Reevaluation of Wolfcampian cyclothems in northeastern Kansas: Significance of subaerial exposure and flooding surfaces

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Abstract Ten cyclothems from the Wolfcampian of northeastern Kansas, including parts of the Council Grove and Chase Groups, were examined in detail with particular attention to discontinuity surfaces and paleosol development. These cyclothems are shown to be bounded by major discontinuities, or sequence boundaries, where marine limestones abruptly overlie paleosol profiles. Occurring within these cyclothemic sequences are prominent meter-scale cycles that are bounded by flooding surfaces, many of which overlie facies exhibiting evidence of subaerial exposure. They are developed within both the marine carbonate and shale intervals and variegated mudstone intervals of the cyclothems. These meter-scale cycles show a consistent carbonate-to-clastic pattern regardless of their stratigraphic position or component facies. Climate fluctuations within a generally monsoonal environment are determined to be the most likely forcing mechanism for the meter-scale cycles, with wetter climate phases resulting in the increased influx of terrigenous clastic sediment and drier climate phases favoring carbonate precipitation. Evidence of climate change at the scale of the cyclothemic sequences is also recognized in the studied interval. Cycles at both scales indicate that relative sea-level rise was associated with increasingly arid conditions and that sea-level fall was associated with an intensification of seasonal rainfall.

Repeated sedimentary cycles were first recognized in the Pennsylvanian of Illinois by Udden (1912) and were later generalized by Weller (1930) into an idealized cycle. Moore (1931) was the first to describe the more complex cyclic pattern of the Pennsylvanian (lower Virgilian) of Kansas and Nebraska. The term *cyclothem* was introduced by Wanless and Weller (1932) to describe the Pennsylvanian cyclicity of the Illinois basin and was subsequently applied to the first description of Permian cyclicity within the midcontinent by Jewett (1933). The glacio-eustatic model of cyclothem development was first proposed by Wanless and Shepard (1936) for the Pennsylvanian and was soon followed by the classic paper of Elias (1937) on Lower Permian sea-level cycles. Moore (1936) introduced the concept of megacyclothems, or cycles of cyclothems, based on his work on the Virgilian cycles of Kansas. This concept was similarly adopted by several researchers to describe cyclic sequences of the Lower Permian [e.g., Hattin (1957)], and eventually the entire sequence was divided into megacyclothems (Moore, 1964).

The facies sequence of Permian cyclothems described by Jewett (1933) began with red and green variegated mudstones, followed by a thin limestone or calcareous zone, a gray to yellow fossiliferous shale, and, last, a thick interval of limestone beds. This description was modified and elaborated by Elias (1937), who placed all the major facies encountered in Permian cycles into an idealized depth-related sequence. All the facies of this idealized cyclothem were never encountered in any single cyclothem, and some predicted facies transitions rarely, if ever, occurred. The actual cycles identified by Elias in the Lower Permian were essentially the same as those recognized by Jewett.

A number of detailed sedimentary and paleontologic studies of individual cyclothems and their member-scale lithologic units were completed following the initial description and interpretation of late Paleozoic cyclicity. The Grenola Limestone (Lane, 1958), Beattie Limestone (Imbrie, 1955; Laporte, 1962; Imbrie et al., 1964), Wreford Limestone (Hattin, 1957), and Red Eagle Limestone (McCrone, 1963) were all the focus of investigation. In all these cases, however, the variegated mudstones were largely ignored and depositional and paleoecologic interpretations were confined to the fossil-bearing marine units.

At present, the most widely accepted cyclothem model is that of Heckel (1977), which, like the earlier model of Wanless and Shepard (1936), assumes primary eustatic control. Heckel's typical "Kansas-type cyclothem" consists of (1) a sandy "outside shale" unit deposited under primarily terrestrial and shallow marine conditions and typically containing coal beds; (2) a thin "transgressive" limestone unit; (3) a black, often phosphatic "core shale" representing deepest marine conditions; (4) a thick, multistoried "regressive" limestone unit; and (5) a return to an "outside shale" at the top. Although based primarily on the Upper Pennsylvanian (Mis-

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sourian) strata of eastern Kansas, it has become a paradigm for Permian-Carboniferous cycles in general.

Although Wolfcampian cycles bear certain general similarities to Missourian cyclothems, the cycle-defining black core shales are essentially absent. The Permian cycles are dominated by shallow marine and paralic facies and contain ubiquitous evidence of subaerial exposure. Stacked variegated paleosol profiles are a particularly prominent feature of the outside shales (Joeckel, 1991; Miller et al., 1992), and coals are present only as rare thin beds. An abundance of flooding surfaces, marked by intraclastic and skeletal lags, divide these cyclothems into meter-scale cycles that display a consistent carbonate-to-clastic pattern and that are commonly capped by subaerial exposure surfaces. The existing cyclothem models, based on Pennsylvanian cycles, do not provide an adequate framework for interpreting these features of Permian cycles. In this paper we develop a testable model for the Wolfcampian that incorporates the distribution of cycle-bounding discontinuities and the observed features of paleosol profiles.

Cycle hierarchies

The increasing recognition of hierarchies of cycles by stratigraphers is providing a needed context within which processes at different temporal scales can be analyzed and compared. The work of Vail et al. (1977) established a hierarchy of depositional sequences composed of first-order (225–300 m.y.), second-order (20–90 m.y.), and third-order (7–13 m.y.) levels, which are major onlap-offlap sequences bounded by unconformities that are recognized globally. This hierarchy was further expanded downward by Busch and Rollins (1984) and Busch and West (1987) as a result of their studies of Pennsylvanian sequences of the Appalachian basin. Cyclothems were integrated into this scheme as fifth-order cycles, and genetic packages down to sixth-order cycles [PACs of Goodwin and Anderson (1985)] were recognized. Barron et al. (1985) and Kauffman (1985, 1988) have proposed a similar hierarchy in which fifth- to seventh-order cycles are based on Milankovitch orbital parameters. A number of regional stratigraphic studies have utilized a hierarchical approach to understand the depositional dynamics of sedimentary basins (Aigner, 1985; Brett and Baird, 1986; Brett et al., 1990; Goldhammer et al., 1990, 1991).

