

PALEOZOIC EPEIROGENY AND OROGENY IN THE CENTRAL UNITED STATES

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ABSTRACT. The central United States embraces that region between the Appalachians and Rocky Mountains, and from the Canadian border southward to and including the Ouachita system. All this region is a part of the North American craton except the Ouachita system, a late Paleozoic depositional trough and fold belt along the southern border of the craton.

Following the craton-wide deposition of Late Cambrian strata upon deeply eroded basement rocks, Paleozoic strata were epeirogenically uplifted and eroded over large areas of the craton during early, middle, and late Ordovician; early and middle Silurian; early, middle, and late Devonian; early Mississippian (two stages); and early Pennsylvanian (three stages). Orogenic disturbances are confined to rocks of the Ouachita system and of the transverse Anadarko-Ardmore basin. The principal orogenic pulses are (1) early Atokan, especially pronounced as the Wichita orogeny in southern Oklahoma and represented by widespread epeirogeny upon the craton; (2) early-to-middle Desmoinesian, the major pulse in deformation of the Ouachita Mountains, also represented by widespread epeirogeny upon the craton; and (3) middle Virgilian-early Wolfcampian, the major pulse of Marathon orogeny in west Texas and of Arbuckle orogeny in southern Oklahoma.

INTRODUCTION

This compilation of geologic data relating to structural disturbances in the central United States was undertaken at the request of James Gilluly as a contribution by American geologists to the International Union of Geodesy and Geophysics. For purposes of this report the central United States region is divided into cratonic basins and cratonic uplifts, a transverse geosynclinal orogenic belt (Anadarko-Ardmore basin and associated uplifts), and the Ouachita fold belt. Thirty basins, uplifts, or critical structural segments are herein considered (fig. 12). Each of the basins and most uplifts are represented by a stratigraphic column of Paleozoic sediments, showing occurrence of conglomerates, arkoses, and evaporites, together with the positions of unconformities and hiatuses. All are accompanied by a tectonic curve. The results are summarized as a composite tectonic curve plotted against a graduated time scale showing standard American series and European stages (fig. 3).

A first draft of the manuscript, compiled by Ham in June, 1965, while geologist for the Oklahoma Geological Survey, was wholly revised, and the scope greatly enlarged in 1966 and 1967 at Lawrence, Kansas. The contributions by Wilson were begun in 1966 while he was geologist for Shell Development Company in Houston, Texas, and continued after his affiliation with Rice University. We are indebted to the Oklahoma Geological Survey and the University of Kansas for defraying costs of drafting, typing, and duplication.

REGIONAL SETTING

The central interior of the United States is a vast region of nearly 1,000,000 square miles, unified and dominated by gently dipping Paleo-

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zoic strata deposited upon a stable basement floor of Precambrian rocks. For the last billion years the basement and its overlying cover of sediments have been essentially cratonic in structural behavior, and accordingly this region is a part of the North American craton. The craton enlarges northward into Canada, where it is generally characterized by outcrops of Precambrian rocks with local thin deposits of lower Paleozoic strata.

That part of the North American craton here considered extends southward from the Canadian border, westward from the Appalachians, and eastward from the Rocky Mountains. It is bordered on the south by a folded chain of rocks belonging to the Ouachita system, partly exposed and partly covered by Mesozoic and Cenozoic rocks of the Gulf Coastal Plain. It is thus clear that on three sides—east, south, and west—this cratonic segment is limited by fold belts, and each belt has been thrust toward and upon the craton through at least a part of its length.

With one conspicuous exception, the central United States craton is characterized by moderately shallow basins separated by broad arches or domal uplifts (fig. 1). The first craton-wide covering by sedimentary strata, of which decipherable record remains, began with late Cambrian submergence. Later coverings continued intermittently through Pennsylvanian time; they too extended over all or most of the central craton, and their depositional remnants are preserved over wide regions despite many episodes of uplift and erosion. Permian strata, however, are now limited to the western third of the craton, where they are locally but extensively covered by Mesozoic beds. Throughout Paleozoic time the central craton remained essentially free from igneous intrusions and other forms of igneous activity. The record to be interpreted consists almost exclusively of sequences of marine strata, together with local continental deposits and evaporites.

This Paleozoic sedimentary cover, normally less than 5000 feet thick in the structural uplifts, reaches a thickness not exceeding 8500 feet in the four shallow intracratonic basins (Williston, Salina-Forest City, Hugoton, and Palo Duro-Hardeman) and maximum thicknesses of about 15,000 feet in the three major intracratonic basins (Michigan, Illinois, and Midland-Delaware). Over most of the craton the rocks dip about half of 1 degree, and on the flanks of locally formed structural features they dip as much as 10 degrees. The greatest fault shown on the Tectonic Map of the United States (U. S. Geol. Survey, 1961) within the craton proper is the Rough Creek fault zone, trending eastward through the southern part of the Illinois basin, which has a length of 200 miles and maximum vertical displacement of about 3000 feet.

Over most of the central craton the Paleozoic tectonic record is epeirogenic, characterized generally by episodes of marine sedimentation which were terminated by episodes of uplift, gentle folding, erosion, and partly by the overlap or overstep of younger strata upon the unconformable surface. Variable within wide limits are the magnitude of fold-

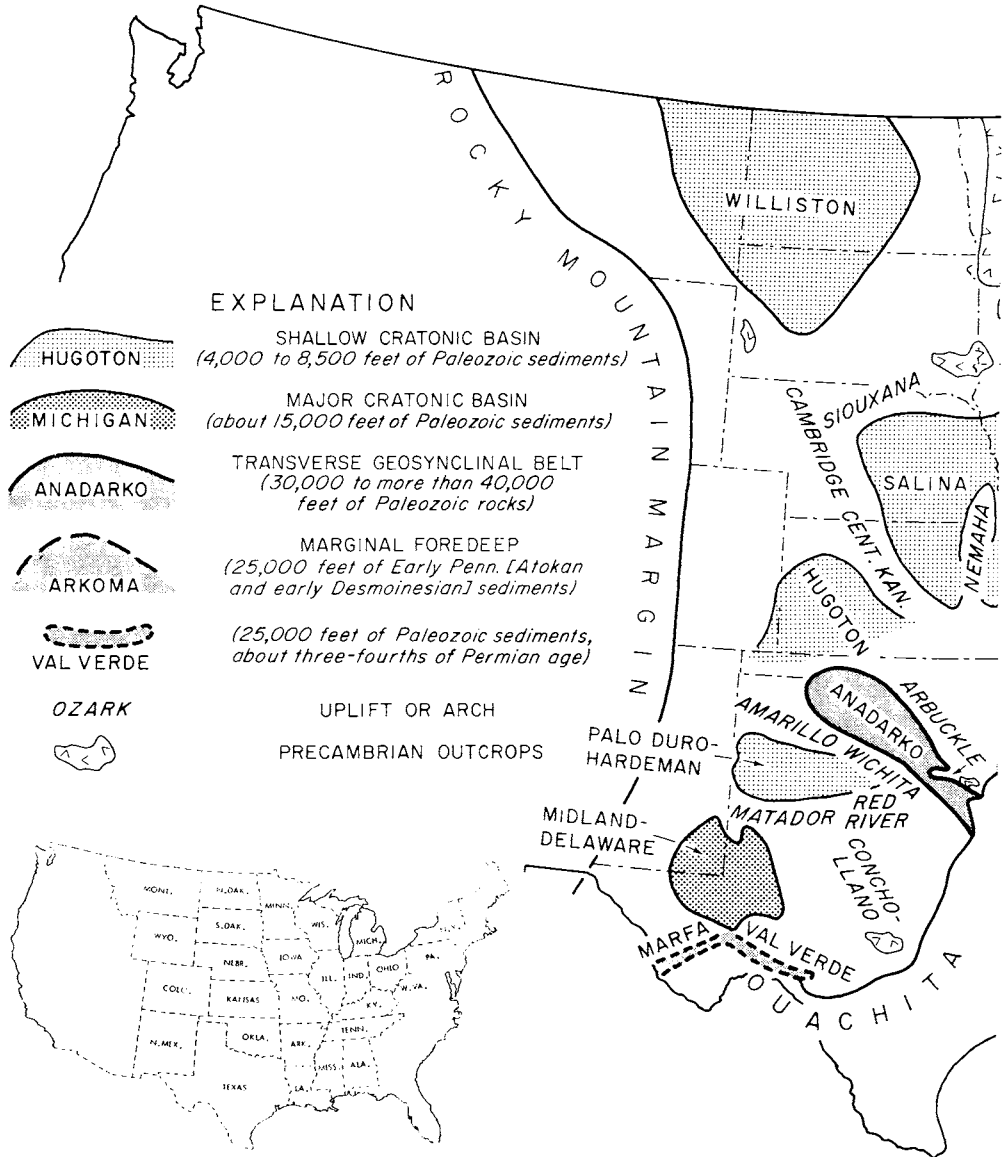
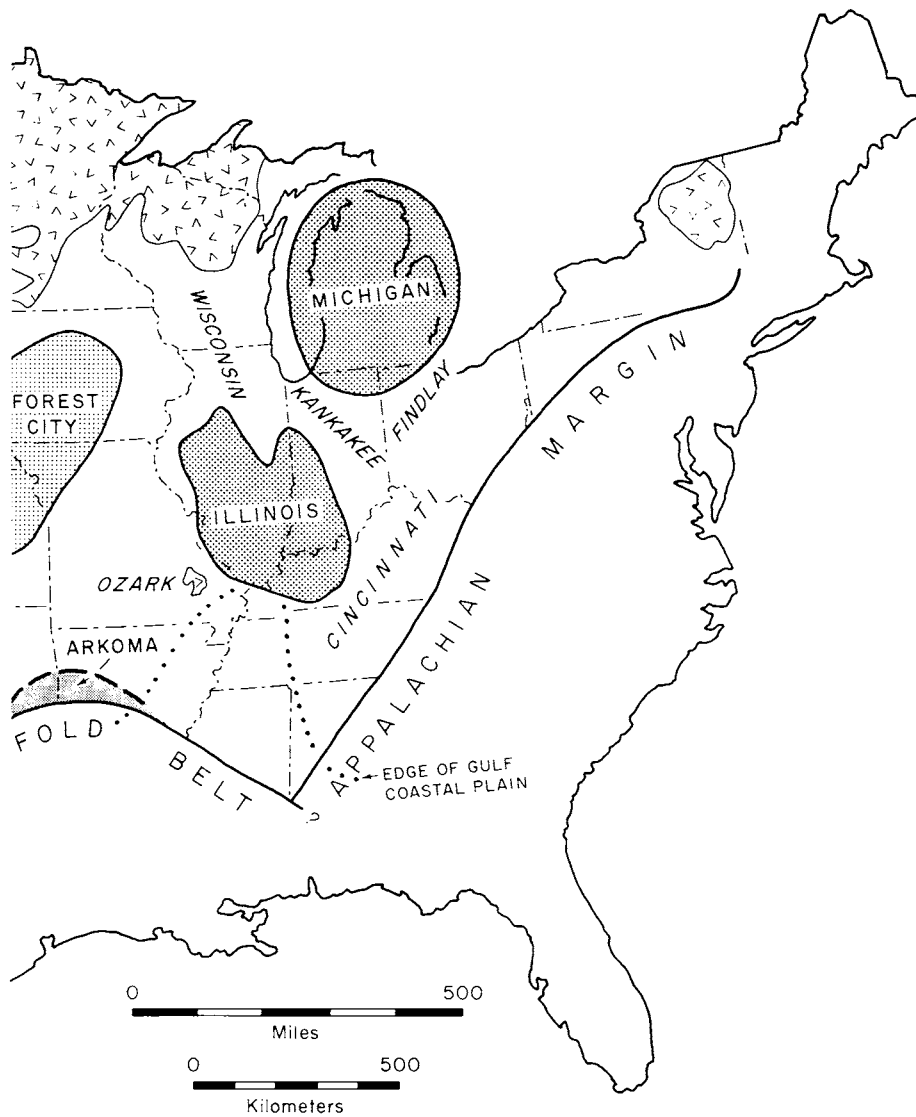


Fig. 1. Principal structural features

ing, geographical extent, and elapsed time represented by the several unconformities, yet 14 of them can be recognized and traced widely.

Along the southern border of the craton, marginal to and elongated parallel with the Ouachita system, are deep basins containing as much as 25,000 feet of Late Paleozoic sediments. They include the Black Warrior basin of Alabama and Mississippi, the Arkoma basin of Arkansas and



of the central United States.

Oklahoma, and the Kerr and Val Verde basins of Texas. Along the western border, in front of and elongated parallel to the Rocky Mountains, are the prominent Denver and Powder River basins, mostly in eastern Colorado and eastern Wyoming. They contain thick Mesozoic and Cenozoic sediments deposited upon thin Paleozoic strata and are genetically related to the geology of the western states, described else-

where in this symposium by Gilluly. In contrast, the eastern margin of the craton has no deep basins, and, except in areas of thrusting, the Paleozoic sediments merge by gradual thickening and increase of dip into the folded Appalachians.

The major exception to epeirogenic behavior of the craton is the region of a transverse belt in the south-central United States. Trending northwestward through southern and western Oklahoma, and adjoining parts of northern Texas, and nearly dividing the craton into separate segments, is the deep Anadarko basin with its associated orogenic uplifts. Nothing like it is present elsewhere upon the craton. Within the basin is a column of late Cambrian-through-Permian sediments 38,000 feet thick, approximately equal to the thickness of Paleozoic sediments of the Appalachian geosyncline. Furthermore, below the Late Cambrian sediments in southern Oklahoma are flows, tuffs, and associated intrusive rocks at least 7000 feet thick, isotopically dated at 500 to 550 million years, and almost certainly of middle Cambrian age. Underneath this sequence are graywackes and other layered rocks, estimated seismically to be some 15,000 feet thick, whose age has not been ascertained. An early Cambrian age is a possibility but so also is a late Precambrian age. If the graywackes are early Cambrian, the combined thickness of Paleozoic rocks (Early Cambrian through Permian) is 60,000 feet, probably a record for the North American continent. If instead the graywacke is Precambrian, then the Paleozoic rocks of the Anadarko basin (middle Cambrian through Permian) have a near-record thickness of 45,000 feet. Even this thickness is three times greater than the 15,000 feet of Paleozoic rocks that fill the three major basins elsewhere upon the craton.

Associated with the collapse and demise of this gigantic trough in late Paleozoic time was the formation of intensely folded marginal uplifts—the Wichita Mountains and Arbuckle Mountains—accompanied by movement along longitudinal faults at least 400 miles long, with vertical displacements of at least 15,000 feet.

The sedimentary sequences and episodes of uplift are substantially the same in the trough-and-fold belt as on the craton proper, so that the principal distinctions of the belt are (1) its greater rate of subsidence, resulting in much greater thicknesses, (2) its earlier beginning, in Early or Middle Cambrian rather than Late Cambrian time, and (3) its much stronger closing orogenic pulses, which are closely associated with those of the neighboring Ouachita fold belt.

TECTONIC DISTURBANCES UPON THE CRATON

The tectonic events here considered range in age from that of the oldest basement rock, 2500 million years, through the Paleozoic and ending with the close of Permian time, about 225 million years ago. Included are four major episodes of the Precambrian and at least 30 separate pulses in the Paleozoic, of which 14 are regionally significant. The regional Paleozoic disturbances are chiefly of Ordovician, Silurian, Devonian, Mississippian, and Pennsylvanian age. All these disturbances

are epeirogenic except those of the Pennsylvanian and early Permian, which are orogenic in southern Oklahoma and in the craton-bordering Ouachita system.

Precambrian

The Precambrian basement is concealed by Paleozoic sediments over most of the central United States craton. The largest outcrop area is in northern Wisconsin and Minnesota; much smaller areas are in the Adirondacks of northeastern New York, Black Hills of southwestern South Dakota, Sioux uplift of southeastern South Dakota, Ozark uplift of southeastern Missouri, Llano uplift of central Texas, and the eastern part of the Arbuckle Mountains in south-central Oklahoma (fig. 1). In other parts of the craton the basement rocks are investigated by the examination of cuttings and a relatively small number of cores, mostly obtained in the course of drilling for oil and gas. The principal criteria for investigation include petrographic examination followed by grouping of similar petrologic types, together with age dating through major use of $\text{Sr}^{87}/\text{Rb}^{87}$ isotopes, either of the whole rock or of potassium feldspar, biotite, or muscovite.

The principal integrated investigation of isotopic ages of the cratonic basement in the United States is that by Muehlberger, Denison, and Lidiak (1964), the generalized results of which are given in figure 2. Substantially the same results have been published by Goldich and others (1966), Muehlberger and others (1966), and Lidiak and others (1966). The age groupings are based on determinations of more than 250 samples of wide geographical distribution, including samples from all but the deepest basins. Four major episodes of igneous intrusion or of extensive thermal recrystallization are indicated, ending in the formation of an outer belt at an age of 1.0 billion years. From this time onward the craton was stabilized. It was deeply eroded up to the time of its great submergence and covering by Late Cambrian marine sediments, approximately 0.5 billion years ago.

From the report by Muehlberger, Denison, and Lidiak in 1964 it appears clearly established that the Precambrian basement was developed by continental accretion beginning in the north-central states by injection and consolidation at 2.5 billion years, and continuing generally southward and outward in three major belts during episodes that culminated successively at 1.6 to 1.8 billion years, 1.2 to 1.4 billion years, and 1.0 billion years. The rocks representing these episodes are chiefly granites and other intrusive igneous rocks, with some schists and gneisses.

In addition to the intrusive rocks, three principal sequences of Precambrian volcanic flows, tuffs, and sediments are known. They range in age from 1.1 to 1.3 billion years. Partly marine and partly non-marine, they are Precambrian surface deposits laid down upon the two outer belts and upon the 2.5 billion year core, but they are not present on the outermost 1.0 billion year belt. Most prominent is a curvilinear belt of basalts and associated sedimentary rocks in the north-central states,

BASEMENT-ROCK AGES

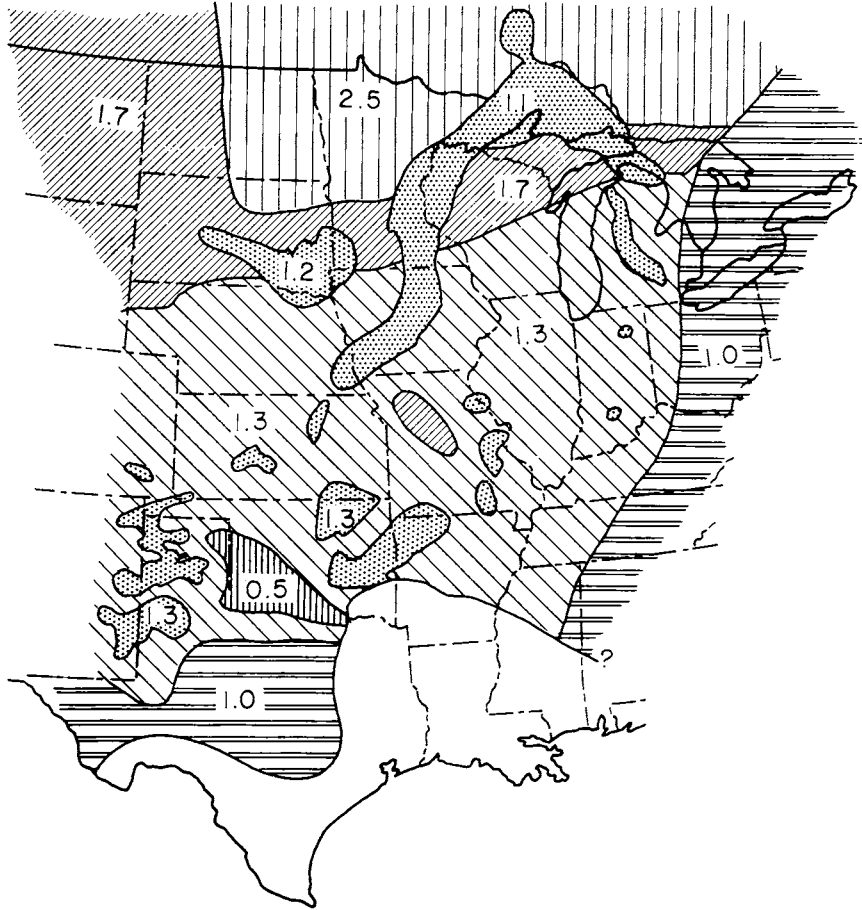


Fig. 2. Distribution of basement rocks by age (billion years) in the central United States. *Line patterns*: areas of basement rocks that are chiefly intrusive and metamorphic rocks, ranging in age from 2.5 to 0.5 billion years; *stipple pattern*: areas of basement rocks that are chiefly extrusive and sedimentary rocks, all ranging in age from 1.1 to 1.3 billion years. Generalized from Muehlberger, Denison, and Lidiak, 1964.

dated at about 1.1 billion years (Keweenaw and associated rocks). Next in prominence are the rhyolite flows and tuffs of the south-central states, dated at 1.2 to 1.3 billion years. Least extensive are the quartzites (Sioux) and allied rocks of the South Dakota area, dated at about 1.2 billion years. The sedimentary sequences consist of remnants which, though substantial in areal extent, are nevertheless only the thicker or basal portions preserved after long erosion.

About two-thirds of the central craton, by far the greatest part that is covered by Paleozoic sediments, consists of a vast platform of mesozone

granites, epizone granites, and rhyolites which originated during the 1.3 billion year episode. It was upon the southern part of this platform, however, that the youngest basement rocks, the oldest Paleozoic rocks, and the deepest basin of the craton were formed. In the Wichita province of southern Oklahoma are intrusive rocks and extrusive flows dated at 525 to 550 million years, and this reliably checked isotopic dating stratigraphically places these rocks in the middle Cambrian. Together with older graywackes of uncertain date, they constitute the beginning stage in the formation of the deep Anadarko basin.

Paleozoic

The study of Paleozoic tectonism upon the craton is mainly a study of unconformities in sedimentary sequences. Because carbonate rocks dominate the craton over much of its area during all periods up to the Pennsylvanian, it follows that critical studies of limestones and dolomites are essential. Unconformities within them are recognized by detailed studies of petrologic and paleontologic criteria. Before Devonian time there were few land plants, and uplifted carbonate terranes were swept clean before later inundation, with the result that typical basal conglomerates are generally lacking. Yet the unconformity itself is recognizable through classical studies of marine invertebrates, greatly implemented in recent years by studies of calcareous and arenaceous foraminifera, conodonts, spores, pollen, chitinozoans, hystrichospherids, and other microscopic organisms. The study of conodonts has been particularly valuable in stratigraphically dating the black shales of late Devonian and Mississippian age. Similar rocks hitherto considered unfossiliferous, including some dolomites and fine-grained limestones, are also yielding datable microfossils. With increasing knowledge of faunal and floral ranges, greater perception of paleoecologic controls on faunas, increased awareness of carbonate rock types, and greater insight and perception in field studies, the demonstration of unconformities both in outcrops and in subsurface is now commonplace.

Other criteria of tectonism are available locally, chiefly in the form of (1) conglomerates, arkoses, and coarse sandstone wedges, all indicating uplift, and (2) the truncation of stratigraphic units below low-angle unconformities, or overstep above them, recognized by detailed surface and subsurface studies. Concentrations of glauconite, phosphate pellets, pyrite, and chert pebbles are likewise present in some rocks that overlie low-dip unconformities, but their presence or absence is considered inconclusive without supporting evidence. Finally, the presence of steeply dipping beds, reverse or thrust faults, and high-angle unconformities are of great value but of little use over most of the craton, because such features are restricted generally to the rocks in southern Oklahoma, west Texas, and the Ouachita fold belt.

The concept elucidated by Sloss (1963), that the pre-Chazyan, pre-Middle Devonian, and pre-Pennsylvanian episodes of craton-wide uplift and erosion are the only three such Paleozoic episodes in the central

United States, is here shown to be considerably oversimplified. Each of the three unconformities certainly is important in the tectonic development but not to the exclusion of at least eight additional ones, each with such major geographical distribution upon the craton that it must be considered in the construction of an integrated cratonic framework.

