the water was less than 180 feet deep because below this depth photosynthetic processes essential for chlorophyll-containing algae are practically impossible, even in the clearest water (Elias, 1937, p. 425).

Ostracodes can be free swimming or bottom dwelling, and can live in foul, stagnant water as well as in water that is clear. Conodonts are apparently the remains of pelagic organisms—not bottom dwellers—and their greater abundance in shales rich in organic matter (Moore and others, 1952, p. 733) suggests life in an environment of unagitated, foul water, although the conodonts themselves may have lived near the surface where the water was better aerated (Moore, 1929, p. 472). Calcareous sponges live only in shallow water of full oceanic salinity and are most abundant at depths of less than 30 feet (deLaubenfels, 1957, p. 1083). Cephalopods, using *Nautilus* as an example, live in normal sea water at depths of about 10 to 2,000 feet, but generally at shallow depths. At night they migrate from deeper into shallower water and come quite close to shore. *Nautilus* is not pelagic, living near or on the bottom, but swims freely (Stenzel, 1957, p. 1137). It is possible that the empty shells, rising to the surface after death of the animal, were widely distributed by winds and currents (Moore and others, 1952, p. 341).

Faunas interpreted by Moore (1949, p. 81) as representing very nearshore conditions include inarticulate brachiopods, certain types of calcareous brachiopods (*Derbyia, Juresania*) in abundance, thick-shelled clams (especially *Myalina*) and radially ribbed scallops (*Aviculopecten* and other genera), more or less common snails (especially bellerophontids), and some bryozoans. He proposed also that offshore faunal assemblages are characterized by a varied group of marine invertebrates, particularly fusulinids, and that predominance of algae indicates shallow-water deposition during the retreating phase of a marine inundation.

The environments in which these faunas and floras lived and were buried ranged from fluviatile to marine water. The water may have been rich in quartz sand, or have contained abundant clay or silt, or have been clear and very saline. Dapples (1947, p. 95-96) suggested that sandstone composed predominantly of quartz but also containing abundant muscovite on bedding planes accumulated chiefly in an environment associated with large alluviating rivers emptying into regions of extensive tidal flats.

Grim (1951, p. 231) summarized that red color in an argillaceous sediment probably is due to a supply of ferric iron oxide or hydroxide from the source area and to deposition in the absence of appreciable organic matter in an oxidizing environment where the higher state of oxidation could be preserved, or possibly to rapid burial under mild reducing conditions. Green, gray, or black shale probably formed under reducing conditions whereby the iron was changed to the ferrous state. Elias (1937, p. 428) concluded that red shale that separates marine phases of two neighboring cycles is a continental deposit and indicates emergence; he believed that green shale, which in places contains *Lingula* or which is mottled or interbedded with red shale, represents marine deposition within the zone of tides, the green color having formed through the reducing action of organic matter upon oxides of the original red silt (1937, p. 426-427). The development of ironstone concretions in shale may, in part, occur during lithification after a considerable time lapse (Krumbein and Sloss, 1951, p. 217).

Moore (1929, p. 469) stated that black platy carbonaceous shale zones represent deposition in very shallow water that was acid because of accumulated humus and poor circulation. He suggested later (Moore, 1950, p. 15) that seaweeds may have furnished most of the carbonaceous material and have grown so thickly in this shallow water that disturbance of the bottom by wind and waves was nil. Weller (1957, p. 351) also suggested that the carbonaceous material in thin fissile black shale was derived from a prolific growth of seaweed which prevented circulation of the water and whose decaying remains exhausted the oxygen adjacent to the bottom. Phosphate in the black shale may have accumulated as a result of bacterial decomposition of organic debris (Barnes, 1957, p. 304-305).

Inorganic precipitates are formed when the solubility product of some substance is exceeded. Supersaturation may be induced by physical agencies such as temperature changes, it may be associated with the removal of carbon dioxide where photosynthesis occurs, or it may be related to changes in hydrogen-ion concentration or oxidation-reduction potential brought about by the organisms. In addition, precipitation may result from evaporation in isolated lagoons and seas (Sverdrup and others, 1942, p. 951).

Present-day oolites (forming in the Great Salt Lake, Utah; on the Great Bahama Bank, Florida; and at Laguna Madre, Texas) are restricted to areas of strongly agitated water near the shoreline or in tidal channels (Eardley, 1938, p. 1371; Illing, 1954, p. 43, 69; Freeman, 1962, p. 482). In the Bahamas the oolites are typically developed near the western ends of tidal channels and on the western beaches, where fresh oceanic water has been swept onto the shallow banks and has been sufficiently warmed and stirred up to become appreciably supersaturated with calcium carbonate (Illing, 1954, p. 43). Under the constant stirring movement induced by the tides and beach wavelets within the break-point, the calcium carbonate is precipitated as concentric oolitic sheaths of aragonite on sand grains (Illing, 1954, p. 69).

Twenhofel (1932, p. 860-862) pointed out that in epicontinental seas: (1) weak tidal action and tidal currents may lead to the presence of large areas of quiet water whose bottoms are covered with black mud rich in hydrogen sulfide; (2) shoreward the water may be so shallow as to destroy the erosional effectiveness of waves for distances of several miles from shore; (3) during times of large storms, the shallowness may allow the stirring up of previously deposited materials; and (4) bottoms adjacent to low shores without streams are apt to receive fine sediments, although some bottoms near such shores may have currents sufficiently strong to bring in coarse sediments. Moore (1948, p. 126) suggested that the marginal portions of very shallow advancing Pennsylvanian seas would be fresher than normal sea water by reason of the precipitation and runoff from the adjacent land and that the marginal portions of a retreating shallow sea may have had excess salinity because of evaporation in coastal lagoons and drainage of salt from connate water in the recently exposed salt-water sediments left behind by the retreating sea. Krumbein and Sloss (1951, p. 208) pointed out that the shoreline of a shallow advancing epicontinental sea becomes progressively submerged and that a sheet sand, which results from the sorting action of water in the zone between high and low tides, will develop without the production of a typical linear beach deposit.

The environmental data just presented have been arbitrarily selected, and it should be emphasized that other conditions of deposition have been proposed for each of these lithologic types and that more than one set of conditions may have operated during the deposition of any one rock type. However, I consider the factors cited above as those most likely to have been effective in the Pennsylvanian seas of Wilson County and have used them in speculating on the conditions under which the various rocks were deposited. The reader should keep in mind also that:

(1) The strata in which fossils are found do not necessarily indicate their environmental habitats, but may merely be their final resting places inasmuch as the animals and plants may have been brought into the area by strong currents after death; or, the animals and plants may have died in great abundance in the area as a result of a radical change in the environment, and the strata in which they are found would then indicate the new environmental conditions which brought about their death rather than those under which they lived and flourished.

(2) The lithologic continuity and constant thickness of a sequence of thin units over many hundreds of square miles indicate environmental changes of continental magnitude

and are not the result of structural movement in a local area such as Wilson County but of movement of worldwide significance. Movement in Wilson County and adjacent area must have been generally downward, however, in order to allow accumulation of a continuous sequence of sedimentary rock 2,700 feet thick containing alternating marine and nonmarine sediments. Small-scale structural movements in Wilson County are known to have modified the depositional environments locally during certain megacyclic stages, but the effects were of small areal and temporal significance and are not considered herein.

(3) The fauna and flora are influenced by water or air temperature, by salinity, depth, movement, or clarity of water, or by the nutrient content in the environment, so that their significance with regard to any one factor is not clear; the thickness and lithology of the units provide a crude measure of the time involved in their deposition.

(4) The distance from, and elevation of, exposed land as the source of terrigenous contamination may have influenced the environment to a greater extent than depth of water. A similar conclusion was reached by Mudge and Yochelson (1962, p. 115).

DEPOSITIONAL STAGES

Because the strata of Pennsylvanian age in Wilson County are parts of repetitious sequences, members of different formations have had similar modes of origin and have the same or nearly the same lithologic and faunal characteristics. To describe each member or formation in detail would lead to much duplication. In the following sections, therefore, the stratigraphic unit that displays most completely the characteristics of each depositional stage is discussed in detail and any striking differences or similarities in thickness, lithology, or fauna displayed by correlative units are pointed out. The environment of deposition of the rocks deposited during each stage is reconstructed, and differences in the depositional environments of the correlative units are indicated.

A, Fluviatile Continental Stage

In Wilson County, deposition during the fluviatile continental stage is represented by the lower parts of the Cottage Grove Sandstone Member of the Chanute Shale, Tonganoxie Sandstone Member of the Stranger Formation, and Ireland Sandstone Member of the Lawrence Shale (Fig. 3). The Ireland (megacyclothem 6) exhibits most completely the characteristics of the fluviatile continental stage and will be used as the example.

Physical Characteristics

Inasmuch as megacyclothemic deposition terminates with a general withdrawal of the sea, the oldest beds in a new megacyclothem —those constituting the fluviatile continental stage—commonly are deposited upon irregular erosion surfaces. Sandstone of the lower part of the Ireland fills channels cut as much as 60 feet into the underlying shale and commonly is strongly cross-bedded. The basal part of such a channel fill is well shown in a roadcut on Kansas Highway 96 about 6 miles northwest of Fredonia (Fig. 4). At this locality abundant fragments of light olive-gray shale from the underlying strata occur in the medium- to fine-grained sandstone of the lowermost 2 inches of the Ireland. Irregularly distributed elongate pods of siltstone and sandstone that contain much finely broken carbonaceous matter and *Calamites* occur in the lower 2 feet of sandstone in the exposure. The sandstone in the upper 12 feet in the roadcut is composed almost entirely of grains of subrounded well-sorted, nearly equant, fine- to very fine grained quartz in beds that are both lenticular and truncated (Fig. 4). Correlation with adjacent outcrops indicates that as much as 50 feet of subaerially deposited fine- to medium-grained, slightly micaceous quartz-rich sandstone occurs above the sandstone of the roadcut. These continental deposits locally contain thin lenses of silty claystone and sandy siltstone and are overlain by sandstone that contains marine fossils in a few places.

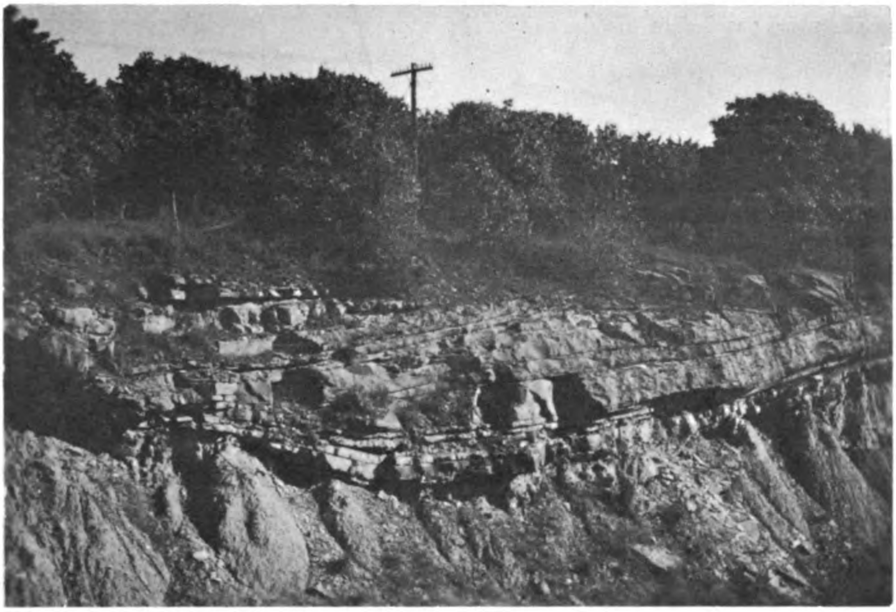

FIGURE 4.—Channel-filling sandstone of Ireland Sandstone Member of Lawrence Shale. Roadcut exposure about 6 miles northwest of Fredonia, Wilson County.

The Tonganoxie Sandstone Member of the Stranger Formation and the Cottage Grove Sandstone Member of the Chanute Shale differ from the Ireland in a few characteristics that presumably reflect minor environmental modifications. The Tonganoxie differs in that the quartz grains are more angular and relatively poorly sorted, and small white mica flakes are abundant. The Tonganoxie, however, is a channel-filling sandstone as much as 60 feet thick, is coarsest at the base, and locally contains wood fragments. The Cottage Grove differs slightly in that the lower part consists of yellowish-gray, slightly micaceous, very fine grained silty sandstone that overlies strata containing a minable coal bed. The sandstone is about 45 feet thick, however, and generally is thin- and even-bedded; logs of exploratory wells suggest that the Cottage Grove fills channels cut 50 or more feet into the underlying shale.

Environment

In Ireland time in Wilson County, the initial phase of megacyclic deposition presumably began when streams that flowed across the county deposited material in largely subaerial channels cut 30 to 60 feet deep into the underlying soft strata of the preceding megacyclothem. The seaward parts of the streams probably occupied sinuous channels on tidal flats and on the adjacent submarine shelf. Delta building and reduction in stream grade or velocity apparently resulted in deposition in the lower parts of the channels of medium and fine sand containing a high proportion of plant debris, including *Calamites*. As the streams continued to meander and spread across the flood plains and delta areas, much fine sand was deposited in locally broad cross-beds, in plane-surfaced layers, or in thick unbedded units. Thirty to 50 feet of fine to medium sand and silt accumulated thusly, and the channels were mostly filled before the transgressing sea terminated the continental deposition.

During Tonganoxie and Cottage Grove times, previously cut channels were apparently also available for subaerial filling. Somewhat different source rocks, however, presumably furnished the more angular and less well sorted quartz grains and abundant small white mica flakes deposited during early Tonganoxie time. In early Cottage Grove time the source area for the materials transported by the streams must have been more distant, or the stream gradient less, so that only very fine sand and silt were carried to the depositional environment.

B, Continental to Marine Transitional Stage

The continental to marine transitional stage contains strata deposited under both nonmarine and marine conditions. The stage is represented by the upper part of the Ireland Sandstone Member and most of the strata in the overlying unnamed part of the Lawrence Shale, middle and upper parts of the Tonganoxie Sandstone Member of the Stranger Formation, and middle and upper parts of the Cottage Grove Sandstone Member of the Chanute Shale (Fig. 3). The Lawrence Shale (megacyclothem 6) will serve as the detailed example.

Physical Characteristics

The widespread sandstone beds of the upper part of the Ireland Sandstone Member of the Lawrence Shale are locally as much as 40 feet thick, but in many places they are separated into three units by two lenticular beds of shale 10 to 20 feet thick. These upper sandstone units of the Ireland are commonly grayish orange to moderate brown and are composed almost entirely of well-sorted, subrounded, very fine grained quartz. Small concentrations of limonite in many places cement the quartz grains and impart a speckled appearance to the rock; mica flakes are rare. The upper sandstone beds commonly have well developed ripple marks on which worm? tracks are locally abundant. Casts of crinoid stems, low-spire gastropods (*Worthenia?* and others), pelecypods (*Wilkingia, Nuculana, Schizodus?*, and *Aviculopecten*), and brachiopods (*Crurithyris* and others) were found in a few places in the lower sandstone unit and locally in the upper sandstone beds. The intervening shale units generally are light olive gray, and silty or sandy.

The part of the Lawrence Shale above the sandstone consists of light-gray to light olive-gray generally silty shale that is overlain by fossiliferous limestone. This limestone, the Amazonia Limestone Member of the Lawrence Shale, consists of 5 to 18 inches of yellowish-gray to light brownish-gray, medium-grained, sparsely fossiliferous, sandy, slightly micaceous limestone or very light gray to very pale yellowish-brown, very fossiliferous limestone. The sand grains in the sandy limestone are mostly moderately well sorted, subangular, nearly equant fine-grained quartz. Fossils in the Amazonia include crinoid stems and calyx parts; encrusting, ramose, and fenestrate bryozoans; productid and echinoid spines; small horn corals; brachiopods (*Juresania, Derbyia,* and *Chonetes*); pelecypods (*Aviculopecten*); and many unidentified shell fragments. The Amazonia is overlain by about 6 feet of dark reddish-brown and moderate olive-gray slightly silty unfossiliferous claystone from which many small ironstone concretions weather. Above the concretionary claystone is a 4-foot dark reddish-brown claystone that has large irregular areas of pale-olive claystone throughout. Reddish-brown and nearly white calcareous nodules ⅛ inch to 6 inches in length, as well as small euhedral gypsum crystals, weather from this unit. The next overlying 8 feet of claystone is mottled light gray and moderate reddish orange and also is unfossiliferous. Immediately above the unfossiliferous reddish-orange claystone is a dusky-blue claystone about 12 inches thick. Although no root systems were found in place, the claystone is unbedded, has a marked plasticity, and probably represents the deeply weathered material of an underclay. The underclay? is overlain by 2 to 4 inches of coal that generally contains argillaceous layers at the middle and near the top. About one-third of the coal bed is vitrain and fusain, about one-third is attrital coal, and about one-third is argillaceous (bony) coal.

The middle and upper parts of the Tonganoxie Sandstone Member of the Stranger Formation consist of a sequence of alternating thin beds of ripple-marked micaceous siltstone and silty claystone. This sequence is missing in the southern part of the county and apparently is replaced by massive sandstone. Farther north in Kansas several coal beds occur in the upper part of the Tonganoxie (Moore, 1936, p. 149). None is present in Wilson County, however.

The middle part of the Cottage Grove Sandstone Member of the Chanute Shale consists of about 15 feet of very light gray, platy, carbonaceous siltstone in which the bedding locally dips northwest at about 10 degrees (Fig. 5). Many well-preserved fern leaves occur amid abundant small carbonized plant fragments on the finely micaceous bedding planes. The ripple-marked bedding surfaces and cross-bedding at a few localities suggest currents moving from south to north. Three sequences of coal beds occur in the Chanute Shale, one at the top of the platy carbonaceous siltstone and two below. Each coal sequence is of small areal extent and consists generally of two or three thin coals separated by three or more inches of carbonaceous claystone.

Environment

In late Ireland time the sea seems to have moved across Wilson County leaving in its wake a shoreline to shallow-water blanket sand that completely filled any remaining channels and overtopped the intervening areas. Brachiopods, gastropods, and pelecypods presumably grew in the nearshore marine water while offshore, beyond the influence of strong wave and current action, clay and silt apparently formed the base for growth of a crinoid community. A few crinoidal remains were carried shoreward during times of storms. Local reduction in wave action, current movement, or size of material furnished by streams resulted in the nearshore deposition in many places of relatively thick layers of clay and silt interbedded with and overlain by sand. In early late Lawrence time the preponderance of clay and silt furnished to the sea created conditions inhospitable to marine plant and animal life in much of the area. A layer of barren silty clay many feet thick accumulated over most of Wilson County. In shallow water where temperature, salinity, and other factors were satisfactory, however, faunas rich in bryozoans, echinoids, solitary corals, brachiopods and pelecypods thrived locally and their remains were concentrated by wave and current action into thin, discontinuous coquinoidal limestone deposits. A very few organic remains were carried into carbonate-rich habitats lacking in nutrients, along with grains of fine quartz sand, and were enclosed in an iron-rich calcareous precipitate. As the sediments compacted, water highly charged with soluble iron moved through the silty clays along slightly more permeable zones, and the iron precipitated into beds and lenses of ironstone concretions.

Presumably the advance of the sea halted, and deeply weathered reddish silt and clay from the adjacent land area were spread subaerially across the broad coastal belt as the marine water withdrew from the county. Possibly some of the silt and clay that was then exposed upon poorly drained flats bordering the sea was subjected to considerable weathering and also developed a reddish color due to oxidation of the iron. Within the tidal zone in some places organic matter enclosed in the sediments presumably produced a reducing environment and small areas of greenish-colored muds formed. Water charged with calcium, sulfate, and carbonate ions provided materials that precipitated into crystals of gypsum and irregular nodules of limestone.

The deeply weathered land surface underlain by these extremely fine-grained materials probably continued to be a nearly level plain on which grassy and reedy plants grew in profusion. Intermittently, streams overflowed their banks and flooded large shallow depressions on the flood-plain surface. At times the streams carried large quantities of small branches and twigs of trees and much finely broken plant material into the low areas, where they settled into and covered thin accumulations of peaty matter derived from the indigenous vegetation. At other times clay and silt formed the chief constituents carried by the flooding streams. The clay and silt later became bony layers in coal, bark or small branches and twigs formed vitrain layers, and the finely broken plant material resulted in attrital coal. The fusain fragments possibly reflect oxidation in air prior to permanent submersion.

During late Tonganoxie time micaceous sand and silt accumulated on the shallow sea bottom adjacent to a low-lying land area, and gentle wave and current action time after time produced ripple-marked surfaces that were covered by thin accumulations of silty clay. Laterally, near the mouths of rivers, sand alone accumulated into thick deposits concurrently.

FIGURE 5.—Platy siltstone beds in upper part of Cottage Grove Sandstone Member of Chanute Shale. Dunbar strip pit about 6 miles southeast of Altoona, Wilson County.

During middle Cottage Grove time, predominantly silt-size material was carried by sluggish streams to form broad deltas along a quiet shallow sea. The silt was spread laterally and formed into even-surfaced layers upon whose upper surfaces accumulated the finely broken remains of ferns and other plants that grew in profusion on the subaerial part of the delta and the adjacent coastal plain. During Cottage Grove time peat-filled swamps formed several times in local basins of small areal extent and relatively short duration. Each period of plant-debris accumulation was interrupted by an influx of clay from the adjacent land, possibly resulting from increased rainfall, from breaching of the basin border, or from both.

C, Argillaceous Transgressive-Regressive Marine Stage

Deposition during the argillaceous transgressive-regressive stage is represented by fossiliferous argillaceous and calcareous sedimentary rocks in the upper parts of the Lane-Bonner Springs and Vilas Shales, Westphalia Limestone Member of the Stranger Formation, uppermost part of the Lawrence Shale, and Toronto Limestone Member of the Oread Limestone. This marine sequence is exemplified by the Westphalia Limestone Member of the Stranger Formation (Fig. 3, megacyclothem 5).

Physical Characteristics

The lower 1 to 2 feet of the Westphalia Limestone Member of the Stranger Formation consists of pale yellowish-brown fossiliferous limestone that contains an appreciable amount of iron-rich detrital material in the calcareous matrix. Impurities of clay size are most common in outcrops in the northern part of the county; silt- and sand-size impurities are most abundant in outcrops in the southern part of the county. In a few localities the clay and sand constituents are predominant, and the rock is an algal mudstone or sandstone.

Both small and large bean-shaped algae (*Osagia?*) are very abundant in the lower part of the Westphalia. The multiple-layered coatings that compose the algae consist of about 2 to 20 thin irregularly crenulated layers of calcium carbonate around shell fragments, oolites, small fossils, and elongate iron-oxide cores. Angular silt-size grains of quartz are abundant throughout the limestone matrix and within the algal growths and the outer chambers of fusulinids. Insoluble residues of samples contain numerous sand-agglutinated foraminifers including *Tolypammina*, *Ammovertella*, and *Hyperammina* amid limonite-cemented siltstone fragments, pitted grains of clear and cloudy quartz, and flakes of muscovite. Fossil fragments of echinoid spines and plates, ramose and fenestrate bryozoans, crinoid columnals, fusulinids, gastropods, pelecypods, and brachiopods locally form a large percentage of the lower part of the Westphalia. Identifiable forms include the brachiopods *Composita*, *Crurithyris*, *Hustedia*, *Neospirifer*, *Punctospirifer*, and *Juresania;* the pelecypods *Astartella*, *Aviculopecten*, and *Nuculana;* and the gastropods *Bellerophon* and *Worthenia*.

Six inches to 1 foot of limestone rubble, which consists of fragments of limestone covered with a white porous coating, locally separates the upper 2 to 3 feet of the Westphalia from the lower part. The upper part of the Westphalia is more widely distributed than the lower part and consists of moderate yellowish-brown impure fossiliferous limestone. Small *Osagia* and sparsely interspersed slender fusulinids (*Triticites*) show in relief on the moderate yellowish-orange weathered surface. The algal layers have formed around centers of echinoid spines and plates, ramose bryozoans, small shells and shell fragments, and quartz grains. Insoluble residues contain the foraminifers *Ammodiscus*, *Ammovertella*, *Glomospira*, and *Tolypammina*, as well as quartz grains and a few mica flakes. This stage extended into earliest Vinland time as indicated by the fusulinid-algal-brachiopod fauna in the lowermost foot of the Vinland Shale. Small gastropods, echinoid spines, bryozoans, and ostracodes are present also.

Correlative strata in the overlying megacyclothem (No. 6) locally contain a somewhat higher percentage of clayey material in the lower part of the sequence. The uppermost part of the Lawrence Shale consists of about 2 to 3 feet of medium light-gray to light olive-gray, very calcareous, fossiliferous, nodular claystone. The lower 18 inches is only sparingly fossiliferous, but concentrations of pelecypods occur locally. In the overlying part of the unit are found the identifiable remains of the brachiopods *Chonetes* and *Dictyoclostus*, fragments of other brachiopods, ramose bryozoans, crinoids, corals, and echinoids. Fusulinids, together with a few foraminifers of the genus *Tetrataxis*, are extremely abundant in the uppermost part where the claystone grades upward into the Toronto Limestone Member of the Oread Limestone. The Toronto, in the lower part, is principally a fine- to medium-grained yellowish-gray argillaceous very fossiliferous limestone that weathers to wavy-bedded outcrop faces. Fossils occur throughout, but the fossil content varies in type and abundance both horizontally and vertically. This part of the Toronto is probably the lateral equivalent of the uppermost 3 feet of the Lawrence Shale, but exposures are too incomplete in the intervening area to provide proof of the equivalence. The fauna of the lower part of the Toronto contains pelecypods such as *Myalina* (*Orthomyalina*), *Aviculopecten*, and *Aviculopinna;* brachiopods such as *Chonetes*, *Composita*, *Crurithyris*, *Derbyia*, *Dictyoclostus*, *Hustedia*, *Juresania*, *Meekella*, *Neospirifer*, *Punctospirifer*, and *Rhipidomella?;* ostracodes such as *Amphissites*, *Bairdia*, and *Hollinella;* a lophophyllidid coral and the coral *Syringopora:* high- and low-spired gastropods; fenestrate, ramose, and encrusting bryozoans; the ubiquitous crinoid stems; and abundant fusulinids. In the uppermost part the Toronto has a brecciated appearance produced by angular fragments of dark yellowish-orange argillaceous limestone in a groundmass of very pale orange limestone. *Cryptozoon*like algae surround crinoid columnals, horn corals, and fossil fragments.

In the rocks of megacyclothem 4, near the top of the Vilas Shale, a series of limestone beds that are intercalated in gray shale possibly represent stage C. The lower limestone beds and underlying and overlying shale contain an assemblage of pelecypods, gastropods, brachiopods, algae, corals, crinoids, and scattered fusulinids. The upper limestone beds have a brecciated appearance due to grayish-orange limestone fragments surrounded by irregularly shaped seams of olive-gray calcite 1/25-inch thick.

Five to 10 feet below the top of the Lane-Bonner Springs Shale in Wilson County is a thin fossiliferous limestone bed that may represent an incomplete development of stage C in megacyclothem 3. The limestone bed and the overlying shale contain abundant crinoid stems and brachiopod fragments. These strata may, however, be representatives of other stages, for, farther north in Kansas, the Lane and Bonner Springs Shales and the intervening Wyandotte Limestone apparently contain most of the elements of an entire megacyclothem (Moore, 1949, p. 78).

Environment

In early Westphalia time abundant sand, silt, and clay apparently entered the Wilson County area from a low-lying land area to the south as the sea transgressed and the water deepened. Much soluble iron was included in this terrigenous material as it accumulated in the carbonate-rich shallow sea. Pelecypods, gastropods, brachiopods, and other shallow-water forms flourished and were buried near the shore in the sandy lime mud in the southern part of the county area. Somewhat farther north the debris from an algal-fusulinid community formed a thin deposit on the near-level sea floor. Such a community suggests that the water deepened rapidly but was very clear and high in the nutrients needed to support such a population. Presumably, as the water shallowed, the progeny of the fusulinid population retreated seaward. Bean-shaped algae, however, continued to flourish in the warm, hypersaline water of late Westphalia time, and their remains accumulated to form a thin, widespread, calcareous stratum.

In late Lawrence time streams or marine water seem to have supplied clay-size material to the shallow sea bottom. Mollusks, brachiopods, and other life presumably grew abundantly in a slightly calcareous muddy habitat. As the sea rapidly deepened, a fusulinid community rapidly populated the area of Wilson County, and their remains accumulated abundantly on the sea floor during latest Lawrence and early Toronto time. In late Toronto time, the water shallowed and *Cryptozoon* algae became a part of the life-community. At times the calcareous mud containing the remains of these algae, as well as crinoids, solitary corals, and other animals, was sufficiently compacted, desiccated by exposure above sea level, or cemented to permit it to break into discrete fragments when subjected to the extreme action of storm waves. The fragments were almost immediately redeposited in lime mud of slightly different character so that the fragment boundaries are well displayed in the resulting rock. Similar conditions apparently prevailed in late Vilas time. A partial oscillation of sea level may have occurred in Wilson County during Lane-Bonner Springs time, but the evidence is inconclusive.

D, Continental Margin Stage

Strata deposited at the continental margin are included in parts of the Vilas Shale, Vinland Shale Member of the Stranger Formation, and Snyderville Shale Member of the Oread Limestone. The Snyderville best typifies deposits of the continental margin stage.