Interest in cyclothem-scale patterns has largely diverted attention from smaller-scale cyclic patterns that may prove to be critical elements in understanding the stratigraphic architecture of the midcontinent. Meter-scale (sixth-order) cycles have been recognized within the Pennsylvanian of the midcontinent (West and Busch, 1985; Busch et al., 1985; Suchy and West, 1991). These cycles are also readily recognized features of the Lower Permian in outcrop and core. Several recent detailed studies of specific members and formations within the Council Grove Group have focused on these cycles as the basis for correlation and paleoenvironmental reconstruction (Bogina, 1986; F. Barrett, 1989; T. Barrett, 1989; Clark, 1989; Cunningham, 1989). Correlation of such higher-order cycles provides a fine time-stratigraphic framework for the reconstruction of lateral facies relationships and the evaluation of models of cycle generation.

Until recently, the delineation and interpretation of cycles had focused on facies rather than on the surfaces that bound them. Eustatic models for Permian cyclothems had largely rested on the bathymetric interpretation of particular marine units. Elias (1937) based his sea-level curves on the interpretation of fusulinids as deep-water foraminifers. Although actual cycles often did not closely match the ideal facies sequence, smooth curves were drawn nonetheless and fusulinid-bearing units were invariably placed at the transgressive peaks of sea-level curves. This resulted in different curves being drawn for cycles of similar lithologic complexity.

In redefining and reinterpreting Pennsylvanian cyclothems, Heckel (1977) similarly focused attention on a specific marine facies. Black, typically phosphatic, conodont-rich shales were interpreted as representing upwelling circulation during times of maximum transgression (Heckel and Baesemann, 1975). The thin limestones that commonly underlie these “core shales” were viewed as recording transgressive conditions and the thicker overlying limestones were interpreted as recording regressive conditions. Limestones not associated with core shales were interpreted as accessory units that are not integral to the general cycle pattern. The reliance of this model on a particular facies for defining the position of transgressive maxima on cyclothemic sea-level curves makes its application difficult in the Lower Permian, where such facies are rare or absent.

Discontinuity surfaces are abundant in the Lower Permian and are associated in many cases with sharp lithologic contacts. The presence of such surfaces places important constraints on any proposed model of cyclothem development and on any proposed eustatic sea-level curves. Understanding the nature and temporal duration of these surfaces is critical both for defining cycle patterns and periodicities and for interpreting their environmental significance (Busch et al., 1989). The environments under which depositional hiatuses form may also be completely distinct from those during deposition of the underlying and overlying rock units. Subaerial exposure surfaces may develop on marine sediments and be overlain by marine sediments as well, with the discontinuities and their geochemical and isotopic signatures being the only preserved record of the intervening nonmarine conditions. Conversely, extensive paleosol development may obscure all record of the environment within which the sediments were originally deposited. An assessment of the amount of time represented by discontinuities is also critical for testing cyclic depositional models, because it is now generally recognized that more time is represented by surfaces than by sediment, particularly at small time scales (Ager, 1981; Dott, 1983). Cycle periodicities thus will tend to be overestimated and sedimentation rates underestimated, perhaps by several orders of magnitude, if the nondepositional and erosional hiatuses are not given adequate consideration (Sadler, 1981; Algeo and Wilkinson, 1988).

Cycle patterns of the Lower Permian

Our focus here is the stratigraphic interval from the Grenola Limestone through the Wreford Limestone (fig. 1). As recently redefined (Baars, 1990; Baars et al., 1990), the Pennsylvanian-Permian boundary is contained within the Grenola Limestone at the base of the Neva Limestone Member. The chosen stratigraphic interval therefore includes all cyclothems in the Permian part of the Council Grove Group and the lower two cyclothems of the Chase Group. Altogether, 10 cyclothemic-scale sequences are represented in the Wolfcampian section described in this study. All stratigraphic sections described here were measured in the vicinity of Manhattan (Riley County), Kansas (fig. 2).

The Early Permian was a time of major climatic change on which the cyclothems were superimposed. Gondwana glaciation was waning in the Early Permian (Crowell, 1978; Veevers and Powell, 1987), and aridity was consistently increasing in North America. These long-term climate trends are recorded by the increased proportion of red terrigenous clastics, evaporites, and carbonates in the Lower Permian relative to the Upper Pennsylvanian. The trend toward increased aridity begun in the Late Pennsylvanian can also be followed in the paleobotanical record (Phillips and Peppers, 1984; Phillips et al., 1985; Cross and Phillips, 1990; DiMichele and Aronson, 1992). Such changes are consistent with the continuing assembly of Pangea and with paleogeographic reconstructions showing the midcontinent drifting into drier latitudes during this time (Rowley et al., 1985; Scotese, 1986; Witzke, 1990).

The transitional character of the Wolfcampian, both in climate and paleogeography, is reflected in a wide variety of facies types. The Grenola Limestone includes the last widespread occurrence of black shale, and the Wreford Limestone represents the first highly cherty limestone of the midcontinent Permian. A wide range of carbonate facies occurs within this interval, including marine bioclastic packstones and wackestones, fusulinid packstones, algal wackestones, tidally laminated carbonate mudstones, and molluskan limestones. Gypsum is a significant component of limestone and mudstone facies and becomes increasingly common upward through the Lower Permian sequence, locally forming beds up to 1 m (3 ft) thick in the subsurface. Variegated mudstones include subaerial facies with diverse pedogenic structures and carbonate facies with brackish-water fossil assemblages.

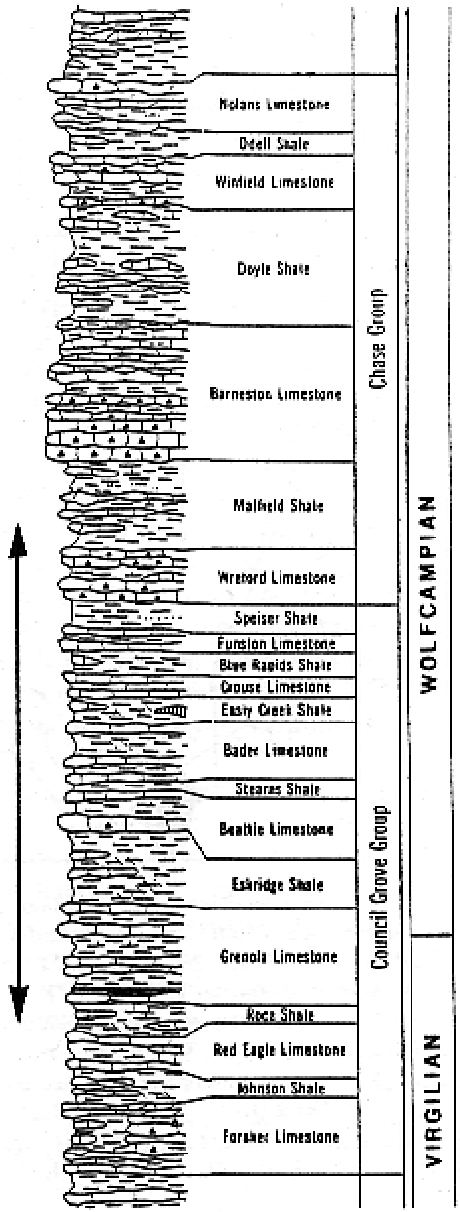

Figure 1. General stratigraphic nomenclature of the Council Grove and Chase Groups in Kansas [from Zeller (1968)] with the Virgilian-Wolfcampian boundary placed according to Baars et al. (1990). Arrow indicates stratigraphic interval examined in this study.

