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The Permian System in Kansas

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COVER—The broad, flat surface in the center of the photo is the top of the Glenrock Limestone Member of the Red Eagle Limestone and the Carboniferous–Permian boundary at Tuttle Creek Lake Spillway in Pottawatomie County, Kansas.

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Abstract

Rocks of Permian age in Kansas were first recognized in 1895, and by the early 21st century the internationally accepted boundary between the Permian and the Carboniferous (Pennsylvanian Subsystem) was recognized in Kansas at the base of the Bennett Shale Member of the Red Eagle Limestone. The upper boundary of the Permian is an erosional unconformity that is overlain by rocks of Cretaceous age. Currently accepted stratigraphic nomenclature for the Permian of Kansas recognizes the Wolfcampian, Leonardian, and Guadalupian Series, and the lithostratigraphic formations within each of these series reflect a wide spectrum of depositional environments. Summaries of the lithofacies, thicknesses, depositional environments, and source areas of, and for, the rocks in each series provide a basis for inferring the history of the Permian in Kansas as currently understood. Fluctuations from shallow-marine to terrestrial environments associated with climate change as a result of the waning of Gondwana glaciers and latitudinal shifts are recorded in the Permian rocks of Kansas. Economically these Permian rocks have been, and are, an important source of hydrocarbons, salt, gypsum, building stone, aggregate, and ground water.

This report on the Permian System in Kansas is "a work in progress" and future multi-disciplinary studies of chrono- and sequence stratigraphy, climate history, structural aspects, sediment transport, and diagenesis will further enhance our understanding of the end of the Paleozoic in Kansas.

Introduction

Our knowledge of Permian rocks in Kansas has increased greatly in recent years. Based on detailed biostratigraphic studies, a global standard for the Carboniferous–Permian boundary has been established and is clearly recognized in the Kansas sequence. Recognition of genetic surfaces and a sequence stratigraphic framework have provided a better understanding of the temporal setting and depositional environments during the Permian. The role of climate has been more widely recognized with the well-preserved paleosols of the Kansas Permian providing useful proxies. Data useful in the study of the Permian climate are coming from a number of disciplines including the analysis of carbon and oxygen isotopes. These new approaches have resulted in more meaningful sea-level curves. In the absence of ash beds, isotopic studies of 1) clay minerals within evaporates, and 2) pedogenic calcite, are providing radiometric dates. Rocks inferred as terrestrial in origin are being studied using the techniques of magnetostratigraphy. By combining and modifying what we knew with what we have learned recently, inferring a more complete picture of Kansas during the Permian is possible.

To arrive at that picture requires a consideration of 1) early research efforts as well as current studies, 2) currently understood aspects of the stratigraphic units composing the Permian in Kansas, and 3) the contents of the major subdivisions of the Permian in Kansas. These constitute the first three major sections of this effort. The inferred history, i.e., the picture referred to above, is the fourth section. Economic aspects and future opportunities for research on the Permian in Kansas are discussed in sections five and six. A summary, acknowledgments, and references complete the paper.

This is a publication of the Kansas Geological Survey and the names of stratigraphic units herein are those currently recognized as acceptable by that organization. Currently, a Stratigraphic Nomenclature Committee of the Kansas Geological Survey is evaluating the names of stratigraphic units and reviewing and revising, as appropriate, the stratigraphic nomenclature of Kansas. Ultimately the efforts of this committee will result in a terminology that is appropriate, current, and more globally recognized.

Historical Aspects

Permian Recognized in Kansas

As is often true in science, controversy exists over who first recognized the existence of Permian rocks in the state of Kansas. As stated by Prosser (1895), four people were involved: Major F. Hawn, G. C. Swallow, F. B. Meek, and F. V. Hayden. According to Prosser's 1895 account, it seems reasonable that Professor Swallow should be credited with the first public announcement that rocks containing Permian fossils occurred in Kansas. This is based on a letter from Swallow read by B. F. Shumard to the St. Louis Academy of Science on 22 February 1858 (Shumard and Swallow, 1858) and publication of a letter from Swallow to J. D. Dana, dated 16 February 1858, in the March 1858 issue of the *American Journal of Science* (Swallow, 1858). Later that year Meek and Hayden (1858) reported probable Permian rocks in Kansas in the Proceedings of the Philadelphia Academy of Sciences.

As quoted by Prosser (1895), the original description given by Swallow (1858) in the Transactions of the Academy of Science St. Louis (v. 1, p. 111–112) would be, based on fossils collected by Major Hawn, as follows: "I can have no doubt that the rocks are Permian, since the proof is very conclusive in my mind . . . All of the described fossils, with perhaps two exceptions, are identical with Permian species of Russia and England, while all of the new species appear to be more nearly allied to Permian forms than to any other."

Original Description

To improve on the general aspects of the Permian of Kansas as given by Prosser (1895, p. 685) would be difficult:

> The region under consideration is a belt of country varying in breadth from fifty to seventy-five miles,

> extending across the state from south to north in an approximate northerly direction. Topographically, it is a region with high hills that (*sic*) generally have rounded slopes capped by escarpments of massive limestone and flint. The valleys are narrow, and the landscape as a whole presents an attractive appearance quite at variance with the preconceived idea of the plains of Kansas.

As can be seen from a geologic map of the state (fig. 1), this statement is inaccurate only in that it omits the exposures of Permian rocks in the counties west and southwest of Wichita, Kansas.

The primary basis for recognizing the Permian, and other geologic systems/periods, are the fossils contained in the rocks, and this is well demonstrated by the discussions of those fossils collected and studied by the early scientists and travelers in the state. As a result, discussions focused on the comparison of the collected fossils rather than on details of the lithologic sequence. Thus, it seems to us appropriate to consider the above quote from Prosser (1895) as close as we might hope to get to an original description of the Permian in Kansas.

Past to Present

Nineteenth Century

It was recognized in the mid-1800s that rocks of Permian age occurred in Kansas, based on the fossils they contained; however, they were considered as part of the Carboniferous (Mudge, 1866, p. 5) and consisted mostly of massive magnesian limestones and calcareous and arenaceous shales (Mudge, 1866, p. 10). Permian rocks, as then understood, were included in the Carboniferous of the first geologic map of Kansas (Mudge, 1875) and the 1878 colored version (Mudge, 1878). However, this complete sequence of the Kansas Permian was not treated in publications until the mid-1890s (Haworth, 1895a; Prosser, 1895, 1897). As pointed out by Merriam (1963), the red-bed sequence in Kansas, now considered to be Leonardian and Guadalupian, received considerable attention during this time and into the next century. It was important, and thus necessary, to determine whether the red-bed sequences in Kansas were Permian or part of the Mesozoic. Thus, much discussion focused on the age of these beds and they were, at different times, considered Cretaceous, Jurassic, and Triassic, as well as Permian. Such divergent views were based on lithologic similarities and to some extent on the age significance of fossil plants and vertebrates. Hay (1893), one of those early workers on the red beds of Kansas, suggested that they belong to the Permian, based on lithological similarities

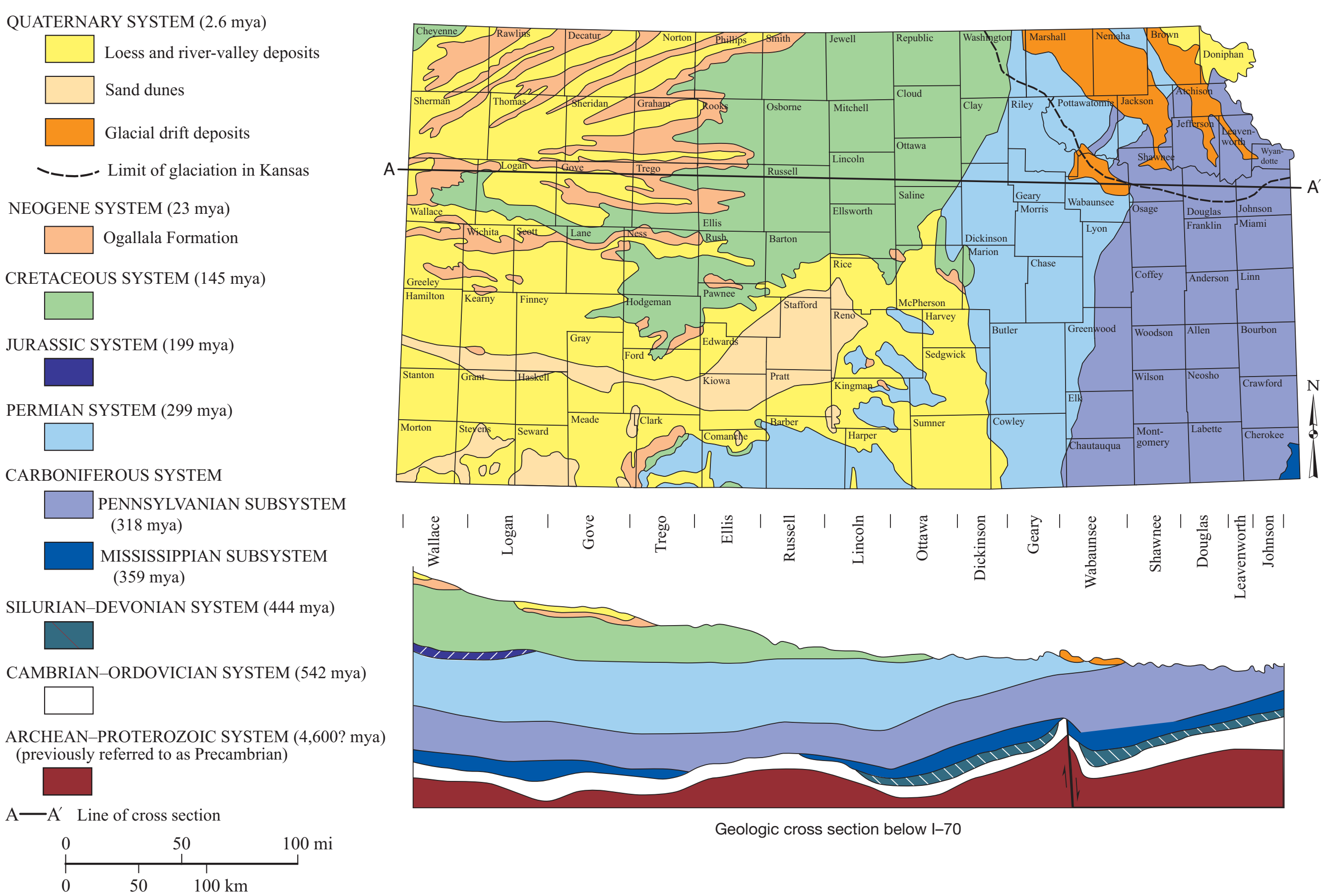


FIGURE 1—Geologic map of Kansas with generalized geologic cross section along I–70.

to the red beds in Texas from which Cope (1888, 1894) had described Permian vertebrates (Prosser, 1897, p. 80). Cragin (1896), in a detailed description of the Kansas red beds, also considered them to be Permian.

Early Twentieth Century (1900–1959)

Discussions during the early 1900s focused on questions of classification of the Permian sequence in Kansas, mainly on the names and extent of formations and larger units, like stages. Obviously, the red beds were still an important topic of study. At this time and well into the century, the U.S. Geological Survey, and some State surveys, including Kansas, considered the Permian as an epoch of the Carboniferous Period (Wilmarth, 1925). Wooster (1930, p. 33), a faculty member at Kansas State Teachers College in Emporia, listed the Permian as a sub-period of the Carbonic Period that he referred to as the “Age of Salt and Gypsum.”

Numerous studies of fossil plants (Sellards, 1900a, 1900b, 1901a, 1901b, 1908a), insects (Carpenter, 1926, 1930a, 1930b, 1930c, 1931, 1932, 1933, 1935, 1939, 1943, 1950; Dunbar, 1923, 1924; Sellards, 1903, 1904, 1906, 1907, 1908b, 1909; Tillyard, 1923, 1924a, 1924b, 1925a, 1925b, 1926a, 1926b, 1926c, 1926d, 1928a, 1928b, 1928c, 1931, 1932a, 1932b, 1936, 1937a, 1937b, 1937c, 1937d, 1937e), and vertebrates (Williston, 1908, 1911a, 1911b, 1914), mostly from the Permian red-bed and evaporite sequence, appeared early in the century. Williston’s studies of Permian vertebrates began in 1897 (1897a, 1897b, 1898), and Carpenter’s study of Permian insects continued into the 1960’s (1966). In 1929 one of the earliest county geologic maps of an area of mostly Permian outcrops, Cowley County, was published (Bass, 1929), as well as a stratigraphic study of the Luta (now Cresswell), a Permian limestone (Boos, 1929). Interest in the oil and gas contained in the Permian rocks of Kansas and adjacent areas also occurred during this period (Heald, 1916; Fath, 1921).

Permian cyclicity, for which the upper Paleozoic sequence in Kansas is so well known, was first documented by Jewett (1933) and was followed in 1937 by another classic paper, this one on the depth of deposition of the Big Blue Series (now Wolfcampian) in Kansas by Elias (1937).

By 1940 the boundary between the Carboniferous and Permian was decided for the Kansas sequence (Moore, 1940) and a standard classification was available by the 1950s. Based on Moore (1948), the standard for some years, was the Kansas Rock Column (Moore, Frye, et al., 1951) and accompanying chart (Moore et al., 1952). Some modifications were made in the late 1950s as noted by Merriam (1963).

As the classification stabilized, more effort was focused on mapping bedrock geology and detailed stratigraphy. Some examples are bedrock geologic maps of Chase County (Moore, Jewett, et al., 1951), Elk County (Verville, 1958), Lyon County (O’Connor, 1953), Marshall County (Walters, 1954), Morris County (Mudge et al., 1958), and Riley and Geary counties (Jewett, 1941). Most stratigraphic studies were on Wolfcampian units; some examples are Hattin (1957) on the Wreford Limestone, Imbrie (1955) on the Florena Shale Member, Lane (1958) on the Grenola Limestone, Newell (1940) on the Whitehorse Sandstone, and Swineford (1955) on Permian red beds.

Late Twentieth Century (1960–1999)

Studies similar to those of the late 1950s characterize the early 1960s with more county mapping and stratigraphic studies. An early paper, often cited, that addressed paleoecology of the time was Laporte’s (1962) study of the Cottonwood limestone. Mudge and Yochelson (1962) agreed with the placement of the Carboniferous–Permian contact at the top of the Brownville limestone, and in 1963 Merriam published his geologic history of Kansas. McCrone (1963) documented the Red Eagle Limestone. A year later, 1964, the Kansas Geological Survey symposium volume on “cyclic sedimentation” (Merriam, 1964) appeared, containing important contributions to the study of the Permian of the state. All these have been important in publicizing the uniqueness of the geology of Kansas, and the 1963 bulletin by Merriam has been useful in introducing the geology of the state to the general public.

Useful lithofacies and depositional environments of the Permian in Kansas relative to the paleotectonics of the United States appeared in McKee and Oriel (1967) and Mudge (1967).

Although Haworth (1895b), Fath (1921), and Bass (1929) had written on oil and gas in Kansas, regional studies focusing on petroleum exploration of the Permian sequences in central and western Kansas appeared in papers by Rascoe (1962, 1968) and Rascoe and Adler (1983). At about the same time, studies on the petrography of evaporites (Jones, 1965) and the palynological content of evaporites (Shaffer, 1964) appeared. Studies characterizing Kansas Permian salt deposits to assess their suitability as high-level radioactive-waste repositories were conducted in the late 1960s and early 1970s (Angino and Hambleton, eds., 1971; Bayne, 1972). Tasch (1958, 1961, 1963, 1964) made useful contributions in regard to these evaporitic sequences in his studies of microfossils and the limnological aspects of the distribution of some of these occurrences.

The Wreford Limestone was the focus of studies by Cuffey (1967), Warner and Cuffey (1973), Fry and Cuffey (1976), Lutz–Garihan and Cuffey (1979), Simonsen and Cuffey (1980), Cuffey and Hall (1985), Pachut et al. (1991), and Pachut and Cuffey (1999). Twiss (1988) and Twiss and Underwood (1988) provided detailed descriptions of the Beattie Limestone and Barneston Limestone, respectively, and attempted to interpret them in terms of the phases proposed by Elias in 1937.

Waugh and Brady (1976) addressed the potential of copper in the Permian rocks of Kansas.

The depositional environment of the black shales in the Upper Carboniferous (Pennsylvanian Subsystem) and some in the Permian sequences in Kansas has been debated. Heckel (1977) extended the study by Schenk (1967) on the origin of these beds. Studies of conodonts from these units sparked additional debate in the early 1980s, and to some extent, that debate continues today.

Climate as an important control on Permian deposition began to enter interpretations (Olson and Vaughn, 1970) as a result of studies of global paleoclimatology and paleomagnetism. Documentation of paleosol profiles in the thick variegated mudrock sequences of the lower Permian in Kansas by Miller et al. (1996), coupled with the concepts of genetic, event, and eventually, sequence and cyclic stratigraphy (Boardman et al., 1995; Busch, 1988; Kutzbach and Ziegler, 1993; Mazzullo et al., 1997; Miller and West, 1993; and others), have revolutionized how we view the depositional environment of the Permian of Kansas. At about the same time, Permian climate models were being tested using paleobotanical data (Rees et al., 1999). Cyclicity in Leonardian evaporates on a regional scale, comparable in thickness and duration to pre-Leonardian Permian–Upper Carboniferous (Pennsylvanian) cyclothems, was suggested by Watney et al. (1988).

Jin et al. (1997) discussed the development of the chronostratigraphy of the Permian. At about the same time, detailed biostratigraphic studies that compared the Kansas Permian to that in the type area of Russia (Boardman et al., 1995; Davydov et al., 1995; Ritter, 1995; Chernykh et al., 1997; Boardman et al., 1998) have resulted in a more reasonable and recognizable lower boundary with the underlying Carboniferous.

Early Twenty-first Century

The Carboniferous–Permian boundary has been more firmly established in reports by Wang and Qi (2002) and Davydov et al. (2002). It has been proposed (Sawin et al., 2006) that the base of the Bennett Shale Member exposed in the Tuttle Creek Lake Spillway in northeastern Kansas be considered for the Carboniferous–Permian boundary stratotype in Kansas. Sawin et al. (2006) also suggested that the stratigraphic position of the Carboniferous–Permian boundary in the Tuttle Creek Lake Spillway section be considered as a potential North American stratotype. Although the lower boundaries for the Sakmarian, Artinskian, and Kungurian have been reported as “in” the Eiss Limestone Member, “near the base” of the Florence Limestone Member, and at the base of the Odell Shale, respectively, GSSPs (Global Stratotype Section and Point) for these boundaries have not been ratified by the International Commission on Stratigraphy (Sawin et al., 2008, p. 2). A worldwide Permian time scale that correlated marine and continental sequences has some significance for Kansas (Menning, 2001). Menning et al. (2006) published a global time scale for the Devonian, Carboniferous, and Permian that includes the Pennsylvanian and Permian sequences in Kansas.

Benison and Goldstein (2001) established the presence of cyclic marine (sabkha) and hypersaline nonmarine evaporates (lacustrine salinas) comprising variegated and red-bed successions of the lower Permian Nippewalla Group. Interestingly, Benison (2006) compared these saline lacustrine deposits in the Nippewalla to strata on Mars. Sequence stratigraphy studies by Olszewski and Patzkowsky (2003) and Boardman et al. (2009) relate the eustasy and climate changes in the Upper Carboniferous (Pennsylvanian) and lower Permian of Kansas to an icehouse world, and Izart et al. (2003), using sequence stratigraphy, correlated globally the late Carboniferous and Permian. The potential usefulness of trace fossils in enhancing our understanding of Permian depositional environments and climate is illustrated by the work of Hasiotis et al. (2002) and Hembree et al. (2004, 2005).

Research on the role of climate relative to depositional environments regionally (Mack et al., 2003) and globally (Golonka and Ford, 2000; Gibbs et al., 2002; and Tabor and Montañez, 2002) continues. DiMichele et al. (2001, 2009) addressed how climate change affected plant communities during the later Carboniferous and early Permian. Beerling and Berner (2000) concluded that an increase in the pO_2 during the Permian–Carboniferous would not have had a significant effect on the terrestrial carbon cycle. Beerling (2002) used fossil lycopsids to infer low levels of atmospheric CO_2 during late Paleozoic glaciation. The model developed by Hyde et al. (2006) provided additional inferences as to the CO_2 levels of the late Paleozoic.

The economic role and environmental impact of gas storage in the shallow Hutchinson Salt Member in central Kansas were brought to the forefront in January 2001. A major gas leak in well casing above a storage cavern in the salt appears to have been responsible for two explosions and surface gas leaks through unplugged abandoned wells in Hutchinson, Kansas. One theory suggests that an oriented-fracture cluster in a thin dolomite interval equivalent to the Milan Limestone Member in the upper Wellington Formation apparently permitted natural gas to migrate along the dolomite layer over a distance of 7 mi (11.3 km) (Watney et al., 2003). This hypothetical fracture cluster may have been created by focused reactivation and flexure along a structural lineament paralleling the Arkansas River. Mapped elongate patterns of halite dissolution in the uppermost Hutchinson Salt Member appear to have further enhanced flexure along the structural lineament.

The lithostratigraphy and petrophysics of the lower Permian Chase and Council Grove Groups were characterized in a five-year study that ended in 2004, utilizing some 60 cores and over 11,000 well logs from wells that produce natural gas from the Hugoton natural gas area (http://www.kgs.ku.edu/Hugoton/results.html). The Hugoton natural gas area covers over 12,000 mi^2 (31,030 km^2) in southwestern Kansas and extends into the panhandles of Texas and Oklahoma; this is the largest gas field in the western hemisphere.

Rocks Currently Recognized as Permian in Age

Lower Boundary of the Permian

Early in the 20th century the Permian, along with the Pennsylvanian and Mississippian, were considered epochs of the Carboniferous Period (Wilmarth, 1925). Of some note is the statement by Wilmarth (1925, p. 73) relative to the lower boundary of the Permian, “The division line between the Permian and Pennsylvanian in the United States is in general a purely paleontological boundary.” It is interesting to compare this to the following from Mudge and Yochelson (1962,

p. 127), “As there is no clear agreement as to what constitutes the Permian, especially in regard to definition on the basis of fossils, any boundary established in Kansas must be regarded as tentative and subject to change when more is known of the type area in Russia…” and concerning the lower boundary at that time “There is apparently no faunal evidence for placing the systemic boundary at the top of the Brownville Limestone Member of the Wood Siding Formation, but since this boundary is commonly accepted by workers in the midcontinent, … it may as well continue as the boundary.” It is because of the conformability of this boundary that its accurate recognition has required the careful and detailed biostratigraphic studies noted below.

The boundary remained at the top of the Brownville limestone until Baars, Ross, et al. (1994) and Baars, Ritter, et al. (1994) proposed moving it to the base of the Neva Limestone, a lithostratigraphic member that they elevated to the status of a formation to “… simplify lithostratigraphic terminology and to begin the redefined Permian System and Council Grove Group with a sequence boundary” (Baars, Ritter, et al., 1994, p. 15). The primary basis for this change was the first occurrence of the *Pseudoschwagerina* fusulinid biozone in the Neva. In this they agreed with the accepted understanding as expressed by Moore (1940), who suggested that the base of the *Pseudoschwagerina* fusulinid biozone should be the base of the Permian. Additionally, Baars, Ross, et al. (1994) and Baars, Ritter, et al. (1994) indicated 1) that the upper boundary of the Admire Group is at the top of the Grenola Limestone, and 2) that the entire Admire Group is the uppermost group of the Upper Carboniferous (Pennsylvanian) in Kansas. Although Ritter (1995) published the detailed conodont biostratigraphy of the Carboniferous–Permian interval, he retained the boundary between the two as published by Zeller (1968).

However, comparison of the base of the Permian stratotype in the Ural Mountains of Russia (the International Commission on Stratigraphy now officially recognizes this biostratigraphic boundary as the Carboniferous–Permian boundary) with the sequence in Kansas, in terms of the ammonoids, fusulinids, and conodonts (Davydov et al., 1995; Ritter, 1995; Chernykh et al. 1997; Boardman et al., 2009), has resulted in international agreement that the base of the Permian in Kansas occurs within the Red Eagle Limestone formation at the base of the Bennett Shale Member (Boardman et al., 1998). This is lower, stratigraphically, than the boundary in the Neva Limestone Member proposed by Baars, Ross, et al. (1994) and Baars, Ritter, et al. (1994).

The base of the Permian System in Kansas, a horizon based on detailed and careful biostratigraphic studies, is at the base of the Bennett Shale Member of the Red Eagle Limestone (Sawin et al., 2006) (figs. 2, 3, 4A, 4B). This is also the base of the Asselian Stage/Age (Boardman et al., 1998, Sawin et al., 2006, 2008) . Concerning this boundary Boardman et al. (1998, p. 19) stated “… the Carboniferous–Permian in the southern Urals can be confidently correlated to the base of the Bennett Shale Member of the Red Eagle Limestone.” The fact

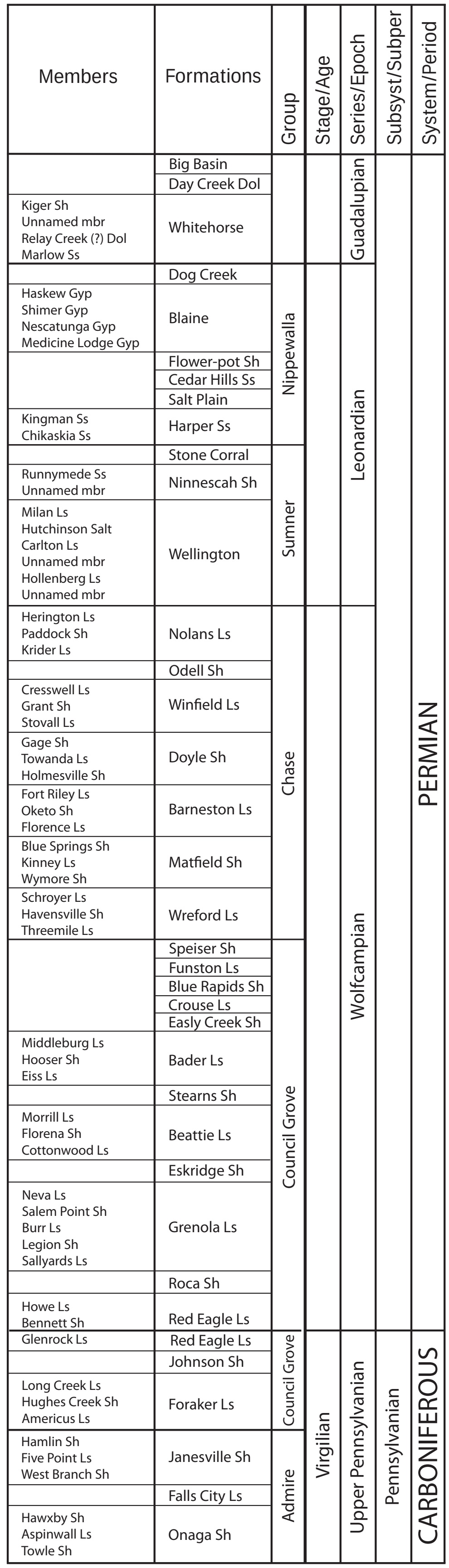
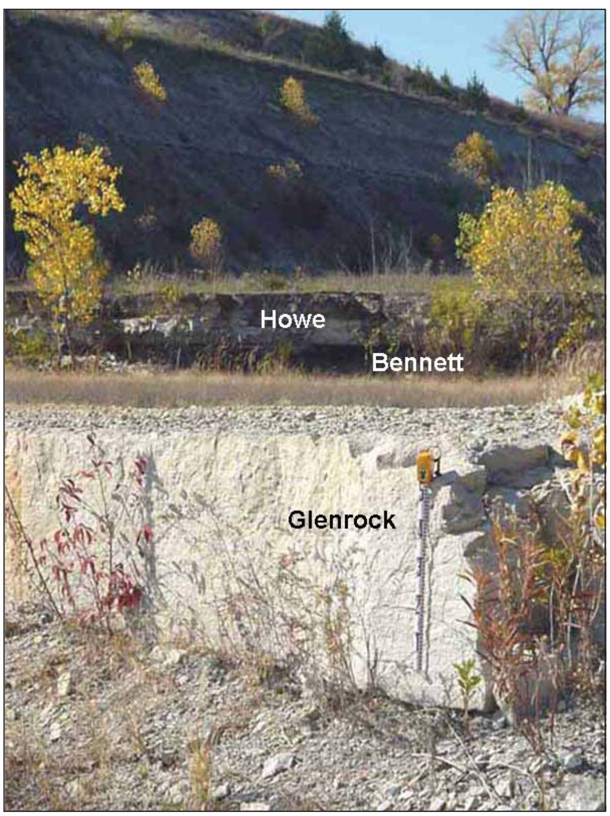


FIGURE 2 (right)—Stratigraphic succession of Permian rocks in Kansas (Sawin et al., 2008).

FIGURE 3—Exposure of the Red Eagle Limestone in an eroded area below Tuttle Creek Lake Spillway; near center N/2 sec. 19, T. 9 S., R. 8 E., Pottawatomie County, Kansas.

A



B

FIGURES 4A and B—Exposure of the Red Eagle Limestone in an eroded area below Tuttle Creek Lake Spillway; the base of the Bennett shale is the boundary between the Carboniferous–Permian; near center of N/2 sec. 19, T. 9 S., R. 8 E., Pottawatomie County, Kansas.

that this boundary occurs within a lithostratigraphic unit, that is, a formation, is irrelevant because such systemic boundaries are by definition biostratigraphic, not lithostratigraphic. Correlation of this biostratigraphic sequence in Kansas with the type area in Russia demonstrates the importance and uniqueness of the upper Paleozoic rocks in the state.

Upper Boundary of the Permian

Not only was there disagreement over who first recognized the Permian in Kansas, there were, and still are, different opinions as to what should be included as Permian, even though the uppermost Permian (Ochoan) is probably missing in Kansas (Sawin et al., 2008). Initially, the red beds of the upper Permian in Kansas (Salt Fork, now the Salt Plain Formation, and above) were frequently correlated with the Dakota Formation and considered Cretaceous (Prosser, 1905, p. 145). Subsequently they were questionably assigned to the Triassic and then the Jurassic–Triassic. It was not until 1893 that they were correlated with red beds in Texas and considered Permian (Hay, 1893; Prosser, 1897, 1905). McLaughlin (1942) and MacLachlan (1972) reported rocks of the Dockum Group (Upper Triassic) in southwestern Kansas, but this age cannot be confirmed because this isolated exposure is unfossiliferous. These rocks are currently considered to be Jurassic (Zeller (1968, p. 53). Triassic rocks are reported from the subsurface in Kansas, but until there is more direct evidence supporting a Triassic age for these rocks where they crop out, they cannot be considered Triassic. Thus, it is geologically prudent to recognize the contact between the Paleozoic (Permian) and Mesozoic (mostly Cretaceous) as the erosional unconformity that separates the Permian red beds from the overlying lighter-colored sandstones, siltstones, and mudrocks of the Cretaceous (fig. 5).

Distribution in Kansas

The distribution of Permian rocks in Kansas at the surface and in the subsurface is shown in fig. 6. An isopach map of the Permian evaporite deposits in Kansas (fig. 7) shows that the maximum thickness of these deposits is about 1,400 ft (427 m) in Clark County. Additional maps of the Permian rocks in Kansas, showing lithofacies and, in some cases, inferred depositional environments, can be found in Mudge (1967) and McKee and Oriel (1967).

Generalized [east-west (fig. 8) and northwest-southeast (fig. 9)] stratigraphic cross sections show the general thickening of the Permian in the west-central part of the state and a conspicuous thickening from the northwest (Cheyenne County) to the southeast (Edwards County). Most of this thickening occurs in the Leonardian and Guadalupian Series, i.e., the red-bed and evaporitic intervals of the Permian. This also is clearly shown by the isopach map mentioned above (fig. 7). Associated thicknesses of halite-bearing strata in the Leonardian Hutchinson Salt Member range from zero (surrounding a marine embayment in western Kansas) to over

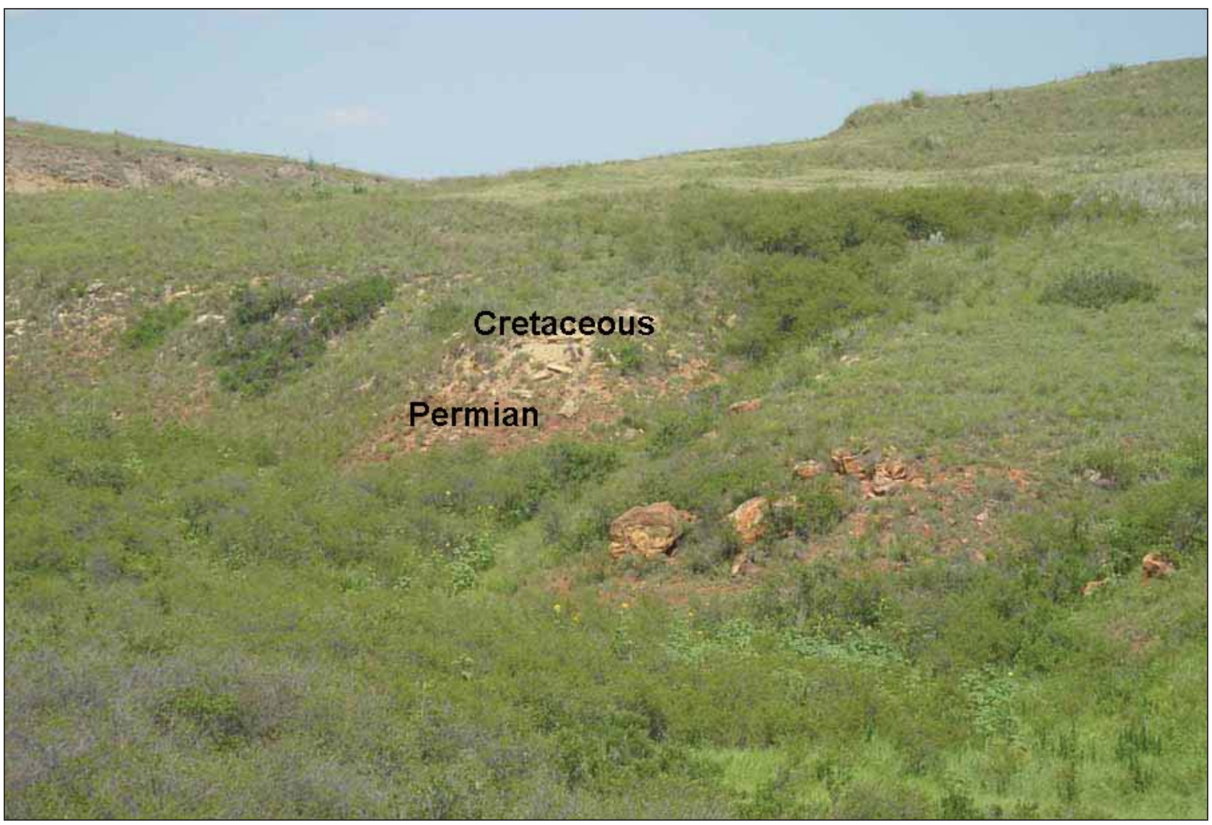


FIGURE 5—Exposure of the Cretaceous–Permian contact; light-colored Cretaceous above red Permian strata crop out along the east side of the road going south from Clark State Fishing Lake; near center of W/2 sec. 18, T. 32 S., R. 22 W., Clark County, Kansas.

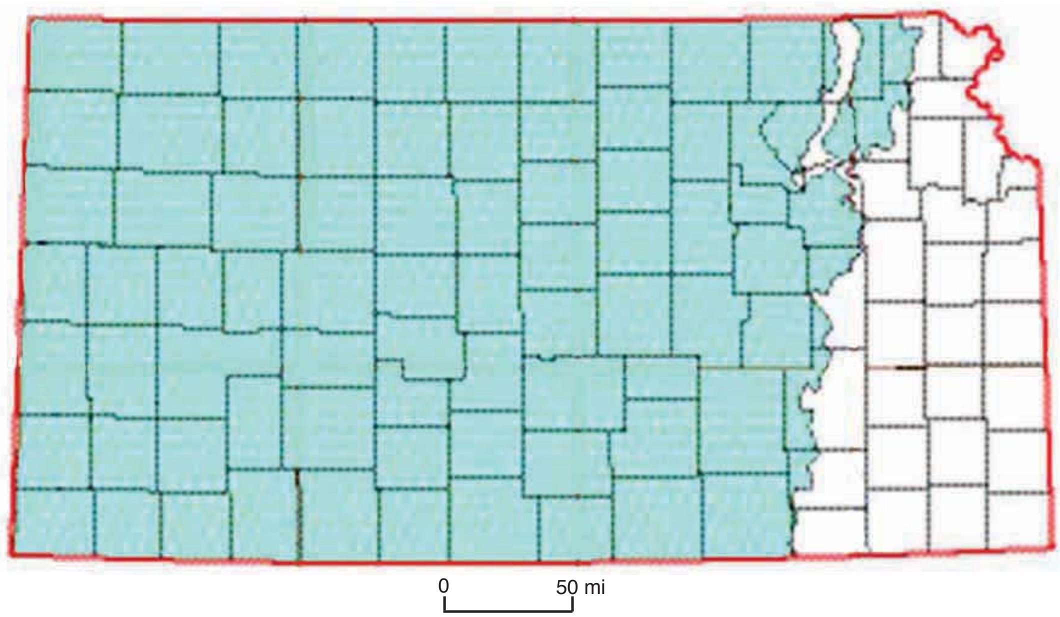


FIGURE 6 —Distribution (surface and subsurface) of Permian rocks in Kansas (modified from Merriam, 1963, fig. 32, p. 80).