Physical Characteristics

The lower two-thirds of the Snyderville consists predominantly of dark reddish-brown claystone in the lower 10 feet and pale greenish-gray silty claystone in the upper 25 feet. However, large irregular greenish-gray areas occur in the lower part, and discontinuous lenses and irregular dark reddish-brown areas occur in the upper part. Two, locally three, lenticular sandstone beds occur 10 to 15 feet above the base of the Snyderville. The beds are yellowish gray, commonly finely micaceous and calcareous, 6 to 10 inches thick, and are composed mainly of well-sorted, very fine grained quartz. Ripple marks and worm tracks? are locally common, and plant fragments were noted at one locality. About 35 and 45 feet above the base are other silty sandstone beds that are pale greenish gray to yellowish gray and very fine grained. The lower bed is locally 5 to 7 feet thick and is composed of well-sorted, very fine grained to silt size subangular quartz grains that are cemented with calcium carbonate in a few places. The upper bed is about 1 foot thick; its upper surface has markings that resemble mud cracks. Except for the uppermost foot, the upper 16 feet of the Snyderville consists predominantly of dark reddish-brown slightly silty claystone with lenticular interbeds of pale greenish-gray silty claystone. Dark yellowish-orange ironstone concretions, ½ to ¾ inch in diameter, are common in some exposures. Irregular-shaped calcareous nodules, which are usually stained reddish brown on their outer surfaces and are brown, red, green, or white within, weather out of the reddish-brown claystone in local abundance. The uppermost foot consists of light olive-gray calcareous shale that contains a nearshore marine fauna consisting of pelecypods (*Astartella*), ostracodes (*Amphissites, Bairdia, Cavellina*, and *Hollinella*), brachiopods (*Chonetes* and *Dictyoclostus*), foraminifers (*Tetrataxis* and *Triticites*), algae (*Osagia*), gastropods, echinoid spines, crinoid columnals and plates, ramose bryozoan fragments, and unidentified conodont remains (Wagner and Harris, 1953).

The lower 2 to 14 feet of the Vinland Shale Member of the Stranger Formation consists predominantly of light olive-gray to yellowish-gray very slightly silty claystone. This part of the Vinland is unfossiliferous except for a few plant remains on bedding surfaces. The uppermost foot, however, is moderately calcareous and contains many large pelecypods of the genus *Myalina* (*Orthomyalina*) in conjunction with *Chonetes* and fragments of other small brachiopods, ramose bryozoans, corals, echinoid spines, crinoid columnals, and ostracodes.

The uppermost 3 feet of the Vilas Shale is light grayish-orange fossiliferous calcareous shale containing crinoid columnals and sparse low-spired gastropods amid fragments of brachiopods, pelecypods and bryozoans. At the base of this uppermost 3 feet is a 6- to 12-inch medium-gray nodular algal (*Osagia?*) oolitic limestone bed. No distinct representative of the continental margin stage was recognized in the megacyclothemic sequences that include the Lane-Bonner Springs Shale and the Chanute Shale.

Environment

As the sea shallowed and receded from Wilson County during early Snyderville time, deeply oxidized material derived from the erosion of weathered rocks of the low-lying coastal-plain is thought to have accumulated as reddish silty clay upon the newly exposed land surface. Concentrations of plant remains brought about reducing conditions in small areas and the clay there became pale greenish-gray. Modification of the weather, possibly in the form of much greater rainfall, resulted in the spreading of relatively thin deposits of silt and very fine sand over the nearly level land surface, thus preserving the clay from further oxidation or reduction. Resumption of distribution of oxidized silty argillaceous material throughout Wilson County resulted in the accumulation of additional quantities of reddish clay. Again, where organic matter was concentrated, the reddish oxidized clay was reduced to a greenish color, and during short periods of excessive precipitation, layers of sand and silt were spread over the land. At times connate water saturated with calcium carbonate moved laterally through the more permeable beds, and the carbonate was precipitated in the form of calcareous nodules. Similarly, much soluble iron, which was subsequently deposited as oval-shaped ironstone concretions, may have been transported. Silty sandstone beds were cemented locally with calcite where percolating saline waters deposited their calcium carbonate between the quartz grains. Snyderville time closed with the Wilson County area again under water that prevented further oxidation or reduction of the iron in the clays and provided a habitat amenable to such shallow-water marine animals as the pelecypod *Astartella* and the brachiopods *Chonetes* and *Dictyoclostus*, as well as gastropods, echinoids, crinoids, and bryozoans.

During most of Vinland time the Wilson County area was possibly a coastal plain or tidal flat receiving fine silt and clay from streams draining the adjacent low-lying land area. Plant remains were brought into the area intermittently and in small quantity. Vinland time closed with the beginning of a general transgression of the sea and the establishment of a fauna consisting of large pelecypods, small brachiopods, solitary corals, echinoids, bryozoans, and ostracodes.

Land conditions apparently never prevailed during stage D in Vilas time. The sea was very shallow, however, and in latest Vilas time nearshore warm, continually agitated, relatively clear marine water made possible the growth and accumulation of abundant small oolites and *Osagia?* algae. Presumably the water deepened to such an extent that the sea floor was below the realm of wave or strong current action. A thick layer of clay then covered the accumulated oolites and algae, and the stage was set for the introduction of a fauna composed of pelecypods, brachiopods, crinoids, and bryozoans.

E. Rapid-Oscillation Marine Stage

Five nearly identical limestone beds compose the representatives of the rapid-oscillation marine stage: the Paola Limestone Member of the Iola Limestone, Merriam Limestone Member of the Plattsburg Limestone, Captain Creek Limestone Member of the Stanton Limestone, Haskell Limestone Member of the Stranger Formation, and Leavenworth Limestone Member of the Oread Limestone. The Leavenworth exemplifies deposition during the stage.

Physical Characteristics

The basal 1½ inches of the Leavenworth Limestone Member of the Oread Limestone consists of a fossiliferous granulite layer in which unbroken shells of brachiopods and large pelecypods are enclosed in a light brownish-gray matrix of subangular to rounded granules of limestone. *Myalina* (*Orthomyalina*) and *Juresania* are abundant in the matrix and are generally oriented concave side down. The remainder of the Leavenworth is medium dark-gray vertically jointed very finely crystalline fossiliferous limestone 1.2 to 1.6 feet thick (Fig. 6A). Fossil remains etch out in relief on the upper pale yellowish-brown weathered surface, and in many exposures the most distinctive feature of this surface is the presence of numerous dark oval-shaped algal bodies that range in length from ½ to 1½ inches and in width from ⅜ inch to ⅝ inch. The algae consist of irregular concentric layers around brachiopod shell fragments, crinoid columnals, horn corals, and other shell fragments. Other fossils include echinoid spines and plates, gastropods, and brachiopods represented by the genera *Marginifera*, *Derbyia*, *Composita*, *Juresania*, and *Linoproductus*. Unbroken shells of small fusulinids (*Triticites*) are locally common in the middle and upper parts of the Leavenworth. Oolites, 1/50 to 1/10 inch in diameter, are also locally abundant near the top.

The thin vertically jointed Haskell Limestone Member of the Stranger Formation is a dense, crystalline limestone (Fig. 6B) that contains oolites, pelecypods such as *Myalina* (*Orthomyalina*), and fragments of brachiopods, fenestrate bryozoans, and crinoids in the lower part. In the upper part it is sparsely oolitic, dense, and crystalline and contains *Cryptozoon?* algae, brachiopod and other shell fragments, and long slender fusulinids. In the uppermost part is a veinlet-studded, brecciated-appearing, somewhat fossiliferous limestone. The entire Haskell is a single limestone bed that averages about 2 feet in thickness.

The Captain Creek Limestone Member of the Stanton Limestone consists of yellowish-gray finely crystalline algal (*Osagia*) and oolitic vertically jointed limestone in the lower 2 to 5 feet. Large nautiloid cephalopods are locally abundant. The remaining 5 to 10 feet of the Captain Creek is chiefly medium-gray, massive to thick-bedded cavernous limestone that weathers almost white, is deeply pitted with holes ½ inch to 2 inches in diameter (Fig 7), and contains the locally abundant remains of crinoids, fenestrate bryozoans, brachiopods, corals, and fusulinids. At or near the top, the Captain Creek locally has an 8-inch zone of thin-bedded, somewhat argillaceous, red-blotched limestone that contains large pelecypods.

Both the Merriam Limestone Member of the Plattsburg Limestone and the Paola Limestone Member of the Iola Limestone contain shallow-water faunas in their upper and lower parts and are single beds about 1 foot thick. The Merriam, however, is very argillaceous limestone throughout and lacks fusulinids, which are found near the middle of the Paola.

Environment

In early Leavenworth time granules and oolites of calcium carbonate presumably were oscillated back and forth in relatively clear, shallow, carbonate-rich water inhabited by large pelecypods and nearshore-dwelling brachiopods. Very shallow water, and wave or current action sufficient to move the gran-

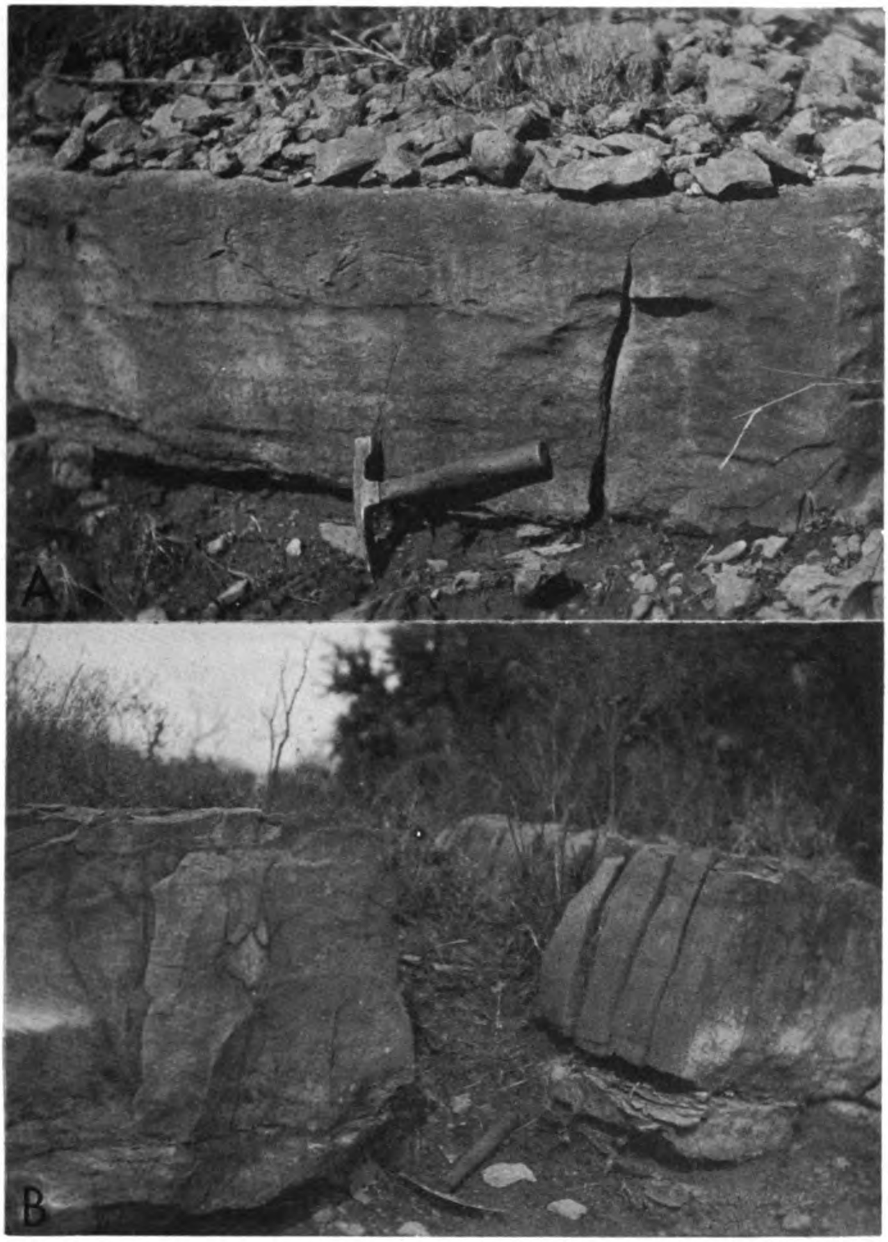

FIGURE 6.—*A*, Leavenworth Limestone Member of Oread Limestone about 9 miles west of Fredonia, Wilson County. *B*, Haskell Limestone Member of Stranger Formation about 14 miles north of Fredonia, Wilson County.

ules were operative only long enough for a few inches of granulite to accumulate in the Wilson County area. Somewhat deeper water and more stable bottom conditions may have led to the introduction of a fauna containing brachiopods, gastropods, echinoids, crinoids, and solitary corals. Physicochemical conditions being optimum, the relatively shallow, clear water may have been warmed sufficiently to produce a gel-like calcareous precipitate on the sea floor. In such a precipitate collected the scattered remains of the indigenous animal and plant life throughout most of Leavenworth time. Calcareous algae, which formed multi-

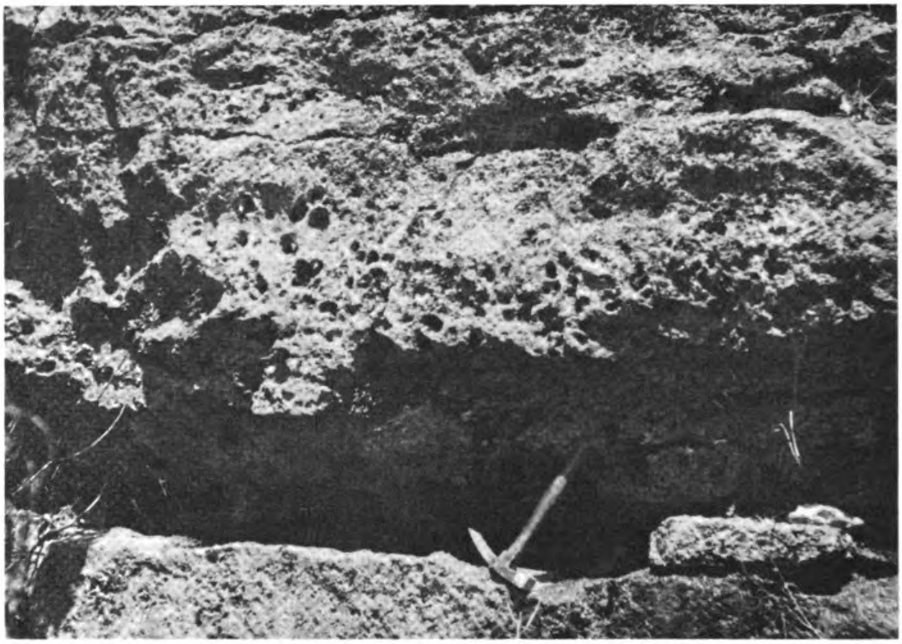

FIGURE 7.—Weathered outcrop of Captain Creek Limestone Member of Stanton Limestone about 4 miles southeast of Fredonia, Wilson County.

ple-layered coatings around broken fragments of the remains of crinoids and other animals, as well as small fusulinids that had apparently formed local colonies on the sea floor for a short period of time when the water was deepest, were among the remains of the different life-types that were enclosed in the cryptocrystalline calcareous precipitate. Leavenworth time closed as conditions necessary for this limestone deposition became inoperative.

Haskell time also opened with a shallow-water marine environment well suited to oolitic development and growth of large nearshore-dwelling pelecypods. Bryozoans, brachiopods, and crinoids soon became the dominant faunal elements, oolitic growth virtually halted, and a precipitate similar to that postulated for Leavenworth time formed. Fusulinids became locally abundant in the fauna in late Haskell time just prior to a general shallowing of the sea. Algae (*Cryptozoon*) became the most abundant life form, and conditions that led to the brecciation and redeposition of semilithified lime mud continued for a short time until Haskell deposition ended.

Captain Creek time also was a period during which the sea deepened and shallowed in a relatively short period of geologic time but probably over a somewhat longer time span and under more complex environmental conditions than operated during Leavenworth, Haskell, Merriam, or Paola times. The general deepening of the sea apparently started in late Vilas time, the water was highly charged with carbonate, was well lighted, and profuse small algae (*Osagia*) and oolites formed thin calcareous sediments. The algal-oolitic environment persisted, and in early Captain Creek time the unbroken shells of large nautiloid cephalopods were enclosed in a matrix of small oolites and *Osagia*. Laterally, in local depressions?, highly charged carbonate-rich waters formed thick flocculating masses of calcium carbonate into which the remains of brachiopods, crinoids, bryozoans, corals, and fusulinids were carried and settled. Large pelecypods that apparently lived in a nearshore environment formed the major part of the fauna in the shallow water of late Captain Creek time.

Throughout Merriam time the sea water apparently contained a high content of argillaceous material in suspension and iron in solution, and it is doubtful that the water ever attained much depth. Crinoids, sponges, brachiopods, horn corals, bryozoans, echinoids, and small and large algae either lived in the somewhat muddy water or were brought in from the clearer water of adjacent areas. The physical aspects of the sea water were, however, very similar to those that operated during the fossiliferous calcareous deposition in stage E of megacycles 2, 4, 5, and 6, and a calcareous precipitate enclosed the remains of the Merriam life-community. A marine environment well suited to invertebrate life existed in early Paola time, and bryozoans, corals, crinoids, and brachiopods grew in profusion. The water presumably deepened throughout the Wilson County area and fusulinids abounded in conjunction with a few algae. In the east-central part of the county the water remained fairly deep until near the end of Paola time, and fusulinids continued to dominate the sea bottom; but in the southern part of the county algal life alone flourished in the hypersaline shallowing water of latest Paola time and furnished abundant remains to the upper part of the dense, gel-like mass of calcium carbonate that presumably blanketed the sea floor.

F, Stagnant-Water Marine Stage

Strata deposited under conditions of the stagnant-water marine stage (except for the Hickory Creek Shale Member of the Plattsburg Limestone) show the least lithologic variation of any rock type in the megacyclothem. Parts of the Heebner Shale Member of the Oread Limestone, Muncie Creek Shale Member of the Iola Limestone, Eudora Shale Member of the Stanton Limestone, and Robbins Shale Member of the Stranger Formation are typical of this stage.

Physical Characteristics

The lower 2 to 3 feet of the Heebner Shale Member of the Oread Limestone consists of nearly black fossiliferous conodont-bearing shale that breaks upon weathering into paper-thin laminae as much as 3 inches across. Finely comminuted plant remains are abundant on bedding planes in a few places. Small (1 to 2 inch) phosphatic concretions are found locally in the central part; the P_2O_5 content of the concretions is 32 percent (Runnels and others, 1953, p. 98). Conodonts identified by L. D. Harris (Wagner and Harris, 1953) from the Heebner in Wilson County and the immediately adjacent area include *Cavusgnathus, Hindeodella, Ideognathodus, Lonchodus, Ozarkodina, Streptognathodus,* and *Trichognathus.* Other microfossils identified are the foraminifers *Ammodiscus, Cornuspira,* and *Tetrataxis,* and the ostracodes *Bairdia* and *Cavellina.* Unidentified small fragments of bryozoans, brachiopods, and crinoids are present also.

The black shale part of the Muncie Creek Shale Member of the Iola Limestone is almost identical in character to the Heebner. It is 1¼ to 2½ feet thick, is very fissile, breaks to paper-thin laminae, and contains abundant flattish, oval-shaped phosphatic concretions in the central part. The Eudora Shale Member of the Stanton Limestone locally contains 1 to 3 feet of almost black very fissile platy shale near the center. The black shale breaks to paper-thin laminae on whose surfaces flattened orbiculoid brachiopods are locally abundant. The lower few inches of the Robbins Shale Member of the Stranger Formation is dark gray and fissile and contains small phosphatic nodules in a few localities. The Hickory Creek Shale Member of the Plattsburg Limestone is yellowish-gray very fossiliferous calcareous shale in Wilson County; but farther north in Kansas the Hickory Creek has a thin carbonaceous platy shale in its lower part (Newell, 1933, p. 47).

Environment

The stagnant-water marine stage is thought to have been a time of poorly circulating, oxygen-poor sea water. Tidal or current movement was at a minimum, and the sea floor was a vast planar surface formed on the top of a thin layer of calcareous precipitate. Generally, little or no land-derived debris reached Wilson County. Seaweed, possibly the dominant life form, essentially filled the uppermost part of the shallow sea and probably had a dampening effect on wind-derived wave action. Abundant ostracodes and conodonts inhabited the water amid the seaweed, and small orbiculoid brachiopods were probably attached to the seaweed and drifted to the sea floor along with the seaweed remains. there to rest in a humus-filled anaerobic environment. Phosphate accumulated as a result of bacterial decomposition of this organic debris, to be concentrated into concretions either concurrently or later during diagenesis. The small broken remains of crinoids, bryozoans, and other invertebrate life were occasionally swept into the area by unusually strong currents.

G. Normal Transgressive-Regressive Marine Stage

Deposits formed during the normal transgressive-regressive marine stage include the Winterset Limestone Member of the Dennis Limestone, Raytown Limestone Member of the Iola Limestone, Spring Hill Limestone Member of the Plattsburg Limestone, Stoner Limestone Member of the Stanton Limestone, very fossiliferous beds in the Robbins Shale Member of the Stranger Formation, Plattsmouth Limestone Member of the Oread Limestone, and parts of subjacent shale members as well. The upper part of the Eudora Shale Member and Stoner Limestone Member of the Stanton Limestone are typical of this depositional sequence.

Physical Characteristics

The upper 3 feet of the Eudora Shale Member of the Stanton Limestone consists of light greenish-gray calcareous shale that grades laterally into clayey limestone. Fossils include crinoid columnals, horn corals, encrusting bryozoans, echinoid spines, and brachiopod and mollusk fragments. The lower part of the Stoner Limestone Member, next above and as much as 15 feet in thickness, consists principally of blotchy-appearing medium-gray and yellowish-gray thin-bedded, wavy-bedded, and locally cross-bedded fossiliferous limestone. In many places thin beds within the Stoner are medium to coarsely crystalline coquinoid limestone made up entirely of crinoid columnals and plates (Fig. 8), echinoid plates, fenestrate bryozoans, or pelecypod and brachiopod fragments. Identifiable fossils include such genera as *Meekoporella*, *Composita*, *Juresania*, *Neospirifer*, *Schizophoria*, and *Syringopora*. In many places, relatively unfossiliferous very finely crystalline limestone predominates, and much of the Stoner is a brecciated-appearing rock consisting of angular areas of light brownish gray in a matrix of yellowish-gray limestone. Fusulinids occur locally near the top of this part of the member, and sinuous bodies of coarsely crystalline calcite, which closely resemble in form the alga *Cryptozoon*, are abundant in some areas. Vugs and fractures filled with sparry calcite are also conspicuous at many places.

The upper part of the Stoner is light-gray irregularly bedded, sparsely oolitic, finely crystalline limestone 5 to 15 feet thick. It contains fusulinids only locally in the lower part. A fauna collected from this part of the Stoner by Newell (1933, p. 136) and others at the cement plant quarry at Fredonia contained abundant remains of brachiopods, pelecypods, gastropods, corals, and crinoids.

The Plattsmouth Limestone Member of the Oread Limestone has a distinct wavy-bedded character (Fig 9), contains brachiopods, pelecypods, gastropods, echinoid spines, and crinoid stems in the lower part, fusulinids in the upper part, and brecciated-appearing limestone in the uppermost part. The Spring Hill Limestone Member of the Plattsburg Limestone is irregularly bedded throughout and contains sponges (*Heliospongia* and *Girtyocoelia*), brachiopods (*Neospirifer, Derbyia, Marginifera, Crurithyris, Echinoconchus,* and *Composita*), solitary corals, bryozoans, and crinoids in the lower part, and *Cryptozoon* and bladelike? algae in conjunction with a few fossil fragments, oolites, and fusulinids in the brecciated-appearing crystalline middle part. The limestone of the Raytown is clayey, fossiliferous, locally algal, and oolitic. Oolites, algae (*Osagia*), brachiopods, pelecypods, and gastropods are abundant in the Winterset. During Robbins time there apparently was too much clayey contamination or insufficient calcium carbonate in the sea water to form thick limestone beds. The fauna in the shale of this part of the Robbins, however, contains pelecypods, gastropods, brachiopods, corals, etc., most of the elements found in the wavy-bedded limestones.

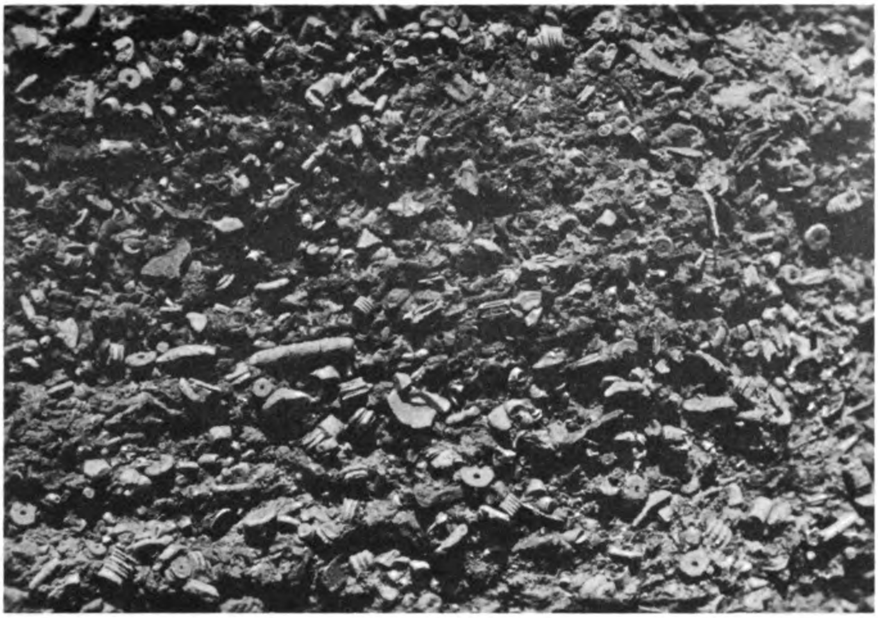

FIGURE 8.—Crinoidal coquina in Stoner Limestone Member of Stanton Limestone about 1 mile southwest of Fredonia, Wilson County.

Environment

The normal transgressive-regressive marine stage seems to have started in Eudora time with muddy carbonate-rich water covering the Wilson County area. Bottom-dwelling pelecypods as well as horn corals, bryozoans, echinoids, and brachiopods formed much of the fauna whose remains collected in the lime-rich mud that accumulated on the sea bottom. In early Stoner time the water deepened somewhat and became clearer, and some small depressions and possibly some reeflike areas well suited to one or a few particular types of invertebrate life developed. In certain small areas the remains of crinoids formed the only faunal element in the carbonate-charged lime mud; in other places the remains were entirely those of fenestrate bryozoans or of echinoids. Physicochemical conditions suitable to calcium carbonate precipitation presumably occurred during much of middle Stoner time and thin irregularly surfaced lenticular calcareous precipitates formed overlapping wedges upon the sea floor. Very thin concentrations of clay apparently were deposited on many of these surfaces, and after lithification and exposure to weathering, the wavy-bedded character becomes apparent. Deepening of the water was probably responsible for the entry of a locally abundant fusulinid fauna, but in late Stoner time the water shallowed and algal? growth predominated as the life form in presumably hypersaline waters. Small particles were oscillated and oolites grew in the relatively shallow water in or near the habitat of a fauna consisting of pelecypods, gastropods, brachiopods, corals, and crinoids. Violent storm waves at times reached the sea floor and disrupted the semilithified bottom sediments which then settled as fragments into the unconsolidated calcareous mud that was being deposited.

The events recorded in Plattsmouth and Spring Hill times were very similar to those of Stoner time. During Raytown and Winterset time, the sea presumably deepened and then shallowed, but without reaching the depth of fusulinid activity. Robbins time was apparently dominated by argillaceous debris from the land, but not to the exclusion of faunas whose habitats ranged from shallow to relatively deep water.

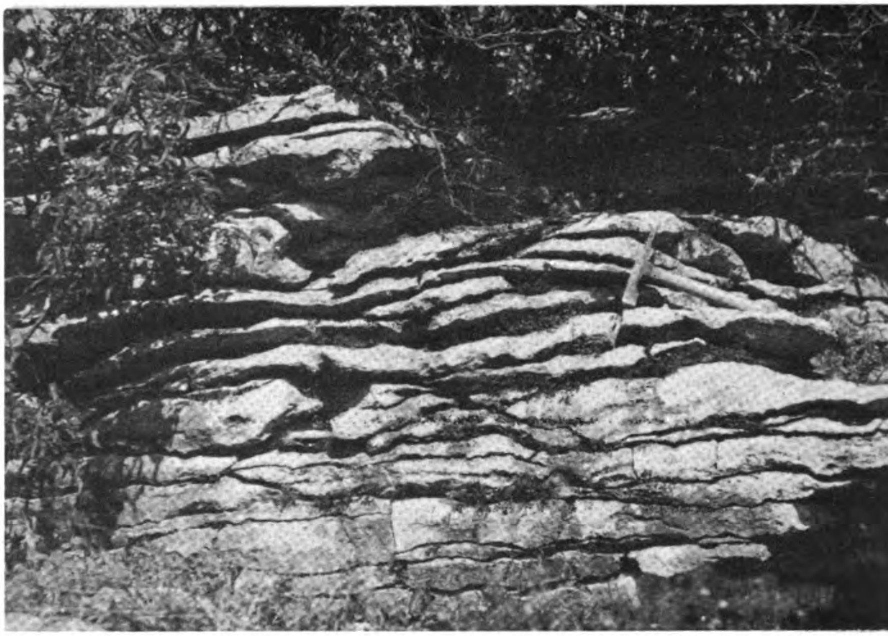

FIGURE 9.—Wavy-bedded limestone of Plattsmouth Limestone Member of Oread Limestone about 9 miles west of Fredonia, Wilson County.