The fossil assemblages of this interval have been well documented by Lane (1958, 1964), Imbrie (1955), Laporte (1962), Mudge and Yochelson (1962), Imbrie et al. (1964), Hattin (1957), and McCrone (1963).

Paleosols are a particularly prominent feature of the Wolfcampian section. Because climate and time are crucial variables controlling soil development (Birkeland, 1984), these paleosols are potentially important sources of paleoclimatic and stratigraphic information. In recent years a

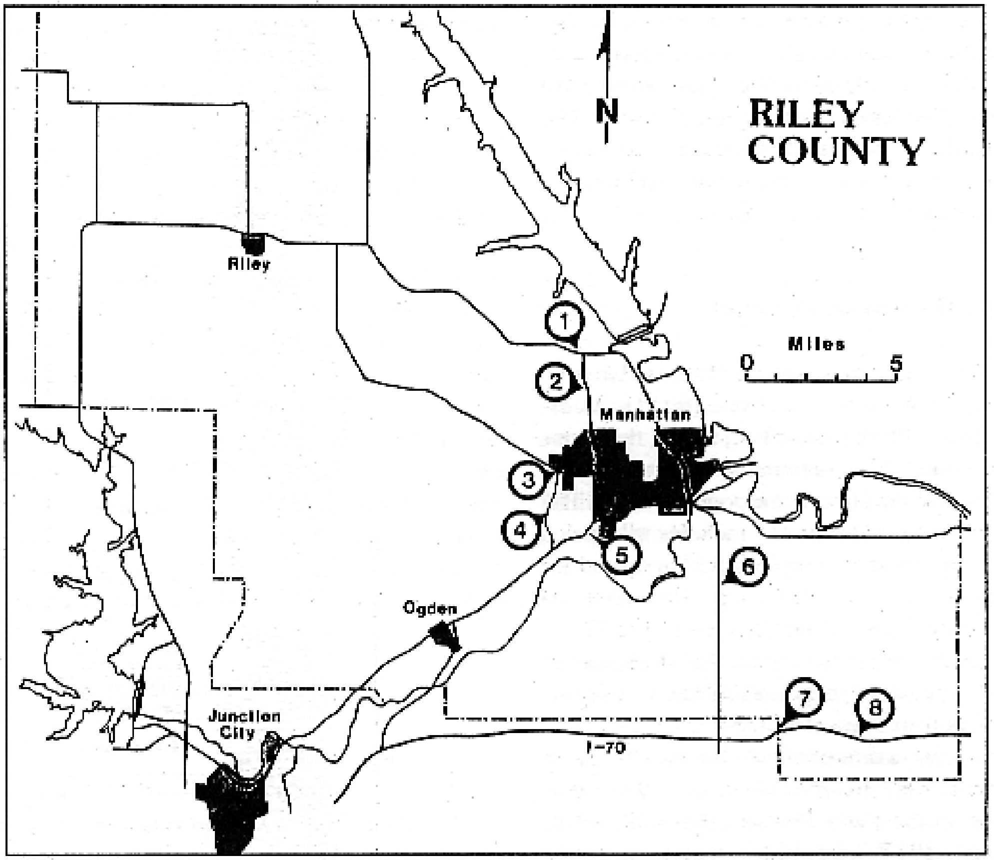

Figure 2. Locations of detailed measured sections in southern Riley County, Kansas. (1) Roadcut on north side of Tuttle Creek Boulevard (US–24) at intersection with Seth Childs Boulevard (K–113), NW sec. 26, T. 9 S., R. 7 E. (2) Roadcut on west side of Seth Childs Boulevard north of Manhattan, NW sec. 35, T. 9 S., R. 7 E. (3) Roadcuts at intersection of Kimball Avenue and Anderson Avenue, SW sec. 10, T. 10 S., R. 7 E. (4) Scenic Drive (K–408) roadcut, NE sec. 21, T. 10 S., R. 7 E. (5) Roadcut on north side of Fort Riley Boulevard (K–18) west of Manhattan, SW sec. 23, T. 10 S., R. 7 E. (6) Roadcut on east side of Pillsbury Drive (K–177), 2.6 mi south of Manhattan, SW sec. 33, T. 10 S., R. 8 E. (7) Roadcut on north side of I–70 at Deep Creek Exit, NE sec. 27, T. 11 S., R. 8 E. (8) Roadcut on north side of I–70, 5.2 mi east of K–177 interchange, SE sec. 30, T. 11 S., R. 9 E.

number of studies of Carboniferous paleosols have appeared in the literature (Walls et al., 1975; Riding and Wright, 1981; Wright, 1982; Goldhammer and Elmore, 1984; Prather, 1985; Schutter and Heckel, 1985; Joeckel, 1989), but only one study has undertaken an analysis of midcontinent Permian paleosols (Joeckel, 1991). Preserved soil horizonation, pedogenic structures, root casts, carbonate accumulation, clay infiltration fabrics, and other soil features provide the basis for paleosol recognition and classification (Retallack, 1990). Once identified, paleosol types can provide insight into climatic conditions during soil formation and into rates of sediment aggradation. Both soil structures observable in the field and the micromorphologic characteristics of paleosols are indicators of specific pedogenic processes that assist in reconstructing former climatic conditions (Bown and Kraus, 1981; Retallack, 1983). The value of paleosols as a means of assessing stratigraphic completeness and the time represented by nondeposition and soil formation has been discussed by Retallack (1984) and Kraus and Bown (1986).