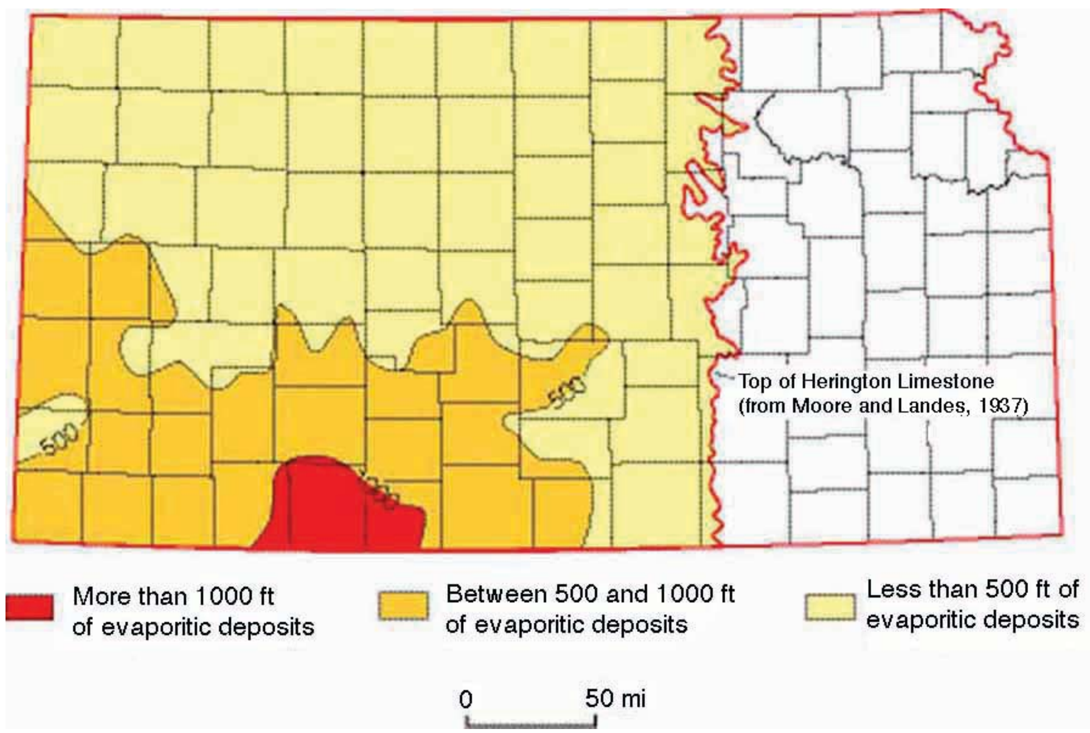


FIGURE 7—Isopach map of the Permian evaporite deposits in Kansas (modified from Merriam, 1963, fig. 35, p. 84).

500 ft (153 m) along the Kansas–Oklahoma border (near the center of the embayment) in Meade County (Watney et al., 1988). This embayment is connected to the Permian seaway in West Texas (Johnson and Denison, 1973).

General Geologic Setting

Essentially continuous deposition from the upper Carboniferous (Pennsylvanian) into the lower Permian in Kansas is shown by McKee and Oriel (1967, plate 2) and is well illustrated by the difficulty associated with the recognition of the boundary between these two late Paleozoic systems. Major structural features during the deposition of Permian rocks in Kansas are, as given by McKee and Oriel (1967, fig. 3), the northern part of the Midcontinent Negative Belt and the Nemaha anticline. West of the Nemaha anticline within the northern part of the Midcontinent Negative Belt are a number of smaller positive and negative features as shown by Mudge (1967, fig. 41). The more prominent of these are the Salina basin, Sedgwick basin, Kansas Permian basin, Hugoton embayment, Los Animas arch, and Central Kansas uplift. The eastern edge of the Permian outcrop is 20–30 mi (32–48 km) east of the Nemaha anticline.

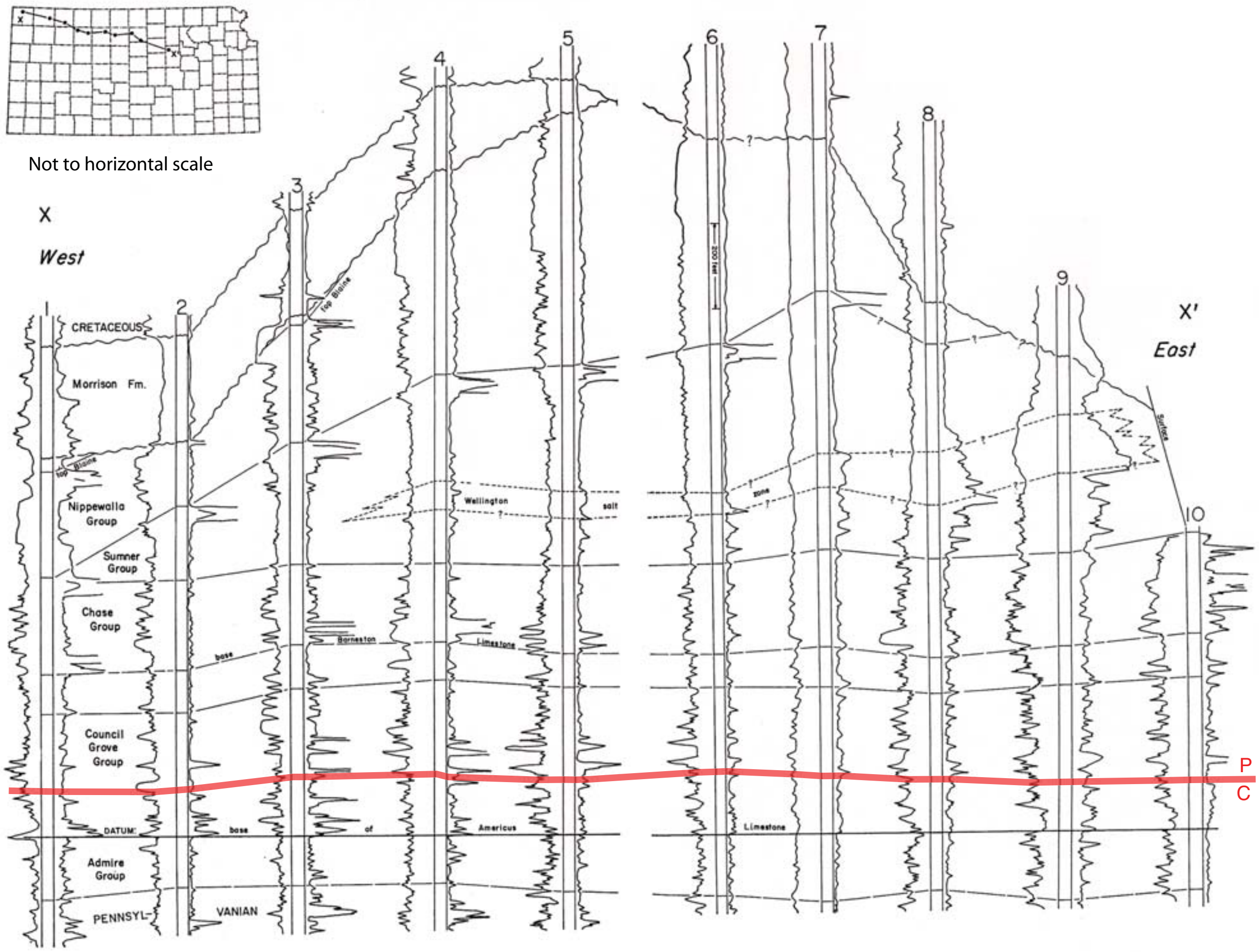


FIGURE 8—Generalized stratigraphic (electric log) cross section of the Permian rocks in Kansas from east (Dickinson County) to west (Cheyenne County) (modified from Merriam, 1963, fig. 33, p. 82–83).

According to Maher (1945), westward tilting of strata in eastern Colorado occurred during the upper Permian and resulted in truncation of the lower Permian units prior to Mesozoic deposition. By association, one can assume that the Permian strata in Kansas were similarly affected. Mudge (1967, p. 123, fig. 43) indicated the inferred drainage during the Mesozoic and Cenozoic that eroded Permian strata in Kansas. Triassic drainage was toward the west and southwest indicating erosion of exposed Permian strata to the east. Although erosion was prevalent during the Lower and Middle Triassic, Upper Triassic sandstones of the Dockum Group were deposited in some areas (Mudge, 1967, p. 122) and are recognized in the subsurface of southwestern Kansas (MacLachlan, 1972, p. 172, fig. 6). Post-Triassic and pre-Jurassic erosion occurred following further uplift that beveled much of the Permian strata in northwestern and western Kansas (Mudge, 1967, p. 122). It seems reasonable to suggest that Upper Triassic rocks might have originally covered a much larger area. The same might also be suggested for the Jurassic, which is present over a relatively large part of the subsurface of northwestern Kansas (Mudge, 1967, p. 121, fig. 42). Merriam (1955) suggested that these Jurassic strata are fluvial and lacustrine in origin and are associated with a southeast to northwest drainage system. Rocks of Cretaceous age overlie the Permian in a broad belt extending across Kansas from the southwest (Grant, Haskell, Meade, and Clark counties) to the northeast (Jewell, Republic, and Washington counties). Along the boundary with Oklahoma in the southwestern part of the state, Neogene rocks overlie the Permian (Mudge, 1967, p. 121, fig. 42). Drainage from the Cretaceous through the Neogene was, and still is, aligned in an east to northeast direction (Mudge, 1967, p. 122).

During most of the Permian, Kansas was a broad shallow-marine shelf that sloped southward toward the Anadarko basin. In current terminology it is more appropriately a ramp, with a large landmass to the east and north that provided most of the terrigenous sediment to the over 3,500 ft (1,068 m) of Permian rocks that accumulated (Mudge, 1967, p. 118, fig. 40). As shown by Ziegler et al. (1997), Kansas was located within the northern tropical latitudes during the Permian with a tropical to dry subtropical climate (Ziegler et al., 1998). According to Kent and Muttoni (2003, fig 3.4), Kansas was in a tropical climatic belt during the lower Permian where precipitation exceeded evaporation; however, by the Middle Jurassic, evaporation exceeded precipitation in Kansas. Hypersaline

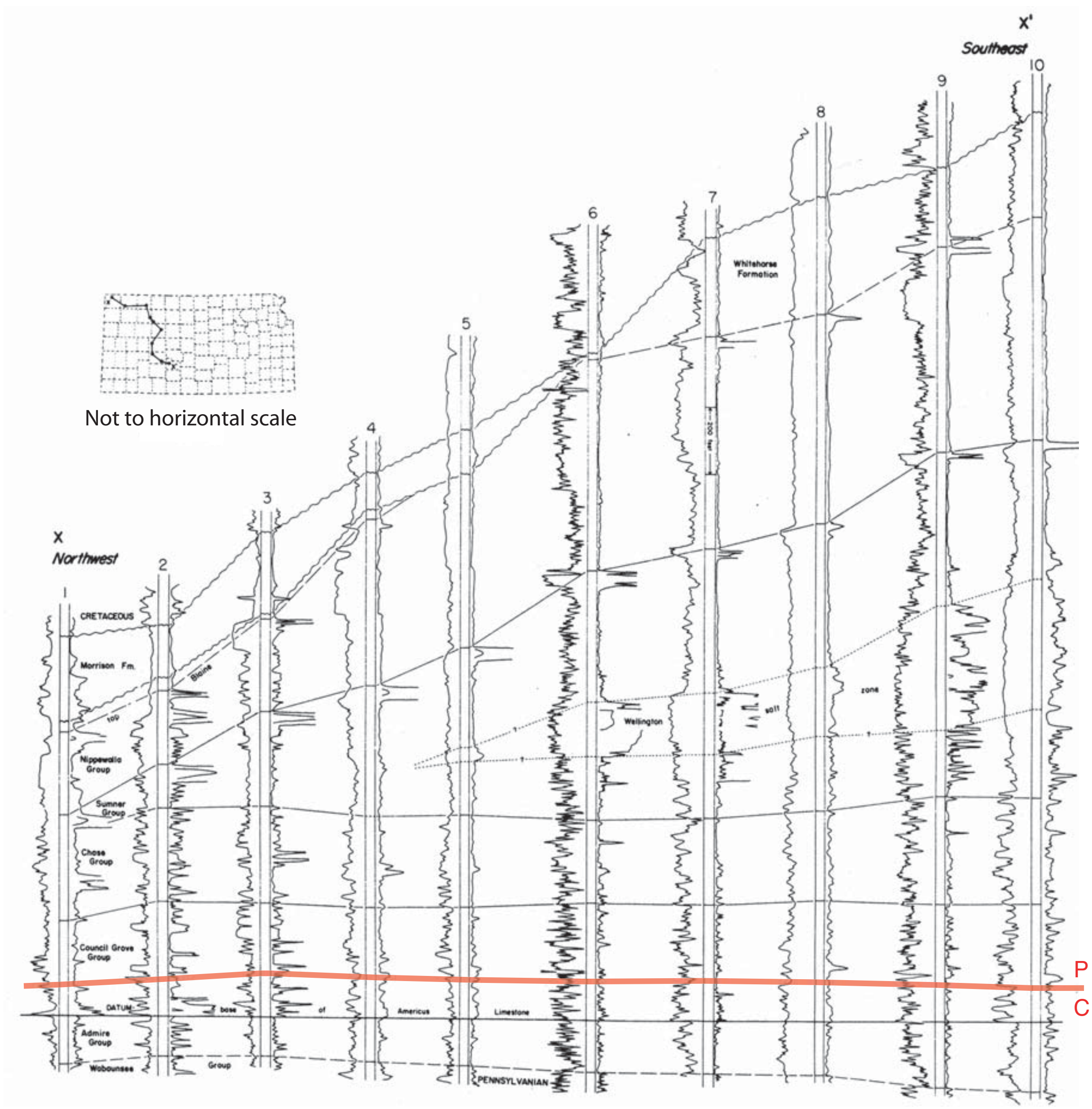


FIGURE 9—Generalized stratigraphic (electric log) cross section of the Permian rocks in Kansas from southeast (Edwards County) to northwest (Cheyenne County) (modified from Merriam, 1963, fig. 34).

conditions seem to have become more extensive from lower to upper Permian. Beds of evaporites in the upper part of the lower Permian (Wolfcampian) and extensive evaporites (halite and anhydrite) in the upper Permian (Leonardian and Guadalupian) suggest extensive evaporation of seawater, or at least excess evaporation over precipitation, runoff, and ground-water recharge. As suggested by Miller et al. (1996) for the Wolfcampian, the climate of this marginal-marine area probably fluctuated from arid to semiarid to seasonal wet/dry (monsoonal conditions). Later, during the Leonardian and Guadalupian, the lithologies, including eolian siliciclastics (Parrish and Peterson, 1988; Johnson, 1989; Soreghan, 1992; Ziegler et al., 1997; Ziegler et al., 1998; Mack et al., 2003), are consistent with a more arid to semiarid climate.

Major Subdivisions

Introduction

Currently the Kansas Geological Survey subdivides the Permian into three series, the Wolfcampian, Leonardian, and Guadalupian; the Ochoan Series is probably not present in Kansas (Zeller, 1968; Sawin et al., 2008; see also fig. 2). This subdivision is similar to that used by McKee and Oriel (1967) and Mudge (1967), who designated the Wolfcampian as Interval A, the Leonardian as Interval B, and the Guadalupian as Interval C. The base of the Permian, Wolfcampian (Interval A) in these two 1967 publications, was placed at the base of the Towle Shale Member of the Onaga Formation as it was in Zeller (1968). Today the base of the Permian is placed at the base of the Bennett Shale Member of the Red Eagle Limestone (Sawin et al., 2006). Thus, the interval from the base of the Onaga Formation to the base of the Bennett Shale Member is now considered part of the upper Carboniferous, Pennsylvanian Subsystem. This should be kept in mind when the Wolfcampian in these two 1967 publications is referred to in this document.

Using the accepted stratigraphic terminology of the Kansas Geological Survey (Zeller, 1968; Sawin et al., 2008), the Wolfcampian includes, in ascending order, the upper part of the Council Grove Group and the Chase Group. This is compatible with the internationally accepted Carboniferous–Permian boundary (Boardman et al., 1998, Sawin et al., 2006; Sawin et al., 2008).

The internationally recognized Carboniferous–Permian boundary at the base of the Bennett Shale Member of the Red Eagle Limestone results in the lower part of the Council Grove Group being Carboniferous and the upper part being Permian (Sawin et al., 2008, p. 2). Wahlman (1998, 2007) referred to the upper Carboniferous part of the Council Grove Group as the lower Council Grove Group. Currently the Kansas Geological Survey (Zeller, 1968; Sawin et al., 2008) considers the base of the Americus Limestone Member of the Foraker Limestone as the base of the Council Grove Group.

Wolfcampian rocks include the rock sequence from the base of the Bennett Shale Member to the top of the Herington Limestone Member. The Leonardian includes the interval from the base of the Wellington Formation to the top of the Dog Creek Formation. Rocks from the base of the Whitehorse Formation to the unconformity at the top of the Big Basin Formation constitute the Guadalupian. Outcrop exposures of strata from these three intervals are shown in the following figures: Wolfcampian (figs. 10, 11), Leonardian (figs. 12, 13, 14), and Guadalupian (fig. 15).

Wolfcampian

Lithostratigraphic Units

The lithostratigraphic nomenclature for the lower Permian of Kansas has undergone nearly as much revision and redefinition as the Carboniferous–Permian boundary itself (see Chaplin [1988] for a summary of the evolution of this nomenclature). Prosser (1895, 1902) was the first to establish

FIGURE 10—Rocks of the Council Grove Group (Neva limestone through Speiser Shale) exposed on the east face of Tuttle Creek Lake Spillway; near the center of SW sec. 18, T. 9 S., R. 8 E., Pottawatomie County, Kansas.

FIGURE 11— Exposure of the Florence Limestone Member and Blue Springs Shale Member along the east side of K–177 just north of the Riley–Geary county line; just south of the center of the west line, sec. 20, T. 11 S., R. 8 E., Riley County, Kansas.

FIGURE 12—Exposure of the Flower-pot Shale on the south side of US–160; NE NE sec. 12, T. 32 S., R. 14 W., Barber County, Kansas.

FIGURE 13— Exposures of the Cedar Hills Sandstone along Gyp Hill Road looking southwest; near center of N/2 sec. 20, T. 32 S., R. 12 W., Barber County, Kansas.

FIGURE 14—Exposure of the Dog Creek Formation near the type area along north side of US–160; near center of north line sec. 9, T. 32 S., R. 14 W., Barber County, Kansas.

comprehensive stratigraphic framework for what he called the "Big Blue Series."

The formal subdivision of the Council Grove and Chase Groups into formation and member-scale units, and the a establishment of the current stratigraphic nomenclature, was largely accomplished by Condra and his colleagues (Condra, 1927; Condra and Upp, 1931; Condra and Busby, 1933). The lithologic sequence of the Wolfcampian is shown in fig.

FIGURE 15—Exposure of the Whitehorse Formation on the north side of US–160 where it crosses Keiger Creek; near center of south line, sec. 3, T. 33 S., R. 24 W., Clark County, Kansas.

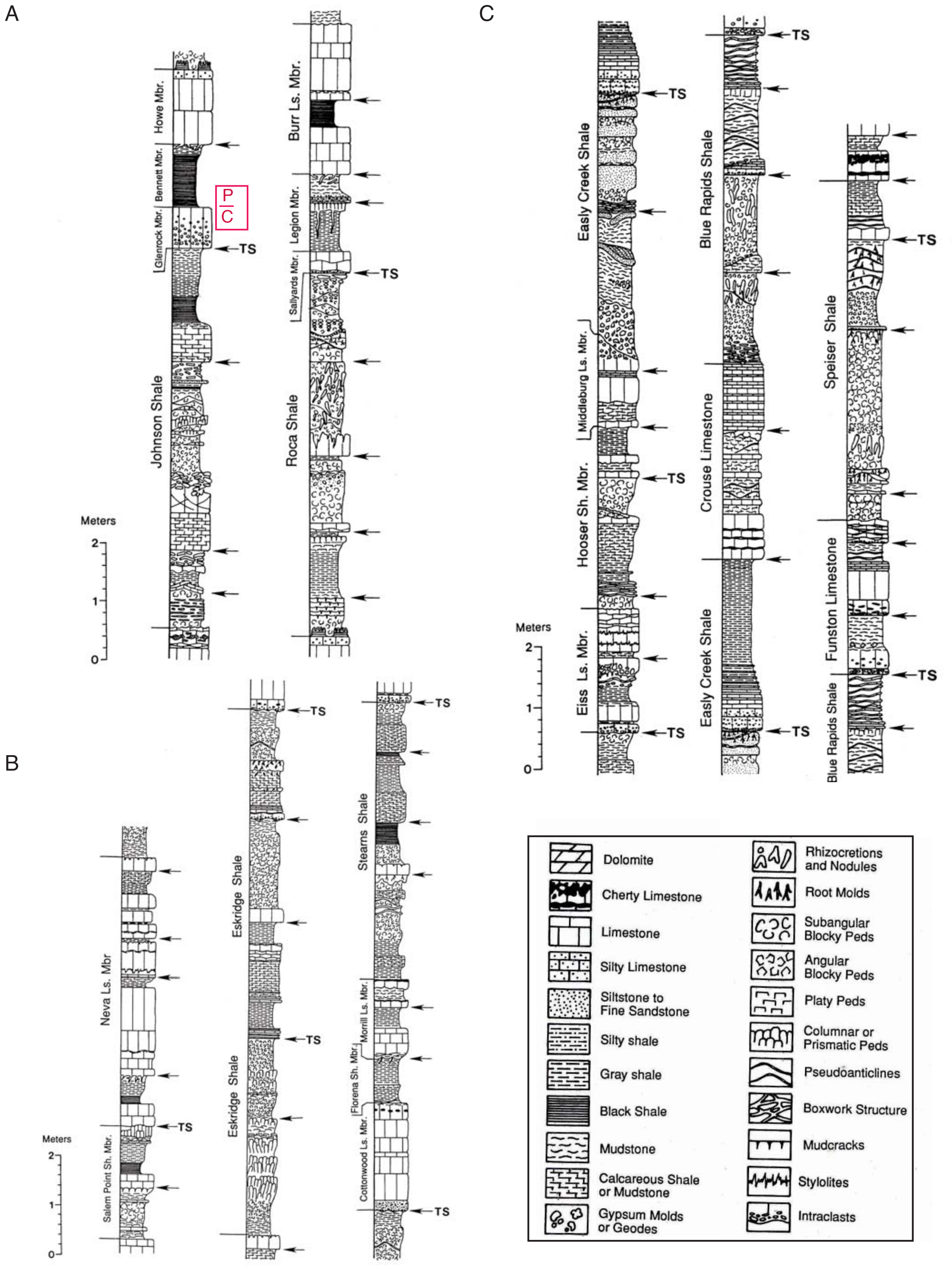
2. However, nomenclatural problems in the lower Permian sequence remain as pointed out by Chaplin (1988), who listed the following: 1) lack of designated type sections for over half of the proposed stratigraphic units; 2) lack of adequate geologic descriptions for some type sections; 3) type sections now poorly exposed or inaccessible; 4) type sections difficult if not impossible to locate due to use of ephemeral geographic markers; 5) designation of more than one type section with different facies; and 6) designation of widely separated type localities for groups (formations) and their component formations (members). These problems become especially acute when trying to correlate these units into southern Kansas and Oklahoma.

Council Grove Group

Excellent summaries and outcrop descriptions of the stratigraphy of the Council Grove Group are given in Mudge and Yochelson (1962) and Mudge and Burton (1959). We will not repeat this information, but rather will give general descriptions and present new observations made since the publication of these important field studies. A detailed stratigraphic column of the Council Grove Group in northeast Kansas is shown in figs. 16A, B, C. These figures provide a reference for the following unit descriptions. As discussed earlier, the recently established stratigraphic position of the Carboniferous/Permian boundary is at the base of the Bennett Shale Member within the Red Eagle Limestone of the Council Grove Group (figs. 3, 4). It is not only a now well-established biostratigraphic boundary, but also a rather abrupt change in the lithologic character of cyclothemic deposition (West et al., 1997). Although the Council Grove Group, as currently defined, contains Pennsylvanian units (Foraker Limestone, Johnson Shale, and the Glenrock Limestone Member of the Red Eagle Limestone), our discussion will begin with the Red Eagle Limestone, the formation containing the Carboniferous (Virgilian)–Permian (Wolfcampian) boundary. Because of the biostratigraphic importance of this formation, our discussion is rather detailed.

Red Eagle Limestone—Over much of its Kansas outcrop, the Red Eagle Limestone consists of two limestone units separated by a dark-gray to black shale and varies from 3 m

FIGURES 16A, B, C (next page)—Detailed stratigraphic column of the Council Grove Group in north-central Kansas showing flooding and transgressive surfaces. Arrows mark flooding surfaces that bound meter-scale parasequences and TS marks transgressive surfaces that mark cyclothem boundaries. **16A**, Johnson Shale through Burr Limestone Member from sec. 18, T. 9 S., R. 8 E., Pottawatomie County, Kansas (modified from Miller, 1994; West, 1994). **16B**, Salem Point Shale Member through Neva Limestone Member of Grenola Limestone from sec. 23, T. 10 S., R. 7 E., Riley County Kansas; Eskridge Shale through Stearns Shale from sec. 10, T. 10 S., R. 7 E., Riley County, Kansas. **16C**, Eiss Limestone Member of Bader Limestone through Speiser Shale from sec. 21, T. 10 S., R. 7 E., Riley County, Kansas (modified from Miller and West, 1993). See also Archer et al., 1995.


A
B
C
Howe Mbr.
Bennett Mbr.
Glenrock Mbr.
Johnson Shale
Burr Ls. Mbr.
Legion Mbr.
Sallyards Mbr.
Roca Shale
P
C
TS
Meters
Neva Ls. Mbr
Salem Point Sh. Mbr.
Eskridge Shale
Stearns Shale
Morrill Ls. Mbr.
Florena Sh. Mbr.
Cottonwood Ls. Mbr.
Easly Creek Shale
Middleburg Ls. Mbr.
Hooser Sh. Mbr.
Eiss Ls. Mbr.
Blue Rapids Shale
Crouse Limestone
Speiser Shale
Funston Limestone
Dolomite
Cherty Limestone
Limestone
Silty Limestone
Siltstone to Fine Sandstone
Silty shale
Gray shale
Black Shale
Mudstone
Calcareous Shale or Mudstone
Gypsum Molds or Geodes
Rhizocretions and Nodules
Root Molds
Subangular Blocky Peds
Angular Blocky Peds
Platy Peds
Columnar or Prismatic Peds
Pseudoanticlines
Boxwork Structure
Mudcracks
Stylolites
Intraclasts

(10 ft) to as much as 10.7 m (35 ft) in thickness (O'Conner and Jewett, 1952; Sawin et al., 2006). These members are, in ascending order, the Glenrock limestone, the Bennett shale, and the Howe limestone. O'Conner and Jewett (1952) and McCrone (1963) studied, in detail, the lithology and paleontology of the Red Eagle Limestone from southern Nebraska to Oklahoma.

The Glenrock limestone is a medium- to light-brownish-gray fusulinid-bearing limestone with algal-coated grains common locally. It has a remarkably uniform thickness of 0.3–0.6 m (1–2 ft) in outcrop north of the Bourbon arch in east-central Kansas. Southward the Glenrock thins to less than 0.15 m (0.5 ft) and cannot be recognized in southernmost Kansas and Oklahoma (McCrone, 1963, p. 23), and the Bennett shale becomes a limestone with several thin shale beds at the base and shale partings in the middle and upper part (O'Connor and Jewett, 1952). O'Connor and Jewett (1952) based their recognition of the Bennett on the *Orbiculoidea* assemblage that is characteristic of the Bennett and can be traced from Oklahoma to Nebraska (McCrone, 1963; Sawin et al., 2006). At Manhattan and Paxico, on either side of the Nemaha anticline, the Glenrock is conglomeratic with abundant granule- to pebble-sized clasts of micrite (McCrone, 1963; Miller, 1994). Between these localities, the Glenrock is missing and the Bennett shale rests on the underlying Johnson Shale formation.

As noted in figs. 16A, B, C, some of the recognized genetic surfaces correspond to the lithostratigraphic contacts between the members of the Red Eagle Limestone. The base of the Glenrock limestone is identified as a transgressive surface and the base of the Howe limestone as a flooding surface. There is some evidence that the top of the Glenrock limestone, the Carboniferous–Permian boundary, is an omission surface (Boardman et al., 1998). This is also true for some of the other lithostratigraphic units in figs. 16A, B, C. Olszewski and Patzkowsky (2003) also indicated the close association between some genetic surfaces and the boundaries of lithostratigraphic units. Thus, the genetic surfaces appear to be much more consistent than the units themselves (Olszewski, personal communication, 2006).

In the northern part of the outcrop belt, the Bennett shale is mainly a calcareous medium-gray laminated shale with a thin dark-gray to black fissile shale at its base (McCrone, 1963). The conodont assemblage in the lowermost mudrocks of the Bennett shale is currently recognized as Permian in age and conodonts from the underlying Glenrock limestone are considered Carboniferous (Boardman et al., 1998). Orbiculoid brachiopods occur throughout the member but are especially abundant in the dark, fissile basal shale. Skeletal remains of fish also occur in the Bennett shale. Part of a eugeneodontid elasmobranch from an exposure of the Bennett shale in the Tuttle Creek Lake Spillway, an exposure that resulted from the 1993 flood, was described by Schultze and West (1996). The Bennett decreases from 2.4 to 1.2 m (8–4 ft) in thickness southward toward Manhattan, and then becomes thicker and increasingly calcareous toward Eskridge. From Eskridge to Council Grove, just north of the Bourbon arch, the facies changes abruptly into a medium-bedded limestone up to 9.1 m (30 ft) thick with brachiopods, crinoids, bryozoans, and fusulinids (McCrone, 1963). It then thins again over the Bourbon arch and becomes shaly. This locally thick facies was identified as a bioherm (O'Connor and Jewett, 1952) and as a biostrome (Mudge and Burton, 1959), but the buildup is not substantially different from other correlative limestone facies in the Bennett (McCrone, 1963). In southern Kansas and into Oklahoma, the Bennett thickens again and changes into a limestone 3–4.6 m (10–15 ft) thick that comprises most of the Red Eagle Limestone. The continued presence of orbiculids at the base has been used in its correlation. However, tracing genetic surfaces (Olszewski and Patzkowsky, 2003) indicates that the limestones are not facies equivalents of the shales.

The Howe limestone, a massive limestone 0.6–1.5 m (2–5 ft) thick, is readily recognized throughout the Kansas outcrop belt (fig. 17). In Nebraska and northern Kansas, it is a fine-grained light-gray vesicular limestone, and in central and southern Kansas it is a fossiliferous grainstone characterized by gastropods, ostracodes, fusulinids, arenaceous forams, coated fossil grains, and ooids. McCrone (1963) described the grain coatings as being algal in origin and referred to the grainstones as "osagites," but more recent work indicates that they are ooids with continuous, concentric laminae (Shapiro and West, 1999). O'Connor and Jewett (1952), McCrone (1963), and Elick (1994) described stromatolites capping the Howe in central Kansas (fig. 18). Shapiro and West (1999) described these domical stromatolites, which vary in shape and microstructure between localities, as dominated by cornuspirid gastropods and calcifying filamentous algae.

Roca Shale—The Roca Shale is predominantly a reddish-brown to light-greenish-gray calcareous mudrock 4.3–5.5 m (14–18 ft) thick in exposures across Kansas (fig. 19). The Roca consists of several mudrock intervals separated by thin micritic limestones with finely fragmented fossil debris (Miller, 1994).

All these mudrocks contain evidence of subaerial exposure, and well-developed paleosol profiles occur in most of them. In Riley County, the paleosols show a consistent vertical pattern from salt-influenced natric paleosols at the base, to reddish calcic paleosols, to greenish-gray vertic paleosols at the top (Miller et al., 1996; McCahon and Miller, 1997; Rankey and Farr, 1997). A relatively well preserved fossil-plant assemblage has been described from the upper Roca in Wabaunsee County (Warren, 1969).

Grenola Limestone—Above the Roca are the alternating lithologies of the Grenola Limestone. The five members of this formation are, in ascending order, Sallyards limestone, Legion shale, Burr limestone, Salem Point shale, and Neva limestone (figs. 19, 20).

The Sallyards limestone is a thin 0.15–1.07-m (0.5–3.5-ft) gray limestone with abundant bivalves (particularly pectinids and myalinids) and cornuspirid gastropods. Brachiopods, crinoids, and other fossils are also locally common. Stromatolites are present at many localities (Mudge and Burton, 1959; Mudge and Yochelson, 1962), and algal-coated bivalves are common in the Manhattan area (Miller, 1994). The basal contact of the Sallyards with the underlying paleosols of the upper Roca is sharp, and locally is marked by a lag of bone fragments and intraclasts of up to cobble size (Miller, 1994; Miller and West, 1998). Overlying the Sallyards is the nearly black to gray fissile Legion shale that varies from less than

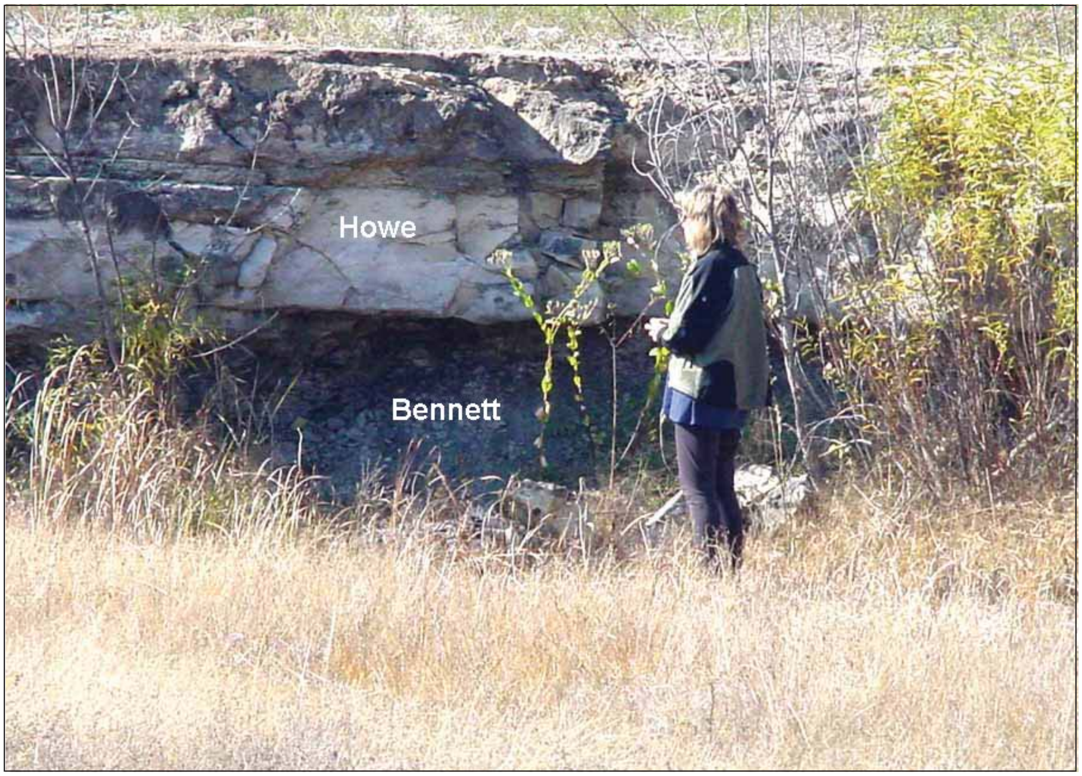


FIGURE 17—Exposure of the Howe Limestone Member with the Bennett Shale Member below, looking north from the eroded area below the Tuttle Creek Lake Spillway; near center of N/2 sec. 19, T. 9 S., R. 8 E., Pottawatomie County, Kansas.

FIGURE 18—Algal stromatolites at the top of the Howe Limestone Member in the eroded exposure below the Tuttle Creek Lake Spillway; near center N/2 sec. 19, T. 9 S., R. 8 E., Pottawatomie County, Kansas.

0.61 m (2 ft) up to 3.66 m (12 ft) in thickness. It is poorly fossiliferous with scattered ostracodes, bivalves, and fine plant debris. In the southern part of the outcrop, thin bivalve-bearing limestone beds are present in the middle of the unit (Mudge and Yochelson, 1962). A superb temporary exposure (1993 flood) in the Tuttle Creek Lake Spillway near Manhattan revealed a thin natric paleosol horizon near the top of the Legion that is sharply overlain by a phosphatic lag up to 10 cm (0.33 ft) thick with granule- to pebble-size clasts and bone debris (Miller, 1994). The geographic extent of this horizon has not been determined.

The Burr limestone consists of two limestone beds separated by a thin black to gray calcareous mudrock. It varies in thickness from a minimum of 0.7 m (2.3 ft) in Lyon County, to over 4.6 m (15 ft) in Cowley County (Mudge and Yochelson, 1962).

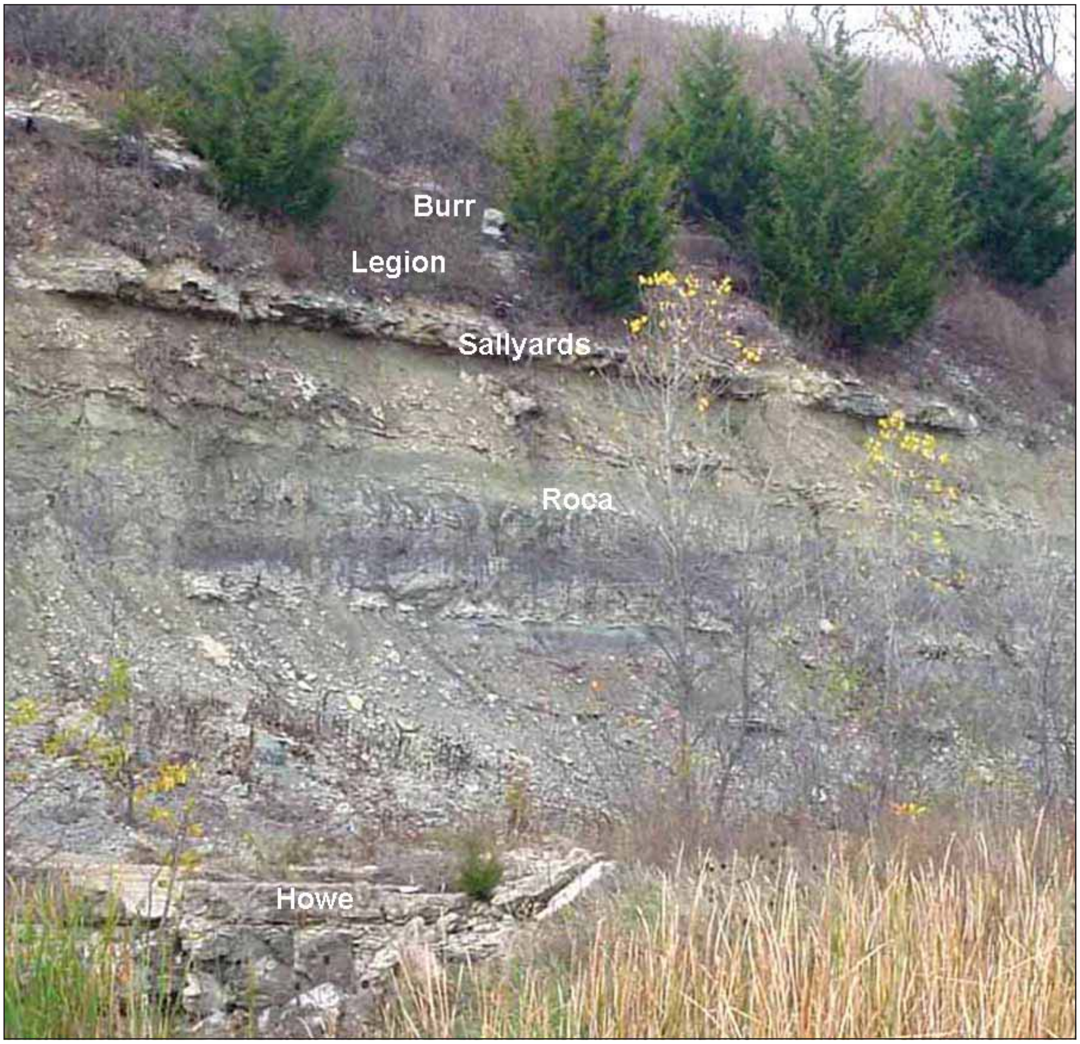


FIGURE 19—Exposure of Roca Shale and Grenola Limestone on the west side of the eroded area below Tuttle Creek Lake Spillway; near center N/2 sec. 19, T. 9 S., R. 8 E., Pottawatomie County, Kansas.