Furthermore, with the exception of the Early Middle Ordovician (pre-Chazyan) episode, it has not been demonstrated that *any* of the Paleozoic epeirogenies or orogenies was active in all the basins and uplifts of the central United States. In spite of the magnitude and widespread occurrence of the early Pennsylvanian unconformity, it can not be recognized in the deep parts of the Anadarko-Ardmore basin; and, in spite of the widespread occurrence of the pre-Middle Devonian unconformity in the northern and eastern parts of the craton, it can be inferred but not proved over vast tracts in the southwestern part of the craton, where middle Devonian strata are absent. An additional point is that the "early Pennsylvanian unconformity" is a single surface locally, but over much of the craton it is a combination of at least three separate episodes—early Morrowan, early Atokan, and early Desmoinesian.

The present investigation attempts to show and to document with a series of paleogeologic maps the existence of 14 principal episodes of uplift and erosion that affected major parts of the craton (fig. 3). Three of them are of Ordovician age, two are Silurian, three Devonian, two Mississippian, three Pennsylvanian, and one late Pennsylvanian-Early Permian. All represent epeirogeny except those of late Paleozoic time—early Pennsylvanian to early Permian—and all the orogenic activity was restricted to the southern and bordering parts of the craton. Approximately 16 disturbances of lesser distribution, some of which are severe and most of which are well known through detailed local investigations, are not included in figure 3 but are discussed in the following pages and are shown graphically by regions in figure 12.

In the stratigraphic-tectonic summary of figure 3, the Paleozoic periods are shown in approximate proportion to their duration in years, as determined by isotopic ages from other parts of the United States and of the world. The correlation of European stages with the American

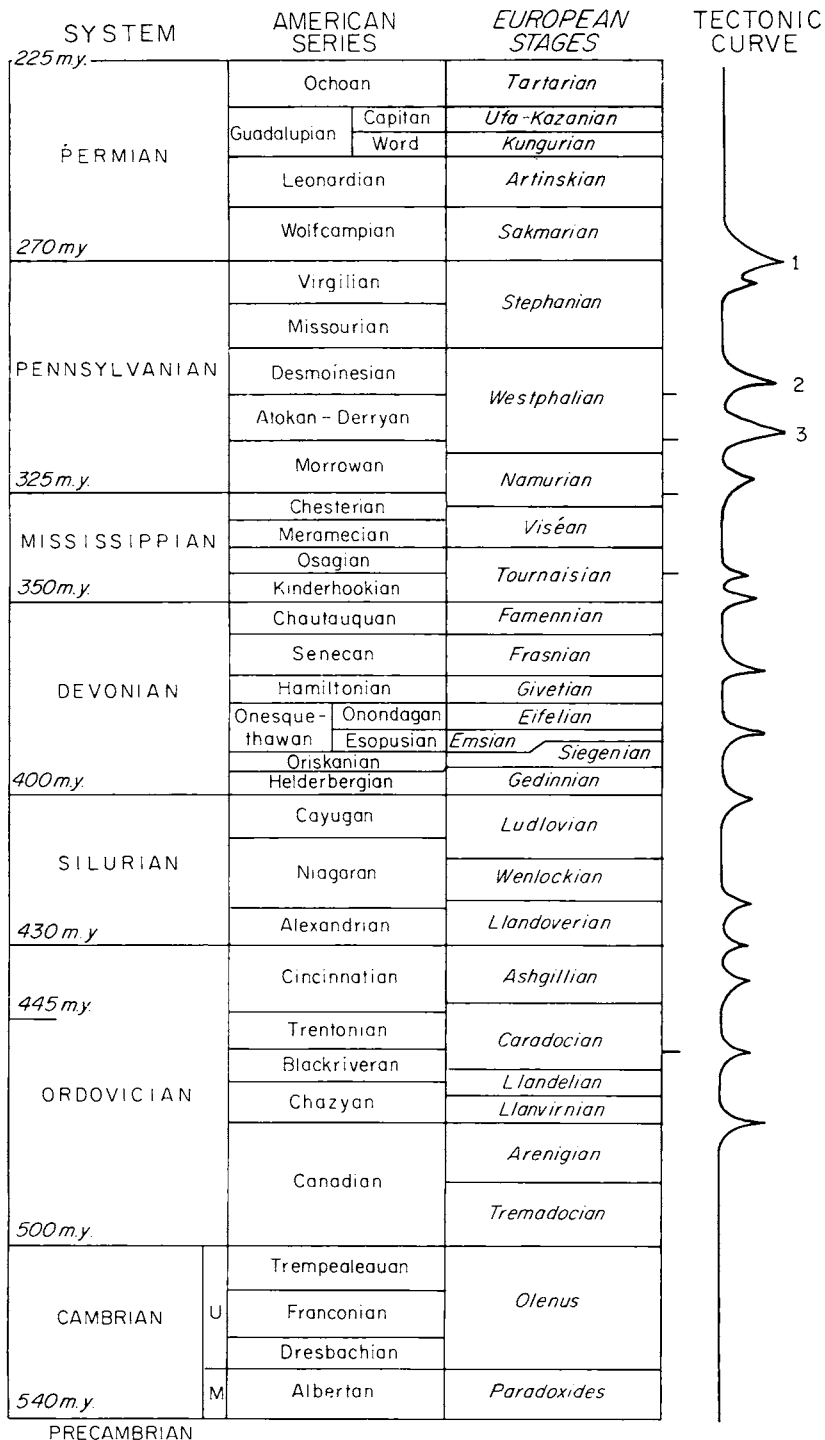
Fig. 3. Major tectonic disturbances of the Paleozoic era in the central United States. Plotted on the tectonic curve are the 14 principal episodes of uplift and erosion that affected most parts of the cratonic interior; lesser disturbances are not shown. The height of the tectonic peak at each episode is roughly proportional to the intensity of uplift and regional folding. No Triassic episode is shown because its effects can not be demonstrated over most of the craton.

All the tectonic disturbances are epeirogenic with the following exceptions, indicated by numbers on the curve.

1. Middle Virgilian-Early Wolfcampian: Arbuckle orogeny of southern Oklahoma; principal pulse of Marathon orogeny; probable late pulse of Ouachita orogeny. Generally not represented upon craton.

2. Early-to-Middle Desmoinesian: principal pulse of Ouachita orogeny; widespread epeirogeny upon craton.

3. Early Atokan: principal pulse of Wichita orogeny in southern Oklahoma; widespread epeirogeny upon craton.



series is likewise approximate but is the best currently available. On the tectonic curve, the height of individual peaks is approximately proportional to the intensity of uplift and regional folding.

Cambrian

Fossiliferous marine strata of the Cambrian system underlie all basins and are present upon all arches of the craton. In outcrops of Texas, Missouri, the Black Hills, and the Minnesota-Wisconsin area, the basal deposits are of Dresbach (Early Late Cambrian) age. Locally, as in Oklahoma, they are of slightly younger Franconian age, whereas in the Michigan and Illinois basins they are probably at least in part of Albertan or Middle Cambrian age. They rest with profound unconformity upon deeply eroded crystalline basement rocks which range in age from 2.5 to 1.0 billion years. How many separate episodes of uplift and erosion may be represented can only be guessed. Yet, because the minimum missing time of approximately 400 million years is just about equal to the duration of the Paleozoic era, it seems likely that 30 or more would not be an unreasonable guess. It is therefore not practical to illustrate, on the tectonic curves of figure 12, any peaks of Precambrian tectonism.

In a few areas of the craton, the "basement rock" underlying Late Cambrian deposits is abnormal in relation to what has been described above. Along the northern shore of the upper peninsula of Michigan is the Jacobsville Sandstone, 1100 feet thick, which is unconformable below the Late Cambrian Mt. Simon Sandstone and unconformable above Precambrian basement rocks (Hamblin, 1958). Its stratigraphic position is uncertain. Similarly, in the subsurface of western Missouri is a pre-Lamotte sequence with a drilled thickness of nearly 1000 feet which consists largely of arkosic sandstones and shales (Skillman, 1948). Its stratigraphic position too is uncertain, although reexamination of the Missouri-Kansas basement rocks has led Denison (ms, p. 60-69) to the conclusion that the arkoses are part of a much larger belt that is partly reconstituted and probably has an age of about 1.2 billion years.

In a third and probably unique area of the craton, the evidence for middle Cambrian and perhaps Early Cambrian deposits is more definitive. This is the area of the deep Anadarko-Ardmore basin, which lies mostly in southern Oklahoma. The pre-Late Cambrian rocks have not been seen from their 40,000-foot expected depth in the trough of the basin, but they crop out in the adjoining Wichita Mountains and in the western part of the Arbuckle Mountains, and they have been encountered in numerous wells in the marginal or more strongly uplifted parts of the basin. Seismic information also is available to help in the interpretations. Of the five rock groups that have been identified and combined into the Wichita province, two are intrusive igneous rocks and are not further considered here. Three of the group, however, consist of sediments and flows. They are divided into the Carlton Rhyolite Group, Navajoe Mountain Basalt-Spilite Group, and Tillman Metasedimentary Group. The rhyolite and basalt groups are known from drilling

to underlie the Anadarko basin. Six wells in southern Oklahoma have penetrated 1000 feet or more of these rock groups, of which three penetrated more than 4000 feet, and one penetrated 6054 feet.

Details of petrology, distribution, thickness, and isotopic ages of the southern Oklahoma basement rocks have been described (Ham, Denison, and Merritt, 1964). Among the general conclusions pertinent to this tectonic study are the following:

1. The rhyolites have a maximum drilled thickness of 4500 feet. They are unconformable beneath the late Cambrian (Franconian) Reagan Sandstone, but they have been folded in structural conformity with the Reagan Sandstone and with the thick overlying column of Paleozoic sediments. Numerous isotopic dates yield a median age of 525 million years, sufficient to permit a stratigraphic assignment to the middle Cambrian.

2. The basalt-spilite group underlies the rhyolites and has a maximum drilled thickness of 1050 feet. Seismic information suggests an additional several thousand feet of thickness. Isotopic ages have not been obtained on rocks of this group, yet they are believed to be equivalent to outcropping gabbros that have been dated at about 535 million years. Thus the basalts and spilites are probably of either middle or early Cambrian age.

3. The oldest rocks of the sedimentary-flow suite are chiefly meta-graywackes, with some quartzite and a little bedded chert. They occur beyond the edge of the Anadarko basin and have not been penetrated by drilling in it. Regional geologic mapping, supported by seismic shooting, indicates that the graywacke group lies beneath the basalts and probably is the earliest sediment of the Anadarko basin.

4. The flows and sediments described above are in regional contact with and presumably lie upon granitic igneous rocks, dated at approximately 1.3 billion years, which are part of the cratonic basement normal for the south-central United States.

5. The tectonic significance is partly clear and partly obscure. In summary:

- A. An unconformity separates the graywacke group from the 1.3 billion year basement granites. The time of uplift that preceded graywacke deposition is doubtless late Precambrian; the unconformity at the base of the graywackes could be early Cambrian but is not proved.

- B. Both the graywacke and overlying basalts are of probable marine origin. They are overlain by a group of rhyolites and tuffs, including welded tuffs that originated upon a land surface, so that an episode of uplift and erosion is presumed to separate them. This episode is pre-rhyolite and probably pre-middle Cambrian.

- C. An undoubted unconformity is present at the top of the Carlton rhyolite, as pebbles and cobbles of it are everywhere present at the base of the overlying Reagan Sandstone. There was no great time-lapse and but little indication of structural adjustment during the time

of unconformity. The middle Cambrian rhyolites, already emplaced upon the land, were merely eroded by streams until epeirogenic subsidence a short time later covered them with the first transgressive deposits of the Late Cambrian sea.

The Carlton rhyolite field is estimated to cover 15,000 square miles. Although small in relation to the size of the craton, it was nevertheless the last major igneous event in the central United States. Marine sedimentation accompanied by epeirogeny followed.

The first Cambrian deposits above the basement-rock surface of the craton are persistently conglomerates and arkoses, grading upward into feldspathic and generally glauconitic sandstones. They are succeeded upward by limestones and dolomites which continue to the top of the Cambrian (Howell and others, 1944). In marginal areas, near remaining exposures of basement rocks, they are interspersed with sandstones. Some of the sandstones, such as that at the base of the Trempealeau in the north-central states, are distinctly unconformable over substantial areas, but the unconformity can hardly be recognized where the sandstone disappears, away from its source. At the present time a single unconformity (pre-Franconian) is known within Late Cambrian strata upon the central craton. Following the initial (Dresbachian) transgression of the craton a widespread regression occurred. Everywhere the top of the Dresbachian is marked by either a unit of coarser clastics, a glauconitic zone, or a very sharp break in sedimentation. That the ensuing Franconian transgression begins after a considerable gap in the record is indicated by the trilobite zonation which is more complete in the bordering geosynclines, a major zone being present here which is absent on the craton. This event is widespread but considerably less impressive than later disconformities such as those within the Ordovician. It is conceivably due either to a mild epeirogenic movement or to eustatic sealevel change. Only small amounts of clastics were furnished from the shield at this time. This break in sedimentation is followed by widespread Upper Cambrian carbonate sedimentation which continues without interruption into the Lower Ordovician.

Ordovician

With a duration of approximately 70 million years, the Ordovician is the longest of the Paleozoic periods fully represented upon the craton. Rocks of the Ordovician system probably covered all the central craton, and in southern Oklahoma they were built up to a maximum thickness of 8500 feet. Everywhere they are principally carbonate rocks, although many argillaceous beds and shales are present, and one extremely important sandstone unit—the St. Peter—is widely distributed. Just as Early Ordovician time is marked almost wholly by the deposition of carbonates, so is Late Ordovician time marked in most areas by the deposition of shales. The shale sequence includes beds of the Maquoketa, Richmond, Sylvan, and Cason, all on the craton, as well as the black Polk Creek shale of the Ouachita Mountains. This closing stage is the

only part of Ordovician time during which land-derived fine clastics were consistently and persistently deposited. Although not derived from the craton, these clastics do suggest a stage of uplift, perhaps in the Appalachians, that culminated in the epeirogenic rise and erosion of the craton at the close of the Ordovician period.

In contrast, the beginning of Ordovician sedimentation in Canadian time is rarely marked by a pronounced unconformity. The base of the Prairie du Chien is well defined in the north-central states as is the base of the Gunter Sandstone in some parts of the Ozark region; but over vast areas of the craton, owing to a general scarcity of fossils, there is no known method by which the Cambrian-Ordovician boundary can be determined precisely. In the Arbuckle Group and Knox Group the position of this boundary is questionable within 50 feet or more, just as the base of the Ellenburger in many parts of Texas can not be distinguished from upper beds of the Late Cambrian Wilberns Formation.

What is probably the most distinctive lithologic boundary within the Canadian series of the craton corresponds to the top of Ulrich's Ozarkian system (Ulrich, 1911). It is the base of the Roubidoux Sandstone in Missouri, the base of the Cool Creek Formation in Oklahoma, and the base of the Gorman Formation in Texas. An episode of short uplift accompanied by an influx of sand is indicated at this time for a substantial southern segment of the craton.

From the top of the Canadian to the top of the Ordovician are successively the Chazyan, Black River, Trentonian, and Cincinnati series. Not less than a dozen unconformities are present within these strata. Some of them are of local derivation, but one, the early Chazyan, has such wide distribution that it is outstanding above all others. The pre-Trenton unconformity likewise is significant, as is one or two of Cincinnati age. Although a pre-Black River unconformity is noteworthy in the northeastern states (Cohee, 1948a; Fettke, 1948; Kay, 1948), it can not be traced with confidence to most other parts of the craton.

Early Chazyan.—The earliest Paleozoic unconformity of craton-wide distribution, and perhaps the only one of all Paleozoic time, occurs at the base of Chazyan strata. That the continental interior was emergent and slightly folded before Chazyan deposition is proved by practically every kind of evidence for unconformity—basal conglomerates, sandstone transgressions, local channeling, overlap, overstep, and truncation. Underlying Canadian beds are generally so deeply eroded that reasonably complete stratigraphic sections of them may be found only where they have been preserved in a few pre-unconformity synclines. In southern Canada, Chazyan beds transgress across eroded Canadian and Cambrian beds, coming to rest upon Precambrian granites. The region in which Chazyan strata rest unconformably upon older rocks is shown in figure 4. An idealized and artistic physiographic and subcrop map of this surface is given by Kay (1951, pl. 1). Absent in those areas marked by diagonal

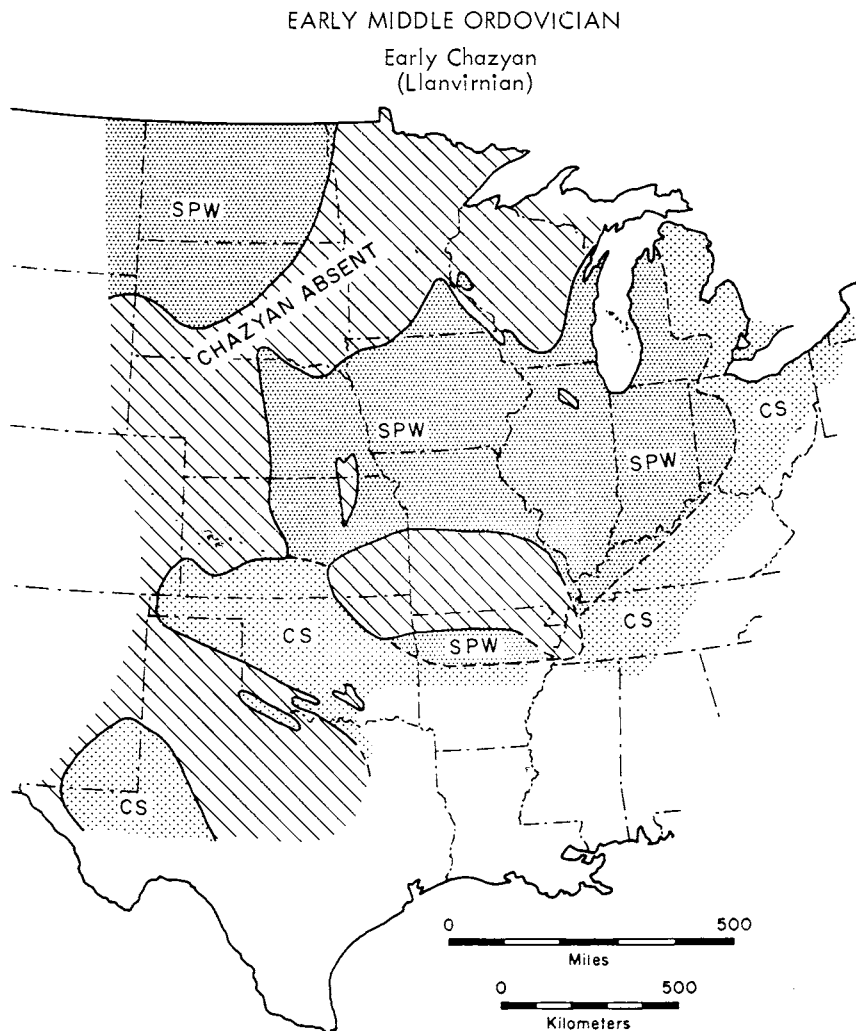


Fig. 4. Early Middle Ordovician (pre-Chazyan) unconformity in the central United States. The map shows Chazyan facies *above* the unconformity. *Dark stipple*: areas of unconformity at base of St. Peter-Winnipeg sandstone facies (SPW). *Light stipple*: area of unconformity at base of Chazy-Simpson carbonate facies (CS). *Diagonal lines*: Chazyan strata absent, mostly eroded. Chazyan strata generally rest upon eroded Early Ordovician Canadian strata (Beekmantown-Knox-Arbuckle-Ellenburger-Prairie du Chien), although locally they are upon Cambrian and Precambrian rocks. The pre-Chazyan episode of uplift, gentle folding, and erosion resulted in the first and most extensive early Paleozoic unconformity in the central United States.

lines, the Chazyan beds are nevertheless presumed to have been deposited over all the craton and to have been removed during several episodes of post-Chazyan erosion.

Basal Chazyan deposits in the northern interior states are mostly sandstones. They belong to the Winnipeg Sandstone in the Williston

basin (Porter and Fuller, 1959; Fuller, 1961) and to the St. Peter Sandstone in the remaining part of the indicated region. Facies of the St. Peter have been well described and mapped by Dapples (1955), from which a part of figure 4 has been adapted. Geologic sections typifying the regional unconformable relations are given by Porter and Fuller (1959), Fuller (1961), and Dake (1921).

The Chazy sandstone facies grades eastward into carbonates and southward into carbonates interbedded with shales and sandstones, maintaining the underlying unconformity throughout. Geologic sections or maps illustrating the regional occurrence and magnitude of the unconformity are given for Ohio by Woodward (1961), for Tennessee by Wilson (1949) and Wilson and Stearns (1963), for Oklahoma by Schramm (1964) and Statler (1965), for the Forest City and Salina basins by Lee and others (1946) and Lee (1956), and for west Texas by Galley (1958) and Wright (1965). Simpson strata of the southern area overstep regionally upon eroded and gently dipping Arbuckle-Ellenburger rocks. The Chazy rests upon the late Cambrian Trempealeau Formation across the Waverly arch of Ohio, and the Buffalo River of Tennessee rests upon eroded Knox. The thickness of beds regionally truncated exceeds 500 feet in many areas.

On the tectonic curves of figure 12, the correspondence of tectonic peaks for early Chazy time is apparent in each of the thirty regions studied, from which Chazy strata have not been eroded.

Early Trentonian.—The sub-Trenton unconformity (late Middle Ordovician) in virtually all areas is present between sequences of carbonate rocks, with the result that it has not been as widely recognized and accepted as certain other Paleozoic surfaces of unconformity. Its existence has been well documented in marginal and central parts of the craton, however, and the probability is strong that it is present as a low-angle slightly truncating unconformity in the remaining parts. Figure 5 shows by stipple pattern the distribution of Trentonian rocks in the central United States; diagonal ruling indicates where they are absent, presumably by post-Ordovician erosion.

In figure 5 the areas of dark stipple, identified by the letter symbol CO, represent maximum uplift and truncation, for all Black River strata have been removed by pre-Trenton erosion, and Trentonian rocks rest unconformably upon the Chazy, Canadian, Cambrian, or Precambrian. The stratigraphic relations in the northeastern region have been described by Kay (1948, p. 1411) as follows: "The lower Trentonian formations of northwestern New York and eastern Ontario . . . disconformably overlap Black River rocks, lying locally on Canadian and Cambrian along the Mohawk River, and on pre-Cambrian in Ontario . . .". Two areas of general similarity are present in the Midcontinent region. In the Forest City basin, principally in northern Missouri, the Decorah Formation (lower Trenton) is unconformable upon Chazy St. Peter Sandstone (McQueen and Greene, 1938, pl. VII; Lee and

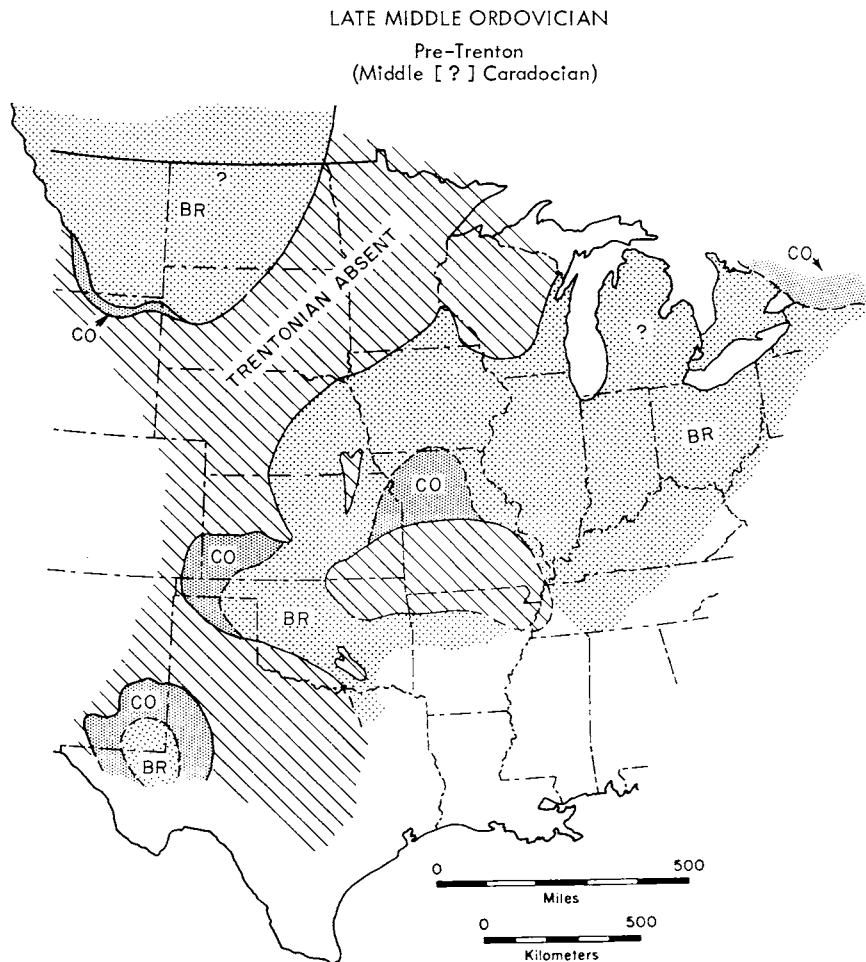


Fig. 5. Late Middle Ordovician (pre-Trenton) unconformity in the central United States. *Light stipple*: Trentonian strata rest disconformably, with local truncation, on Black River strata (BR). *Dark stipple*: Trentonian strata lie unconformably upon Chazy and older rocks (CO). The least amount of truncation is in Michigan and southern part of the Williston basin, where, as shown by queries, the unconformity itself has been questioned by some authors. *Diagonal lines*: Trentonian strata eroded.

others, 1946); and in adjoining parts of Kansas, Colorado, Oklahoma, and Texas, the Viola Limestone (Trentonian) rests with low-angle unconformity upon eroded Arbuckle (Canadian) beds (Maher and Collins, 1949). Finally, around the margins of the Permian basin of Texas and New Mexico, the base of the Montoya rests upon eroded Ellenburger (Canadian), according to Galley (1958).