H, NEARSHORE ARGILLACEOUS MARINE STAGE

Nearshore argillaceous marine deposition is represented by strata of the Cherryvale Shale, lower part of the Lane-Bonner Springs Shale, Rock Lake Shale Member of the Stanton Limestone, and middle part of the Robbins Shale Member of the Stranger Formation. The Cherryvale Shale (Fig. 3, megacyclothem 1) is considered typical.

Physical Characteristics

The Cherryvale Shale consists of as much as 40 feet of yellowish-gray to medium-gray finely micaceous, thin-bedded clayey siltstone and silty claystone. A light olive-gray hard unfossiliferous limestone bed, 9 inches thick, occurs about 14 feet above the base, and several 1/4 inch to 1/2 inch platy unfossiliferous limestone beds occur in the next overlying 2 feet. A few beds of small ironstone concretions occur below these limestone beds and also in the upper 5 feet. The lower 2 feet of the Cherryvale has current ripple marks locally.

The lower part of the Lane-Bonner Springs Shale consists of light olive-gray unfossiliferous silty claystone. Beds of unfossiliferous limestone concretions, 5 to 10 inches thick, are both underlain and overlain by claystone containing small moderately abundant ironstone concretions.

The Rock Lake Shale Member of the Stanton Limestone is poorly exposed in Wilson County but may represent this stage. It consists of locally calcareous claystone that is dark yellowish orange in the lower foot and very light olive gray in the upper foot. A marine fauna, consisting of several foraminifers and ostracodes as well as fragments of crinoids, bryozoans, echinoids, and brachiopods, was noted at a few localities.

The middle part of the Robbins Shale Member of the Stranger Formation consists of light olive-gray silty to sandy shale that characteristically contains abundant ironstone concretions. Two thin beds of moderate yellowish-brown very fine grained sandstone or sandy siltstone occur locally in this part of the Robbins.

Environment

In early Cherryvale time the Wilson County area was covered by a shallow sea whose water was presumably low in nutriments, was clouded by abundant clay and silt supplied by erosion of a nearby low-lying land area, and apparently was inhospitable to marine animal or plant life. Current action locally developed ripple marks on the surfaces of the silt and clay layers. Near the middle of Cherryvale time, the calcium carbonate content and other physical characteristics of the sea water were such that limy gels? collected on the bottoms of shallow depressions and precipitated as large discrete oval-shaped bodies or lenticular beds. Soluble iron became concentrated locally into ironstone concretions, possibly during diagenesis.

In Lane-Bonner Springs time almost identical conditions prevailed; but in middle Robbins time small amounts of sand-size detritus were distributed occasionally throughout the area and thin sandy beds accumulated upon the clayey mud. During Rock Lake time, physical and biological conditions remained locally suitable to marine life throughout this stage in the Wilson County area.

I, Nearshore Clear-Water Marine Stage

Sediments of the nearshore clear-water marine stage are found in the Drum Limestone, oolitic phase of the Spring Hill Limestone Member of the Plattsburg Limestone, South Bend Limestone Member of the Stanton Limestone, and limestone beds in the upper part of the Robbins Shale Member of the Stranger Formation.

Physical Characteristics

The lower 6 to 10 inches of the 18-inch Drum Limestone is composed of brownish-gray to medium-gray sparingly fossiliferous limestone. Broken crinoid stems are the dominant fossils and in conjunction with shell fragments of brachiopods, occur in a finely crystalline calcite matrix. The upper part is much more fossiliferous, generally is oolitic, and in the easternmost part of the county contains abundant *Osagia* and *Cryptozoon*-like algae. At a few localities the oolites, algae, and invertebrate fossil remains fill scour channels or large desiccation cracks that apparently formed in the lower part of the Drum prior to accumulation of the upper part. The oolites are much larger at the top of the bed than in the lower part and are concentrically banded; the outer rings in many are broken and stripped back or folded, possibly as a result of partial desiccation. The fauna of the upper part of the Drum consists of the brachiopods *Composita, Derbyia, Echinoconchus, Hustedia, Juresania, Marginifera, Neospirifer,* and *Punctospirifer;* horn corals and *Syringopora;* ramose, fenestrate, and encrusting bryozoans; crinoid stem segments and calyxes; small bellerophontid and high-spired gastropods; and *Myalina* (*Orthomyalina*) and small pelecypods.

The uppermost few feet of the Spring Hill Limestone Member of the Plattsburg Limestone consists principally of oolites and algae (*Osagia?*) that have diameters generally less than 1/8 inch but locally as much as 1/4 inch. The oolites are concentrated into pockets in a very finely crystalline limestone. In some of the oolites the concentric bands extend to the center of the oolite, but more commonly crinoid stem segments, shell fragments, or subangular microcrystalline limestone grains form the centers.

The South Bend Limestone Member of the Stanton Limestone is similar to the Drum and Spring Hill in being oolitic, but generally it is sandy, cross bedded, and contains a pelecypod-brachiopod fauna. It commonly contains brachiopods of the genera *Rhipidomella, Punctospirifer, Hustedia, Meekella, Derbyia, Streptorhynchus,* and *Dielasma;* and the pelecypods *Streblopteria?,* and *Aviculopecten* (Newell, 1933, Pl. 1, p. 140; 1937, p. 53). About 10 percent of the oolites have quartz grains at their centers. In a few areas, fusulinids were observed in the South Bend.

Three lenticular, locally developed limestone beds in the upper part of the Robbins Shale Member of the Stranger Formation consist primarily of the remains of *Osagia?* and crinoid stem segments, numerous large and small brachiopods, pelecypods, and gastropods. Small fusulinids were abundant in a thin bed in one exposure.

Environment

Early in Drum time the shallow clear sea that covered the Wilson County area apparently was not particularly suitable for marine life because of low nutriment content, excessive salinity or temperature, or some other important factor. Conditions for the precipitation of calcium carbonate, however, were apparently near optimum for a short period, and the remains of a scanty invertebrate fauna were enclosed in a viscous calcareous precipitate. In middle Drum time shallowing of the water may have brought this newly formed precipitate above low-tide level so that the upper surface became desiccated and was locally channeled by tidal-current action. Better conditions for marine life followed, as shown by the broken remains of brachiopods, corals, bryozoans, and crinoids that were carried into these desiccation cracks and tidal channels. There they were concentrated and, in conjunction with abundant oolites, were oscillated back and forth by small waves and shoreline or tidal currents. Continued oscillation and accretion during most of late Drum time led to the formation of a thin accumulation of oolites and fossil fragments throughout the Wilson County area. Occasional temporary exposure above low-tide level allowed many of the oolites to become partly desiccated and flattened. They were subsequently incorporated in the calcareous sediments of latest Drum time.

In latest Spring Hill time a shallow-water marine environment also prevailed in which small oolites and algae (*Osagia*) were being oscillated back and forth in carbonate-rich water by current or wave action. Time was sufficient for the oolites to form a thin, widely distributed calcareous deposit on the flat or gently undulating surface.

During South Bend time many fine-size quartz grains were carried into the shallow clear sea, were oscillated in water highly charged with calcium carbonate, and formed the nuclei of many oolites. Wave and wind action concentrated the oolites and grains of lime sand into locally cross-bedded deposits. A brachiopod-pelecypod fauna inhabited the marine water and nearshore lime mud, and their shells were added to the deposits formed during South Bend time. Fusulinids may have lived in a few scattered places in the Wilson County area, or their remains may have been brought into the area by current action.

During Robbins time, the calcareous remains of abundant marine plant and animal life formed a major part of several thin lenticular accumulations of lime mud on the shallow sea floor. Land-derived clay, however, was apparently the predominant material furnished to the sea and several times formed thick deposits upon which calcareous matter could accumulate.

J, Nearshore Regressive Marine Stage

The nearshore regressive marine stage brought to an end the marine phase of each megacycle; the sea then receded from the Wilson County area and erosion cut channels as deep as 60 feet into the newly deposited strata. Sediments laid down by nearshore regressive deposition occur in the lower part of the Chanute Shale, middle part of the Lane-Bonner Springs Shale, lower part of the Vilas Shale, much of the Weston Shale, and upper part of the Robbins Shale Member of the Stranger Formation. The Weston Shale will serve as the typical example.

Physical Characteristics

The Weston Shale is composed mainly of medium olive-gray claystone that is silty in the upper part, where it incorporates several beds of grayish-orange very fine grained micaceous thin-bedded sandstone. The sandstone beds are 1/8 inch to 6 inches thick and contain finely broken plant fragments. The claystone is vertically jointed and fissile and breaks readily into small rectangular fragments (Fig. 10). Ironstone concretions, one of which contained an unabraded marine gastropod, occur in lenticular beds and as separate oval bodies in the middle part of the Weston.

The upper 20 to 50 feet of the Robbins Shale Member of the Stranger Formation is light olive-gray silty to sandy shale that characteristically contains abundant dark yellowish-orange oval ironstone concretions. A thin sandstone bed or sandy concretionary bed is present locally.

The lower part of the Vilas Shale is light olive-gray slightly silty claystone that locally contains thin yellowish-gray siltstone beds in the south-central part of Wilson County.

The middle part of the Lane-Bonner Springs Shale consists of medium olive-gray slightly

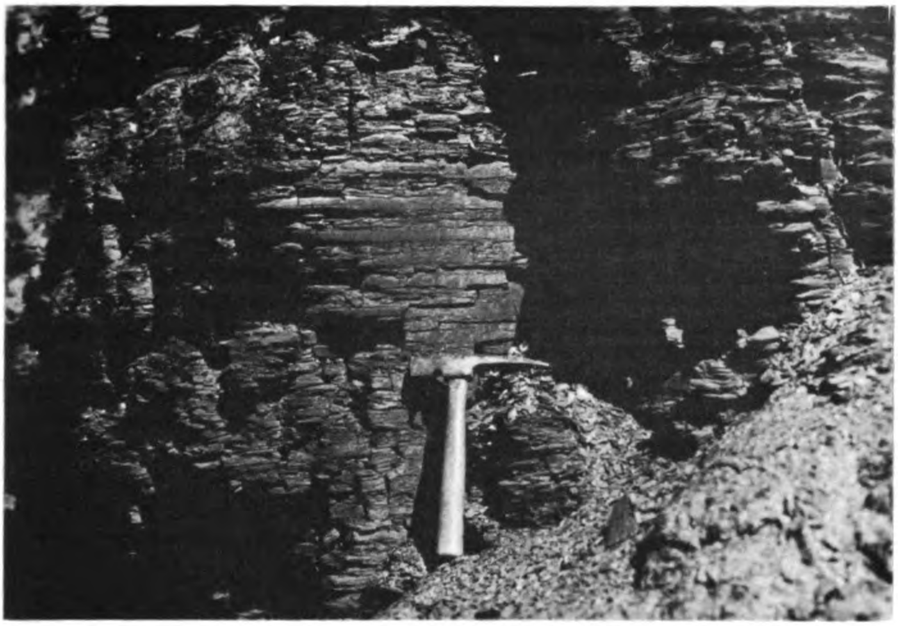

FIGURE 10.—Weston Shale in brick plant quarry at West Mound, Fredonia, Wilson County.

silty claystone that contains two thin (1-inch thick) finely micaceous siltstone layers with plant fragments. Small ironstone concretions generally occur abundantly above the siltstone beds.

The lower part of the Chanute Shale consists mainly of medium-gray unfossiliferous slightly silty claystone. Near the top of this part of the Chanute is a moderate yellowish-brown spongy unfossiliferous limestone bed that becomes soft and porous on weathering.

Environment

Most of Weston time was a period of quiet, shallow marine water unaffected by strong current action. Thin even beds of clay, without ripple marks or other sedimentary structures, were the main depositional result. Paucity of nutriment and freshening of the water due to greater rainfall may have contributed to the general disappearance of the previously abundant marine fauna. However, marine gastropods which later became the nuclei for concentration of iron carbonate? were present in the muddy environment. In late Weston time the land area furnishing terrigenous debris presumably rose slightly and furnished silt and fine sand to the receding sea. An abundant land flora contributed small carbonaceous fragments to the sand and silt brought in by the rivers.

Very similar conditions probably prevailed during early Chanute time but an accumulation of iron-rich calcareous mud interrupted the clay deposition for a short period. Water and sediment conditions during parts of Lane-Bonner Springs, Vilas, and Robbins time were apparently very similar to those of Weston time.

SUMMARY

The 13 formations of Pennsylvanian age that crop out in Wilson County may be grouped into 6 major repetitive cycles of sedimentation (megacycles) that seemingly reflect deposition in a sequence composed of 10 distinct stages. This megacyclic pattern is not perfect and all 10 stages are not represented in each of the 6 megacyclothems. Where complete, however, megacyclic deposition seems to have taken place under the conditions described below.

The megacycle began with stage A, in which fluviatile sand was deposited in deep erosional channels cut during the major period of erosion between each succeeding megacycle.

During stage B a blanket sand with a small nearshore marine faunal assemblage was deposited as the sea transgressed upon the land. Slight fluctuations in water depth and the amount of nutriments and land-derived sediments may have been the factors that led to the successive deposition of barren marine muds, sandy lime muds with crinoidal and other shallow-water remains, and silty marine clays. A slight regression presumably left the clays bared to weathering processes and oxidation for a short period during which an abundant land flora furnished materials to form a thin bed of peat.

Stage C began with a major transgression of the sea, and the peat was covered with gray silt and clay, abundantly supplied by streams from the adjacent land. The shallow nearshore water must have teemed with organisms whose remains formed a large part of the iron-rich clayey calcareous mud that accumulated on the sea floor. Apparently the water deepened very rapidly, and the remains of a shallow-water community that consisted of gastropods, pelecypods, algae, brachiopods, bryozoans, crinoids, and corals became mixed with the remains of a deeper water fusulinid fauna. Fusulinids became less abundant as the water shallowed and algae and nearshore invertebrates again were the predominant life forms.

In stage D shoreline marine and dry land conditions prevailed for a short period of time. Weathered, oxidized red clay and fine-grained quartz sand from the adjacent low-lying land area formed the dominant depositional material.

As stage E began, the sea is presumed to have rapidly transgressed upon the land and covered it with a thin calcareous precipitate. This precipitate contained faunal elements that indicate a change from shallow water in which heavy-shelled pelecypods lived amid continually accreting calcareous granules and oolites, to locally fusulinid-rich deeper water, and then to shallow clear water of greater than normal salinity inhabited by abundant calcareous algae.

Stage F seems to have recorded a rather drastic change in the marine environment. Calm shallow water, which is presumed to have been low in oxygen and certain nutriments, covered the Wilson County area. Water motion was presumably reduced to a minimum by an extremely dense seaweed growth, and stagnant organic-rich bottom conditions appear to have resulted. As the seaweed died and fell to the bottom, an anaerobic resting place developed for the conodonts and ostracodes that lived in the water.

As stage G began, the calm, poorly aerated water was again subjected to tidal and wave action and a normal transgressive-regressive cycle of the sea was initiated. A fauna composed mainly of mollusks, crinoids, brachiopods, bryozoans, and corals flourished at the beginning of the stage. At about the middle, this fauna was augmented and largely replaced by a profuse fusulinid fauna and sparse algal flora, and calcareous precipitates formed irregularly shaped deposits upon the sea floor. Small amounts of clay intermittently fell to the wavy-surfaced top of the lime mud. Shortly, the water became shallower, algae became abundant, and the fauna changed again to corals, bryozoans, brachiopods, crinoids, and mollusks.

Stage H was a time of silty nearshore conditions, which, possibly as a result of very high rainfall and consequent freshening of the nearshore water, formed an environment inhospitable to marine life. Barren deposits of iron-rich clay and, locally, very calcareous silt and precipitated calcium carbonate accumulated in the shallow water.

During stage I saline water presumably drained from the compacting marine clay, adding its salt to that of the sea water; the nutriment content of the sea seemingly became higher than normal; and plant and invertebrate animal life again flourished in the Wilson County area. Brachiopod shells and crinoids, broken by strong wave action, accumulated in deposits rich in calcareous algae and oolites that formed in the continually agitated shallow water.

In stage J the megacycle closed with slight uplift in the land area and influx into the sea of sand and silt as well as clay. The marine population slowly migrated seaward, generation after generation, as its chosen habitat moved; the water shallowed and disappeared; and subaerial erosion cut deeply into the newly deposited clay as land conditions prevailed for the next protracted period in the Wilson County area.

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Local and Regional Factors in Pennsylvanian Cyclic Sedimentation

ABSTRACT

Previous emphasis in the interpretation of Pennsylvanian cyclothems has been placed largely on the frequent repetition of rather complex successions of strata, with individual thin beds traceable over several states. Here it is noted that these uniform sequences may be interrupted at any stratigraphic position by clastic wedges thickening in the direction of their source. With these wedges local coals, underclays, or marine limestones may occur, giving the impression of the insertion of additional cyclothems into the succession.

Environmental maps of the Midwest area indicate that within a single widespread cyclothem, clastic wedges may reach the sedimentary basin from three or four different directions. Their stratigraphic positions and directions of source of sediment provide excellent clues to the time and place of contemporary tectonism. Widespread cyclothemic successions may become indistinguishable where traced away from sources of clastic wedges toward a marine environment where the marine limestones of several separate transgressions may merge into a single limestone. It is proposed that the megacyclothem of the northern Midcontinent is equivalent to a single cyclothem of the Illinois type, rather than a number of these as has been suggested.

INTRODUCTION

In the author's early studies of Pennsylvanian cyclic successions in western Illinois (Wanless, 1931a, 1931b) he was particularly impressed by the resemblances between successive sequences later called cyclothems (Wanless and Weller, 1932), the extraordinarily widespread distribution of many very thin members of the sequences, and the generally orderly succession of the cyclothems.

Later, when studies were extended into the southern and eastern borders of the Illinois Basin, the eastern Midcontinent, and the Appalachian Coal Field (Wanless, 1939, 1946, 1962), it became evident that: (1) the cyclic pattern varies greatly from place to place (Wanless, 1947) and from time to time at the same place, (2) in some regions there is a greater degree of variability and there are fewer thin widely persistent units, and (3) a certain stratigraphic interval is not everywhere represented by the same, or even the same number of cyclic successions throughout a large region.

This paper is written to present evidence of and to give interpretation for the variability in the number of cyclic successions in the Appalachian, Illinois, and Midcontinent Coal Basins. It is also concerned with the problem of classification in the cyclothemic framework of variable numbers of successions of a cyclic nature. The paper also deals with the relations between cyclothem sequences as developed in Illinois and the more complex megacyclothems of the northern Midcontinent.

Acknowledgments.—Many of the examples cited in the paper are derived from environmental mapping studies done under the author's direction of the Brereton cyclothem, by John B. Tubb, Jr., of the Liverpool cyclothem by Cynthia Roseman, of the Summum cyclothem by John Weiner, and of the Sparland cyclothem by Constantine Manos. Interpretations frequently arose from fruitful discussions with these persons. Aid in preparation of illustrations has been supplied by the Department of Geology, University of Illinois; David A. Waltrip drafted the illustrations.

The manuscript has been critically read by H. B. Willman, J. A. Simon, J. Baroffio, J. B. Tubb, Jr., Cynthia Roseman, and Julie Rystrom.

LOCAL CLASTIC WEDGES

During the past several years the author has engaged in a very fruitful attack on the mechanisms responsible for repetitive cyclic patterns of sedimentation through a series of student thesis projects involving bed-by-bed environmental (paleogeographical) mapping of middle Pennsylvanian sequences in the Illinois Basin and the eastern Midcontinent, especially Missouri and Iowa (Wanless, Tubb, Gednetz, and Weiner, 1963). These studies have demonstrated that although all lithologic units in the cyclic successions change facies within the studied area, several underclays, coals, black fissile shales, and marine limestones possess spectacular uniformity over hundreds of miles, whereas thicker intervening gray shales and sandstones display far greater variability in thickness as well as lithology. These units generally seem to form clastic wedges which may appear in the interval classified by Weller (1930, 1931, 1956) as including the top of one cyclothem and the base of an overlying one. The wedges may be considered to consist of two principal lithologic components—a lower moderately well-bedded gray shale with clay ironstone in nodules or bands and an upper, generally fine-grained sandstone. The shale commonly exhibits maximum thickness of 30 to 60 feet, but in a few instances reaches or exceeds 100 feet, and it is roughly fan-shaped with its apex away from the basin. The sandstone is normally a sheetlike deposit grading down through siltstone into the underlying shale, but is separated locally and abruptly from the shale by an erosional unconformity which has been used to divide the sequences into cyclothems (Weller, 1930). In such cases the sandstone occupies linear depressions cut into the underlying shale. The mapping of several clastic wedges has shown that they may consist of three environmental components: (1) valley-flat sandstones and associated shales, (2) distributary channels of a birds-foot-type delta with much associated interdistributary shale, and (3) prodelta muds generally underlying the coarser sands of the delta. The last mentioned constitutes the bedded gray shales with ironstones, whereas both delta and valley-flat deposits may be recognized among the overlying sandstones. Because of removal by post-Pennsylvanian erosion, it is no longer possible to see the entire clastic wedge in its initial form.

Because the deposits just described fit well into a general cyclothemic pattern, it has also become evident that other clastic wedges may appear during the formation of a widespread coal, limestone, or black shale. Where this has taken place, the persistent units may be spread so far apart that they may appear to belong to different cyclic successions. Indeed, in association with the wedge of shale and sandstone there may be locally a coal and limestone added to the new sequence, so as to simulate a full-fledged cyclothem. The author has made several errors in earlier correlations through failure to recognize the insertion of these local cyclic units into the more widespread layer-cake successions of cyclothems with which he was already familiar. It is now evident that several of the studied cyclothems contain as many as three or four clastic wedges in addition to the ones including their basal and topmost beds. Should the strata associated with each such wedge be designated a cyclothem, where present, to be combined into a single cyclothem at their distal margins? Or, should the definition of a cyclothem be modified so that it applies only to cyclic successions with great regional extent, considering the local clastic wedges as stray members or sequences? If the latter is done, a cyclothem may have three or four coals and similar numbers of other lithologic types in one area and only one of each in a location beyond the distal margins of the clastic wedges.

In many places at the distal margin of a clastic wedge, the wedge is reduced to a bedding plane or occasionally a very thin unusual layer such as the Covel Conglomerate (Willman, 1939), suggesting that numerous other abrupt lithologic changes at bedding planes may mark nondepositional intervals.

The megacyclothem of the northern Midcontinent (Moore, 1931, 1950) has been considered to be a sequence of cyclothems of unlike character in Illinois (Weller, 1958). Its distinctive features are three unlike marine limestones, and locally one or two others, separated by characteristic types of argillaceous sediment. The most distinctive part of the sequence is a black fissile shale a few feet thick grading up through several feet of gray shale into the principal marine limestone, the third limestone from the base. This black fissile shale is underlain with knife edge contact by a single bed of marine limestone, generally less than 18 inches thick which in turn rests on poorly bedded gray shale. The author suggests that this limestone may be wholly or in part the marine correlative of a coal bed, for in many areas the coals of the Pennsylvanian are immediately overlain by entirely similar black shale and underlain by poorly bedded gray claystone, the underclay of a coal bed. The lower of the three principal marine limestones may be equivalent to the underclay limestone of the Illinois Basin, generally nodular, algal and nonmarine, but also in some places carrying a marine fauna. In such a case a megacycle, at least the three lower limestones and associated shales, would be equivalent to one, rather than a succession of cyclothems of Illinois type.

TYPES OF VARIATION IN CYCLOTHEMIC SUCCESSIONS

The examples given are mainly taken from intervals for which bed-by-bed environmental maps have been prepared in the Illinois Basin and the northern Midcontinent (Wanless, Tubb, Gednetz, and Weiner, 1963); other studies now in progress by C. Roseman, C. Manos, D. Orlopp, and R. Palomino; and field examples studied by the author in the Appalachian, Illinois, and Midcontinent Coal Basins.

Clastic Wedges Developed in Coal Beds

There are several known examples of small partings in coal beds which may expand into 5 to 50 feet of shale and sandstone.

The Cedar Grove coal of West Virginia, of Kanawha age, is a 6-foot 9-inch coal near Holden, Logan County, where it contains a 6-inch parting of clay 4 feet above the base (Hennen and Reger, 1914, p. 171-175). Within the same county the clay parting expands quite abruptly to a massive gray ledge of sandstone up to 60 feet thick. Where this wedge intervenes, the Cedar Grove coal is considered two separate beds, the upper and lower Cedar Grove, separated by the middle Cedar Grove Sandstone. This sandstone is prominent in southeastern Logan and Mingo Counties, but absent in the northwestern portions of the two counties. Therefore, it appears to be a clastic wedge thickening to the southeast. Figure 1 shows a generalized cross section of this wedge.

A similar section, or perhaps the same one, is found at Lynch, Harlan County, Kentucky, in the Middlesboro Basin, where the Kellioka coal of the Hance Formation, has been mined extensively. This coal is 4 feet 7 inches thick with a clay parting 5 inches thick. Mine tunnels in this coal have been extended under Big Black Mountain to daylight on the Virginia side of the mountain less than 5 miles away. Here the parting has expanded to 32 feet of sandstone, shale and underclay (Wanless, 1946, p. 84-87), and the two coals are called Taggart Marker (below) and Taggart. The sandstone is massive, forming a minor cliff. A cross section of this clastic wedge is shown in Figure 2. Here also the clastic wedge appears and expands toward the southeast.

One of the most widespread coals of the Midwest is the coal known as the Herrin (No. 6) in Illinois, No. 11 in western Kentucky, Mystic coal in Iowa and Lexington coal in Missouri. This coal has a very widespread clay parting generally about 1½ to 2½ inches thick, known as the "blue band." In central western Missouri the coal is split by a clastic wedge in Johnson County. The wedge expands southwestward to about 30 feet and contains a limestone cap for the coal, which is called the Alvis. The limestone is overlain by shale and a sandstone, the Englevale, which becomes fairly massive near the Missouri-Kansas line. This sandstone is overlain by the Lexington coal, which generally lacks an underclay (Fig. 3). Because this clastic wedge expands westward, a western source is indicated for the sand and clay, perhaps the

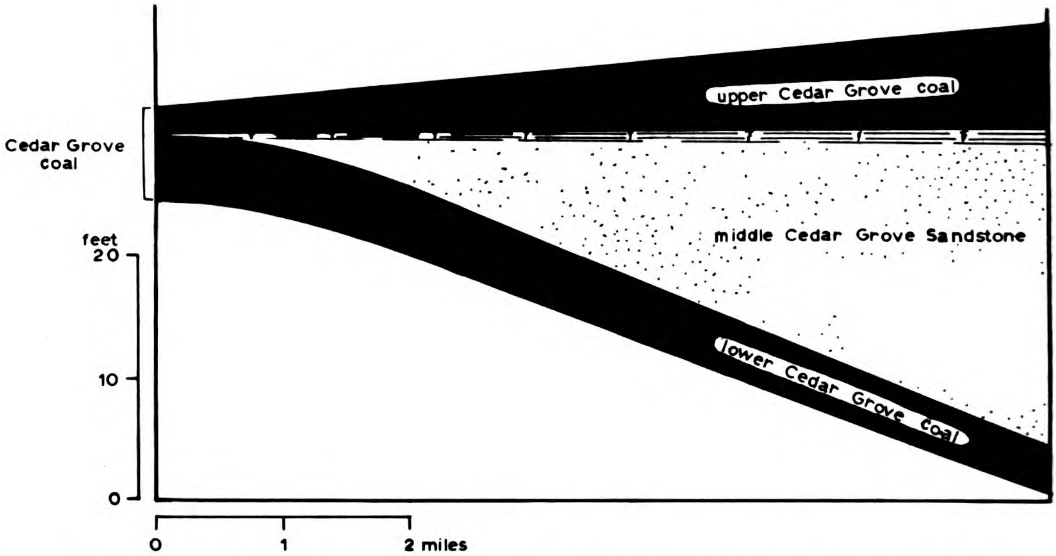

FIGURE 1.—Wedge of sandstone dividing Cedar Grove coal into two beds, Logan County, West Virginia.

Nemaha granite ridge. Neither split of this coal is generally mineable; whereas, the No. 6 coal is the most extensively mined coal in Illinois.

In the same general area the important coal which is commonly called Bevier in eastern Missouri, where it has a shale parting 1 to 3 inches thick, divides into two coals, the Wheeler (lower) and Bevier. Strata as thick as 30 feet, mainly shale, intervene between the coals. The lower (Wheeler) coal has a marine limestone cap rock, and there is locally some sandstone in the clastic wedge between the coals. Because it expands and coarsens westward, it may have been derived from the Nemaha ridge. The Wheeler-Bevier coal is

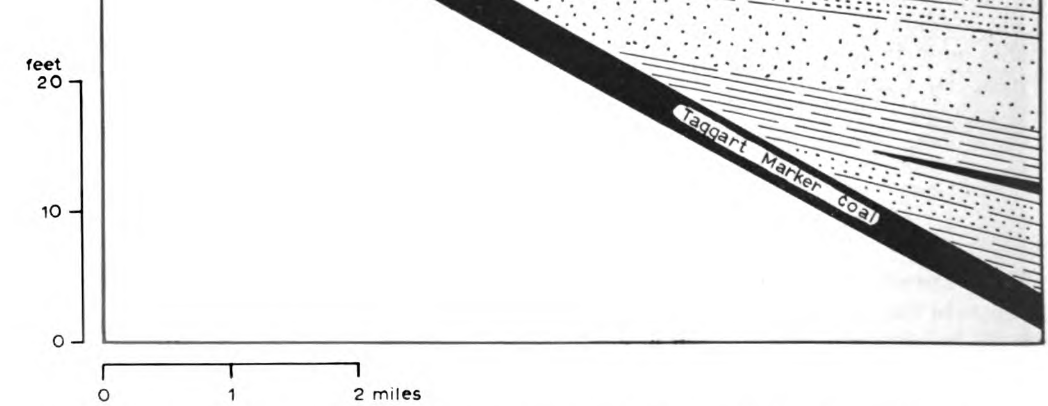

FIGURE 2.—Clastic wedge dividing Kellioka coal southeast of Lynch, Harlan County, Kentucky.