Above the Burr is a gray to yellowish-gray silty mudrock, the Salem Point, with a sparse assemblage of ostracodes, small bivalves, and plant fragments. Interbedded thin argillaceous limestone beds contain pectinids and myalinids (Lane, 1958). Desiccation cracks and a well-developed natric paleosol horizon (McCahon and Miller, 1997) record important exposure surfaces in the Salem Point in Riley County.

The Neva, an argillaceous limestone with mudrock interbeds, is relatively uniform in thickness, about 6.1 m (20 ft). A diverse assemblage of brachiopods, bryozoans, echinoderms, and fusulinids is preserved, and chert occurs in southern Kansas. In the northern part of the state, black carbonaceous shales in the lower Neva are characterized by orbiculid and lingulid brachiopods (Condra and Busby, 1933). These shales thin and become gray to the south and contain conodonts. Because of its consistent thickness and lateral extent, the Neva limestone is a distinctive marker bed in the subsurface.

Eskridge Shale—A variegated mudrock, between 6.1 and 12.2 m (20–40 ft) thick, the Eskridge Shale overlies the Neva (fig. 20). It contains two intervals of thin limestone beds and calcareous mudrocks that can be recognized over most of the outcrop belt (Mudge and Yochelson, 1962). Pectinid and myalinid bivalves are abundant in these thin limestones, and the variegated mudrocks consist of stacked well-developed calcic and vertic paleosol profiles (Joeckel, 1991; Miller and West, 1993).

Beattie Limestone—Three members, in ascending order, the Cottonwood limestone, Florena shale, and Morrill limestone, are recognized in the Beattie Limestone, which overlies the Eskridge (fig. 21). Imbrie et al. (1964) provided a comprehensive description of this formation.

The Cottonwood is a prominent, fusulinid-bearing limestone 0.9–2.7 m (3–9 ft) thick in Kansas. A thin bed with mudrock intraclasts up to 10 cm (4 inches) in diameter, phosphatic grains, and fragments of bone and skeletal debris occurs locally near the base (Miller and West, 1993). Laporte (1962) published a detailed study of the Cottonwood from Nebraska to Oklahoma. In northern and central Kansas, Laporte recognized a lower bioclastic facies with abundant algal-coated grains (osagite) and an upper facies dominated by fusulinids. In Greenwood County, the Cottonwood is dominated by a platy alga with a cup-shaped thallus identified as *Calcipatera cottonwoodensis* by Torres et al. (1992). Sawin and West (2005) described a bafflestone composed of in

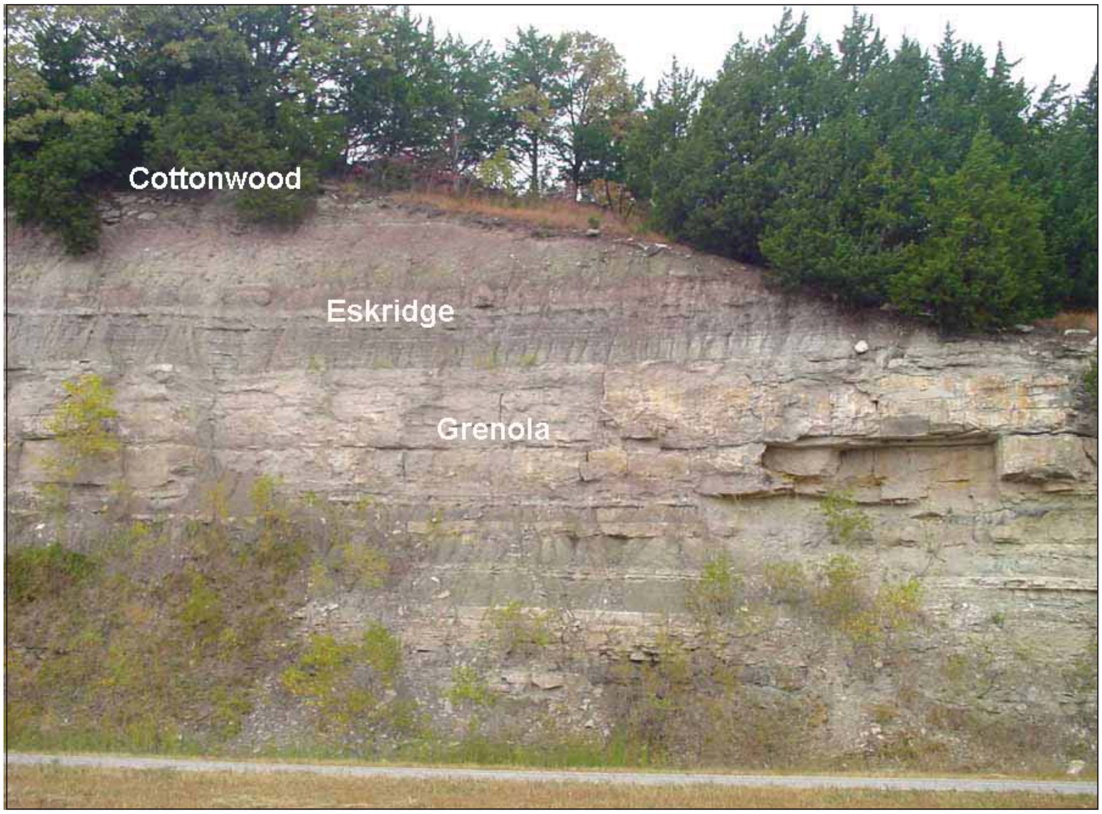


FIGURE 20—Exposure of Grenola Limestone, Eskridge Shale, and Cottonwood Limestone Member of the Beattie Limestone along the north side of K–18; near center of north line NW sec. 26, T. 10 S., R. 7 E., Riley County, Kansas.

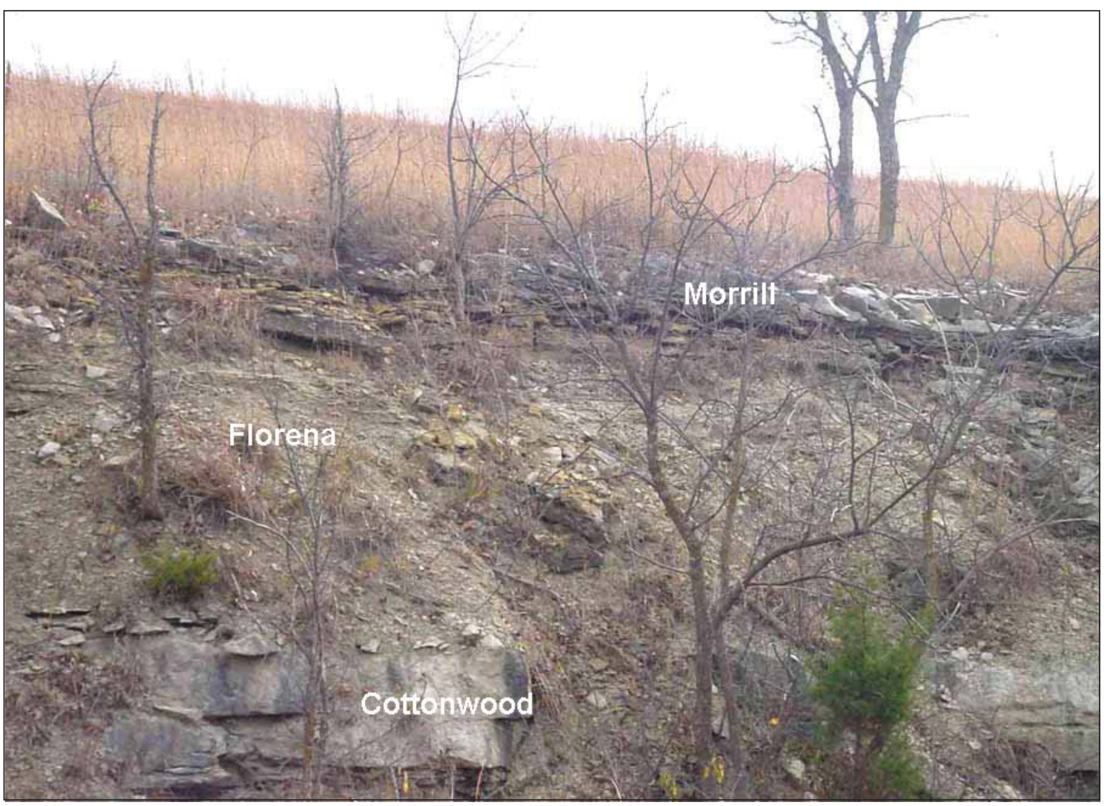


FIGURE 21—Exposure of the Beattie Limestone along the north side of K–18; near center of north line NW sec. 26, T. 10 S., R. 7 E., Riley County, Kansas.

situ *Calcipatera* and a packstone composed of *Calcipatera* fragments. These two carbonate rock types correspond to what Samankassou and West (2004) referred to, respectively, as constructional and accumulational modes of occurrence in algal mounds. South of Greenwood County the Cottonwood limestone becomes more argillaceous with a diverse brachiopod and mollusk assemblage.

The Florena shale is a 0.9–4.6-m (3–15-ft)-thick mudrock that was studied in detail by Imbrie (1955). The lower beds are typically very fossiliferous gray mudrocks dominated by brachiopods (especially *Neochonetes* and *Derbyia*). The upper part is poorly fossiliferous and dolomitic with secondary calcite filling fractures and geodes.

Two or more porous limestones with thin gray calcareous mudrock interbeds compose the Morrill, which contains skeletal fragments of brachiopods, echinoderms, bryozoans, and bivalves; locally it is stromatolitic (Mudge and Yochelson, 1962). Over much of Kansas, the Morrill has a well-developed boxwork structure of calcite-filled fractures, and it is characterized by an algal breccia facies in Greenwood County (Imbrie et al., 1964).

Stearns Shale—The Stearns Shale is a 1.5–8.8-m (5–29-ft)-thick sequence of reddish to greenish-gray stacked paleosols in its lower part, and dark-gray to olive-gray shales and mudrocks and calcareous siltstones in its upper part (Miller and West, 1993; fig. 22). A thin coal bed is locally present in Lyon and Morris counties (Zeller, 1968).

Bader Limestone—The three members of the Bader Limestone are, in ascending order, the Eiss limestone, Hooser shale, and Middleburg limestone (fig. 23). Intraclastic beds occur locally at the base of the Eiss and Middleburg, where they truncate underlying variegated mudrock units (Miller and West, 1993).

The Eiss, a thin but persistent unit, ranges from 2.1 to 5.5 m (7–18 ft) in thickness. Like most carbonate units in the Wolfcampian, it generally consists of two beds of limestone separated by a thin mudrock bed. The lower limestone bed contains a diverse brachiopod-dominated assemblage, and the upper bed is characterized by abundant pyramidellid gastropods, bivalves, and algal-coated grains (Mudge and Burton, 1959). At the base of the upper limestone, a boxwork structure is locally well developed (Miller and West, 1993). Based on conodonts the base of the Sakmarian Stage/Age is thought to be within the Eiss limestone (Mei et al., 2002; Wardlaw, 2004; Wardlaw et al., 2006; Menning et al., 2006; Sawin et al., 2008; Boardman et al., 2009); however, the International Commission on Stratigraphy has not yet established a GSSP for this boundary. A variegated mudrock unit 0.9–3.3 m (3–11 ft) thick, the Hooser consists of stacked calcic paleosol profiles, including a salt-influenced natric horizon in its upper part (McCahon and Miller, 1997). The gray to light-brown Middleburg limestone, a 0.6–2.4-m (2–8-ft)-thick unit, is characterized by abundant pyramidellid gastropods and algal-coated grains.

Easly Creek Shale—The Easly Creek is 3.05–6.1 m (10–20 ft) of variegated mudrock, the basal part of which, in northeastern Kansas, is marked by a red and green mudrock breccia that corresponds to an approximately 2-m (6.6-ft)-thick bed of gypsum in the subsurface (Miller and West, 1993). This gypsum bed is also reported in outcrop in Marshall County (Zeller, 1968). The lower part of the Easly Creek consists of stacked olive and grayish-red paleosols and beds of siltstone and fine sandstone (fig. 24). Folding and faulting are responsible for some of the local deformation of this variegated interval. This deformation is especially well displayed in K–177 roadcuts south of Manhattan (Miller and McCahon, 1999). Sharply truncating this lower variegated interval is a thin intraclastic limestone containing rounded granule to pebble-size micrite clasts, pyramidellid gastropods, and brachiopod and bivalve fragments. The overlying mudrocks are poorly fossiliferous with scattered bivalves and lingulid brachiopods (Miller and West, 1993).

FIGURE 22—Exposure of the Stearns Shale on the north side of K–13 just after turning northeast off US–24 to go over the dam at Tuttle Creek Lake, SW sec. 23, T. 9 S., R. 7 E., Riley County, Kansas.

Crouse Limestone—Overlying the Easly Creek are the three widely traceable units of the 1.8–5.5-m (6–18-ft)-thick Crouse Limestone: a lower wackestone to packstone interval with pyramidellid gastropods and bivalves, a middle dolomitic mudrock, and an upper thin-bedded to laminated, dolomitic micrite with pavements of ostracodes (West et al., 1972; West and Twiss, 1988; fig. 25). The lower limestone is locally cherty.

Blue Rapids Shale—Above the Crouse is a 4.6–9.1-m (15–30-ft)-thick variegated mudrock, the Blue Rapids Shale, which consists of a series of well-developed paleosol profiles each truncated by thin calcareous beds containing ostracodes, fish bones, and intraclasts. The familiar pattern of reddish calcic paleosols with caliche nodules, overlain by greenish-gray to olive vertic paleosols (Miller and West, 1993), characterizes the Blue Rapids (fig. 26). Zeller (1968) reported a thin coaly layer within the upper part of the Blue Rapids in Geary County.

Funston Limestone—The Funston Limestone consists of gray fossiliferous limestones and yellowish-gray mudrocks and ranges from 1.5 to 8.5 m (5–28 ft) in thickness (fig. 26). It is not recognized in northern Oklahoma (Chaplin, 1988). At its base is a bed with mudrock intraclasts and fragmented skeletal debris (Miller and West, 1993). A diverse assemblage of brachiopods, bryozoans, crinoids, and mollusks characterize the lower beds; algal-coated grains and pyramidellid gastropods occur in the upper limestone. A "biostrome" of algal-bound oolitic limestone over 7.6 m (25 ft) thick is developed within the Funston in east-central Kansas (Mudge and Burton, 1959).

Speiser Shale—At the top of the Council Grove Group is 5.5–10.7 m (18–35 ft) of mudrock, the Speiser Shale, which generally thickens to the south. In northern Oklahoma where the Funston is absent, the name Speiser is used to include the interval from the top of the Crouse to the base of the Wreford Limestone (Chaplin, 1988). Like the Blue Rapids, it is composed of a stacked series of paleosols with thin truncating carbonate beds (fig. 27). Reddish and greenish-gray calcic paleosols occur in the lower part. Overlying these paleosols are vertic paleosols and laterally equivalent gray organic-rich shales (Miller and West, 1998). Schultze (1985, p. 12, fig. 9) reported skeletal remains of both marine and euryhaline vertebrates (palaoniscoids, platysomoids, acanthods, elasmobranchids, petalodontids, bradyodonts, cladodonts, xenocanthids, *Gnathorhiza* [lungfish], and tetrapods) with marine invertebrates in the Speiser Shale in Kansas. Amphibian burrows in the Speiser Shale were associated with ephemeral ponds (Hembree et al., 2004). A very persistent thin limestone occurs near the top of the Speiser, sharply overlying the upper paleosol. This limestone contains a diverse marine assemblage of productid brachiopods, bryozoans, crinoids, and bivalves, and is overlain by a thin, fossiliferous, gray mudrock (Miller and West, 1993).

Composite Sequences in the Council Grove Group—Boardman and Nestell (2000) and Boardman et al. (2009) identified third-, fourth-, and fifth-order depositional sequences in the Council Grove Group. Olszewski and Patzkowsy (2003) recognized two composite sequences in the lower part (from the base of the Glenrock limestone to the upper part of

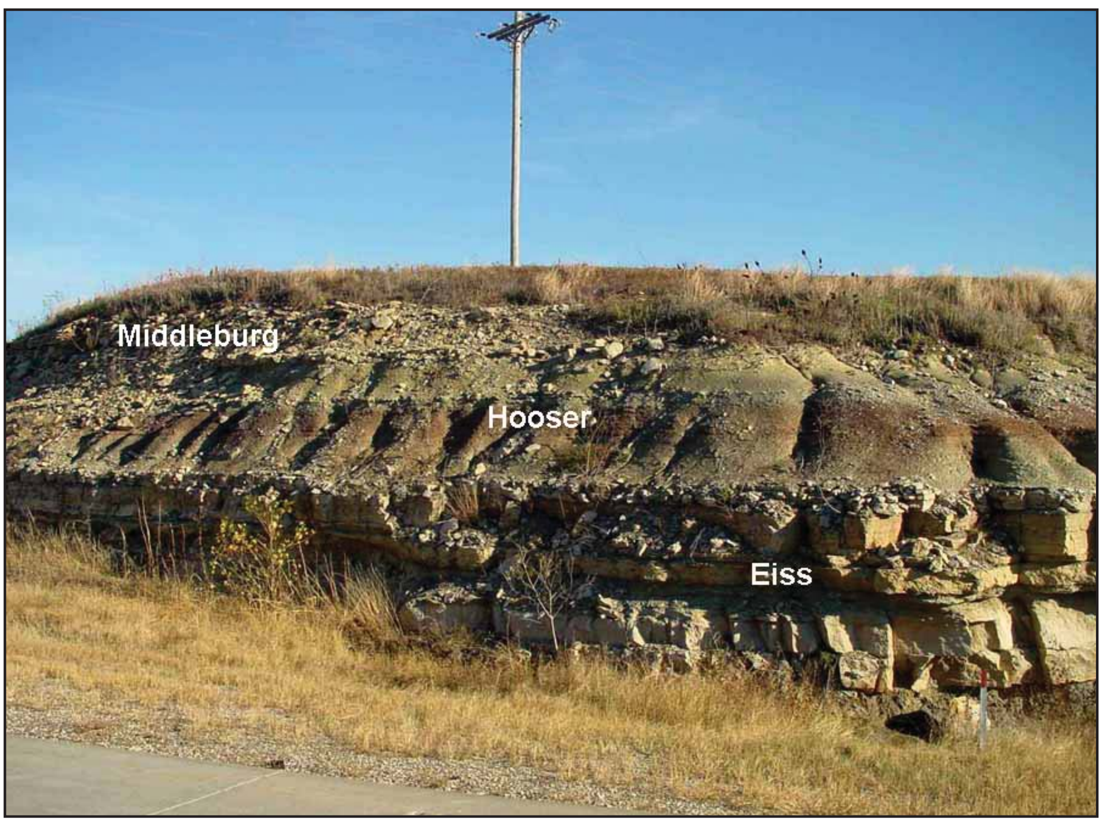


FIGURE 23—Exposure of the Bader Limestone on the southeast side of the access road on the north side of the interchange of I–70 and Deep Creek Road; just north of center of east line, sec. 27, T. 11 S., R. 8 E., Geary County, Kansas.

FIGURE 24 — Exposure of the Easly Creek Shale on the northwest side of the access road on the north side of the interchange of I–70 and Deep Creek Road; near center of SE NE sec. 27, T. 11 S., R. 8 E., Geary County, Kansas.

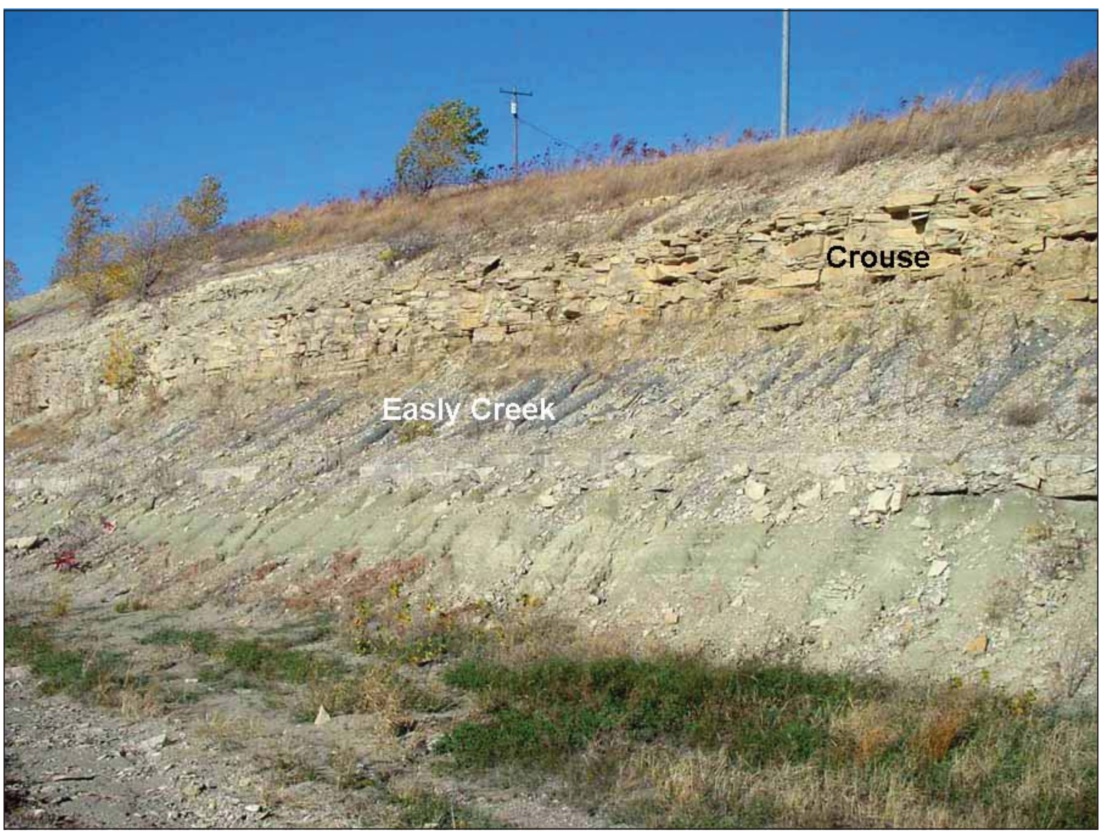


FIGURE 25—Exposure of the Crouse Limestone and Easly Creek Shale on the east side of K–177 south of Manhattan just north of the Scenic Overlook; near center of east line, sec. 29, T. 10 S., R. 8 E., Riley County, Kansas.

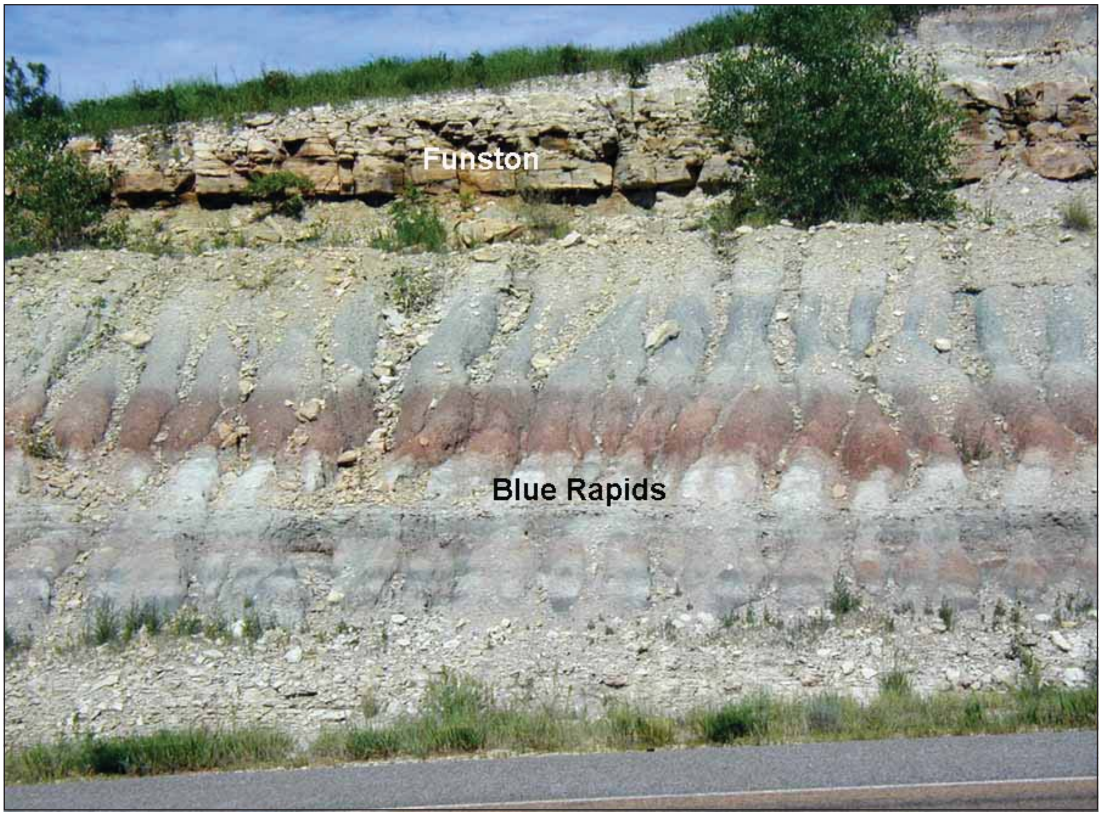


FIGURE 26—Exposure of the Blue Rapids Shale and Funston Limestone on the east side of K–177 south of Manhattan; along west line SW sec. 33, T. 10 S., R. 8 E., Riley County, Kansas.

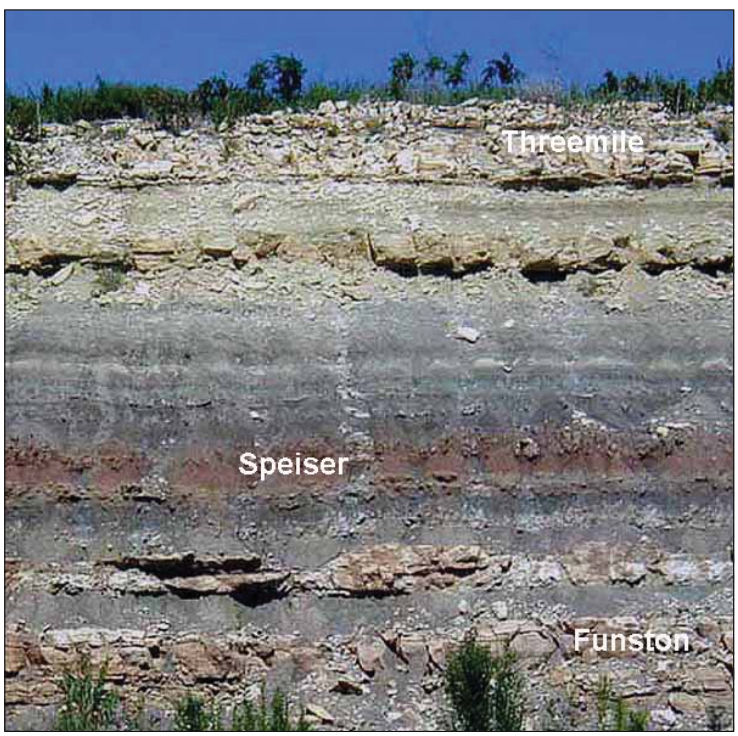


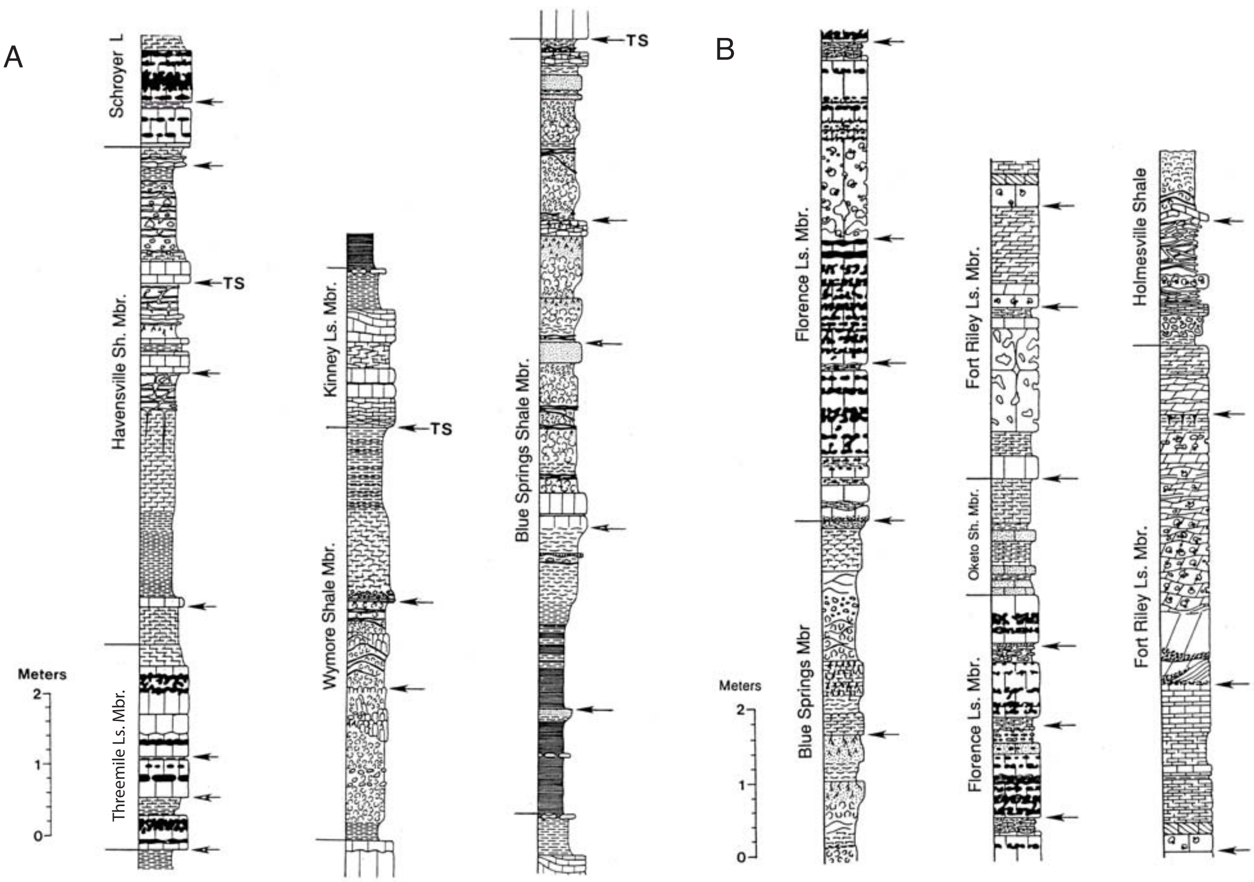
FIGURE 27—Exposure of the Speiser Shale on the east side of K–177 south of Manhattan; along west line SW sec. 33, T. 10 S., R. 8 E., Riley County, Kansas.

the Eskridge Shale) of the Council Grove Group. They termed these the Red Eagle and Grenola Composite Sequences and correlated them from Cowley County in southern Kansas to Nemaha County in northern Kansas. Correlations of meter-scale cycles within these sequences revealed angular unconformities bounding these composite depositional sequences (Olszewski and Patzkowsky, 2003, p. 28). In addition, Olszewski and Patzkowsky (2003) pointed out the importance of this sequence and smaller-scale framework to understanding the role of eustasy and climate in the rock record of this interval.

Chase Group

The Chase Group begins with the Wreford limestone, the first prominent carbonate interval containing abundant chert. The last prominent limestone of the Permian section, the Herington limestone, is the uppermost unit of the Chase Group, but it only contains chert nodules in southern Kansas (Condra and Upp, 1931; Bayne, 1962). The chert-bearing limestones of the Chase Group, primarily the Wreford (Threemile and Schroyer) and Barneston (Florence) are largely responsible for the topography of the lower Permian outcrop in Kansas, and the reason for the designation of the region as the "Flint Hills." On the basis of sequence stratigraphy, Mazzullo et al. (1997) and Mazzullo (1998) recognized a number of cycles within seven depositional sequences within the Chase Group. A detailed stratigraphic column for the Chase Group in north-central Kansas is shown in figs. 28 A, B, C, D.

Wreford Limestone—In ascending order the Threemile limestone, Havensville shale, and Schroyer limestone, make up the Wreford Limestone (figs. 29, 30). A detailed study of the Wreford along the entire outcrop belt from Nebraska to Oklahoma was conducted by Hattin (1957). Cuffey (1967) and Lutz–Garihan and Cuffey (1979) published detailed studies of

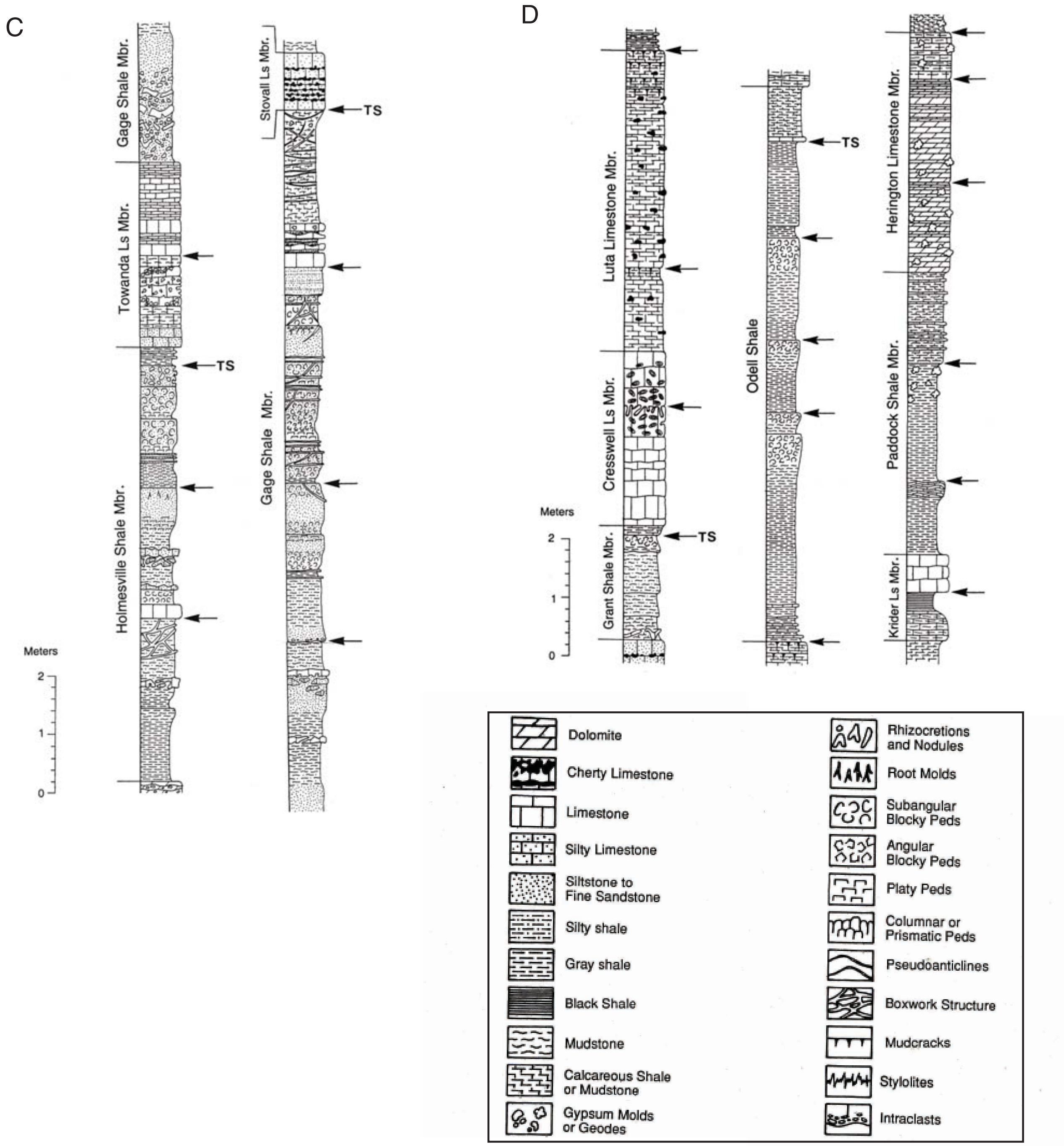


FIGURES 28A, B, C, D (above and next page)—Stratigraphic sections for the Chase Group in north-central Kansas. Arrows mark flooding surfaces that bound meter-scale parasequences, and TS denotes transgressive surfaces that mark cyclothem boundaries. **28A**, Threemile Limestone Member through the Schroyer Limestone Member of the Wreford Limestone sequence is from an exposure in sec. 21, T. 10 S., R. 7 E., Riley County, Kansas (modified from Miller and West, 1993); Wymore Shale Member through the Blue Springs Shale Member of the Matfield Shale is from an exposure in sec. 35, T. 9 S., R. 7 E., Riley County, Kansas. **28B**, Florence Limestone Member through the Fort Riley Limestone Member of the Barneston Limestone is from an exposure in sec. 29, T. 11 S., R. 5 E., Geary County, Kansas (modified from Miller and Twiss, 1994). **28C**, Holmesville Shale Member of the Doyle Shale is from an exposure in sec. 17, T. 7 S., R. 6 E., Riley County, Kansas; Gage Shale Member of the Doyle Shale through the Stovall Limestone Member of the Winfield Limestone is from an exposure in sec. 6, T. 12 S., R. 4 E., Dickinson County, Kansas. **28D**, Grant Shale Member of the Winfield Limestone is from an exposure in sec. 3, T. 8 S., R. 6 E., Riley County, Kansas; Cresswell Limestone Member of the Winfield Limestone through the Herington Limestone Member of the Nolans Limestone is based on descriptions in Mazzullo et al., 1995, from south-central Kansas. See also Archer et al., 1995.

the paleoecology of the Wreford. Schultze (1985, p. 12, fig. 9) reported an assemblage of marine and euryhaline vertebrate skeletal remains from the Wreford Limestone that is similar to what occurs in the underlying Speiser Shale. As in the Speiser Shale, these vertebrate remains were associated with marine invertebrates. A few of these vertebrates also occur in the overlying Wymore shale (Schultze, 1985, p. 12, fig. 9). Abundant chert and a diverse assemblage of brachiopods (especially productids), bryozoans, and crinoids characterize the Threemile limestone.

The upper limestone bed of the Threemile limestone thickens dramatically to over 7.3 m (24 ft) from southern Wabaunsee to southern Chase counties (Hattin, 1957). This thickened chalky facies is dominated by bryozoans and includes corals. In southern Kansas, algal-coated grains (osagite) become abundant in the upper Threemile and infaunal bivalves (*Wilkingia*) are prominent.