Elsewhere upon the craton, carbonate rocks of Trentonian age rest upon beds of Black River age, identified on figure 5 by light stipple

with the letter symbol BR. In most areas the unconformable surface between them has been established by detailed regional studies. The work by Schramm (1964, p. 1191) shows that Viola Limestone cuts progressively downward across stratigraphic units of the Simpson Group from central Oklahoma northwestward to Colorado, where, from the work of Maher and Collins (1949), the Viola is known to rest upon Arbuckle. Likewise, in central Tennessee, rocks of the Trentonian Hermitage Group are unconformable by erosion and overstep upon the Stones River Group (Wilson, 1949, p. 23, 24, 48; Wilson and Stearns, 1963). In Illinois and through much of the upper Mississippi valley the relations are equally indisputable. According to Templeton and Willman (1963), the basal Trentonian ". . . Decorah is unconformable upon the underlying Platteville. On the flanks of the Ozarks the Decorah is overlapped by Dunleith (Galena) strata that locally truncate the Guttenberg and Kings Lakes Formations and, less commonly, the entire subgroup (Decorah)" (p. 105). The Spechts Ferry or basal formation of the Decorah ". . . is unconformable on the ferruginous, phosphatic, pitted surface of the Quimby Mills (Platteville) Formation, and locally contains Quimby Mills fragments. It truncates the underlying Platteville in Iowa, Minnesota, and southwestern Wisconsin, and rests on beds as old as Grand Detour (Platteville)" (p. 106). The same conclusion was reached in the study of Iowa Ordovician rocks by Agnew (1955), who states in his summary of the Decorah (p. 1730-1731) that "The Decorah formation rests disconformably on the Platteville formation . . .". Finally, the Trentonian Kimmswick Formation is regionally unconformable on the Plattin on the east flank of the Ozarks in Missouri (Martin, Knight, and Hayes, 1961, p. 28) and on the south flank of the Ozarks in Arkansas (Miser, 1922, p. 20). A disconformity separates the Lexington Limestone from underlying beds in outcrops of central Kentucky.

The foregoing discussion has attempted to illustrate the many areas of the craton at which pre-Trentonian uplift and erosion can be supported by evidence for unconformity. All major geographic and geologic elements are included except the Michigan basin and central part of the Williston basin, indicated on figure 5 by queries. Cohee (1948a, b) shows no unconformity between Trenton and Black River beds in the subsurface of the Michigan basin, and none is shown in the subsurface of the Williston basin by Carlson (1960), Fuller (1961), or Patterson (1961). The Trenton-Black River contact in North Dakota is placed from conodont studies by Carlson in the upper part of the Winnipeg Formation, approximately at the base of the Roughlock Member (Carlson, 1960, p. 74). Along the southwestern margin of the Williston basin, upper Winnipeg or Trentonian beds are unconformable upon the Deadwood Formation of Late Cambrian and Early Ordovician age, but otherwise neither the Williston nor Michigan basins can be said to have late Middle Ordovician unconformities. Thus they are exceptions to the general conclusion that a pre-Trenton unconformity characterizes the craton.

Cincinnatian.—The occurrence of an unconformity in Cincinnatian strata in the central part of the United States has been recognized from the time of early work in the Mississippi valley by Weller (1907). More recent investigation, combining the results of surface and subsurface studies, now show that at least one significant unconformity is present in Late Ordovician strata in all interior parts of the craton. The area of occurrence is within a broad northeast-trending segment extending from Michigan and eastern Nebraska to west Texas and Tennessee (fig. 6). It is bordered by areas of continuous deposition to the northwest and to the southeast, so that the region of unconformity is clearly a broad arch of nearly craton-wide dimensions.

At its eastern margin the unconformity disappears along a line where the sediments increase in thickness and dip eastward, toward and into the Allegheny synclinorium. Full sections of Eden, Maysville, and Richmond strata occur in outcrops east of the line in the Cincinnati region of southwestern Ohio, southeastern Indiana, and central Kentucky (Cumings, 1908), as well as in the subsurface of central Ohio, southeastern Indiana, and west-central Kentucky (Rooney, 1966; Freeman, 1953). Similar full sections occur low on the east flank of the Nashville dome in central Tennessee (Wilson and Stearns, 1963). The opposite or northwestern margin of the unconformity region is eroded along the Transcontinental arch (where the words "Cincinnatian absent" appear on fig. 6), but in the adjoining Williston basin there is no unconformity, and the thick Stony Mountain and Stonewall Formations of Late Ordovician age overlie the Middle Ordovician Red River Formation with regional conformity (Fuller, 1961).

Most parts of the uplifted central arch are characterized by a single late Ordovician unconformity, identified stratigraphically and regionally as follows.

1. A single unconformity is recognized as pre-Maquoketa, post-Trenton in the northern and central region of Illinois, Iowa, northeastern Kansas, eastern Nebraska, and northeastern and eastern Missouri. It has been described in surface exposures and in subsurface by many investigators (Weller, 1907; Ladd, 1929, p. 348-349; DuBois, 1945, p. 14-15, 19; Lee and others, 1946, sheet 2; Rubey, 1952, p. 23-24; Agnew, 1955, p. 1719; Martin, Knight, and Hayes, 1961, p. 30). The recent observations of Templeton and Willman (1963) are especially convincing, for they state (p. 98-99) that the Maquoketa Group, including the Cape or Fernvale limestone at the base, rests upon progressively older rocks of the Galena Group in the 500-mile distance from Stewartville, Minnesota, southward to Cape Girardeau, Missouri. At Cape Girardeau, slightly more than the upper half of the Galena Group, about 150 feet, has been removed by pre-Maquoketa erosion.

2. A pre-Fernvale unconformity is everywhere recognized in southeastern Missouri, northern Arkansas, and northeastern Oklahoma (Martin, Knight, and Hayes, 1961, p. 30; Miser, 1922, p. 22; Maher and

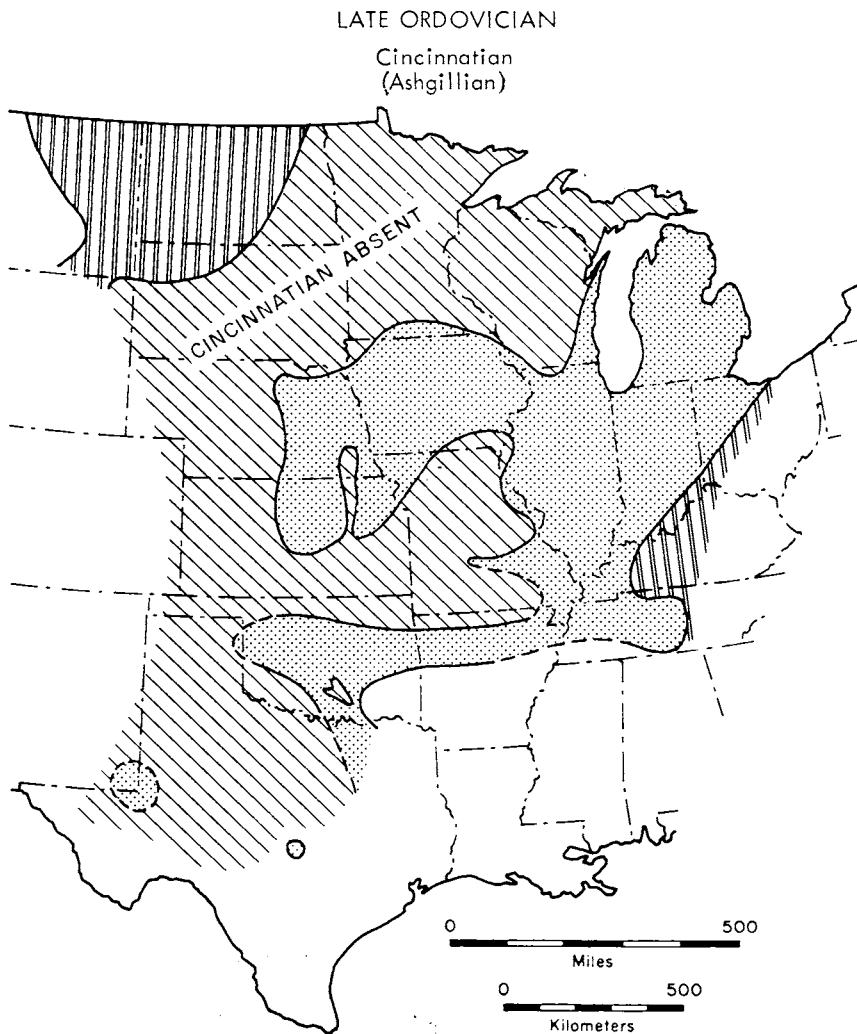


Fig. 6. Late Ordovician unconformity in the central United States. *Stipple*: Cincinnatian strata rest unconformably upon older Ordovician strata, generally Trentonian but locally, in parts of Arkansas, Oklahoma, and Texas, upon Black River or Early Ordovician beds. *Vertical lines*: Cincinnatian and Trentonian beds are in stratigraphic contact, with little or no evidence for disconformity. *Diagonal lines*: Cincinnatian strata absent. The region of Cincinnatian unconformity is a broad belt trending northeastward across the central United States, arched between the area of the Willis-ton basin and what is now the Cincinnati-Findlay uplift.

In constructing the map, two or possibly three erosional surfaces were used—pre-Maquoketa for the northern region, pre-Fernvale for the south-central region, and pre-Sylvan or pre-Cason for the southwestern region of the central craton. Uncertainty as to the number of unconformities represented is related to problems of correlating Eden and Maysville equivalents.

Lantz, 1952, 1953; Huffman, 1958, p. 26). Beds below the unconformity are locally the Kimmswick (Trentonian), Plattin (Blackriveran), or Fite (Blackriveran).

3. A post-Fernvale, pre-Cason, or pre-Sylvan unconformity is recognized in northern Arkansas (Miser, 1922, p. 27), central Oklahoma (Glaser, ms, p. 117), and west Texas (Galley, 1958, p. 402). No other unconformity of Late Ordovician age has been demonstrated in central Oklahoma or in west Texas.

4. A pre-Richmond unconformity is regionally extensive across the Nashville dome of central Tennessee, whereas three additional unconformities of late Ordovician age are confined to the crestral area of the dome (Wilson and Stearns, 1963). A pre-Richmond unconformity also is known from scattered outcrops in central Texas (Barnes, Cloud, and Duncan, 1953).

5. A pre-Cincinnatian, post-Trenton unconformity is recognized in the subsurface of Indiana, eastern Illinois, northwestern Ohio, and Michigan. According to the interpretations of Rooney (1966), the Trenton limestones were exposed and subaerially eroded before deposition of early Cincinnatian shales.

An analysis of the five regions discussed above reveals the occurrence of unconformities variously called pre-Maquoketa, pre-Sylvan, pre-Fernvale, pre-Richmond, and pre-Cincinnatian. The correlations of Twenhofel and others (1954) would indicate three separate unconformities, but regional field studies do not substantiate the presence of more than two. Regardless of the problems of correlation (well known to exist between Trentonian and early Cincinnatian strata), it remains true that a single late Ordovician erosional surface characterizes most parts of the central craton and as such represents widespread late Ordovician epeirogeny.

Silurian

Silurian strata of the central interior of the United States are typically marine limestone, dolomites, and argillaceous carbonates. They are presently distributed in all major geographic divisions of the craton but are absent over large central and west-central areas (fig. 1), mainly because of erosion during numerous episodes of uplift in Devonian, Mississippian, and Pennsylvanian time. The Silurian rocks that have been preserved are normally 300 to 500 feet thick in the main central region and 1000 to 5000 feet thick in three cratonic basins peripheral to the central region.

In the central region are many well-exposed outcrops where Silurian beds are richly fossiliferous, have been intensively studied, and have been divided into stratigraphic units that are widely recognizable. Many of these units can be readily identified in subsurface. At least five unconformities have been demonstrated. Two of them—pre-Alexandrian and early Niagaran—characterize all interior parts of the craton, and the area of their occurrence is shown by dark stipple on figure 7. The

EARLY AND MIDDLE SILURIAN
 Early Alexandrian and Early Niagaran
 (Early Llandoveryan and Early Wenlockian)

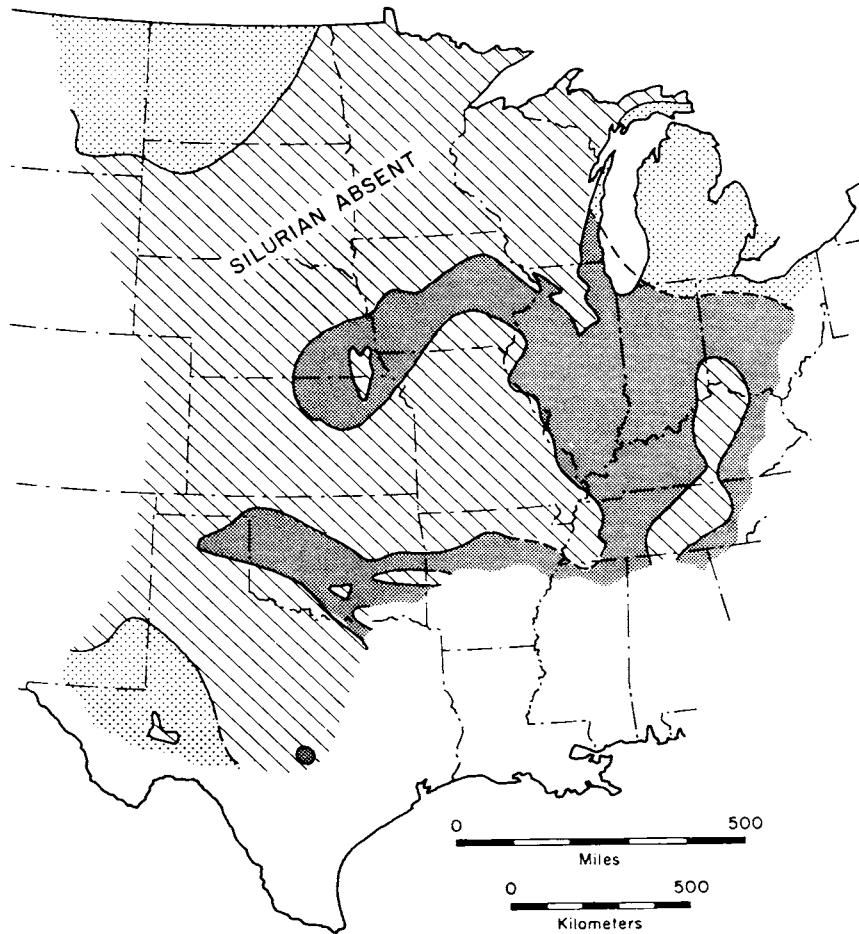


Fig. 7. Distribution of Silurian strata and the two principal Silurian unconformities in the central United States. *Stipple patterns*: area of Early and Middle Silurian strata. *Dark stipple*: interior and southeastern parts of the craton where early Alexandrian and early Niagaran unconformities are widely recognized. *Light stipple*: bordering cratonic basins containing thick Silurian subsurface sequences in which these unconformities are not generally recognized. *Diagonal lines*: Silurian absent, mostly eroded. The early Alexandrian episode of uplift, regional folding, and erosion is characterized in the cratonic interior by truncation of underlying Cincinnati and Trentonian beds. The uplift was at a maximum along the southeastern part of the craton, in a belt extending through Indiana, Kentucky, Tennessee, Arkansas, and most of Oklahoma, where truncation is locally deep and where beds that overlie the unconformity are late Alexandrian Brassfield and equivalents. The principal Middle Silurian unconformity of widely recognized extent throughout the central craton is at the base of Niagaran or Wenlockian strata, including the Osgood, Rockdale, Joliet, Hopkinton, St. Clair, and Clarita Formations. They rest unconformably upon Ordovician rocks locally in Oklahoma, Arkansas, Kansas, Iowa, and probably in Nebraska and central Texas.

early works of Savage (1913, 1916, 1926) established the essential concepts of the Alexandrian Series in the Mississippi Valley—basal Girardeau Limestone, middle Edgewood Limestone, and, at the top, Sexton Creek or Brassfield Limestone. One of his conclusions is stated with unmistakable clarity: "The strata comprising the Alexandrian series in Illinois and Missouri are everywhere unconformable on some horizon of the Richmond, and they are separated by a similar sedimentary break from the rocks that lie above them" (Savage, 1913, p. 356). Regarding the lower unconformity, he showed that the Girardeau is absent in most areas and that the Edgewood is absent locally. The top of the Alexandrian, according to Savage, is separated by pronounced faunal hiatus from the overlying Niagaran deposits, and thus the Brassfield-Kankakee is unconformable below the Niagaran Joliet in Illinois, Hopkinton in Iowa, and Waldron in Indiana (Savage, 1926, p. 533).

Early Alexandrian.—Later workers have confirmed and extended the conclusions of Savage. An unconformity at the base of the Alexandrian marks all interior parts of the craton. In central and western Tennessee the Brassfield Limestone is a major truncating formation, as it rests unconformably upon the Mannic, Fernvale, Sequatchie, and Leipers Formations of Late Ordovician age and locally upon the Catheys Formation of Middle Ordovician (Trenton) age (Wilson, 1949, p. 243). Similarly the Brassfield Limestone rests upon eroded Ordovician beds in southern Indiana, west-central Kentucky, and northern Tennessee (Foerste, in Swartz and others, 1942). The same is true in northern Indiana (Shaver, 1961). In the subsurface of west-central Illinois the Edgewood Formation is overstepped by the Kankakee (Brassfield) over wide areas of the Sangamon arch, so that the Kankakee rests unconformably upon the Maquoketa (Whiting and Stevenson, 1965, p. 3-7). Ireland (1966, 1967) has shown precisely the same relations in the subsurface of north-eastern Kansas. Brassfield Limestone is unconformable on Late Ordovician shales in Arkansas (Maher and Lantz, 1953). In Oklahoma, the Cochrane and Blackgum Formations of Brassfield age, and locally the Keel-Ideal Quarry Formations of Edgewood age, rest unconformably upon the Late Ordovician Sylvan Shale (Amsden, 1960; Amsden and Rowland, 1965).

Two general conclusions are evident. First, the Brassfield Limestone, with its equivalent Sexton Creek, Kankakee, Waucoma, Cochrane, and Blackgum beds, is the most widely distributed stratigraphic unit of Alexandrian age upon the craton. It is one of the remarkable and distinctive sequences of all Paleozoic time. Second, as was pointed out by Savage in the Mississippi Valley and confirmed by Amsden in Oklahoma, unconformities separate the formations of Alexandrian age. One is therefore dealing, not with a single pre-Alexandrian unconformity, but with a pre-Girardeau unconformity, a younger pre-Edgewood unconformity, and a third and still younger pre-Brassfield unconformity. In the common case of Brassfield resting upon Ordovician, the pre-Brass-

field unconformity has overtaken, overridden, and generally obliterated all evidence of the two earlier unconformities. In the tectonic curves of figures 3 and 12, these Early Silurian unconformities are represented as a single peak at early Alexandrian or early Llandoveryan time.

Early Niagaran.—A post-Alexandrian, pre-Niagaran episode of uplift and erosion is amply demonstrated upon the central craton by faunal hiatus together with physical evidence for unconformity. The opinion of Savage (1926, p. 533), that Clinton or earliest Niagaran equivalents are missing in outcrops of Illinois, Missouri, Iowa, Wisconsin, and Indiana, is sustained in the preliminary correlation chart of Silurian strata by Berry and Boucot (ms). Essentially the same faunal hiatus has recently been demonstrated in rocks of Oklahoma and Arkansas by Amsden (1962, p. 1503; Amsden and Rowland, 1965, p. 16), who has also made faunal comparisons and correlations with the European stages. The Clarita Formation is shown to be of early Wenlockian (approximately middle Niagaran) age, whereas the underlying Cochrane or Brassfield is of upper Llandoveryan age. Uppermost Llandoveryan equivalents are absent. An unconformity at the base of the Clarita is clearly observable in quarries and outcrops and has been mapped throughout the Arbuckle Mountains; locally the Clarita rests unconformably upon the Late Ordovician Sylvan Shale (Amsden, 1960).

The St. Clair Formation of Arkansas is equivalent to the Clarita. At the Cason mine the St. Clair rests with evident unconformity upon the Cason Shale (Amsden and Rowland, 1965, p. 16), whereas in other parts of Arkansas it is underlain unconformably by the Brassfield Limestone, Cason Shale, or Fernvale Limestone (Maher and Lantz, 1953). Where St. Clair is on Fernvale, all the Alexandrian Series and uppermost Cincinnati strata are absent by erosion at the pre-St. Clair unconformity. Similarly, in outcrops of northeastern Iowa, the Hopkinton Dolomite of Niagaran age is underlain by the Maquoketa Shale (Late Ordovician), and here too all the Alexandrian is absent (Ladd, 1929, p. 354). Ireland, working with arenaceous Foraminifera in the subsurface of northeastern Kansas, recognized and traced a Clarita-Osgood equivalent, which locally rests upon the Maquoketa (Ireland, 1966, 1967). In central Tennessee the Niagaran Osgood Formation is separated by regional unconformity from the underlying Brassfield (Wilson, 1949, p. 243, 246). And, in central Texas, the newly discovered Starke Limestone of Wenlockian-Niagaran age is presumed to rest upon limestones of Early or Late Ordovician age (Barnes and others, 1966).

In summary, Niagaran strata extend across the craton from Texas to northern Illinois and Indiana. A facies of pink crinoidal limestone is widespread and recognizable in the Starke, Clarita, St. Clair, and Joliet Formations, and far southwest in the subsurface Fusselman of west Texas. Dolomite or shale equivalents are the Osgood, Rockdale, and Hopkinton Formations. A regional unconformity separates these strata from underlying rocks, which in many areas are of Ordovician age.

The unconformity is plotted on the tectonic curves as a peak of early Wenlockian age.