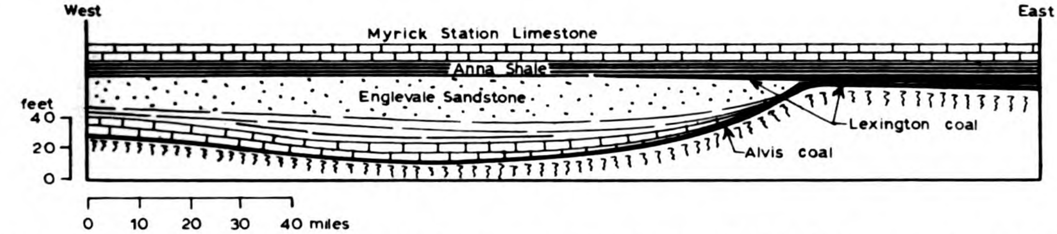

FIGURE 3.—Clastic wedge of Englevale Sandstone and associated strata dividing Lexington coal in western Missouri (adapted from Searight, 1959, pl. 2).

restricted in distribution in Illinois, but is reported to have two benches with a tiny clay parting east of St. Louis suggesting that the parting extends at least one hundred miles east of the distal margin of the clastic wedge (Fig. 4).

As the succession of Pennsylvanian strata is traced from central Ohio southward to east-central Kentucky, the upper Pottsville (Breathitt) strata expand from a little over 100 feet to nearly 2,000 feet. There are many clastic wedges in this expanding section, and it is suggested (Wanless, 1946, Pl. 20) that 30 feet of strata in central Ohio in the position of limestones of the Mercer expand to nearly 500 feet within about 200 miles, in central eastern Kentucky, and that several of the units may result from clastic wedges splitting coals. Some of the correlations have been proven in error, but this does not alter the picture of a very rapidly expanding section with several clastic wedges in the position of coals.

The division of coals by these clastic wedges would not indicate the division of a cyclothem into two, except as additional clays, shales or limestones are found in the wedge interval.

Composite Clastic Wedges

The Brereton and Liverpool cyclothems, both named from western Illinois localities, show much more complex examples of splitting than the examples given above.

Brereton Cyclothem

The Brereton cyclothem is represented by a cross section from Missouri across Illinois to Indiana (Fig. 5). The cross section shows that the cycle is initiated by a delta complex spreading southwestward from west-central Indiana into southern Illinois. This is followed by deposition of a coal (Illinois No. 5a) on the higher part of the delta, while no sediment formed in much of northern Illinois, and marine waters occupied much of Missouri and Iowa. At the close of coal accumulation the sea transgressed from Missouri to southern Illinois, slightly overlapping the No. 5a coal. The transgression was followed by the formation of another clastic wedge, a shale and sandstone delta complex similar in distribution to that below the No. 5a coal in southern Illinois and western Kentucky. This transgression, however, was followed by general marine regression both in Illinois, Missouri, and Iowa, so that the succeeding coal (No. 11 in Kentucky, No. 6 in Illinois, Mystic in Iowa, and Lexington of eastern Missouri) accumulated through large parts of the area and is the only coal in the western Illinois area where the cyclothem was named.

During the accumulation of this coal in

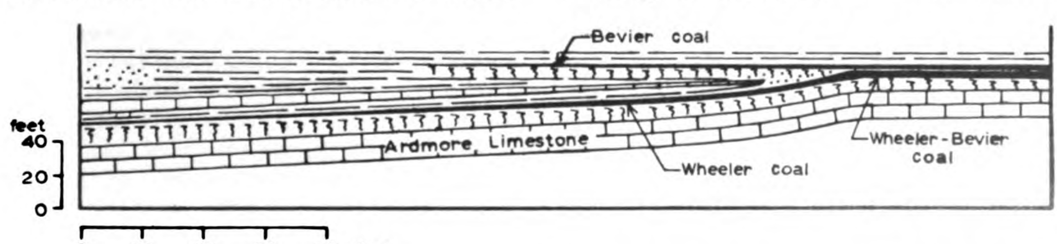

FIGURE 4.—Clastic wedge separating Bevier and Wheeler coals in western Missouri (adapted from Searight, 1959, pl. 2).

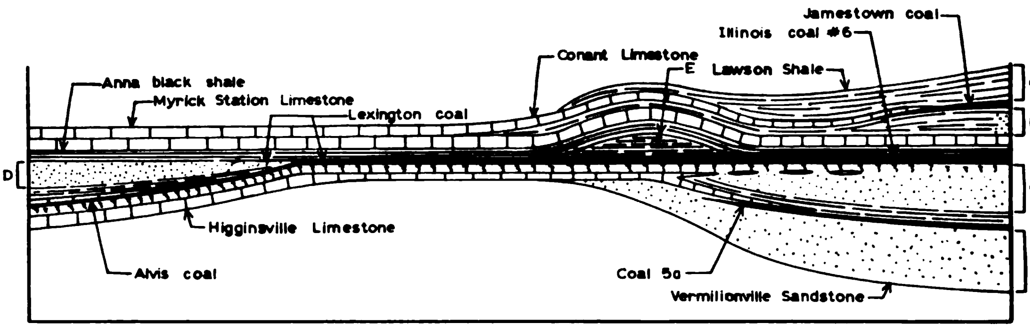

FIGURE 5.—Idealized cross section showing clastic wedges within Brereton cyclothem and its correlatives (not to scale): (A) Vermilionville Sandstone equivalent, southern Illinois Basin, (B) Vermilionville Sandstone of northern Illinois (not shown), (C) sandstone between coals 5a and 6, southern Illinois Basin, (D) Englevale Sandstone between Lexington and Alvis coals, western Missouri, (E) gray shale between No. 6 coal and Anna black shale, southern Illinois, (F) sandstone and shale between Brereton Limestone and Jamestown coal, southern Illinois Basin, and (G) Lawson Shale, above Conant Limestone (lower part of wedge; upper part is Anvil Rock Sandstone, Sparland cyclothem).

western Missouri, the clastic wedge which divides the eastern Missouri Lexington coal into the Lexington and Alvis coals was spread from a westerly source, as described above (Fig. 3).

After the widespread deposition of black fissile shale (Anna) and marine limestone (Providence of western Kentucky, Brereton of Illinois, and Myrick Station of Missouri and Iowa), another small and local clastic wedge was introduced from the east in southern Indiana. The sediment of this wedge is mainly shale with some deltaic sand. Probably the greater part of this delta complex is east of the present Illinois Basin and has been destroyed. On this surface a commercial coal was deposited in parts of Indiana (locally coal VI) and western Kentucky (No. 12) and a thin noncommercial coal (Jamestown) in southern Illinois. This is capped in southern Illinois around the distal margin of the delta with another marine limestone, the Conant. Westward this limestone has been recognized in southern Iowa about 1 foot above the Myrick Station Limestone, but southward in Missouri this shale dies out and the Conant Limestone equivalent becomes only the upper bed of the Myrick Station. Figure 6 shows generalized outlines of the four clastic wedges thus far mentioned. Another wedge following the Conant Limestone separates the Brereton and Sparland cyclothems.

The sequence in western Kentucky, southwestern Indiana and parts of southern Illinois may readily be divided into three cyclothems containing respectively the No. 5a, No. 6, and Jamestown coals as in the present Illinois classification (Kosanke, Simon, Wanless, and Willman, 1960). In northern and western Illinois and south-central Iowa and eastern Missouri the whole sequence constitutes one cyclic succession, but the clastics of the lower portion are replaced by the marine Higginsville Limestone west of the Mississippi. In western Missouri and eastern Kansas the sequence might be divided into two cyclothems including respectively the Alvis and Lexington coals, and a similar split of the Mystic coal into beds, Mystic and Marshall, has been reported by Cline (1941) in central Iowa. Thus, the interval may be locally treated as one, two or three cyclothems, but for the whole region four are possible, namely Jamestown, Brereton, Alvis, and the No. 5a coal. It seems to the author that one major episode of cyclic sedimentation marked by: (1) the delta complex in the southern part of the Illinois Basin and a channel sandstone (Vermilionville) in northern Illinois and a smaller delta (Little Osage-Flint Hills) in southern Iowa and northern Missouri; (2) a lower limestone, Higginsville, in the Midcontinent, and underclay limestone in the Illinois Basin; (3) a very widespread underclay; (4) a widespread coal; (5) a very widespread black shale (Anna); (6) a widespread thin marine limestone (Providence, Brereton, Myrick Station); followed by (7) the advance prodelta of another clastic wedge (Lawson Shale) which constitute the regionally important elements of a representative cycle. The other

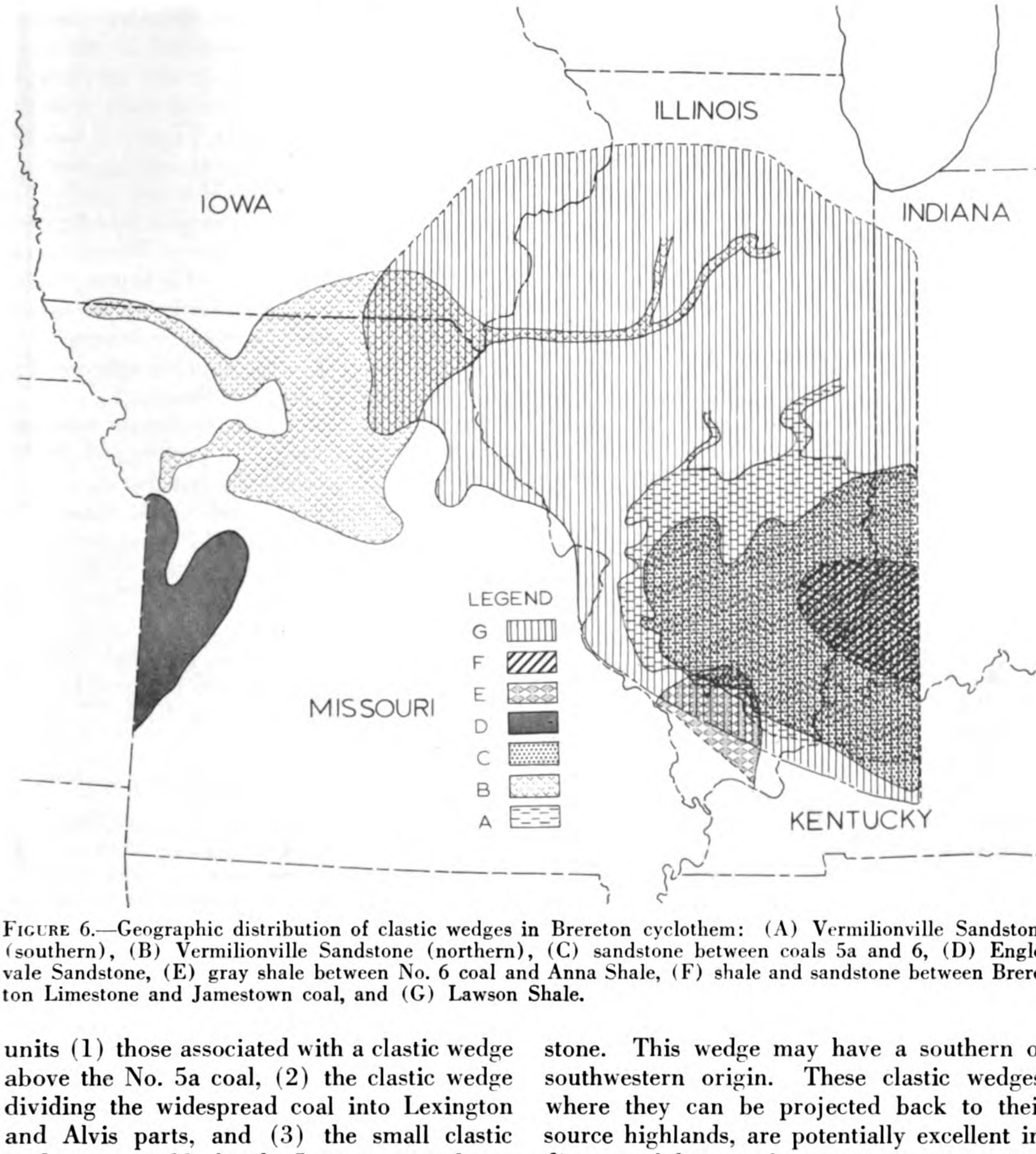

FIGURE 6.—Geographic distribution of clastic wedges in Brereton cyclothem: (A) Vermilionville Sandstone (southern), (B) Vermilionville Sandstone (northern), (C) sandstone between coals 5a and 6, (D) Englevale Sandstone, (E) gray shale between No. 6 coal and Anna Shale, (F) shale and sandstone between Brereton Limestone and Jamestown coal, and (G) Lawson Shale.

units (1) those associated with a clastic wedge above the No. 5a coal, (2) the clastic wedge dividing the widespread coal into Lexington and Alvis parts, and (3) the small clastic wedge responsible for the Jamestown coal, are local elements, and indications of the import of sediment from different directions, perhaps in response to contemporaneous tectonism. These sequences should not be given the same significance in interpretation as the regionally more widespread units. There is another clastic wedge, in southern and southwestern Illinois that is not mentioned above. It consists of a series of lenses of gray shale between the Herrin (No. 6) coal and the black fissile Anna Shale roof that are locally 40 to 60 feet thick, and generally without associated sandstone. This wedge may have a southern or southwestern origin. These clastic wedges, where they can be projected back to their source highlands, are potentially excellent indicators of the age of contemporary tectonism, but introduce confusion into systems of classification.

Liverpool Cyclothem

The Liverpool cyclothem, in its typical area in western Illinois, includes, from the base up: (1) a sandstone, the Browning; (2) an underclay; (3) a coal, the Colchester (No. 2); (4) a gray shale, the Francis Creek, (5) a black fissile shale; (6) a massive limestone, equivalent to the Ardmore of Missouri; (7)

a succession of four very thin marine limestones or ironstones (Oak Grove) separated by shales and in one instance locally siltstone or sandstone; and (8) an upper gray shale with ironstones. Because the lime-shale-sand-ironstone succession, the Oak Grove Member, appears to bear significantly on the complex regional problems of this interval, the units are separately listed here:

Ironstone bed with fossil casts and molds (*Crenipecten* bed)	0'2"
Gray shale with ironstones	1'6"
Ferruginous fossiliferous limestone (*Linoproductus* bed)	0'6"
Dark-gray flaky shale (*Dunbarella* shale)	2'0"
Ferruginous limestone (*Cardiomorpha* bed)	0'3"
Calcareous fossiliferous shale (*Mesolobus* bed),	0'4"
Gray septarian limestone with cone-in-cone (*Desmoinesia muricatina* bed)	1'0"
Unfossiliferous silty shale (Jake Creek Sandstone)	1'0"

This sequence is unusual in the presence of the thick gray Francis Creek shale, which is a clastic wedge in the typical area, and in having such a complex sequence of limestones and shales as the Oak Grove Member in place of a single marine limestone to represent the transgression. Figure 7 is a very idealized cross section from northern Illinois southwestward and westward to Iowa, western Missouri and eastern Kansas. The clastic wedges involved in the Liverpool cyclothem are: (1) the Sebree-Palzo Sandstone of western Kentucky and southern Illinois (Potter, 1962, Pl. 1), a delta complex directed west and southwest in southern Indiana, western Kentucky and southeastern Illinois at the base of the Liverpool cyclothem; (2) a system of channels probably forming distributaries of a separate delta in northern Illinois, southeast Iowa and west-central Illinois (Browning), probably contemporary with (1); (3) the Francis Creek Shale, a prodelta shale extending southwestward from northern to west-central Illinois (this shale is sandy in its northeasternmost outcrops and in the same area contains the ironstone concretions rich in plant and animal fossils which have long been associated with Mazon Creek, Grundy County); (4) the Jake Creek "sandstone," a shale-sand complex from an easterly direction, on which the Lowell-Wheeler-Bevier coal swamp was supported, in part: (5) a clastic wedge which divides the Wheeler (lower) from the Bevier coal westward in Missouri, expanding from an inch or two of shale in eastern Missouri to 30 feet of shale near the Kansas line, illustrated in Figure 4 and described above (this wedge has a westerly source and the lower Wheeler coal locally has as a marine limestone caprock the *Desmoinesia muricatina* bed of western Illinois); and (6) a composite prodelta (Purington Shale) probably from the east or northeast, the uppermost portion of the Liverpool cyclothem. Figure 8 is a map showing approximate areas of the six clastic wedges mentioned.

In the type area of the cyclothem only two of the clastic wedges are present, wholly or in part, the Browning Member, basal, and the outer margin of the Francis Creek Shale. Because of this, Worthen (1870) miscorrelated the principal coal of the cyclothem as No. 2 where its roof is gray Francis Creek Shale and No. 3 where it is black fissile shale.

The ironstone, limestone, and shale units of the Oak Grove Member are believed to have the following significance in terms of clastic wedges:

Crenipecten ironstone bed (ironstone band in lower Lagonda Shale)
Gray Shale (lowermost part of Lagonda Shale)
Linoproductus limestone bed (cap of Bevier coal)
Dunbarella shale (roof shale of Bevier coal)
Cardiomorpha limestone (marine correlative of Bevier coal)
Mesolobus shale (calcareous marine shale above Wheeler coal)
Desmoinesia muricatina limestone bed (cap rock of Wheeler coal)
Jake Creek silty shale (clastic wedge below Wheeler coal)

As thus interpreted, the Oak Grove Member, only about 6 to 10 feet thick on the average, includes cap rocks of two coals (Bevier and Wheeler); two distal margins of clastic wedges; one marine roof shale; and the marine equivalent of one coal. Had the typical section of the Liverpool cyclothem been located elsewhere it might have been divided into a Bevier cycle, a Wheeler cycle, and a Croweburg cycle.

The Liverpool cyclothem has the following very widely extensive units of regional as opposed to local significance, listed in ascending order: (1) a basal sandstone (Sebree, Palzo,

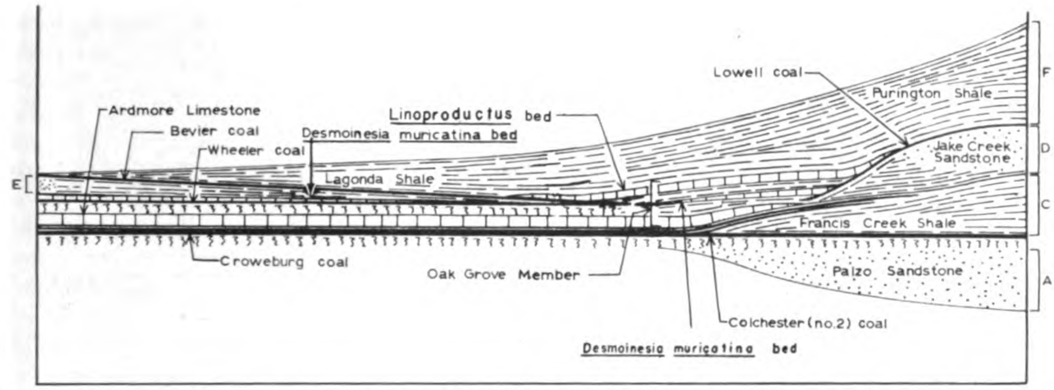

FIGURE 7.—Idealized cross section showing clastic wedges within the Liverpool cyclothem and its correlatives (not to scale): (A) Palzo Sandstone, southern Illinois Basin, (B) Browning Sandstone, northern Illinois (not shown), (C) Francis Creek Shale, (D) Jake Creek Sandstone and shale, (E) shale between Wheeler and Bevier coals, (F) Purington Shale (lower part of wedge; upper part is Pleasantview Sandstone, Summum cyclothem).

Browning); (2) a very widespread underclay; (3) the most extensive coal of the Pennsylvanian (No. 2 of Illinois, IIIa of Indiana, Schultztown of western Kentucky, Whitebreast of Iowa, Croweburg of the Midcontinent); (4) a widespread black fissile shale; (5) a cap limestone (Verdigris, Ardmore); (6) the Oak Grove marine zone; and (7) an upper shale (Purington, Lagonda). This suite of regionally extensive strata seem to compose a representative cyclothem. The other units of this complex succession are local and are present because of the influence of the clastic wedges which interrupt the regionally extensive Liverpool cyclothem.

Convergence of Limestones

In the Midcontinent there are several places where shale units wedge out bringing two marine limestones into contact. Thus, in western Missouri the Houx Limestone of the St. David cyclothem merges with the Higginsville Limestone of the lower part of the Brereton cyclothem, as the part of the Little Osage Member of the Fort Scott Formation equivalent to the Canton Shale of Illinois, wedges out (Fig. 9.) This leaves the black fissile shale as the only recognizable unit of the St. David cyclothem, as the Summit coal is virtually gone, and its underclay is shaly.

Other examples of limestone convergence are the Oolagah Limestone of northeastern Oklahoma, formed by the joining of the Myrick Station Limestone, Brereton cyclothem, and Coal City, Amoret, and Worland limestones of the overlying Sparland cyclothem. In the subsurface many limestones of the Kansas City and Lansing Groups merge through the disappearance of the shale wedges which separate them farther east (Kellett, 1932.) It is possible that individual components of the several limestones may be recognized by texture or fauna in the merged unit, but this has not yet been demonstrated. This convergence takes place in areas remote from contemporary supplies of clastic sediment and resembles somewhat the "starved basin" sedimentary thinning described by Adams and others (1951) except that the starved basin sediments are commonly dark shales formed in deeper water.

MEGACYCLOTHEMS

The megacyclothem sequence (Fig. 10), involving the third or principal marine limestone and the underlying black fissile shale, finds a close counterpart in the limestone cap rock and black roof shale of many coals of the Illinois Basin. The principal differences are that in the megacyclothem the black fissile shale rests on a single bed of fossiliferous marine limestone, whereas in Illinois the substratum of the black shale is generally coal, and in a "lower" limestone position in the Illinois Basin the underclay limestone is com-

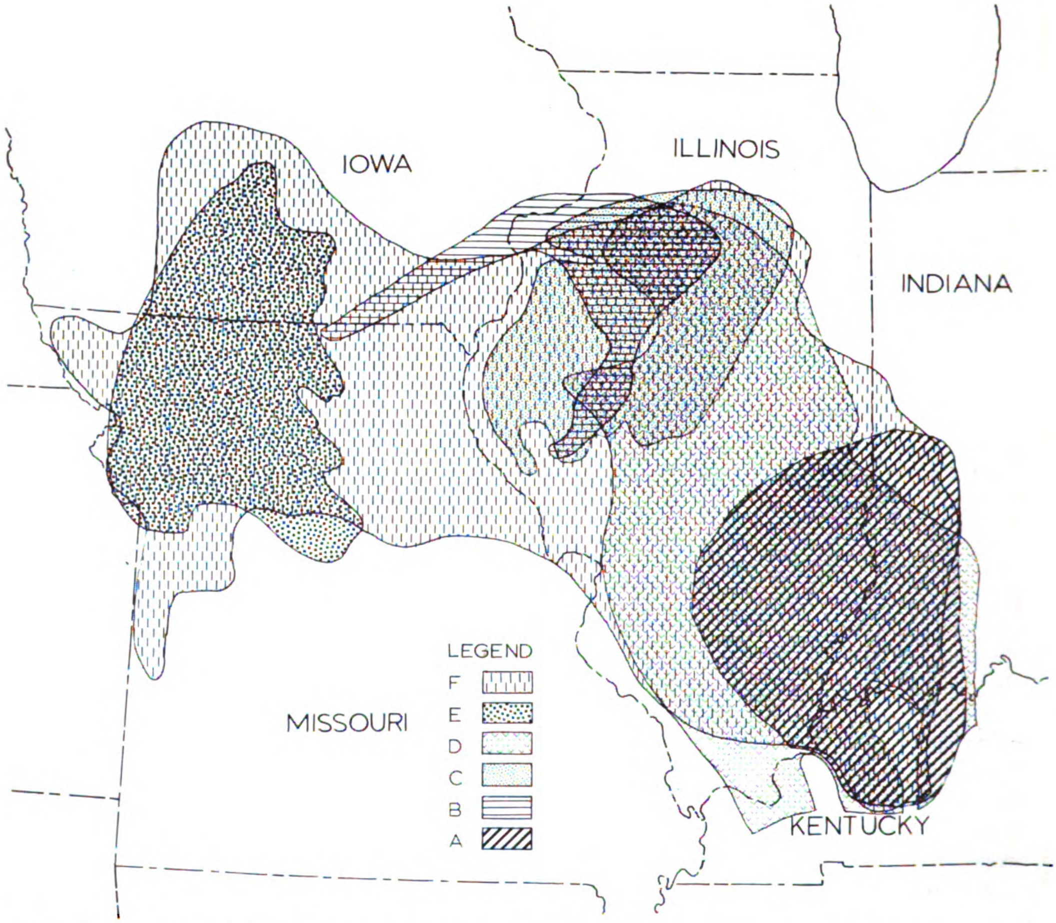

FIGURE 8.—Geographic distribution of clastic wedges in Liverpool cyclothem: (A) Palzo Sandstone, (B) Browning Sandstone, (C) Francis Creek Shale, (D) Jake Creek Sandstone and shale, (E) shale between Wheeler and Bevier coals, (F) Purington Shale.

monly considered of fresh-water origin. The fourth and fifth limestones of the megacyclothem are principally found in the Shawnee Group.

In western Illinois the Springfield (No. 5) coal thins gradually northward at about the average rate of 1 inch per mile for more than 60 miles to final disappearance in northern Illinois. Where it outcrops northeast of Galesburg, it is about 14 inches thick, and in a drill core near Sparland, Illinois, it is 6 inches thick. Thinner developments of the coal have not been seen, but may occur. At Cambridge in northwestern Illinois about 15 miles north of the 14-inch coal outcrop, the coal is absent, the black fissile roof shale rests immediately on a 2-inch fossiliferous marine limestone which in turn overlies a poorly laminated shale in the position of the underclay of the coal. A marine limestone 0.6 foot thick is found directly below this black shale in Johnson County, western Missouri (Searight, 1959, p. 34.) These relations suggested to the author that the limestone of the megacyclothem immediately below the black fissile shale may be at least in part the marine correlative of a coal. The "ideal cyclothem" (Wanless and Weller, 1932) includes a limestone immediately below the black fissile shale as unit 7 of the units designated, whereas the coal is unit 5, below a gray shale of the Francis Creek Shale type. There are a few outcrops in Illinois in which both a limestone below the black fissile shale and a coal are

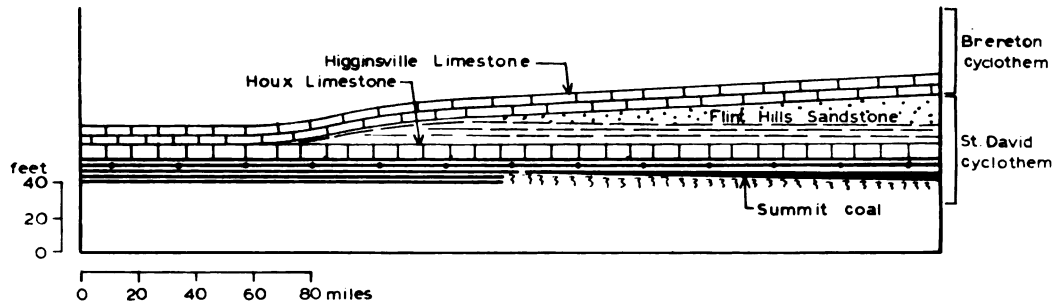

FIGURE 9.—Cross section showing merging of Houx Limestone, St. David cyclothem, and Higginsville Limestone, Brereton cyclothem in western Missouri.

present, but in Illinois the limestone is commonly in a series of discontinuous lenses, whereas in Kansas it is the most uniform member of the megacyclothem, and coal practically never underlies it.

The underclay limestone of Illinois is commonly a mass of nodules or a very unevenly bedded nodular limestone containing only algae of supposed fresh-water adaptation (Norman, 1959), but there are several instances of a marine limestone in the lower part of an Illinois cyclothem. The most widely distributed is the Bankston Fork Limestone (Universal of Indiana) which immediately overlies the basal Anvil Rock Sandstone of the Sparland cyclothem of southern Illinois, southwestern Indiana and parts of western Kentucky. This is equivalent to the Coal City or Upper Pawnee Limestone of Missouri and Iowa. There are several other examples of marine limestones in Illinois between the coal and the underlying sandstone, which will not be enumerated here.

There are other instances, notably: (1) the limestone below the Herrin (No. 6) coal, which is generally "fresh water" in Illinois, but is marine in the Midcontinent region (Higginsville Limestone or upper Fort Scott); and (2) the underclay limestone below the Summum (No. 4) coal of Illinois which is not known to carry a marine fauna in Illinois or eastern Missouri, but which becomes the marine Breezy Hill Limestone of western Missouri, Kansas, and northeastern Oklahoma. These observations suggest that, while underclay limestones in the Illinois basin commonly formed in fresh-water lakes or brackish lagoons, they were contemporary with transgressive marine limestones to the southwest.