Overlying the Threemile are the gray to yellowish-gray shales and mudrocks of the Havensville shale, which varies in thickness inversely with the underlying Threemile from about 1.5 to 7.6 m (5–25 ft). It contains thin molluscan limestone beds in the north and osagite limestones with infaunal bivalves in the south (Hattin, 1957). At least in Riley County, the middle Havensville is characterized by boxwork structures (fig.



31), calcite- and quartz-replaced evaporite nodules (geodes), and thin olive-gray paleosol horizons (Miller and West, 1993).

The Schroyer is a rather uniform cherty limestone 1.8–4 m (6–13 ft) thick with a diverse brachiopod, bryozoan, crinoid assemblage; a grainstone bed is usually present at the top.

Matfield Shale—The Matfield Shale is divided into three members, in ascending order the Wymore shale, Kinney limestone, and Blue Springs shale (fig. 32). The Wymore Shale Member, 2.7–7.6 m (9–25 ft) thick, is a variegated and silty mudrock with very well developed calcic paleosols in the lower part. These color-mottled paleosols are overlain by greenish-gray vertic paleosols (Miller and West, 1993). Williams (1972) described spiral coprolites from sharks that were collected from a lens of gray-green mudrock in the lower part of the Wymore shale. The coprolites were associated with plant debris and skeletal remains of other vertebrates and invertebrates and the depositional environment was inferred to be a freshwater marsh or swamp. McAllister (1985) provided additional information on these coprolites.

In the subsurface, at least in Riley County, the upper bed of the Wymore is 0.9 m (3 ft) of gypsum (Twiss, 1991a). Two limestone beds, between 2 and 7 m (6.5–23 ft) thick, separated by mudrock containing very thin fossiliferous limestones, constitute the Kinney. Brachiopods (particularly *Derbyia* and *Composita*) and bryozoans are common throughout the unit. The mudrocks are dark gray, green, or black to the north and yellowish gray to the south (Mazzullo, 1998). Boxwork structures are locally developed at the top of the mudrock interval in Riley County. Overlying the Kinney is 4.6–10.7 m (15–35 ft) of Blue Springs shale consisting of variegated silty mudrock with preserved stacked and truncated red and green silty paleosol profiles (fig. 33). Miller and McCahon (1999) reported several paleosols in the upper part that are capped by massively rooted siltstone beds, and that locally lungfish burrows penetrate these upper paleosols. Yellowish-gray mudrock occurs at the top of this member. Hasiotis et al. (2002) discussed this lungfish-burrowed interval.

Barneston Limestone—Of all the Permian carbonate units in Kansas, the Barneston is the thickest and most prominent and its 24.4 to 27.4-m (80–90-ft) thickness is responsible for a lot of the conspicuous topographic benches over much of the Flint Hills. This formation includes three members, in ascending order: Florence limestone, Oketo shale, and Fort Riley limestone (fig. 34).

The 3.7–13.7-m (12–45-ft)-thick Florence contains abundant chert nodules and beds, some of which have a branching morphology (Miller and Twiss, 1994; Twiss, 1991b, 1994; Miller, 1996). It is a fusulinid-bearing limestone with a diverse assemblage of brachiopods, bryozoans, crinoids, and echinoids. Based on conodonts, the proposed base of the Artinskian Stage/Age is thought to be within the Florence limestone (Mei et al., 2002; Wardlaw, 2004; Wardlaw et al., 2006; Sawin et al., 2008; Boardman et al., 2009), but Menning et al. (2006, p. 348) suggested it was somewhere within the interval between the Schroyer and Florence limestones (Sawin et al., 2008). The International Commission on Stratigraphy has not established a GSSP for this boundary. The Oketo shale is a thin (generally less than 1.5 m [5 ft]), silty, calcareous interval

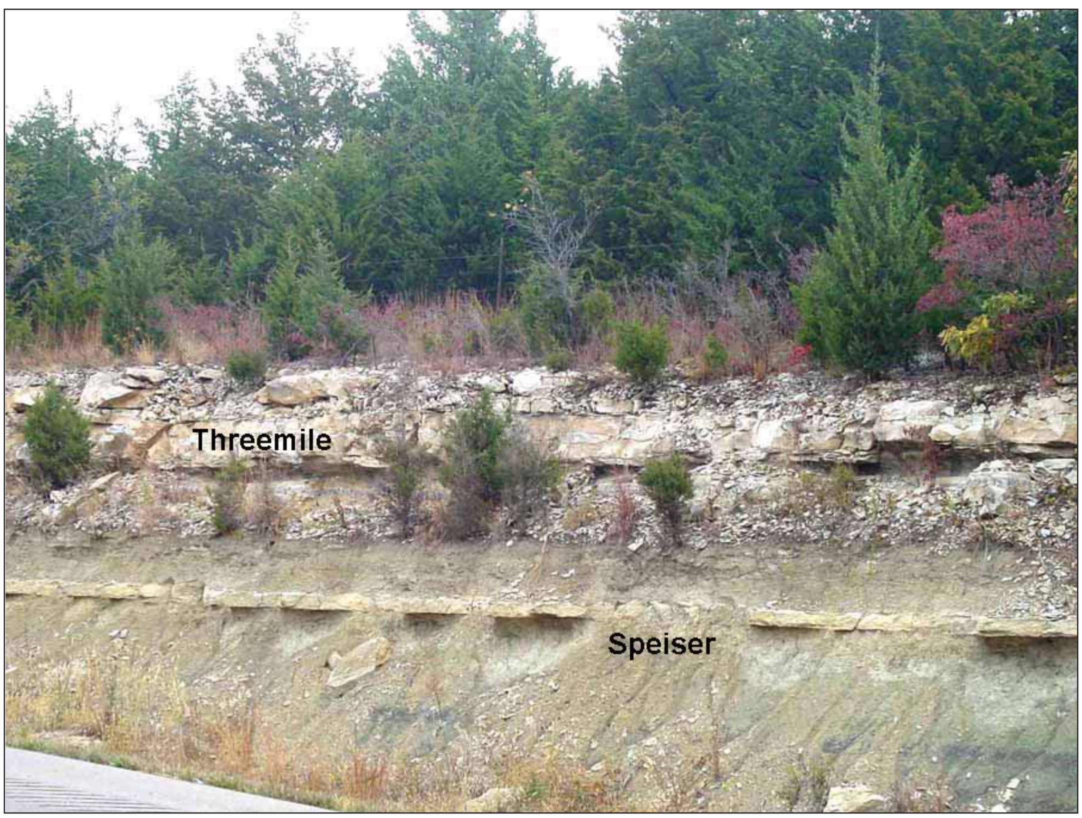


FIGURE 29—Exposure of the Threemile Limestone Member of the Wreford Limestone and Speiser Shale along the east side of Scenic Drive in Manhattan, Kansas; just west of center of east line NE NE sec. 21, T. 10 S., R. 7 E., Riley County, Kansas.

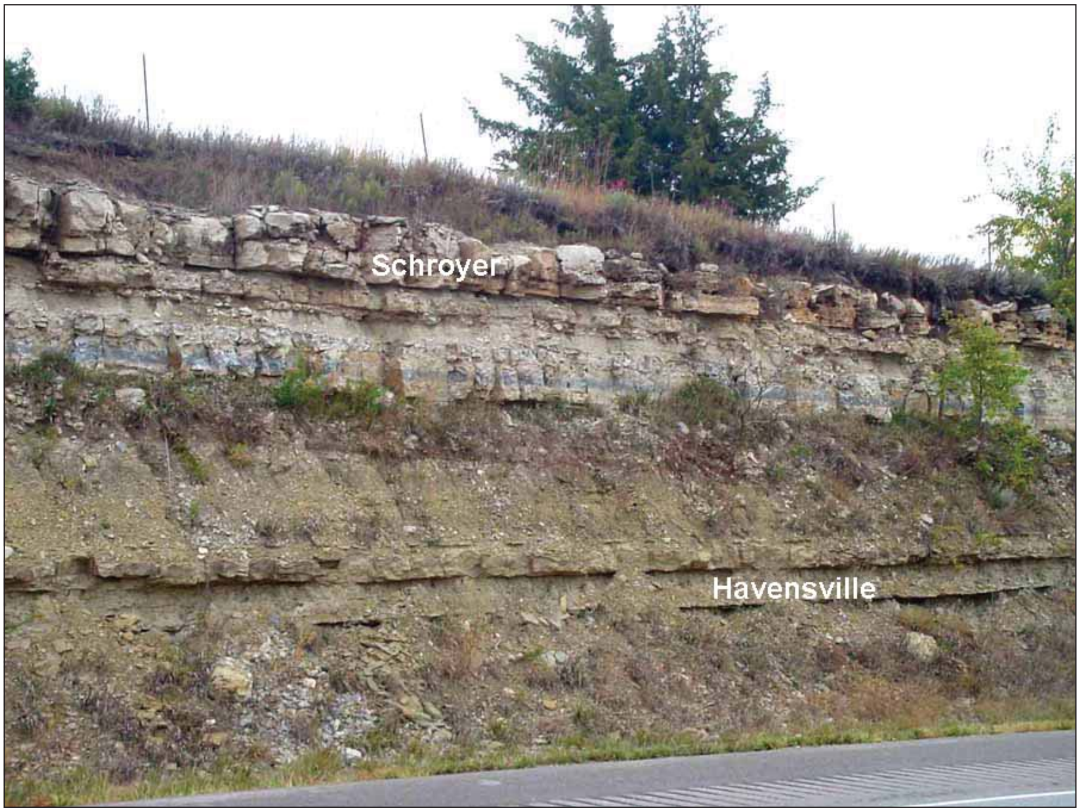


FIGURE 30—Exposure of the Schroyer Limestone Member and Havensville Shale Member of the Wreford Limestone along the east side of Scenic Drive in Manhattan, Kansas; near center of south line SE SE sec. 16, T. 10 S., R. 7 E., Riley County, Kansas.

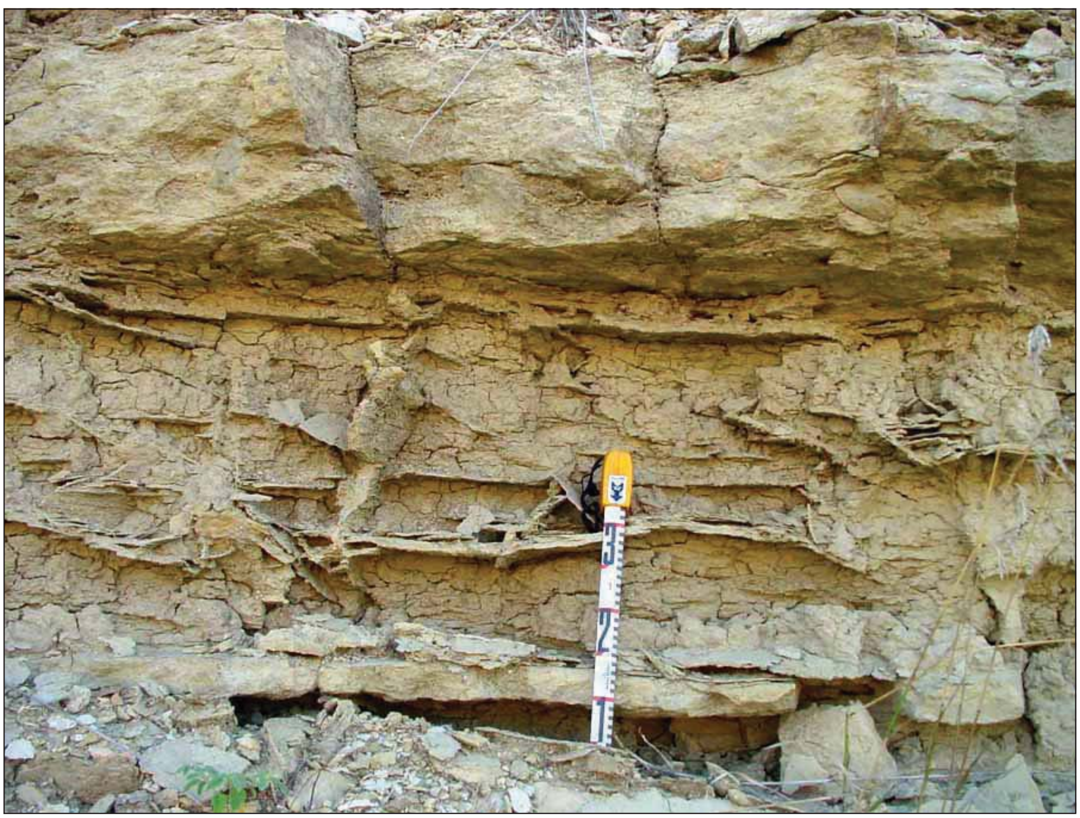


FIGURE 31—Boxwork in the Havensville Shale Member of the Wreford Limestone in a roadcut exposure along the east side of Scenic Drive in Manhattan, Kansas; near center of south line SE SE sec. 16, T. 10 S., R. 7 E., Riley County, Kansas.

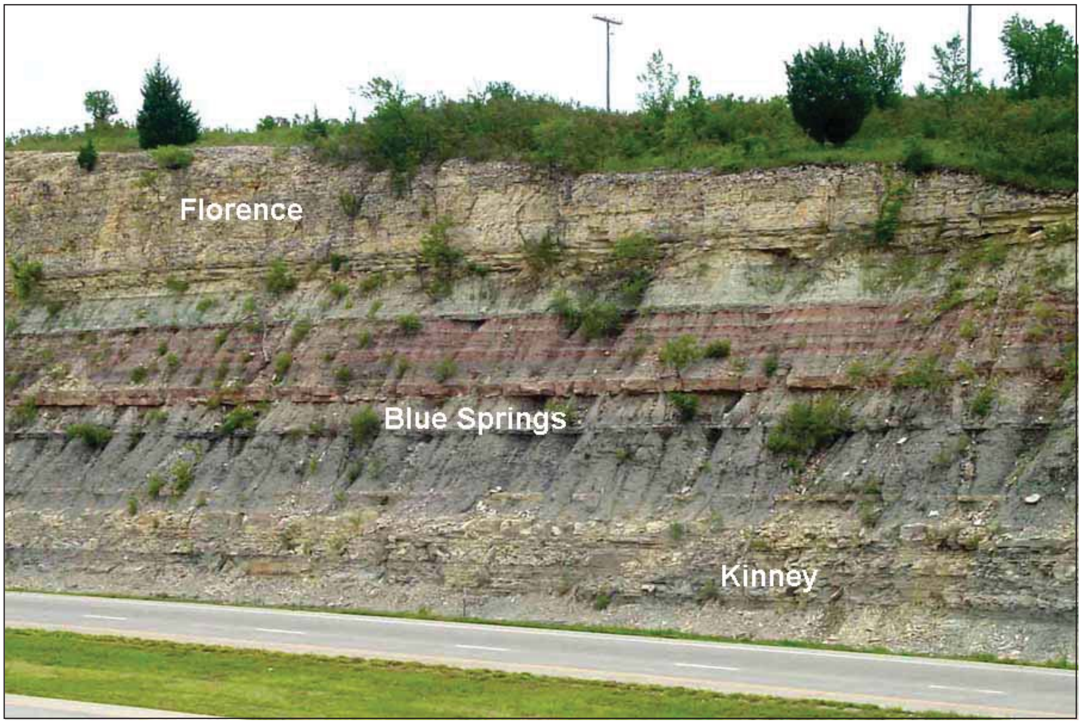


FIGURE 32—Exposure of the upper Matfield Shale (Kinney and Blue Springs) and lower Barneston Limestone (Florence) along the south side of I–70 just east of exit 299; near NW corner, sec. 8, T. 12 S., R. 6 E., Geary County, Kansas.

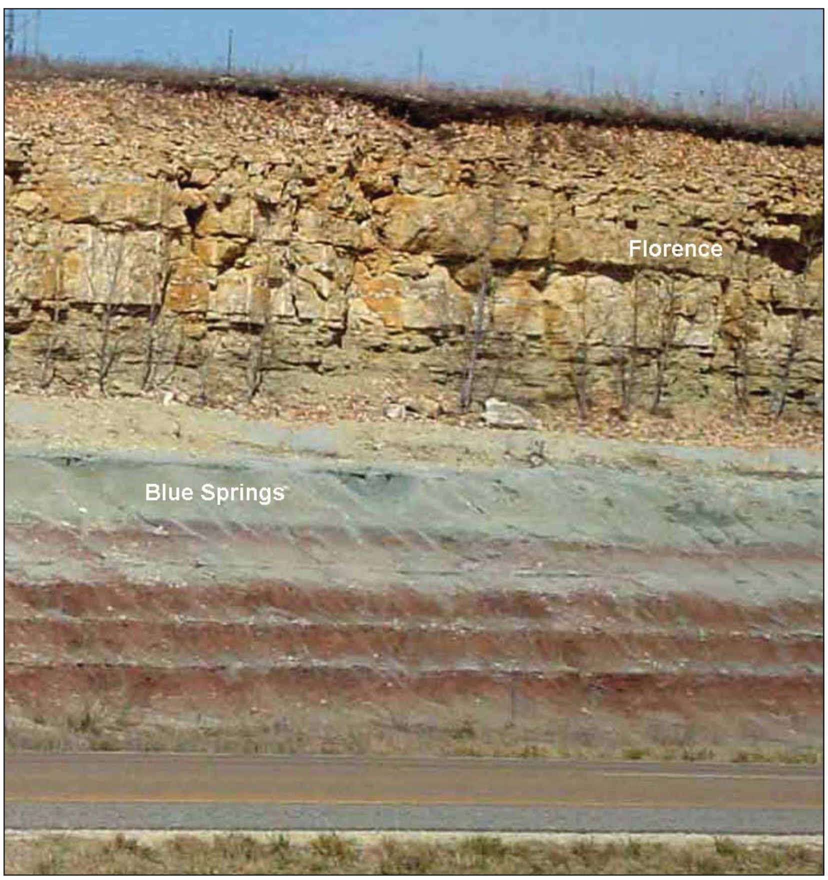


FIGURE 33—Variegated mudrock in Blue Springs Shale Member of Matfield Shale with the Florence Limestone Member of the Barneston Limestone above; along the west side of K–177 at the Riley–Geary County line; near NE corner, sec. 29, T. 11 S., R. 8 E., Geary County, Kansas.

and much less fossiliferous than the Florence. It thins to the south and is not recognized south of Chase County (Mazzullo, 1998). The Fort Riley begins with a massive ledge-forming unit ("rimrock") near its base that has a diverse brachiopod, echinoderm, and bryozoan assemblage and is often bioturbated (burrows and borings; figs 35, 36). To the south this interval becomes oncolitic with algal-coated grains (osagite). The presence of this algal facies marks the base of the Fort Riley equivalent in outcrop and core (Toomey, 1992; Mazzullo, 1998). Above this massive unit, the Fort Riley becomes thin bedded and dominated by an assemblage of pectinids, myalinids, and *Permorphorus*. The upper Fort Riley becomes increasingly dolomitic upward with voids from dissolved evaporite nodules, algal laminations, and desiccation polygons (Miller and Twiss, 1994). In the subsurface of Riley County, the uppermost Fort Riley contains several thin gypsum beds (Twiss, 1991a).

Doyle Shale—Three members are differentiated in the Doyle Shale (figs. 37, 38). These are, in ascending order, the Holmesville shale, Towanda limestone, and Gage shale. The Holmesville is a variegated mudrock 2.1 to 10.1 m (7–33 ft) thick. A very well developed boxwork (see fig. 39) capped by teepee structures occurs in the lower part of this unit in Geary County and is overlain by a red silty paleosol (Miller and Twiss, 1994). A dark-colored mudrock occurs in the upper Holmesville in the central and southern parts of the outcrop belt (Mazzullo, 1998). The Towanda is generally a slabby to platy, yellowish-gray limestone 2 to 4.9 m (6.5–16 ft) thick. It consists of carbonate mudrocks, brecciated carbonate mudrocks, and foraminiferal wackestones and packstones. The former presence of evaporites is indicated by molds of evaporite nodules (Mazzullo, 1998). The Gage consists of variegated mudrocks and siltstones 5.8 to 10.1 m (19–33 ft) thick. A variegated appearance is reflected by the stacked sequence of red and green silty paleosols and rooted siltstones in the Gage. Frequent laminae of calcite and laminar pores suggest dissolution and replacement of former evaporite layers (fig. 40). The upper Gage is a gray, calcareous mudrock with a moderately diverse assemblage of articulate and inarticulate brachiopods, and pectinid and myalinid bivalves. In Dickinson County, the base of the Gage is coarsely brecciated and normal faults cut through the entire interval (Miller and McCahon, 1999).

Winfield Limestone—The 7–13.7-m (23–45-ft)-thick Winfield Limestone is divided into three members, in ascending order, the Stovall limestone, Grant shale, and Cresswell limestone (fig. 41). The Stovall is a very thin limestone nearly everywhere less than 0.9 m (3 ft) thick, typically 0.3–0.5 m (1–1.5) ft thick. Over much of the outcrop belt, it contains abundant chert and a fossil assemblage of brachiopods, bryozoans, and crinoid ossicles. In southern Kansas it becomes a thin shaly calcareous mudrock with bivalves and occasionally oncolites (Mazzullo et al., 1995, 1997; Mazzullo, 1998). Brachiopods, bivalves, bryozoans, and crinoids characterize the 2 to 4-m (6.5–13-ft)-thick gray to yellowish-gray Grant shale. In southern Kansas the Grant is a shaly wackestone to packstone with abundant oncolites (Mazzullo et al., 1995, 1997). The Cresswell is a massive limestone with abundant large concretions and scattered chert nodules (fig. 42). Thin-bedded and shaly limestone beds, previously referred to as the "Luta limestone" (Zeller, 1968, p. 49), occur above this massive limestone. The combined interval ranges in thickness from 3 to 11 m (10–36 ft), with a dramatic thickening in Marion County (Mazzullo, 1998). The lower Cresswell is quite fossiliferous with echinoid spines, bryozoans, and brachiopods being common. To the south, this interval becomes an oncolite grainstone with infaunal bivalves. The upper Cresswell consists of carbonate mudrock with cryptalgal laminations, silicified evaporite nodules, evaporite molds, and desiccation polygons (Mazzullo, 1998).

Odell Shale—Overlying the Winfield is the Odell Shale, another variegated mudrock unit that ranges from 6.1 to 12.2 m (20–40 ft) thick. Calcareous shales at the top and bottom

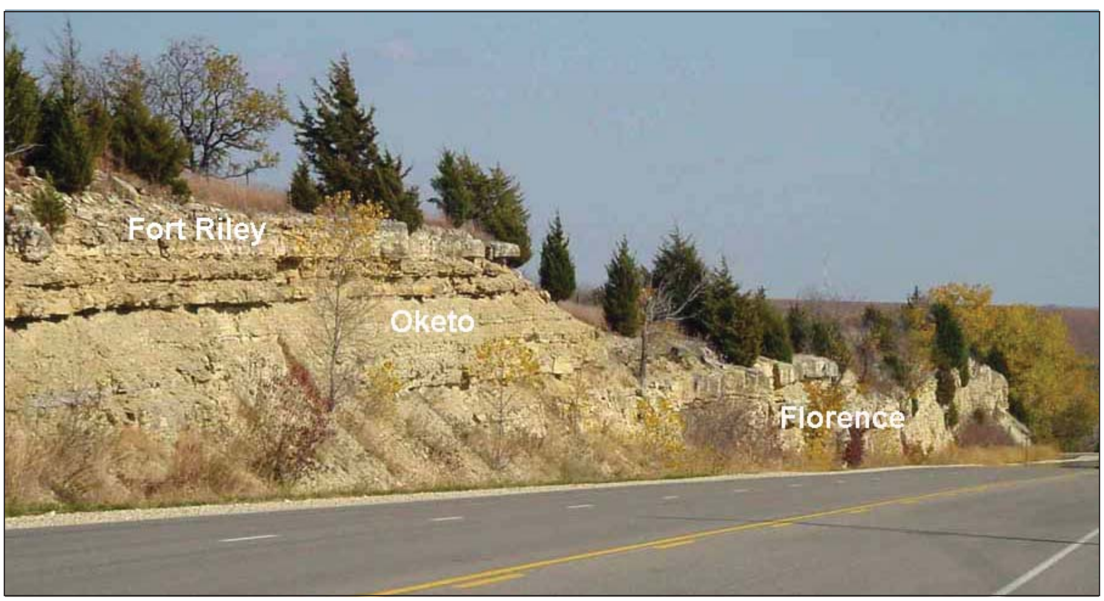


FIGURE 34—Exposure of the Barneston Limestone along north side of US–24 and K–177; near center of S/2 sec. 22, T. 9 S., R. 7 E., Riley County, Kansas.

FIGURE 35—Fort Riley limestone “rimrock” along the east side of Lyons Creek Road; near the east side of NW sec. 20, T. 13 S., R. 5 E., Geary County, Kansas.

FIGURE 36—Exposure of the Fort Riley limestone along north side of US–24 and K–177; near center of S/2 sec. 22, T. 9 S., R. 7 E., Riley County, Kansas.

FIGURE 37—Exposure of the Doyle Shale [upper Holmesville Shale Member (mostly covered by limestone rubble from Towanda) and Towanda Limestone Member] approximately 1.1 mi (1.8 km) north of the junction of K–24 with US–77 and K–177 along the west side of US–77; near center of east line of NE sec. 33, T. 8 S., R. 6 E., Riley County, Kansas.

FIGURE 38—Doyle Shale (Gage Shale Member) approximately 8.7 mi (13.9 km) north of junction of K–24 with US–77 and K–177 along the east side of US–77; near center of north line of sec. 28, T. 7 S., R. 6 E., Riley County, Kansas.

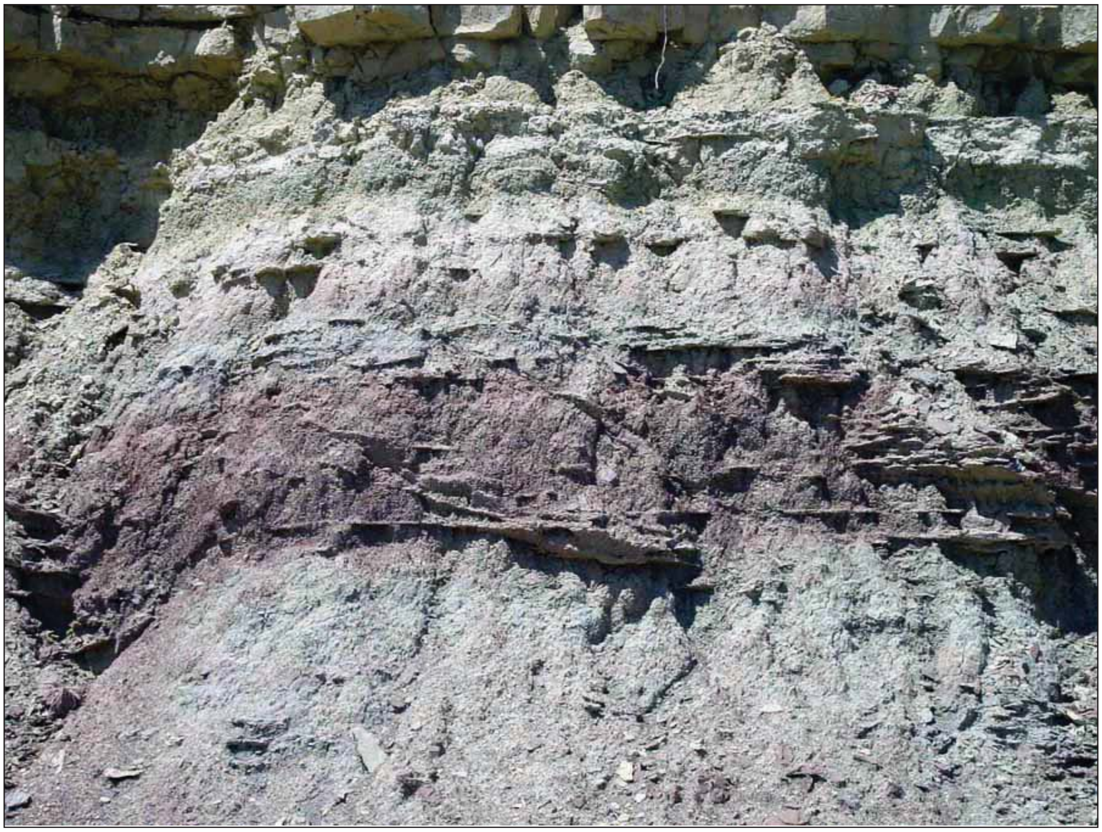


FIGURE 39—Boxwork in the Gage Shale Member (Doyle Shale) on the north side of the roadcut along old US–40 just west of Chapman, Kansas; near center of south line of N/2 NW sec. 31, T. 12 S, R. 4 E., Dickinson County, Kansas.

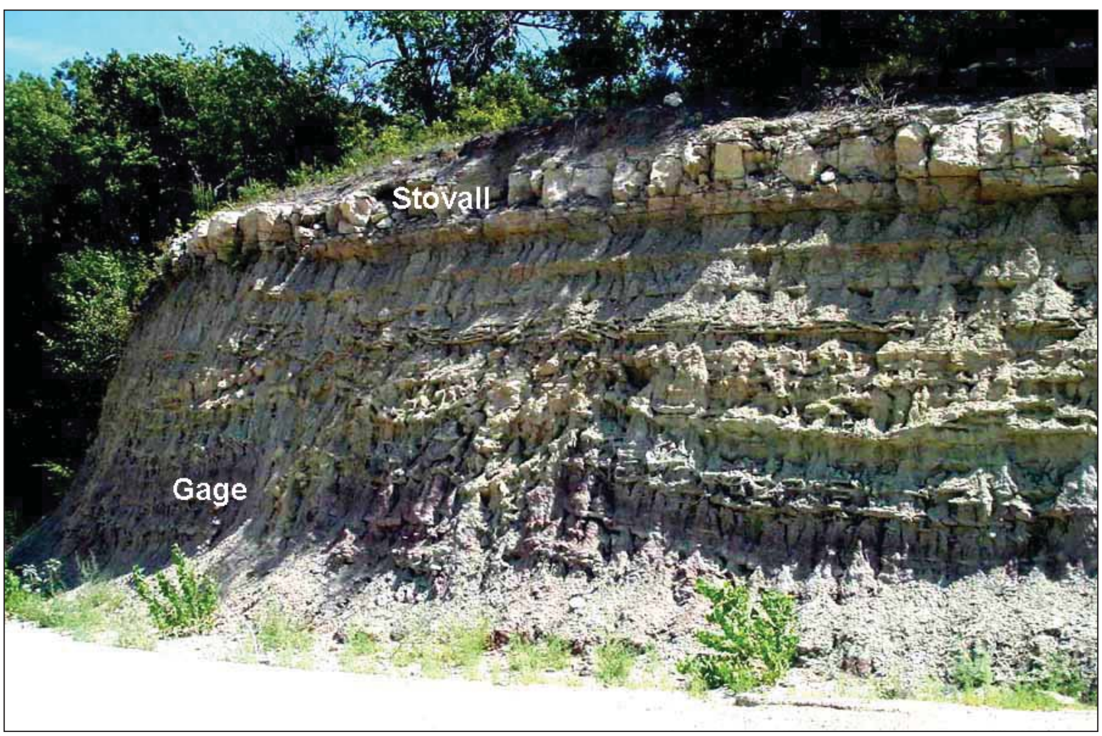


FIGURE 40—Exposure of the Doyle Shale (Gage Shale Member) and Winfield Limestone (Stovall Limestone Member) in a roadcut on the east side of Trail Road; north of center of west line sec. 3, T. 15 S., R. 4 E., Dickinson County, Kansas.

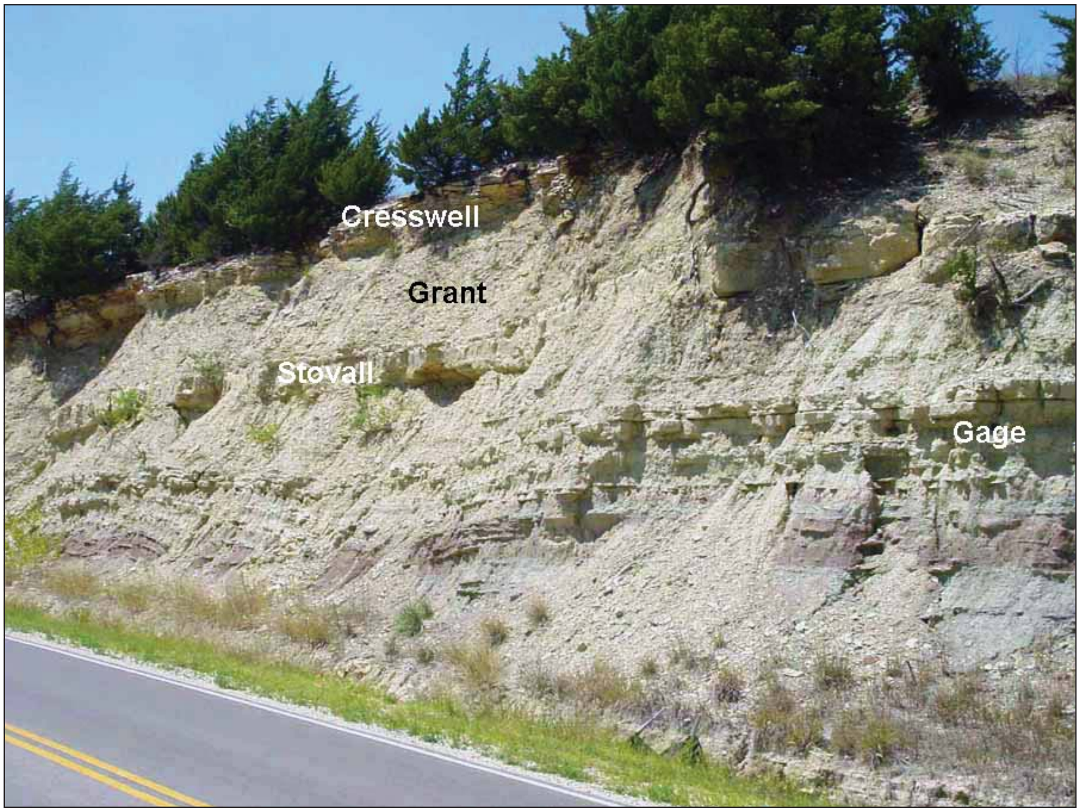


FIGURE 41—Exposure of Doyle Shale (Gage Shale Member) and Winfield Limestone (Stovall, Grant, and Cresswell) in a roadcut on the north side of old US–40 just west of Chapman, Kansas; near center of south line of N/2 NW sec. 31, T. 12 S, R. 4 E., Dickinson County, Kansas.

are transitional with the over- and underlying carbonates (figs. 43, 44). The base of the Odell Shale has been suggested as the possible base of the Kungurian Stage/Age (Menning et al., 2006), but they noted that this position is questionable (Sawin et al., 2008). The Kungurian Stage/Age is not represented by good marine fossils in Kansas (Wardlaw, 2004).

Nolans Limestone—The uppermost formation of the Chase Group in Kansas, the Nolans Limestone, is 7 to 11 m (23–36 ft) thick, and consists of, from bottom to top, the Krider limestone, Paddock shale, and Herington limestone (fig. 45, 46). The Krider is 0.7 to 2.8 m (2.4–9.3 ft) of porous dolomites and mudrocks to the north and relatively fossiliferous limestones and mudrocks to the south (Mazzullo et al., 1995, 1997) with the maximum thickness in southernmost Cowley County (Mazzullo et al., 1997, p. 104). It contains bivalves, pyramidellid gastropods, brachiopods, bryozoans, and crinoids. An olive to yellowish-gray poorly fossiliferous mudrock, 3 to 4.9 m (10–16 ft) thick, is defined as the Paddock. In the south it is composed of yellowish-gray calcareous mudrocks with bivalves and brachiopods. Within the mudrock are cryptalgal laminations, calcite-replaced evaporite nodules, and laminae of "palisade calcite crystals" (Mazzullo et al., 1995, 1997). The upper surface of the Herington, the uppermost carbonate of the Wolfcampian, marks the top of the Chase Group. It is a 2 to 4.9-m (6.5–16-ft)-thick interval of calcitic dolomites and laminated dolomites (fig. 47). Calcite and silica-replaced evaporite nodules (geodes) are typically abundant. At the base, where it is fossiliferous, it contains an assemblage of pectinids, myalinids, and gastropods.

Upper Boundary of the Wolfcampian

The Chase Group was defined by Prosser (1895, 1902) on the basis of chert content, and included the prominent chert-bearing carbonate units of the "Wreford Limestone, Florence Flint, Fort Riley Limestone, and Winfield Limestone." As noted by Condra and Upp (1931), although the formations included were readily identifiable, the definition of the group was not well founded. They stated (p. 30), "... it should not be overlooked that chert occurs, but in less abundance, in all the limestone members of the so-called Council Grove group and that it is found as high as the Herington limestone in the vicinity of Arkansas City, Kansas." The Chase Group was, in fact, later extended into what was then the overlying Sumner Group to incorporate units up to and including the Herington Limestone (Moore, Frye, et al., 1951).

Lithofacies and Thickness of the Wolfcampian

General thickness and lithologic trends of the Wolfcampian in Kansas are well summarized by Mudge (1967) with the greatest thickness in the south-central part of the state, the Kansas Permian basin (fig. 48), thinning toward the Nemaha anticline and the outcrop belt to the east, and to the northwest where its thickness is reduced by about half (Mudge, 1967).

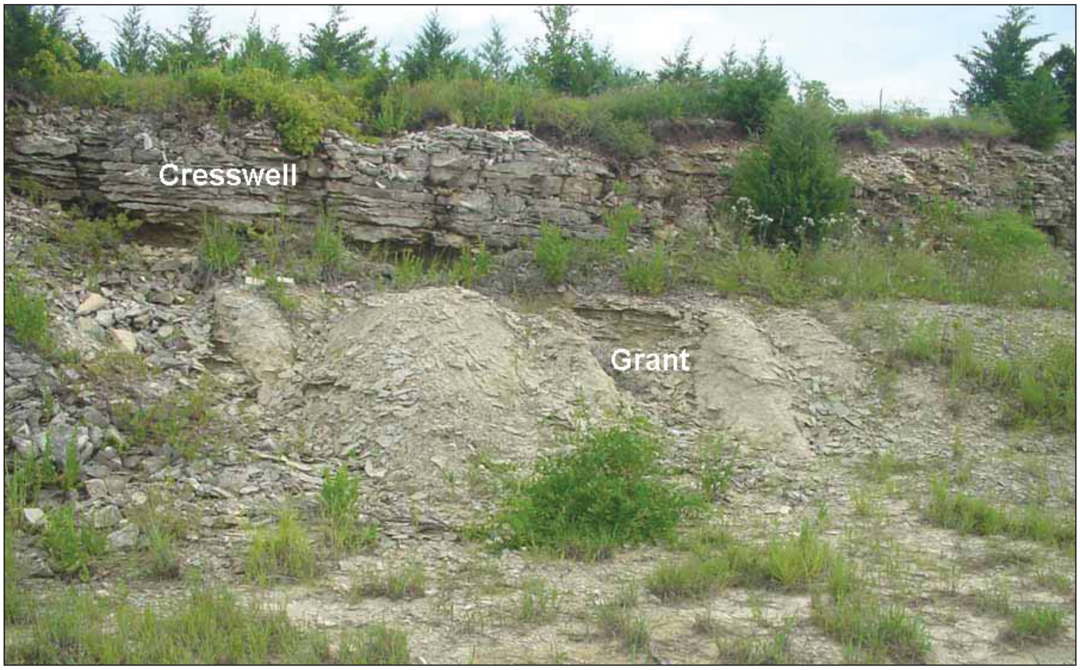


FIGURE 42—Exposure of the Winfield Limestone (Grant Shale Member and Cresswell Limestone Member) in a roadcut along the south side of I–70 on the west side of Exit 286 at Chapman, Kansas; south and east of center of S/2 sec. 19, T. 12 S., R. 4 E., Dickinson County, Kansas.