Thick Silurian Sequences of Cratonic Basins.—Rimming the central craton are three cratonic basins, each containing thick Silurian beds (light stipple, fig. 7). The greatest thickness of 5000 feet is in the central part of the Michigan basin, where the Salina Group alone is 3150 feet thick, of which 2000 feet is rock salt (Cohee, 1948a; 1965, p. 217). That little or no evidence for unconformity has been described in the Silurian of the Michigan basin is not surprising, in view of a thickness there that is approximately 10 times greater than is normal for the central craton.

In the southwestern or Permian basin and in the northwestern or Williston basin, however, the Silurian strata are mostly dolomites or argillaceous dolomites and limestones approximately 1000 feet thick. The studies of Porter and Fuller (1958) in the Williston basin subsurface led them to believe that continuous sedimentation prevailed from the late Ordovician Stonewall Formation through the Silurian Interlake Group; and Baillie, reporting on the paleontology of the Interlake outcrop area of Manitoba, states: "No hiatuses were observed within the Interlake group and consequently these strata probably represent continuous deposition from Early Alexandrian to Niagaran, up to and including the Guelph" (Baillie, 1951, p. 51). The paleontologic conclusion of Stearn (1956), indicating that the Interlake Group is of Middle Silurian age and that Alexandrian equivalents are absent, has been reviewed and rejected by Porter and Fuller. Hopefully, further work will reveal additional evidence to bear on the question of regional uplift in the Williston basin during Silurian time.

In west Texas and southeastern New Mexico, Silurian rocks are sparsely fossiliferous dolomites (Fusselman) at the outcrop and in the subsurface of the northern part of the Midland-Delaware basin; in the subsurface to the south occur argillaceous limestones and shales underlain by carbonate rocks lithologically similar to the Clarita (Niagaran), Cochrane (Brassfield), and Keel (Edgewood) of the Arbuckle Mountains (Wilson and Majewske, 1960). Faunal control from subsurface cores is sufficient to demonstrate a probable Niagaran-Alexandrian age for the sequence, but insufficient to demonstrate whether unconformities are present here as they are on the central craton. In his study of the Permian basin Galley (1958) places an unconformity at the base of the Silurian (p. 402) and shows in a paleogeologic map (p. 405) that Silurian-Devonian strata lie upon the eroded surface of the Ellenburger Group (Early Ordovician) on the east side of the Tobosa basin.

Devonian

The interpretation of Devonian strata in the central United States is a study in cratonic differentiation. Carbonates and evaporites are widely but unevenly spread, as in earlier systems, but for the first time a blanket of dark shale (Late Devonian) covers much of the region. Total

Devonian thickness is at a maximum of 4500 feet in the Michigan basin; it is 2000 feet in the Williston basin, and 1500 feet in both the Illinois and Midland-Delaware basins, whereas in all other areas it is normally less than 500 feet. Only in the Illinois basin is there a reasonably complete sequence of Devonian beds. Other basins contain greater thicknesses but, generally lacking the rocks of two or more series, have less stratigraphic representation. Finally, three unconformities—Early, Middle, and Late Devonian—can be easily recognized and traced in different regions, but no one of them can be carried entirely across the craton.

The principal sequences and unconformities are as follows:

1. Early Devonian carbonates are present in all major areas in a wide southeastern border of the craton, but no Early Devonian is present in central and northern regions, except in one small area of northern Michigan. Where present, Early Devonian beds are separated by an unconformity from underlying Silurian and Ordovician beds.

2. Middle Devonian cherty carbonates are widely spread in a broad central and southeastern region and occur with evaporites in the northern regions of Iowa, Michigan, and the Williston basin, lying unconformably upon beds as old as Ordovician. In the southwestern Midland-Delaware basin, Middle Devonian beds are thin and presumably conformable upon underlying Early Devonian carbonates. Middle Devonian strata are absent over a broad area of central and western Oklahoma, although Early and Late Devonian strata are well represented.

3. Late Devonian strata are present in every major basin of the craton, consisting dominantly of dark shales with some cherts and thin carbonates in all regions except the Williston basin, where the sequence consists instead of carbonates and evaporites. Probably the greatest unconformity of Devonian time in the central United States occurs at the base of this sequence, the pre-unconformity uplift and erosion profoundly affecting all areas except the Michigan basin and interior parts of the Illinois and Williston basins. Dark shales of Late Devonian and Early Mississippian (Chattanooga-Woodford-Bakken) age constitute a distinctive clastic sequence that covers the craton, being recognizable even more widely than the Late Ordovician Maquoketa-Sylvan sequence.

Early Devonian.—As used herein, Early Devonian refers to Helderbergian and Oriskanian (Deerparkian) strata, which are approximately equivalent to the Gedinnian and Siegenian stages of European nomenclature. The occurrence of these beds in the central United States, as shown in figure 8, is limited generally to the southern part of the craton but includes a small outlying area in northern Michigan. Beds of Early Devonian age are not recognized elsewhere upon the craton.

The principal belt consists of discontinuous areas extending from the Illinois basin southward into western Tennessee, thence westward across Oklahoma and southwestward into central Texas and the Midland-Delaware basin. Maximum thickness of 800 feet is in the deep southern part of the Illinois basin (Workman, 1944); substantially similar

but much thinner sequences crop out in southeastern Missouri (Branson, 1923; Croneis, 1944), southern Illinois (Weller, 1944a), and western Tennessee (Dunbar, 1919; Wilson, 1949). The Midland-Delaware sequence is entirely in subsurface and is known principally from cores. Carbonates and cherty carbonates dominate the Oriskanian and Helderbergian strata here, as they do in the Illinois basin (Wilson and Majewske, 1960). Large areas of Early Devonian limestones extend across Oklahoma, partly exposed in outcrops but mostly in subsurface (Amsden, 1960, 1961; Amsden and Rowland, 1965, 1967). Two remaining small areas consist of Helderbergian limestone in central Texas (Barnes, Cloud, and Warren, 1947) and Oriskanian limestone in northern Michigan (Landes, Ehlers, and Stanley, 1943).

Rocks of the two Early Devonian series crop out and are well developed in the southeastern Missouri-southern Illinois region, in western Tennessee, and in Oklahoma, where the Oriskanian Little Saline-Backbone-Harriman-Frisco sequence overlies the Helderbergian Grassy Knob-Bailey, Flat Gap-Ross, and Bois d'Arc-Haragan sequence. In these regions a pronounced unconformity occurs at the base of the Oriskanian sequence as well as at the base of the Helderbergian. Oriskanian strata truncate across Helderbergian in Michigan and eastern and central Oklahoma and are the oldest Devonian beds in those areas, whereas in all other places the basal Devonian unconformity is pre-Helderbergian. Below the unconformity are rocks ranging in age from Silurian to Early Ordovician. Latest Silurian (Cayugan) beds are missing in all areas except the Michigan basin.

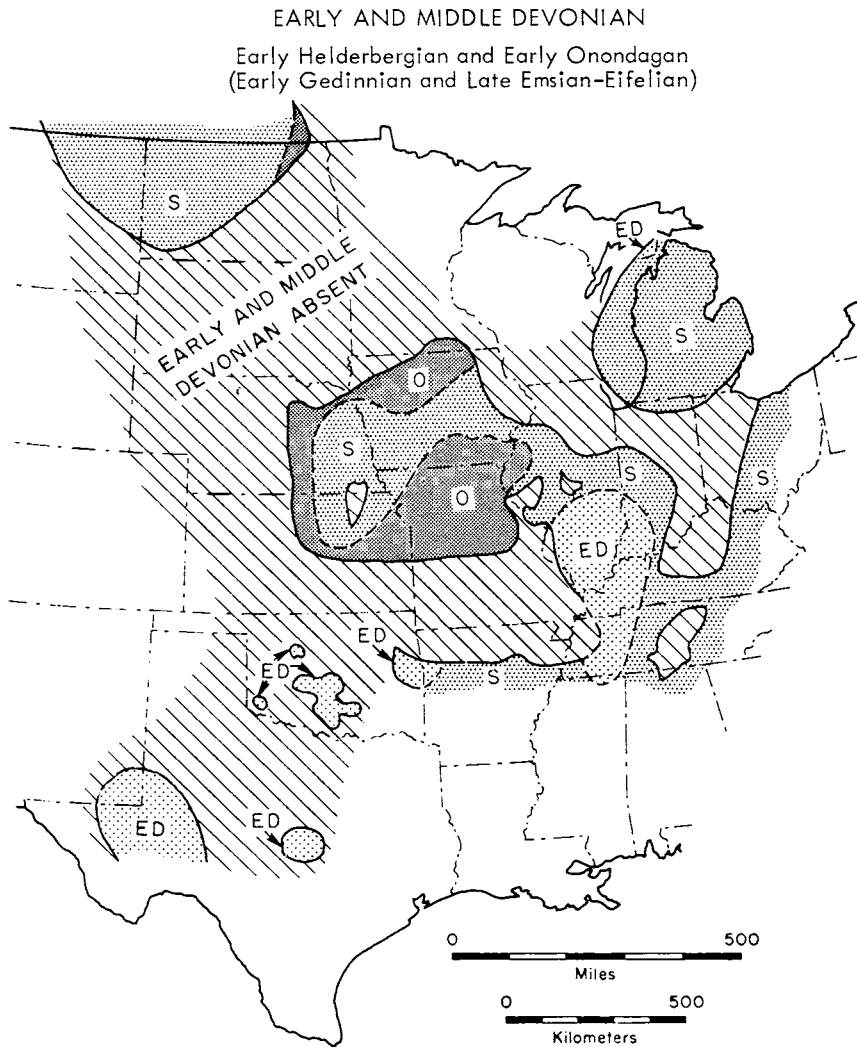
Widespread epeirogenic uplift, gentle folding, and erosion of Early Devonian age is plainly indicated. Maximum known uplift is in Oklahoma and central Texas. In the Arbuckle Mountains of south-central Oklahoma, Helderbergian limestones and marlstones (Haragan-Bois d'Arc) cut across all the underlying Silurian formations and rest locally

Figure 8. Pre-Middle Devonian subcrop map, showing areas of Middle Devonian and of Early Devonian unconformities in the central United States. *Stippled*: subcrop of Ordovician (O), Silurian (S), and Early Devonian (ED) strata (all areas except western Oklahoma, where the Middle Devonian is absent). *Diagonal lines*: Early and Middle Devonian absent, generally eroded.

The pre-Middle Devonian unconformity is conspicuous in southeastern, central, and northern parts of the craton. Middle Devonian (Onondagan) beds overlying the unconformity are the Penters, Camden, and Sallisaw sequence and the Pegram, Grand Tower-Dutch Creek, Cooper-Mineola, Wapsipinicon, Amherstburg, Jeffersonville-Geneva, Bois Blanc, and Elk Point sequence. Toward the northwest, in the Williston basin and possibly in Iowa, they become slightly younger and are of Givetian (late Middle Devonian) age. They rest unconformably upon Silurian and Ordovician strata in most of the region from Arkansas and Tennessee northward to Michigan and North Dakota. The unconformity is not recognizable and sedimentation evidently was continuous from Early to Middle Devonian in the deep part of the Illinois basin and in the Midland-Delaware basin. The absence of Middle Devonian beds in the western half of Oklahoma is anomalous but precludes recognition of the Mid-Devonian unconformity there.

The Early Devonian unconformity is recognizable chiefly within a wide, discontinuous belt near the southern margin of the craton, where Early Devonian Helderbergian and Oriskanian strata (ED) lie unconformably upon eroded Silurian or Ordovician beds.

upon the Sylvan Shale of Late Ordovician age, representing structural relief in excess of 300 feet (Amsden, 1960). Similar though even greater relief is known in the subsurface of southwestern Oklahoma, where the Frisco Limestone (Oriskanian) truncates Helderbergian, Niagaran, Alexandrian, and Cincinnati strata and rests upon the Trentonian Viola Limestone (Amsden and Rowland, 1967). A minimum uplift of 500 feet is apparent. Four hundred miles to the south, in the Llano area of central Texas, the Helderbergian Pillar Bluff Limestone is unconformable upon Early Ordovician carbonates of the Ellenburger Group (Barnes, Cloud, and Warren, 1947).



Middle Devonian.—As used herein, the term Middle Devonian refers to all beds of Onesquethewan and Erian age as given in the Devonian correlations of North America (Cooper and others, 1942). The time range therefore includes equivalents of the Esopus, Onondaga, Marcellus, and Hamilton Formations and is closely correlative with the Emsian, Eifelian, and Givetian stages of Europe. The usage here adopted corresponds with that of Weller (1944b). It differs slightly from that of Cooper and others (1942), in which the Onesquethewan was considered to be questionably of early or middle Devonian age, and from the usage of many more recent workers, who tend to split the Onesquethewan into a lower Esopusian-Emsian, which is placed in the Early Devonian, and an upper Onondagan-Eifelian, which is placed in the Middle Devonian. The upper boundary, taken as post-Erian (Givetian) and pre-Senecan (Frasnian), is consistently used by all workers.

Rocks of Middle Devonian age upon the craton are principally carbonates and cherty carbonates, with evaporites in the Michigan, Forest City, and Williston basins.

An unconformity generally separates Middle Devonian strata from older rocks of the craton, although the time value ranges widely as a result of well-defined northward transgression. The oldest beds above the unconformity are of early Esopusian (early Emsian) age in Texas and southern Oklahoma; of late Esopusian (late Emsian) age in central-eastern Oklahoma, northern Arkansas, Tennessee, and southern part of the Illinois basin; of Onondagan (Eifelian) age in the central part of the craton; and of Hamilton (Givetian) age in the Williston basin. The several unconformities represented are here referred to as the pre-Middle Devonian unconformity, whose median age is pre-Onondagan.

Differentiation into the following three provinces illustrates the northward transgression and northward-increasing value of the unconformity.

1) Southern part of craton.—This province corresponds in a general way with the occurrence of Esopusian-Emsian beds upon Early Devonian beds, so that the stratigraphic discontinuity in most areas is slight. At the southwestern edge of the province is the early Middle and Early Devonian succession of the Midland-Delaware basin, entirely in subsurface and approximately 900 feet thick (Wilson and Majewske, 1960). No unconformity is recognized in this succession, which rather is interpreted as one of continuous deposition (Wilson and Majewske, 1960, p. 77). To the east, in the Llano area of central Texas, are scattered outcrops of the early Esopusian Stribling Formation, occurring with inferrable unconformity upon the Helderbergian Pillar Bluff Limestone (Barnes, Cloud, and Warren, 1947). In the southern part of Oklahoma is a limestone unit (Turkey Creek), approximately equivalent in age to the Stribling, which rests unconformably upon late Ordovician strata (Amsden, personal communication). This is the northernmost occurrence of early Esopusian beds within the craton.

No beds of Middle Devonian age are present in central and western Oklahoma, presumably having been eroded at pre-Woodford or pre-Mississippian unconformities. They are preserved in eastern Oklahoma as the Sallisaw Formation, of late Esopusian age, resting unconformably upon Oriskanian or Silurian limestones (Amsden, 1961; Amsden and Rowland, 1965, 1967). The Sallisaw is a chert-rich limestone equivalent to the Penters Chert of Arkansas, Camden Chert of Tennessee, and the Clear Creek Chert of southern Illinois. In Arkansas the Penters is unconformable upon Silurian or late Ordovician limestones (Miser, 1941; Amsden, personal communication), whereas in Tennessee (Wilson, 1949) and in Illinois (Weller, 1944a,b) the Camden-Clear Creek is unconformable upon Oriskanian beds. The unconformity here is of slight value; in fact, no Middle Devonian unconformity is clearly establishable in the deep part of the Illinois basin (Workman, 1944).

2) Central part of craton.—The central province of the craton includes those areas in which beds of Onondagan (Eifelian) limestone appear, where Early Devonian strata are absent, and where the underlying beds are of Silurian and Ordovician age (fig. 8). The pre-Middle Devonian unconformity in this region is locally pronounced, especially in northern Missouri (Lee and others, 1946), northeastern Kansas (Lee, 1956), eastern Nebraska (Carlson, 1963, pl. III), Iowa, and central Illinois (Workman, 1944). In this region, below the unconformity, are large areas of Ordovician strata. Substantial though lesser magnitude is indicated over a region of equal size—in Michigan, Indiana, Ohio, Kentucky, and central Tennessee—where the underlying rocks are of Silurian age. The overlying rocks are mostly of Onondagan-Eifelian age, including the Pegram of Tennessee (Wilson, 1949), Grand Tower-Dutch Creek of southern Illinois (Weller, 1944a,b), Cooper-Mineola of northeastern Missouri (Branson, 1944b), Jeffersonville-Geneva of Indiana (Sutton, 1944), Bois Blanc of Michigan (Landes, Ehlers, and Stanley, 1945), Anherstburg-Kiddeville of Ohio and Kentucky (Cooper and others, 1942) and Wapsipinicon of Iowa, northern Illinois, and Nebraska (Stainbrook, 1944; Workman, 1944).

3) Northwestern part of craton.—A large segment of Devonian rocks lies in the Williston basin, at the northwestern edge of the central United States, detached from the central province by post-Devonian erosion on the Transcontinental arch. Because they occur chiefly in subsurface, knowledge about the Devonian succession in the Williston basin has increased greatly in recent years following the discovery of petroleum and of valuable evaporite deposits. The first definitive publication was by Baillie (1953), who established a framework of stratigraphic ages and nomenclature. A good early statement is given by McCabe (1954), and probably the best general summary is by Sandberg and Hammond (1958). By far the best published subsurface mapping is that of Sandberg (1961). Assignment of stratigraphic ages is contained in publications of Sandberg (1961, 1963), DeWit (1964, p. 92, fig. 3), and Klapper

(1966). The following summary includes much original, but as yet unpublished, work on Devonian beds of the Williston basin by James Lee Wilson.

According to current concepts, thickness of Devonian beds in the central part of the Williston basin is 2000 feet. The oldest strata are of Middle Devonian (Givetian) age; they have a maximum thickness of 870 feet and are divided into the basal Elk Point Group and overlying Dawson Bay Formation. At the base of the Elk Point Group, as defined and mapped by Sandberg (1961, p. 112-113, pl. 8), is the Winnipegosis Formation, consisting of reefoid carbonates surrounding a central basinal area of thin dolomites and calcareous shale. It is the oldest unit of the Devonian sequence and, owing to the absence in this region of Early Devonian strata, it rests unconformably on Silurian rocks of the Interlake Group. In figure 8 of this report, most of the area shown for the pre-Middle Devonian unconformity in the Williston basin coincides with the subsurface distribution of the Winnipegosis Formation. The Prairie Formation, consisting of dolomite, anhydrite, and salt, is restricted to a much smaller overlying area, fills the basin center above the Winnipegosis, and does not rest upon Silurian beds. The late Givetian Dawson Bay Formation, however, oversteps all strata of the Elk Point Group and, in the eastern part of the Williston basin, rests upon rocks of Ordovician age (fig. 8).

Beds younger than Dawson Bay are post-Givetian and are assigned a Late Devonian (Frasnian and Famennian) age. They have a maximum thickness of 1250 feet and are divided into the Souris River Formation and Jefferson Group (Frasnian) and uppermost Three Forks Formation (Famennian). Both the Souris River Formation and the Duperow Formation, at the base of the Jefferson Group, extend far beyond the limits of the Middle Devonian beds (Sandberg, 1961) and rest unconformably upon beds of Silurian and Ordovician age (fig. 9). This unconformity is of Late Devonian age and accordingly is discussed in the following section.

Late Devonian.—Late Devonian strata which lie upon all the craton except the Williston basin are composed chiefly of dark shales. They belong to a sequence that is called the *Woodford* Formation in Oklahoma and the Midland-Delaware basin, *Houy* Formation in central Texas, *Chattanooga* Shale in Tennessee, Arkansas, Kansas, and Nebraska, *Ohio* Shale in Ohio, *New Albany* Shale in Indiana, Kentucky, and Illinois, *Antrim* Shale in Michigan, *Grassy Creek-Saverton* in Missouri and Illinois, and *Maple Mill* in Iowa. The one feature in common is the universal occurrence of shale, normally black but also occurring in shades of dark gray or greenish-gray. Locally at the base of the black shales are thin sandstone beds variously called *Hardin* in Tennessee, Kentucky, and Illinois, and *Sylamore* or *Misener* in Arkansas, Oklahoma, and Kansas.

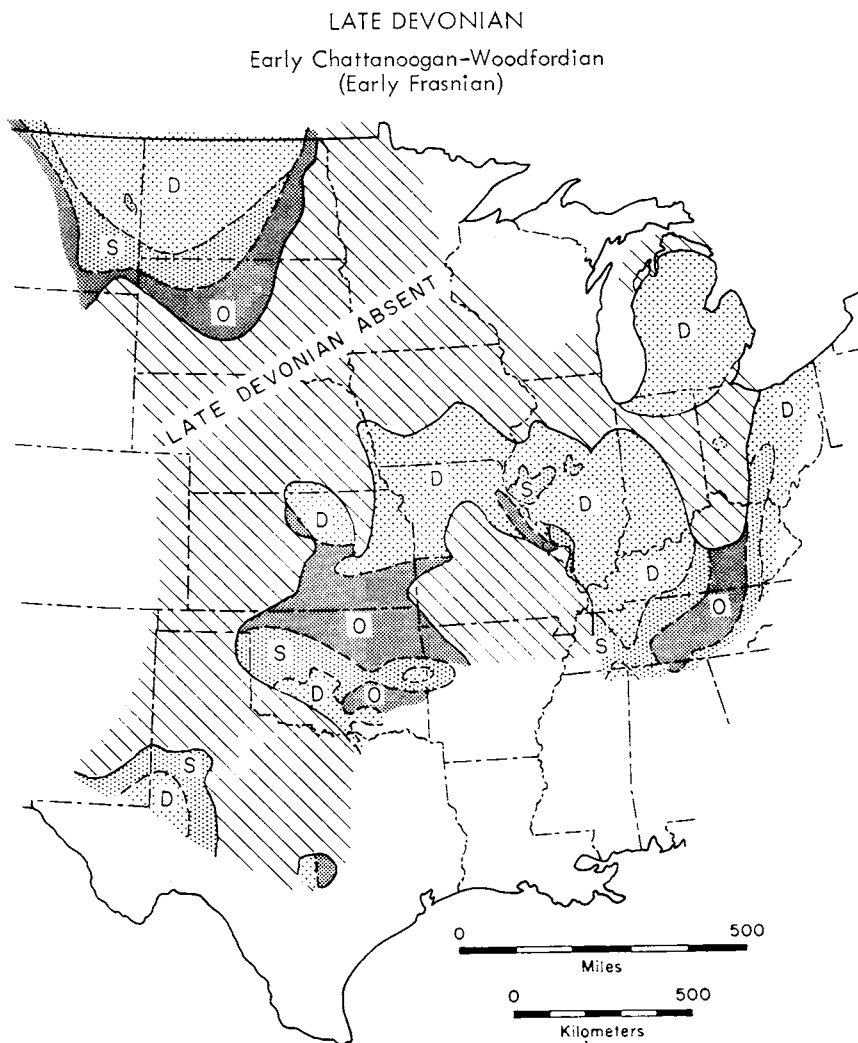


Fig. 9. Late Devonian unconformity in the central United States. *Stipple patterns*: area of Late Devonian strata, showing pre-Late Devonian subcrops. *Diagonal lines*: Late Devonian strata absent, generally eroded. The map shows a broad southeastern segment of Late Devonian strata separated from a northwestern or Williston basin segment. In the southeastern segment, extending from Michigan into Texas, the Late Devonian strata are mostly black shales (Chattanooga-Woodford-Houy-Ohio-New Albany-Antrim-Grassy Creek: Saverton-Maple Mill), with local basal sandstones (Hardin-Sylamore-Misener). The Late Devonian unconformity is most pronounced in the southern part of this segment, in Tennessee, Kentucky, Illinois, Missouri, Kansas, Oklahoma, and Texas, where underlying strata over wide areas are of Ordovician (O) and Silurian (S) age. In the northern part of the segment the Late Devonian shales rest with slight disconformity upon Devonian strata (D), generally Middle Devonian carbonates. Late Devonian strata of the Williston basin are cyclic carbonates with some evaporites; in the central part of the basin they rest with little or no unconformity upon Middle Devonian beds, but toward the margins the Souris River and Duperow are unconformable over wide areas on Silurian and Ordovician beds.