If these suggestions are correct, the megacyclothem may be the Midcontinent equivalent of the Illinois basin cyclothem, rather than a combination of individual cyclothems as proposed by Weller (1958).

CAUSES FOR DISTRIBUTION OF CLASTIC WEDGES

Thickening of clastic successions in certain localities may result from either downwarping of the locality to make room for a greater thickness of sediment, or proximity of the locality to sources of sediment supply.

It is commonly thought that in most situations sediment supply has been adequate to maintain a profile of equilibrium, so that most sediment in transit would bypass the area, continuing on until a region of active downwarping is reached (Eaton, 1929; Twenhofel, 1950). Thus, a local thickening of a stratigraphic interval by 10 feet might be an indication of local downwarping in that amount. The Illinois Basin is divided into segments by the LaSalle Anticline, which is mainly a monocline with a steep west flank, and the Duquoin Anticline, similar to the LaSalle, but with a steep east flank. If thickening of stratigraphic intervals resulted simply from differential movement along these axes, most clastic intervals should be much thicker in the deeper Fairfield Basin between these folds than on the flanks. In the environmental mapping of middle Pennsylvanian strata recently completed (Wanless, Tubb, Gednetz, and Weiner, 1963, and later unpublished studies by C. Roseman, C. Manos, and D. Orlopp) there are numerous clastic wedges, generally delta and prodelta complexes, de-

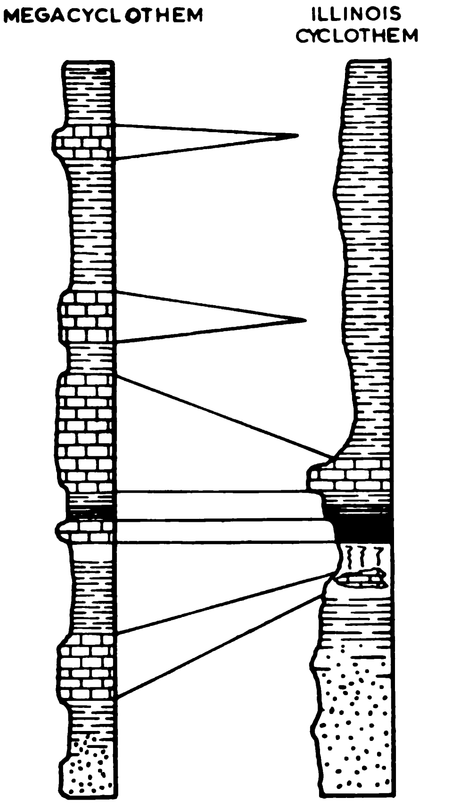

FIGURE 10.—Generalized columns showing suggested relations between the megacyclothem of the northern Midcontinent and the cyclothem of Illinois.

rived from a northeastern source. Most of these cross the LaSalle anticlinal belt nearly at right angles. Although hundreds of thicknesses have been plotted of the several clastic intervals, these have uniformly failed to show abrupt thickening on the downslope flank of the fold. From this it is deduced that this structure was inactive during the intervals mapped, having no topographic expression, and the sediment distribution was controlled by distance from the source area, paleoslope, climate, and the position of the strandline. The LaSalle Anticline was evidently tectonically active during parts of the early Pennsylvanian, where the clastic intervals have not yet been environmentally mapped. In such cases the shales and sandstones probably thicken abruptly on the down slope flank of the fold.

SUMMARY

Cyclic Pennsylvanian strata of the eastern and central United States are considered in terms of widespread blanketing beds and sequences whose distribution appears to be independent of local tectonic factors, and sequences generally involving or resulting from clastic wedges introduced into the basin as a result of contemporary tectonism. Both types of sequences may be cyclic in character. The clastic wedges may be introduced into the basin at any time during the accumulation of a sequence. They are more common in basins nearer highlands with tectonic activity. Thus, they are more widespread in the Appalachian Coal Basin than in the Illinois Basin which in turn has more than the northern Midcontinent area. The discrimination between local and widespread cyclic units may be difficult in a small area, but becomes evident in interstate studies of large areas, particularly where environmental mapping is done on a bed-by-bed basis. These local clastic wedges may be introduced into a basin from three or four different source directions during a single cyclothem. Their presence complicates the problem of cyclothemic classification, for what appears to be a typical cyclothem in one area may easily be subdivided into two, three, or four in other areas. The existence of these local clastic wedges and the formation of local coals associated with them emphasizes the objection of numbering coal beds, and this is doubtless one of the reasons there are so many lower, middle, upper, Rider, Little, 3a, and 2b coals in the literature.

For the interpretation of geologic history local clastic wedges and associated strata afford excellent bases for determination of exact times and places of contemporary tectonism. Rough calculations involved in the volume of such a clastic wedge as the Francis Creek Shales, Liverpool cyclothem, would permit estimates as to magnitude of each separate uplift. Changes in paleoslope resulting from movements around the borders of a sedimentary basin may be determined from the directional trends of lenticular sandstones in successive cyclothems.

Another type of variation in number of cyclic sequences is found at a great distance from tectonically active areas where a series of marine limestones is no longer separated by shale or sandstone wedges, or in a deeper "starved" basin where shales replace most other sediment types.

It is proposed that the megacyclothem of the northern Midcontinent is the equivalent of the cyclothem of the Illinois Basin formed in regions nearer sources of marine transgression and farther from frequent sources of clastic sediment.

It is suggested that, although the clastic wedges may result from tectonism in distant highlands, their distribution is not influenced by differential downwarping of the sedimentary basin except where the axis of downwarping is coincident with the location of a thickened portion of the clastic wedge. Studies of thickness variation patterns of individual clastic wedges can therefore indicate times of local tectonism and of quiescence in the sedimentary basins.

It is hoped that this discussion may aid in the separation of local from regional elements in late Paleozoic cyclic successions and permit a sounder interpretive analysis of their depositional history than has been possible.

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Development of the Concept and Interpretation of Cyclic Sedimentation

INTRODUCTION

The idea of geologic cycles is an ancient one going back at least to the catastrophic theories of Cuvier and d'Orbigny (Weller, 1960, p. 1008, 1010), who believed that the earth witnessed a succession of organic creations and extinctions. In America, Amos Eaton, an adherent to Wernerian principles, outlined a five times repeated sequence of rocks termed Primitive, Transition, Lower Secondary, Upper Secondary, and Tertiary.

> All geological strata are arranged in five analogous series; and that each series consists of three formations; viz. Carboniferous [more properly schist, slate, or shale], Quartzose, and Calcareous. (Eaton, 1830, p. 64.)

> The geological deposits of this country (and probably those of the eastern continent), exhibit grounds for conjecture, if not absolute demonstration, that the surface of the earth has undergone five general modifications, which no animals survived. Four of these modifications were followed by as many new creations of animals. Also, that two new creations of animals succeeded the final deposition of all regular strata. In the whole, there appears to have been five creations of animals (perhaps ten) since the primitive mass of the earth was formed; and a long interval succeeded each creation. (Eaton, 1832, p. 48.)

Eaton's correlations were so confused that his formations cannot be identified in a way that has much modern meaning.

SYSTEMIC CYCLES

Edward Hull in Britain, partly on theoretical grounds, outlined a natural sequence of sedimentary rocks related to distance from the shore and transgression and regression of the sea. Examples were provided by the Carboniferous System of England and Scotland as well as other strata.

> We cannot fail to have observed that the many groups have a tendency to arrange themselves into threefold divisions, the upper and lower being composed of sands or clays, the middle of limestone. . . . Phenomena of so general a character cannot be accidental, but must be in accordance with the system of nature. (Hull, 1862, p. 134.)

In America, T. Sterry Hunt (1863, p. 166-167) recognized a sequence consisting of (1) basal siliceous strata, (2) dolomite with some gypsum and salt, (3) limestone, and (4) carbonaceous shale. This sequence was stated to be repeated three times in the Cambro-Silurian (Ordovician), Middle and Upper Silurian, and Lower Devonian of New York and adjacent regions.

In Nova Scotia, J. W. Dawson distinguished a general succession of Carboniferous rocks consisting of (1) coarse sediments deposited in shallow water at the base, (2) limestone and gypsum indicating the existence of deeper, clearer water, and (3) detrital sediments with coal indicating withdrawal of the sea. Wider application of the idea suggested by this succession led him to outline in tabular form a four times repeated "cycle" representing (1) subsidence and coarse sediment, (2) marine conditions and limestone, (3) elevation followed by slow subsidence, and (4) a subsiding basin filled with sediments.

> . . . the Carboniferous period constitutes one of four great physical cycles, which make up the Paleozoic age in Eastern America—and each of which was characterized by great subsidence and partial re-elevation, succeeded by a second very

gradual subsidence. (Dawson, 1866, p. 102; 1868, p. 137.)

Dawson's cycles corresponded with the Lower Silurian (Ordovician), Upper Silurian, Devonian, and Carboniferous Systems as then recognized. He also remarked that the Permian rocks of Europe suggest the existence of a fifth cycle.

Hull in a second article presented a classification of the stratigraphic column extending from the Upper Silurian through the Miocene in amplification of his concept of sedimentary sequences including middle limestone units. Ten sequences or groups were recognized, most of which corresponded to geologic systems except that the Jurassic was represented by three sequences.

. . . each natural group was composed of the representatives of three periods—the 1st, one of movement, accompanied by change of land and sea and much denudation; 2nd, a period of comparative repose, and a minimum of denudation; 3rd, of change, gradually increasing in intensity to the close of the epoch. (Hull, 1868, p. 144.)

At a meeting of the American Association for the Advancement of Science in 1860, Newberry (1874a, p. 186-187, 194, 196) read two papers that were never published (1861a, 1861b) in which he called attention to the Cretaceous section in the southwestern United States.

In this region I found the base of the Cretaceous system composed of coarse sandstone, sometimes conglomerate, containing everywhere the impressions of Angiospermous leaves, and in many places heavy beds of lignite. . . . Above this lies a laminated impure limestone, containing characteristic fossils . . . . Above the last mentioned group is a heavy mass of calcareous strata abounding in . . . characteristic Cretaceous mollusks. The fourth member of the series. . . . is formed by a group of calcareous sandstones and shales, with impressions of plants, sheets of lignite and some mollusks . . . . From this sequence of strata, I read the history of a submergence of the Triassic continent and an invasion of the sea which resulted, first, in the formation of a wide-spread sheet of beach sand and gravel . . . . Second a mixture of mechanical and organic sediments, constituting the offshore deposits of the invading sea. Third, a great calcareous mass, the organic sediments of the open sea during the long continued period of greatest submergence. (Newberry, 1874a, p. 185-186.)

Newberry's later work, particularly in Ohio, directed his attention to a generally similar "circle" of deposition that was said to be repeated in the Paleozoic rocks of the eastern half of North America.

The history recorded in each case is the same, viz., a submergence of such portions of the continental surface as now carry the sedimentary strata enumerated: in the progress of each submergence, the spread of shore materials, over all the surface covered by the advancing sea; this sheet being followed first, by mixed mechanical and organic sediments, then by those almost purely calcareous deposits from the open ocean, and finally earthy limestones—mixed sediments—indicating a retreating, shallowing sea and a return to land conditions during which no deposition would be made on the surface, but which was the necessary starting point for a new circle of deposits. (Newberry, 1873, p. 64.)

In an elaboration of his "circle," Newberry emphasized the role of fluctuating sea level and the advance and retreat of shorelines on the type of sediment deposited. He summarized his ideas in a table (1874a, p. 193), which is reproduced here in slightly modified form (Table 1). He also referred to the observations of European geologists who had recorded the existence of strata exemplifying a similar succession of beds in the Permian and Triassic. Finally, he expressed an interesting and prophetic opinion.

In all our works on geology the Portage, Chemung and Catskill formations are included in the Devonian system, but in my judgment it would be better to consider the *Portage sandstones* . . . as the true base of the Carboniferous system . . . forming an indivisible mass of mechanical sediments . . . evidently the record of a new era in the geological history of the continent. (Newberry, 1874a, p. 192.)

Thus Newberry stated the idea that geologic systems should conform to a physical cycle recorded in the rocks.

PERIODICITY

From this time onward, recognition of the proper limits of the geologic systems, by some of the foremost geologists in America, seems to have been influenced more and more by the idea of periodic sea level fluctuations or diastrophic pulsations.

There is a rhythmic relation between the successive grand subsidences and emergences of the interior of the continent that we believe should be the basis for a revised classification of the rocks of North America. (Ulrich and Schuchert, 1902, p. 659.)

TABLE 1.—Newberry's "circles" of deposition.*

	Lower Silurian ("Cambrian")	Upper Silurian	Devonian	Carboniferous
Retreating Sea	Cincinnati Group	Helderberg Group	Hamilton Group	Pennsylvanian Coal Measures
Open Sea	Trenton Limestone	Niagara Limestone	Onondaga Limestone	Mississippian Limestone
Off Shore	Beekmantown Group	Clinton Group	Schoharie Grit	Waverly Group
Shore	Potsdam Sandstone	Medina Sandstone	Oriskany Sandstone	Portage Sandstone

* Some of the stratigraphic names have been modified to correspond more nearly to modern terminology. In the construction of this table, Newberry undoubtedly was influenced by Dawson's table of 1866.

We believe that there is a natural basis of time-division, that it is recorded dynamically in the profounder changes of the earth's history, and that its basis is worldwide in its applicability. (Chamberlin and Salisbury, 1906, v. 3, p. 192.)

Have diastrophic movements been in progress constantly, or at intervals only, with quiescent periods between? Are they perpetual or periodic? The latter view prevails, I think, among American geologists. (Chamberlin, 1909, p. 689.)

The North Atlantic, for instance, is bounded on the east and west by lands, which have been disturbed or have been at rest during the same epochs, ... These cycles are indeed those on which the time-scale of geologic history is based, and each one corresponds in general with a standard period . . . . (Willis, 1910, p. 247.)

Assuming that baseleveling was in progress through all the ages, yet it seems that at certain recognizable times the process was strongly revived. . . . . Referring on this occasion only to the Paleozoic, they took place at what I conceive to have been rhythmically recurring intervals, corresponding essentially to the systemic divisions of the stratigraphic column as drawn in the revised classification to be proposed. (Ulrich, 1911, p. 313-314.)

Nature vibrates with rhythms, climatic and diastrophic, . . . which have divided earth history into periods and eras. (Barrell, 1917, p. 746.) The profound revolutions, . . . were relatively brief periods closing long eras marked by diastrophic quiet and low continental relief. (Barrell, 1917, p. 752.) It is clear that epochs of diastrophism are more or less closely correlated in widely different regions. Changes in sealevel are necessarily felt over the whole earth. (Barrell, 1917, p. 756.)

At these times ranges of mountains are slowly raised up near the margins of the continents . . . the "disturbances," which are coming more and more to be regarded as the basis for dividing the eras into periods of time . . . . (Schuchert, 1918, p. 70-71.)

As our study progresses, the fact becomes more and more evident that transgression and regression are primarily "hologeodetic"--that is, universal so far as the earth is concerned—and that, moreover, they proceed in a rhythmic manner . . . . (Grabau, 1936a, p. 540.)

A review of American geologic literature shows that the idea of more or less worldwide periodicity in diastrophism and marine transgression and regression was firmly held for many years. Attempts were made at first to equate the orogenic and marine cycles with the standard geologic systems. As important discrepancies came to light, however, several influential American geologists sought to revise the systems in conformity with their interpretations of the presumed cycles. To the five or six Paleozoic systems recognized by Europeans, Chamberlin and Salisbury (1906, v. 2, p. vi) added one, Schuchert (1910, p. 513-576) seven, Ulrich (1911, p. 379-380, Pl. 26) four, and Grabau (1936b, p. 27-44) at first six and then (1938, p. 22-23) one more system.

The possibility that diastrophic and marine cycles may not have been contemporaneous everywhere was considered, but generally this was not seriously entertained. Willis, however, seems to have disagreed.

Each region has experienced an individual history of diastrophism, in which the law of periodicity is expressed in cycles of movement and quiescence peculiar to that region. (Willis, 1910, p. 247.)

The logical reasoning of Chamberlin (1909) evidently satisfied most others in Europe as well as in America that the worldwide periodic theory was acceptable. Early objections received little notice and aroused less interest.

The writer has no desire to attack the well-established idea of peneplanation and relative quiescence locally over long periods, but . . . to replace this idea [worldwide periodicity] with the suggestion, that diastrophism has been continuous . . . . (Shepard, 1923, p. 599.)

The twentieth century was half gone before a vigorous and well documented reconsideration reversed this trend of thinking.

Worldwide orogenic revolutions do not appear to me to have been demonstrated . . . . It is my belief that such changes are not yet required by the evidence at hand. (Gilluly, 1949, p. 589.)

GRAND CYCLES

In the meantime attention had been called to the possible existence of supra-systemic cycles.

It is possible to recognize at least three grand cycles from the late pre-Cambrian to the close of the Mesozoic, each grand cycle consisting of a long period of activity [diastrophism] and a still longer time of relative quiet . . . . (Willis, 1910, p. 247.)

A two-fold division of the Paleozoic was made at first to correspond with the supposed tectonic history of New England. A break was provided by the Taconic "revolution" at the end of the Ordovician Period. Later, this was altered to conform to the better established structural development of Europe where a division was indicated by the Caledonian "revolution" at the end of the Silurian Period. Snider (1932, p. 72-76) presented this concept clearly. These cycles were marked off by orogenesis at (1) the late Precambrian, (2) the late Silurian, (3) the late Permian, and (4) the late Cretaceous continuing to the present. The epochs of Ordovician, Mississippian, and Cretaceous limestone deposition identified the quiescent phases of widespread marine transgression. The opinion now is common that these grand cycles, although much generalized. probably have more reality than the lesser systemic ones so far as the whole world is concerned.

PENNSYLVANIAN CYCLOTHEMS

While some geologists theorized about the larger patterns of geologic history, others engaged in detailed field work noticed repeated associations of different kinds of rocks on a much smaller scale. The economic importance of Carboniferous coal beds led to some of the earliest observations of this sort. The intermittent occurrence of coal seams in a succession of dominantly detrital strata is obviously cyclic in some degree and had long been recognized. Different interpretations of these associations, however, introduced and perpetuated a longstanding controversy concerning the origin of coal. Were the seams formed in place by the local growth and preservation of vegetation, or do they consist of the remains of transported vegetable material? This question was not resolved in favor of local origin to most persons' satisfaction before the publication of an exhaustive review of all the evidence by Stevenson (1911-1913).

Early Notice in America

The sea cliffs at the South Joggins in Nova Scotia probably present the finest display of outcropping Carboniferous coal measures to be seen anywhere in the world. There, in a distance of about 7 miles, a nearly continuous, gently dipping section exposes more than 14,500 feet of strata containing at least 76 coal beds (Logan, 1845). Much of this section was carefully studied by Dawson. He observed the general presence of underclay with roots beneath the coals and argued strongly for the local origin of coal. He also noted the occurrence of thin limestones.

It is remarkable that in almost every instance the conditions requisite for the formation of these limestones and their allied *Modiola*-shales have followed immediately on the formation of layers of coal based on underclays. (Dawson, 1854, p. 15.)

This seems to have been the first report of the sequence that is so characteristic of many Pennsylvanian cyclothems.

In the United States, Newberry observed comparable associations in the Ohio coal measures.

. . . it will be seen that the elements composing the Coal Measures occur in an order of superposition that is so constant, or at least so frequently repeated, that it cannot be a matter of chance, but must be the expression of a general law. The order of sequence . . . is this, namely, that the coal strata almost invariably rest upon beds of fire-clay. They are also almost always covered with shale of greater or less thickness, and this in turn is overlaid sometimes with sandstone, more rarely with limestone; and thus each section is divisible into series of three or more members each, in which the elements hold nearly a constant relation to each other. (Newberry, 1874b, p. 114.)

Many discontinuous but relatively good Pennsylvanian outcrops occur in parts of western Illinois. By piecing them together, Udden built up a stratigraphic section in the vicinity of Peoria nearly 250 feet thick consisting of plainly developed cycles (1912, p. 27, Fig. 2).

. . . the coal-bearing rocks present an unusual persistence of the 21 recognizable divisions [lithologic members] . . . grouped into an almost perfect quadruple repetition of a sedimentary cycle. Each cycle may be said to present four successive stages, namely: (1) accumulation of vegetation; (2) deposition of calcareous material; (3) sand importation; and (4) aggradation to sea level and soil making. (Udden, 1912, p. 47.) . . . the most remarkable feature bearing on the physical conditions prevailing at the time of the deposition of the coal measures of this quadrangle is the horizontal extent and uniformity in thickness of each deposit. (Udden, 1912, p. 50.)

These statements, together with the graphic section, were the clearest expression of the Pennsylvanian cycle yet published. In the following years several papers, in one way or another, mentioned comparable cyclic arrangements of strata. One curious publication by a Belgian geologist in Wales refers to "cycles" with coal beds in their midst. This author made casual mention of the writings of Dawson, Hull, and Newberry.

. . . all rocks of the coal measures form a succession of cycles of deposition, with the finest sediments in the center . . . . (Simoens, 1918, p. 7.)

In Ohio, Stout evidently was aware of the cyclic arrangement of Pennsylvanian strata.

In the coal formations of the United States and other countries, clay and coal occur as associated materials with great regularity; in fact, one is not often present without the other. This constancy of relations is so universal that it is not a matter of chance. (Stout, 1923, p. 533.) With few exceptions marine limestones lie on or not far above coal beds. (Stout, 1923, p. 538.)

It is a strange fact that the statements concerning the existence of a repeated Pennsylvanian sedimentary cycle by Dawson and Newberry and its clear description by Udden so generally escaped the attention of stratigraphers. The principal reasons for this neglect seem to have been: First, most Paleozoic stratigraphers were so accustomed to dealing with continuous marine strata that they failed to recognize or to be impressed by the repeated alternations of marine and nonmarine members in the Pennsylvanian. Even the presence of coal beds had little effect on their preconceptions.

. . . nearly all of the present Appalachian Coal Measures area bears the marks, either paleontological or stratigraphical, of the continued transgression of the sea. (White, 1904, p. 277; see also, Wilson and Stearns, 1960.)

Second, most coal geologists were so concerned with the economic aspects of their work that they neglected to comment on some rather obvious stratigraphic associations, if they noticed them at all. Third, the idea seems to have prevailed that Pennsylvanian strata are so variable and discontinuous that the local occurrence of different kinds of sediments and their associations are not significant.

Because of the lenticular character of the strata . . . a generalized section . . . is of little value. (Cady, 1919, p. 64.)

On account of this variable and lenticular character of the strata it has not been possible to identify any easily recognized stratigraphic units . . . . (Savage and Udden, 1922, p. 143-144.)

Fourth, in many areas either marine beds or coals of noteworthy thickness are missing from the cycles. Finally, most theoretical speculation was devoted to the problem of the origin of coal.

Rediscovery

The Pennsylvanian cycle so well described by Udden was rediscovered in Illinois in 1926.

. . . each series of beds starts with an unconformable sandstone below, contains an underclay and coal horizon in the middle, and continues above with limestone and shale. Such a series of beds . . . may be observed in almost every section from the bottom to the top of the system as developed in western Illinois. (Weller, 1930, p. 102.)

These cycles were demonstrated in the Peoria area on a field trip following a meeting of the Association of American State Geologists in 1927. This evidently stimulated interest because cycles were soon distinguished in other states both to the east and west.

> . . . each sandstone represents the definite termination of a stratigraphic substage or depositional cycle [and] it is evident that there have been nine such cycles in the history of Monongahela deposition . . . [in West Virginia]. (Reger, 1929, p. 136.)

> Detailed stratigraphic studies of the Pennsylvanian deposits of Kansas, Nebraska and northern Oklahoma show that well marked rhythms or cycles of sedimentation characterize at least a considerable part of the section . . . . These sequences so closely duplicate one another that it is easily possible to mistake the identity of a formation . . . . (Moore, 1930, p. 51-52.)

An essentially similar cycle in the English Carboniferous was reported at about the same time.

> An interesting feature of the detailed stratigraphy of the Millstone Grits and Lower Coal Measures, and to a less degree of the Middle Coal Measures, is the occurrence of a well-marked rhythm in the sedimentation. Throughout we find repeated in varying degrees of completeness the four-fold cycle [in descending order] Coal, Sandstone, Mudstone, Marine Band. (Wright and others, 1927, p. 9.)

A symposium (Weller and others, 1931) on Pennsylvanian stratigraphy was held in Urbana, Illinois, in 1930 which served further to publicize the renewed interest that had developed in Pennsylvanian cycles.

A historical resumé of the development of Pennsylvanian cyclic studies in the United States has been published (Weller, 1961, p. 130-135) and does not need to be repeated here. In 1932 the word, cyclothem, was introduced for Pennsylvanian cycles.

> The word "cyclothem" is therefore proposed to designate a series of beds deposited during a single sedimentary cycle of the type that prevailed during the Pennsylvanian period. (Weller, *in* Wanless and Weller, 1932, p. 1003.)

Evidently, cyclothem filled a need because it was soon adopted and used by other geologists. Besides numerous individually published papers, symposia devoted to cyclic sedimentation, generally with emphasis on the Pennsylvanian, were held in London in 1948 (International Geological Congress, 1950) and in Houston, Texas, in 1963 (Society of Economic Paleontologists and Mineralogists, 1963). Pennsylvanian cyclic sedimentation formerly met with considerable skepticism, but it is now well known to be more or less characteristic of the Upper Carboniferous in many parts of the world.

OTHER CYCLOTHEMS

Cyclic sedimentation is not restricted to the Pennsylvanian. Although it occurs and has been recognized in rocks of other ages, it is, however, nowhere developed so clearly or so widely in other systems. For this reason, the Pennsylvanian cyclothem may be taken as a model with which other types of cycles can be compared.

Strata of the Mississippian, below the Pennsylvanian in some areas, and those of the Permian, above it in others, are distinctly cyclic in their arrangement. For example, cycles are evident in some of the descriptions of stratigraphic sections in parts of England and southern Scotland that were published long ago.

> . . . the most striking feature of the mountain limestone [lower Carboniferous] deposits of the North of England, [is] the repeated succession of nearly similar combinations ["terms," p. 182] of limestone, gritstone, and shale. . . . (Phillips, 1836, p. 175.)

Later accounts have noted them more specifically.

> The alternations of these beds fall into a certain orderly sequence which marks them into zones and cycles . . . a complete cycle of deposition, of which the lower part is marine and calcareous, and passes up into mechanical sediment in a fine state of division; while the upper part is marked by a coarsening of the deposits, by an intermingling of plant remains, and by the presence (general), near the top, of Coal or the roots of *Stigmaria* in situ. . . . (Miller, 1887; Dunham, 1950, p. 47; see also, Peach, 1888, p. 17.)

> . . . the general succession is one of shale, sandstone and limestone, repeated in the same order several times. . . . (Hudson, 1924, p. 125.) Occasionally this sedimentation culminates in emergence, and coal seams result either at the top, or near the top, of the sandstone. (Hudson, 1924, p. 132.)

The outcropping Chester Series (Upper Mississippian) of Illinois, Indiana, and western Kentucky also provides a good example. Stuart Weller (1920, p. 285) distinguished 16

alternating sandstone and limestone-shale formations.

> Throughout the alternating succession of Chester formations, the several units should be considered in pairs, each pair consisting of a sandstone formation below, passing upward into a limestone-shale formation. . . . Each one of these pairs doubtless represents one oscillatory advance and retreat of the waters of the basin. (S. Weller, 1920, p. 414.)

Moreover:

> In four or five of the units [pairs] thin coal beds are present between the sandstone and limestone-shale portions [formations] and thus these units resemble the cyclothems of the Pennsylvanian system. (Weller and Sutton, 1940, p. 847.)

Permian sedimentary cycles in Kansas generally lack sandstones and coals but otherwise they are not greatly different from some of those in the underlying Pennsylvanian.

> . . . there is a strikingly remarkable recurrence in the same sequence of very similar strata. . . . there are eight or ten complete or nearly complete cycles of sedimentation, or cyclothems, each of which, where complete, has the following parts: (1) beds of varicolored [generally red] shales . . .; (2) a thin bed of limestone . . .; (3) highly fossiliferous . . . shale . . .; and (4) a series of limestone beds . . . much thicker than the [other] limestone . . . these rhythmic cycles are quite as persistent and regular . . . as are those in the Pennsylvanian of Kansas. . . . (Jewett, 1933, p. 138-139.)

The Devonian "Old Red Sandstone" of northern Scotland includes considerable thicknesses of nonred strata arranged in a recurrent sequence of (1) fine-grained, cross-bedded sandstone at the base, (2) greenish, mudcracked shale, (3) dark-bluish to black, calcareous shale, and (4) dark, impure limestone with fossil fish (Crampton and Carruthers, 1914, p. 102).

> . . . the rhythmic sequence is confined to continental, alluvial, and lacustrine deposits, and has resulted from variations in the height of the flood-water level on the one hand, and from a recurrence of periods of quiescence and crustal deformation on the other. (Crampton and Carruthers, 1914, p. 89-90.)

Twelve sedimentary cycles, which seem to be closely similar to those of the Pennsylvanian, have been described in Sweden in a section of uppermost Triassic or lowermost Jurassic beds 250 meters thick.

> Each cycle begins with nonmarine beds, contains clays and coal in the upper part, and is terminated by a calcareous or ferruginous bed with marine fossils. (Troedsson, 1950, p. 64.)