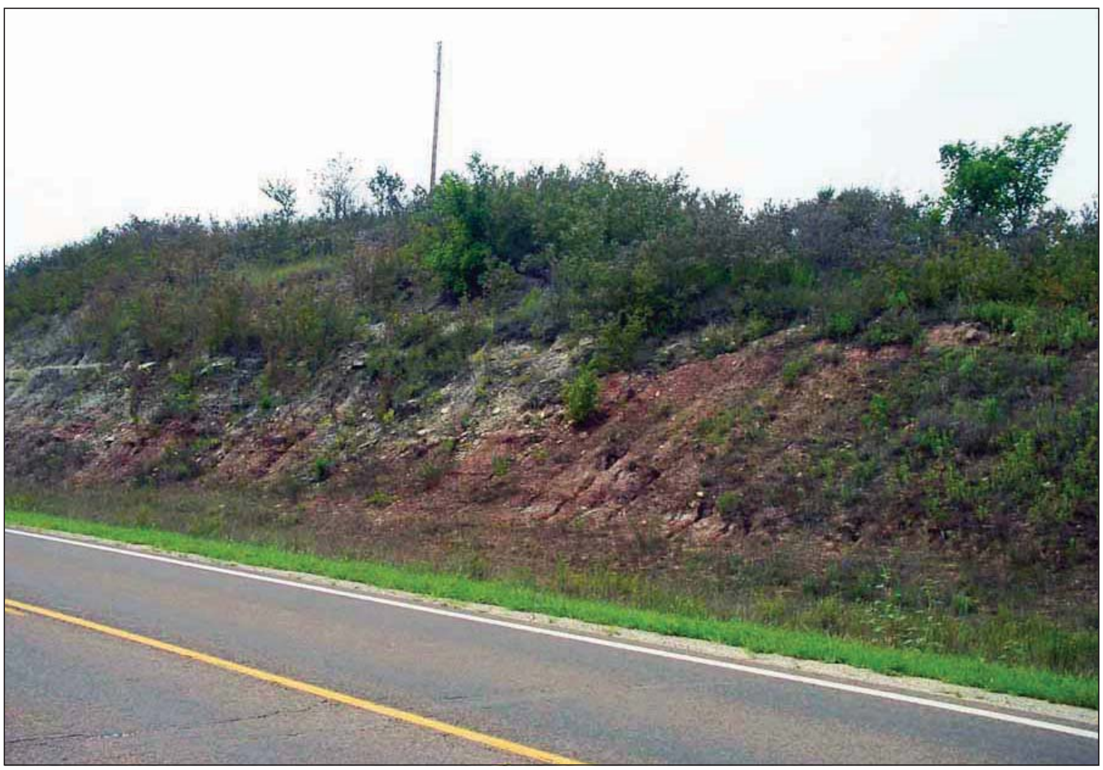


FIGURE 43—Exposure of the Odell Shale in a roadcut approximately 1.5 mi (2.4 km) north of the junction of US–36 and K–148 on the west side of K–148; near center of east line, sec. 21, T. 2 S., R. 5 E., Washington County, Kansas.

McKee and Oriel (1967, p. 7) referred to this area as the Kansas depositional basin that is defined by the Nemaha anticline on the east and by the Las Animas arch on the west (see fig. 49). The structural Anadarko basin lies to the south, but was separated from the deep basins of west Texas by the Amarillo–Wichita and Arbuckle belt of uplifts. Because there was no

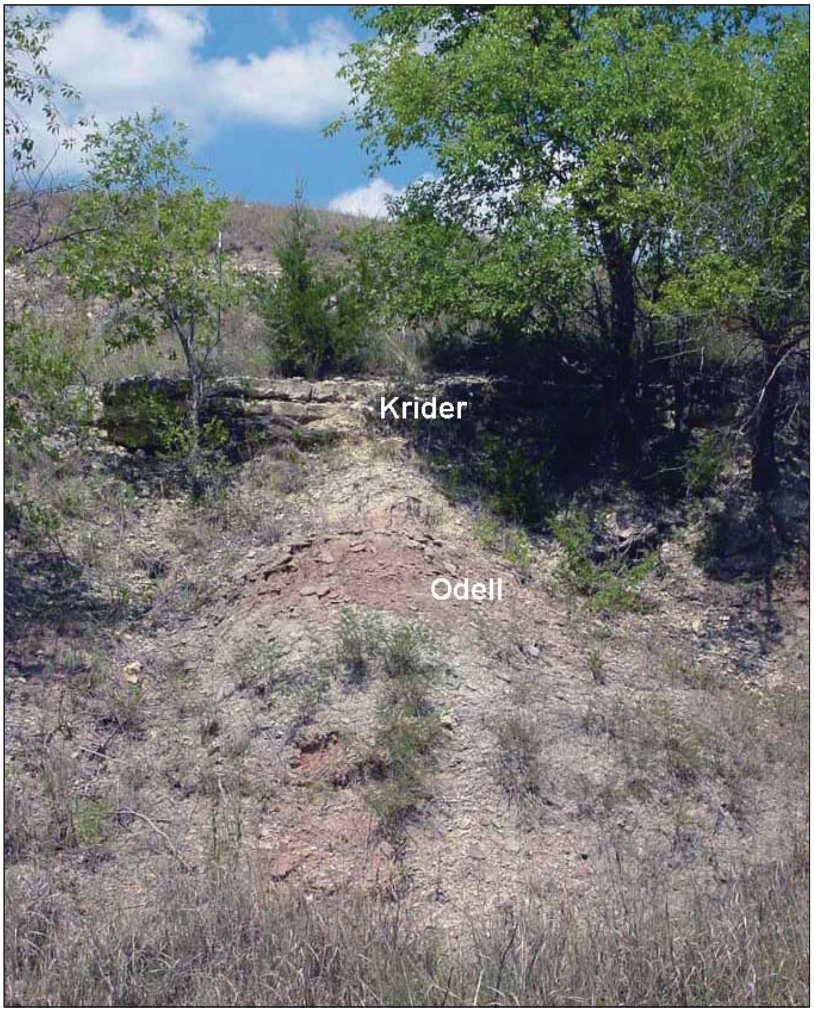


FIGURE 44—Exposure of the Odell Shale and Nolans Limestone (Krider Limestone Member) in a roadcut on the north side of the road; near the center of north line NW sec. 20, T. 12 S., R. 4 E., Dickinson County, Kansas.

true shelf edge, the Kansas depositional basin is best described as a ramp. In northeastern Kansas, lower Permian rocks are exposed east of the Nemaha anticline (fig. 48) as an outlier due to post-Permian erosion. To the southeast, the Cherokee basin lies east of the Nemaha and south of the southeast-trending Bourbon arch. The influence of the Bourbon arch is seen in local thickness and facies changes. The presence of the Central Kansas uplift is indicated by a gradual thinning of rocks of this interval in central and northern Kansas. To the west, Wolfcampian rocks thin over the Las Animas arch that extends from southeastern Colorado toward southwestern Nebraska and separates the Hugoton embayment of the Anadarko basin from the Denver basin. Mudge (1967) described several general lithologic trends across what he referred to as the Kansas basin, or Kansas depositional basin. The carbonate percentage increases toward the basin center in south-central Kansas, western Oklahoma, and the Texas Panhandle. The abundance of chert also increases in these carbonates toward the basin center. Mudge (1967, p. 103) stated "In the central parts of the basin, chert is common to abundant in many limestone beds. Toward the northeast margin of the basin, it occurs only in some beds, the Beattie, Wreford, and Barneston Limestones. At the edge of the platform, in western Kansas, chert is sparse, and on the platform it is absent." Another trend within the carbonate units is a decrease in the dolomite-to-limestone ratio toward the basin center. Moving from the more marginal depositional settings of the west and northwest toward the southeast, the earliest occurrence of dolomite beds moves progressively upsection. In northwestern Nebraska and north-central Colorado, the equivalents of the Council Grove and Chase Groups are dominantly dolomite and anhydrite. Along with an increase in dolomite toward the basin margins to the west and northwest is an increase in the proportion of red clastics. Extensive core data from the Hugoton embayment in the southwest reveals other broad lithofacies trends. The marine units of the Hugoton not only include limestones and dolomites, which may be sandy or argillaceous, but also marine siltstones and sandstones. Within the carbonates, anhydrite is locally common and chert is largely absent. These marine units alternate with red siltstones and fine sandstones (Caldwell, 1991; Olson et al., 1997). This increased clastic content reflects the paleogeographic position of the Hugoton on the northwestern margin of

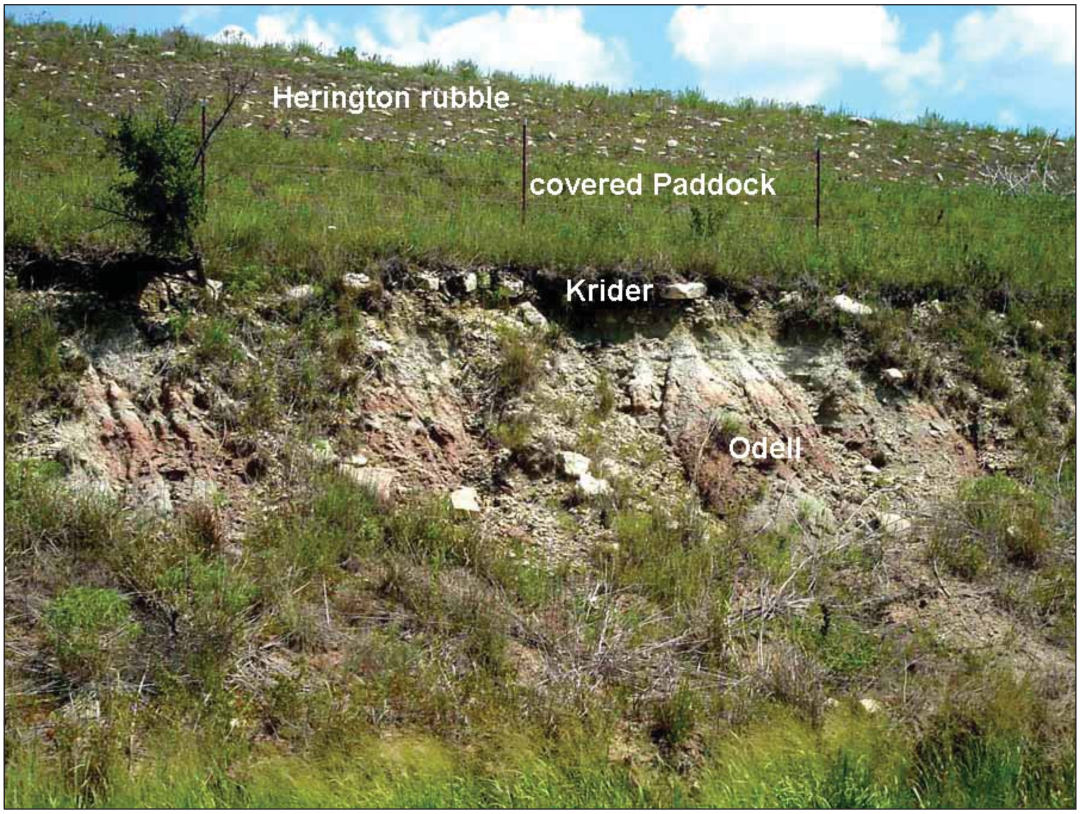


FIGURE 45—Exposure of the Odell Shale and Nolans Limestone (Krider Limestone Member, grass-covered Paddock Shale Member, and rubble of the Herington Limestone Member) in a roadcut on the east side of Rain Road; near center of west line, sec. 17, T. 12 S., R. 4 E., Dickinson County, Kansas.

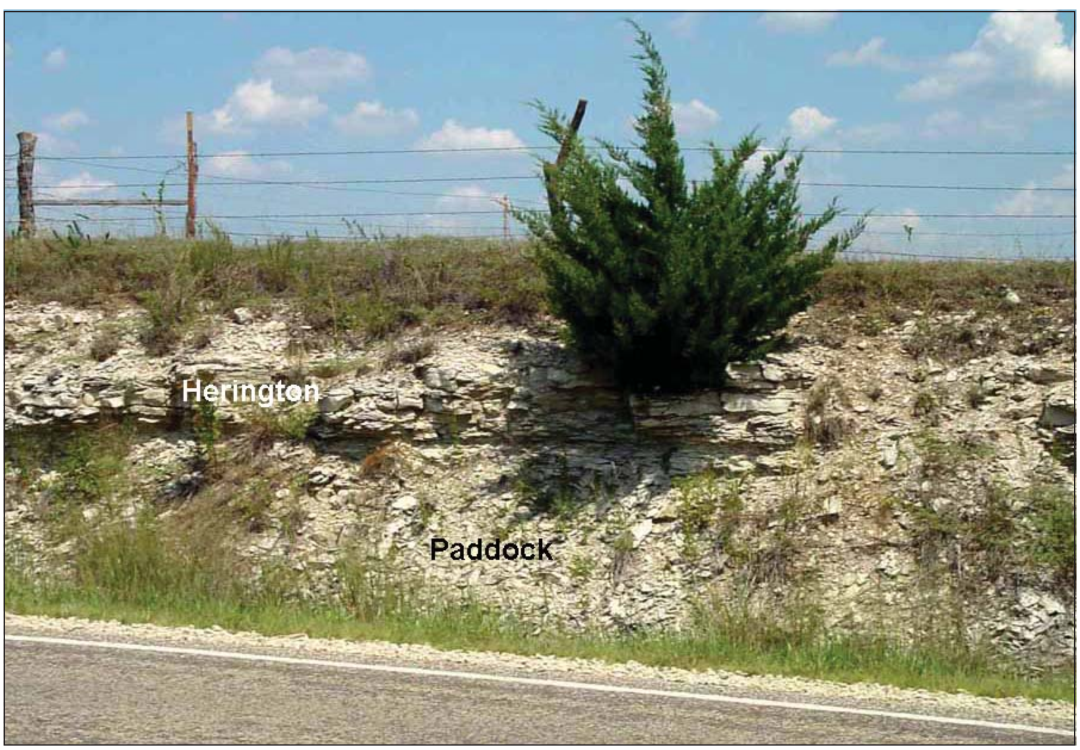


FIGURE 46—Exposure of the Nolans Limestone (Paddock Shale Member and Herington Limestone Member) on the east side of Rain Road; along the west line, sec. 17, T. 12 S., R. 4 E., Dickinson County, Kansas.

FIGURE 47—Exposure of the Nolans Limestone (Herington Limestone Member) in a roadcut on the west side of US–77; SW sec. 24, T. 16 S., R. 4 E., Dickinson County, Kansas.

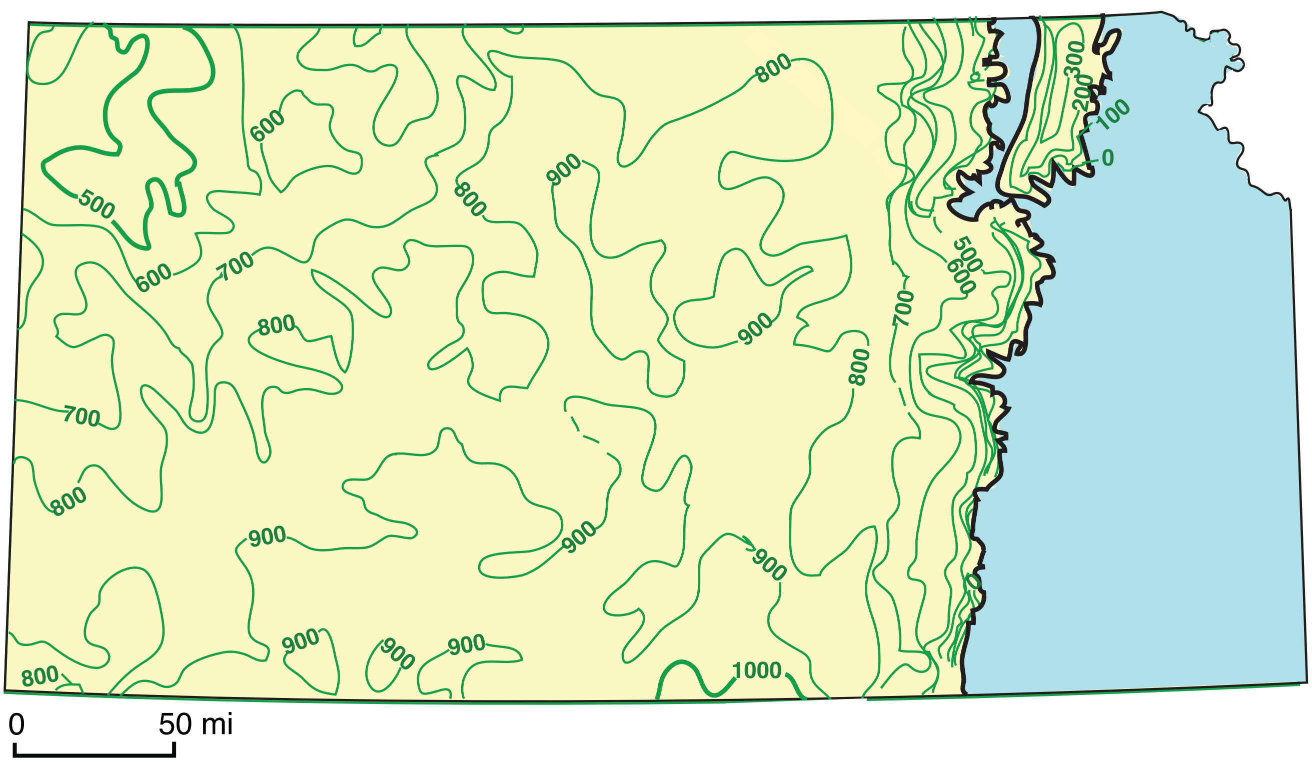


FIGURE 48—Isopach map of Wolfcampian rocks in Kansas; isopach interval = 100 ft; rocks older than Permian exposed in blue area (modified from Mudge, 1967, p. 102, fig. 34).

the Anadarko basin on a shallow eastward-dipping ramp where siliciclastics were being shed into the basin from the Ancestral Rockies and Sierra Grande uplifts to the west (Rascoe, 1988). Several lithologic trends can be observed from north to south along the eastern outcrop belt. Substantial lithologic changes are largely confined to southern Kansas and northeastern Oklahoma. Dramatic changes occur within the Council Grove and Chase Groups in Kay County, Oklahoma, just south of the Kansas border (Chaplin, 1988). Although the aggregate thickness of the interval remains relatively constant, the general pattern is one of thinning and loss of carbonate units and the thickening and coarsening of siliciclastic units. As in the Hugoton on the western basin margin, there is a loss of chert and an increase in the silt and sand content of the carbonates. Several of the thinner, shallower-water limestone units, particularly those of the upper Council Grove Group, are lost or locally cut out to the south. Referring to the Council Grove Group, Chaplin (1988, p. 92) stated that these units are "the most variable in lithology, thickness, and lateral extent of the entire Lower (sic) Permian section, not only in Oklahoma but also in Kansas and Nebraska." For this reason Chaplin (1988, p. 92) provisionally reintroduced the Garrison Formation of Prosser (1902) for the interval from the top of the Cottonwood limestone to the base of the Threemile limestone. This leaves the Cottonwood limestone as the only member of the Beattie Limestone (Chaplin, 1988, p. 95, fig. 10). In neither text nor figures does Chaplin indicate that he would now consider the Cottonwood as a formation and the Florena, Morrill, Stearns, Eiss, Hooser, Middleburg, Easly Creek, Crouse, Blue Rapids, Funston, and Speiser as members of the Garrison Formation. Another trend is the loss of the tripartite subdivision of the limestone formations typical from Nebraska to central Kansas. The central shaly intervals either pinch out or pass laterally into carbonates to the south. The member subdivisions of most limestone formations (e.g., Red Eagle, Beattie, Wreford, Barneston, Winfield, Nolans) are thus difficult, if not impossible, to recognize (McCrone, 1963; Chaplin, 1988; Mazzullo et al., 1995, 1997; Mazzullo, 1998).

Several important temporal lithofacies trends occur within the latest Carboniferous and earliest Permian sequence, which reflect changes in clastic source areas, as well as changes in sea level and climate. An important study in this regard is that of Olszewski and Patzkowsky (2003). In contrast with the Virgilian, the lower Wolfcampian (Council Grove Group) has little coarse clastic input and virtually no alluvial or channel sandstones (Mudge, 1967). Coarse clastics from the south appear to have been trapped in the subsiding Anadarko basin, and the only sandstones occur near source areas to the southwest. By the upper Wolfcampian (Chase Group), the major source areas lay to the west (Mudge, 1967). This input was from the positive elements of the Ancestral Rockies, including the Sangre de Cristo, Ancestral Front Range, and Wet Mountains uplifts. According to Rascoe (1988), the Amarillo and Wichita uplifts were partially buried by Wolfcampian arkosic sediments and covered by carbonates stratigraphically equivalent to the Chase Group, suggesting diminished tectonism and basin filling. In turn, these processes probably contributed to the rather abrupt onset of evaporites in the Wellington Formation because marine circulation in the Kansas depositional basin was restricted.

In addition to the evidence of changing patterns of clastic influx, several lithologic trends suggest a long-term shallowing trend from the upper Carboniferous (Pennsylvanian) through the Permian (West et al., 1997) and the occurrence of angular unconformities (Olszewski and Patzkowsky, 2003). Conodont-rich phosphatic black shales, interpreted as representing relatively deep anoxic waters (Heckel and Baesemann, 1975; Heckel, 1977), are rare by the early Wolfcampian and absent thereafter. Marine limestones and fossiliferous mudrocks are prominent through the Wolfcampian but decline rapidly in the Leonardian, and variegated mudrocks with well-developed paleosols increase, as do evaporites, ranging from marine deposits (bedded halite with elevated bromine in the early Leonardian Wellington Formation) to nonmarine (chaotic red-bed halite in the Leonardian Blaine Formation) (Holdaway, 1978; Watney et al., 1988). Although progressive shallowing as seen in the midcontinent is also apparent on a global scale, it was not a smooth, continuous trend, with some reversals as noted by Olszewski and Patzkowsky (2001, 2003). The increasing emergence of continents through the Carboniferous and Permian is reflected in the global sea-level curves of Vail et al. (1977) and in the estimates of continental area-elevation distributions of Algeo and Wilkinson (1991). The global shallowing trend of the late Paleozoic may be a consequence of changes in elevation of the continent due to thermal uplift and changes in the volume of the mid-ocean ridges. According to Veevers (1994), assembly of the Pangean supercontinent trapped mantle heat beneath the thickened continental crust. The resulting thermal uplift of Pangea is estimated by Veevers to have reached a maximum in the early Permian. Also, Fischer (1984) argued that by the early Permian the mid-ocean ridge within the single Panthalassan ocean was both slow-spreading and greatly reduced in length, and would have displaced less water, thus lowering global sea level.

In addition to the regional thickness and lithofacies trends within the Kansas depositional basin as defined by Mudge (1967), there are significant local lateral facies changes. Many of these facies changes appear to be spatially related to basement structural controls (fig. 49). In several cases, thickened carbonate deposits are developed on or near known structural highs (Mudge, 1967; Burchett et al., 1985). The Bennett shale changes facies and thickens into a brachiopod, bryozoan, and crinoid limestone up to 9.1 m (30 ft) thick just north of the southeast-trending Bourbon arch in east-central Kansas (McCrone, 1963). Higher in the section, the Funston Limestone thickens to over 7.9 m (26 ft) of algae-bound oolite over the faulted eastern flank of the Nemaha anticline just to the west (Mudge and Burton, 1959). Similarly, the Threemile limestone thickens to 7.6 m (25 ft) of chalky limestone with bryozoans, brachiopods, and crinoids over the Nemaha anticline from southern Wabaunsee to southern Chase counties (Hattin, 1957). A bedded packstone, 3 m (10 ft) thick, containing a diverse brachiopod and molluscan assemblage and wood and fossil leaves, is developed within the overlying Havensville shale on the crest of the Nemaha anticline farther to the north (Miller et al., 1992; Mazzullo, 1998). The internal inclined truncation surfaces suggest that it may represent a shallow nearshore bank of transported bioclastic debris. Several stratigraphic intervals are observed to thin where they cross structural highs. McCrone (1963) described the absence of the Glenrock limestone and the truncation of the underlying Johnson Shale over the Nemaha anticline in southeastern Riley and northern Wabaunsee counties, with conglomeratic facies developed on the flanks of the high. The Beattie Limestone shows an overall thinning and a marked facies transition in southeastern Chase and western Greenwood counties. Laporte (1962) and Imbrie et al. (1964) attribute these trends to a topographic high they named the "Greenwood Shoal" that may be equivalent to the Otto–Beaumont anticline, which parallels the Nemaha to the east (McCrone, 1963). Higher in the Council Grove section, the Crouse Limestone thins toward the faulted eastern side of the Nemaha with the loss of the middle shaly interval (West, 1972; West and Twiss, 1988). Another interesting trend is developed within the paleosol-dominated Speiser Shale in northern Geary and southern Riley counties. Associated with an overall thinning of the Speiser Shale onto the Nemaha anticline is a transition from a series of stacked paleosol profiles to a single well-developed profile (Miller and West, 1998). This pattern suggests a more stable, continuously exposed, soil-forming environment on the crest of the anticline. Not all variegated mudrock units show this pattern, and indeed the stratigraphically older Blue Rapids Shale shows no thinning. This may suggest episodic tectonic activity along the Nemaha during Council Grove time.

Structural control of facies in the Chase Group is not seen as clearly as in the Council Grove Group. This may be due, in part, to the more western position of most of the outcrop belt farther from the crest of the Nemaha anticline. However, thickening and thinning trends are observed (Mazzullo, 1998) and are probably related to the structure of the underlying basement rocks (fig. 49). The upper Kinney limestone thickens in Chase County, suggesting more accommodation space where it overlies a graben in the Nemaha anticline. The peritidal facies of the upper Cresswell limestone similarly thickens in Marion County on the western side of the Nemaha at the margin of the Sedgwick basin. Within both the Fort Riley and Towanda limestones, the development of peritidal facies and crossbedded sandstones seems to be controlled by proximity to the Nemaha anticline (Mazzullo, 1998). Basement reactivation seems to have affected thickness and lithofacies of the lower Leonardian Wellington Formation along km-scale, deep-seated structural lineaments (Watney et al., 2003).

Depositional Environments and Source Areas of the Wolfcampian

The Permian rocks of Kansas record sedimentation in a shallow shelf/ramp setting far from the shelf edge and equally far from potential clastic source areas (McKee and Oriel, 1967; Mudge, 1967; Heckel, 1980; Rascoe and Adler, 1983; Rascoe, 1988). The midcontinent epeiric sea was relatively restricted with limited connections to the open ocean to the southwest between the Amarillo–Wichita and Apishapa uplifts, and to the west through breaks in the Ancestral Rockies (McKee and Oriel, 1967). A paleogeographic reconstruction for Kansas during the Wolfcampian is shown in fig. 50. Figures 51 and 52 are global paleogeographic maps for the Permian with the position of Kansas marked with an **X**.

Assembly of the Pangean supercontinent was in its final stages during the Permian. Virgilian to Wolfcampian rocks

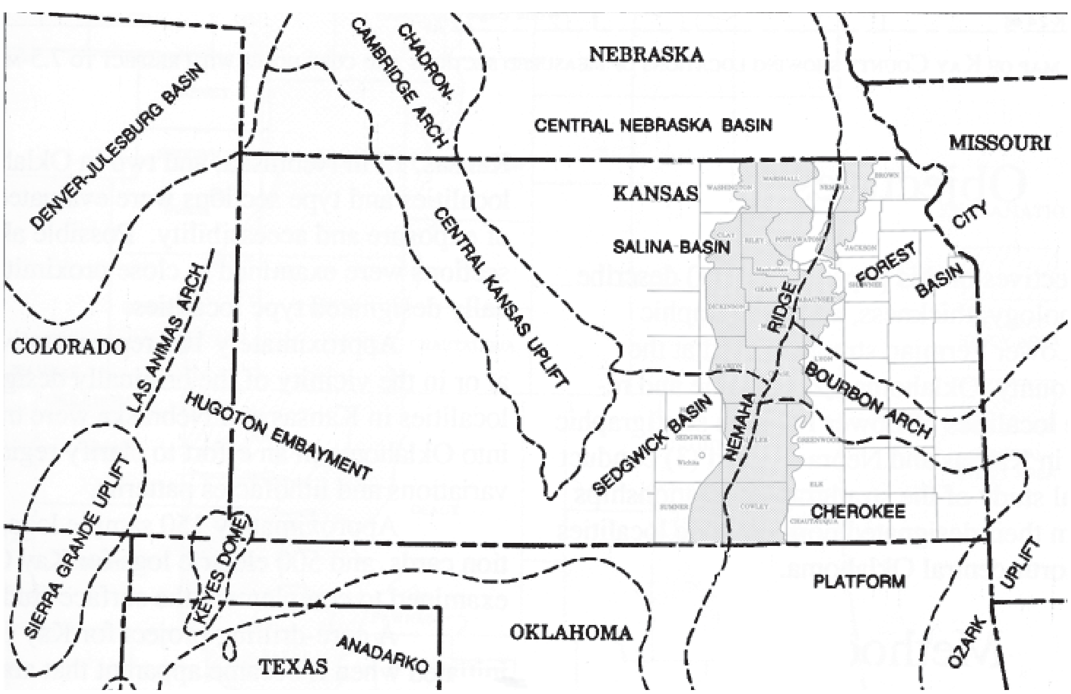


FIGURE 49—Tectonic features of Kansas and adjacent areas (modified from Chaplin, 1988, p. 82, fig. 3) overlain on the Permian outcrop in eastern Kansas (modified from Chaplin, 1988, p. 80, fig. 1).

record the final collision between Gondwana and Laurasia at the western end of the Ouachita–Marathon–Huastecan orogenic belt (Rowley et al., 1985), a tectonically active area and a southern source area for clastics. To the west, the positive elements of the Ancestral Front Range, Wet Mountains, and Sangre de Cristo uplift shed large volumes of clastic sediment to form the thick Fountain Formation in Colorado (Mudge, 1967; McKee and Oriel, 1967; Soreghan, 1994). Extensive eolian-sand seas developed from the Permian into the Triassic within the U.S. Western Interior (Peterson, 1988; Parrish and Peterson, 1988; Soreghan, 1992). The Apishapa–Sierra Grande uplift of southeastern Colorado was probably a stable low-lying area but was at times a source of arkosic sediment (Mudge, 1967). East of the midcontinent was a broad low-lying landmass extending to the now (Permian) eroding Appalachian orogen. As coarse clastics from the Appalachians accumulated in the small Permian basin of the Allegheny region to form the Dunkard Group, large volumes of sediment also were transported to the west and south, but little, if any, reached Kansas.

Moving gradually northward throughout the Permian, the midcontinent lay in generally tropical to subtropical latitudes. Paleogeographical reconstructions indicate paleolatitudes for Kansas ranging from the equatorial belt to approximately 15 degrees north (see Scotese and McKerrow, 1990, figs. 10–13). Based on paleogeographic reconstructions and lithologic and paleontologic data, Ziegler et al. (1998) have attempted reconstructions for the geographic distribution of water-mass characteristics for the Permian. They concluded there was a rapid transition in the early Permian from brackish conditions in the Permian basin of west Texas, to normal-marine salinities associated with the carbonate buildups of the Texas/New Mexico border region, to increasingly higher salinities toward the Denver and Williston basins to the north. Evaporitic conditions became more dominant later during the Permian in the region.

One of the persistent debates about the depositional environments of the midcontinent Permian concerns the bathymetric interpretation of the marine facies. In his description of lower Paleozoic cyclicity in Kansas, Elias (1937) arranged lithologies and fossil assemblages into an onshore-offshore gradient. Seven “phases” were recognized: 1) red shale phase, 2) green shale phase, 3) *Lingula* phase, 4) molluscan phase, 5) mixed phase, 6) brachiopod phase, and 7) fusulinid phase. In his model, these phases recorded progressively deeper environments from terrestrial to deep shelf settings, respectively.

Abundant fusulinids occur only within the Glenrock limestone of the Red Eagle Limestone, the Neva limestone of the Grenola Limestone, the Cottonwood limestone of the Beattie Limestone, and the Florence limestone of the Barneston Limestone. Elias (1937, 1964) interpreted fusulinid-bearing limestones and calcareous mudrocks as representing the deepest-water facies with estimated water depths of 60 m (195 ft). Mudge and Yochelson (1962) subsequently questioned this paleoecological interpretation of fusulind occurrences and cited evidence that modern, large benthic foraminifera occupy a wide range of environments from near intertidal to deep marine. Other workers (Laporte, 1962; McCrone, 1963, 1964; Imbrie et al., 1964; Lane, 1964) placed maximum water depths at less than 20 m (65 ft), based primarily on paleoecological interpretations of marine-fossil assemblages, and on the recognition of sedimentary indicators of shallow water. One major factor in this reappraisal was the recognition that fusulinids were commonly associated with algal-coated (osagite) grains and other indicators of current

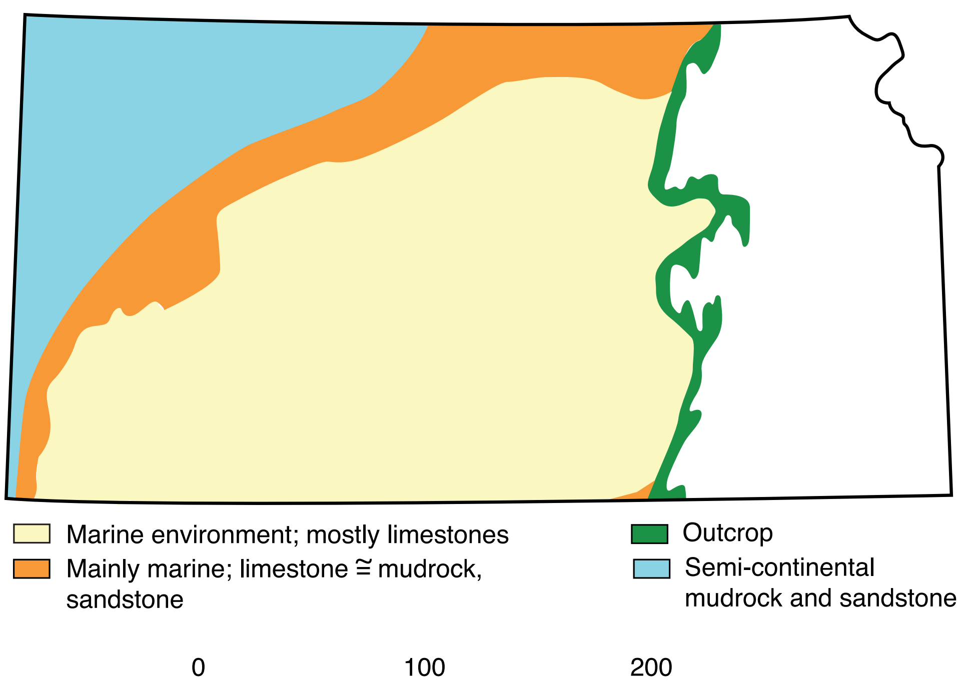


FIGURE 50—Paleogeography of Kansas during the late Wolfcampian; modified from Rascoe (1988).

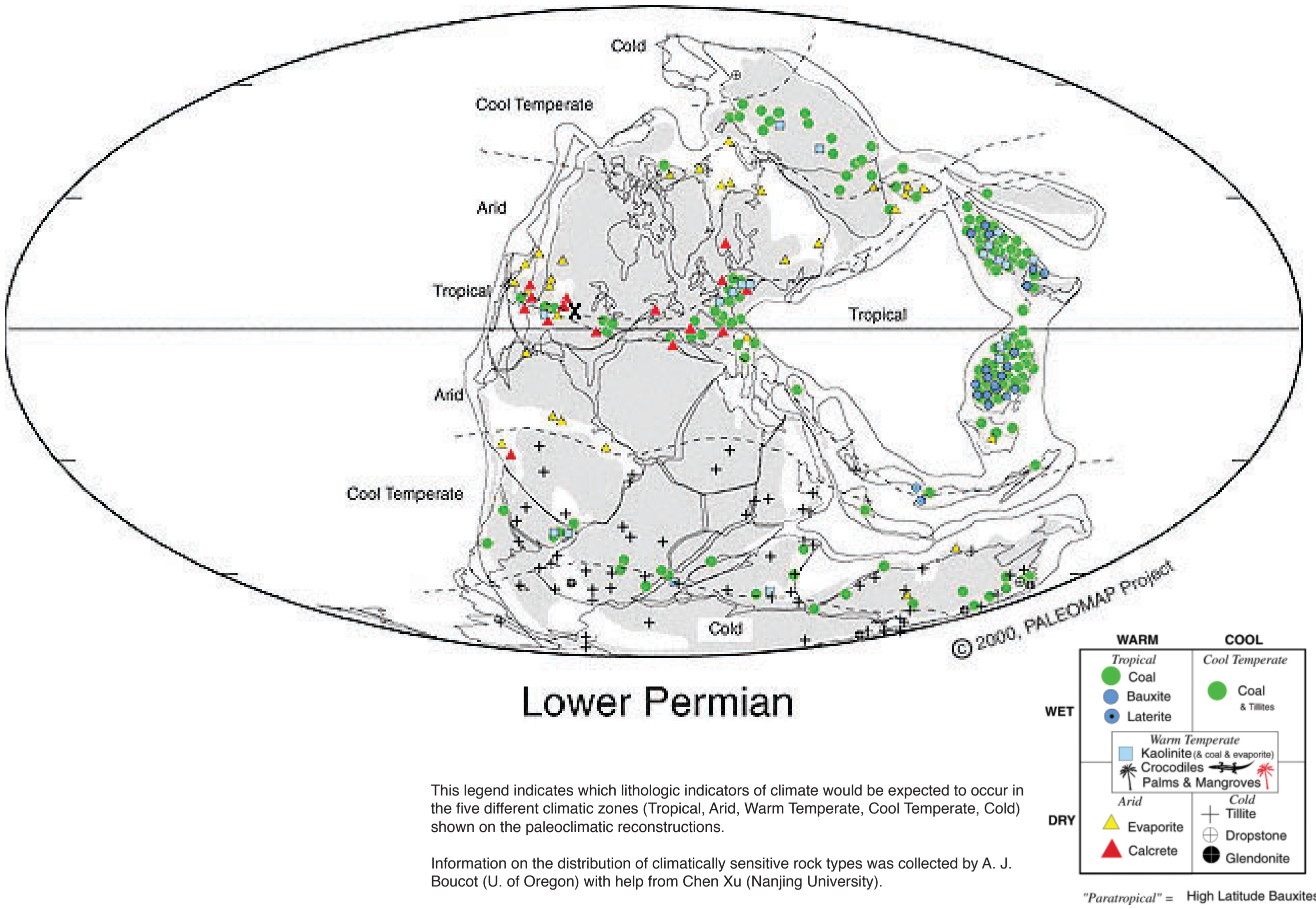


FIGURE 51—Global paleogeographic map and the inferred climate of the lower Permian (280 Ma); modified from Scotese, 2001, online at http://www.scotese.com/epermcli.htm.