From the extensive and detailed investigations of conodonts, it has been possible to place stratigraphic dates upon all essential parts of this extremely widespread sequence and to correlate the units confidently with the standard European series. The work of Hass and of Collinson in particular has been outstanding and has served to establish Late Devonian elements in each of the above-named beds. The oldest part of the black shale sequence normally is at or near the base of the Late Devonian and is of early Senecan (early Frasnian) age. The sequence continues upward through the Chautauquan (Famennian) series and in some areas continues uninterrupted well into the Kinderhookian or Tournaisian, thus extending through Late Devonian and Early Mississippian time.

The outstanding features of this sequence are (a) the widespread distribution of black shales as a blanket upon the craton, and (b) the profound unconformity that occurs in most areas at its base.

1) Principal part of craton.—The region in which the black shales are now present is the principal segment of the craton that lies south of the Transcontinental arch (fig. 9). This region extends from Michigan to southeastern New Mexico, and from southeastern Nebraska to central Tennessee. It is therefore about 1500 miles long and as much as 1000 miles wide, so that the region over which the black shales were originally deposited was well in excess of 1,000,000 square miles. As a result of its wide distribution and distinctive lithology, the black shale is probably the most easily recognizable of all Paleozoic sequences of the craton. The base of the sequence is not everywhere of the same age, but ranges through modest stratigraphic limits—early Frasnian to early Famennian. In most areas it is of Frasnian age.

Details of stratigraphic age, rock subdivision, and subcrops below the black shale unconformity have been drawn from many sources to compile the map of figure 9. Particularly valuable are the regional investigations of Collinson and co-workers in the upper Mississippi valley (Collinson, 1961; Scott and Collinson, 1961; Collinson, Scott, and Rexroad, 1962) and the regional investigations of eastern and southern interior strata by Hass, especially as summarized in his major work on the Chattanooga Shale (Hass, 1956). Other useful stratigraphic dating is found for Texas rocks in the publications of Wilson and Majewske (1960), Ellison (1950), and Barnes, Cloud, and Warren (1947); for Missouri, the papers of Branson (1944a) and Branson and Mehl (1934); for Iowa, Thomas (1949); for the New Albany Shale in Indiana, Kentucky, and Ohio, the report by Campbell (1946); for Oklahoma, Hass and Huddle (1955); and for general correlations the work of Cooper and others (1942). Important regional maps showing distribution, on surface and in subsurface, of rocks lying below the Woodford-Chattanooga unconformity, are contained in the following publications: Tennessee—Wilson (1949) and Wilson and Stearns (1963); Texas—Galley (1958) and Wilson and Majewske (1960); Oklahoma—Tarr, Jordan, and Rowland (1965),

Amsden and Rowland (1967), and Huffman (1959); Kansas—Lee (1943, 1956), Huffman (1959), and Merriam (1963); Forest City basin—Lee and others (1946); Ohio and Kentucky—Ballard (1938); and Illinois—Workman and Gillette (1956).

The pre-late Devonian unconformity is one of the most conspicuous of all Paleozoic unconformities in the southern and central regions of this great interior province. Chattanooga, Woodford, and equivalent black shales rest with marked unconformity upon beds that generally are of Ordovician and Silurian age. Major continental uplift, warping, and erosion of 500 to 1000 feet of strata are common in Texas, Oklahoma, southern Kansas, eastern Missouri, western Illinois, southern Ohio, central Kentucky, and central Tennessee (fig. 9). However, the northern interior basins were apparently much more stabilized and were only slightly uplifted, with the result that late Devonian black shales rest disconformably upon Middle Devonian carbonates within the Michigan basin, in the deep part of the Illinois basin, and in the Forest City-Salina basin.

2) Williston Basin.—Northwestward across the Transcontinental arch, from which Late Devonian strata have been eroded, is the Williston basin—the largest of all Devonian basins of the craton (fig. 9). Its beds of late Devonian age are lithologically unrelated to those of the central interior, as they consist not of black shales but generally of cyclically deposited carbonates and evaporites, with thin siltstones and shales. As described earlier, the Souris River Formation and Jefferson Group (including the Duperow and Birdbear Formations) are assigned a Senecan-Frasnian age, and the Three Forks Formation is Chautauquan-Famennian. The most widely spread Devonian formations of the Williston basin are the Frasnian Souris River and Duperow Formations; they extend far beyond the Middle Devonian Givetian beds and, toward the wide basin margins, rest successively upon Silurian and Ordovician strata. Thus a pronounced unconformity of late Devonian, pre-Frasnian age is developed here just as in the southern and central regions of the craton, and the total geographic distribution of this unconformity (fig. 9) is sufficient for characterization as a major episode of Paleozoic epeirogeny.

Mississippian

Mississippian strata occur over all major parts of the central United States. The succession generally begins with Kinderhookian dark shales and/or carbonates, continues upward with limestones and cherty limestones of Osagian and Meramecian age, and terminates with interbedded shales, carbonates, and sandstones of Chesterian age. Evaporites occur with middle Mississippian dolomites in Indiana and in the Williston basin. Where the Mississippian system is reasonably complete, including Kinderhookian through Chesterian strata, the rock thickness is substantial—2000 feet in the Illinois basin (Weller and Weller, 1939, p. 8); 3000 feet in the Williston basin (McCabe, 1954, p. 2005-2006); 2700 feet in

the Texas panhandle (Nicholson, 1960, p. 59-60); and 4000 feet in southwestern Oklahoma. The maximum thickness upon the craton, in Oklahoma, is in the deep part of the Anadarko basin, where the lithology is abnormal in consisting mainly of dark shales.

The limestone sequence of Middle Mississippian (Osage-Meramec) age is spread as a vast triangular blanket extending from the Williston basin across the craton to the Kentucky-Tennessee area and back to southeastern New Mexico (Weller and others, 1948, pl. II). It is the youngest of the Paleozoic carbonate blankets, the last to mark an episode of extreme continental stability. It was followed by a flood of Chesterian clastics, derived beyond the margins of the craton, which probably covered all the central United States. These clastics, however, were shortly afterward removed by erosion and covered by Pennsylvanian beds over a broad central belt that extends from Kansas to North Dakota and eastward to Ohio and Michigan. The close of the Mississippian period preceded the continent-wide epeirogeny and orogeny of early Pennsylvanian time.

Pre-Osagian unconformity.—Pre-Chester, pre-Meramec, and pre-Osage unconformities have been recognized as significant in some parts of the craton, but only the pre-Osage unconformity is locally profound and has sufficient geographic extent for discussion here.

The unconformity is at the base of the Osagian series, normally at the base of the Fern Glen or Burlington Formations (or their equivalents). Of wide distribution in the central interior, the unconformity extends from Illinois across southern Iowa, southeastern Nebraska, and Kansas into Missouri, northeastern Oklahoma, and northern Arkansas. The pre-Osagian surface is generally underlain by different units of the Kinderhookian series. Seven Kinderhookian units are recognized on the pre-Osage subcrop map of Illinois by Workman and Gillette (1956, p. 11). In Nebraska the unconformity is underlain by the Gilmore City or the Hampton-Chouteau (Carlson, 1963, p. 20), whereas in Missouri the Burlington is unconformable upon the Hannibal Formation in the northeast and upon Chouteau-Northview in central areas (Spreng, 1961, p. 64). The Burlington disappears westward, and in the subsurface of southwestern Kansas the overlying Keokuk limestone of Osagian age rests unconformably upon Kinderhookian Gilmore City Limestone; locally in southwestern Kansas the pre-Osagian unconformity overrides all older unconformities with the result that the Keokuk is unconformable upon Ordovician carbonates—Viola and Arbuckle (Goebel, ms).

In the southern and eastern parts of the Ozark uplift, the pre-Osagian uplift also was substantial. Huffman's work in northeastern Oklahoma outcrops shows that the St. Joe or Reeds Spring Formations, of early Osagian age, are unconformable upon rocks as old as the St. Clair Formation of Silurian age (Huffman, 1958, p. 42-44). Even greater uplift is indicated in northern Arkansas, where the St. Joe

or Boone Formations are unconformable over wide areas upon rocks of Ordovician age (Croneis, 1930; Gordon and Kinney, 1944). On the eastern edge of the Ozarks too are similar stratigraphic relations—the Fern Glen is unconformable upon Maquoketa Shale of Ordovician age near Valmeyer in southern Illinois (Weller and Weller, 1939, p. 7). The geologic maps of Oklahoma, Arkansas, and Illinois show the surface extent of the pre-Osage unconformity in its most profound development.

Kinderhookian unconformity.—The principal unconformity associated with Mississippian rocks, however, is that of Kinderhookian time. Known mainly in subsurface, it has for many years been recognized by petroleum geologists as the major Paleozoic unconformity in a north-trending belt that extends from central Texas through western Kansas into South Dakota (fig. 10). Within this belt, Mississippian limestones and shales are unconformable generally upon Middle and Early Ordovician strata, although locally they are on Silurian, Cambrian, and Precambrian rocks (Galley, 1958; Totten, 1956; Nicholson, 1960; Huffman, 1959; Merriam, 1963; Carlson, 1963; Goebel, ms). Rocks above the unconformity generally are carbonates of Kinderhookian age—Hampton (Chouteau) in central and western Nebraska, Gilmore City in western Kansas, and late Kinderhookian-early Osagian limestones related to the Chappel Limestone in Texas. The stratigraphic and geographic magnitude of pre-Mississippian erosion in this 400,000-square-mile region far exceeds that of any earlier Paleozoic unconformity.

What has been called the pre-Kinderhookian or pre-Mississippian unconformity in the Williston basin is generally at the base of dark shales of the Bakken Formation and is well known in the United States and Canada (McCabe, 1954; Fuller, 1956; Sandberg and Hammond, 1958; Sandberg, 1961; Kume, 1963). The Bakken consists of three units in the central Williston basin—upper and lower black shales separated by a fossiliferous siltstone. The lower shale is probably Devonian. It rests sharply on rocks of Late Devonian age, above siltstones, shales, and evaporites of the Three Forks Formation in the central part of the basin, and above carbonates of the older Birdbear Formation toward the eastern and southern margins (regional cross-section of Sandberg, 1961, pl. 7; and Kume, 1963, pl. II and III). The Sappington of central Montana is the outcrop representative of the subsurface Bakken. Recent studies by R. C. Gutschick (1964) show its basal black shale to be Fammenian in age and to rest unconformably on the Fammenian Three Forks shale. The unconformity is therefore latest Devonian in age in more basinal areas. The upper Bakken-Sappington onlaps the older parts of the formation across the Central Montana High. Here the unconformity lies at the base of the Kinderhookian strata.

The only prominent local uplift accompanied by block faulting known on the craton during Late Devonian time occurred just west of the Williston basin. The principal uplift of the Cedar Creek horst re-

EARLY MISSISSIPPIAN
Early Kinderhookian and Early Osagian
(Early and Middle Tournaisian)

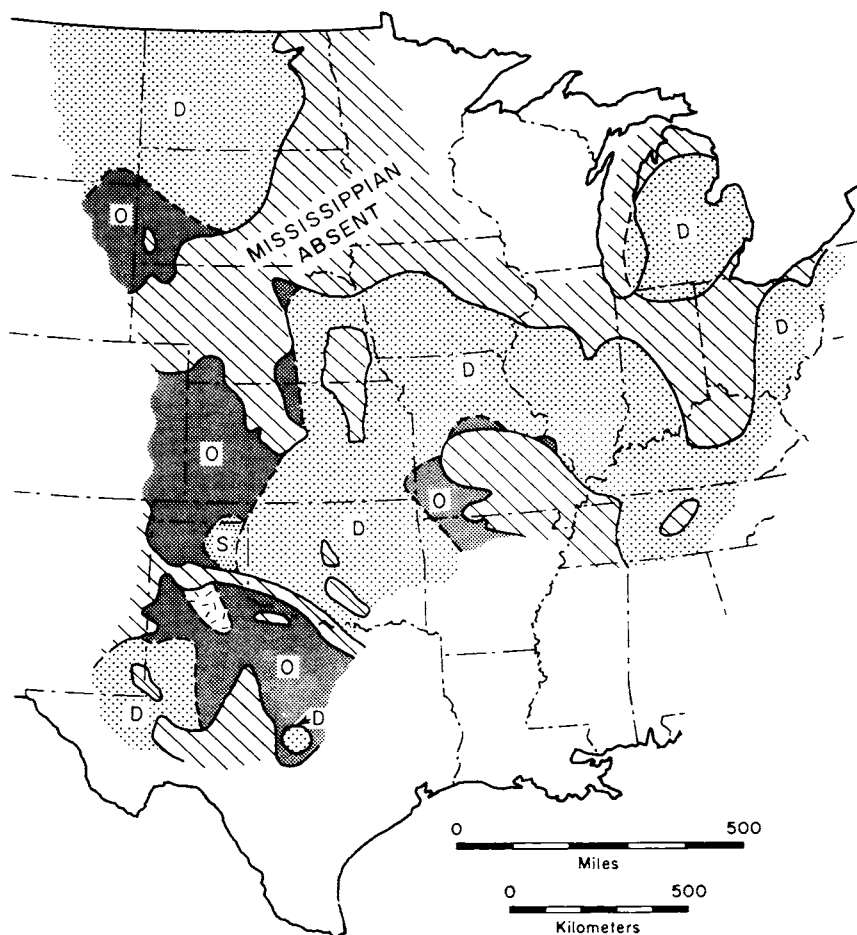


Fig. 10. Early Mississippian unconformity in the central United States. *Stipple and hachure patterns:* area of Mississippian strata, showing pre-Mississippian subcroppings. *Diagonal lines:* Mississippian strata absent. The principal unconformity shown is early Kinderhookian. It is most pronounced in the western part of the craton, from central Texas through western Kansas into southwestern South Dakota, where Kinderhookian and locally Osagian strata are unconformable upon rocks that range in age from Silurian (S) and Ordovician (O) to Precambrian (hachured). A second though much smaller area of similar stratigraphic relations is in western Missouri and northern Arkansas. Resting upon late Devonian (D) strata with low-angle regional truncation are Kinderhookian black shales and/or carbonates in the north-central states (Chouteau-Hampton-Gilmore City-North Hill-Bushberg-Hannibal), in the Williston basin (Bakken-Englewood), and in Tennessee (Maury). Elsewhere the Mississippian-Devonian boundary lies within thick dark shales, in which the pre-Kinderhookian unconformity is establishable only with difficulty. The younger pre-Osagian unconformity, widely recognizable in the central United States, is not shown in most areas of the map.

sulted in erosion of the Devonian and exposure of Silurian strata in a small area now covered by Kinderhookian (?) black shale. The central Montana uplift was upfaulted and also severely eroded at this time. Thin (less than 3 feet) Kinderhookian black shale rests upon lower Upper Devonian and pre-Devonian strata forming an inlier on the apex of the uplift.

The Bakken Formation is not recognized in the southern part of the Williston basin or in adjoining outcrops of South Dakota, Wyoming, or Montana, where instead shales and carbonates (Englewood Formation and others) occupy a similar stratigraphic position. The age of these strata has been determined from conodont studies as uppermost Devonian (latest Famennian) and earliest Mississippian (early Tournaisian), according to Klapper and Furnish (1962), Sandberg (1963), and Klapper (1966). In three of the five outcrop localities examined by Klapper, the basal dark shale is of latest Devonian (late Famennian) age and rests unconformably upon carbonate rocks of Devonian or Ordovician age, whereas at a fourth locality the basal dark shale is Tournaisian or early Mississippian and rests unconformably on lower Three Forks (Klapper, 1966, p. 5).

General conclusions regarding the occurrence in the Williston basin of this interesting and widely developed unconformity, in the present state of knowledge, are well summarized by Sandberg and Hammond (1958, p. 2328): "Upper Devonian rocks are disconformably overlain by the Bakken formation of Devonian (?) and Early Mississippian age in the central part of the Williston basin and in northeastern and north-central Montana. . . . Where the Bakken was not deposited on the southern and eastern margins of the Williston basin, the lowermost Mississippian beds are correlated with the Englewood limestone . . . of the Black Hills, South Dakota, and Wyoming. Elsewhere, Devonian rocks are overlain unconformably by the Lodgepole limestone of the Madison group (Mississippian)".

From its striking development in the western region of the craton and its modest development in the Williston basin, the unconformity at or near the base of the Kinderhookian extends eastward into the central states, where it is still recognizable though much less profound. Clearly it is significant where the Hannibal or Bachelor lies upon Maquoketa Shale or Kimmswick Limestone in Missouri (Spreng, 1961, p. 54; Mehl, 1960, p. 102), but, in much of the region of the central states, there has been considerable uncertainty as to stratigraphic ages in the carbonate-shale sequence referred to in earlier years as "Kinderhookian". Rocks of the Mississippi valley also were involved in controversy, so that age assignments and stratigraphic relations about Late Devonian-Early Mississippian rocks were incompletely understood in much of Illinois, eastern and northern Missouri, Iowa, southeastern Nebraska, and eastern Kansas. As the result of detailed subsurface work and the extensive use of conodont faunas, reasonable agreement has now

been reached and certain general conclusions appear well founded. They may be summarized as follows:

1. The Kinderhookian series is restricted to rocks of Early Mississippian age (Collinson, 1961, p. 100-102).

2. As shown by exhaustive conodont studies, the Sylamore, Grassy Creek, Saverton, and Louisiana Formations are of late Devonian (Frasnian and Famennian) age, whereas the "Glen Park", Hannibal, and Chouteau Formations are of Kinderhookian (Tournaisian) age (Collinson, 1961; Scott and Collinson, 1961; Collinson, Scott, and Rexroad, 1962).

3. Late Devonian equivalents probably are the Maple Mill in Iowa (Collinson, 1961), the Chattanooga Shale as used in Nebraska by Carlson (1963), and the Chattanooga Shale as used in eastern Kansas by Lee and others (1946).

4. Early Mississippian Kinderhookian equivalents include most of the English River Formation and the North Hill Group of southeastern Iowa (Collinson, 1961; Collinson, Scott, and Rexroad, 1962). In Nebraska, eastern Kansas, northern Missouri, and through central and western Iowa, the Hannibal or Boice Shales are recognized as basal Kinderhookian; overlying formations are the Chouteau or Hampton (Chouteau); and, at the top of the Kinderhook series, is the Gilmore City Limestone (Carlson, 1963; Lee, 1943; Koenig, 1961).

5. Of the two unconformities involving dark shales, the major one in the region described is at the base of the Sylamore-Chattanooga-Grassy Creek-Maple Mill; it is pre-Late Devonian, generally pre-Frasnian or early Frasnian. The younger pre-Kinderhook or pre-Tournaisian unconformity is illustrated by the occurrence of the Hannibal-Bushberg upon older strata down to the Ordovician in northeastern Missouri (Branson, 1944b, p. 175; Spreng, 1961, p. 54) and elsewhere by the occurrence of Hannibal-Boice upon Saverton-Chattanooga. Typical Boice in Nebraska contains a basal 10-foot unit of oölitic hematite, partly interbedded in red shale, which helps to support a regional unconformity above the Chattanooga (Carlson, 1963, p. 12), but in general the early Kinderhookian unconformity is inconspicuous because of the similarity in lithology of the beds above and below.

Similar sequences of shale span the Devonian-Mississippian boundary and thus obscure pre-Kinderhookian stratigraphic relations in many other areas in the central and eastern parts of the craton. An unconformity is recognized at this boundary in Tennessee, between the Chattanooga and Maury Formations (Hass, 1956), but it is difficultly recognizable in the New Albany of Indiana and Kentucky, the Ohio Shale of Ohio, the Antrim-Ellsworth-Coldwater sequence of Michigan, and the Woodford of central Oklahoma. In these areas a stratigraphic discontinuity without appreciable erosion must be inferred, reflecting regional stability here that is strongly in contrast with the instability of the western region.

Pennsylvanian

Rocks of Pennsylvanian age upon the central United States craton consist of interstratified limestones, shales, sandstones, and coal, partly of marine and partly of nonmarine origin, and generally arranged in strongly cyclic order. Evaporites are rare upon the craton, although they occur prominently in Desmoinesian rocks of the Paradox basin to the west. Where reasonably complete successions are present, the thickness of Pennsylvanian rocks is as follows: 600 feet in the Williston basin; 900 feet in the Alliance basin of northwestern Nebraska; 2500 feet in the Illinois basin; 2500 feet in Kansas; 3000 feet in the Palo Duro, Dalhart, and Delaware basins of Texas; 12,000 feet in the Fort Worth basin; and 15,000 feet in the Anadarko-Ardmore basins of southern Oklahoma. The thick accumulations in the Fort Worth and Anadarko-Ardmore basins are associated with other similar basins adjacent to the marginal fold belt of the Ouachita system; they have exceptional depositional and tectonic histories and are reserved for discussion in a following section.

Pennsylvanian rocks of the central craton are bound together in having essentially the same stratigraphic development and are generally similar in cratonic behavior to the rocks of earlier Paleozoic systems, with the following conspicuous exceptions. Pennsylvanian rocks in most areas are dominated by clastic sediments and lack thick widespread carbonate blankets. They are conspicuously cyclic. They contain a new kind of sediment—coal—which occurs extensively in thin seams, and a new marine organism—the fusulinids—which are extremely valuable for correlation. Pennsylvanian rocks are further characterized by their deposition upon a profound surface of unconformity and by the development within Pennsylvanian time of epicratonic folds, all reflecting epeirogeny and near-orogeny that was sympathetic to much stronger orogenic movements in the Appalachians and the Ouachita system.

Early Pennsylvanian unconformities.—Clearly the most widely developed and profound Paleozoic unconformity of the craton occurs below strata of Early Pennsylvanian age. It can be recognized in all parts of the central craton except in the trough of the Anadarko-Ardmore basin, where clastic sedimentation from late Mississippian through Early Pennsylvanian time was both thick and continuous, with the result that the systemic boundary can hardly be identified. But, because this basin is geosynclinal in so many characters that it should be excluded from the craton proper, the pre-Pennsylvanian unconformity perhaps could be considered as truly craton-wide.

Rocks below the unconformity have been shown in many regional paleogeologic maps, of which the following have been extensively used in compiling the map of figure 11: central United States (Levorsen, 1960, p. 134); Oklahoma (Jordan, 1962); Texas and southeastern New Mexico (Galley, 1958, p. 418); Kansas (Merriam, 1963, p. 170, 171); Illinois basin (Wanless, 1955, p. 1760-1761); central Midcontinent region

(Branson, 1962, p. 434); and Nebraska (Carlson, 1963, pl. III). Erosion before deposition of Pennsylvanian strata was sufficient to expose large areas of Precambrian basement rocks along the Transcontinental arch in parts of South Dakota, Nebraska, Wyoming, Colorado, and Kansas. Another large segment of similar rocks is along the Amarillo uplift in the Texas panhandle, which extends and enlarges westward into New Mexico (Totten, 1956; Nicholson, 1960). A smaller though nevertheless conspicuous area of Precambrian rocks also is at the crest of the Nemaha uplift in southeastern Nebraska and northeastern Kansas (fig. 11).

Around these greatest of pre-Pennsylvanian uplifts and in similar though smaller anticlinal folds are numerous subcrops of Late Cambrian and Early Ordovician strata, exposed chiefly on the flanks of the Chadron uplift in Nebraska and at the broad crest of the Central Kansas uplift, on the flanks of the Amarillo-Wichita-Muenster uplifts and the genetically similar Red River-Matador uplifts, on the Pecos arch and a much larger part of the Concho or Texas arch in west-central Texas, along a chain of uplifts extending from southeastern Nebraska to south-central Oklahoma, and smaller areas in central Missouri and northern Illinois. At the crests of some of these anticlinal folds are subcrops of Precambrian rocks, too small in area to be shown on figure 11 but enough to extend the localities of profound uplift to all major parts of the central craton. Most of the area remaining between the principal folds is underlain by Mississippian strata, but they too have been beveled by pre-Pennsylvanian folding, marked especially by the loss through erosion of all Chesterian rocks in the north-central states.