Cyclothemic sequences The Lower Permian cycles originally described as cyclothems by Jewett (1933) and Elias (1937) were recognized by them and subsequent researchers on the basis of general facies patterns. However, these cyclothems can be more clearly and consistently defined by the use of prominent discontinuities. In this study *a cyclothem boundary is recognized at the base of the stratigraphically lowest marine limestone occurring above a paleosol-bearing interval.* In a few cases a thin interval of calcareous shale or mudstone may occur between a paleosol and a limestone containing open-marine fossils such as crinoids and bryozoans. Commonly, however, the fossiliferous marine limestones directly overlie and partially truncate the paleosol profiles. Cyclothem boundaries are always surfaces of inferred deepening and facies dislocation. They 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 (8 in.) thick with granule- to pebble-size mudstone and carbonate clasts eroded from underlying units. Skeletal debris and fish bone are also common components of these transgressive lags.

The cyclothem-bounding surfaces, as defined here, are equivalent to the transgressive surfaces of depositional sequences (Van Wagoner et al., 1988). Depositional sequences are bounded by regional subaerial exposure surfaces caused by sea-level fall (Van Wagoner et al., 1988). In applying this sequence model to the midcontinent Pennsylvanian, Watney et al. (1989, p. 63) chose "the stratigraphically highest regional subaerial exposure surface of each depositional sequence" as their criteria for type I sequence boundaries. Thus, where the marine limestones directly truncate underlying paleosols, cyclothem boundaries also correspond to depositional sequence boundaries. An alternative genetic sequence model proposed by Galloway (1989a,b) also may be usefully applied to these Permian cyclothems. By contrast to depositional sequences, genetic stratigraphic sequences are "deposited between periods of maximum marine flooding of the coastal plain" (Galloway, 1989a, p. 463). The genetic stratigraphic sequence model is more compatible with glacio-eustatic sea-level curves with abrupt rises in sea level, as indicated for the Pleistocene (Crowley and North, 1991). This model is also easier to apply to the Wolfcampian section because of the ubiquitous occurrence of subaerial exposure surfaces. It avoids the necessity of equating a particular subaerial exposure surface with maximum eustatic sea-level fall or lowstand.

Meter-scale cycles Discontinuity surfaces mark the contacts of many lithologic units and provide the basis for defining small-scale cycles within cyclothems (Miller et al., 1991). These discontinuities include flooding surfaces, phosphatic layers, and subaerial exposure surfaces. Flooding surfaces are typically associated with intraclastic beds, skeletal lags, or both. Phosphatic beds are represented by phosphatized skeletal lags and particularly by bone beds rich in fish debris. Skeletal phosphate is also a common component of the lags at flooding surfaces. Subaerial exposure is recorded by a wide range of features, including paleosols, rooted intervals, mudcracked horizons, and boxwork structures. These features, which have been largely overlooked in the past, have important implications for both the delineation and interpretation of cycles.

Meter-scale cycles are both ubiquitous and prominent in the studied interval. As defined here, they are bounded by flooding surfaces that overlie paleosol profiles or other subaerial indicators or mark sharp changes in depth as indicated by lithology or fossil content. Importantly, flooding surfaces at cyclothem boundaries are often marked by prominent intraclastic beds, but those surfaces bounding meter-scale cycles within limestone formations are not. Within the variegated mudstone intervals, lags associated with flooding surfaces are often thin (<1 cm) and may contain ostracodes, fish bone, or granule-size intraclasts. Immediately overlying the flooding surfaces of meter-scale cycles are a variety of carbonates ranging from marine limestones to intertidal limestones and calcareous mudstones. The facies discontinuities associated with the boundaries of meter-scale cycles are less pronounced than at cyclothem boundaries and could be generated by relatively little change in water depth.

Stacked paleosol profiles typify the nonmarine parts of the variegated mudstones. A variety of pedogenic features have been recognized, including color horizonation, root casts and molds, rhizocretions, well-developed blocky and columnar ped structures, caliche nodules and calcretes, pedogenic slickensides, and pseudoanticlines (mukkara structure). Delineation and characterization of paleosols together with the record of flooding surfaces and condensed beds makes possible a fine-scale stratigraphy for the variegated mudstones (Miller, 1993).

Although the meter-scale cycles are developed within the full range of facies present in the studied interval, the general pattern is an alternation between carbonate and clastic deposition. In the more marine parts of cyclothems, the most common small-scale cycle pattern is marine bioclastic limestone followed by gray fossiliferous shale. Less commonly, a bioclastic limestone is overlain by unfossiliferous shale or calcareous mudstone. The facies succession of marine limestone, black shale, and gray shale typical of the core shale of Pennsylvanian cyclothems occurs only in the Grenola Limestone at the base of the studied stratigraphic section. Cycles of the variegated mudstone intervals typically begin with molluskan or ostracode-bearing limestones that are overlain by calcareous or silty mudstones upon which paleosol profiles have been developed. These paleosols have in many cases completely obliterated the original sedimentary features of the mudstones. Significantly, even these cycles display the general pattern of carbonate deposition followed by an influx of clastics.

General descriptions of measured cycles

Lower Grenola cyclothem Condra and Busby (1933) originally subdivided the Grenola into its five members and described its alternating limestone and shale units. This interval was then interpreted as a single cycle by Elias (1937) with maximum water depth attributed to the fusulinid-bearing parts of the Neva Limestone Member. Although Lane (1958) followed this interpretation in his study of the Grenola in southern Kansas, he proposed that the Legion and Salem