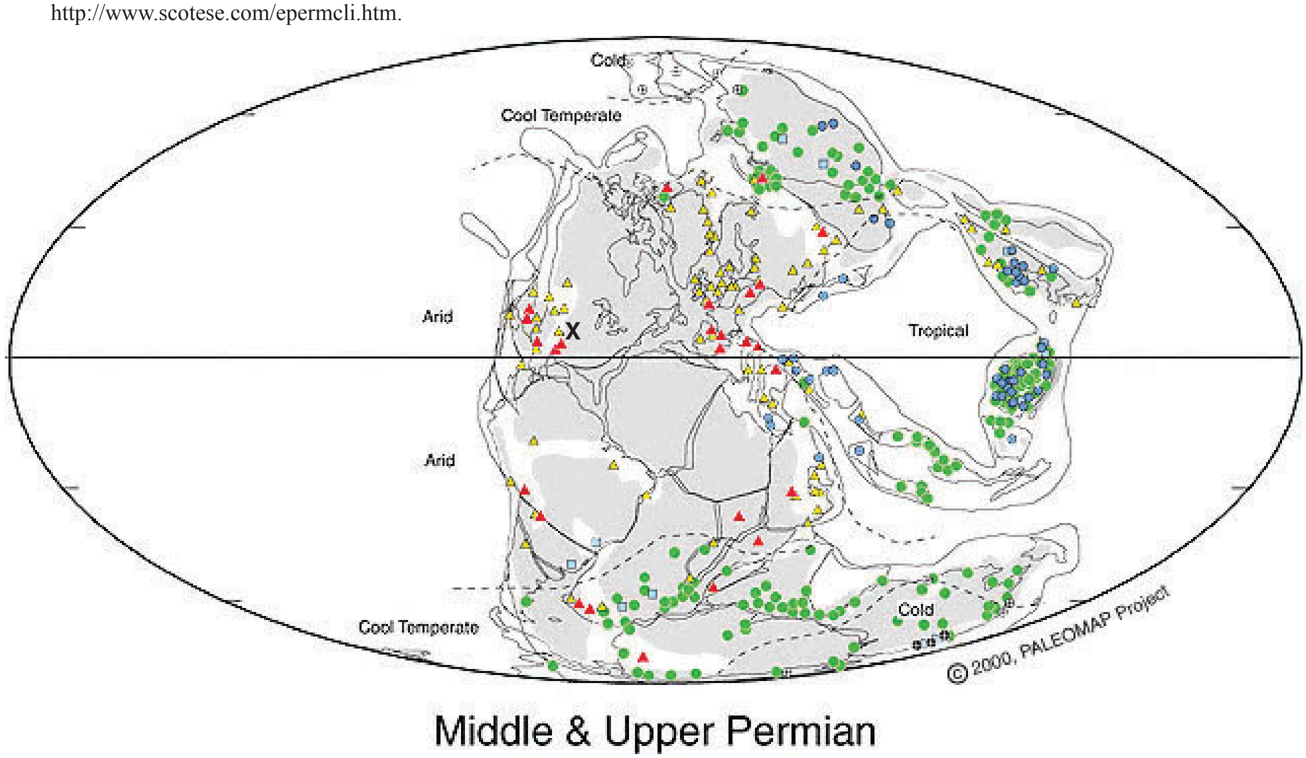


FIGURE 52—Global paleogeographic map and the inferred climate of the middle and upper Permian (255 Ma); modified from Scotese, 2001, online at http://www.scotese.com/lpermcli.htm. See fig. 51 for legend.

and wave agitation such as finely comminuted skeletal debris and oolites. Lane (1964) also argued that fusulinids may have had algal symbionts and thus required shallow well-lit waters. More recent work (Ross, 1982) has supported the view that most species of fusulinids were benthic and lived in relatively shallow carbonate depositional settings including back-reef lagoonal environments.

Elias estimated the depth range of the brachiopod phase as 30–50 m (97.5–162.5 ft) based on the argument that most modern articulate or calcareous brachiopods live below a depth of 30 m (97.5 ft). Important constituents in the brachiopod-dominated assemblages are bryozoans, crinoids, and echinoids. Fusulinid-rich biofacies commonly grade both vertically and laterally into brachiopod and mixed brachiopod/molluscan biofacies (Lane, 1958; Laporte, 1962; Mazzullo et al., 1995, 1997). Limestones characterized by the brachiopod and mixed assemblages typically occur in the lower beds of carbonate formations and members. Some of these units also contain algal-coated grains (osagite) or, locally, even oncolites. Platy algal facies occur in both the Neva and Cottonwood limestones (Laporte, 1962; Miller and West, 1993; Torres et al., 1992; Sawin and West, 2005). Brachiopod and mixed assemblages also occur within fossiliferous calcareous gray mudrocks located between, or immediately below these marine limestones. Nearly all workers have concluded that the fusulinid, brachiopod, and mixed mollusk-brachiopod phases all represent similarly shallow-marine environments. Mudge and Yochelson (1962) concluded from their paleontological study of the lowermost Permian that depth was not a significant factor in controlling the distribution of these marine-fossil assemblages. Similarly, based on his detailed study of the Cottonwood limestone, Laporte (1962) stated that turbulence, clastic sediment influx, and water circulation, rather than depth, were the critical controls.

Elias (1937) estimated a depth range of 20–30 m (65–97.5 ft) for his molluscan phase. This occupied an intermediate position between what he recognized as the shallowest limit for articulate brachiopods and the deepest occurrence of modern *Lingula*. Mollusk-dominated biofacies tend to occur in the upper parts of some carbonate units (e.g., Bader, Crouse, Barneston, Winfield, and Nolans) in the Council Grove and lower Chase Groups, and in thin limestone beds within mudrock units (e.g., Legion, Salem Point, Eskridge, and Havensville) (Hattin, 1957; Lane, 1958; Miller and West, 1993; Mazzullo et al., 1995, 1997). The most diagnostic taxa are *Aviculopecten*, *Septimyalina*, and *Permophorus*, with pyramidellid gastropods and ostracodes being common associates. *Permophorus* occurs in otherwise fossil-poor, thin-bedded to laminated micritic limestones, often in nearly monospecific bedding-plane accumulations. Some mollusk-dominated facies also include algal-coated grains. The Sallyards limestone, for example, has locally abundant algal-coated bivalve shells forming algal biscuits (Lane, 1958; Miller and West, 1993). One common facies is characterized by abundant algal-coated grains (osagite) with a low-diversity assemblage of small pyramidellid gastropods, ostracodes, and, sometimes, arenaceous foraminiferids. Lane (1958) estimated water depths of about 20 m (65.6 ft) for the development of such "osagites" by analogy with the Bahama Banks. Interestingly, facies of the molluscan phase are commonly associated with evidence of evaporitic conditions. The mollusk-dominated limestones of the upper Burr, Crouse, and upper Fort Riley limestones contain molds of evaporite nodules or crystal laths (West, 1972; Miller and West, 1993; Miller and Twiss, 1994; Mazzullo et al., 1995, 1997). Quartz- and calcite-replaced evaporite nodules and boxwork structures are abundant in the Havensville shale (Miller and West, 1993), and gypsum beds overlie the Burr, Middleburg, and Fort Riley limestones in the subsurface (Twiss, 1991a). Furthermore, the thin-bedded to laminated carbonate mudstones of some molluscan facies, combined with a restricted biotic assemblage, indicate peritidal conditions. Both the upper Crouse and the upper Fort Riley, for example, have been interpreted as recording intertidal to supratidal environments (West, 1972; West and Twiss, 1988; Mazzullo, 1998; Mazzullo et al., 1995, 1997). As noted above, the molluscan facies tend to grade into peritidal deposits suggestive of sabkha-like environments. These peritidal limestones and calcitic dolomites dominate the stratigraphic interval above the Barneston Limestone (the upper Chase Group). This facies characterizes the Towanda, Stovall, Cresswell, and Herington limestones. These carbonate mudstones are typically unfossiliferous to very poorly fossiliferous with rare bivalves, arenaceous foraminiferids, and algal laminites or oncolites. Typical features include cryptalgal laminites, laminated dolomites, evaporite molds, calcite- and quartz-replaced evaporite nodules, and desiccation polygons (Mazzullo et al., 1995, 1997).

The *Lingula* phase is characterized by inarticulate brachiopods, particularly *Orbiculoidea,* and is represented by dark-gray to black shales. Interestingly, only a few shale beds within the Wolfcampian actually contain abundant inarticulate brachiopods. The two most significant are the Bennett shale and the black shale beds within the lower Neva limestone (Condra and Busby, 1933; McCrone, 1963). These shales also contain conodonts, shark teeth, and locally fusulinids. The Bennett changes facies laterally into a brachiopod, bryozoan, and crinoidal limestone; however, this is not supported by tracing genetic surfaces associated with this unit (Olszewski and Patzkowsky, 2003). To the south inarticulate brachiopods are absent from a mudrock within the Neva, and the assemblage includes fusulinids, ostracodes, conodonts, bryozoans, and productid brachiopods (Lane, 1958). These *Lingula*-phase shales thus grade into brachiopod- and fusulinid-phase facies. Elias (1937) suggested a depth range for the *Lingula* phase at 32 to 64 ft (10–20 m), and although Mudge and Yochelson (1962) suggested even shallower depths, no values were given.

Most early workers were unanimous in associating inarticulate brachiopods, the *Lingula* phase, with very shallow, even freshwater-influenced environments (Lane, 1964). However, the facies relationships and associated microfossils seem at odds with this interpretation. In fact, examination of the sea-level curves of Elias (1937) shows that he did not, in fact, interpret these units as shallow water. Furthermore, recent micropaleontological studies of the Wolfcampian by Boardman (1993) have identified so-called deep-water conodont species in both the Bennett shale and shales within the Neva limestone. Only one other such conodont interval has been recognized in the lower Permian and that is within the lower Florence limestone. Ironically, the facies most confidently assigned to the shallowest environments may actually record a deeper one. However, another possibility pointed out by Olszewski (personal communication, 2006) is that there are two distinct lingulid associations, one shallow and the other deeper water. These shales, however thin, are widespread and generally serve as good subsurface markers.

Other poorly fossiliferous dark-gray to black mudrocks occur within the Council Grove stratigraphic interval, but these lack both deep-water conodonts and abundant inarticulate brachiopods. These units include the Legion, dark-gray mudrocks within the Burr limestone, and the Salem Point. These units are characterized by ostracodes, occasional small bivalves, and carbonized plant fragments (Miller and West, 1993). Lane (1964) identified freshwater ostracode taxa and charophytes from the Salem Point. Interestingly, evidence of subaerial exposure, including natric paleosol horizons, is present in the Legion and Salem Point (McCahon and Miller, 1997). These dark mudrock units appear to record shallow, marginal-marine environments. In contrast to the black phosphatic "core shales" typical of the upper Carboniferous (Pennsylvanian, Missourian) cyclothems of the midcontinent (Heckel and Baesemann, 1975; Heckel, 1977), these organic-rich facies may have been the result of periods of high freshwater runoff into the basin (Olszewski, 1996).

Elias (1937) divided the variegated mudrocks of the lower Permian into green- and red-shale phases. Greenish-gray to yellowish-gray mudrocks typically overlie the reddish intervals within these stratigraphic units (e.g., Roca, Eskridge, Stearns, Blue Rapids, Speiser, Wymore, Blue Springs, Holmesville, Gage, and Grant). Like Elias, most early workers interpreted the red units as recording terrestrial conditions and the green shales as representing shallow subtidal environments. However, this interpretation is probably incorrect based on the recognition that the green mudrocks, like the red, are commonly characterized by paleosol development (Miller and West, 1993; Miller et al., 1996). Paleosols in the greenish-gray intervals of the Council Grove Group display pedogenic features (poor horizonation, pseudoanticlines, slickensides, and low color value) identifying them as vertisols in U.S. Department of Agriculture taxonomy (Soil Survey Staff, 1992), or calcic vertisols (Mack et al., 1993). Modern vertisols develop under wet-dry monsoonal climatic conditions. The vertic paleosols may grade laterally into mudrocks with abundant terrestrial plant debris. The few fossil-plant localities within the Council Grove Group seem to be lateral equivalents of these upper greenish-gray intervals, such as the Mill Creek flora of the Roca Shale (Warren, 1969). The paleosols themselves often contain charcoal fragments suggesting forest fires, an observation consistent with a seasonal wet-dry climate regime. Charophytes and freshwater ostracodes are common microfossils within these green-shale intervals (Lane, 1964).

Within the Council Grove Group, the red mudrocks of the variegated shales invariably display calcic paleosols with clay illuviation and well-developed color horizonation (Miller et al., 1996). These paleosols can be classified as alfisols in U.S. Department of Agriculture taxonomy (Soil Survey Staff, 1992), or as calcic argillisols according to Mack et al. (1993). Soil-carbonate precipitation is especially characteristic and occurs as isolated caliche nodules and rhizocretions. Climatic conditions of soil formation probably ranged from subhumid to semi-arid. Vertebrate burrows and bone occur in association with some of these paleosol horizons (e.g., Eskridge, Speiser, Havensville, and Blue Springs shales). These include primarily the lungfish *Gnathorhiza* and the burrowing amphibian *Lysorophus* (Schultze, 1985; Cunningham, 1989; Hasiotis et al., 2002; Hembree et al., 2004). Based on the association of marine invertebrates with both marine and euryhaline vertebrate teeth, bones, and scales in the interval from the upper Speiser Shale to the lower Wymore shale, Schultze (1985) proposed a marine to marginal-marine depositional environment for this interval.

Paleosols within the variegated mudrocks of the Chase Group differ from those lower in the section. Silt and very fine sand, probably eolian, become dominant in these lithologies, and the paleosols are more poorly developed. In addition, there is increasing evidence of evaporitic conditions. The mudrocks in both the Havensville and Holmesville exhibit well-developed boxwork structures and calcite- and quartz-replaced evaporite nodules (Miller and West, 1993; Miller and Twiss, 1994; Mazzullo et al., 1997). Well-developed tepee structures also are associated with the boxworks of the lower Holmesville. The Gage shale has abundant laminae of recrystallized micrite and palisade calcite crystals interpreted by Mazzullo et al. (1997) as resulting from the dissolution and replacement of evaporites.

Leonardian

Lithostratigraphic Units

The Kansas Geological Survey (Zeller, 1968; Sawin et al., 2008) divides the Leonardian rocks into the Sumner Group below and the Nippewalla Group above. This stratigraphic succession is shown in fig. 2. The former consists of three formations, in ascending order, the Wellington Formation with six members (two unnamed), the overlying Ninnescah Shale with two members (one unnamed), and the Stone Corral Formation. The Nippewalla Group consists of six formations with the Harper Sandstone and Blaine Formation subdivided into two and four members, respectively. In the subsurface the Wellington Formation, Ninnescah Shale, Stone Corral Formation, Blaine Formation, and Dog Creek Formation can be recognized, but the intervals between the Stone Corral and Blaine and the Blaine and Dog Creek are undifferentiated (Mudge, 1967, p. 109). The Stone Corral Formation is a very useful stratigraphic marker and has been used as the datum in numerous studies of the Permian in the Kansas subsurface.

Sumner Group

Wellington Formation—Marine, brackish, and freshwater fossils have been reported from the nearly 700-ft (214-m)-thick Wellington Formation with the marine depos-

FIGURE 53—Exposure of the Wellington Formation (Carlton Limestone Member) in a field on the south side of the road; near center of north line NW sec. 28, T. 16 S., R. 2 E., Dickinson County, Kansas.

its in the lower part (Zeller, 1968, p. 50). Three of the six members in the Wellington Formation are thin, argillaceous, dolomitic limestones: the Hollenberg and Carlton in the lower part and the Milan at the top of the formation.

As reported by Zeller (1968, p. 50), the Hollenberg is 0.3–1.5 m (1–5 ft) thick, the Milan is up to 2.4 m (8 ft) thick, and the Carlton is lenticular (fig. 53). Fossil insects have been reported from the Carlton at some localities (Zeller, 1968, p. 50). The Milan Limestone Member is typically a succession of discontinuous, thin carbonate beds (Berendsen and Lambert, 1981; Watney et al., 2003).

The two unnamed shale members of the Wellington separate the Hollenberg from the underlying Herington Limestone Member of the Nolans Limestone (Chase Group) and the Carlton from the Hollenberg. Overlying the Carlton and underlying the Milan is the thickest and economically most important member of the Wellington Formation, the Hutchinson Salt Member. The solubility of the salt precludes its exposure at the surface but it has been reported as 213 m (700 ft) thick in the subsurface of Clark County (Kulstad, 1959). The distribution of the Hutchinson Salt Member in Kansas is shown in fig. 54 (see also Watney et al., 1988). As noted by Mudge (1967, p. 109), the salt originally extended farther east but has been removed by erosion.

In general the lower part of the Wellington is gray anhydritic mudrock interbedded with anhydrite; the middle part, the thickest, is mostly red mudrock, anhydrite, and salt; and the upper part is interbedded gray anhydritic mudrock and red mudrock. The well-known and classic fossil-insect collection at Elmo, Kansas, the so-called "Elmo fossil bed" occurs along with plant fossils in the Carlton Limestone Member 76.2 to 91.4 m (250–300 ft) above the base of the Wellington Formation (fig. 55). An excellent synopsis of the history, biota, and literature of this classic locality at Elmo, Kansas, is given by Beckemeyer (2000). Beckemeyer and Hall (2005) and Hall et al. (2005) discussed the entomofauna and depositional aspects of these beds, respectively. Fossil insects, plant fossils, and conchostracans occur at several levels within the Wellington from Oklahoma well into Kansas (Tasch, 1958, 1961, 1963; Tanner, 1959; Tasch and Zimmerman, 1959, 1961). Tasch (1964) interpreted these as limnic deposits and described a paleolimnological cyclicity.

Ninnescah Shale—The Ninnescah Shale is 91.4 to 137.2 m (300–450 ft) of essentially red anhydritic, dolomitic, calcareous mudrock that thins to about 15.2 m (50 ft) in the subsurface near the Nebraska line (Zeller, 1968, p. 50–51; fig. 56). In northwestern Kansas, sandstones and sandy mudrocks are present, but interbedded salt, anhydrite, and mudrock occur in south-central and western Kansas where it is thickest (Martinez et al., 1996). Mudge (1967, p.110, fig. 38) shows the distribution of salt in the Ninnescah Shale. Conchostracans ("clam shrimp") have been found in the non-red beds, and the "Red Jaw" country of Reno County is the result of the weathering of the middle part of this formation that contains calcareous concretions (Zeller, 1968, p. 50).

At the base of the Ninnescah Shale (Zeller, 1968) is an unnamed member that is overlain by the Runnymede Sandstone Member. The Runnymede sandstone is a 2–2.4-m (7–8-ft)-thick, gray to grayish-green siltstone to very fine sandstone (Zeller, 1968, p. 51). A disconformity separates this formation from the underlying Sumner Group and although the Runnymede is absent because of erosion in some areas,

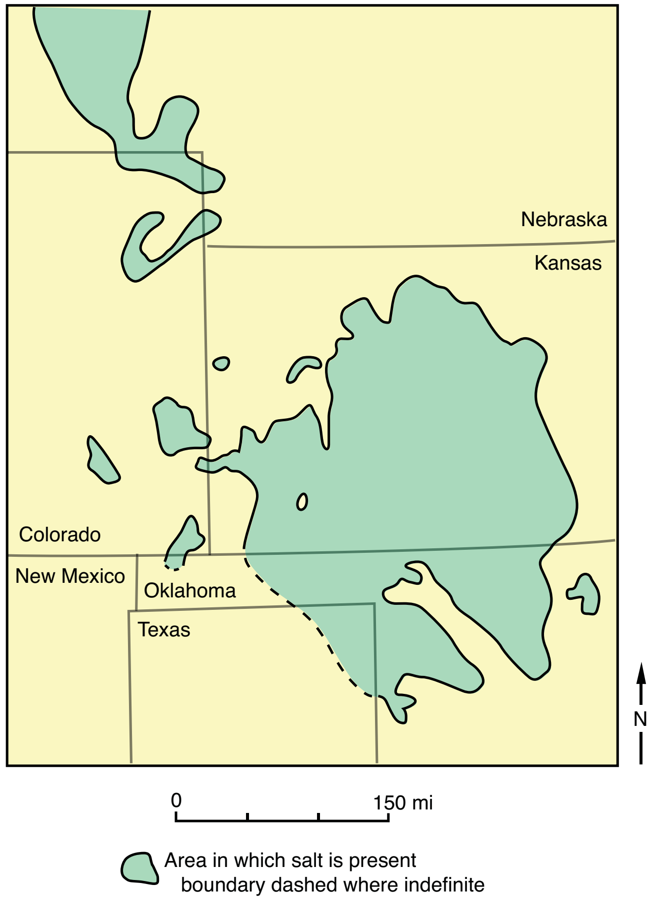


FIGURE 54—Distribution of the salt in the Wellington Formation in Kansas and adjacent areas (modified from Mudge, 1967, p. 109, fig. 37).

FIGURE 55—Gully exposures of the classic Elmo fossil insect beds, SW sec. 21, T. 16 S., R. 2 E., Dickinson County, Kansas.

FIGURE 56—Exposure of the Ninnescah Shale in a road ditch looking northeast at the junction of K–14 and West Parallel Road; SW corner, sec. 34, T. 25 S., R. 8 W., Reno County, Kansas.

FIGURE 57—Exposure of the Stone Corral Formation along the south side of Avenue Q, 1.6 mi (2.6 km) west of the McPherson/Rice County line; just west of the center of the north line, sec. 26, T. 20 S., R. 6 W., Rice County, Kansas.

the Stone Corral Formation, which overlies the Runnymede, is commonly present (Rascoe, 1988). Rascoe and Baars (1972, p.147, fig. 3) refer to this as an intra-Leonardian lacuna.

Stone Corral Formation—The Stone Corral Formation, at the top of the Sumner Group, is in surface exposures basically a dolomite to dolomitic mudrock with evaporites—anhydrite and gypsum (fig. 57). In the subsurface of south-central and west-central Kansas, near the depositional axis, the Stone Corral Formation includes thin halite beds that occur both above and below dolomite-anhydrite layers (Merriam, 1963). Because of the solubility of these evaporates, this unit is often vuggy in surface exposures. In the subsurface it may be mostly anhydrite (Mudge, 1967, p. 109). This 2–30.5-m (6–100-ft)-thick formation is an easily recognized "marker bed" in the red-bed sequence of Kansas.

Nippewalla Group

Harper Sandstone—Overlying the Stone Corral Formation is the Harper Sandstone, a formation 67.1 m (220 ft) thick of mostly red argillaceous siltstone and very fine silty sandstone (fig. 58). The two members, Chikaskia sandstone below and the Kingman sandstone above, are lithologically very similar. They are separated by a prominent 0.9-m (3-ft) bed of white, sandy siltstone.

Salt Plain Formation—Above the Harper is the Salt Plain Formation, which is composed of silty mudrocks with beds of coarse silty sandstone (figs. 59A, B). Salt is associated with some of the mudrocks below the Crisfield sandstone bed in the lower part of the formation (Zeller, 1968).

Cedar Hills Sandstone and Flower-pot Shale—Two formations are recognized above the Salt Plain Formation and below the Blaine Formation. These are the Cedar Hills Sandstone below (figs. 13, 60), and the Flower-pot Shale above (fig. 12). A thin, white sandstone at the base of the Cedar Hills separates it from the underlying Salt Plain. Both the Cedar Hills and Flower-pot are predominantly red mudrocks that contain gypsum (fig. 61).

Beds of gypsum are particularly conspicuous in the Flower-pot, as are thin beds of coarse siltstone and coarse to fine sandstone (fig. 12). Mudge (1967, p. 110) suggested that these coarser siliciclastics might be channel-fill deposits. The Flower-pot Shale contains up to 76.2 m (250 ft) of halite in northwestern Kansas in a localized basin called the Syracuse basin (Holdaway, 1978). The halite is distinctive, coarsely crystalline and clear, and has apparently displaced a red siltstone matrix, referred to as a chaotic red bed salt. The halite in the Flower-pot Shale is in marked contrast to the Hutchinson Salt Member that is typically a distinctively bedded, cloudy halite with thin continuous layers of gray mudrock. The distribution of salt in the Nippewalla Group is shown by Mudge (1967, p. 110, fig. 39) and is more extensive than the distribution of the salt in the Ninnescah Formation (Mudge, 1967, p. 110, fig. 38).

Blaine and Dog Creek Formations—The two uppermost formations of the Nippewalla Group are the Blaine below and the Dog Creek above (fig. 2). The Blaine Formation

FIGURE 58—Exposure of the Harper Sandstone in a bluff on the northwest side of US–54 east of Kingman, Kansas; near center sec. 33, T. 27 S., R. 7 W., Kingman County, Kansas; based on a section measured and described by A. Swineford on file at the Kansas Geological Survey.

A

B

FIGURES 59A, B—Exposure of the Salt Plain Formation looking north from near the center of south line, sec. 3, T. 32 S., R. 9 W., Harper County, Kansas; **59A** is a general view of the exposure; **59B** is a closer view of the sandy and silty beds; based on a section measured and described by A. Swineford on file at the Kansas Geological Survey; according to Bayne's (1960) geologic map of Harper County, this is an area where the Harper Sandstone and Salt Plain Formation are undifferentiated.

is essentially gypsum and anhydrite (Kulstad et al., 1956), but beds of gypsum and anhydrite also occur in the Dog Creek Formation. Thus, the base of the Blaine, and the top of the Dog Creek, are easily recognized in the subsurface, but it is hard to differentiate between the two; therefore, they are commonly lumped together in subsurface studies. Both are absent in northern Kansas, possibly as a result of pre-Jurassic erosion (Mudge, 1967, p. 110). The four gypsum members, separated by dolomite and red mudrock (Zeller, 1968, p. 52), compose the approximately 15.2-m (50-ft)-thick Blaine Formation (fig. 62). The Dog Creek is a maroon silty mudrock with siltstone; very fine grained, feldspathic sandstone; dolomitic sandstone; dolomite; and gypsum beds (Swineford, 1955, p. 91; Zeller, 1968, p. 52; fig. 15). Like the Blaine, the Dog Creek is up to 15.2 m (50 ft) thick, with 0.9 m (3 ft) of maroon mudrock normally occurring at the top, but locally, a red and white

FIGURE 60—Exposures of the Cedar Hills Sandstone along Gyp Hill Road looking southeast from near center of N/2 sec. 20, T. 32 S., R. 12 W., Barber County, Kansas.

FIGURE 61—Natural outcrop of gypsum, upper Permian, Clark County, Kansas; from photo files of the Kansas Geological Survey.

FIGURE 62—Permian red beds near Medicine Lodge, Barber County, Kansas; the light-colored “rim rock” is probably the Medicine Lodge Gypsum Member of the Blaine Formation above the red beds of the Flower-pot Shale; from photo files of the Kansas Geological Survey.

laminated gypsum bed 0.3 m (1 ft) thick can occur at the top (Zeller, 1968, p. 52).

Upper Boundary of the Leonardian

A summary by Mudge (1967, p. 112 [his Interval B]) discusses the upper boundary of the Leonardian. As he pointed out, some argue the contact with the overlying Guadalupian rocks is conformable and others consider it a major unconformity. Difficulty in differentiating the Blaine from the Dog Creek in the subsurface does little to support either view. Mudge (1967) suggested that thinning of the Blaine and its absence, and that of the Dog Creek, in some areas is the result of wedging out rather than erosion. However, the Blaine Formation serves as an excellent regional marker bed in the subsurface, extending well north of Kansas into Wyoming and south through Oklahoma.

Lithofacies and Thickness of the Leonardian

Siliciclastics and evaporites are the predominant Leonardian lithologies in Kansas, and their current thickness is largely the result of post-Permian (Mesozoic and Cenozoic) erosion. In northwestern Kansas the 106.7 m (350 ft) of Leonardian rocks are mainly sandstones, some siltstones, and evaporitic mudrocks. In south-central Kansas, where the Leonardian sequence is thickest, 731.5 m (2,400 ft), evaporites make up a large part of the succession; along the eastern outcrop, the rocks are largely evaporitic mudrocks. A well-log cross section (see Watney et al., 1988) encompassing the Leonardian extending from the updip landward margin to the thick axis of the depocenter indicates that the Hutchinson Salt Member composes most of Leonardian thickening with upper salt beds stepping basinward to the south. The Hutchinson Salt Member, although dominantly halite over much of its depositional area, grades southwestward to increasing proportions of anhydrite, a trend that continues basinward into Oklahoma. Halite thickness and proportions are greatest in central Kansas along a northwest-southeast elongated trend of thickening lying west of the city of Hutchinson and crossing the axis of the Central Kansas uplift. A thick correlatable anhydrite divides the Hutchinson Salt Member into an upper and lower interval. The depocenter of thick, clean halite in the upper Hutchinson Salt Member shifts southwestward relative to the lower interval, and the edges of the salt basin retreat basinward (southwest) indicative of regression (Watney et al., 1988). An isopach map of the Leonardian rocks in Kansas illustrates the large embayment centered in south-central Kansas (fig. 63); see Mudge, 1967, p. 107, fig. 35). Merriam (1963, p. 90, fig. 40) illustrated the lithologic variation of the Stone Corral Formation. The area of thick Leonardian rocks more or less parallels the western side of the Central Kansas uplift, the axis of the Kansas depositional basin (Mudge, 1967, p. 113). Leonardian rocks are also thicker in the Hugoton embayment after thinning slightly along the western edge, the Selden anticline, of the Kansas depositional basin (Mudge, 1967, p. 112).

Depositional Environments and Source Areas of the Leonardian

Although some Leonardian rocks occur in the Salina and Sedgwick basins, they are particularly significant in the Central Kansas uplift, Kansas depositional basin (see Mudge, 1967), and Hugoton embayment. These three features were the major parts of a large depositional basin during Leonardian time and received siliciclastic sediment from two major source

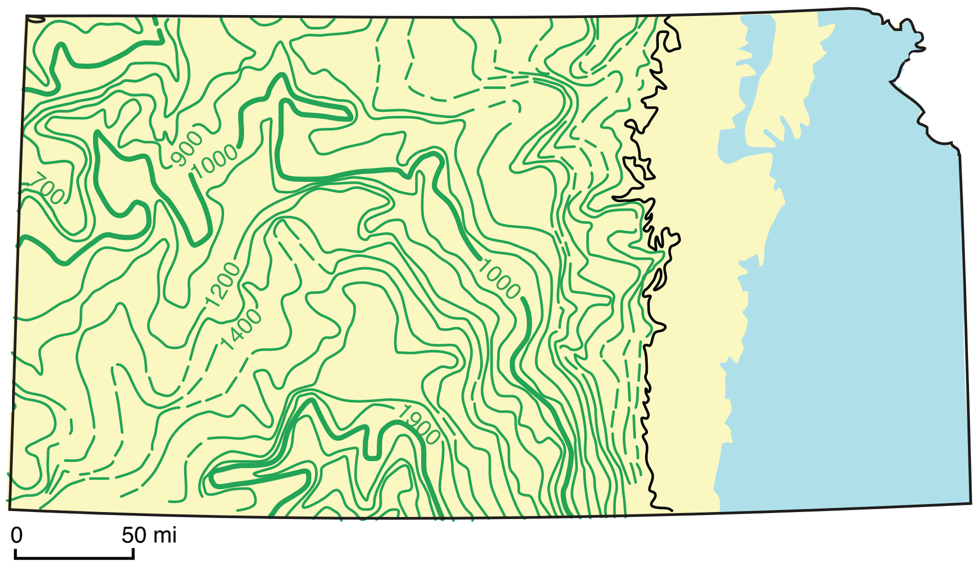


FIGURE 63—Isopach map of Leonardian rocks in Kansas; contour interval = 100 ft, poor control where dashed; rocks older than Permian exposed in blue area (modified from Mudge, 1967, fig. 35, p. 107).

areas: the Front Range, especially the Wet Mountains, to the west, and Siouxia landmass to the north and northwest. Leonardian rocks originally covered a much larger area, but the area was reduced by post-Permian erosion. Swineford (1955, p. 164) indicated that most of the immature siliciclastics, such as feldspathic sandstones, came from the Wet Mountains. Mudge (1967, p. 113) suggested that some feldspathic debris could have come from the south and cited Swineford (1955, p. 164–166) as indicating that the coarseness of these siliciclastics increased in a southern direction and that certain grains were typical of second-cycle orthoquartzites, i.e., they might have had a Cambrian–Ordovician source. The Siouxia landmass supplied finer siliciclastics such as silt, very fine grained sand, and clay. It has been suggested that some of these finer siliciclastics are a result of eolian deposition (Parrish and Peterson, 1988; Johnson, 1989; Soreghan, 1992; Ziegler et al., 1997; Ziegler et al., 1998; Mack et al., 2003).

Structural features controlled the environments of deposition of Leonardian rocks (Mudge, 1967, p. 113). In general these environments alternated between marine, brackish-water, and continental, with coastal and continental environments becoming more dominant as the climate became more arid, and circulation more restricted, as the area was periodically isolated from the open ocean. The distribution and relationship between the different depositional environments inferred during Leonardian time is shown in fig. 64 (see McKee and Oriel, 1967, Plate 10A). Obviously, evaporation of marine water was a dominant process given the thick salt beds and the numerous beds of gypsum and anhydrite. Coastal-marine, alluvial and fluvial, and eolian environments are represented. Coastal-marine and fluvial deposits occur along the edges of the basin and near smaller, local source areas (islands). The basin was essentially a large alluvial plain with little relief. Of course, eolian deposits would have accumulated over the entire area, and this mechanism is now receiving more serious consideration as the depositional agent of the finer (silt and clay) siliciclastics.

Apparently the Syracuse basin developed in the late Leonardian creating accommodation space for the pronounced thickening of the Flower-pot Shale and associated halite. This basin is bordered by current-day structural features on the east (Oakley anticline) and on the west (Los Animas arch), representing a westerly shift in subsidence on the Kansas shelf, perhaps indicating further southwesterly migration of tectonism to the south.

Application of sequence stratigraphy to Leonardian rocks in Kansas is limited, and few have attempted to document the cyclicity of this stratigraphic interval. Mudge (1967) recognized two major cycles in the Kansas Leonardian, one from the top of the Wolfcampian to the top of the Stone Corral Formation and the other from the top of the Stone Corral Formation through the Dog Creek. "Each cycle closed with prolonged and widespread deposition under restricted-marine conditions" (Mudge, 1967, p. 114). The alternation of depositional conditions produced many small-scale cycles, but these have rarely been documented in detail. Tasch's studies (1958, 1961, 1963, 1964) of limnic sequences and his documentation of paleolimnological cycles is an obvious exception, as is the more recent study by Watney et al. (1988) on the origin and distribution of the Hutchinson Salt Member.

Using cores through the Hutchinson Salt Member, Watney et al. (1988) documented a high-frequency depositional cyclicity consisting from bottom to top of 1) a thin magnesite/dolomite bed, 2) a thin anhydrite bed, 3) a succession of thicker halite beds, and 4) a thin, gray silty mudrock bed often containing fractures filled with polyhalite and anhydrite. The thicker halite beds in number 3 above range from well-bedded, cloudy, fine- to medium-crystalline halite interrupted by multiple, thin, dark-gray mudrock beds to salt beds consisting of halite of varied crystal size with patches of clear large halite crystals and an irregular upper surface with occasional dissolution pipes or microkarst surfaces. The lower halite beds typically contain hopper and chevron halite crystals indicating primary deposition of halite crystals formed at the surface

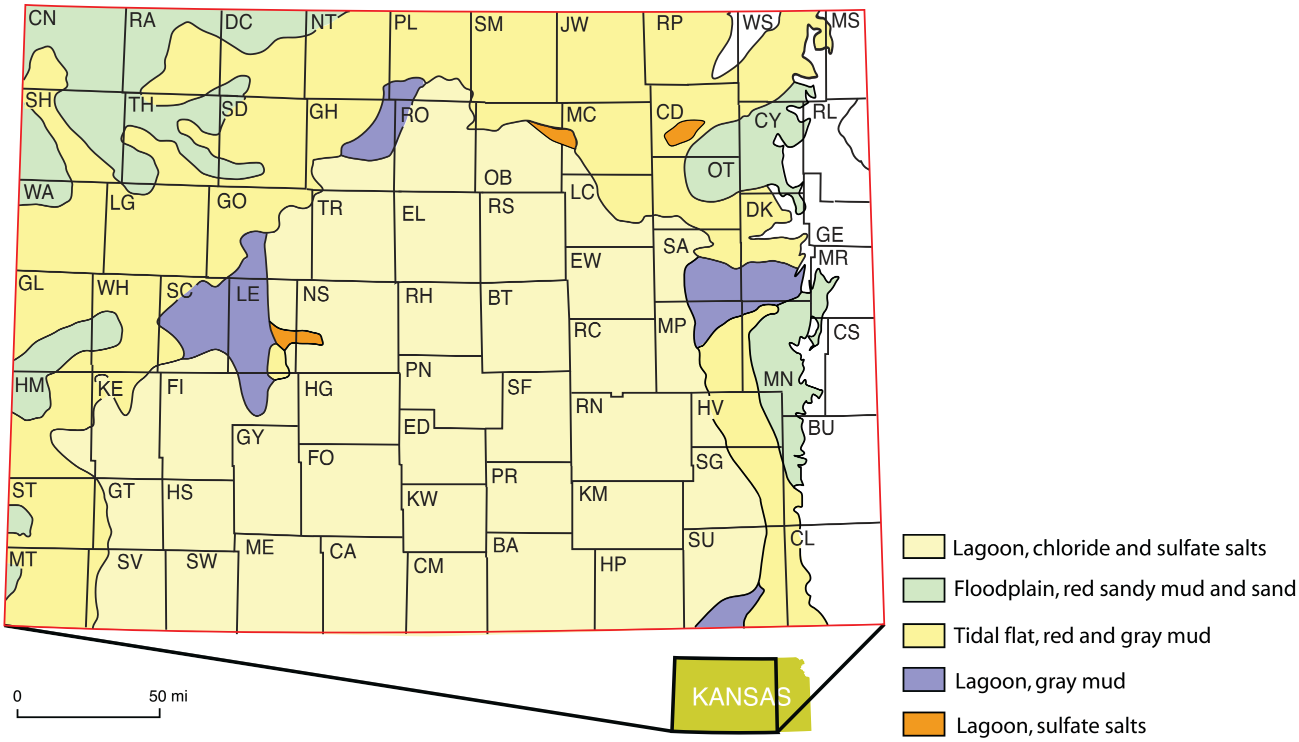


FIGURE 64—Depositional environments during the Leonardian in Kansas (modified from McKee and Oriel, 1967, plate 10A).

of the brine (hoppers) and on the seafloor (chevrons). When seen in roofs of the salt mines, discontinuous fractures in the cycle-capping mudrock bed (number 4 above) often form large meter-scale polygons, probably due to desiccation. The salt mines are located along the landward edges of the Kansas Permian salt basin where one would expect to find desiccation features. Dissolution along the upper surface of the halite beds may be related to either desiccation or influx of low-salinity water from runoff along the periphery of the salt basin.