Pennsylvanian rocks above the unconformity throughout the craton range in age from Morrowan through Virgilian, or through the entire span of Pennsylvanian time. Examination of geologic relations in many areas reveals that this "pre-Pennsylvanian unconformity" is not a single surface formed at a single time but rather is the composite result of several Pennsylvanian uplifts. Within southern Oklahoma alone at least six individual episodes of Pennsylvanian tectonism—pre-Morrowan, pre-Atokan, early Desmoinesian, early Missourian, early Virgilian, and late Virgilian—can be identified. The highest Pennsylvanian uplifts of the craton, such as the Nemaha, Red River-Matador, and many anticlinal folds in southern Oklahoma, are covered by Missourian or Virgilian rocks. The area of these folds is small in comparison to the size of the craton, yet geologic relations plainly indicate uplift and erosion in Late Pennsylvanian time.

The major uplifts responsible for "the pre-Pennsylvanian unconformity" as shown in figure 11 are those of Early Pennsylvanian time—Morrowan, Atokan, and early Desmoinesian—for these stratigraphic units cover the surface of unconformity over about 95 percent of the central craton. Slightly more than half is covered by Morrowan and Atokan strata, including all of Michigan (Moore and others, 1944; Cohee,

EARLY PENNSYLVANIAN

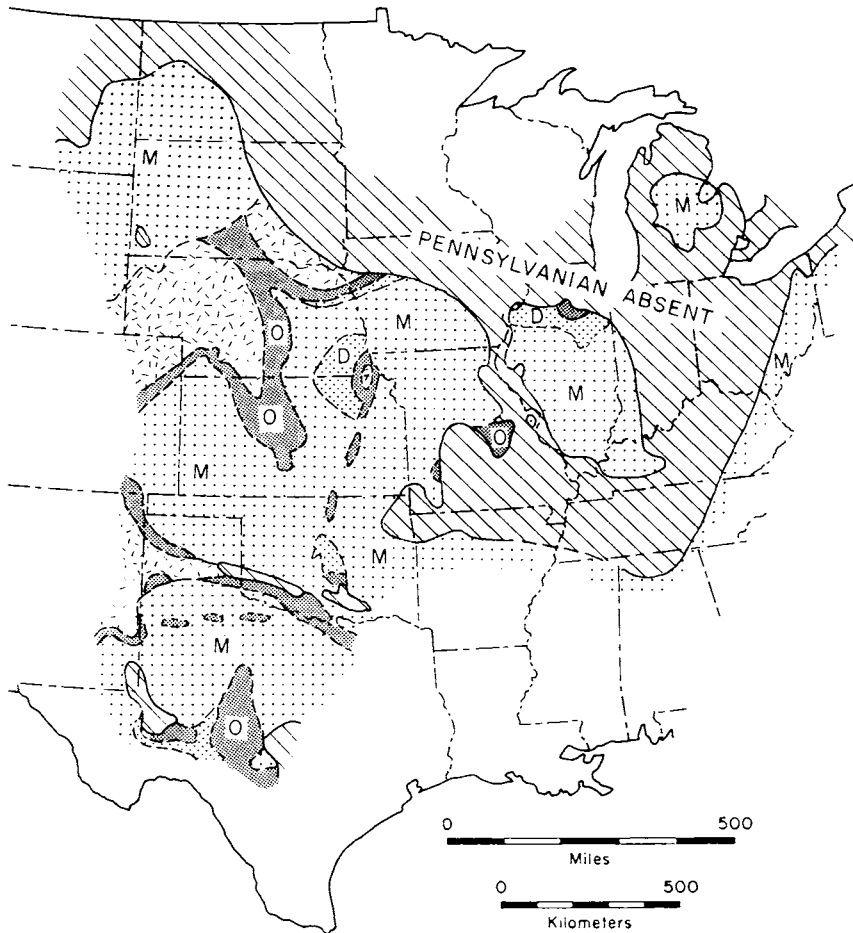
Morrowan, Atokan, and Early Desmoinesian
(Early Namurian; Early and Middle Westphalian)

Fig. 11. Early Pennsylvanian unconformities in the central United States. *Stipple and hachure patterns*: area of Pennsylvanian strata, showing pre-Pennsylvanian subcrops. *Diagonal lines*: Pennsylvanian absent. The map shows paleogeologic subcrops beneath the combined unconformities of early Morrowan, Atokan, and early Desmoinesian times. Desmoinesian strata cover virtually all pre-Pennsylvanian uplifts, where subcrop beds are Precambrian (hachured), Late Cambrian through Ordovician, (O), and Silurian through Devonian, (D), as well as the areas of eastern Kansas, Nebraska, Iowa, and Missouri, where underlying beds are Mississippian, (M). In all other areas shown the oldest Pennsylvanian strata are of Morrowan and Atokan age, resting with slight angular unconformity upon tilted and eroded Mississippian beds. The combined early Pennsylvanian episodes of folding, uplift, and erosion were the greatest of Paleozoic time, affecting all parts of the interior craton and uncovering, for the first time, extensive areas of Precambrian granites. Orogeny was locally developed and severe, particularly in southern Oklahoma (Wichita orogeny), producing as much as 30,000 feet of structural relief.

Macha, and Holk, 1951), the southern part of the Illinois basin (Wanless, 1955), eastern and southwestern Oklahoma and western Kansas (Huffman, 1959), central and western Texas (Galley, 1958; Adams, 1962), adjoining parts of Nebraska, Wyoming, and South Dakota (MacLachlan and Bieber, 1963), southwestern North Dakota (Ziebarth, 1964), and a small area at the common corner of Nebraska, Missouri, and Kansas (Branson, 1962).

The occurrence of Atokan strata in southeastern Nebraska is of special significance because these beds are probably erosional remnants in the heart of the central interior, indicating widespread distribution of Atokan sediments in the central states before their removal by Desmoinesian uplift and erosion. Desmoinesian strata now cover the pre-Pennsylvanian surface in the northern two-thirds of the Illinois basin (Wanless, 1955) as well as most of Missouri, Iowa, Kansas, Nebraska, and north-central Oklahoma (Branson, 1962; Huffman, 1959; Lee and others, 1946; Lee, 1956; MacLachlan and Bieber, 1963).

The occurrence of Desmoinesian strata as a cover upon pre-Pennsylvanian beds over a broad uplift in the central states is duplicated on a smaller scale in west-central Texas. The maps of Adams (1962, p. 375, 378) show that Atokan and Morrowan rocks are present on the flanks of the Concho and Texas arches, whereas on the crests they are eroded, and Desmoinesian (Strawn) sediments rest unconformably upon Mississippian or Ellenburger strata. That the Atokan sediments extended upon and perhaps over the broad crestal region is demonstrated by the general absence of marginal clastics and by truncation of various Atokan facies at the line where overlapped by the Strawn. The principal Pennsylvanian unconformities of this region are pre-Atokan and early Strawn (Cheney, 1940).

The domical structure of the Llano uplift was formed during the early Strawn unconformity. Late Strawn (Desmoinesian) beds onlap and lie unconformably on Atokan (Marble Fall-Smithwick) sediments on the western and northern sides of the dome (Plummer, 1950, p. 57). The dome is cut by a number of north-northeast-trending faults which form a series of horsts and grabens striking across the dome. These probably began growth during Atokan time, but their culmination was in the Strawn. They extend into the subsurface of the Fort Worth basin north of the uplift and east of the Bend arch and die out upward in Late Strawn beds. This mid-Pennsylvanian doming and faulting on the craton may be related to an orogenic pulse in the Ouachita belt. Steeply dipping deep-water sandstones and shale of Atokan age on the southeast corner of the Llano uplift indicate that the Ouachita belt was thrust across a narrow foredeep almost onto the buttress afforded by the Llano positive area at the edge of the craton (Barnes, 1948). This occurred in post-Atokan time and probably during the early Strawn because just north of the uplift the onlapping Strawn strata are unfolded (Ablilene Geol. Soc., 1950).

Pennsylvanian strata in the northwestern part of the central craton are abnormally thin and regionally persistent but otherwise are like those of the western interior. They crop out in the Hartville uplift and Black Hills and extend in subsurface through southwestern North Dakota, western South Dakota, and western Nebraska (fig. 11). Maximum thickness of Pennsylvanian rocks is 600 feet in the south-central part of the Williston basin (McCauley, 1956) and 900 feet in the Alliance basin of northwestern Nebraska (MacLachlan and Bieber, 1963). Subsurface nomenclature is derived by extension from the Hartville Formation of eastern Wyoming, from the Minnelusa Formation of the Black Hills, from the Midcontinent region, or from central Montana. Thus different names are used in different areas by different writers, but, because fusulinid-bearing marine limestones are widely present, it has been possible to establish equivalents throughout the region. The principal investigators in subsurface have been McCauley, 1956; Taylor, 1958; Willis, 1959; Ziebarth, 1964; Mompers, 1963; Hoyt, 1963; and MacLachlan and Bieber, 1963. They agree that a nearly complete sequence of Pennsylvanian and Early Permian beds is present and that major unconformities occur at the base of the Pennsylvanian and at the base of the Permian. Mompers (1963), using the cyclic concept, separates by an unconformity each series and major group as well.

The major Paleozoic unconformity of the region is at or near the base of the Pennsylvanian. It is most profound in western Nebraska and adjoining areas, where the floor beneath Early Pennsylvanian strata consists of Precambrian rocks (Carlson, 1963, pl. III). Here the pre-Pennsylvanian basement floor is a part of the much longer northeast-trending Transcontinental arch, which extends with similar relations for 1000 miles from eastern South Dakota across western Nebraska through central Colorado into New Mexico (Mompers, 1963, p. 62). Rocks overlying the basement floor are of Morrowan and Atokan age in westernmost parts of Nebraska and of Desmoinesian and Missourian age to the east (MacLachlan and Bieber, 1963, p. 86-87 Mompers, 1963, p. 58-59).

Northward from the Transcontinental arch into the Williston basin, the Pennsylvanian beds are unconformable but rest upon a floor of slightly folded late Mississippian rocks. The basal Pennsylvanian beds over most of the area are of Atokan or Morrowan age, assigned to the Reclamation, Fairbank, and Tyler Formations (McCauley, 1956; Willis, 1959; Ziebarth, 1964). Willis (1959, p. 1956) describes an obvious erosional unconformity or scour zone at the base of the Tyler, and Ziebarth (1964, p. 119) has published a pre-Tyler subcrop map of western North Dakota showing truncation of the Madison Group and of the Chesterian Kibbey, Otter, and Heath Formations. Earlier writers describing the unconformity called the overlying rocks Amsden carbonates and a basal sand, assigning them an Atokan age and stating: "The Amsden overlaps progressively the Heath, Otter, Kibbey, and Charles

as a result of post-Mississippian, pre-Atokan erosion" (McCabe, 1954, p. 2007-2008). No other unconformity of Pennsylvanian age is widely recognized in the Williston basin.

The pre-Atokan or early Atokan unconformity is probably the most profound of all unconformities involving strata of Pennsylvanian age upon the craton, judged by its widespread areal extent and by the intensity of uplift and erosion of underlying rocks.

Permian

Distribution of Permian strata is limited to approximately the western third of the central United States craton. Permian clastics, carbonates, and evaporites crop out and are locally well exposed in eastern Nebraska, east-central Kansas, western Oklahoma, and north-central Texas. They dip westward and extend into subsurface virtually to the Rocky Mountains, establishing a north-trending belt about 1200 miles long and as much as 500 miles wide. The position of the Permian shore line to the east is unknown but is presumed to have been not far from present lower Permian outcrops of deltaic sandstones, non-marine shales, and thin limestones. No Permian rocks are known from eastern Kansas to the outcrops of Dunkard clastics in the Allegheny Plateau. Beds previously thought to be of Permian age in the intervening region, in particular the Fort Dodge Formation of north-central Iowa and the redbeds of central Michigan, are now known from their content of spores and pollen to be of Jurassic age (Cross, 1967). Thus much of the interior craton was probably an emergent lowland undergoing erosion during latest Paleozoic time.

Moreover, an episode of similar quiescence is indicated for the transition from Pennsylvanian to Permian in outcrops through most of the Midcontinent region from north-central Texas to Nebraska. No physical discontinuity can be identified, and the stratigraphic position of the boundary itself is in considerable doubt, having been variously placed in Kansas through a range of 400 feet (Moore, 1949, p. 19-22).

In marked contrast to the structural stability of the inner craton is the structural instability of the southern margin, in the folded and thrust-faulted 1200-mile belt of the Ouachita system. One of its principal orogenic pulses was in early Permian time. Near-orogenic disturbances of the same date were manifest in adjoining segments of the craton, particularly in southern Oklahoma and in west Texas. Meanwhile, a sympathetic epeirogenic movement far to the northwest produced an early Permian unconformity in the Williston and Alliance basins. The northwestern epeirogeny is described below, whereas the orogeny of the southern region is reserved for a later section.

The subsurface Permian-Pennsylvanian sequence of the Williston basin, together with western Nebraska and adjoining parts of Colorado and Wyoming, has been described by McCauley (1956), Hoyt (1963), MacLachlan and Bieber (1963), Mompers (1963), and Maughan (1966). All are in agreement in recognizing that Early Permian or Wolfcampian

strata lie unconformably above Pennsylvanian. For the southern part of the region the cross sections of Hoyt (1963, p. 69, 71, 72, and 73) are particularly useful because fusulinid determinations are given for outcrop and subsurface rocks, showing that sediments of Virgilian age are truncated by Wolfcampian strata at a surface of conspicuous unconformity, above which a basal sandstone is locally present. Middle and Upper Virgilian strata generally are absent. For approximately the same area, MacLachlan and Biber are in substantial agreement except for their interpretations that Virgilian rocks are absent, and lower Wolfcamp (Admire) rests upon rocks of the Missouri series. In both papers, Midcontinent and Permian basin stage names are used, along with locally derived nomenclature which includes the Ingleside, Fountain, Hartville, and Minnelusa Formations. McCauley, working in the Williston basin at an earlier date, arrived at the conclusion that the Wolfcampian Broom Creek Formation over wide areas of North Dakota and Montana is unconformable upon strata of Missourian or Desmoinesian age (McCauley, 1956, p. 151).

Evaporites with red shales and dolomite characterize the Permian sequence in the northwestern part of the craton. The upper part especially contains few fossils, so that the locally attempted division into Wolfcampian, Leonardian, and Guadalupian equivalents is insecurely established. A regional unconformity at the base of the Opeche Formation is generally recognized and assigned a Leonardian age (Maughan, 1966, p. 37); an earlier unconformity, at the base of the Cassa Formation, of late Wolfcampian or early Leonardian age, is recognized by McCauley (1956) and Hoyt (1963).

In summary, the tectonic history of Permian time in the northwestern part of the central craton includes a strongly defined pulse of earliest Wolfcampian epeirogenic uplift and truncation of Pennsylvanian strata, followed in Leonardian time by a second and weaker pulse. This tectonic pattern is the same as that at the southern margin of the craton.

LATE PALEOZOIC SEDIMENTATION AND DEFORMATION AT THE
SOUTHERN MARGIN OF THE CRATON

Introduction

Regional studies along what is now the southern margin of the craton suggest that the most critical stage in margin collapse was the Late Paleozoic development of a broad unstable linear zone, characterized especially by the formation of deep basins that became filled with clastic sediment. Much of the filling took place from middle Mississippian through Pennsylvanian time, although individual basins were filled unequally and not necessarily during the same sedimentational episode. In part the basins probably coalesced to form an elongate trough. By Early Permian time the outer segments in this chain of basins had been folded and thrust toward the craton, and the resulting orogenic belt comprises the Ouachita system.

All the basins containing thick Mississippian clastics, including the Tesnus of the Marathon region and the Stanley-Jackfork of the Ouachita Mountains, were involved in mountain building and are clearly a part of the fold belt. Of the marginal basins that were filled or partly filled during the Pennsylvanian only that part containing the Haymond and Gaptank in the Marathon region is known to be strongly folded as a part of the Ouachita system. In the Arkoma basin a much thicker sequence of Atokan rocks (19,000 feet), lying along the margin and just foreland of the Ouachita Mountains, is only moderately deformed. Other marginal basins with slightly folded Pennsylvanian sediments, deposited in greater thickness than that of the Marathon region, are the Kerr, Fort Worth, and Black Warrior basins. Possibly the Kerr and Fort Worth basins in deep subsurface merge into the folded Ouachitas, but the Arkoma and Black Warrior basins are separate entities, so close to the craton that they escaped incorporation into the marginal fold belt. Another type of accumulation is represented by the Val Verde and Delaware basins, which contain as much as 18,000 feet of Permian sediments. These marginal basins were formed after the principal orogeny, in front of the already folded mountains, and as a result their sediments also escaped strong deformation.

Geographic progression of basins toward the craton through time is a logical conclusion. Those basins of the outer belt, generally containing older sediments, were everywhere engulfed in orogeny. Marginal basins of intermediate position, generally filled with Pennsylvanian sediments, were deformed by late Pennsylvanian orogeny if they lay within the orogenic belt and were undeformed if they lay beyond it. The youngest marginal basins, filled with Permian sediments, occupy innermost positions and are essentially undeformed because they are post-orogenic.

The principal tectonic significance in the formation of the marginal basins is their rapid subsidence and thick filling within a short span of geologic time. During the life of the basin, sedimentation was continual and was independent of systemic boundaries that are generally well-defined upon the craton. Thus the Mississippian-Pennsylvanian boundary cannot be confidently established in either the Marathon or Ouachita provinces, just as the Pennsylvanian-Permian boundary is vaguely defined in the Val Verde and Delaware basins.

Recently published papers that deal with regional aspects of structural and stratigraphic evolution at the craton margin, and contain extensive bibliographies as well, are those of Flawn and others (1961) and Goldstein and Hendricks (1962). Additional excellent papers are contained in *The Filling of the Marathon Geosyncline*, Permian Basin Section, Society of Economic Paleontologists and Mineralogists, Midland, Symposium and Guidebook, 1964, and in *The Geology of the Ouachita Mountains, a Symposium*, Dallas and Ardmore Geological Societies, Guidebook, 1959.

Marginal deep basins and foredeeps

Delaware basin and Val Verde foredeep.—At the southwestern edge of the central United States craton, covering parts of west Texas and southeastern New Mexico, are basins famous for their great thicknesses of Permian strata. The Delaware basin lies upon the craton and is elongated northward, approximately at right angles to the adjoining fold belt, but in Early Permian time it was joined with the Val Verde foredeep, lying in front of and parallel to the folded rocks of the Ouachita system. Both were Permian depositional basins, receiving accumulations of Permian sediments locally in excess of 18,000 feet. Both are dominated by Wolfcampian strata, about 8000 feet thick in the deep part of the Delaware basin (Galley, 1958, p. 425) and 14,000 feet thick in the Val Verde trough (Young, 1960, p. 100). According to the isopachous maps of Galley, in the Delaware basin the thickness of the overlying Leonard series is 4000 feet, Guadalupe strata are 3000 feet thick, and uppermost Permian Ochoa beds, including thick evaporites, are 4000 feet. Depocenters are not coincident, however, so the maximum aggregate thickness of Permian beds totalling 21,000 feet is not attained at any locality. The Val Verde foredeep contains 18,000 feet of Permian beds in single wells, of which 12,000 is Wolfcampian; the form of the foredeep and its restriction to Wolfcamp time are shown in the cross sections of Young (1960, p. 105).

Downwarping at the beginning stage in the formation of the deep Wolfcamp basins was accompanied by uplift of the Central Basin platform and truncation of the platform rocks locally down to Precambrian granites (Galley, 1958, p. 425). This north-northwest-trending major horst block probably began its uplift in earlier Pennsylvanian time. Its formation connected the early Pecos arch or Fort Stockton uplift with another pre-Pennsylvanian positive feature in southeastern New Mexico (Galley, 1958, figs. 16, 19). Progressive uplift and marginal downfaulting continued in Pennsylvanian time, culminating in the Wolfcampian. By early Permian time, the uplift had effectively separated the west Texas marginal cratonic basin into the eastern or Midland basin and western or Delaware basin. Wolfcamp beds cover the platform with sharply defined unconformity, whereas in surrounding areas the transition from Pennsylvanian to Permian was marked by nearly continuous sedimentation, as it was in most parts of the central craton. During Pennsylvanian time, the continuously subsiding basins were starved of sediment and were deep. Beginning in Permian time, considerably more sediment was deposited in them. The early Permian near-orogeny of the Central Basin platform represents localized uplift upon the craton, near the craton edge, in sympathy with simultaneous orogeny in the bordering Marathon-Ouachita fold belt.

Other deep basins or foredeeps extend at the craton margin from west Texas to northern Alabama, a curvilinear distance of 900 miles. They include the Kerr, Forth Worth, Arkoma, and Black Warrior basins,

which are genetically similar to the Val Verde basin but share the common feature of being downwarped and filled at a much earlier time—Early or Early-to-Middle Pennsylvanian.

Kerr and Forth Worth basins.—Eastward from the Val Verde basin, along the foreland of the Ouachita system, is the little-known Kerr basin of south-central Texas. Into it the Early and Middle Pennsylvanian sediments thicken southward from the Llano-Concho arch, the pre-Strawn rocks attaining a thickness of 6000 feet and the Strawn rocks a thickness of 2500 feet (Adams, 1962). The Fort Worth basin lies eastward from the Concho-Llano arch and has similar Pennsylvanian thicknesses—5000 feet of pre-Strawn and 4000 of Strawn rocks (Weaver, 1956; Turner, 1957; Adams, 1962). As far as is now known, the earlier Paleozoic rocks of these basins are like those of the Val Verde basin, which in turn are like those of the craton. The distinguishing feature of each is its rapid downwarp and filling during a short span of late Paleozoic time at the unstable southern margin of the craton.

Arkoma foredeep.—A major basin or foredeep, generally called the Arkoma basin, lies between the Ozark uplift of the craton and the frontal belt of the Ouachita system. It is filled chiefly with early Desmoinesian and Atokan sediments. The early Desmoinesian sediments include in ascending order the Hartshorne, McAlester, Savanna, and Boggy Formations, which have an aggregate thickness of about 7000 feet (Hendricks, 1939, p. 263-273; Reinemund and Danilchik, 1957; Haley, 1961). The underlying Atoka Formation has a thickness that ranges from about 5000 feet near the western edge of the basin (Hendricks, 1939, p. 265) to 19,000 feet in west-central Arkansas (Stone, 1966, p. 202-205). The thickness of basin sediments therefore ranges from about 12,000 feet in the west to 26,000 feet in the east. As the basin is situated along the edge of and parallel to the Ouachita Mountains, it has the form and thickness of a linear foredeep.

The area of maximum thickness or depocenter of the Atoka Formation lies south of the line of the early Desmoinesian depocenters, and its structural position with respect to the frontal segment of the Ouachita Mountains changes from Oklahoma into Arkansas. In Oklahoma and westernmost Arkansas the frontal zone of Ouachita deformation cuts into the Atoka basin, strongly involving Atoka rocks in the southern part of the basin, whereas in west-central Arkansas the frontal zone of Ouachita deformation lies just south of the Atoka outcrops (Hendricks, 1939; Reinemund and Danilchik, 1957; Meremether, 1961; Stone, 1966). It thus appears that the greater thrusting of the frontal belt in Oklahoma has resulted in a transection of the foredeep in that area.

Black Warrior basin.—At the southern edge of the craton in northwestern Alabama and northeastern Mississippi is the Black Warrior basin (Mellen, 1947). A sequence of Early Pennsylvanian (Pottsville) shales and sandstone with some arkose has a maximum probable thickness of 10,000 feet in the deep subsurface part of this triangular-shaped

basin (Braunstein, 1958, p. 514-515). Little else is known except that its floor probably consists of sediments that are cratonic in character as well as in thickness, so that marginal deep subsidence and filling was confined to the Early Pennsylvanian. As a genetic type it is thus virtually identical to the Arkoma, Fort Worth, and Kerr basins.