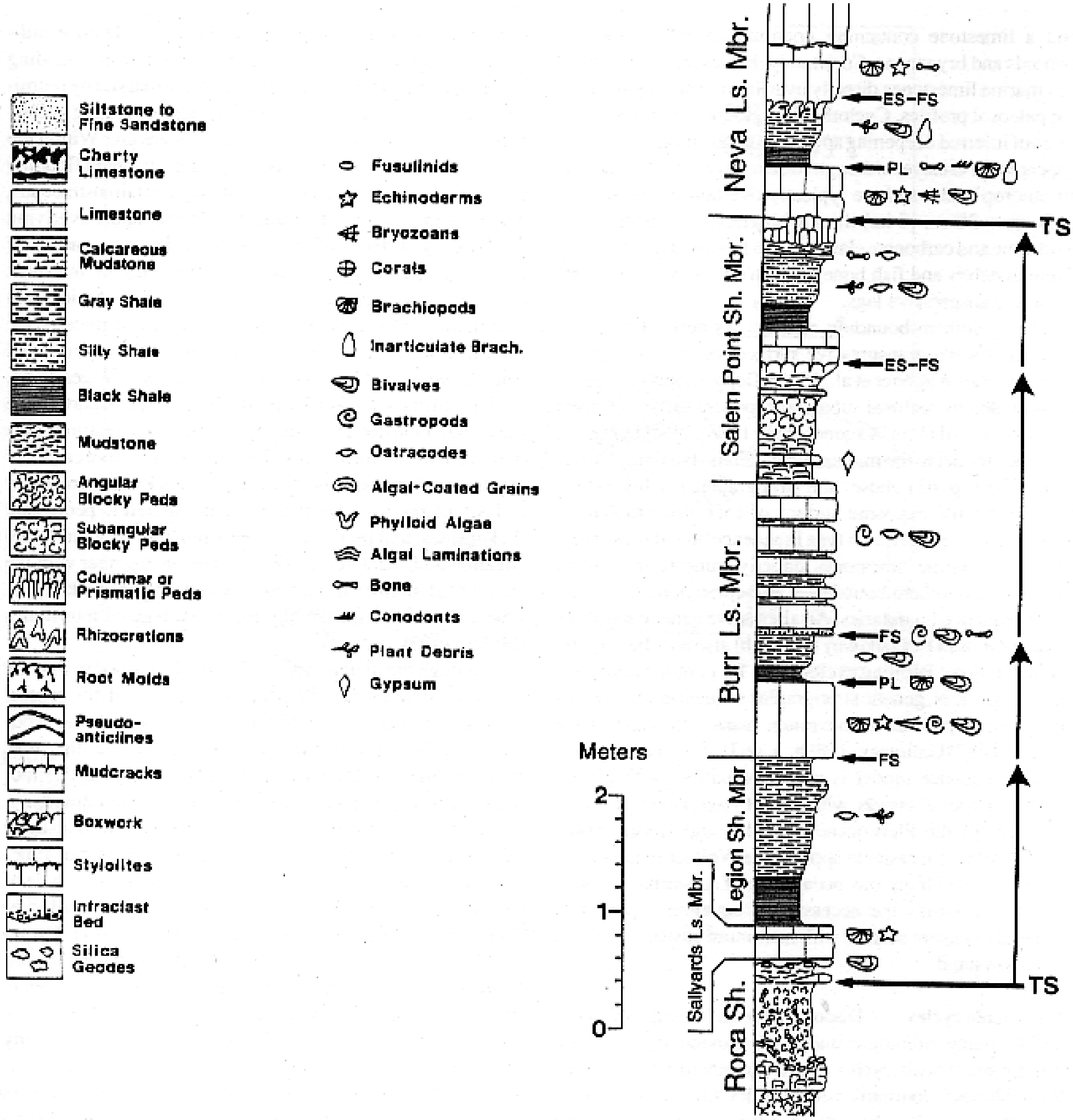

Figure 3. Detailed section of lower Grenola cyclothem measured at locality 5 showing lithology, general fossil content, and position of discontinuity surfaces. Surfaces identified are flooding surfaces (FS), exposure surfaces (ES), and phosphatic lags (PL). Interpreted cyclothem boundaries are equivalent to transgressive surfaces (TS) of depositional sequences. Position of meter-scale cycles indicated by arrows to the right.

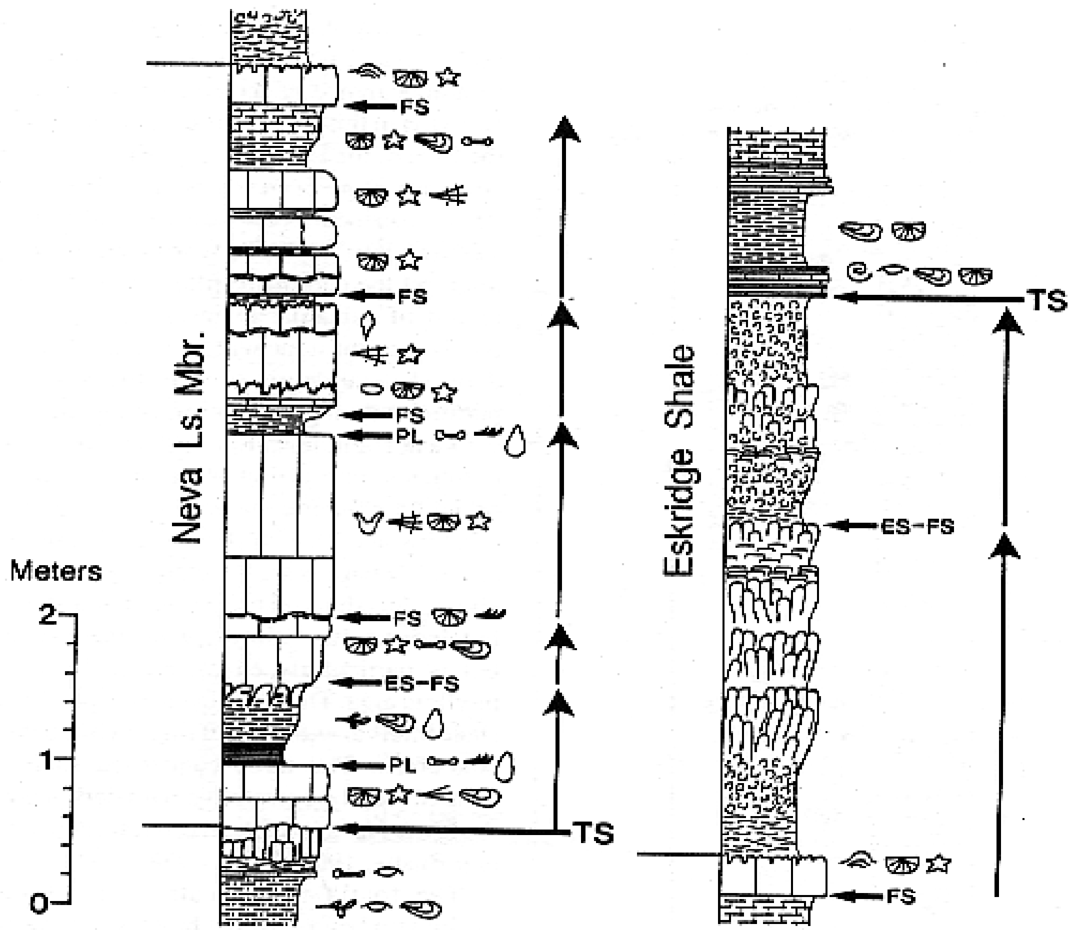

Figure 4. Detailed composite section of upper Grenola cyclothem measured at localities 3 and 5 showing lithology, general fossil content, and position of discontinuity surfaces. Interpreted transgressive surfaces (cyclothem boundaries) and position of meter-scale cycles indicated by arrows to the right. See fig. 3 for key to lithology and fossils symbols.