The typical thickness of the halite-dominated cycles in the Leonardian is less than 15.2 m (50 ft), which is similar to those of underlying Wolfcampian carbonate-dominated cycles. Similar thicknesses of these marine cycles coupled with indications of rapid marine inundation and slower regression suggest that these halite cycles represent the continuation of a eustatic cycle similar to those in the Wolfcampian. However, restricted circulation in the Leonardian is inferred to have led to dominant hypersaline subaqueous conditions during each cycle accompanied by intermittent subaerial conditions, a feature common to both periods of time. The thin magnesite/dolomite and anhydrite bed at the base of the cycle likely represents transgressive to highstand marine conditions. Halite beds accumulated in a shallowing, hypersaline water body. Mixing with more-open-marine waters from the Permian seaway to the south precluded precipitation of potash salts in any of these cycles in Kansas. Limited occurrences of polyhalite accumulated as thin irregular beds and fracture filling during deposition of the upper halite beds suggesting maximum salinities were only slightly higher than that required for halite precipitation (Jones, 1965).

Correlation and subsurface mapping of the Hutchinson Salt Member, using over 3,700 wells, recognized six carbonate and anhydrite markers that delineate the transgressive bases of cycle sets. These marker beds represent periods of more prolonged and extensive open-marine (less-hypersaline) conditions. Each cycle set contains five or six higher-frequency cycles that are believed to be comparable to cycle sets in other Permian and upper Carboniferous (Pennsylvanian) strata (Watney et al., 1995).

The abrupt shift from carbonate-dominated Wolfcampian cycles to Leonardian halite cycles is attributed to rapid shallowing of the Palo Duro and Dalhart basins as they filled with sediment as tectonic subsidence decreased at the end of Wolfcampian (Hanford and Dutton, 1980). These southern basins continued to provide access of marine waters from the Permian basin to the Kansas shelf, but return circulation was restricted enough to produce increasingly hypersaline brines in most distal sectors of the basin in Kansas. This is consistent with the reflux model of Scruton (1953).

Depositional cycles are developed above the Hutchinson Salt Member in the upper Wellington and Ninnescah shales. These cycles consist of thin anhydrite or dolomite beds indicative of flooding followed by accumulation of marine mudrocks (Watney et al., 2003). The cycles are capped by poorly studied, variegated paleosols containing desiccation polygons, breccias, and ped structures. Halite accumulation in the Ninnescah Shale is limited to southwestern Kansas indicating a continued basinward shift in marine lithofacies and relative fall in sea level through the base of the Runnymede sandstone.

Recognition of paleosols requires carefully detailed study of lithologic characteristics. Such studies would enhance a sequence-stratigraphic approach and would provide some much needed information on the climate during this time interval. Thus, there is ample opportunity for further study of this interesting and challenging sequence.

The regionally significant Runnymede sandstone and Stone Corral Formation reflect a major marine inundation unconformably overstepping the "lowstand" marginal-marine to nonmarine red beds of the Ninnescah Shale. The Runnymede sandstone contains lithofacies consistent with eolian and fluvial deposition and may be the result of a climate change associated with a rise in sea level. Continued rise in sea level led to halite accumulation of the lower Cimarron Salt beds (Martinez et al., 1996) and the anhydrite and dolomites of the Stone Corral Formation. The succeeding red beds of the Nippewalla Group represent regressive conditions dominated by eolian siliciclastic and nonmarine evaporite accumulation across broad saline areas that were isolated from the marine source to the south.

The Blaine Formation, Flower-pot Shale, and Cedar Hills Sandstone represent another major marine inundation that overstepped the predominantly red-bed, nonmarine succession of the Nippewalla Group. Mobilized sand and a rising water table led to preservation of extensive deposits of the Cedar Hills Sandstone, equivalent to the widespread Glorieta Sandstone of Texas and New Mexico (Presley and McGillis, 1982). The Flower-pot Shale is a red-bed deposit containing a halite succession limited to western Kansas in the Syracuse basin where thicknesses are upwards of 76 m (250 ft; Holdaway, 1978). The basin was delimited by the Oakley anticline on the east, the Las Animas arch on the west and north, and a thick accumulation of Cedar Hills Sandstone on the south. Displacement growth of large, clear halite crystals in the silty red mudrocks of the Flower-pot Shale, isolation of the Flower-pot halite from a marine source, and low (<1 ppm) bromine content of the halite indicative of recycled halite support a nonmarine-halite accumulation. Halite was precipitated in the basin center through evaporation of hypersaline ground water. Again, climate change, concurrent with a sea-level rise, may have led to the rise in the water table (i.e., more rainfall). Eventually, marine transgression occurred, resulting in deposition of the regionally extensive anhydrite and dolomite of the Blaine Formation. The marine transgression associated with the Blaine Formation advanced onto the craton as far north as Wyoming.

Guadalupian

Lithostratigraphic Units

This interval is subdivided into three formations, in ascending order, the Whitehorse Formation (figs. 14, 65), Day Creek Dolomite (fig. 66), and Big Basin Formation (fig. 67). From bottom to top the members of the Whitehorse are the Marlow Sandstone, Relay Creek (?) dolomite, an unnamed member, and the Kiger shale (fig. 2). Of these three formations, the Whitehorse is the thickest with the Marlow sandstone and the unnamed member accounting for most of its 82.3-m (270-ft) thickness (Zeller, 1968, p. 52).

Formations

Whitehorse Formation—At the outcrop, the Whitehorse is a very fine grained red sandstone and siltstone with some mudrock and dolomite (Swineford, 1955, p. 92; fig. 65). The two intervals of this formation that contain beds of dolomite are the thin Relay Creek (?) dolomite and Kiger shale members. Maher (1946, p. 2; 1947, p. 3) indicated that the White-

FIGURE 65—Exposure of the Whitehorse Formation on the south side of US–160 where it crosses Keiger Creek; near center of north line, sec. 10, T. 33 S., R. 24 W., Clark County, Kansas.

horse is mostly red mudrock to sandy red mudrock with some red sandstone and thin beds of dolomite in the subsurface. Newell (1940, p. 272, fig. 2) identified marine fossils from the "Whitehorse Springs lens," near the base, and the "Woodward lens," near the top of the Whitehorse Formation from exposures in southern Kansas and northern Oklahoma. In both units the bivalve *Dozierella* is present, indicating a Guadalupian age (Newell, 1940, p. 280–281).

Day Creek Dolomite—Although the Day Creek Dolomite is thin, 0.6–0.9 m (2–3 ft) at the outcrop (Zeller, 1968, p. 53), Swineford (1955, p. 92) reported a thickness of 36.6 m (120 ft) in the subsurface. At the surface this formation is a fine-grained, dense dolomite with some chert nodules associated with red silty mudrocks. In the subsurface, anhydrite and red mudrocks are conspicuous, and where the Day Creek is thickest, it is mostly anhydrite (Mudge, 1967, p. 115; fig. 66).

Big Basin Formation—The uppermost Permian unit in Kansas is the Big Basin Formation, named for Big Basin, a depression in Clark County. Lithologically, it is similar to the other Permian red-bed units of Kansas—red silty mudrocks and fine-grained red silty sandstones with some anhydrite and dolomite (fig. 67). According to Zeller (1968, p. 53), the thickness is a maximum of 13.7 m (45 ft) at the outcrop, but Merriam (1963, p. 81) reported a thickness of 91.4 m (300 ft) in the subsurface.

Upper Boundary of the Guadalupian

The top of the Permian in Kansas is an erosional unconformity; the Guadalupian Big Basin Formation marks the top of the Permian (Ochoan rocks are probably missing). Zeller (1968) judged the overlying rocks to be Jurassic in age, cropping out at only one locality (Morton County) and occurring in the subsurface in northwestern Kansas (see Zeller, 1968, p. 53, fig. 9). East of the Jurassic pinchout, the Permian is overlain by rocks of Cretaceous (figs. 68, 69) and Neogene age. The outcrop in Morton County was previously classified as Triassic Dockum Group, and a figure in MacLachlan (1972, p. 172, fig. 6) suggested the same.

Lithofacies and Thickness of the Guadalupian

Red siliciclastics with associated evaporites and dolomite are the dominant lithology of the Guadalupian sequence in Kansas. The lithologies are very similar to the underlying Leonardian except that salt, so prominent in the Leonardian, is absent. Present-day thickness of the Guadalupian rocks in Kansas (fig. 70; see Mudge, 1967, p. 108, fig. 36) is the result of post-Permian erosion with rocks of either Jurassic or Cretaceous age directly overlying the Permian in Kansas (Mudge, 1967, p. 121, fig. 42).

Depositional Environments and Source Areas of the Guadalupian

Subsequent erosion makes it difficult to comment accurately on the source of and environment within which the Guadalupian rocks were deposited. Using lithologic features and the thin fossiliferous beds of the Whitehorse Formation, it is reasonable to suggest that conditions were not very different from those that prevailed during the Leonardian: coastal to continental environments associated with restricted marine basins. In addressing this issue, Swineford (1955, p. 166) stated, "An influx of fine feldspathic sand, perhaps

FIGURE 66—Day Creek Dolomite in the Red Hills, Clark County, Kansas; from photo files of the Kansas Geological Survey.

FIGURE 67—Big Basin Formation at Big Basin, looking east-southeast from US–160 and 283 from the NW corner sec. 25, T. 32 S., R. 25 W., toward the center sec. 25, T. 32 S., R. 25 W., Clark County, Kansas.

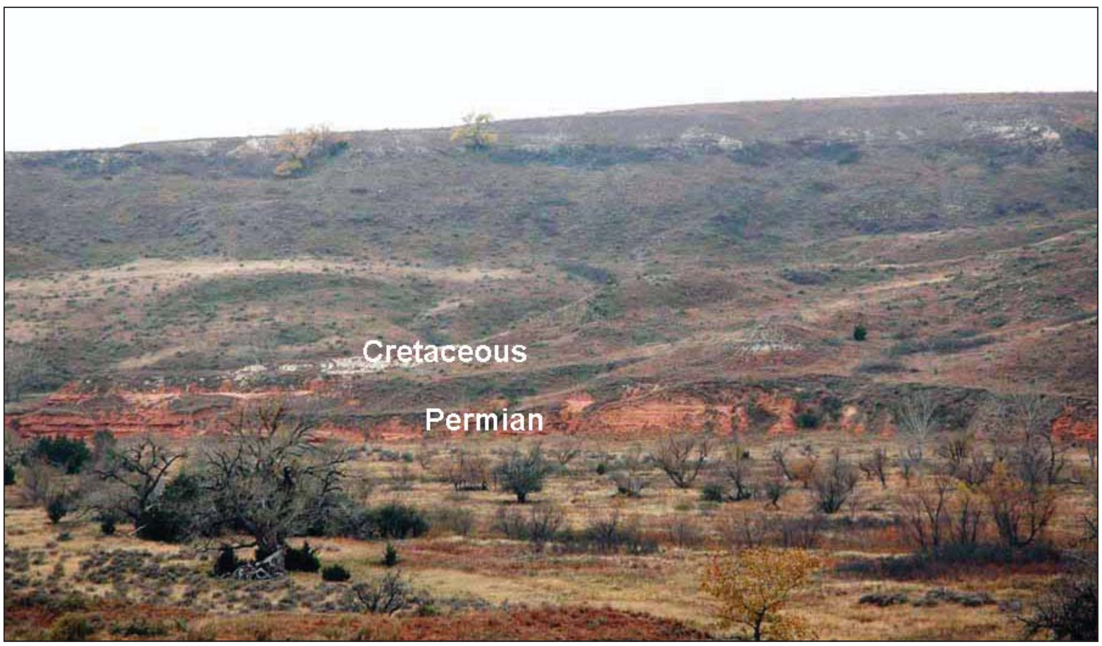


FIGURE 68—View looking west at the Cretaceous–Permian contact from the road on the east side of Clark State Fishing Lake; taken from near center of E/2 sec. 36, T. 30 S., R. 23 W., Clark County, Kansas. The dark-reddish rocks in the lower third of the photo are Permian and the lighter-colored rocks above are Cretaceous.

both from the west and south, produced the Whitehorse formation (sic). The supply of medium-grained clastic material gradually diminished during Whitehorse time, montmorillonite (bentonitic?) clays were deposited, as was also a thin persistent dolomite (Day Creek). The poorly sorted sands and silts of the Taloga formation [today's Big Basin Formation] suggest the incidence of slight instability, and perhaps the deposition of poorly reworked flood-plain debris before the Permian seas withdrew entirely from the area."

The Guadalupian sequence in Kansas, like the underlying Leonardian, is also an appropriate interval for detailed studies within the conceptual framework of sequence stratigraphy and other modern techniques. As noted by Miller and West (1998) relative to paleosol sequences in the Wolfcampian, it will be difficult to recognize and document those events that are essential to this approach. However, careful stratigraphic documentation can only improve our understanding of this unique time during Kansas history.

FIGURE 69—Close-up of the Cretaceous–Permian contact below the dam at Clark State Fishing Lake in the SW sec. 36, T. 30 S., R. 23 W., Clark County, Kansas; red rocks are Permian and lighter-colored rocks are Cretaceous.

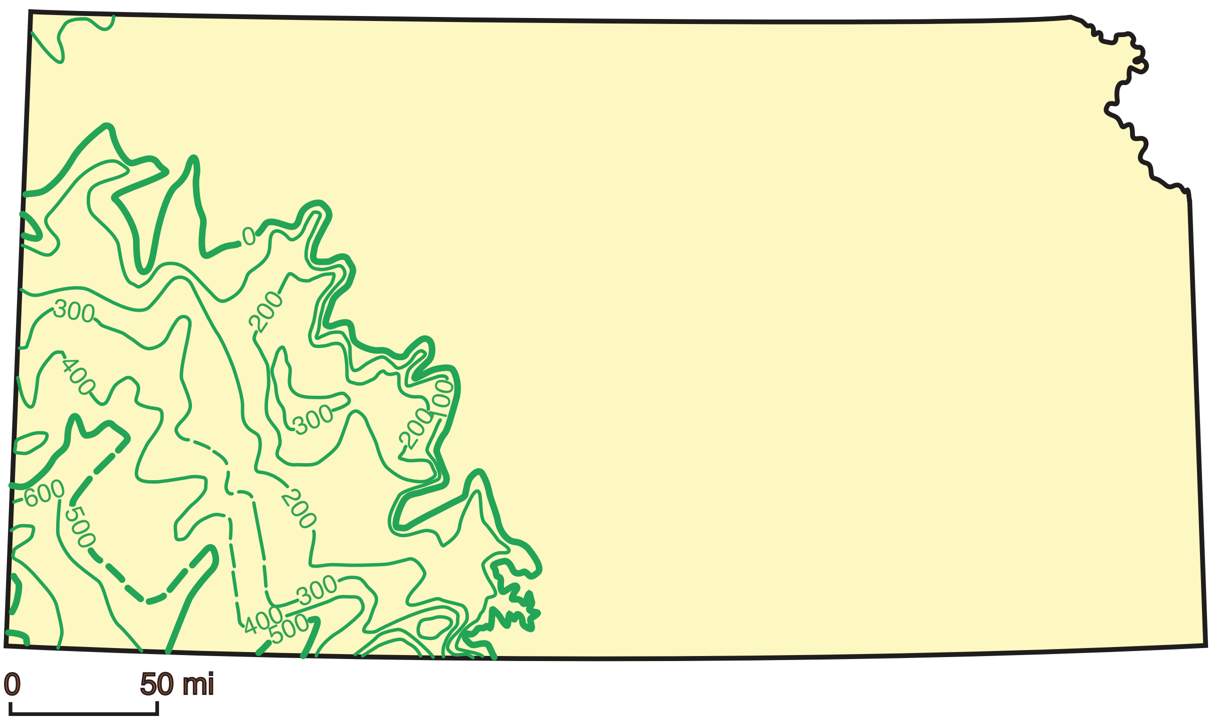


FIGURE 70—Isopach map of Guadalupian rocks in Kansas; contour interval = 100 ft, poor control where dashed (modified from Mudge, 1967, fig. 36, p. 108).

Inferred History of the Permian Period

Cycles and Cycle Hierarchies

Wanless and Weller (1932) introduced the term "cyclothem" to describe upper Carboniferous (Pennsylvanian) cyclicity of the Illinois basin. Jewett (1933) applied the term to the cyclicity he observed in the Permian rocks in Kansas. This description was modified and elaborated by Elias (1937), who placed all the major facies encountered within Permian cycles into an idealized depth-related sequence (see also Moore et al., 1934). A number of detailed sedimentary and paleontological studies of individual Wolfcampian cyclothems and their member-scale lithologic units followed (e.g., Imbrie, 1955; Hattin, 1957; Lane, 1958; Laporte, 1962; McCrone, 1963; Imbrie et al., 1964). Moore (1936) introduced the concept of "megacyclothems" based on his work in the Virgilian of Kansas, and subsequently (Moore, 1964) divided the lower Permian section into megacyclothems, which he correlated across the Kansas outcrop belt.

The facies sequence of Wolfcampian cyclothems typically begins with a thin marine limestone overlain by a gray fossiliferous shale/mudrock. One or more additional limestone-shale/mudrock alternations may follow. An interval of variegated red and green mudrocks with extensive paleosol development lies above these shallow marine facies. This general pattern persists to the top of the Chase Group. Thin dolomite and dolomitic mudrock units occasionally interrupt the thick interval of finer-grained red siliciclastics and evaporites in the overlying Sumner Group. Cyclicity developed in the Hutchinson Salt Member of the Wellington Formation appears to be similar to the Wolfcampian cycles. Also, cyclicity persists in the siliciclastic-dominated intervals of the Sumner and Nippewalla Groups, but detailed stratigraphic classification and nomenclature remain unresolved due to limitations of surface exposures and efforts to distinguish and correlate individual cycles.

The Wolfcampian cyclothems were originally defined using repetitive facies patterns rather than discontinuity surfaces. Elias (1937) constructed smooth depth curves for these cyclothems, even though actual cycles often did not closely match his ideal facies sequence (Mudge and Yochelson, 1962). Nonetheless, Elias (1937) constructed sea-level curves in which the environmental change from deepest to shallowest water were centered on those facies. In particular, he relied on a depth-controlled biofacies model to identify the points of maximum transgression for his cycle model. This resulted in very different curves being drawn for cycles of similar lithologic complexity. The absolute magnitude of sea-level fluctuation and the stratigraphic position of maximum transgression have been subsequently disputed.

Until recently, the focus has remained on the bathymetric interpretation of specific facies rather than on the character of the surfaces that bound them. Although discontinuities are very abundant within the Wolfcampian and are associated in many cases with sharp lithologic contacts, they have received comparatively little attention. Understanding the meaning and temporal duration of these surfaces is critical for defining cycle patterns and periodicities, and for interpreting their regional significance (Miller and West, 1993, 1998). Recent efforts have been made to reinterpret the cyclothems of the Council Grove and Chase Groups within a sequence stratigraphic context (Mazzullo et al., 1995, 1997; Mazzullo, 1998; Miller and West, 1998; Boardman and Nestell, 2000; Olszewski and Patzkowsky, 2003; Boardman et al., 2009). Furthermore, Mazzullo (1998) has attempted to define systems tracts within the Chase Group cycles. Such efforts mark an important future direction for cyclostratigraphic research in the midcontinent. In other recent work, the occurrence of certain trace-fossil associations have been found to correlate with hiatuses in deposition associated with transgressive and regressive events (Chaplin, 1996). Thus, ichnology may provide another tool for identifying these important surfaces in the subsurface.

Sequence boundaries are defined as unconformities resulting from erosional truncation or subaerial exposure and their correlative conformities (van Wagoner et al., 1988). Although not necessarily associated with maximum eustatic sea-level lowstand, sequence boundaries do represent the maximum seaward limit of terrestrial sedimentation and the time of maximum subaerial exposure of the shelf (Posamentier et al., 1988). However, on the shelf, depositional sequence boundaries are difficult to recognize beyond the limits of individual valley-fill systems (van Wagoner et al., 1990; Aitken and Flint, 1995). This problem is accentuated in the Permian of Kansas where incised valleys and valley fills are virtually absent. Furthermore, the red and green mudrock intervals of the Permian cyclothems are commonly composed of multiple subaerial exposure surfaces ranging from desiccation cracks to mature paleosols (Joeckel, 1991; Miller and West, 1993; Miller et al., 1996). Stacked paleosol profiles are ubiquitous features. The problem of identifying sequence boundaries thus becomes one of the determining criteria for selecting among several exposure surfaces in a stacked series. Although defining precise boundaries is difficult, general sequence boundary intervals can nonetheless be recognized. When rocks of marine origin overlie paleosols, sequence boundaries are more easily recognized as shown by Olszewski and Patzkowsky (2003).

Another important surface in depositional sequences is the marine transgressive surface. Correlation of midcontinent Wolfcampian cyclothems, on the outcrop and in the subsurface, has historically been based on marine limestones that can be recognized from Nebraska to Oklahoma. The base of the stratigraphically lowest, fossiliferous, fully marine limestone occurring above a paleosol-bearing interval is equivalent to the transgressive surface (van Wagoner et al., 1988). Commonly, these marine limestones directly overlie and partially truncate the uppermost paleosol profiles. The contacts often appear to be erosive, although little or no relief is evident at an outcrop scale, and are typically overlain by intraclastic beds up to 20 cm (0.7 ft) thick (Miller and West, 1998). These transgressive surfaces can be identified with relative confidence and also can be used as informal boundaries for the cyclothems (figs. 16A–C, 28A–D).

Meter-scale cycles are both ubiquitous and prominent within the Wolfcampian cyclothems of eastern Kansas (Archer et al., 1995; Miller and West, 1993, 1998; Olszewski and Patzkowsky, 2003). Flooding surfaces overlie paleosol profiles and other indicators of subaerial exposure, or mark sharp changes in depth as indicated by lithology and fossil content. Thin (<2-cm-thick) skeletal and/or intraclastic lags mark these cycle-bounding flooding surfaces. A variety of carbonates ranging from marine bioclastic limestones to laminated intertidal limestones and calcareous mudrocks overlie the flooding surfaces. These carbonate facies are followed by siliciclastic units that include gray fossiliferous mudrocks and variegated red and green mudrocks. Although rocks containing evidence of subaerial exposure cap many of these small-scale cycles, they do not show basinward shifts of facies.

At the other end of the temporal hierarchy from meter-scale sequences, Ross and Ross (1988) have argued that the upper Carboniferous (Pennsylvanian) and Permian cyclothems can be grouped into larger-scale transgressive-regressive cycles that can be recognized and correlated among the world's cratonic shelves using fusulinids, bryozoans, and other taxa. They recognized four such globally correlated cycles within the Council Grove and Chase Groups. The first begins at the Roca Shale and extends upward to the Grenola Limestone, the second extends from the Eskridge Shale to the Wreford Limestone, the third from the Matfield Shale to the Barneston Limestone, and the fourth from the Doyle Shale to the Nolans Limestone. Ross and Ross (1988) also identified four global cycles within the overlying Sumner and Nippewalla Groups. The Wellington Shale, Ninnescah Shale to Stone Corral Formation, Harper Sandstone to Salt Plain Formation, and Cedar Hills Sandstone to Dog Creek Formation represent these cycles. However, the lack of fossils, faunal provinciality, and the common occurrence of restricted environments in stable cratonic areas prohibited them from recognizing and correlating cycles in the upper Permian. Interestingly, the thickest and most widespread limestone units cap the lower Permian (Wolfcampian) cycles of Ross and Ross (1988). Similarly, the variegated mudrock units at the base of these cycles all contain evidence of significant times of subaerial exposure with some of the most mature paleosol profiles in this stratigraphic interval. This suggests that the cycles delineated by Ross and Ross (1988) may indeed record the transgressive and regressive extremes of a higher-level cyclicity.

Cycle durations for the upper Carboniferous (Pennsylvanian) cyclothems of the midcontinent have generally been estimated at 200,000 to 400,000 years (Heckel, 1986). This periodicity provides a first approximation for cyclothem duration in the Permian. Within the Permian, generally 4–6-m-scale cycles occur within each cyclothem (Miller and West, 1993) and thus probably record time-periods of 40,000 to 100,000 years. These values are in broad agreement with the common occurrence of mature paleosols capping these meter-scale cycles that likely required tens of thousands of years to form. The large-scale, globally correlated cycles identified by Ross and Ross (1988) are estimated to range from 1.2 to 4 million years in duration, with an average of 2 million years.

Higher-level cycle sets were also recognized in the upper Carboniferous (Pennsylvanian, Missourian) strata (Watney et al., 1995). These cycle sets are based on stacking patterns of lower-level cycles along the shelf margin bordering the northern Anadarko basin and parallel changes in the development of cycle components, particularly "core" shales and paleosols. Trend analysis of Th/U ratios obtained by gamma-ray spectral logs show distinctive and coupled patterns of redox conditions in these strata at different positions on the Kansas shelf (Watney et al., 1992, 1995).

Controls on Cyclicity and Sedimentation

Like the upper Carboniferous (Pennsylvanian) cyclothems of the midcontinent, sedimentary cycles of the Wolfcampian probably record glacio-eustatic fluctuations in sea level as well as paleoclimatic and tectonic influences on clastic-sediment supply. Wanless and Shepard (1936) were the first to propose a glacio-eustatic model for cyclothem formation in the upper Carboniferous (Pennsylvanian). This model was followed by Elias (1937) in his interpretation of the lower Permian cycles. The widely accepted cyclothem model of Heckel (1977), based on the Missourian of Kansas, also assumes primary eustatic control. Recent models for Permian cyclothems have incorporated climatic as well as eustatic controls on the observed lithologic patterns (Miller and West, 1993; Miller et al., 1996; West et al., 1997; Olszewski and Patzkowsky, 2003).

Because upper Carboniferous (Pennsylvanian) to Permian sedimentary cycles coincide temporally with Gondwanan glaciation (Crowell, 1978; Veevers and Powell, 1987; Crowley and Baum, 1991), glacio-eustasy is recognized by most workers as the predominant forcing mechanism for cycle formation. Climatically forced eustatic models have been supported by comparisons of the estimated periodicities of upper Carboniferous (Pennsylvanian) cyclothems with Milankovitch orbital modulations (Heckel, 1986, 1994; Boardman and Heckel, 1989; Boardman and Nestell, 1993). The estimated cycle duration and the observed nested hierarchy of cycles are broadly consistent with glacio-eustatic curves reconstructed from the Pleistocene isotopic record (Denton and Hughes, 1983; Crowley and North, 1991). It also is significant that the glacially driven Pleistocene cycles are asymmetric with rapid sea-level rises followed by slow falls interrupted by minor deepening. This pattern seems to mimic that seen in the lower Permian (and upper Carboniferous) cycles with abrupt transgressive surfaces at the bases of cyclothems followed by a series of flooding surface-bounded meter-scale cycles (Watney et al., 1991; Miller et al., 1996).

Changes in the global extent of glacial ice cover would be expected to affect both the potential amplitude of glacio-eustatic sea-level fluctuations and the amount of exposure of the midcontinent "shelf" during lowstand. A recent summary of the age distribution of glacial deposits by Frakes et al. (1994) suggested two peaks in continental glaciation: one in the Westphalian (Desmoinesian) and one in the Asselian–Sakmarian (Wolfcampian). Although both Desmoinesian and Wolfcampian cyclothems were formed during times of extensive Gondwana glaciation, they are very different in their lithologic compositions (West et al., 1997). Generally, Desmoinesian cycles are siliciclastic with associated coal beds, Missourian cycles are largely carbonate, siliciclastics are more conspicuous in Virgilian cycles, and well-developed paleosols typify the Wolfcampian. These differences probably reflect the increasing emergence of continents during the Carboniferous and Permian as well as long-term climatic change. Emergence of the shelf and shallowing of seaways that connected Kansas with the Permian ocean are supported by the evaporitic cycles that dominated Leonardian deposition. The rapid waning of glaciation at the end of the Wolfcampian explains the absence of well-developed cyclothems in post-Leonardian rocks.

Several observations at both the meter and cyclothem scale indicate that climate, in addition to sea-level change, must be considered to adequately explain the lithologic expression of the cyclicity. First, a consistent carbonate-to-siliciclastic pattern of meter-scale sequences exists within both the open-marine facies and paleosol-bearing intervals of cyclothems. Both carbonate and clastic units display a range of facies recording environments from open marine to subaerial exposure (Miller and West, 1993). A simple bathymetric facies model does not work for these cycles. Furthermore, the shallow marine and paralic facies of the carbonate units typically contain dry-climate indicators such as replaced-gypsum nodules, evaporite-crystal molds, laminated dolomitic mudrocks, and tepee structures. When present in the subsurface, bedded gypsum commonly is closely associated with carbonate units. For example, within the Council Grove and Chase interval in Riley County, subsurface gypsum beds occur above the Burr limestone, above the Middleburg limestone, immediately below the Kinney limestone, and at the top of the Fort Riley limestone (Twiss, 1991a). Thus, relatively arid conditions seem to be associated with times of carbonate deposition. These observations are consistent with a model for climatic control over facies development proposed by Cecil (1990). In this model, clastic sediment transport is predicted to be highest in seasonal wet-dry climates and lower in both arid and tropical wet climates (see also Wilson, 1973; Perlmutter and Matthews, 1989). Carbonates and evaporites accumulate during arid and semiarid conditions, and mappable coal beds form during relatively wet climates where clastic influx is low. This model of climatic control over chemical and clastic deposition can be combined with paleosol evidence and sea-level curves to yield integrated models for cyclothem formation (Miller and West, 1993).

Halite, in cycles dominated by halite, represents an extension of the dry-climate carbonate phase. The thick mudrock that caps the halite-dominated cycles was deposited late during the regression, and the associated dissolution of the underlying halite can be explained by a change from dry to a seasonal wet-dry climate, analogous to the carbonate-siliciclastic cycle. Alternatively, inundation during halite accumulation may have flooded the basin margin and inhibited clastic influx.

A persistent pattern has been recognized in the characteristics of the paleosols and exposure surfaces of successive meter-scale cycles within a given cyclothem (Miller et al., 1996; McCahon and Miller, 1997). For most of the thicker variegated mudrock units within the Council Grove and lower Chase Groups (i.e., Roca Shale, Eskridge Shale, Blue Rapids Shale, Speiser Shale, and Matfield Shale), a very similar vertical succession of paleosol profiles has been observed. Paleosols from the lower part of these units have reddish-brown calcic profiles with carbonate nodules and rhizocretions indicative of semi-arid to subhumid conditions. By contrast, pseudoanticlines (mukkara structures) and other features of vertic paleosols that form under highly seasonal monsoonal conditions characterize the uppermost greenish-gray paleosols within these units. When present, salt-influenced natric paleosols occur near the base or top of variegated mudrock intervals (i.e., Roca Shale, Hooser Shale, Easly Creek Shale) or within gray-mudrock units sandwiched between marine carbonates (i.e., Legion shale and Salem Point shale) (McCahon and Miller, 1997). These lithologic and paleosol patterns suggest that climate changed together with relative sea level during the course of cyclothem deposition. In order of decreasing aridity, a spectrum of features can be recognized as follows: evaporites, tepee structures, laminated dolomitic mudrocks, natric paleosols, calcic paleosols, vertic paleosols, and organic-rich shales. The consistent vertical pattern of these climatically sensitive sedimentary features within Wolfcampian cycles indicates that climate changed from arid to progressively wetter and more seasonal conditions during the formation of each cyclothem (Miller et al., 1996; McCahon and Miller, 1997).

Climate Change

A spectrum of lithologic and paleosol climate indicators provides a basis for reconstructing climate change within the early Permian (Wolfcampian) of Kansas. Patterns of change in these climate indicators reveal a hierarchy of cyclic climate changes from those occurring during the formation of single paleosols (recording tens of thousands of years) to long-term climate trends encompassing the entire late Paleozoic.

Meter-scale Cycles

At the highest level of stratigraphic resolution, climate change can be recognized within meter-scale cycles (Miller et al., 1996). The consistent carbonate-to-clastic pattern of these meter-scale cycles, regardless of their position within the cyclothem, suggests some climatic control (fig. 71). The paleosols capping these cycles are commonly composite or polygenetic profiles and provide additional climate information. In nearly all cases, the latest stage of pedogenesis seems to have occurred under the driest conditions. The reddish-brown calcic paleosol profiles, for example, have the highest carbonate concentrations above horizons showing well-developed clay cutans, suggesting carbonate precipitation following clay illuviation.

Cyclothems

The lithofacies and paleosols of successive meter-scale cycles within cyclothems of the Council Grove and Chase

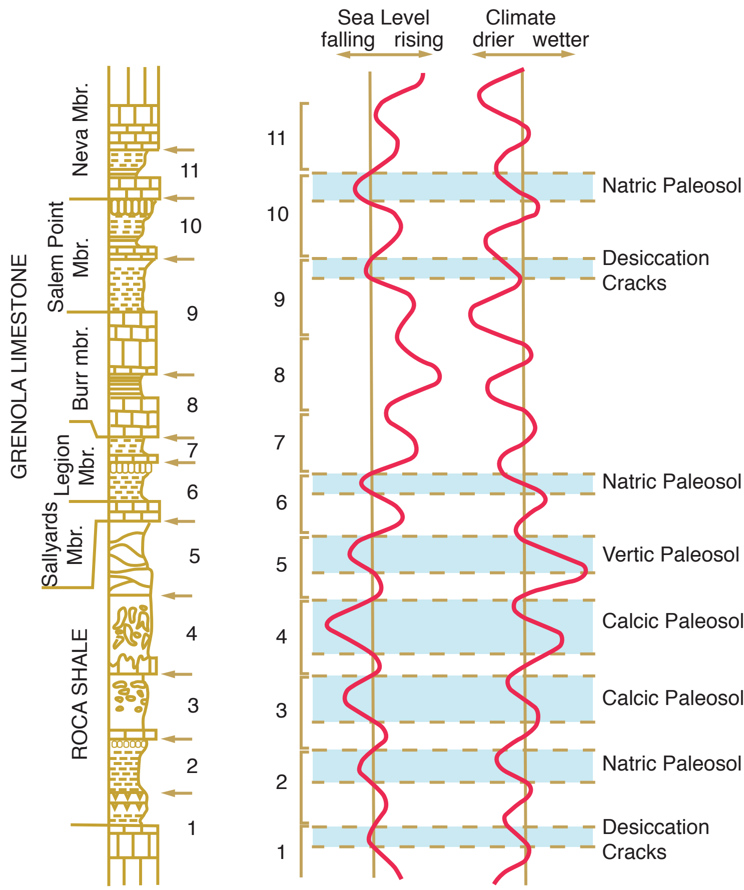


FIGURE 71—Interpreted relative sea-level and climate curves for the Roca Shale and Grenola Limestone. Arrows mark flooding surfaces that bound meter-scale parasequences. The vertical line for the sea-level curve marks the sediment surface, a position to the left represents subaerial exposure and paleosol development. The vertical line for the climate curve indicates the threshold between carbonate deposition (drier climate) and siliclastic deposition (wetter climate) (modified from McCahon and Miller, 1997).

Groups indicate climate trends toward wetter and more seasonal climates (fig. 71). The carbonates and mudrocks of meter-scale cycles immediately above transgressive surfaces usually do not contain diagnostic climatic indicators. However, the shallow-marine and paralic facies of the carbonate units of subsequent meter-scale cycles typically contain dry-climate indicators. Within the overlying variegated-mudrock facies of cyclothems, meter-scale cycles with salt-influenced natric paleosols occur below those with calcic paleosols, thus recording semiarid conditions that, in turn, occur below those with vertic paleosols, indicating monsoonal climates. Based on the interpreted maturity of paleosol development, the boundary intervals of the cyclothems tend to be located near the middle of the variegated mudrock facies (Miller and West, 1998). A straightforward reading of this pattern would result in the conclusion that the driest climates were associated with early highstand (i.e., occurring a few meter-scale cycles above the transgressive surface), and the wettest climates with lowstand (i.e., within meter-scale cycles between the sequence boundary and transgressive surface) (McCahon and Miller, 1997; Miller and West, 1998).

Long-term Climate Changes During the Permian

Parrish (1998) has addressed pre-Quaternary climate changes based on the geologic record. Based on the distribution of coals, red beds, eolian sandstones, and evaporites, a consistent trend toward increased aridity has been recognized in North America from the late Carboniferous into the Triassic (Parrish, 1993; Parrish and Peterson, 1988; Kutzbach and Ziegler, 1993; Golonka and Ford, 2000; Gibbs et al., 2002). This drying trend also is recorded in the paleobotanical record (Phillips and Peppers, 1984; Phillips et al., 1985; Cross and Phillips, 1990; DiMichele and Aronson, 1992; DiMichele et al., 2001; DiMichele et al., 2009). Within the midcontinent, a long-term climate trend toward increased aridity is recorded by the increase of red terrigenous clastics and evaporites and the virtual absence of coal beds and channel sandstones within the Permian relative to the upper Carboniferous (Pennsylvanian) (West et al., 1997). In particular, the Wolfcampian seems to have been a time of major climatic transition from generally wetter conditions in the Virgilian to significantly drier conditions in the Leonardian and Guadalupian. This trend is reflected in the changing lithologic composition of cyclothems (West et al., 1997). In particular, carbonates become progressively dominated more by sabkha-like dolomitic and peritidal facies with nodular evaporites (Mazzullo et al., 1995, 1997), and the clastic intervals become increasingly silty. Calcic and vertic paleosols characteristic of the Council Grove Group give way to more poorly developed paleosols and evidence of evaporites. No well-developed vertic paleosols, indicating monsoonal conditions, appear above the Wymore Shale Member of the Matfield Shale.

Climate Models

Two global climate models attempt to explain the climate trends within Wolfcampian glacial/interglacial cycles, as well as the longer-term trend toward drier climates throughout the Permian. One of these models assumes a zonally organized global climate system, and the other emphasizes the establishment of a non-zonal circulation pattern caused by an intensifying Pangean "megamonsoon."