Marginal Fold Belt—the Ouachita System

Introduction

The name Ouachita system is applied to an elongate belt of folded and faulted Paleozoic rocks that borders the southern edge of the central United States craton, in the same way that the Appalachian system borders the eastern edge of the craton. In the United States the Ouachita system extends from west Texas to east-central Mississippi along a curvilinear belt about 1100 miles long. Rocks of the system are concealed by Cretaceous and younger sediments of the Gulf Coastal Plain in most areas, but they are well exposed in the Ouachita Mountains of Oklahoma and Arkansas and in the Marathon region of west Texas. Mapping of the rocks in subsurface, detailed descriptions of outcrops, and regional interpretations are contained in the comprehensive report by Flawn and others (1961).

Most of the depositional and tectonic activity in the building of the Ouachita system belongs to what King identifies as the late geosynclinal phase and the orogenic phase (King, *in* Flawn and others, 1961, p. 182-188). They begin with deposition of the first strata above the novaculite formations—Tesus and Stanley—and close with the late Pennsylvanian-early Permian orogeny. The time span is middle Mississippian to early Permian. During this time the basins were filled with substantial thicknesses of clastic sediment, and the rocks of the Ouachita system from west Texas to Mississippi were folded and thrust toward the craton.

Much of the information regarding ages and thickness of sediments, as well as times of structural deformation, is gained from studies of outcropping rocks of the Ouachita and Marathon regions. They are geologically alike in displaying three stages of sediment accumulation, accompanied and followed by one or more stages of deformation. The first or quiescent stage is represented by deposition of a relatively thin black shale-chert facies of Early and Middle Paleozoic age. Normal thicknesses of these beds are 3000 feet in the Marathons and 6000 feet in the Arkansas portion of the Ouachitas. The second and certainly most critical episode is the Mississippian and Early Pennsylvanian geosynclinal stage of thick clastic sedimentation, as shown by a maximum thickness of 10,000 feet in the Marathons and as much as 35,000 feet in the Ouachitas. The sediments are mostly turbidite sandstones interstratified with dark shales; also present are a few beds of water-laid tuff and some persistent sequences of siliceous shale, interpreted in part as devitrified ash falls (Goldstein and Hendricks, 1953). The third stage is represented by Middle and Late Pennsylvanian beds which, judged by their thickness and character, are post-geosynclinal deposits, much more

typical of the shelf environment. Middle and Late Pennsylvanian strata in the Marathon region (Gaptank) are 2400 feet thick and are incorporated in the Marathon fold-belt. Beds of the same age are absent in the Ouachita Mountains but are present in the coal basin and shelf of east-central Oklahoma, foreland of the Ouachita fold-belt, where they are generally less than 5000 feet thick.

Tectonism in the Ouachita province was long-ranging. The major episode of uplift, folding, and faulting probably is Desmoinesian, as shown by the presence of thick chert conglomerates of that age in adjoining parts of the Ardmore basin—the conglomerates increase in coarseness, number of beds, and thickness toward the Ouachitas. Additional but probably lesser pulses of uplift are recorded by Ouachita-derived conglomerates in Missourian and early Virgilian strata of the Oklahoma shelf. A final episode of thrusting, in late Virgilian time, is inferred from certain structural relations of the Ouachita system to the Arkuckle Mountains. In the Marathon region the principal folding and thrusting is sharply defined as Late Pennsylvanian-Early Permian, although an earlier episode of uplift also is recorded in Missourian time, by the presence of conglomerates in the Gaptank Formation. Thus, although the culmination of orogeny was earlier in the Ouachitas than in the Marathons, it is clear that the time span of deformation was approximately the same in each region.

Early and Middle Paleozoic Quiescent Stage

Early and Middle Paleozoic rocks exposed in the Marathon and Ouachita uplifts are distinctively different from equivalent rocks of the craton in consisting mostly of dark shales, sandstones, beds of chert or novaculite, and some cherty limestones. The sequence, age, and thickness of rocks in the two uplifts are similar, as the exposed strata range from Late Cambrian or Early Ordovician to Early Mississippian and are not more than 3000 feet thick in the Marathons and 6000 feet thick in the Ouachitas (Flawn and others, 1961; Goldstein and Hendricks, 1962; Ham, 1959). This early phase of black shale-chert sedimentation is closed by the deposition of Caballos Novaculite in the Marathons and the equivalent Arkansas Novaculite in the Ouachitas, the uppermost beds of which are of Meramecian (early Mississippian) age (Hass, 1951). The novaculite formations and older rocks are said to comprise the early geosynclinal phase, even though the measured section thicknesses are hardly of geosynclinal proportions. The principal reasons for believing that much thicker sequences were involved in orogeny have been summarized by King (*in* Flawn and others, 1961, p. 177), including in particular the general conclusions that (A) the characteristic folds and faults of the Ouachita Mountains and Marathon region could have formed only over a thick mass of incompetent strata, and (B) negative gravity anomalies characterize both regions, further indicating a buried thick mass of low-density rocks.

Neither the Ouachita Mountain nor Marathon exposures display compelling evidence for widespread or significant unconformities in the Early and Middle Paleozoic rocks. They have rather the features of leptogeosynclinal or starved-basin sediments, accumulating slowly in waters of at least intermediate depth (King, *in* Flawn and others, 1961, p. 181; Thomson, 1964; Thomson and McBride, 1964, p. 65-57). Moreover, the deposition of sediments was independent of and generally undisturbed by tectonic pulses of the craton. Minor clastic wedges in Ordovician and Silurian strata were formed from sediments derived from uplifts seaward in the geosyncline, but these are not comparable in thickness to the Late Paleozoic trough-filling sediments.

Ouachita Mountains: geosynclinal sedimentation and orogeny

Above the Arkansas Novaculite in the Ouachita Mountains begins the thickest sequence of Middle Mississippian-Early Pennsylvanian turbidites known in North America. The total of maximum formational thicknesses over the region is approximately 42,000 feet, consisting in ascending order of Stanley Shale (12,000 feet), Jackfork Sandstone (10,000 feet), Johns Valley Shale (1200 feet), and Atoka Sandstone (19,000 feet). The Stanley and Jackfork are of Meramecian and Chesterian age; the Johns Valley is Chesterian and Morrowan, and the Atoka is pre-Desmoinesian early Pennsylvanian (Cline, 1960; Goldstein and Hendricks, 1962). That these formations were deposited in a rapidly subsiding trough is plainly shown by their abrupt thinning northwestward onto the Oklahoma shelf and northward, across the Arkoma basin, onto the south flank of the Ozark uplift.

The key to establishing total filling of the trough from place to place is the Atoka Sandstone, which is the thickest unit and dominant outcropping formation in the frontal belt, but unfortunately is completely eroded from most central and southern outcrops of the Ouachita Mountains. The lower 5000 feet of Atoka Sandstone is present in a syncline along the southern margin in the Athens plateau (Walthall and Bowsher, 1966, p. 131-132), and 6800 feet of Atoka (with top eroded) is preserved in the Boktukola syncline of the central Ouachitas (Shelburne, 1960). Although these outcrops are helpful in showing that the Atoka Formation covered all the presently exposed region of the Ouachita Mountains, they do not indicate original Atoka thicknesses, nor do they reveal a direction or rate of thinning. The maximum Atoka thickness is consistently about 19,000 feet for 100 miles along the Ouachita frontal belt and adjoining Arkoma basin in central Arkansas (Reinemund and Danilchik, 1957; Scull, Glover, and Planalp, 1959; Stone, 1966).

The Stanley, Jackfork, and Johns Valley Formations crop out widely and have been measured with confidence in enough areas to establish thickness patterns. The Jackfork Sandstone thins generally but erratically northwestward. It has a maximum measured thickness of 10,000 feet in the Athens plateau (Walthall and Bowsher, 1966, p. 127-130).

It is generally 5700 to 6000 feet in the central and north-central Ouachitas (Cline, 1960; Shelburne, 1960; Seely, 1963), 8000 feet thick in northwest-central outcrops (Hart, 1963), and 1150 feet thick in the two northwesternmost belts of outcrop (Goldstein and Hendricks, 1962, p. 394). Maximum thickness of the Stanley Formation ranges between 10,000 and 12,000 feet in central and southern parts of the Ouachita Mountains (Cline, 1960; Goldstein and Hendricks, 1962), and, from the thinning of individual units, it is assumed that the entire formation is thinner in northwestern and northern parts of the mountains. Stone (1955, p. 197-198) estimates a thickness of 7000 feet for the Stanley in the northeastern part of the Ouachitas, near Little Rock, strengthening the general interpretation that the formation thins northward. Finally, the Johns Valley Shale is generally 300 to 750 feet thick in central areas but is as much as 1200 feet in Winding Stair range (Hart, 1963) and evidently is thickening northward.

A compilation of thickness data reveals that the two oldest formations—Stanley and Jackfork—are thickest in the south, where they have a combined thickness normally about 20,000 feet but ranging up to 22,000 feet, compared with a combined thickness of about 13,000 to 15,000 feet in the central frontal belt. Along the eastern part of the central frontal belt the beds are overlain by about 20,000 feet of Johns Valley and Atoka strata, yielding a total thickness on the order of 33,000 feet. Estimates of total depositional thicknesses in the southern Ouachitas are necessarily conjectural, owing to lack of knowledge concerning the Atoka Formation. If it thickens toward the south at the same rate as the Stanley and Jackfork, the Atoka would be 30,000 feet in the Athens plateau, and the total Stanley-through-Atoka sequence would be 50,000 feet thick. If, however, the Atoka thins toward the south at the same rate as the Johns Valley Shale, it would have a thickness of some 8000 to 10,000 feet in the Athens plateau, of which only the lower 5000 feet is preserved. Under this conjecture the depositional thickness of Stanley-through-Atoka beds would be not more than 30,000 feet, but an important corollary concept is that the depocenter of the younger beds was shifted northward. The shifting of basin centers through time, toward the craton, is seen in many other geosynclines and is favored by the writers.

By the close of Atokan time the depositional filling of the Ouachita trough had come to an end. Beds younger than Atoka are not present in the Ouachita Mountains, and accordingly the stratigraphic dating of the Ouachita orogenic phase, which resulted in the formation of complexly deformed and thrust-faulted segments, must be interpreted from structural and stratigraphic relations in nearby geologic provinces. Younger beds through early Desmoinesian are present in the Arkoma basin to the north, where they are about 7000 feet thick and consist of sandstone, shale, and beds of coal. They are folded gently, in structural conformity with the frontal Ouachita belt, and two of the formations—Savanna and Thurman—contain chert conglomerates derived from the Ouachita Mountains.

Some chert conglomerates are also present in the Atoka formation near the town of Atoka, at the western edge of the mountains.

Excellent summaries of Ouachita orogenic history are given both by Goldstein and Hendricks (1962, p. 424-427) and by King (*in* Flawn and others, 1961, p. 186-188). A particularly concise statement by King (p. 187) is as follows:

Absence of beds of Des Moines age from the Ouachita Mountains is probably not merely an accident of erosion, as that area was probably in process of deformation. From Stanley and Jackfork time, through Atoka time, into Des Moines time the axis of the depositional trough shifted from the interior of the mountains to its margin, and thence into the foreland area beyond. The depositional environment also changed progressively to shallower water, with occasional coal swamps toward the end.

Deformation thus presumably began in the Ouachita system during Atoka time and continued through Des Moines time. Moreover, the Des Moines strata in the McAlester and Arkansas basins are thrown into linear folds parallel with those in the Ouachita Mountains that diminish in intensity outward to the north and northwest, indicating that thrusting from the Ouachita area continued even later. During these times of deformation, the Ouachita rocks were extensively thrust toward their foreland—probably on the order of 50 miles in the western part of the exposed area.

Even more detail appropriate to structural interpretation is given by Goldstein and Hendricks (1962, p. 427):

Structural movement and uplift of the Ouachita Mountains increased in late Atoka time and continued concurrently with the progressive downwarping of the McAlester basin to the north in later Pennsylvanian (Des Moines) time. As the pre-Atoka and early Atoka geosynclinal sediments were uplifted, eroded, and redeposited farther out in the basin, the axis of the active geosyncline migrated northward and westward over the foreland. . . . Conglomerates in the Thurman sandstone, and involvement of beds as young as Boggy shale, and possibly the Thurman sandstone, in Ouachita Mountain folding indicate that structural movement definitely continued as late as middle Des Moines time, and it is possible that folding and minor faulting produced by generally north-south compression was more or less continuous throughout the Pennsylvanian. Some thrust faulting may have occurred by the end of Atoka time, particularly in the more southerly interior fold belts of the Ouachita system, but most of the thrusting in the frontal part of the system appears to have occurred in middle or late Pennsylvanian time, culminating in the major thrusting of the Ti Valley and Windingstair faults.

Interpretations of Pennsylvanian structural history of the Ouachita province are strengthened and enlarged by the occurrence of Ouachita-derived chert conglomerates other than those listed above, all of which demonstrate that the Ouachita Mountains were being uplifted and were orogenically active in Desmoinesian, Missourian, and early Virgilian time. The principal additional Desmoinesian conglomerates are those of the Devils Kitchen and Rocky Point members of the Deese group in the Ardmore basin, which are thicker, more numerous, and coarser toward the Ouachita system (Tomlinson and McBee, 1959, p. 31, 32, 37). At the base of the Missouri series in east-central Oklahoma is the Seminole Formation; it contains a basal chert conglomerate 50 feet thick in maximum development, in southwestern Hughes County, at a point where it is only 40 miles away from the frontal Ouachitas (Weaver, 1954, p. 76; Ries, 1954, p. 50). Similarly, at the base of the Virgil series in east-central Oklahoma is the Boley conglomerate member of the Vamoosa Formation. It is 50 to 60 feet thick and, in northern Seminole County, contains chert cobbles as much as 7 inches in diameter (Ries, 1954, p. 82-83;

Tanner, 1956, p. 92-96). The chert pebbles and cobbles are partly derived from the Arbuckle Mountains and partly (notably the green cherts) from the Ouachita Mountains. Cherts derived from the portion of the Ouachita fold belt in North Texas now covered by the Cretaceous are known in conglomerates of upper Desmoinesian to Wolfcampian age across and west of the Fort Worth basin. These extend to the Llano uplift.

A final late Pennsylvanian (late Virgilian) episode of Ouachita thrusting is deduced from structural relations with the Arbuckle Mountains. Critical to this interpretation is the major structural discontinuity between the two structural provinces as mapped in subsurface in Bryan, Atoka, and Johnson Counties, Oklahoma (Jordan, 1962). Here the major frontal fault of the Ouachita Mountains has a 25-mile southeastward reentrant around the Tishomingo-Belton segment of the Arbuckle Mountains. This reentrant is generally interpreted as being the result of overriding of the Arbuckle segment by the frontal Ouachitas along a low-angle thrust fault, followed by downdip erosion of the fault trace. The relations have been alternatively interpreted by Flawn (1959; Flawn and others, 1961, p. 171-172) as tear faults produced by thrusting of the Ouachitas against an unyielding Arbuckle buttress. In an earlier article Ham (1956, p. 426) had concluded that, in outcrops of the Arbuckle Mountains, the Tishomingo uplift was bordered by strike-slip faults and that the Tishomingo segment has been moved northwestward, probably as a result of stress transmitted from the Ouachita Mountains. The principal point involved in controversy is the extent to which the buried Arbuckle segment, about 20 miles wide and consisting chiefly of Precambrian granite, is an unyielding buttress. Ham believes it is no coincidence that the only known strike-slip faults of the Arbuckle Mountains are those that bound the Tishomingo segment, left-lateral on the southwest fault and right-lateral on the northeast fault (Ham and McKinley, 1954), such that the fault-enclosed block either has moved to the northwest or the outer segments each have moved southeast. As the fault block or Tishomingo segment is almost exactly at right angles to the frontal Ouachita belt and as the northwest-directed overthrusting of the Ouachitas has clearly brought this belt in contact with the Tishomingo segment, it seems equally clear that the Tishomingo fault-block has been displaced northwestward in response to the Ouachita thrusting and that at least part of the Arbuckle buttress yielded by lateral translation.

The discussions above are of considerably more than scientific interest, for if Ouachita thrusting has moved the Tishomingo block and if the time of movement can be dated, the dating will establish an episode of Ouachita thrusting. Such information is available: in excellent outcrops at the western edge of the Arbuckle Mountains, Ham has observed that the south fault of the Tishomingo block (Washita Valley fault) cuts the basal part of the late Virgilian Vanoss conglomerate and dies out upward in the conglomerate sequence. Thus, although not

conclusive, these arguments strongly suggest that the Ouachita Mountains had a significant pulse of thrusting in latest Pennsylvanian time. This interpretation is strengthened, too, by the knowledge that the principal orogenic phase of folding and thrusting in the geologically related Marathon region also is latest Pennsylvanian.

A final, possibly epeirogenic pulse of Ouachita deformation in early Permian time is suggested by joint systems in gently dipping beds of central Oklahoma. The joints, chiefly in Pennsylvanian and early Permian sandstones, have orientation patterns that led Melton (1930) to conclude they are genetically related to an episode of uplift or thrusting in the Ouachita province.

Tectonic summary.—Studies in the Ouachita Mountains are of extraordinary importance because in this region are the most extensive exposures and by far the thickest sediments of the geosynclinal fold-belt at the southern margin of the craton.

Pre-orogenic stage.—A Mississippian-Early Pennsylvanian trough, filled with 30,000 to 35,000 feet of clastic sediments, constitutes the geosynclinal stage. The filling was accompanied by pre-orogenic uplifts, mostly in extra-basinal sources, that contributed a virtually constant flood of clastics to the trough. The general background of uplift in the principal source areas was punctuated by three uplifts, each recorded by sedimentary deposits within the geosyncline. The first is represented by deposition of conglomerates at the base of the Hot Springs Sandstone, above the Arkansas Novaculite and below the Stanley Shale (Miser and Purdue, 1929). Although restricted in distribution to the eastern part of the Ouachita province, the conglomerates nevertheless significantly record the beginning of geosynclinal sedimentation. The second and much more powerful tectonic episode is that represented by the enormous exotic boulders in the Johns Valley Shale (Ulrich, 1927; Miser, 1934; Cline and Shelburne, 1959). These boulders, mostly limestones of the Arbuckle facies, are inferred to have been derived from fault scarps at the geosynclinal margin. Uplift and erosion of 8000 to 10,000 feet of strata is required to expose the oldest rocks that occur as boulders in the shale. Finally, the occurrence of coarse chert conglomerates in the Atoka Formation near Atoka (Hendricks, 1959, p. 54) demonstrates intra-basinal uplift near the close of the geosynclinal stage but in advance of the principal orogenic stage.

Orogenic stage.—This stage is defined as that time during which the major structural features of the Ouachita Mountains were formed. Complexly folded and faulted anticlinoria, intensely distorted and crumpled zones, open folds, the linear imbricate fault segments of the frontal belt, and the northwestward thrusting toward the craton, with horizontal movement on the order of 50 miles in the northwestern belt, have been described by numerous authors (Miser, 1929, 1934, 1959; Hendricks and others, 1947; Hendricks, 1959; Harlton 1938; Viele, 1966). Deformation was episodic, beginning in Middle Pennsylvanian and continuing through Late Pennsylvanian time. Especially

powerful were the Desmoinesian pulses, which elevated the mountains to such height that chert was contributed in abundance to the upper Desmoinesian Devils Kitchen and Rocky Point conglomerates of the Ardmore basin. Two later conglomerates, similarly derived, were deposited above unconformities at the base of the Missouri and Virgil series in east-central Oklahoma. Uplift of the Ouachitas, as shown by the occurrence of these conglomerates, probably was accompanied by folding and thrusting. A culminating pulse of Late Virgilian age is judged to have been chiefly an episode of late orogenic thrusting.

In figure 12 is a tectonic curve graphically summarizing the pre-orogenic and orogenic pulses of the Ouachita Mountains.

Marathon region: geosynclinal sedimentation and orogeny

Introduction.—In broadest comparative aspects, the geology of the Marathon region in west Texas is basically a duplication of the Ouachita Mountains and related provinces in central Arkansas and eastern Oklahoma, although the Marathon exposures are much smaller in areal extent and the sediments there are only about one-third the thickness of those in the Ouachita region. Furthermore, the Tertiary Marathon uplift has exposed Pennsylvanian thrust plates from an area of sedimentation comparable only to the most northerly (exterior) facies belts of the Ouachitas. Nevertheless, the two regions are strikingly similar in having (A) the same early geosynclinal thin deposits of Early and Middle Paleozoic black shales and cherts, (B) the same principal stage of geosynclinal filling by thick flysch clastics during Mississippian and Early Pennsylvanian time, (C) the same general sequence of thin Middle and Late Pennsylvanian shelf sediments containing orogenic conglomerates, (D) the same kind of deformation by close folding and thrusting toward the craton, and (E) the same Middle-to-Late Pennsylvanian span of structural deformation. They furthermore share the common feature of containing exotic boulders of enormous size, deposited not at the same time but nevertheless within comparable sequences of flysch deposits. Three wells drilled in the Marathon basin in the 1950's showed that the exposed Marathon folds are allochthonous and are formed in a thrust plate only a few thousand feet thick. A minimum displacement of 15 miles has been demonstrated for this plate.

In the Marathon region the Mississippian-Early Pennsylvanian flysch deposits are represented by the Tesnus, Dimple, and Haymond Formations, deposited to a maximum thickness of about 11,500 feet. This sequence comprises the principal stage of filling. It is overlain by the Gaptank Formation, of Middle and Late Pennsylvanian age, deposited to a maximum thickness of 2400 feet and consisting of limestones and other largely marine shelf deposits, along with conglomerates derived from older rocks of the Marathon region. The Gaptank distinctly represents a late stage in Marathon evolution, and it corresponds in age as well as in character and relative thickness of sediments with the foreland-shelf facies of the Ouachita province. Uplift of the Marathon region, as

reflected in the conglomerates of the Gaptank, is matched by uplift in the Ouachita province, as reflected in conglomerates of Desmoinesian, Missourian, and Virgilian strata in Oklahoma. Finally, the culminating pulse of Marathon orogeny at the close of the Pennsylvanian probably is matched, as discussed on earlier pages, by a late pulse of thrusting in the western frontal belt of the Ouachita Mountains.

Other than in thickness of sediments, the chief dissimilarity between the Marathon and Ouachita regions is in the different spatial arrangement of the late Paleozoic sediments. The late Paleozoic Marathon depositional basin contains sediments that range in age from early or middle Mississippian (Tesnus) to highest Pennsylvanian (Gaptank). They evidently were deposited in a single basin, attaining a maximum thickness of perhaps 14,000 feet in the south and east and a much lesser thickness toward the northwest. These sediments are wholly involved in folding and thrusting. In the Ouachita region, however, sediments of the same age are distributed partly in the Ouachita trough and partly beyond it, in foreland basins and shelf. The Mississippian and Early Pennsylvanian sediments of the Ouachita trough, possibly as much as 40,000 feet thick, are orogenically deformed and thrust-faulted, whereas the much thinner Middle and Late Pennsylvanian foreland sediments are but gently folded and are not cut by thrust faults. In the Marathon region the transit of orogeny engulfed the Middle and Late Pennsylvanian foreland facies, but in the Ouachita region it did not. The Middle and Early Paleozoic foreland facies lies beneath the Marathon folds and has been penetrated by two wells in the northern Marathon basin.

Major regional features of Marathon geology have been described by many writers, in particular King (1937), Flawn and others (1961), and Goldstein and Hendricks (1962). Additional stratigraphic and sedimentological data of value are contained in reports of Wilson (1954), Berry (1960), Ross (1963), Thomson (1964), Thomson and McBride (1964), Thomson and Thomasson (1964), McBride and Thomson (1964), McBride (1964a,b), and Sanderson and King (1964). These writers are in substantial agreement that the principal phase of basin filling was attained through deposition of thick, generally fine-grained turbidite sandstones and interbedded dark shales, beginning directly upon the Caballos Novaculite and continuing without significant interruption or change in depositional environment to the top of the Haymond Formation. This first or flysch phase was succeeded upward by a much thinner foreland filling phase (Gaptank), which in turn was followed by the principal or late Pennsylvanian-early Permian orogenic phase.