Point Shale Members represented shallower-water environments than the over- and underlying limestone members. The Grenola Limestone is here subdivided into two cyclothemic sequences. As defined here, the lowest cyclothem begins at the base of the Sallyards Shale Member and includes the overlying Legion, Burr, and Salem Point Members (fig. 3).

The lower cyclothem boundary is marked by a bivalve- and brachiopod-bearing limestone resting sharply on a well-developed calcic paleosol of the upper Roca Shale. Four meter-scale cycles compose this cyclothem. Each of these carbonate-to-clastic alternations was recognized by Condra and Busby (1933) and was correlated from Nebraska to Oklahoma. In the study area the clastic intervals of three of these cycles are black to dark-gray shales containing ostracodes, bivalves, and plant debris; the other clastic unit is a greenish-gray mudstone. The black shale within the Burr Limestone Member is bounded below by a thin lag of skeletal and phosphatic debris and above by a skeletal lag including abundant tiny pyramidellid gastropods and fish teeth. Below this shale the lower Burr Member contains a diverse fossil assemblage. By contrast, the upper Burr is mollusk dominated and overlain by a 1-m-thick (3-ft-thick) gypsum bed in the subsurface (Twiss, personal communication, 1992). The upper two clastic intervals in the Salem Point Shale Member are capped by subaerial exposure surfaces, marked by desiccation cracks and well-developed columnar ped structures.

Upper Grenola cyclothem The second cyclothem of the Grenola Limestone consists of the Neva Limestone Member and the lower part of the Eskridge Shale and is here subdivided into seven meter-scale cycles (fig. 4). These cycles correspond closely to units recognized by Mudge and Yochelson (1962) throughout much of the Kansas outcrop belt. The cyclothem boundary at the base of the Neva is marked by a marine limestone overlying a thin paleosol horizon with columnar peds and root traces. This exposure

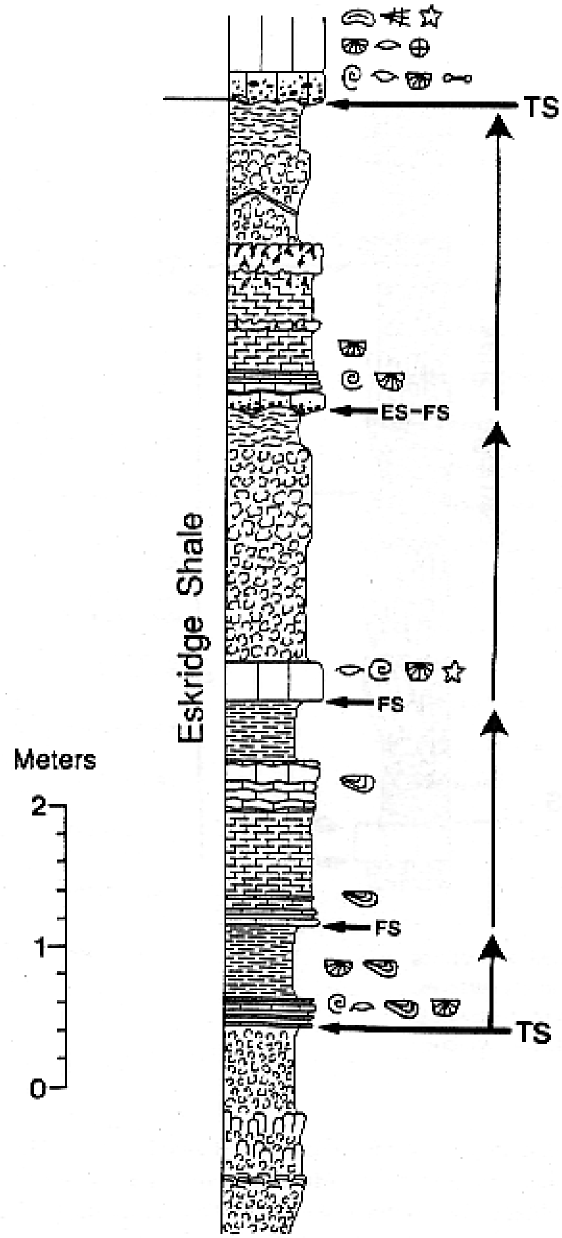

Figure 5. Detailed section of Eskridge cyclothem measured at locality 3 showing lithology, general fossil content, and position of discontinuity surfaces. Interpreted transgressive surfaces (cyclothem boundaries) and position of meter-scale cycles indicated by arrows to the right. See fig. 3 for key to lithology and fossil symbols.

and flooding surface was also recognized by Bogina (1986) in his detailed stratigraphic study of the Neva and Eskridge in northeastern Kansas.

The lower three meter-scale cycles of the Neva are capped by black shales or shaly partings. The black to dark-gray shale of the first cycle contains lingulid brachiopods and plant debris and is marked at its base by a condensed phosphatic bed up to several centimeters thick containing brachiopod shell debris and abundant fish bone and conodonts. The first appearance of the conodont species *Streptognathodus barskovi* in this horizon is used by Baars et al. (1990) to mark the base of the Permian. This shale is overlain by a boxwork structure of micritic carbonate. Boxwork structures have been described from modern tidal flats (Read, 1974) and salinas (Warren, 1982; Warren and Kendall, 1985), and we interpret the carbonate-filled fractures of this boxwork as a record of subaerial exposure and subsequent flooding. A bioclastic limestone with brachiopod, bryozoan, and echinoderm skeletal debris overlies the boxwork and has a shale parting at its top containing abundant conodonts (S. Ritter, personal communication, 1991). The shale parting probably correlates with a thin black shale containing lingulid and orbiculid brachiopods occurring to the north into Nebraska (Condra and Busby, 1933) and represents the top of the second Neva cycle. A relatively thick, massive limestone above this shaly parting contains a diverse assemblage of brachiopods (including *Composita*), bryozoans, and crinoids but is particularly characterized by a large, unidentified phylloid alga. This third cycle is capped by another thin black shale interval with a lag of lingulid shell debris, fish bone, and conodonts. The three condensed shaly intervals just described may be correlative with dark-gray shale interbeds in the lower Neva from southern Kansas and Oklahoma (Condra and Busby, 1933; Lane, 1958).