Using a zonal model of global circulation, Matthews and Perlmutter (1994) attempted to predict the general direction and extent of climatic change during glacial-interglacial cycles. The humid and arid climatic zones of the earth today are largely controlled by the position of global atmospheric-circulation cells. Latitudinal shifts in these circulation cells associated with Milankovitch-driven cyclicity would have resulted in the latitudinal migration of climatic zones. During glacial periods the mid-latitude dry high-pressure atmospheric-circulation cells would shift toward the equator, and during interglacials the humid equatorial low-pressure cell (Inter-Tropical Convergence Zone) would expand into higher latitudes (Matthews and Perlmutter, 1994). These shifts of circulation cells during glacial-interglacial cycles could generate climate alternations between humid tropical during interglacials to arid temperate during glacials, but only for latitudes between 15 and 20 degrees. However, more recent paleogeographic reconstructions (Witzke, 1990; Scotese and McKerrow, 1990; Scotese and Golonka, 1992) do not place the midcontinent above 10 degrees north by Wolfcampian time (compare the position of Kansas in figs. 51, 52).

The zonal model also may be relevant to understanding the long-term climate trend toward increasing aridity from the late Carboniferous through the Permian. One problem in applying this zonal global climate model to the Permian of the midcontinent is the uncertainty in determinations of paleolatitude. Was the progressive northward movement of Pangea sufficient to move the region of the midcontinent into higher and drier latitudes? The paleogeographic reconstructions of Witzke (1990) show a northward shift of Kansas from near the equator to about 20 degrees north from the middle Morrowan (Westphalian) to the Guadalupian, a change in latitude that might well have had a major impact on long-term climate change. However, alternative reconstructions by Scotese and McKerrow (1990) show only a shift from 3 degrees south to 12 degrees north for the same time interval.

As an alternative to the zonal model, global circulation models for Pangea (Parrish et al., 1982; Kutzbach and Gallimore, 1989; Crowley et al., 1989; Patzkowsky et al., 1991) have strongly indicated the presence of a monsoonal circulation pattern that intensified from the early Permian to a maximum in the Triassic. Development of this Permian "megamonsoon" was a consequence of the assembly of the Pangean supercontinent and the increasing symmetry of the landmass across the equator (Parrish, 1993). Establishment of a Permian monsoon would have disrupted zonal circulation and diverted the moisture-laden equatorial easterlies flowing from the Tethys, resulting in a drying of equatorial Pangea. With the development of a monsoonal circulation pattern, the drying of the midcontinent in the Permian can be explained even if the Kansas area remained within low paleolatitudes.

Miller et al. (1996) have proposed a cycle model assuming that the climate of the midcontinent was strongly affected by a Pangean monsoon, and fluctuations in the intensity of the monsoon produced oscillations between wetter and drier conditions. Both climate models (Kutzbach and Guetter, 1984) and Pleistocene paleoclimate data (Fairbridge, 1986; Crowley and North, 1991; McKenzie, 1993) indicate that monsoons are strengthened during early interglacial periods and significantly weakened during glacial periods due to albedo effects. Thus, during interglacial periods when the monsoon was strong, the wet equatorial air would have been diverted to the north or south, resulting in a dry midcontinent. However, the weakening of the monsoon during glacial periods would have permitted the equatorial easterlies to penetrate into the continental interior. This model thus predicts that strong monsoons during interglacial highstands would have been associated with more arid conditions in the midcontinent, and weakened monsoons during glacial lowstands would have been associated with wetter, although still very seasonal, conditions.

The timing and location of orogenic activity also may have had a significant impact on midcontinent climate. Gondwana and Laurasia collided in the Namurian (Chesterian) to produce the Appalachian and Mauritanide mountains. As discussed by Rowley et al. (1985), the rise of this high mountain range should have acted as a high-altitude heat source producing an area of low pressure, in a manner similar to the modern Himalayas. Being located at the equator, however, these mountains would have intensified the normal equatorial low pressure, thus inhibiting the development of fully monsoonal conditions and producing high rainfall in the mountains (Rowley et al., 1985; Patzkowsky et al., 1991; Otto–Bliesner, 1993). However, with the end of orogenic activity and the subsequent erosion of the mountains, their climatic influence would have declined, permitting the development of fully monsoonal conditions during the Permian (Rowley et al., 1985). This scenario is supported by changes in the coal-swamp vegetation of the Appalachian basin during the upper Carboniferous (Pennsylvanian) (Phillips et al., 1985). The delay in establishment of a Pangean monsoon caused by the Alleghenian Orogeny may have made the onset of monsoonal conditions more abrupt. Perhaps this accounts for the rapid climatic shift in the Wolfcampian suggested by the cyclothems in Kansas (West et al., 1997).

Economic Aspects

General

Hydrocarbons (oil and gas), salt, gypsum, building stone, aggregate, and ground water are the main economic products associated with Permian deposits in Kansas. Underground salt mines (Hutchinson Salt Member) have been utilized for large underground storage areas that provide conditions of relatively constant temperature and humidity. Although salt is an abundant important natural resource, the Permian red-bed sequence in Kansas has been a source of gypsum, paint pigment, building stone, construction aggregate, and clay for bricks (Swineford, 1955, p. 166).

Hydrocarbons

Hydrocarbon production, particularly natural gas, has been important in Kansas since the 1930s (Carr and Sawin, 1997, p. 1). Within the Hugoton embayment in southwestern Kansas, the largest areas of natural gas production are the Panoma field in the Council Grove Group and the Hugoton field in the Chase Group (Carr and Sawin, 1997). Minor gas production from the Chase Group occurs in central Kansas over structurally controlled oil fields whose main production is from deeper reservoirs.

The decline in reserves and production of natural gas in carbonate and siliciclastic reservoirs of the Chase and Council Grove Groups in the giant Hugoton and Panoma fields has led to renewed efforts to characterize these reservoirs by petroleum geologists. Over 27 trillion cubic feet (TCF) of gas has been produced from these fields covering over 4,100 mi^2 (10,620 km^2) and containing nearly 8,000 producing wells in Kansas. These fields comprise the largest gas area in the western hemisphere. Gas accumulated in a giant structural-stratigraphic trap as porous and permeable carbonate reservoirs grade updip to nonpermeable fine-grained siliciclastics. Anhydrite beds of the overlying Sumner Group form effective seals that trap the gas. The original pore volume of gas in place in the Hugoton field alone is estimated at 34.5 to 37.8 TCF (Olson et al., 1997). Thus, an estimated 10 TCF of natural gas is available as a target for improved recovery technologies.

Regional correlation of Chase and Council Grove strata from the outcrop to the subsurface using both cores and wireline logs enhances the application of formal stratigraphic classification and nomenclature to the petroleum reservoirs. Using this stratigraphic information, a sedimentologic and petrophysical framework aids in the construction of quantitative three-dimensional diagrams of reservoirs in these gas fields. Mapping of genetic units and lithofacies in conjunction with structure indicates a distinct association with the regional shelf-to-basin configuration of the shelf, modified by local changes in inferred paleotopography. Thus, shelf elevation and sediment accommodation space created by eustasy exerted significant controls on the details of the reservoir architecture.

Salt

Significant salt accumulations occur at three positions in the Permian of Kansas; these are, from the oldest to youngest: 1) Hutchinson Salt Member in the Wellington Formation (Wat-

FIGURE 72—Underground mining of Permian salt in Reno County, Kansas; from photo files of the Kansas Geological Survey.

FIGURE 73—Room-and-pillar mining of salt at Hutchinson, Kansas; from Sawin and Buchanan (2002, p. 3, fig. 5).

ney et al., 1988), 2) Ninnescah Formation, and 3) in the Blaine Formation and Flower-pot Shale (Sawin and Buchanan, 2002). Sawin and Buchanan (2002, p. 2, fig. 3) illustrated the areal extent of these three natural occurrences of salt in Kansas. Salt has been mined from the Hutchinson Salt Member of the Wellington Formation in central Kansas since the late 1800s for use as a food preservative, rock salt for livestock and ice melting, table salt, and industrial applications (fig. 72). Both room-and-pillar and solution salt mining in Kansas are accomplished at relatively shallow depths (under 1,000 ft [305 m]) in proximity to the Hutchinson Salt Member subcrop, thus the mine locations in central Kansas (Sawin and Buchanan, 2002). Large open rooms left after salt removal by room-and-pillar techniques (fig. 73) are used for underground storage of vital records and documents in one of the Hutchinson mines. Salt removed by solution methods creates cavities or vugs. Some of these vugs are created solely for storage of liquefied petroleum (LPG) and natural gas. Today's solution mining leaves at least 50 ft (15 m) of halite above the solution cavity to ensure that the sealing and plastic behavior of the halite envelops the cavities.

The total underground-gas-storage capacity in Kansas amounts to over 302 billion cubic feet (BCF) with less than 1% of this storage in salt caverns (Energy Information Administration, 2005). The combined gas storage and pipeline capacity in central Kansas has resulted in this area becoming one of several large national hubs for natural gas transmission.

The Hutchinson Salt Member was considered for possible underground storage of nuclear-waste products near Lyons, Kansas, in the early 1970s. However, concerns for unaccounted, abandoned, and unplugged oil and gas wells that penetrated the salt precluded implementation of the nuclear-waste storage (Angino and Hambleton, 1971; Walker, 2006–07). Abandoned, unplugged wells in the Hutchinson Salt Member also factored into the catastrophic gas escape and explosions at Hutchinson, Kansas, in January 2001.

An additional hazard can occur when the salt beds are near the present-day land surface where it is easily dissolved by ground water. The dissolution of the salt creates cavities, sometimes quite large, that can result in the collapse of the rock layers overlying the salt. Such collapse produces surface depressions called sinkholes (Sawin and Buchanan, 2002, p. 5, fig. 6).

Gypsum

Gypsum and anhydrite, both calcium sulfate minerals, commonly occur in the Permian rocks of Kansas (figs. 74, 75) and are often associated with beds of salt. All three of these minerals are precipitated from seawater with salt being precipitated after the calcium sulfate minerals. Although gypsum and anhydrite are common in the Permian rocks of Kansas, there are only three areas (all different rock layers) where the occurrence of gypsum is economical. These are, from oldest to youngest, 1) Easly Creek Shale in Marshall and eastern Washington counties; 2) Wellington Formation in Dickinson, Saline, and Marion counties; and 3) Blaine Formation in Comanche and Barber counties (Jewett, 1942; Kulstad et al., 1956). Gypsum mining was well established in Marshall County by 1872 (Jewett, 1942), and high-quality gypsum is still mined from a 1.5–1.8-m (5–6-ft)-thick bed at the base of the Easly Creek Shale near Blue Rapids, Kansas.

A number of gypsum mines operated in the Wellington Formation in central Kansas between the late 1880s into the

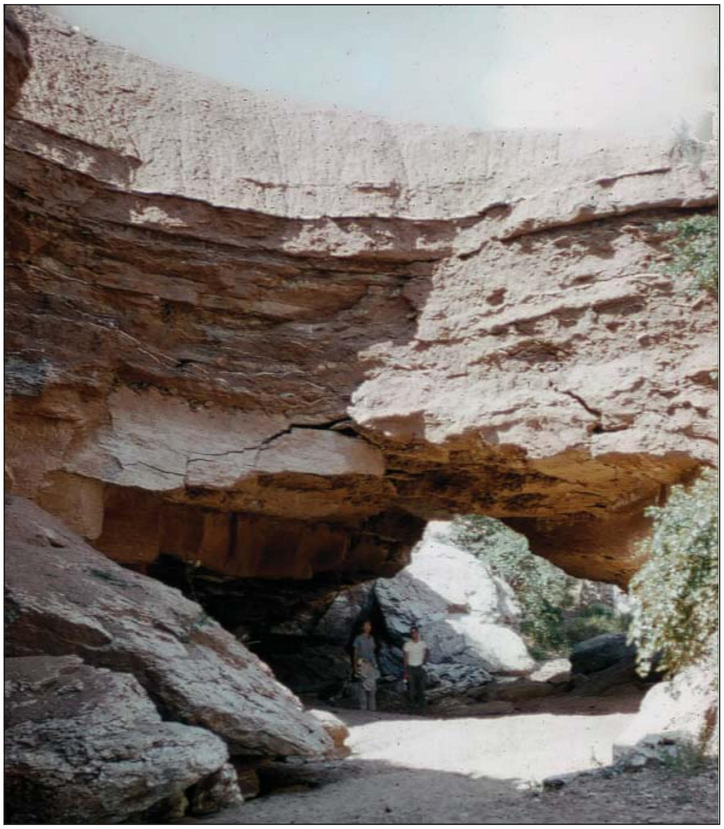


FIGURE 74—Natural bridge (now collapsed) in Barber County, Kansas, created by the solution of soluble minerals, halite and gypsum; from photo files of the Kansas Geological Survey.

FIGURE 75—Entrance to Big Gyp Cave in the Blaine Formation in the Red Hills of Comanche County, Kansas; from photo files of the Kansas Geological Survey.

1940s (Kulstad et al., 1956). The mine at Gypsum City in Saline County was awarded a medal for the quality of the plaster it provided for the buildings at the 1893 Chicago World's Fair (Kulstad et al., 1956, p. 55).

The "Red Hills" (Jewett, 1942, p. 140), also known as the "Gypsum Hills" (Kulstad et al., 1956, p. 24), in south-central Kansas are so named because this is the general outcrop area of gypsum in the Blaine Formation. Mining of gypsum began near Medicine Lodge, Kansas, in the 1880s. Today, gypsum from a mine and quarry at Sun City is converted to a stucco (referred to as plaster of Paris) that is used in the manufacture of gypsum wallboard (Sawin et al., 2002).

Although gypsum is a useful natural resource (Kulstad et al., 1956), it along with anhydrite can, because of their solubility, be a hazard to near-surface structures. Solution of these soluble calcium sulfate minerals can result in surface depressions (fig. 76) such as the Big Basin in Clark County, Kansas. In such areas the ground surface can be unstable and still subsiding.

Building Stone and Aggregate

Building stone and aggregates are quarried from the limestone beds of Wolfcampian age along the eastern edge of the Permian outcrop. Stone from most of these limestone beds has been used at one time or another for buildings, especially locally by early settlers where trees were scarce or absent (Risser, 1960). The most commonly used Permian limestones for public and residential buildings are the Neva, Cottonwood, Funston, Fort Riley, and Cresswell (Risser, 1960; Grisafe, 1976; Aber and Grisafe, 1982). Although soft, vuggy limestone (parts of the Neva) and hard limestone containing chert (Threemile, Schroyer, Florence, and parts of the Cottonwood and Cresswell) are not suitable building stone, these limestones are crushed and used for aggregate (Risser, 1960). Two of the best-known building stones in Kansas are the Cottonwood (fig. 77) and Fort Riley (fig. 78); at one time the Cottonwood was the most important source of building stone in the state (Risser, 1960, p. 106). The Cottonwood was extensively quarried in Chase County (fig. 79) and was used in the construction of the Chase County Courthouse. Near Silverdale, Kansas, in Cowley County, the Fort Riley has produced what is called the "Silverdale" (fig. 80), and in Geary County limestone from the Fort Riley is known as the "Junction City" (fig. 81; Risser, 1960). Original buildings on the Fort Riley Military Reservation were constructed using "Junction City" stone.

Grisafe (1997, p.1, fig. 1) showed the location of 13 crushed-stone (aggregate) operations across the Permian outcrop of Kansas. Although the stratigraphic unit being used was not indicated, it is safe to assume that some, if not all, of these operations were using Permian rocks. Aggregate is widely used in construction and road maintenance.

Ground Water

Ground water is available to farms and small communities from limestone aquifers in the Council Grove, Chase, and Sumner Groups. Wells, streams, and springs receive water from these aquifers and wells may yield up to 100 gallons per minute and springs a much greater amount (Buchanan and Buddemeier, 1993). Sawin et al. (1999) provided information on 47 springs in the Flint Hills, including historic data for 13. Of these, 11 are springs and two are artesian wells. Water from one of the artesian wells is from the Barneston Limestone; the source of the water in the other is not known (Sawin et al., 1999, table 6). The source of the water in the 11 springs is the Wellington Formation, Winfield Limestone, Barneston Limestone, and Wreford Limestone. Water for most of the springs comes from the Barneston Limestone (Sawin et al., 1999, table 6). Also a number of unnamed springs supply water for domestic use, livestock, and farm ponds (Sawin et al., 1999, p. 27).

A common stop along the Santa Fe Trail in the 19th century was Diamond Springs and others in Morris County, and even today a local spring is the source of the municipal water for Florence in Marion County (Buchanan and Buddemeier, 1993; Sawin et al., 1999).

Opportunities

Questions being raised by current research based on a foundation of over a century of geological studies pose a number of exciting directions for future work. At least four broad areas provide clear opportunities for significant contributions to our understanding of the midcontinent Permian: 1) climatic history of the midcontinent, 2) relationship between basement structure and tectonism to facies distributions, 3) source and diagenesis of Permian clastic sediments, and 4) prediction and delineation of systems tracts, meter-scale cycles, and lithofacies and associated petrophysical properties in a regional, three-dimensional framework. Enhancing our understanding in these four areas can best be accomplished through multidisciplinary research involving chronostratigraphy, sequence stratigraphy, climate history, structural controls, and sediment transport and diagenesis.

Chronostratigraphy

Further refinement in temporal control of the Permian section will provide important insights into many outstanding questions about midcontinent geologic history. The benefits of improved chronostratigraphy include 1) improved regional and global correlation; 2) better estimates of the temporal duration of sedimentary cyclicity and of the forcing glacio/eustatic fluctuations; and 3) the detailed calibration of paleoclimate records for better understanding the evolution of the Permian climatic system. An important step toward this end recently has been made with the biostratigraphic identification of the Carboniferous/Permian boundary within a well-exposed stratigraphic section in northeastern Kansas (Boardman et al., 1998; Sawin et al., 2006). The ongoing comprehensive

FIGURE 76—Sinkhole in a pasture in Clark County, Kansas; from photo files of the Kansas Geological Survey.

FIGURE 77—Roadcut exposure of Cottonwood Limestone Member of Beattie Limestone along northwest side of K–13, just south of center, sec. 18, T. 9 S., R. 8 E., Pottawatomie County, Kansas.

FIGURE 78—Exposure of lower beds and “rimrock” of the Fort Riley Limestone Member of the Barneston Limestone; near center of east line NE sec. 30, T. 12 S., R. 6 E., Geary County, Kansas.

FIGURE 79—Bayer Stone Company quarry in the Cottonwood Limestone Member of the Beattie Limestone; NW sec. 36, T. 19 S., R. 8 E., Chase County, Kansas; courtesy of R. S. Sawin.

FIGURE 80—Quarry in the “Silverdale” Fort Riley Limestone Member of the Barneston Limestone near Silverdale in Cowley County, Kansas; from photo files of the Kansas Geological Survey.

FIGURE 81—Quarry in the “Junction City” Fort Riley Limestone Member of the Barneston Limestone near Junction City in Geary County, Kansas; from photo files of the Kansas Geological Survey.

biofacies analysis of the Virgilian and Wolfcampian interval, including conodonts, fusulinids, and ammonoids (Boardman, 1993; Boardman and Nestell, 1993; Boardman et al., 2009; and others), promises both an improved paleoecologic resolution and a more precise chronostratigraphy.

In the absence of commonly occurring dateable ash beds, more sophisticated approaches are being used to improve the temporal framework of Permian rocks. Such techniques include the Rb-Sr dating of Mg-rich authigenic clays within evaporites (Long et al., 1997), and the U-Pb dating of pedogenic calcite (Rasbury et al., 1997; Rasbury et al., 1998). Another approach has been the application of high-resolution magnetostratigraphy to the study of rocks inferred to have a terrestrial origin (Molina–Garza et al., 1989). These methodologies, and others, are currently being actively pursued by a diverse group of researchers working on the Permian terrestrial succession of western Pangea (Tabor and Montañez, 2002, 2004, 2005; Tabor and Yapp, 2005; Tabor et al., 2002; Tabor et al., 2004; Tabor et al., 2008).

The results of these and other chronostratigraphic studies will contribute to the adoption of the GSSPs for the Permian stages by the International Commission on Stratigraphy and their recognition in Kansas.

Sequence Stratigraphy

Sequence-stratigraphic approaches applied to the midcontinent upper Carboniferous (Pennsylvanian) and Permian are those of Watney et al. (1995), Mazzullo (1998), Miller and West (1998), Boardman and Nestell (2000), Olszewski and Patzkowsky (2003), and Boardman et al. (2009). These studies are not limited to surface exposures, but are being extended into the subsurface. For example, large-scale, three-dimensional sequence stratigraphic-based petrophysical models are being developed to describe gas-bearing Wolfcampian strata in southwest Kansas, namely the Hugoton and Panoma fields. These models will provide new insights into the relationships between structure, deposition, and diagenesis of the pore-space distribution in these rocks. Using these reservoir models, large-scale fluid-flow reservoir simulations can be made that will be used to reconstruct the history of the gas that has been produced and help to predict where and how additional gas resources might be extracted. Results also will be useful in understanding ground-water transport. Calibrated models using strategic cores will also provide a perspective on the combined effects of tectonism, eustasy, and sediment supply.

Sequence-stratigraphic studies of the Leonardian and Guadalupian of Kansas face some significant obstacles for future researchers. As emphasized by Sloss (1996), sequence-stratigraphic concepts and terminology were developed for rapidly subsiding basin margins with distinct shelf breaks. Slowly subsiding cratonic interior basins with ramp margins provide a very different tectonic and paleogeographic context. Several distinctions of cratonic basins discussed by Sloss are 1) lateral changes in subsidence rates of only centimeters per kilometer, 2) virtually horizontal sea floors with bathymetries of meters to tens of meters, 3) low rates of net accommodation of only meters per million years, and 4) low stratigraphic completeness of perhaps 10% or less. Clearly, with the very low accommodation rates on the craton, most time was not represented by active sediment deposition. Sediment aggradation was probably relatively rapid, followed by considerable periods of sediment bypass. Each well-developed paleosol profile within the variegated mudrock intervals probably accounted for up to tens of thousands of years. Determining the relative durations of these periods of nondeposition or subaerial exposure is difficult, but it is critical for recognizing regionally significant surfaces.

A major problem facing the application of sequence stratigraphy in the midcontinent Permian is the difficulty in recognizing sequence boundaries in a cyclic succession with ubiquitous subaerial exposure surfaces (Miller and West, 1998). Maximum relative-lowstand surfaces would be expected to record the longest period of subaerial exposure on the shelf. Thus, a sequence boundary also may be considered equivalent to the most mature, and most areally extensive, paleosol profile in a vertically stacked series of paleosols. In some cases, a stacked series of paleosols or exposure surfaces will show a progressive upward trend from less to more mature. When recognized, such trends toward increasing paleosol development strongly suggest formation within a highstand systems tract (Martîn–Chivelet and Giménez, 1992; Wright, 1996). However, determining the relative maturity of paleosol profiles is a difficult task especially when they were developed under different environmental (climatic) conditions or were truncated significantly by subsequent flooding surfaces.

Although we believe that marine transgressive surfaces provide the best basis for delineating cyclothems, the ability to recognize major episodes of relative lowstand is vital for correlation to basins outside of the midcontinent. Because of the many scales of cyclicity present in the section, different workers have recognized depositional sequences at several different temporal scales and have placed differing degrees of significance on specific boundaries. Any future consensus on these issues will require the development of criteria for determining the temporal magnitude of these cycle-bounding unconformities.

Climatic History

The Late Paleozoic Ice Age (LPIA) has become increasingly important to those interested in pre-Quaternary paleoclimate (Soreghan and Montañez, 2008; Fielding et al., 2008). The major focus of climate modeling for the Permian has been the long-term climate trends associated with the assembly of Pangea and its northward migration. A major limitation to understanding the development of Permian climates at a higher spatial and temporal resolution is the general absence of extensive field-based data. The retrodictions of numerical climate models for the Permian have been tested principally against the global distribution of coals, evaporites, red beds, and eolian sands (Patzkowsky et al., 1991; Parrish, 1993). However, these geologic data are averaged over time periods that include multiple glacial and interglacial cycles and over which major shifts of climate likely occurred. Such time averaging also may be a factor in the disparities found between geologic data and model retrodictions (Taylor et al., 1992; Yemane, 1993). For these reasons, efforts are being made to model climate change associated with glacial-interglacial cycles (Kutzbach and Guetter, 1984; Kutzbach and Ziegler, 1993; Golonka and Ford, 2000; Gibbs et al., 2002; Hyde et al., 2006). A model developed by Peyser and Poulson (2008) suggests that aridification during the Permian–Carboniferous resulted from the combined effects of elevated CO_2 and deglaciation. Further testing of such models requires additional high-resolution climatic data with adequate chronostratigraphic control as pointed out by Tabor and Poulson (2008).

Widespread evidence for extensive glaciation occurs in Gondwanan sequences at high latitudes, but recent studies indicate glaciation at low altitudes in the Pangean tropics (Soreghan, Soreghan, Poulson, et al., 2008). Soreghan et al. (2002) documented loessite from the upper Paleozoic in the Paradox basin and reviewed the occurrence of it in western equatorial Pangea (Soreghan, Soreghan, and Hamilton, 2008). Differences in the sedimentology, whole-rock geochemistry, and detrital zircon geochronology in meter-scale couplets of loessites and paleosols indicate changes in the relative humidity and wind directions between glacial and interglacial periods (Soreghan, M., et al., 2008). Evidence for equatorial glaciation in western Pangea at low latitudes and altitudes comes from polygonal cracking in coarse sandstones and gravels of the Fountain Formation in Colorado (Sweet and Soreghan, 2008) and from paleogeomorphological studies of Unaweep Canyon in Utah (Soreghan et al., 2007).

A wide range of sedimentologic, mineralogic, isotopic, and paleontological data can provide useful proxies for climate (Parrish, 1998). Information on Paleozoic forest fires is providing information on the concentrations of atmospheric oxygen (Scott and Glasspool, 2006). A connection between climate, biogeography, and rates of evolution during the late Paleozoic is indicated by the latitudinal diversity gradients of brachiopods (Powell, 2007). Using fossil floras, DiMichele et al. (2008) reviewed the transition from wetland to dry land during the late Permian–Carboniferous, pointing out that the complex gene pool of plant species reflects climate at many different spatial-temporal scales. Results from Buggisch et al. (2008) using the stable isotopes in the apatite of conodonts suggest that there is some ambiguity between atmospheric CO_2 and climate evolution in the late Paleozoic. Future studies are needed to test their results.

Paleosols are one source of climatic data with great promise. Significant work has been done on Carboniferous paleosols (Joeckel, 1991, 1994, 1995) and more attention is now being given to the Permian paleosols of North America. The work that has been done in the midcontinent needs to be extended in both temporal scope and areal extent (Joeckel, 1991; Miller et al., 1996; McCahon and Miller, 1997). Such work is being pursued in the Permian of Texas and Oklahoma (Mack et al., 2003; Tabor and Montanez, 2002, 2004, 2005; Tabor and Yapp, 2005; Tabor et al., 2002, 2004, 2008).

A great, untapped, source of climatic data for the midcontinent Permian is available from the stable isotope analysis of some invertebrate fossils and pedogenic carbonates. Based on the stable isotopes from well-preserved brachiopod shells, Grossman et al. (2008) indicated that the usefulness of such data for paleoclimatic purposes requires additional information on paleocirculation and paleosalinity of late Paleozoic epicontinental seas. The potential, and limitations, of using the stable isotopic composition of soil carbonate as a climate proxy has been extensively examined (Cerling, 1984; Cerling and Quade, 1993; Ekart et al., 1999). Some stable isotopic data have been collected from Permian paleosols (Joeckel, 1991; Kenny and Neet, 1993; Mack et al., 1993; Tabor and Montañez, 2002, 2004, 2005; Tabor and Yapp, 2005; Tabor et al., 2002, 2004, 2008), but a far more extensive data base will be necessary to contribute to our understanding of Milankovitch-scale climatic fluctuations.

Another important factor in climate change that can be addressed by the stable-isotope study of paleosols is the partial pressure of CO_2 (pCO_2) level in the Permian atmosphere. Berner (1991, 1994) has modeled the evolution of Phanerozoic pCO_2, and his model curve indicates an increase in pCO_2 levels during the Permian. Such an increase would have obvious implications for forcing mechanisms for the Permian global-warming trend. However, the proposed trend in pCO_2 has yet to be adequately tested by geologic field data. It has been demonstrated that carbon isotopes from pedogenic carbonates can yield useful estimates of atmospheric pCO_2 (Cerling, 1992; Mora et al., 1993), and there are ongoing efforts to apply this tool to the testing of Berner's model (Mora et al., 1996; Ekart et al., 1999; Montañez et al., 2007).

The Permian extinction events are often discussed in terms of late Paleozoic climate changes (Chumakov and Zharkov, 2002). Two Permian extinction events are recognized—one in the middle Permian (Guadalupian) and another at the end of the Permian—and both are attributed to release of massive amounts of methane (Retallack et al., 2006). No doubt climatic changes played a role in these extinction events, but they are probably only one of a number of interrelated causes.

Structural Controls

As discussed earlier, many local thickness and facies changes in the Permian section seem to be related to underlying basement structures. More attention needs to be given to the role of basement tectonics in controlling Permian sedimentation. On a shallow and very low relief platform, local tectonic uplift or subsidence of only a few meters would have a significant impact on sedimentation.

At least two important directions for future research on this topic are 1) the improved seismic analysis of subsurface structures, and 2) the detailed mapping of thickness and facies changes at the level of meter-scale flooding surface-bounded units. Kilometer-scale 3D seismic volumes, increasingly utilized in oil and gas provinces such as Kansas, can be processed via different attribute models to resolve seismic facies and structural anomalies and, in turn, more closely examine possible causes and effects. Interpretations of deeper portions of the seismic data are markedly affected by complex dissolution of shallow Permian evaporites. Better understanding of the processes involved in evaporite dissolution, the so-called dissolution front, and the role of structure would be helpful to the petroleum industry and environmental concerns because the salt that subcrops in central Kansas—the karst plain between McPherson and Wichita—impacts water resources and integrity of surface facilities such as roads, railroads, and buildings. The latter data are critical for assessing changes in local topography with time, which provide clues to the magnitude and timing of local uplift or subsidence. Studies based on detailed drilling in and around Hutchinson demonstrated the major role of basement reactivation on deposition of the dolomites and episodic evaporite dissolution that may have enhanced fracturing of overlying strata along a lineament (Watney et al., 2003).

Some high-resolution mapping along the Permian outcrop belt already has been accomplished for several carbonate units. This includes the classic work of McCrone (1963) on the Red Eagle Limestone, Laporte (1962) and Imbrie et al. (1964) on the Beattie Limestone, and Hattin (1957) on the Wreford Limestone, as well as the recent sequence-stratigraphic work of Mazzullo (1998) on the carbonates of the Chase Group. However, virtually no high-resolution work has been done on correlation and mapping within the clastic variegated units. The preliminary work that has been done in the Wolfcampian (Miller and West, 1998; Olszewski and Patzkowsky, 2003) provides promise that detailed correlation at a meter scale is possible within these largely paleosol-dominated intervals.

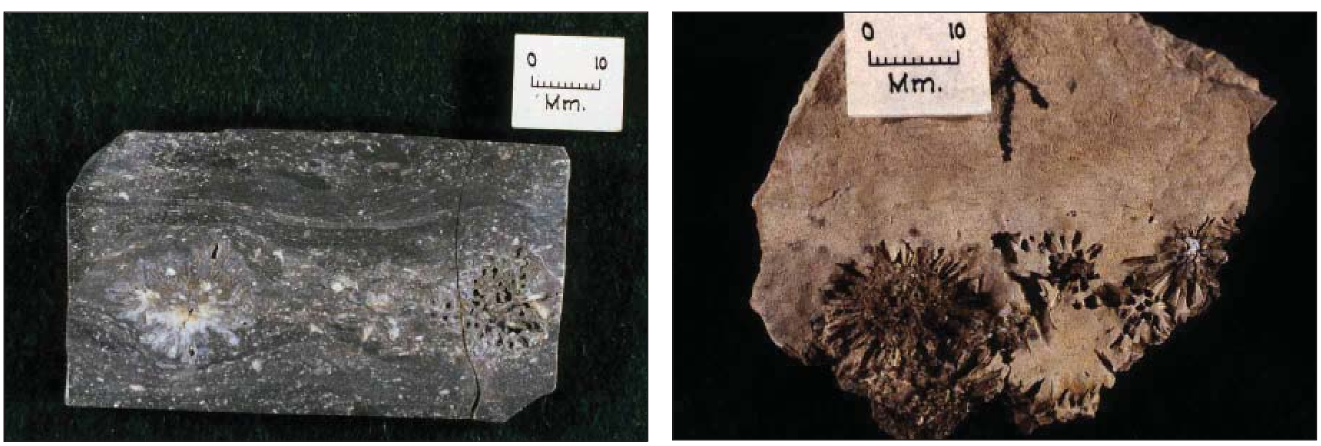
Another important area for future work concerns the cause and timing of deformation within some stratigraphic units. Small-scale normal and reverse faulting occurs within at least some intervals of the Wolfcampian. In particular, the Easly Creek and Gage shales locally display extensive faulting as well as thick brecciated beds in Riley, Geary, and Dickinson counties (Miller and McCahon, 1999). The lateral extent of this deformation and its relationship to possible basement structure is currently unknown and such studies would help to provide analogs for use with subsurface studies where control is sparse. It also is unclear whether such deformation is largely syn- or post-depositional. The perception of the midcontinent as a tectonically stable platform overlain by flat, undeformed strata has probably discouraged tectonic investigations; however, the structural complexity of the Proterozoic/Archean (Precambrian) basement has affected the overlying sequences, including the Permian.

Sediment Transport and Diagenesis

An interesting problem, and one that has received little attention, is how clastic sediments within the Permian section were transported and deposited. Two general observations provide the framework within which this problem must be resolved. The first is the near absence of coarse-grained siliciclastics and the predominance of coarse silt to very fine sand throughout the Permian section. The second is the absence of channel or valley-fill deposits and the lack of any clearly alluvial facies in the lower Permian.

The original depositional setting for the mudrocks and siltstones within the variegated units has been largely obscured by pedogenesis. Where pedogenesis is absent or weak, the mudrocks are generally either laminated or thin-bedded mudrocks with charophytes and freshwater ostracodes (Lane, 1964) or massive siltstones. The former suggests deposition in nearshore paralic environments, but the latter is suggestive of eolian sedimentation. An eolian origin may help explain the dominance of coarse silts to fine sands throughout the Permian section. Paleowind direction estimates from the extensive sand seas of the Permian are compatible with wind transport from the north and west into the midcontinent region (Parrish and Peterson, 1988; Peterson, 1988). Trace-element analyses of rocks from the Ancestral Rockies to central Kansas suggest derivation of the sandstones and siltstones from silicic source rocks of the uplifted blocks of Colorado and Oklahoma (Soreghan, Soreghan, and Hamilton, 2008; Soreghan, Soreghan, Poulson, et al., 2008), but a significant component of recycled sediment is found within the clay-sized fraction (Cullers, 1994). This is consistent with an eolian source for the silts and fine sands, with a different provenance for the clays.

A B



FIGURES 82A, B—Threemile Limestone Member. **82A**, gypsum crystal-rosette molds in a chert bed, roadcut exposure on the south side of I–70, 5.6 mi (9 km) east of junction with K–177; near center E/2 sec. 29, T. 11 S, R. 9 E., Riley County, Kansas. **82B**, gypsum crystal-rosette molds in the Threemile limestone from the east bank of a stream on Konza Prairie Research Natural Area; white area in the lower right is length-slow chalcedony; near center SE SE NE sec. 20, T. 11 S., R. 8 E., Riley County, Kansas.

Future work on the mineralogy, texture, and distribution of siltstone beds within the midcontinent may help to confirm or reject this possibility.

Because of the ubiquitous occurrence of paleosols, study of the pedogenic alteration of siltstones and mudrocks also presents a significant future research opportunity. The precipitation of pedogenic carbonate and sequioxides within the matrix, as well as the downward illuviation of clays, would have significant impacts on the porosity and permeability of clastic units. Bridging of silt and sand grains by illuviated clays may also affect the electric-log responses of subsurface units. The development of blocky and platy soil structures from an original depositional fabric also affects the mechanical durability of these units (Miller and McCahon, 1999). Understanding the character and extent of these different mineralogical, textural, and mechanical pedogenic changes has direct relevance to issues in hydrology, petroleum exploration, and engineering.

An enduring problem has been the origin of the extensive chert beds and nodules of the Permian. The source for such a vast amount of silica is a major puzzle. Volcanic-ash deposits, if present within the Permian, are rare. Siliceous sponge spicules and radiolarian tests do occur in Permian rocks; however, it seems questionable whether siliceous sponge spicules and radiolarian tests alone would have been sufficient to provide the large amount of silica required. West et al. (1987) reported evidence of aggregates of gypsum crystal rosettes associated with chert beds in the Threemile (figs. 82A, 82B). Twiss (1991b, p. 131) reported silicified evaporite rosettes and nodules as well as inclusions of gypsum and chert in the Schroyer and Florence limetones, in addition to the Threemile. Silica replacement of gypsum nodules occurs in other limestone units such as the Minkinfjellet Formation (mid-Carboniferous) of Spitsbergen (Eliassen and Talbot, 2003). The associated silica in the Threemile chert was length-slow chalcedony (West et al., 1987), which indicated replacement of evaporates (Folk and Pittman, 1971). West et al (1987) and Twiss (1987) suggested one possible source of silica for the diagenetic chert in the Permian limestones in Kansas was ground water enriched in terrestrial biogenic silica, including plant silica such as phytoliths.

Summary

The geology of Kansas is classic, from the cyclic sedimentation of the east to the marine vertebrates in the chalk beds of the west, but it seems to be largely misunderstood by those who have not looked at the rocks carefully. The phrase "layer cake," commonly applied to the Carboniferous and Permian rocks in the eastern third of Kansas, is well known. Rarely recognized is the fact that the accumulation of these layers was discontinuous. Flooding events, or surfaces of subaerial exposure, often separate the layers. Flooding surfaces may contain evidence of colonization by boring and/or encrusting marine invertebrates before they were buried by subsequent sedimentation. Exposure surfaces may contain evidence of soil development and associated plant debris that may be subsequently reworked and buried by marine sedimentation. These genetic surfaces sometimes cut across lithologic layers, with each genetic layer a possible facies mosaic that contains subtle evidence of a number of different environments. Some of the thick mudrock units between limestones in the Kansas Permian contain evidence of numerous paleosols, and in many cases, may represent much more time than the marine limestones that have received the most attention by geologists. The alternation between 1) marine carbonates and siliciclastics, 2) flooding and subaerial exposure surfaces, and 3) climate changes are hallmarks of Permian rocks in Kansas. A simple bathymetric model does not explain this alternation, or cyclicity; such a model is inadequate to explain and understand the complexities of these cyclic sequences. The rocks are recording a much more complicated sequence of events, a complexity that offers exciting challenges for anyone interested. Great opportunities are found through a multi-disciplinary approach to test new and different models and add to a better understanding of this important period, which ended with the greatest mass extinction event in earth history.

Forty-five years ago a Kansas geologist told me "we know all there is to know about the geology of Kansas." We now know that this statement was not true for the Permian in Kansas, and we are still far from knowing it all. It is important to remember that "If you think you have all the answers then you're not up to date on all the questions." All scientific endeavors are just "a work in progress," as is this, "The Permian System in Kansas."

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