Cycles of a somewhat different kind occur in the Upper Cretaceous of Utah and Colorado. There, the Mesaverde Sandstone, and its subdivisions, and the Mancos Shale intertongue extensively in the Book Cliffs and elsewhere. Excellent exposures permit the tracing of individual beds for long distances. Several coals are present.

> A generalized cycle of four units can be recognized in these deposits: (1) basal marine shale, (2) littoral marine sandstone, (3) lagoonal rocks, (4) coal. (Young, 1955, p. 177.)

Rather regularly spaced Tertiary coals in part of the Philippines are separated by intervals of clay which include, alternately, coral fragments grading laterally into limestone, and local sand bodies.

> A pair of these contrasting intervals might be interpreted as a depositional cycle, and the two associated coal beds might have accumulated under transgressive and regressive conditions respectively. (Crispin and others, 1955, p. 15.)

Many other examples of cycles or cyclothemlike sequences in all parts of the stratigraphic section might be cited (Wells, 1960). Some undoubtedly record interesting recurrent series of conditions, but others are little more than the alternations of two kinds of strata. In the absence of both coal, or other surely terrestrial material, and sediments with marine fossils, comparisons with Pennsylvanian cyclothems are uncertain and interpretations in terms of geologic history are doubtful.

CYCLES OF CYCLOTHEMS

The idea of a cycle involves repetition because a cycle can be recognized only if units are repeated in the same order. The question that inevitably arises is: How closely similar must the repetition be? An answer seems to depend on two requirements: (1) nearly complete transitions between variants must be observed, and (2) a generalization must be made reducing the cycle to its simplest form by excluding all unessential details. The cycles, then, must be closely similar with respect to this simple form.

Some Pennsylvanian cyclothems are so similar that they are easily mistaken for each other but others are so different that their similarities are not immediately apparent (Wanless, 1947; 1950, p. 20; Weller, 1961, p. 142-148). When all common variants are considered, a single "ideal" cyclothem can be constructed that embodies most of the variant characters. This consists of ten or more members (Weller and Wanless, 1939, p. 1377), but all of these are not necessary for the cycle to be recognized. In its simplest or most reduced form, the Pennsylvanian cyclothem requires only three or four members (Weller, 1961, p. 142). Those likely to be most important are underclay, coal, and strata with marine fossils. In early cyclothemic studies, a marine limestone was observed to be a common development of the last (Weller, 1930, p. 102).

The Pennsylvanian cycle originally recognized in Kansas (Moore, 1930) contains several, up to five, marine limestones. Each of these limestones was believed to identify a different, simple but compressed cyclothem.

> This repeated succession of cyclothems of different character indicates a rhythm of larger order than that shown in the individual cycles and suggests the desirability of a term to designate a combination of related cyclothems. The word "megacyclothem" will be used in this sense to define a cycle of cyclothems. (Moore, 1936, p. 29.)

Later field studies in Illinois showed that many seemingly simple cyclothems include two marine limestones. Therefore, the possibility was entertained that a megacyclothem might be only a further elaboration of this more complex sequence (Wanless and Shepard, 1936, p. 1202; Wanless, 1950, p. 21).

Detailed lithologic analyses of the Kansas megacyclothems have revealed the presence of rudimentary representatives of certain previously unrecognized members of the simple cyclothem in some, but not all, of the shaly intervals between the limestones (Weller, 1958, p. 198-201). This seems to confirm the original conclusion that the megacyclothem is a cycle of simple cyclothems. It also suggests that a cycle of cyclothems of a different kind recognized in Illinois (Weller, 1942) can be equated with the Kansas megacyclothem.

Further consideration of the Kansas section reveals a still larger, four times repeated cycle.

> This great cycle may be termed a *hypercyclothem*. Each consist of four megacyclothems and an alternating detrital sequence of more than ordinary thickness and complexity. (Weller, 1958, p. 203-204.)

Other so-called cycles consisting of subordinate cyclothems have been reported (Young, 1955, p. 199-200; D. Moore, 1959, p. 523-524; Jablokov and others, 1961, p. 298-299). Mostly these seem to be groups of cyclothems which resemble each other in some of their characters rather than recurrences of similar sequences of cyclothems.

INTERPRETATION OF CYCLOTHEMS

Surely no single explanation can account for the origin of all sedimentary cycles (*see*, Robertson, 1948, p. 143). Primary attention in the following, therefore, is directed to Pennsylvanian cyclothems and other cyclothemlike stratigraphic sequences. These cycles have been observed most carefully and commented upon most commonly, and they, more than any others, have been productive of the most varied interpretations. At the very outset, the observation should be made that much remains to be learned about these cycles and it is safe to say that no interpretation yet made can be accepted more than very tentatively. Furthermore, the only truly scientific approach to a problem of this kind is one of critical appraisal and sympathetic skepticism.

Before proceeding with this consideration, several other general observations are in order: (1) The existence of sedimentary cycles of a particular type must be conceded. This is obvious but necessary because some experienced stratigraphers have denied the existence of cyclothems.

> . . . were these recurrences rhythmic or cyclic in character? My own answer is "yes" to the extent of the coal and its underclay, and "no" beyond that. (Ashley, 1931, p. 241.)

It is quite natural that: (2) The opinions of every person are likely to be biased in a way that depends upon the region with which he is most familiar. Thus, most geologists working in the central United States are impressed by the great lateral persistence and uniformity of many cyclothems, or at least some of their principal members.

> Individual phases of various Pennsylvanian and Permian cyclothems in the northern midcontinent have been traced along the outcrop for distances of 400 miles or more. Many of them have been identified down dip into basins for distances of at least 300 miles from outcrop. (Moore, 1950, p. 12.)

On the other hand, those whose experience has been gained at places closer to the source of sediments are more aware of lateral changes occurring in short distances and of possible confusing irregularities such as splitting coals (Thiadens and Haites, 1944). In the same way, views will differ depending upon whether marine strata are rare or dominant in the local stratigraphic section. Furthermore: (3) some of the Mississippian and Permian cycles that have been recognized differ more or less notably from the ordinary Pennsylvanian cyclothems. Good reasons, however, are believed to exist for concluding that these are all related in their origin and that they differ mainly because they represent somewhat different environments. Any adequate theory must take into account whatever evidence is provided by each variety of the cycle.

Theories interpreting the origin of Pennsylvanian-type cyclothems can be classified roughly in three groups, each of which includes several variations (Westoll, 1962, p. 767-768). These are (1) diastrophic theories —sinking basins, rising sedimentary source areas, either continuous, intermittent, or reversing, (2) climatic theories—glaciation producing sea-level oscillations, rainfall cycles and variable erosion, and (3) sedimentation theories—differential deposition related to depth of water, strength of currents, or distance from a river's mouth, compaction of sediments, etc. Most of these theories have been critically reviewed recently (Weller, 1956, p. 18-25; Wheeler and Murray, 1957, p. 1986-1998; Weller and others, 1958; Goodlet, 1959, p. 220-224; Beerbower, 1961) and details cannot be repeated here. All or most of these theories seem to be unsatisfactory in one or more respects.

Diastrophic Theories

Subsidence probably has prevailed in any basin where an appreciable amount of sediment accumulated and, in the long run, sediment thickness generally can be accepted as an approximate measure of the total amount of subsidence. Confidence in such a probability is increased if sedimentary characters indicate that deposition occurred close below or above sea level. Evidence of deposition within this narrow range is provided by all late Paleozoic sedimentary cycles. Likewise, elevation must have prevailed in the source area to account for a great amount of sediment contributed over a long period of time.

(1) Continuous subsidence of basins—If cycles developed in a continuously and evenly subsiding basin, changes in sedimentation must have resulted from other factors, particularly those controlling the kind and quantity of sediment provided. Therefore, diastrophism within the basin was not primarily important in their origin.

(2) Intermittent subsidence of basins—One of the oldest theories accounts for cyclothems by only intermittent subsidence. The origin of this rather obvious explanation is not known but it has been expressed many times.

> . . . downward movement . . . was marked by pauses, long enough for the silting up of lagoons and the spread of coal jungles. (Geikie, 1882, p. 722.)

> The movement was one of slight but rather rapid depression, followed by a pause, this order being repeated over and over for each succeeding cycle. (Stout, 1931, p. 211.)

> Each subsidence was followed by accumulation of sediments, leading to the filling of basin and formation of a swamp. (Trueman, 1947, p. lvi.)

The simple idea involved here is that deposition lagged behind subsidence and that during the pause deposition occurred in progressively shallowing water. Nothing is inferred about conditions in the source area.

A somewhat more sophisticated idea has been presented.

> The regularity of the pattern [of rhythms] throughout long periods of time, and its relationship to the present structures suggests that the pattern is due to areal stresses [resulting in subsidence in synclines], more or less constant in direction, deep seated in origin, and probably related to the contemporaneous Variscan orogeny. (Goodlet, 1959, p. 227.)

Intermittent subsidence may have produced cycles, but it need not have involved the sedimentary basins.

> . . . the two processes of displacement of [ocean] water by sedimentation and accommodation of water

by sea bottom movement [subsidence] as proceeding side by side and of the same order of magnitude, but by no means always counteracting each other [unsynchronized]. This would result in a continual oscillation of absolute sea level . . . . (Wells, 1960, p. 401.)

(3) Alternate subsidence and elevation—Some evidence has been considered to suggest that dominant subsidence in the basins was interrupted by periodic minor uplifts.

The alternations of limestones containing marine remains, and of sandstones, shales and coal-beds with no trace of a marine creature in them, are exceedingly remarkable, and seem difficult of explanation without calling in the aid of oscillations of the solid surface of the earth, by which very gradual rises and depressions are effected. (De la Beche, 1837, p. 264.)

. . . the Appalachian and Eastern Interior [coal] fields . . . were characterized by slow, widespread sinking with many long pauses and frequent slight uplifts followed by surface erosion. (Ashley, 1931, p. 245.)

. . . the depth of erosional entrenchment [below sandstones], . . . indicate a connection between erosional wash-outs and tectonic uplifts in the area of sedimentation. (Jablokov and others, 1961, p. 297.)

The kinds of sediments delivered to the basins can be explained if basin movements paralleled those of the adjacent uplands.

. . . cyclothems were developed by repeated [synchronous] oscillations [of both basins and source areas], each consisting of a long gradual subsidence followed by a short sharp uplift both centering in the area from which sediments were derived. (Weller, 1956, p. 47.)

. . . upward crustal movements . . . lead to the emergence of the coalbelt, and to the beginning of hinterland erosion. (Rutten, 1952, p. 534.)

Climatic Theories

Climate is a factor that may have influenced sedimentation importantly. Repeated glaciations could account for eustatic shifts in sea level. Rainfall cycles might affect erosion directly, or indirectly in a reverse way by contributing to the growth of vegetation.

(1) Glaciation—Late Paleozoic glaciation has been called upon to explain rise and fall of sea level in either a gradually or an intermittently subsiding basin.

. . . the depositional basins are thought to have subsided slowly as sediment accumulated, the cyclic fluctuations being due to the rise and fall of sea level . . . . (Wanless and Shepard, 1936, p. 1206.) . . . the cycles are inferred to be causally related to glaciation . . . . (Wanless and Shepard, 1936, p. 1202.) . . . widespread glaciation, particularly in the southern hemisphere . . . must have lowered sea level, and caused the temporary withdrawal of waters from large portions of shallow interior seas. (Wanless and Shepard, 1936, p. 1205; see also, Wanless, 1950; Beerbower, 1961.)

A variant of this theory seeks to relate a more complex double cyclothem to a pair of glaciations produced during a single solar radiation cycle (Simpson, 1934).

. . . a typical cyclothem records four distinct base-level reversals rather than two [i. e., sea level rose and fell twice] . . . . (Wheeler and Murray, 1957, p. 1993.) . . . Simpson's theory or its modifications demand eustatic fluctuations and climatic changes of the same magnitude and sequential order as those indicated by Paleozoic stratigraphy. . . . (Wheeler and Murray, 1957, p. 1985; see also, Wilson and Stearns, 1960.)

These theories obviously require a great number of glaciations continuously from the late Mississippian to the early Permian.

(2) Rainfall—Humid and arid epochs resulting from glaciation or some other cause have been suggested as either the main or a contributory factor in the origin of cyclothems.

The aridity, the cold and the temperature extremes [during a glacial epoch] would have tended to reduce the vegetation on the upland source area. As a result these areas would have been subject to . . . greatly increased erosion. (Wanless and Shepard, 1936, p. 1200.)

The major clastic pulse [sand deposition] is the result of a relatively arid climate in the source area . . . . With increasing humidity and more effective plant cover at the source, a smaller supply of fine sediment cannot keep up with the rate of basin sinking. (Swann, 1963.)

The opposite idea that increased rainfall resulted in more rapid erosion and greater amounts of detrital sediments also has been expressed.

If there was a cyclical climatic variation . . . it is likely that periods of aridity would be represented by the limestones and periods of humidity by the terriginous sediments and coal. . . . (Brough, 1928, p. 125.)

Sedimentation Theories

All sedimentation theories are more or less complex. They relate the production, delivery, or deposition of different materials to a variety of factors such as earth movements, fluctuating climate, physiographic development of the land, changing sea level, strength of currents, distance from source, compaction of sediments, and the building and breaking of barriers to the distribution of sediments. Several of these theories have been included in the foregoing.

(1) Peneplanation — Successive uplifts of the land each followed by peneplanation might account for an intermittent supply of variably coarse sediment.

The major succession of shale, sandstone and limestone can thus be read in terms of uplift and denudation, reduction of land level, and finally cessation of erosion of the land [i. e., peneplanation]. (Hudson, 1924, p. 135.)

Coarse grained detritus from the remnants of the hinterland hills is still being spread over the coal-belt area, up till the time when the entire region has been peneplained. (Rutten, 1952, p. 535.)

(2) Differential settling — Several theories relate coarseness of sediment to settling in different depths of water and explain vertical changes in the deposits by advance and retreat of shore lines and the resulting variation in water depth. One of them supposes that coal, next to limestone, records the deepest water environment.

. . . the rivers were carrying . . . all kinds of materials . . . and . . . debris of fragile plants. . . . All . . . were submitted to the action of separation in order of density, and . . . to the distance from shore. . . . (Simoens, 1918, p. 7.) . . . organic matter is able to travel [float] much farther out to the high seas. . . . (Simoens, 1918, p. 8.) The coal is a terriginous sediment which has been deposited in the sea very far from shore. . . . (Simoens, 1918, p. 9.)

(3) Currents—Strength of currents in the sea would have much the same effect as depth of water in influencing the kind of sediment deposited.

The sands alternate with slightly finer sediments that were, no doubt, actually suspended in the same currents. . . . In the deeper seas the currents might be stronger because less interrupted, and might more rapidly bring forward the continental deposits [particularly sand] from their evidently somewhat distant source. . . . (Udden, 1912, p. 49.)

(4) Shifting deltas—The distributaries in a deltaic area shifted from side to side so that detrital sediments were delivered to the sea now at one place and later at another where sand bodies were built up. There, the sediment surface rose to sea level and coal swamps may have formed. At the same time, normal marine conditions prevailed elsewhere. Lateral shifting of the actively growing delta front and submergence of its older parts resulted in the development of cycles.

Each major cyclothem is the result of interplay of two environments: a shallow epicontinental sea whose normal sediment was limestone, and the delta of a large river. . . . Regional subsidence, slower than delta deposition but continuing after the delta built up above sea level, gradually drew the [older] bypassed parts of the delta plain below the sea. (D. Moore, 1959, p. 522.) . . . the apparent periodicity in delta deposition . . . resulted from crevassing [breaking of natural levees] in the trunk river. . . . (D. Moore, 1959, p. 538).

A river pushes its delta hundreds of miles across a gradually subsiding basin, then is unable to keep up with the sinking, so that the sea reclaims the basin. Two factors seem to be involved—rate of basin subsidence and the rate of sediment supply, with cyclic development dependent upon the change of one with respect to the other. (Swann, 1963; see also, Goodlet, 1959; Duff and Walton, 1962.)

(5) Alluvial vs. deltaic environment—If strata below coal beds were deposited on an extensive alluvial or coastal plain, the channels cut below sandstones would be the result of subaerial erosion.

It is highly improbable that such channels could have been eroded in the bottom of a shallow epicontinental sea. (Weller, 1930, p. 116.)

The succeeding shale and coal [above the sandstone] are clearly continental in origin and indicate deposits made on an extremely low, flat coastal plain. (Moore, 1936, p. 25.)

In sedimentation cycles of coal measures alluvial [as distinct from deltaic] deposits are always beneath the coal seam with which they are paragenetically connected by a gradual transition from channel deposits through flood plain deposits and to bog deposits. (Jablokov and others, 1961, p. 296.)

The channels apparently are nonmarine and most of their fill material . . . is very likely nonmarine in origin. (Mudge and Yochelson, 1962, p. 98.)

Those who have favored eustatic or deltaic theories, however, generally considered the channels to be submarine.

These valleys . . . may have been cut in part below sea level. . . . (Wanless and Shepard, 1936, p. 1202.)

The writers believe that they [channel sandstones] mark submarine distributaries down which sediment-laden water moved from shallow to deeper water. (Wilson and Stearns, 1960, p. 1459-1460.)

Actually the base of the sandstone in most places was deposited well below sea level, and in some instances may represent deposition at the greatest depth of any of the parts of the cyclothem. (Swann, 1963.)

(6) Compaction—Differential compaction of sediment has been included as a more or less important part of several theories. For example, compaction of a thick peat bed might have had the same effect in a basin as subsidence or rising sea level.

. . . immediately after the deposition of the first sedimentary covering to the drowned peat, considerable sinking of the region must have taken place [because of compaction]. If the sea happened to be near at that moment, marine incursion naturally followed. (van der Heide, 1950, p. 40.)

(7) Barriers—Different deltaic environments were separated by barriers in the form of natural levees and coastal sand bars. When barriers were broken, sudden environmental change resulted.

. . . the barrier broke, and the swamp area was flooded. (Robertson, 1948, p. 163.) . . . a return to salt or brackish water conditions . . . was due to the breakdown of a barrier or levee. . . . (Robertson, 1948, p. 171.) The barrier was built up again by current action. . . . (Robertson, 1948, p. 168.) . . . the return to fresh water conditions was due . . . to the restoration of a levee or lagoonal bar which had shut off the mass of swamp vegetation from the sea or river. (Robertson, 1948, p. 167.)

Swamp vegetation also constituted barriers to the distribution of detrital sediment.

Plant growth holds back deposition of other sediments [acts as a filter] until subsidence [and compaction] has taken place to such an extent as to induce extensive and rapid flooding. (Robertson, 1948, p. 173.)

The vegetation prevents the sediment bearing stream from spreading its load all over the delta. (Robertson, 1952, p. 519.)

CONCLUSIONS

Almost every conceivable factor that might have influenced the development of late Paleozoic sedimentary cycles has been incorporated ingeniously into one theory or another. Many of the views expressed are irreconcilable, and it is obvious that no agreement is presently in prospect.

. . . the cycles represent recurrent submergences, alternating with periods during which the sunken areas were filled to the level of the surface of the sea. (Udden, 1912, p. 49.)

. . . the geosyncline [coal basin] emerges from the marine transgression through upward crustal movement, and not through sedimentary silting up . . . . (Rutten, 1952, p. 533.)

. . . progressive compaction of the sediments . . . must have played an important part . . . . (Trueman, 1954, p. 15.)

. . . compaction *combined with strong differential subsidence*—and not compaction alone—had caused the rhythmic development. (Fearnsides, 1950, p. 63.)

[It is] unnecessary to assume intermittent subsidence in order to account for the production of a rhythmic sequence of Coal Measures type. (Robertson, 1950, p. 62.)

. . . there remains clear evidence that the intermittent (cyclical) subsidences of the area of sedimentation were related to the wider tectonic events of the period. (Trueman, 1947, p. lxii.)

[It is not] necessary to invoke actual individual tectonic rhythms in any one place . . . . (Wells, 1960, p. 401.)

Only the theories of glaciation-eustatic fluctuations explain the localization of this type of cyclothem within the late Paleozoic. (Beerbower, 1961, p. 1048.)

The sedimentary cycles resulted directly from the pluvial-interpluvial alternations, and their relations to glacial cycles was secondary. . . . Neither worldwide eustatic sea-level change nor regional tectonism was needed for cyclic development. (Swann, 1964.)

It seems most unlikely that each rhythm could be the result of a series of complex diastrophic movements affecting large areas. Moreover, it seems highly improbable that each rhythm records a glacial and an interglacial episode in the Southern Hemisphere and it is almost inconceivable that it should record two each of such episodes. (Goodlet, 1959, p. 223.)

The relations between the rock types and faunal assemblages of the midcontinent area, attributed by some individuals to rapid fluctuations of sea level, might be explained equally well by combinations of other physical and chemical factors. Cyclic sedimentation may be as much a reflection of changes on the land as of changes in sea level. (Mudge and Yochelson, 1962, p. 115.)

. . . cyclic causes . . . all fail to account for one or another features of these cyclothems. (D. Moore, 1959, p. 538.)

When, if ever, the true explantion of late Paleozoic sedimentary cycles is discovered, it probably will embody parts of several of the theories that have been proposed. In the meantime:

No more fascinating field for research and speculation exists within the entire domain of stratigraphy. (Weller, 1956, p. 48.)

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Baselevel Transit Cycle

ABSTRACT

All stratigraphic "datum" points either coincide with or relate directly to the lithosphere surface at the time of their origin. At any moment, any point on the lithosphere surface may be undergoing either deposition or degradation, or may be in a condition of equilibrium (baselevel). Because deposition and degradation always alternate by the also alternating upward and downward transit of baselevel across the lithosphere surface, baselevel may be seen as an undulating, abstract, worldwide surface. Consequent, area-time, stratigraphic patterns are cyclic, in which the depositional and hiatal phases alternate. Because the major baselevel transit cycles generally differ from the "insignificant" ones by several orders of magnitude, the fragmentary preserved record of the depositional phases of these major cycles may be distinguished as unconformity-bounded *sequences* which serve as the stratigraphic basis for interpretation of the major episodes in geologic history.

INTRODUCTION

As its title implies, most of the considerations of this symposium properly involve cyclic phenomena in terms of their sedimentological or other exclusively depositional aspects. Through a somewhat broader view of stratigraphy, however, it has become increasingly evident that there exists a sizable family of stratally manifested cycles, in one group of which deposition comprises only a cyclic phase. It is with this group that this paper is primarily concerned.

The writer, among others in recent years, has attempted to demonstrate the importance of not only the general concept that stratigraphy is four dimensional, but also of devising a system in which the dimensional configuration of such entities as nondeposition and erosionally removed former deposits in the framework of area-time is no less essential to the ultimate interpretation of geologic history than is the configuration of the preserved stratal record in both geologic and stratigraphic space (Wheeler, 1958, 1959, 1964). Parenthetically, the fact that the appreciably compromised, and thus partly outdated, "Stratigraphic Code" (American Stratigraphic Commission, 1961) gives no consideration to most of these problems makes them no less paramount. The point is that although such units are all present-day abstractions, the genesis of each has comprised a continuous succession of real or tangible *lithosphere surface-moments,* without the envisagement (and at least general interpretation) of which, anything approaching a proper reconstruction of geologic history is impossible. Abstract and volumeless though they are in the fragmented stratal record of present geologic space, two of these entities, holostrome and hiatus, constitute the alternate depositional and nondepositional phases of the countless succession of cycles comprising the stratigraphic history of any given place on the earth's surface.

Proper appreciation for the constitution and role of these cycles may be enhanced by the consideration of a few stratigraphic principles, one of which involves the concept of the above-mentioned lithosphere surface-moments.

LAW OF LITHOSPHERE SURFACE RELATIONS

Wheeler (1959) has cited the U. S. S. R. Stratigraphic Committee (Rotay, 1956) and Dunbar and Rodgers (1957) as pointing out that all surface-accumulated rocks, whether they be sedimentary or not, comprise the stratigraphic record, and that all subsurface-emplaced rocks, whether or not they consist of "sedimentary materials" (igneous intrusions, metamorphic bodies, veins, sandstone or evaporite intrusions, and cavern deposits) are nonstratigraphic in their relations to enclosing rocks. Only by making this distinction can a consistent system of universally operative stratigraphic concepts, principles, and laws be derived. In this essential sense, contrary to the implication of the American Stratigraphic Commission (1961), all rocks of the earth's crust do not comprise stratigraphic units or entities. (This is not to argue that a formation, in all instances, must be a stratigraphic unit.)

Once this restriction is accepted, not only does the law of superposition become universally operative, but any stratigraphically defined point at the base, the top, or within any stratal succession, either was located on the lithosphere surface or its being was directly related to that surface at the time of its genesis. The base of a detirital particle, organic fragment or lava flow, for example, rests upon the lithosphere surface (depositional interface) at the moment of its emplacement. Such a particle fragment or layer may or may not be in "depositional continuity" with the underlying surface on which it rests; and regardless of whether such entities are followed in "continuity" by succeeding entities or whether they subsequently are wholly or in part removed, the lithosphere surface is always at hand, either as a surface of aggradation or of degradation. Moreover, in such a world of "pure" stratigraphy the ceaseless alternation of deposition and hiatus prevails throughout, regardless of the scale at which one may choose to interpret or recognize "continuity" and "discontinuity."

In these terms it is true that many fossils and lithic entities do not occur in precisely proper depositional succession, even though no "reworking" or structural derangement has occurred. Boring animals, for example, live beneath the lithosphere surface in rocks of any older age, but their stratigraphic significance is not diminished when they are properly related to the inevitable overlying surface (and depositional interface) to which they directly relate; or a regolith or a residual soil, though nondepositional, relates temporally to the surface beneath which it is formed and thus also to the base of the stratal unit which directly succeeds it, rather than to the older rock body which it occupies and of which it is composed. If this logic is correct, it leads to the simple and universally valid concept that any physical or biostratigraphic datum or any temporally conceived surface in any stratal succession at any specific locality has meaning only in the sense that it either coincides with the lithosphere surface or is directly relatable to that surface at the time of its origin. And it is equally obvious that any "continuous" stratal accumulation is a "complete" physical manifestation of a succession of *lithosphere surface-moments.*

But what of stratigraphic discontinuities as manifestations of nondeposition and accompanying erosion? Here we pass into the no less important but completely abstract, area-time framework, in which a discontinuity takes on volumetric configuration in the form of the lacuna, which in turn consists of hiatus and erosional vacuity. Here again, however, though now undergoing degradation, it is the evolution of the lithosphere surface which not only determines the configuration of the hiatus and consequent erosional vacuity, but which also culminates in the depositional interface at the base of the next succeeding deposition at any given locality. It is true, of course, that subsurface events may profoundly effect the evolution of the lithosphere surface, but the consequent subsurface-emplaced bodies themselves do not belong to the stratigraphic succession in this properly restricted sense of the term. From this it follows that any ultimate interpretation of the ebb and flow of events in area-time (geologic history) must attempt to envisage the succession of lithosphere surfaces relative to all other geological entities, as the *only universal* physical geologic "datum" surfaces with stratigraphic implication. This implies the following stratigraphic principle, which may be called the *law of surface relations: time as a stratigraphic dimension has meaning only to the extent that any given moment in the earth's history may be conceived as precisely coinciding with a corresponding worldwide lithosphere surface and all simultaneous events either occurring* *thereon or directly related thereto* (Wheeler, 1964).

At any given moment the earth's lithic surface is divisible into innumerable areas, each of which belongs to one or the other of two categories—depositional or degradational. The boundary between any two of these is *baselevel*, the concept of which, though basically simple, has tended to remain unnecessarily elusive among geologists.

BASELEVEL AS A WORLDWIDE ABSTRACT SURFACE

Past difficulties with the baselevel concept appear to stem largely from the understandable desire to identify it with an obvious and tangible datum. There is no question that *sea level* exerts a significant influence on the distribution of the factors which actually control baselevel, but it is utterly without control of many interior accumulation-degradation patterns. Baselevel is an abstract concept or principle which cannot be equated with any intrinsic datum. Barrell (1917) demonstrated that in any applicable geological field baselevel is simply a condition of equilibrium between deposition and degradation, and that it intersects the lithic surface at all points where the two processes are in contact. Many authors have cited Barrell in recent years, but the concept continues to remain elusive in one or another of its aspects. For example, Dunbar and Rodgers (1957) imply that baselevel intersects the surface as a "horizontal plane," and that "from the stratigraphers point of view it is the *baselevel of aggradation;*" while from another "viewpoint it is the baselevel of erosion." Many failures stem from the inadequate notion that stratigraphy is the science of past *sedimentation,* to the exclusion of degradation; but if a properly dimensioned stratigraphic system is admitted, there need be no modification of the baselevel concept which depends on whether it is being contemplated by the stratigrapher or some other kind of geologist. It is true, as more explicitly pointed out below, that a change through the equilibrium that is baselevel may *initiate* either deposition or degradation, but in the same stroke it also *terminates,* respectively, either degradation or deposition. The *direction* of change indeed differs in the "progressive" and "regressive" cases, but the viewpoint in no way alters either case. The notion that baselevel is a "horizontal plane" also leads to disparities which preclude adequate comprehension of this simple principle. It would demand countless numbers of "baselevels," each one of which would come into "being" or cease to "exist" with each change in the constantly fluctuating deposition-degradation patterns; and in some situations even takes an inverse position relative to deposition and degradation (see discussion of Figure 1, below).