The fourth meter-scale cycle of the upper Grenola cyclothem begins with a bioclastic limestone with crinoids, bryozoans, and fusulinids that grades upward into a micritic wackestone with abundant gypsum crystal molds. This cycle is capped by a thin shaly interval. The base of a bioclastic packstone with brachiopod, crinoid, and echinoid debris marks the flooding surface of the next overlying cycle. A dark-gray to yellowish-gray shaly and silty interval completes this fifth cycle. Beginning the next cycle, the uppermost limestone bed of the Neva contains brachiopod and crinoid debris and is capped by a thin algal-laminated layer that is represented at some localities by small domal stromatolites. The paleosols of the lower Eskridge Shale compose the top of this sixth cycle. A stacked series of grayish-red calcic paleosols at the base of the Eskridge contains horizons of closely packed carbonate rhizocretions. Above, a second series of stacked paleosols is truncated by a molluskan limestone that marks the base of the next cyclothem (fig. 5).

Eskridge cyclothem A thin lag of ostracodes and pyramidellid gastropods occurs at the cyclothem boundary overlying the paleosols of the lower Eskridge Shale. The thin-bedded limestone and shale above contain unfragmented shells of pectinid and myalinid bivalves and the brachiopod *Derbyia* and compose the first of four meter-scale cycles. The second cycle is represented by an interval of calcareous mudstone with molluskan skeletal debris overlain by an unfossiliferous greenish-gray fissile shale. At the top of this

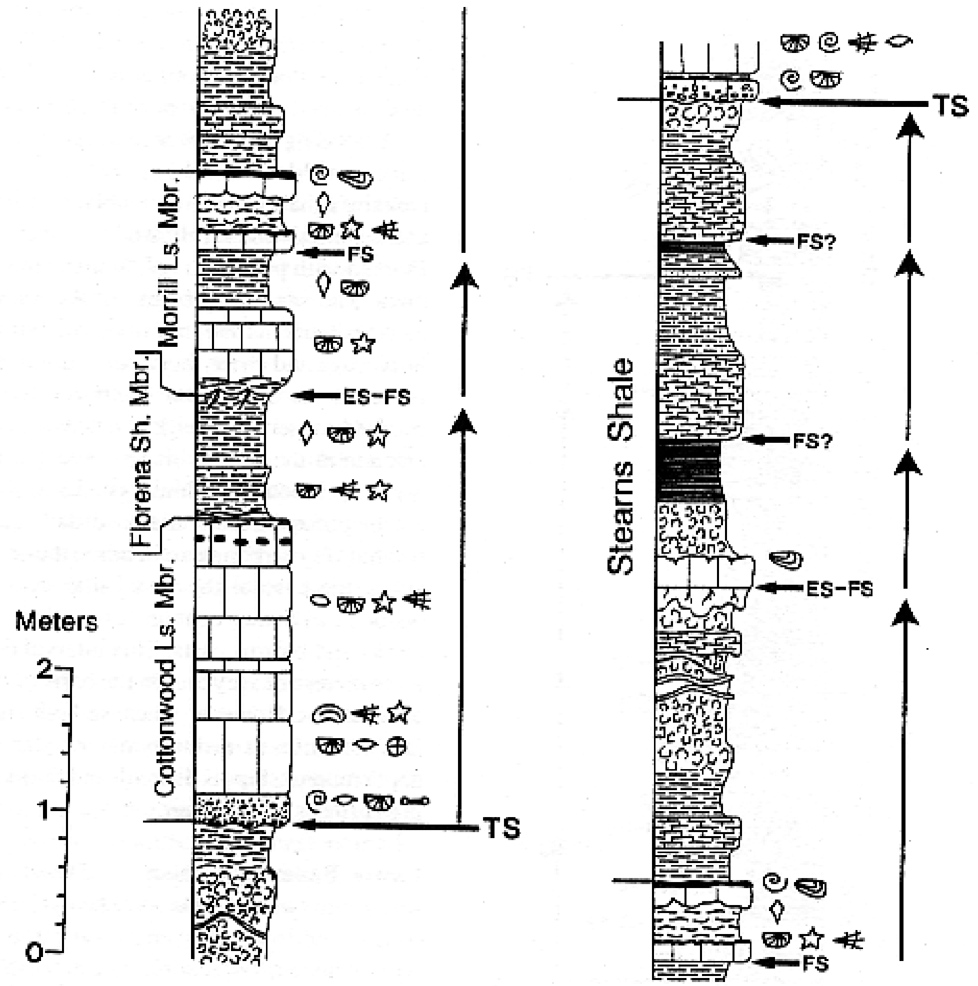

Figure 6. Detailed section of Beattie cyclothem measured at locality 3 showing lithology, general fossil content, and position of discontinuity surfaces. Interpreted transgressive surfaces (cyclothem boundaries) and position of meter-scale cycles indicated by arrows to the right. See fig. 3 for key to lithology and fossil symbols.

shale interval is another flooding surface overlain by a packstone with abundant ostracodes, fine skeletal debris (pyramidellid gastropods, productid spines, crinoid ossicles), and fish bone. The variegated red and green mudstones above this packstone bed have been overprinted by pedogenesis. Truncating this second paleosol interval in the Eskridge and marking another flooding surface is an intraclastic carbonate containing granule- to cobble-size mudstone clasts, pyramidellid gastropods, productid spines, and shell fragments. Above this intraclastic bed are calcareous mudstones that are poorly fossiliferous, except for pavements of *Derbyia* and productid brachiopods. The upper part of this second calcareous interval is intensely rooted and overlain by a grayish-green paleosol with possible pseudoanticlines.

The three paleosol packages and two intervening calcareous intervals just described for the Eskridge have been previously recognized over a three-county area in northeastern Kansas by Bogina (1986) and in southern Nebraska by Joeckel (1991). Furthermore, Mudge and Yochelson (1962) had described two molluskan limestones within the Eskridge that they said could be recognized in most counties along the Kansas outcrop belt.