Mississippian and Early Pennsylvanian depositional phase.—These strata are of major interest because they account for about 80 percent of the Late Paleozoic filling of the Marathon basin. They include first the Tesnus Formation, 6500 feet in maximum thickness, consisting of shale and cherty shale below and turbidite sandstones interbedded with shale above, and ranging in age from early or early middle Mississippian

to late Morrowan. Next above is the Dimple Limestone, as much as 900 feet thick and consisting of flysch carbonates with interbedded dark shales, of late Morrowan and early Atokan age (Sanderson and King, 1964). Overlying the Dimple is the Haymond Formation, 4200 feet in maximum measured thickness, consisting mostly of turbidite sandstones and shales, and of middle Atokan to early Desmoinesian age. The clastics were derived from a vaguely defined southeastward source, whereas the turbidite Dimple limestones were derived from a northwestward carbonate shelf (Thomson and Tomasson, 1964). The depositional sequence begins with a thin basal conglomerate and was interrupted much later by uplift that resulted in the deposition of a prominent boulder bed. The thin conglomerate at the base of the Tesnus is of significance because it marks the beginning of the principal filling stage, bearing the same relation to the Marathon basin in Texas as the Hot Springs conglomeratic sandstone bears to the Ouachita trough in Arkansas. A slightly later event, presently of unknown significance, is recorded low in the Tesnus by a northward-tapering deposit of cleanly washed coarse sandstone, incompatible in texture and character with the normal sandstones of the Tesnus (Thomson and McBride, 1964). By far the principal tectonism of the filling stage, however, is shown by the occurrence in the upper part of the Haymond Formation of distinctive boulder beds, associated with thick coarse-grained feldspathic sandstones. The boulders, described in some detail by Baker (1932), King (1937, p. 65-72, 89-92), and McBride (1964, p. 37-38), consist of older strata of the basin together with igneous and metamorphic rocks from an exotic source. Well-rounded pebbles and cobbles occur with blocks as much as 130 feet in length. Although the mode of transportation has been much debated, there can be no question about the profound uplift that was necessary to expose the heterogeneous boulder rocks, for some of them are derived from strata 10,000 feet stratigraphically below the boulder beds. King (1937, p. 91) suggested that the older rocks had been brought to the surface by thrusting, but regardless of whether the mechanism was thrusting, normal faulting, or folding, there is a clear record of structural relief on the order of 2 miles. This is the first great pulse of orogeny in the Marathon basin.

The Haymond boulder beds have a counterpart in the boulder beds of the Johns Valley Shale in the Ouachita Mountains. The two formations are alike in containing blocks a hundred feet or more in length, as well as boulders derived from exotic sources. Moreover, the age of the boulders in each formation requires accompanying structural relief of 8000 to 10,000 feet. The boulder beds are clearly of different age, however, as the Johns Valley is late Mississippian and early Pennsylvanian (Chesterian and Morrowan), corresponding in stratigraphic position to the middle Tesnus, whereas the Haymond boulder beds are late Atokan or earliest Desmoinesian. An additional difference is that the Haymond boulders were derived substantially from older rocks of the same facies as the Marathon folded belt, whereas the Johns Valley boulders were

derived mostly from carbonate facies situated outside the present limits of the Ouachita Mountains.

Middle and Late Pennsylvanian depositional phase.—Above the Haymond Formation are the youngest deposits of the Marathon geosyncline. Assigned to the Gaptank Formation, the strata consist of sandstones interbedded with limestones and shales, and, in the lower part, beds of limestone-chert conglomerate. In thickness the formation ranges from 1800 to 2400 feet (McBride, 1964b, p. 41, 43), and according to fusulinid studies by Ross (1963, p. 11, 16-20), it ranges in age from Desmoinesian to late Virgilian. That these strata are different in depositional character from preceding strata is plainly shown by the abundance of limestones, typical of the shallow-water environment, as well as by a marked diminution in depositional rate—only 2400 feet deposited in approximately the upper half of Pennsylvanian (Gaptank) time compared with about 8000 feet deposited in the lower half of Pennsylvanian time (Haymond, Dimple, and upper Tesnus). Tectonically significant are the conglomerate beds in the lower and middle part of the Gaptank Formation, for they contain pebbles and cobbles derived from older beds of the Marathon fold belt and further signify, by their abrupt northward thinning, that the source area lay nearby to the south. Ross (1963, p. 11) determined the stratigraphic position of the conglomerate beds as early and middle Missourian, thus establishing the date of an important Marathon uplift.

Orogenic phase.—A comprehensive treatment of structural deformation in the Marathon region is contained in the 1937 report by King. Anticlinoria and synclinoria involving Pennsylvanian and older beds are cut by several thrust faults, along which displacement on the order of 6 to 15 miles can be inferred. The major deforming pulse was latest Pennsylvanian, pre-Wolfcamp, as coarse conglomerates occur at the base of gently dipping Wolfcamp strata directly above steeply folded Gaptank beds. Later pulses of early Wolfcamp dating are indicated by overthrusting along the Dugout Creek fault, bringing Caballos Novaculite upon Wolfcamp beds, and by the occurrence of some thrust faults in the lower Wolfcamp beds themselves. Through these observations the main event in Marathon orogeny is established as latest Pennsylvanian and earliest Permian.

Structural deformation of major proportions occurred simultaneously in the epicratonic early Paleozoic Tobosa basin to the north, where the Central Basin platform was sharply elevated and eroded, dividing what is now the Permian basin into a central uplift, an eastern or Midland basin, and a western or Delaware basin (Galley, 1958, p. 399, 423, 425).

The latest pulses of Marathon uplift are recorded in Permian strata of the Glass Mountains, adjoining the Marathon region on the north (King, 1931). Uplift accompanying the early Wolfcamp thrusting resulted in the formation of thick middle Wolfcamp conglomerates (Ross, 1963, p. 26-31), and even later uplift produced limestone conglomerates

as much as 250 feet thick at the base of the Leonard (Ross, 1963, p. 33-36). Corresponding early Leonard uplift also is indicated locally on the Central Basin platform, as in the McKee field of Crane County, where Leonard strata rest unconformably upon the Silurian Fusselman dolomite (Creager, 1957, p. 208).

In figure 12 the orogenic elements of the Marathon region are summarized in the form of a tectonic curve.

TRANSVERSE PALEOZOIC GEOSYNCLINAL OROGENIC BELT: THE ANADARKO-
ARDMORE BASIN AND ASSOCIATED UPLIFTS

As shown in figure 1, and conspicuously shown also on the Tectonic Map of the United States (U. S. Geol. Survey, 1961) and the Basement Map of North America (Am. Assoc. Petroleum Geologists, 1967), an elongate deep trough known as the Anadarko-Ardmore basin lies transversely across the craton in south-central and southwestern Oklahoma. From a shelf area in the Oklahoma and Texas panhandles, it plunges southeastward and extends for about 300 miles to an abrupt termination against subsurface rocks of the Ouachita system. Throughout most of its length it is characterized by great thicknesses of Paleozoic rocks—37,500 feet of Late Cambrian through Permian strata in the western or Anadarko basin and 30,000 feet of Late Cambrian through middle Pennsylvanian (Missourian) sediments in the eastern or Ardmore basin. Below the Late Cambrian sediments are volcanic flows and tuffs at least 7000 feet thick, isotopically dated at 525 million years, and therefore probably of Middle or Early Cambrian age. Not only are these rocks about 3 times thicker than the 15,000 feet of Paleozoic rocks in the Michigan, Illinois, and Midland-Delaware basins, but in addition the rocks of the Anadarko-Ardmore basin are in places thrown into closely compressed folds and are cut by through-going faults with vertical displacement locally in excess of 15,000 to 25,000 feet. Moreover, marginal and intrabasinal uplifts are developed on a major tectonic scale: the Wichita uplift is elevated more than 40,000 feet structurally above the adjoining deep part of the Anadarko basin, some parts of the Arbuckle Mountains are at least 35,000 feet structurally above the deep part of the Ardmore basin, and the Ardmore basin itself is divided into two parts by the strongly uplifted Criner Hills. The deformation is of Pennsylvanian age, occurring chiefly during the Morrowan-Atokan Wichita orogeny and the late Virgilian Arbuckle orogeny.

The greatest thickness of sediments, the principal orogenic deformation, and the floor of Early or Middle Cambrian volcanic rocks are confined to a belt that is now barely 50 miles wide, although its original width before deformation must have been at least 75 miles. In an earlier publication (Ham, Denison and Merritt, 1964, p. 149-154), this deformed belt is called the southern Oklahoma geosyncline. The belt is geosynclinal in thickness of sediments, in linearity, and in structural deformation, yet it is totally abnormal in geographic position because it lies upon the craton instead of being marginal to it. As a stratigraphic-

structural entity, the Anadarko-Ardmore basin and accompanying uplifts, which constitute the southern Oklahoma geosyncline, are unique in the central United States. Certainly no other area of this region contains a linear belt of strongly deformed Paleozoic sediments and flows as much as 45,000 feet thick.

Depositional History

The sedimentary filling of the Anadarko-Ardmore basin was accomplished in two principal depositional sequences—a Late Cambrian-Early Devonian stage of carbonate sedimentation and a Late Devonian-Permian stage of clastic sedimentation. Where fully represented the sequences are respectively about 11,000 and 27,000 feet thick, and the sediments themselves, except for their great thicknesses, are much like those of the craton on either side of the depositional trough.

Wholly unlike the rocks of the craton, however, is the volcanic floor beneath the sediments of the trough. These underlying volcanic rocks, with a known thickness of at least 7000 feet, consist of flows and tuffs injected with granitic sills. As some of the contained rocks are isotopically dated at 525 million years, it is probable that the age of the entire volcanic suite is Middle or Early Cambrian. The volcanic rocks are a part of the depositional trough because they are confined to its floor and margins, and accordingly the total Paleozoic filling, including the relatively thin basal sequence of Cambrian volcanics, is approximately 45,000 feet.

Age relations and tectonic implications of the pre-volcanic rocks of southern Oklahoma have been considered previously in the sections entitled "regional setting" and "Cambrian" and are not discussed further in this section.

Late Cambrian-Early Devonian carbonate stage.—Rocks of the first sedimentational stage are composed dominantly of carbonates 10,500 to 11,000 feet thick, ranging in age from Late Cambrian through Early Devonian (table 1). More than half this thickness—6000 to 7000 feet—is assigned to limestones and dolomites of the Arbuckle Group, of Late Cambrian and Early Ordovician age. Included at the base are the thin Honey Creek Limestone and Reagan Sandstone. Succeeding strata above the Arbuckle Group are the Simpson Group, Viola Limestone, and Sylvan Shale, of Ordovician age, and the Hunton Group of Silurian and Early Devonian age. In the deep part of the southern Oklahoma geosyncline their thicknesses are respectively 2500, 1000, 500, and approximately 800 feet, and their combined thickness is 4000 to 4500 feet (Ham, 1955; Huffman, 1959; Amsden and Rowland, 1967). Excepting the relatively thin Sylvan Shale and some sandstone-shale strata of the Simpson Group, all the sediments are limestone and dolomites.

Unconformities that characterize Early Paleozoic rocks of the craton are likewise present in rocks of the southern Oklahoma geosyncline, although generally the greatest uplift and erosion is well toward the depositional margins (see Anadarko basin, fig. 12).

TABLE 1
Thickness of Late Cambrian-Permian strata in Anadarko-Ardmore basin

System	Western deep basin* (Anadarko basin)	Central uplift**	Eastern deep basin (Ardmore basin)	Dominant lithology
Permian	6500	2000+	eroded	In Anadarko basin, basal arkosic clastics of Wolfcampian age grade upward into marine carbonates with red shales and evaporites of Leonardian and Guadalupian age.
Pennsylvanian	Virgil	6000*	13,000	Generally marine shales, sandstones, and limestones. Conglomerates are present locally in Ardmore basin and central uplift. Sequence in Anadarko basin contains many thick beds and lenses of conglomerate and arkose derived from Wichita Mountains.
	Missouri			
	Des Moines			
	Atoka			
	Morrow			
Mississippian	Springer	1600	4500	Mostly dark shales. Springer contains thick sandstones. Sycamore is silty limestone.
	Goddard			
	Caney			
	Sycamore			
Late Devonian	500 ^d	500	400	
Early Devonian	Hunton	4500 ^d	4000 ^b	Chiefly carbonates. Sylvan is shale; Simpson contains shale and sandstone.
	Sylvan			
	Viola			
Late Cambrian	Simpson	6500 ^d	7000 ^b	
	Arbuckle			
	37,500 feet	30,000 feet		

* Shell no. 5 Rumberger, Sec. 16-T10N-R21W, Beckham County. Total depth: 24,002 feet.

** Northwestern Carter County and southeastern Stephens County, in area of Velma, Shalom Alechem, Tatum, and Fox-Graham oil fields.

^a Stratigraphic sequence is highly variable and greatly abbreviated owing to uplift, truncation, and overlap at three major unconformities.

^b Measured outcrops in Arbuckle anticline, adjoining and structurally conformable with Ardmore basin.

^c Measured outcrops on north flank of Wichita Mountains, adjoining Anadarko basin.

^d Estimated from regional subsurface isopachous studies.

Late Devonian-Pennsylvanian stage of thick clastic sedimentation.—Above rocks of the Hunton Group begins a great thickness of Late Devonian, Mississippian, and Pennsylvanian clastic sediments. They are slightly more than 20,000 feet thick, of which 15,000 feet or nearly three-fourths is of Pennsylvanian—Morrowan through Virgilian—age (table 1). The basal deposit is dark shale of the Late Devonian Woodford Formation (Hass and Huddle, 1965), 400 to 500 feet thick, and resting with pronounced unconformity upon older rocks (Tarr, Jordan, and Rowland, 1965). Overlying strata of Mississippian age are in ascending order the Sycamore, Caney, and Goddard Formations, together with the still younger Springer Formation, regarded by Elias (1956, p. 70) as post-Chesterian yet pre-Morrowan in age. Total thickness of the Sycamore-Springer sequence is 5000 to 5500 feet (table 1), consisting almost wholly of dark shales with thin silty carbonates and, in the Springer Formation, highly petroliferous sandstones. It will be remembered that equivalent Mississippian beds of the Ouachita Mountains—Stanley and Jackfork Formations—have a maximum thickness of 22,000 feet, indicating that the principal stage of filling of the Ouachita geosyncline has no substantial counterpart in the southern Oklahoma geosyncline.

Sedimentation in southern Oklahoma reaches the culmination of a long depositional history during the Pennsylvanian period, when more than 15,000 feet of dominantly clastic sediment was deposited in a deeply subsiding western or Anadarko segment and in a corresponding eastern or Ardmore segment of the southern Oklahoma geosyncline (table 1). Gross thicknesses are approximately the same in the two regions but are unequally divided among the series. The two regions are different also in that the Anadarko segment received conglomerates almost continuously from the adjoining Wichita Mountains whereas the Ardmore segment received its conglomerates from sharply defined orogenic pulses of the Criner Hills and Ouachita Mountains.

Stratigraphic thicknesses in the western segment are illustrated by the Shell no. 5 Rumberger well, drilled to a total depth of 24,002 feet, in a position slightly north of the deepest part of the Anadarko basin. Pennsylvanian beds 15,000 feet thick are distributed among the several series as follows: Virgil, 1300; Missouri, 2350; Des Moines, 1600; Atoka, 4900; and Morrow, 4300 (Jordan, 1959). The well was drilled in the Elk City oil field, which is characterized by gently dipping strata, and as shown by cores the dip at the bottom of the well is nearly horizontal. In other deep parts of the Anadarko basin the Morrow and Atoka generally are not reached by drilling, but the penetrated thicknesses of the upper series are the same order of magnitude as those in the Rumberger well, the Virgil ranging between 1700 and 2700 feet, the Missouri 2000 to 2200 feet, and the Des Moines 1200 to 2400 feet (McNeal, 1953; Edwards, 1959). Thus the thickness of Pennsylvanian sediments near the axial part of the Anadarko basin is approximately 15,000 feet, at

least five times more than the normal maximum for the same rocks upon the craton.

The Pennsylvanian sequence in the Ardmore basin consists of Morrowan through Missourian strata, generally marine shales and sandstones with thin limestones and some prominent beds of conglomerate. They are well exposed in steeply dipping folds near the town of Ardmore, where total thicknesses of 12,000 to 16,000 feet have been measured (Tomlinson, 1929; Tomlinson and McBee, 1959). Both the Dornick Hills Formation (Morrowan-Atokan) and the Hoxbar Formation (Missourian) attain thicknesses of 4000 feet, but the dominating stratigraphic unit is the Deese Formation (Desmoinesian). Normally about 5300 feet thick, the Desmoinesian beds increase southeastward from Ardmore to a maximum of 8000 feet (Tomlinson and McBee, 1959, p. 30). The 8000-foot thickness of Desmoinesian strata near Lake Murray is more than three times greater than that in the Anadarko basin and is approximately equal to that of the Arkoma basin.

Permian clastics and evaporites.—Deposition of Permian clastics and evaporites is post-orogenic and marks the close of the southern Oklahoma geosyncline. The depocenter is in the Anadarko basin. Complete sections are about 7000 feet thick, of which 6500 feet was drilled in the Rumberger well. Arkosic clastics derived from the Wichita Mountains continue upward from the Pennsylvanian beds into the Wolfcampian, which in turn grades upward into marine carbonates, red shales, and evaporites of Leonardian and Guadalupian age (Jordan and Vosburg, 1963, p. 100). Permian strata, as well as Virgilian strata, have been removed by erosion from much of the outcrop area of the Ardmore basin.

Tectonic History

The major structural features of southern Oklahoma, as revealed by configuration of the basement-rock surface (Ham, Denison, and Merritt, 1964, pl. II), are dominated by a northwest-trending deep basin with parallel or en echelon bordering and intrabasinal uplifts, wherein structural relief exceeds 40,000 feet. The basin is the principal part of the southern Oklahoma geosyncline. In the eastern (Ardmore) area it is divided by the Criner Hills uplift into a northern or Ardmore segment and a southern or Marietta segment, and the Ardmore segment is separated by a low oil-rich uplift from the western or Anadarko segment. South of the Anadarko segment is the Wichita uplift, which plunges eastward and merges with the Criner Hills. At the south border of the Marietta segment is the Waurika-Muenster uplift, the margin of the craton of north Texas, whereas along the north boundary of the Ardmore segment are the Arbuckle Mountains. The Arbuckle Mountains, with a relatively small outcrop area of about 1000 square miles, are anomalously split into two parts along the craton margin. The northern segments—Tishomingo, Belton, and Hunton uplifts—lie upon Precambrian rocks of the central United States craton, contain relatively thin

Paleozoic sediments, and are deformed mainly by block faulting. In notable contrast is the southern or Arbuckle anticline segment, definitely a part of the southern Oklahoma geosyncline, which contains thick Paleozoic sediments, has thick Cambrian volcanic rocks as a floor, and is deformed so severely that in part it is a gigantic fan fold.

The present structural development of southern Oklahoma is mainly the result of Pennsylvanian deformation acting in two episodes, called by Waterschoot van der Gracht (1931) the Wichita or early Pennsylvanian orogeny and the Arbuckle or late Pennsylvanian orogeny. Closer analysis by the Ardmore Geological Society (1956, p. 8-12, tables VIII, IX, and X), following the drilling of several thousand additional deep wells and the completion of much more detailed paleontologic and stratigraphic investigations than were available to Waterschoot van der Gracht, confirms the widespread extent in southern Oklahoma of both orogenies and shows still a third orogenic deformation in early and middle Desmoinesian (Deese) time.

Among the many authors describing structural and stratigraphic relations in *Petroleum Geology of Southern Oklahoma*, volumes 1 and 2, published by the American Association of Petroleum Geologists in 1956 and 1959, the outstanding contribution is that by Tomlinson and McBee (1959). Tomlinson had spent a lifetime devoted to scientific and economic investigations in southern Oklahoma, and the cited paper was the most comprehensive as well as the last before his death.

The essential conclusions involve deformation within various segments of the Anadarko-Ardmore-Marietta basin, the Criner Hills, along the north flank of the Wichita Mountains, in the Arbuckle Mountains, and upon the Muenster uplift in north Texas. A summary in the form of tectonic curves is given in figure 12. The deep basins, being the site of active sedimentation, contain generally minor unconformities but play the important role of recording orogeny by receiving conglomerates and arkoses, the products of orogenic uplift. The elevated areas, on the other hand, record times of uplift by unconformities in their stratigraphic sequences, unless the uplift was so great that all or most of the sediments are lost by erosion.

Early Pennsylvanian uplifts—Wichita orogeny.—The record of Early Pennsylvanian orogeny in southern Oklahoma is well documented in all marginal and intrabasinal uplifts. As a general rule, conglomerate-bearing strata of Atokan age unconformably overlie older strata down to the Early Ordovician Arbuckle Group. The most precise dating is available in outcrops of the Criner Hills, where first the Joliff Conglomerate and later the Bostwick Conglomerate were deposited. Respectively they are of early Morrowan and early Atokan age, and together they represent structural uplift of 10,000 to 15,000 feet (Tomlinson and McBee, 1959, p. 24). These two episodes, taken together, compose the Wichita orogeny, although in most areas the stratigraphic record is incomplete and the unconformable surface is widely referred to as the pre-Atoka unconformity.

The second episode of deformation is early to middle Desmoinesian. By this time the Wichita Mountains had been uplifted and stripped of at least 15,000 feet of covering rocks above the Wichita granite, which contributed extensive conglomerates to Desmoinesian strata of the Anadarko basin. Conglomerate-bearing Deese beds unconformably overlie older rocks in exposures of the Arbuckle Mountains and Criner Hills, as well as in the Muenster uplift and most other subsurface uplifts which have been drilled for petroleum. The greatest uplift of this episode is that of the Wichita Mountains; other uplifts of the region, as recorded by lithologies of pebbles in the conglomerate beds, had been denuded well down into the Arbuckle Group. In the Ardmore basin, the thick Rocky Point and Devils Kitchen chert conglomerates of Desmoinesian age record an important uplift of the Ouachita system.

Late Pennsylvanian uplifts—the Arbuckle orogeny.—The final and culminating deformation was one of strong compression and locally profound uplift, exemplified by the Arbuckle anticline after which the orogeny is named. Most of the prominent folding of the Arbuckle anticline, Ardmore-Marietta basin, Criner Hills, and deep part of the Anadarko basin originated at this time. Structural limbs normally dip in excess of 45 degrees and some, such as the north flank of the Arbuckle anticline, are folded through an arc of 125 degrees. Part of the total structural relief was achieved through high-angle faulting, and, along the two major faults of the region, vertical displacement of 5000 to 10,000 feet is common. As much as 25,000 feet of displacement occurs at a fault zone separating the deep part of the Anadarko basin from the Wichita uplift, the uplifted part having moved by high-angle thrusting over the basin rocks.

Orogenic conglomerates were widely spread as a result of the various uplifts, and basement-rock granites were extensively exposed for the first time in many areas. Perhaps the best known outcropping conglomerate of this date is the Collings Ranch Conglomerate (Ham, 1954), derived by uplift of the Arbuckle anticline and deposited to a minimum thickness of 2000 feet upon the steeply folded anticlinal rocks. The conglomerate strata, traced northward into the central Oklahoma shelf, are dated as late middle Virgilian, which is clearly the time of the strongest phase of Arbuckle orogeny. A later pulse resulted in the formation of the still younger Vanoss conglomerates, of latest Virgilian and early Wolfcampian age. The Vanoss and its equivalents were deposited throughout southern Oklahoma, lying unconformably upon older rocks that range in age from Virgilian to Precambrian. Orogenic uplift was definitely at an end, although the residual height of the vast Wichita uplift was sufficient for it to contribute marginal granitic debris until being covered by upper Hennessey (late Leonardian) red shales.

The persistent sinking of the Anadarko basin, initiated in Cambrian time and continued with only slight interruptions through the Pennsylvanian, now continued without pause into the Permian. The deep part of the basin was unaffected by the Arbuckle orogeny and shows

no unconformity between its arkosic sediments of Virgilian and Wolfcampian age (fig. 12). The youngest beds of Permian age in the basin are reddish-brown shales and mudstones of the Doxey Formation, almost completely unfossiliferous but presumably late Guadalupian or Ochoan. Slight folding of the Permian strata occurred at a later date and is perhaps an outlying manifestation of Laramide orogeny in the Rocky Mountains.

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