The writer suggests the simple notion of a single, ever-present, worldwide, baselevel "sphere," constantly undulating and "vibrating" in response to the ever-changing patterns of sediment supply-energy relationship—rising above the surface wherever accumulation is initiated, and dropping beneath the surface as degradation commences, without regard for whether the increment is volcanic or sedimentary; marine or nonmarine; chemical, biogenic, or detrital or for the nature of the degradational process. It seems useful to envisage the supply factor as a buoyant force and the energy factor as a depressant force on baselevel. It thus intersects the lithosphere surface at all points of equilibrium, and its momentary "depth" beneath or "height" above the surface at any locality depends, not on the kind of increment, but on the relative "values" of supply and energy. Better understanding of the foregoing may be facilitated by diagrammatic representation (Fig. 1). Both cross sections show the same seawardly inclined lithosphere surface profile (S-S′), at a particular "moment," from an upland area to beneath sea level, along which two segments are undergoing erosion and two undergoing deposition.

The lower part of the profile in Figure 1A is taken from Dunbar and Rodgers (1957, p. 129), in which baselevel (A-A′) is shown as a horizontal plane. In addition, the upper part of the profile shows a subsiding interior basin in which deposition is occurring. If the notion of A-A′ is valid, then so is that of another baselevel plane represented by B-B′. Similarly, there should be such a plane in the position of C-C′. In this part of the profile,

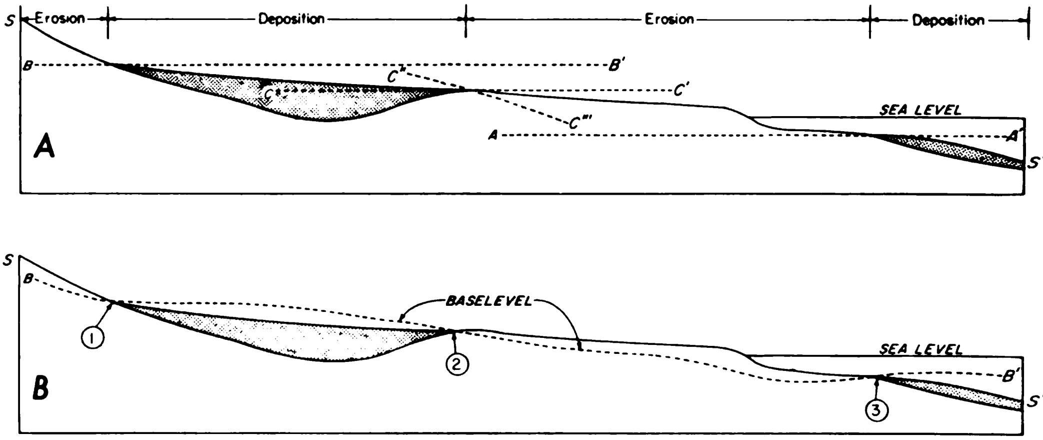

FIGURE 1.—Relation of baselevel to erosional and depositional surfaces: *A*, if baselevel is considered a "horizontal plane" (in part from Dunbar and Rodgers, 1957), and *B*, if baselevel is considered a single, ever-present, and worldwide "sphere" in response to changing patterns of sediment supply energy relationships.

however, as is often the case along exterior drainage profiles, it will at once be seen that any such horizontal surface as C-C′ does not obtain, for the depositional segment would be above such a "baselevel," and the erosional segment would be below it. (This is only one among the demonstrable disparities inherent in such a system of "horizontal baselevel surfaces.")

It is evident that the true baselevel surface in case C must have a downgrade slope, the inclination of which exceeds the surface slope, in the manner of C″-C‴. From this it may be readily seen that this C″-C‴ surface will merge with the B-B′ surface in the up-grade direction, and with the A-A′ surface in the down-grade direction; and if this logic is sound, an undulating surface approximated by B-C″-C‴-A′ represents the gross (not detailed) form of baselevel for the moment under consideration. The appropriate segment of this worldwide abstract surface (baselevel) is shown as B-B′ in Figure 1B. It is intrinsically represented, however, only at points 1, 2 and 3 on the profile.

Baselevel at any moment may thus emerge from and drop beneath the lithic surface many times on any profile, regardless of whether that profile includes marine, nonmarine, or both environments. Wherever and whenever baselevel in this sense intersects the surface in its transit either up or down, it marks a boundary between the two phases of the cycle under discussion.

BASELEVEL TRANSIT CYCLE

If under a degradational environment at a given locality, the supply-energy "ratio" increases sufficiently to induce deposition, baselevel crosses the lithosphere surface at that point, from below to above, at the moment deposition begins, thus initiating the first or depositional phase of a new cycle. This cyclic phase continues until the supply-energy "ratio" is decreased sufficiently to stop deposition and induce erosion, at which time baselevel makes its downward transit of the surface, thus beginning the second or hiatal cyclic phase. Whenever the supply-energy relationship is again reversed to the degree that baselevel rises to the surface the cycle is completed, and as it rises above the surface the initial phase of a new cycle begins. In this case the cycle is said to begin with upward transit of baselevel across the lithosphere surface as deposition is initiated. To break the cycle at this point, of course, is arbitrary, for it would be equally logical to envisage the break at either the next preceding or the next following downward transit as degradation is introduced. The choice here may indeed depend on the viewpoint of the geologist; i. e., whether he is primarily concerned with events and phenomena which accompany the depositional cyclic phase or those which relate to the nondeposition-erosion phase. For example, Wheeler and Murray (1957) commenced the cycle represented by a typical Pennsylvanian coal cyclothem (each of which is actually a binary pair of cycles in the terms discussed here) with the hiatal phase; while others have regarded the same cycle as beginning with the next following (depositional) phase.

Although in somewhat less explicit terms, this kind of cycle involving any two successive (and therefore opposite-direction) transits of baselevel through the lithic surface was defined by Wheeler (1959) as the "stratigraphic cycle." However, it is now evident, as it then should have been, that there are other cycles which are no less stratigraphic, and which may involve baselevel oscillation, but whose patterns may lie entirely within either the supra- or the sub-baselevel phase of the cycle considered herein. In other words, such cycles differ in the important respect that no baselevel-lithosphere surface intersection or transit takes place. Because this distinction is significant when expressed in terms of the ebb and flow of events in area-time (geologic history), the kind of cycle under present discussion may be more appropriately called the *baselevel transit cycle.*

In concept these cycles may be of any conceivable magnitude. Their depositional phases may vary in order of magnitude from the area and thickness of a clay particle to, say, a "continuously deposited" pan-continental *sequence* measuring thousands of meters in thickness; and their nondepositional phases may vary from similarly minute areas through a few successive moments of time, to vast interregional hiatuses with durations measured in many millions of years. Those of grosser magnitude, of course, may occur as cyclic entities only in a relative sense in which the lesser ones are deemed nonexistent (ignored). Such appeal to the principle of "existentialism" is admissible, however, only insofar as the cycles of great magnitude may generally differ in scale from the "insignificant" ones by at least several orders of magnitude.

Dunbar and Rodgers (1957) emphasize this ordinate distinction in their discussion of diastems and unconformities.

> As clearly seen by James Hutton, an unconformity records a change in the overall conditions . . . involving, at the least, regional uplift and erosion if not tectonic disturbance or metamorphism of the rocks that were formed before the break. Diastems, on the contrary, are smaller breaks that occur without any basic change in the general regimen . . . breaks resulting from fluctuations of stage . . . . The distinction can thus be generalized from the sediments [and discontinuities] of shallow marine waters to sediments [and volcanic accumulations (and associated breaks)] of all environments. Of course, there are many borderline cases where . . . judgments by competent observers will differ, but the two main groups of breaks are different enough in character [magnitude] and origin to warrant separation.

Although an appreciable range of magnitude characterizes each of these two categories, they generally differ, not only in order of magnitude, but also in the marked difference in the degree of their deformational and consequent erosional differentials. In other words, the widespread depositional "constants" which commonly characterize the major "conformable" successions are seldom "damaged" to any appreciable extent by the erosional effects of the myriads of included diastems or lesser baselevel transit cycles; while the original depositional patterns which represent the sub-baselevel phases of the major cycles are markedly fragmented by differential erosion during their ensuing hiatal or supra-baselevel phases. Appreciation for this distinction has led to the delineation of the preserved record representing the depositional phases of several of the major North American baselevel transit cycles as *sequences* (Sloss and others, 1949; Sloss, 1959, 1963; Wheeler, 1956, 1960a, 1960b, 1963; Shannon, 1962; Wheeler and Mallory, 1963). Sloss (1963) currently subdivides the Phanerozoic record of the North American cratonic interior into six major sequences—Sauk, Tippecanoe, Kaskaskia, Absaroka, Zuni, and Tejas. Except for the writer's interpretation that the "Kaskaskia" comprises two sequences, Piankasha and Tamaroa (Wheeler, 1963), and that there are breaks of comparable magnitude in addition to the sub-Zuni and sub-Tejas unconformities in the Mesozoic and Tertiary, his patterns are otherwise in remarkable agreement with those derived by Sloss.

In addition to naming the sequences, which designations apply equally well to their respective holostromes or depositional cyclic phases, Wheeler (1963) extends the common practice of naming the major "breaks," which names in each case apply equally well to the unconformity, the hiatus or nondepositional cyclic phase, and the orogeny, if any. Thus, any contiguous pair such as Sauk-Owl Creek, Tippecanoe-Wallbridge, and Piankasha-Acadian, when viewed in area-time, comprises a complete cycle.

The significant question here, however, is not whose current interpretations and nomenclatural treatment are the more valid, but rather the correctness and implications of this general approach to stratigraphic integration and historical interpretation, as opposed to the traditional one in which the preserved record and deposition tend to be regarded as synonymous, and in which the arbitrary "standard" column is generally regarded as essentially complete.

Because of the deep-rooted misapprehensions inherent in the traditional approach, it has taken several generations to begin to overcome the erroneous notion of a genetic relationship between the "standard" temporally conceived units (especially era and period) and the actual stratigraphic patterns in North America. Moreover, as a consequence of our slowness in developing the bases for interpreting the fragmentary unconformity-bounded sequences, not to mention the markedly episodic baselevel transit cycles which they partially represent, much of the reaction in recent years has taken the form of the equally erroneous notion that the stratigraphic patterns (and hence the tectonic history) have been continuously differential. Although the advocates of this newer notion (of whom the writer was one for some years) have generally recognized ephemeral local order, and sometimes regionally extensive orderly patterns, most of the current interpretations continue to envisage the differentials in the stratal record as the consequence of differential tectonic fluctuation accompanying deposition, commonly to the exclusion of differential deformation and erosional removal during the suprabaselevel cyclic phases. Even cursory studies of such features as the Appalachian, Michigan, Illinois and Williston Basins, and the Cincinnati, Nashville and Ozark Positives, among many others, in the light of the major holostromes (depositional cyclic phases) indicates that these structures, as such, had little, if any, significant influence on the constitution of the strata of which they are mainly composed. Such an integrated approach based on an adequately conceived, multi-dimensional, stratigraphic system is indeed in its infancy, but it is nevertheless abundantly clear that unless we employ and improve these presently demonstrable cyclic patterns which are best displayed at a scale of at least continental framework proportions, we can only continue the common but unrewarding practice of attempting to interpret the past parade of events *directly* from the thoroughly fragmented record, and thus to continue the relative stagnation that has beset stratigraphy for the past several decades.

Are these problems which relate to the interpretation of the major episodic framework patterns characteristic only of the regions outside the tectonic realm of the European systemic types? If the writer and associates can justifiably judge from their preliminary efforts to interpret a few of the major cyclic patterns on the basis of interregional relationships in Great Britain and elsewhere in western Europe, they are not. Contrary to popular opinion, there appear to be amazingly similar disparities between at least a number of the baselevel transit cycles and the systemic subdivision of the "standard" column in that region also. However, the statistical bases for these interpretations are not yet sufficiently adequate to justify a reporting of cases. Significant progress in these terms has been made in the Soviet Union by Schatsky (1958) and others in recent years. It will be interesting to learn more of the specific experiences and evolution of concepts which have led to these developments in that region.

The foregoing is the writer's response to his invitation to participate in this symposium on cyclic sedimentation. It is obvious that this brief paper does not precisely comply with the specifications, for the cycles discussed here, as a category, cannot be classed as purely sedimentologic in any normal or even acceptable sense. Nevertheless, like all stratigraphically derived cycles, they are ultimately based upon the presently preserved, surface-deposited record. But, unlike the elements of cyclic *sedimentation* in its proper sense, these cycles may be delineated only in the area-time dimensional framework, and thus exist only as abstractions; moreover, cycles of this kind are universally present in the sense that any stratal succession comprises the preserved record of the depositional phase of one or more of them. They are also universally present in the further sense that although the stratal record may be removed at any place, such cyclic patterns, insofar as they may be interpreted from surrounding relationships, are nonetheless present. In fact, the common failure to interpret the patterns of this "lost" record has resulted in innumerable naive or otherwise anomalous interpretations of geologic history. Regardless of these fundamental distinctions, it is equally obvious that many sedimentary cycles in the more restricted sense also involve the baselevel transit cycle. In the last analysis, however, it is on the basis of the fundamental stratigraphic principles which these and the other kinds of cycles share in common that these words may seek an appropriate place in the symposium. Even so, the writer is fully aware that there are presently many who will regard them at best as a mental exercise in abstract, "theoretical" stratigraphy, and therefore of little "practical" importance. He is also aware, however, of the growing minority who realize that progress in stratigraphy has long been inhibited by the self-imposed restriction of most of our thinking and practice to that which is both tangible and dimensionally simple.

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Cycles and Psychology

INTRODUCTION

One of the companion papers in this volume (W. C. Pearn) has furnished an example of a new means for dealing with cyclic, or more properly, repetitive sedimentary sequences. With the development of high-speed computer techniques we have a tool at hand that will allow us to attain greater objectivity in dealing with complex stratigraphic successions. These methods are so new that some time will be needed to work them out for application to the routine problems of geology. Meanwhile, we must continue to use those established techniques to which we have become accustomed. In an evaluation of our present techniques we find that the stratigraphic sequences of the Pennsylvanian present us with problems which are not entirely geologic but are, in part, related to the psychologic make-up of the geologists themselves.

Psychologists, anthropologists, and philosophers of science have long recognized the fact that there is a fundamental need in man to explain the nature of his surroundings and to attempt to make order out of randomness (Nagel, 1961). The Western mind does not willingly accept the concept of a truly random universe even though there may be much evidence to support this view. The scientist unfortunately cannot escape from his own humanness, and in fact, it is this very need to explain and organize which furnishes him with the basic drive to become a scientist. Science, to an extent matched by no other human endeavor, places a premium upon the ability of the individual to make order out of what appears disordered. Therefore, the scientist more than anyone else needs to maintain his objectivity about his work, and perhaps even more rigorously, about himself.

PSYCHOLOGICAL CYCLES

A test was devised to attempt to determine the extent to which psychological factors actually influenced geological thinking. Initially, a set of three logs plotted in the conventional form and each involving about 700 feet of section was given to a group of graduate students. They were asked to correlate the logs and, in every case, less than five minutes were required to complete the correlation. The correlation was frequently defended with considerable vigor when an attempt was made to question it or to suggest other possible correlations. The sections presented are reproduced in Figure 1 and show a typical Pennsylvanian type of cyclic sequence. The reader is asked to examine the sections carefully and to note the correlation line, which is that most commonly chosen by the students. A careful check of the correlation should be made with special attention being given to the cyclic nature of the beds, and the difficulty which this presents in making the correlation. It will be seen, however, that the correlation agreed upon by the students is the most appropriate one which can be made. The students were then given a log of a deep mine shaft located in Leavenworth County and asked to correlate the three logs with it. This section is also shown in Figure 1 with the stratigraphic units labeled. Again, the length of time necessary to complete the correlation was always less than five minutes, and there was little tendency to change the correlation

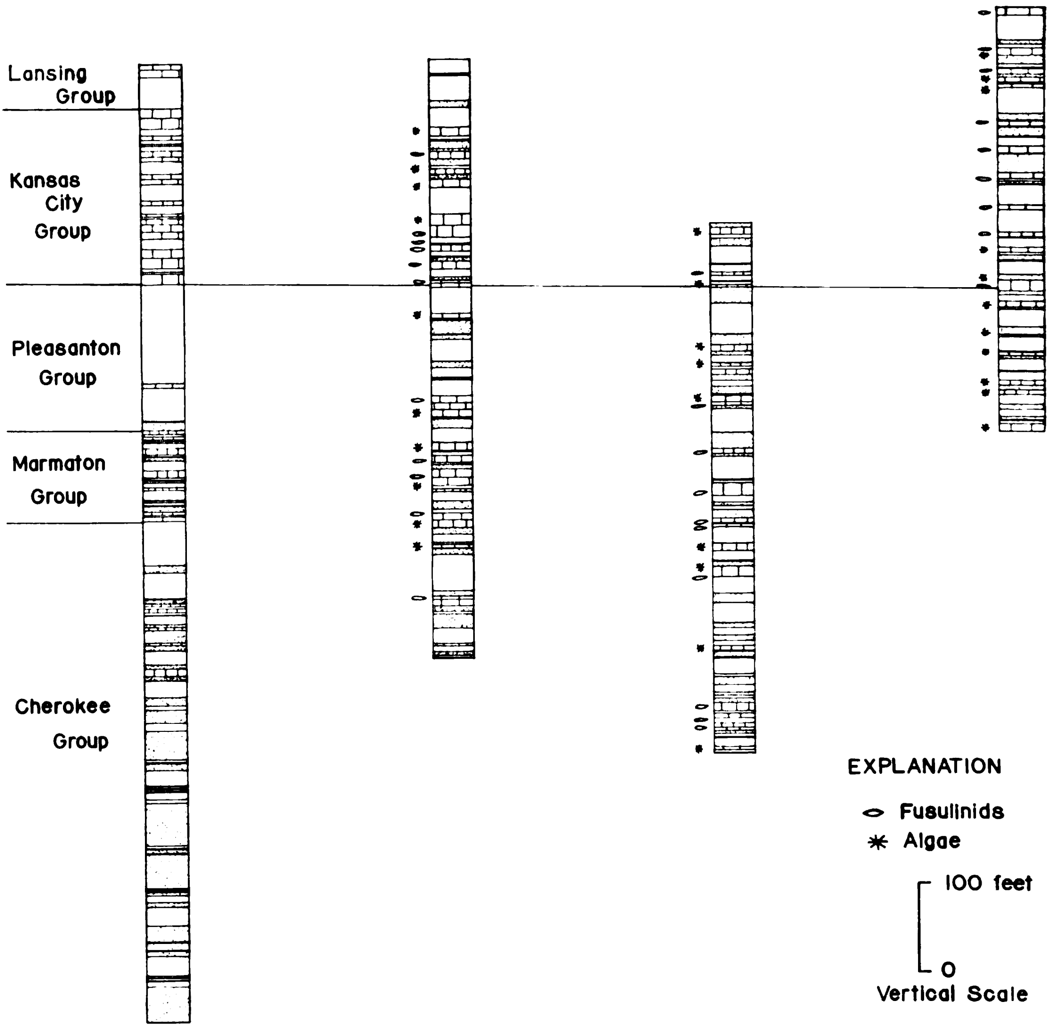

FIGURE 1.—Typical Pennsylvanian cyclic sequence: (1) lithologic log of deep mine shaft located in Leavenworth County with stratigraphic nomenclature, and (2, 3, 4) logs of lithologies plotted in conventional form (sequences numbered from left to right).

of the first three logs because of new information given in the mine shaft section. As before, the reader is asked to examine the proposed correlation given by the students and see if he agrees with their identification. These tests showed correlation of cyclic sequences by inspection to be relatively easy. When confronted by sections which had a familiar appearance, no one had difficulty in making correlations and no more than a normal amount of hesitation was exhibited by any of the geologists to whom the test was given. At this point a psychological question arose. Suppose that geological data were presented in a different way. What would happen if we reduced a geologic section in the Pennsylvanian to a series of numbers which could be used to represent the various lithologies? It is obvious that computer techniques will require that such numerical representations be used. At the same time, such a presentation would provide the geologist with data in an unfamiliar form, and in this instance, we were seeking to determine the extent to which geologists had become dependent upon a conventionalized presentation of data.

There is considerable precedent for the use of numbers in representing lithologic units.

Following the method proposed in Bulletin 22 of the Kansas Geological Survey (Moore, 1936) a series of columns was prepared. The numbering system is identical to that used in the description of the ideal cyclothem except that whole numbers are used instead of decimals. The stratigraphic section through the Kansas City Group was reduced to a column of numbers which is reproduced in Figure 2. When asked to correlate this section with three other columns also reproduced, the students encountered severe difficulty. The reader is asked to try his hand at a correlation using this set of columns. He will certainly find it much more difficult to make this type of correlation than was the case with the plotted logs. Part of the difficulty is related to the lack of thickness information. In a cyclic sequence, however, thickness should play a much less important role than that of the lithologic succession. Our tests have shown that geologists are indeed very dependent upon

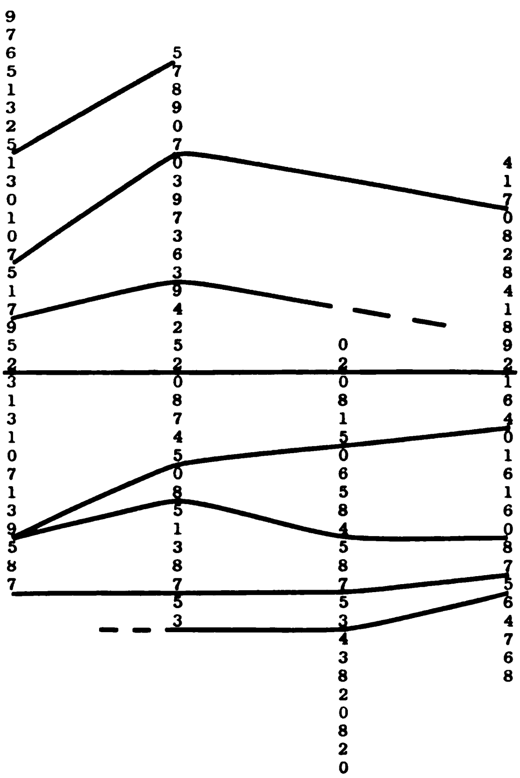

FIGURE 2.—Stratigraphic sections through Kansas City Group represented by columns of numbers (numbers refer to those used in description of ideal cyclothem).

the mode of presentation of data, but the tests have shown something else far more important.

In fact, both the students and the reader should have found it completely impossible to make any correlation either with plotted stratigraphic sections or with the columns of figures! In both cases only the left hand column was taken from real stratigraphic sections of actual rocks—the other sections were made up from columns of digits taken from a random number table (Lawrence, Kansas. Telephone Directory, 1961)! In the case of the plotted logs, the lithologies were assigned using the names for the units of the standard cyclothem and the thickness was determined by allowing an adjacent row of figures in the random number table to represent thickness in feet. Thus, except for the left hand column neither the logs nor the number sequences represent anything real, and they do not contain any genuine cyclicity.

If these stratigraphic sections and columns of figures are nothing more than a trick, a kind of joke, one can reasonably ask if they have any value beyond that of entertainment. It should be apparent to all that psychological factors play a much larger role in these and other phases of geology than most geologists would care to admit. In these tests, cycles were seen repeatedly in purely random sequences, and correlations were made where none was possible. It can be argued that the writer did not act in good faith. It should be remembered, however, that "good faith" is a human value and is related to a set of human ethics which did not influence the natural processes that combined to produce the stratigraphic section with which we must work.

Let the reader be assured that it is not the writers' intention to show that cyclothems are "a false creation proceeding from the heat oppressed brain." The paper by W. C. Pearn shows by a method which is about as objective as possible that the ideal cyclothem as proposed by Moore (1936) is a very good approximation of the true natural sequence. No attempt is being made to imply that the Pennsylvanian of Kansas, as seen on the outcrop, is the result of totally random processes. The repetitive nature of the lithologies which appear in the outcrops cannot be ignored. The rocks that the geologist sees in the field are clearly less subject to false interpretation than a column of figures on a sheet of paper. Outcrops of rocks provide us with more than the three or four parameters of which we are aware with our conscious minds. More data are taken in by the senses of a geologist than appear in his field notes. Even though this is true, it is not unreasonable to ask that a closer look be taken at some of the kinds of stratigraphic successions which have been considered to be classic examples of true cyclicity.

THE TWO-COMPONENT SYSTEM

In order to hold complicating factors to a minimum we can begin by considering a situation in which only two types of lithologies are involved. This type of stratigraphic succession can often be found in certain portions of an evaporite basin in which alternating layers of salt and anhydrite were deposited. We see at once that we have a seemingly perfect cyclic sequence. The cycles consist of an anhydrite bed followed by a salt bed and the cycle is begun again with the deposition of the next anhydrite. The thickness of the beds is unimportant for we can always argue that thickness of beds is a function of rate and duration of deposition. It is clear that such a sequence is perfectly "cyclic" if we wish to extend the term to cover simple repetition. It is at once apparent, however, that the term becomes meaningless if we permit ourselves to apply it in such a broad manner.

Let us consider a sequence of numbers chosen by a roulette wheel. If we let red represent 1, and black represent 2, we might obtain a sequence something like this: 1 - 1 - 2 - 1 - 2 - 2 - 2 - 1 - 2 - 1 - 1 - 2 - 1 - 1. This random selection of numbers would result in a geologic section which would be an exact counterpart of the anhydrite-salt section. The geologist would be able to distinguish adjacent beds only if they were different but not if they were the same lithology. Two salt beds which were adjacent to each other would necessarily appear as only one lithologic unit. In this instance we see that random selection of components in a two-component system results in what would give the *appearance* of perfect cyclicity.

We must also remind ourselves that in nature, as in the roulette analogy, we are faced with the possibility that we will come up with a zero, which we can use to represent nondeposition, or a double zero, which can represent removal of beds. With a two-component system it is immediately apparent that we will not see the effect of zero or double zero unless we have sufficient lateral information to make it apparent. Neither nondeposition nor actual erosion will interrupt the seemingly perfect cyclicity of our two-component stratigraphic section. Objections can be raised to the use of the two-component system as an example of false cyclicity. One can contend that no geologist would be led astray to the extent that he would consider any two-component system as cyclic. Yet varves, a two-component phenomenon, furnish us with the only example of a stratigraphic sequence that is known to be truly cyclic in the strict mathematical sense. It should be remembered that a rigorous definition of the term cycle involves the parameter of time. Thus, in the strictest sense, each sedimentary cycle would have to be completed in the same amount of time. In the case of varve deposition this condition is met, and thus, they represent probably the only perfectly cyclic sedimentary sequences.

Returning to our original anhydrite-salt sequence, it can be argued that such a system is so rare that it almost never occurs in nature. One can usually expect a shale parting or a gypsum bed to break the sequence and thus dispel the illusion of cyclicity for the geologist who is studying the section. Following this line of reasoning it would appear that by increasing the complexity of the system we should have less difficulty in detecting incongruities in cyclicity. The incorporation of a third component should help greatly in allowing us to decide whether the system is random or cyclic.

THE THREE-COMPONENT SYSTEM

Another idealized system could be constructed using a three-component cycle. Such a cycle could begin with sandstone followed by an intermediate member of shale and completed with an upper member of limestone. This would represent the normal type of marine transgressive sedimentary sequence. We can proceed to set up a test to determine whether we can detect randomness in a hypothetical section which is plotted from randomly selected digits. In this instance 0 represents either nondeposition or actual erosion (1) sandstone, (2) shale, and (3) limestone. If we make up a section from fifteen digits taken from a random number table we obtain the section shown in Figure 3. In this instance we do not obtain fifteen separate lithologies because some of the adjacent numbers are the same and, in one case, a 0 occurs between two like digits. We now have a means to test the contention that a three-component system can be tested for cyclicity more easily and with more confidence than a two-component system.

Would it be possible to conclude falsely from a randomly selected set of lithologic units that the sequence is cyclic? Let us assume that we have encountered this section in the field and see if it can be made to fit a cyclic pattern without resorting to some totally bizarre interpretation. Purely by chance, our section begins with sandstone. This is overlain by limestone and no intervening shale is present. Because we have no information other than that contained in our single section, we can easily conclude that the shale, which should belong between the sandstone and the limestone, was not deposited in this area but may be represented elsewhere. Next we find from our column of random numbers that we have encountered a period of nondeposition and another limestone is deposited upon the first. The fact that a period of nondeposition existed cannot be discerned from the section, however, and we are unable to distinguish the lower limestone from the upper one.

Above the limestone we have a shale followed by a sandstone. We can easily conclude that this represents a regressive phase rather than a transgressive phase of the cyclic deposition. Above the sandstone lies a thick shale unit which actually represents three individual digits and above that, a limestone. This, of course, comprises a perfect cyclic sedimentary sequence by our definition of the three-component system. Overlying the limestone is a sandstone. We conclude that this

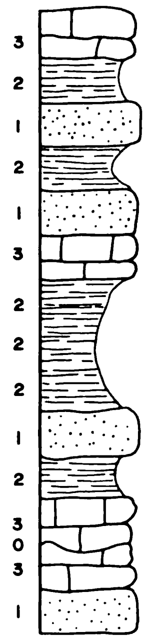

FIGURE 3.—Section made up from fifteen digits taken from a random number table to illustrate the three-component system.

too is normal and that the regressive phases were either eroded or never deposited. The next transgressive phase is thus beginning. Further evidence for this conclusion comes from the fact that the next lithology is a shale, which is just as it should be. We find this shale overlain by a sandstone; however, we can easily take the view that the intervening limestone is missing because of erosion which occurred before the deposition of the sandstone. It could also be concluded that in this particular instance the extent of the transgression was not great enough to permit limestone deposition conditions to occur in this area. Finally, the top of the sequence shows a perfect repetition of the three lithologies which comprise our cycle.

From the preceding story, it will be seen that our stratigraphic section, composed of randomly selected lithologies, does indeed show most of the characteristics that can be expected in a truly cyclic sequence. At this point the reader may wish to complain that the writer has gone too far in making up samples with which to taunt his colleagues. Let the reader be assured, however, that the writer's humble efforts at creating confusion are of truly minute proportions when compared to those of nature.

We must seek to use every means at our command to avoid seeing in events or things a greater degree of order than that which actually exists. We should seek to eliminate, whenever possible, the confusion which arises between randomly occurring events and the nonrandom consequences of the events. Thus, the rising of a nearby land mass will effect the sedimentation in an adjacent basin in a highly predictable and by no means random fashion, but the elevation of the land may be a totally random event. Before we speak of cyclic sedimentation we should attempt to be sure that we are dealing with a sedimentary sequence which is the consequence of events which are, in fact, cyclic.

The stratigraphic record has been likened to the pages of a book in which we can read the history of the earth. Geologists are well aware that many pages are missing and that they are often obliged to read much between the lines. It is well to remember, however, that the meaning of every book is interpreted through the eyes of the reader, and these eyes are human. In all fairness we may ask if, in some cases, too much has not been read between the lines.

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State Geological Survey
of Kansas

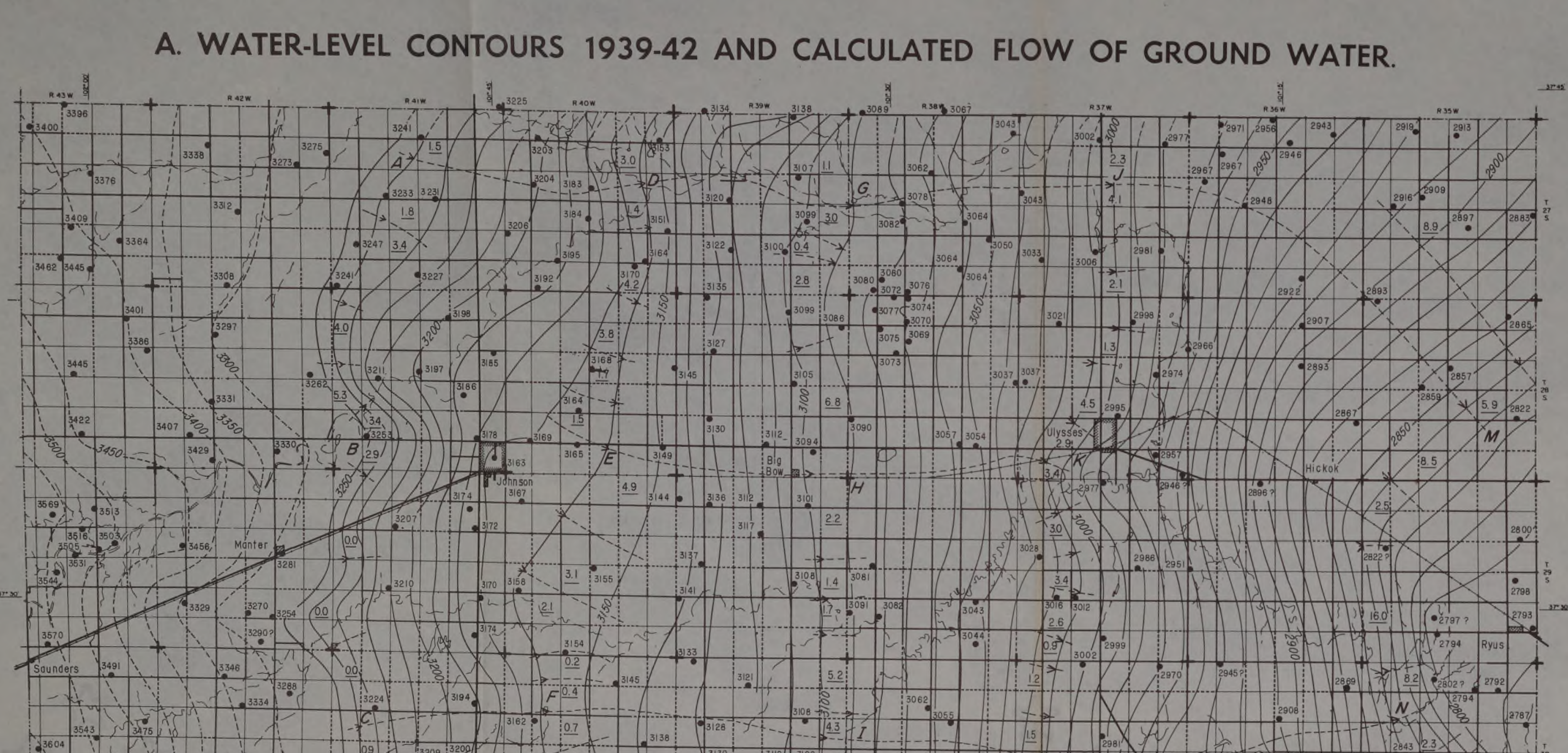
MAPS OF GRANT AND STANTON COUNTIES, KANSAS.

By S. W. Fader, W. R. Meyer, and W. A. Long

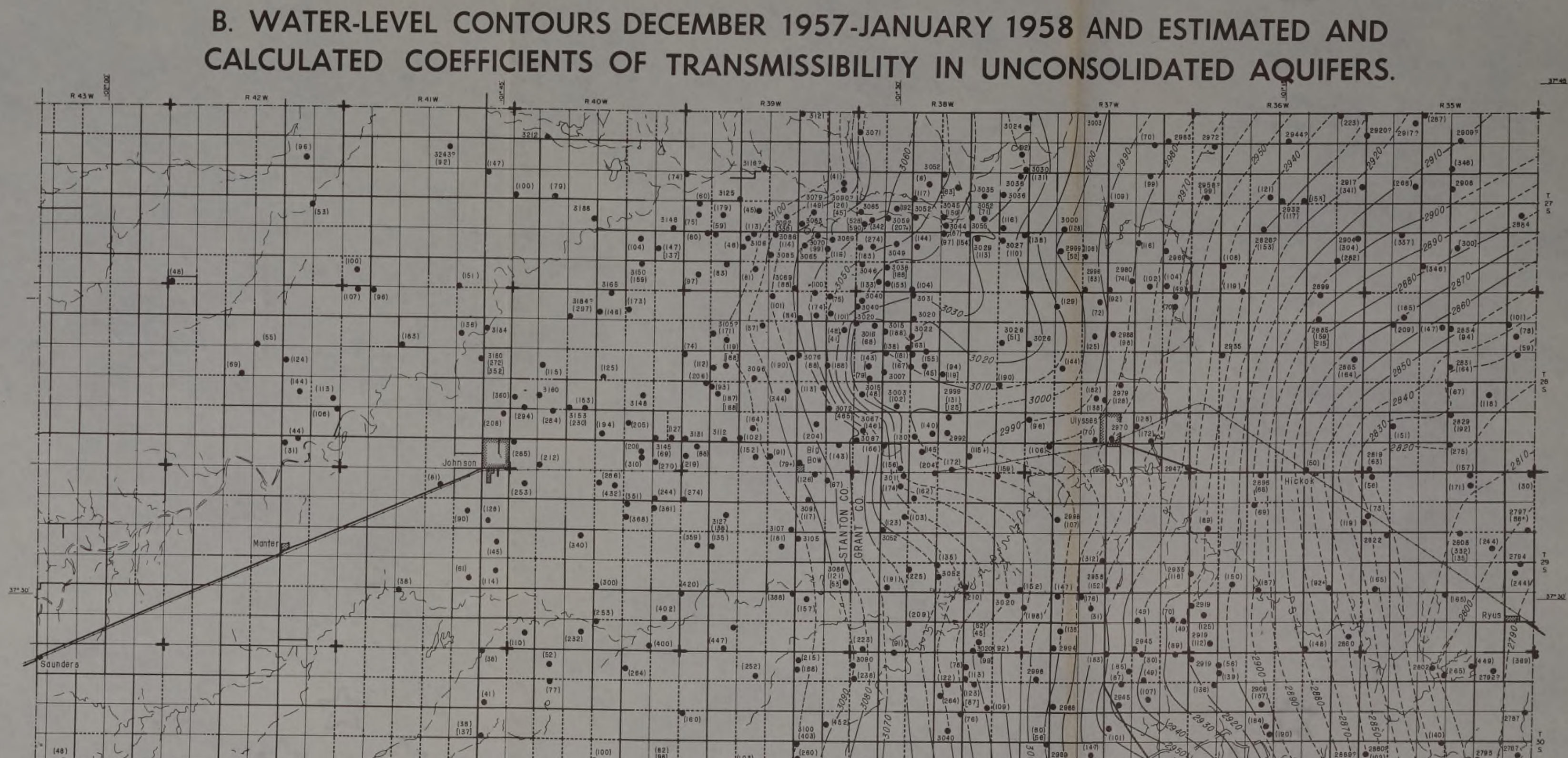
1964

Bulletin 168
Plate 11

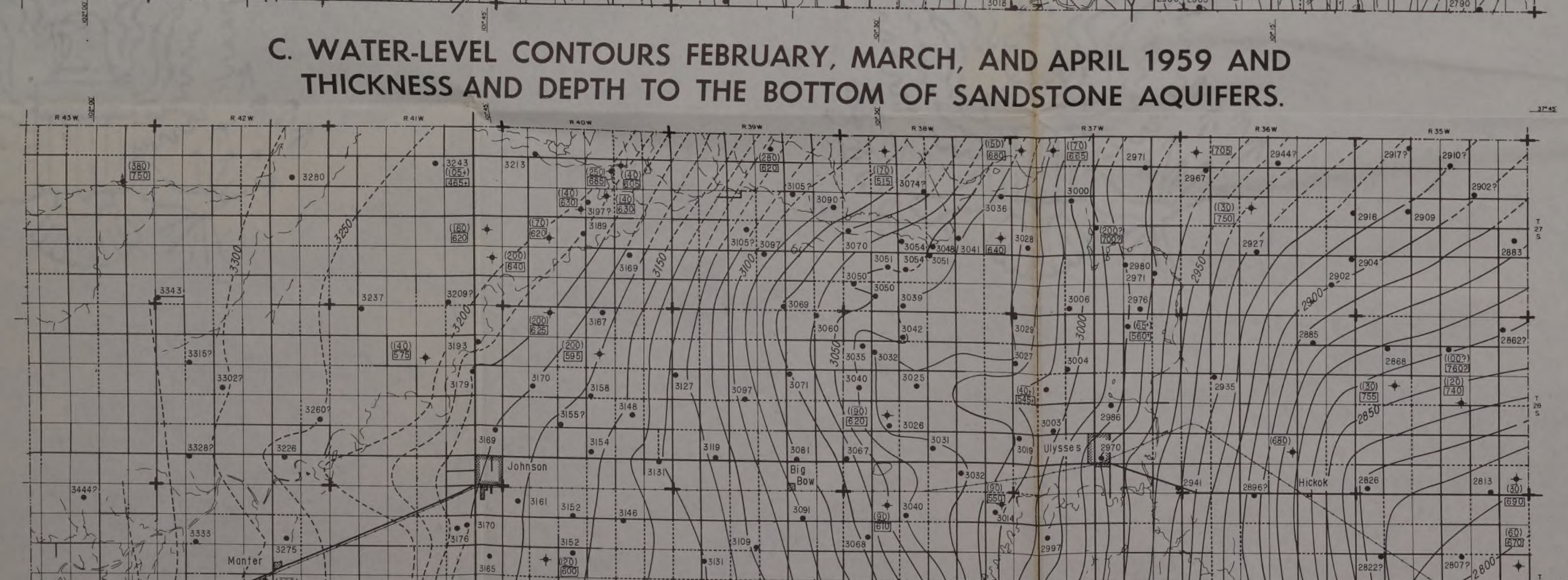
A. WATER-LEVEL CONTOURS 1939-42 AND CALCULATED FLOW OF GROUND WATER.



B. WATER-LEVEL CONTOURS DECEMBER 1957-JANUARY 1958 AND ESTIMATED AND CALCULATED COEFFICIENTS OF TRANSMISSIBILITY IN UNCONSOLIDATED AQUIFERS.

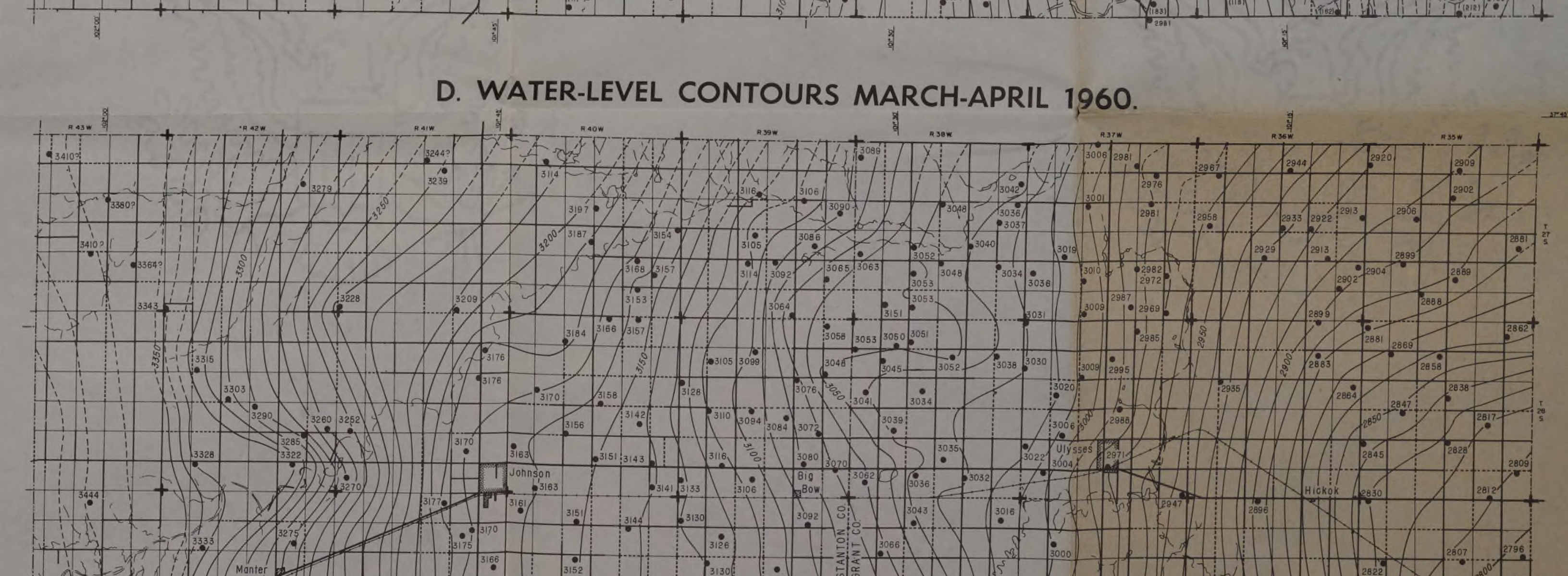


C. WATER-LEVEL CONTOURS FEBRUARY, MARCH, AND APRIL 1959 AND THICKNESS AND DEPTH TO THE BOTTOM OF SANDSTONE AQUIFERS.



Base compiled from maps prepared by the Soil Conservation Service.

D. WATER-LEVEL CONTOURS MARCH-APRIL 1960.



EXPLANATION

● 2995 Altitude of water level in feet above sea level (query indicates approximate).

— 2950 — Water-level contours (dashed where approximate); contour interval 10 feet.

1.86 Calculated flow of ground water between adjacent flow lines, in millions of gallons a day.

- - -> Ground water flow lines (arrows show direction of flow).

✦ Gas or oil test hole.

(77) Estimated coefficient of transmissibility of Pliocene and Pleistocene deposits, in thousands of gallons a day per foot.

[467] Calculated coefficient of transmissibility of Pliocene and Pleistocene deposits, in thousands of gallons a day per foot.

(330) Aggregate thickness of sandstones underlying the Pliocene and Pleistocene deposits.

[465] Depth to bottom of Triassic or Cheyenne sandstones.

0 4 8 12
Scale, in miles.

NORTH-SOUTH GEOLOGIC CROSS SECTIONS KK', LL', AND MM', GRANT-STANTON AREA.

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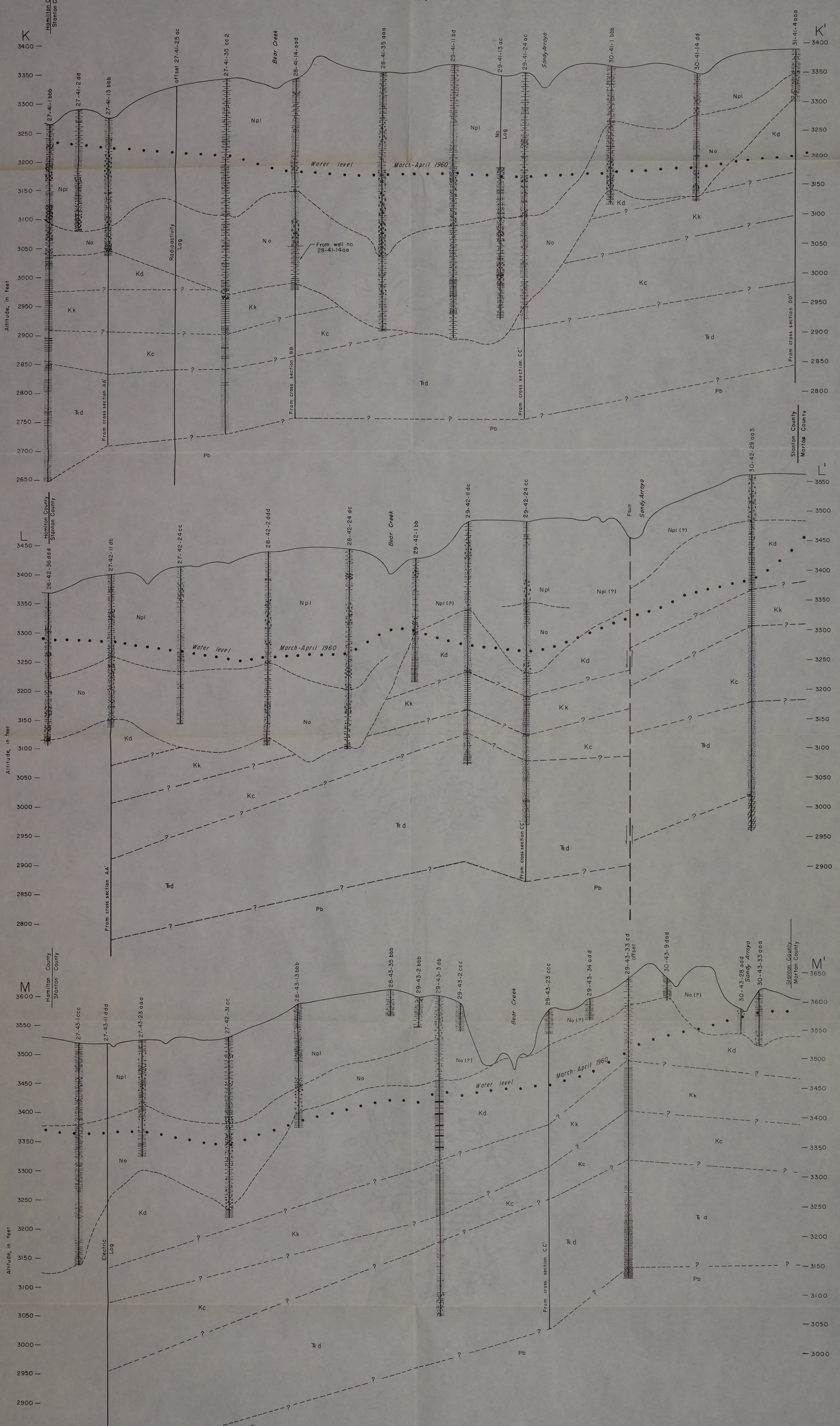
Plate 7

By S. W. Fader, E. D. Gutentag, D. H. Lobmeyer, and W. R. Meyer

1964



EXPLANATION

Npl Pleistocene deposits

No Ogallala Formation, Pliocene

Kd Dakota Formation, Cretaceous

Kk Kiowa Shale, Cretaceous

Kc Cheyenne Sandstone, Cretaceous

Ŧd Dockum Group, Triassic

Pb Big Basin Formation, Permian

LITHOLOGY

Sand

Gravel

Silt and clay

Limestone

Shale

Caliche

Datum is mean sea level

0 1 2 3 4 5

Scale, in miles

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Plate 6

NORTH-SOUTH GEOLOGIC CROSS SECTIONS HH′, II′, AND JJ′, GRANT-STANTON AREA.

By S. W. Fader, E. D. Gutentag, D. H. Lobmeyer, and W. R. Meyer

1964

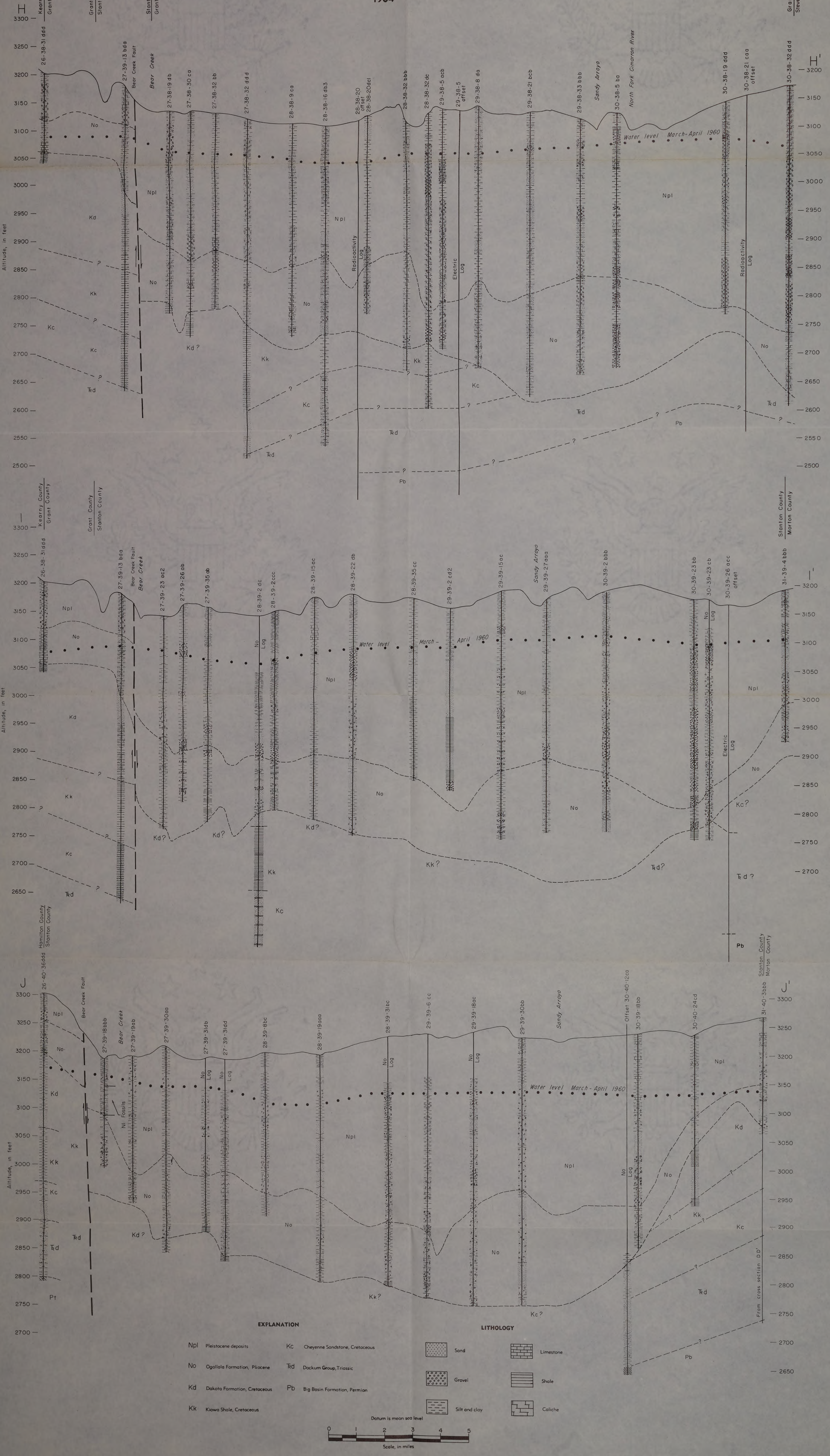

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Plate 5

NORTH-SOUTH GEOLOGIC CROSS SECTIONS EE′, FF′, AND GG′, GRANT-STANTON AREA.

By S. W. Fader, E. D. Gutentag, D. H. Lobmeyer, and W. R. Meyer

1964

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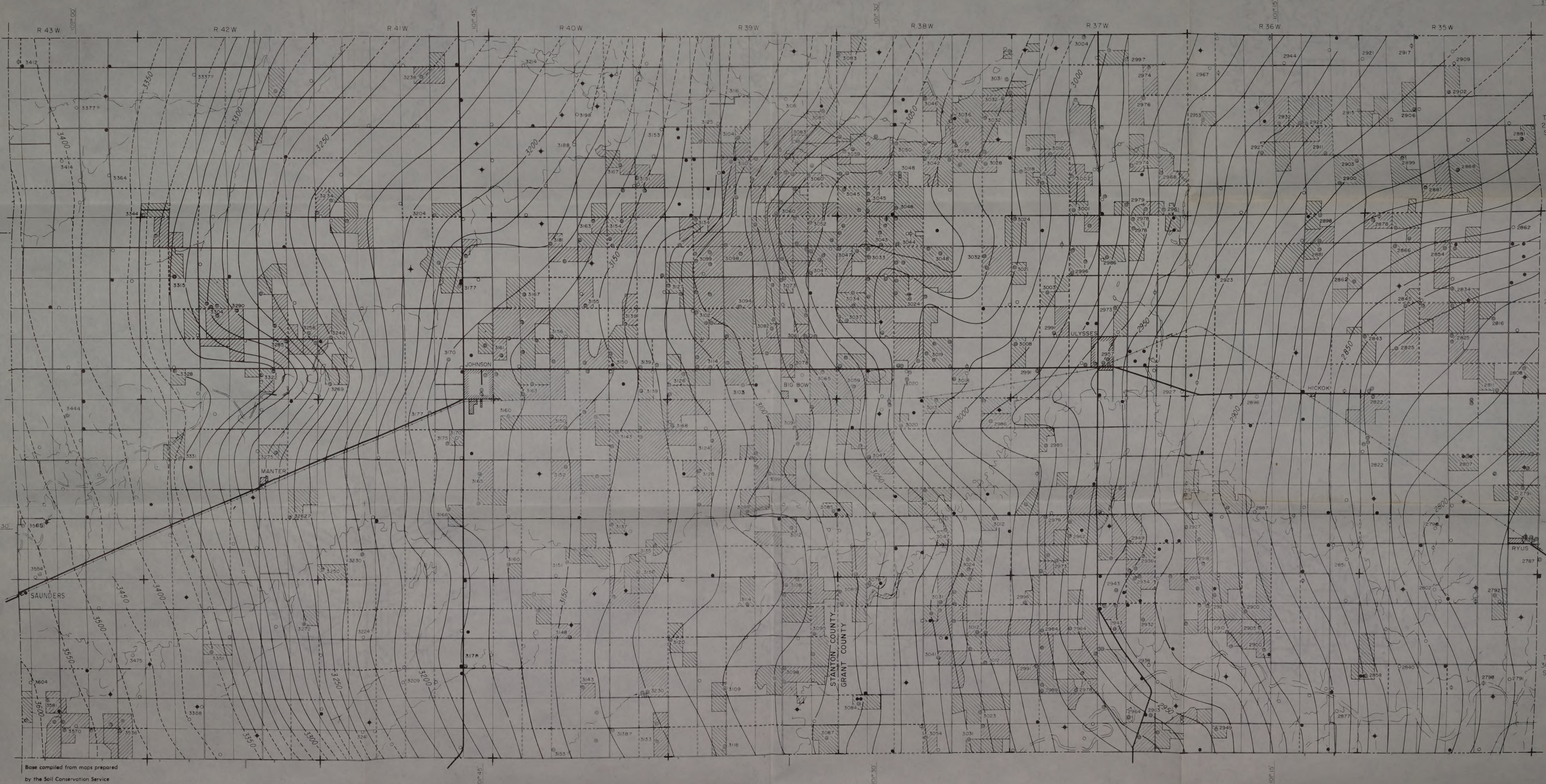
SHOWING WATER-LEVEL CONTOURS, OCTOBER 1959, ACREAGE FOR WHICH APPLICATIONS FOR WATER RIGHTS HAVE BEEN RECEIVED, AND LOCATION OF WELLS AND TEST HOLES.

By S. W. Fader, E. D. Gutentag, D. H. Lobmeyer, and W. R. Meyer.

1964

Bulletin 168

Plate 12



EXPLANATION

○ 2917	Altitude of water level in feet above mean sea level, October 1959 (queried where doubtful).		Oil or gas test hole.
○	Domestic well.		Well equipped with recording gage.
●	Test hole.		Acreage for which applications for water rights have been received.
◎	Irrigation, public supply, or industrial well.	— 3150 —	Contour on the water table (dashed where approximate). Interval 10 feet and 50 feet.
	Abandoned or destroyed well.		

0 2 4 6

Scale, in miles.