Beattie cyclothem The Eskridge Shale is capped by a condensed phosphatic bed at the base of the Cottonwood Limestone Member of the Beattie Limestone. This bed contains mudstone clasts up to 10 cm (4 in.) in diameter, phosphate nodules, bone fragments, and skeletal debris (pyramidellid gastropods, ostracodes, and brachiopods). This transgressive lag marks the base of a cyclothem that includes the Beattie Limestone and the overlying Stearns Shale (fig. 6). The Beattie has been studied intensively across the Kansas outcrop belt (Imbrie, 1955; Laporte, 1962; Imbrie et al., 1964), and its lithofacies and biofacies have been well de-

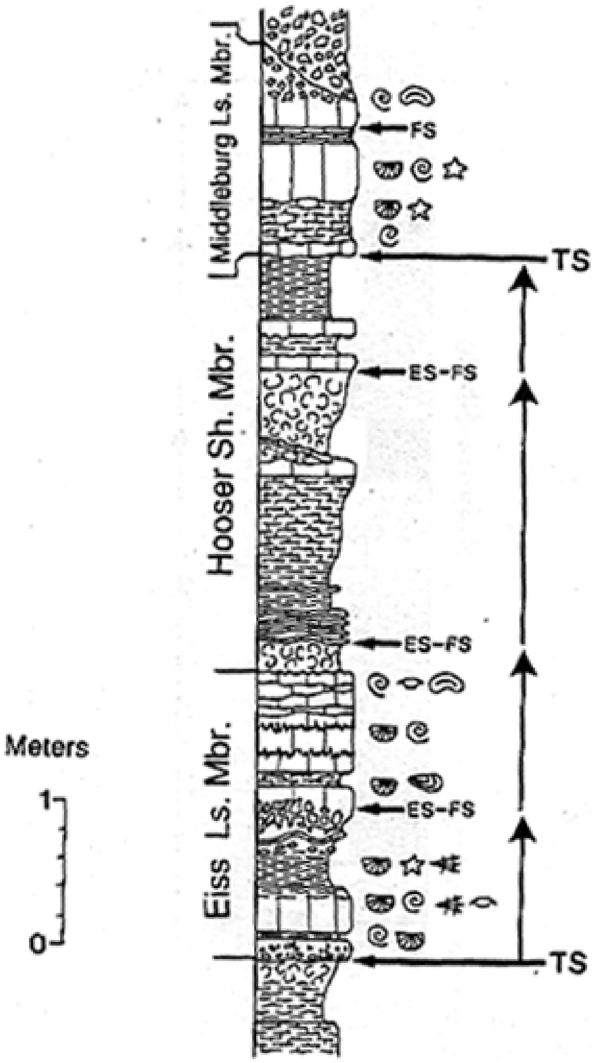

Figure 7. Detailed section of lower Bader cyclothem measured at locality 4 showing lithology, general fossil content, and position of discontinuity surfaces. Interpreted transgressive surfaces (cyclothem boundaries) and position of meter-scale cycles indicated by arrows to the right. See fig. 3 for key to lithology and fossil symbols.

scribed. Throughout the northern half of the outcrop belt the Cottonwood Limestone Member is divisible into two parts: a lower bioclastic facies with abundant algal-coated grains and an upper fusulinid facies. Above the Cottonwood the gray shale of the Florena Shale Member contains abundant *Derbyia* and *Neochonetes* brachiopods. Fossil content decreases upward in the Florena, which becomes less fissile and somewhat dolomitic. Gypsum-filled fractures and tepeelike structures near the top of the Florena are locally developed into a boxwork structure (Twiss, 1988) and were likely the result of subaerial exposure. Tepees are typical features of the peritidal environment resulting from alternate wetting and desiccation, fracture filling, and the force of crystal growth (Evamy, 1973; Assereto et al., 1977). Tepees, boxwork limestones, and evaporites are a common association in modern and ancient evaporitic settings (Warren, 1982).

A flooding surface is recognized at the base of the Morrill Limestone Member. The lower limestone bed of the Morrill contains a marine fossil assemblage of brachiopods, crinoids, and echinoids and is followed by a shale similar to the upper Florena with pavements of *Derbyia* and gypsum-filled fractures. The next cycle begins at the top of this shale with a recrystallized marine limestone containing abundant quartz-lined vugs and cherty horizons. Laminated calcareous mudstones at the base of the overlying Stearns Shale are succeeded by a series of stacked paleosol horizons with a rooted calcrete at the top. In sharp contact with this calcrete is a micritic carbonate with recrystallized shell debris. An interval of unfossiliferous black to dark-gray shales and thin-bedded silty carbonates extends to the next cyclothem boundary at the base of the Eiss Limestone Member. The thin-bedded carbonates contain desiccation cracks as well as tool marks and burrow casts. This interval could be divided into three meter-scale cycles on the basis of the carbonate-clastic alternations. However, because both shales and carbonates lack macrofossil invertebrates or plants, interpreting their depth relationships is difficult and the identification of flooding surfaces is uncertain.

Lower Bader cyclothem The Bader Limestone is divided into two cyclothems. The cyclothem boundary at the base of the Eiss Member is overlain by an intraclastic bed with abundant pyramidellid gastropods (fig. 7). This limestone grades upward into a fossiliferous shale with abundant brachiopods (productids and *Composita*), bryozoans, and crinoids. At the top of this shale is an undulatory carbonate band overlain by greenish-gray shale and a well-developed boxwork structure. Like those described previously, this boxwork facies is interpreted as evidence of subaerial exposure. The next cycle begins with a brachiopod-dominated limestone that is replaced upward by a gastropod-dominated limestone with algal-coated grains. This cycle ends with a thin truncated paleosol at the base of the Hooser Shale Member. Thin carbonate beds and laminated silty calcareous mudstone overlie the next flooding surface. A rooted and rubbly calcrete and a greenish-gray paleosol profile cap this cycle. The fourth and final cycle of this cyclothem is represented by a fenestral micrite overlain by an olive-gray shale.

Upper Bader cyclothem The next cyclothemic sequence within the Bader begins at the base of the Middleburg Limestone Member, where it is marked by a packstone of pyramidellid gastropods and locally by micrite intraclasts (fig. 8). A thin-bedded micrite caps the first of three meter-scale cycles recognized in this cyclothem. This micrite horizon is represented at some nearby localities by a black to olive-gray shale with desiccation cracks at the top (Miller et al., 1992). A wackestone with gastropods and algal-coated grains begins the second cycle that includes the lower part of the Easly Creek Shale. At the base of the Easly Creek is a mudstone breccia of pale-olive clasts in a grayish-red matrix. This breccia corresponds to a 1.8-m-thick (5.9-ft-thick) gypsum bed in the subsurface (Twiss, personal communication, 1992) and thus probably represents a solution collapse breccia. Both the mudstone matrix and the clasts show evidence of having been subjected to pedogenic processes. Above this breccia is an interval of light greenish-gray and light-brown mudstone that shows extensive synsedimentary deformation. The flooding surface that marks the top of this cycle is overlain by thin calcareous beds containing root traces and plant debris. The next cycle is represented by a series of alternating greenish-yellow to grayish-yellow mudstone and siltstone beds. These decimeter-scale units also display incipient soil development with angular to subangular peds. A rubbly, rooted silty mudstone with a poorly developed columnar ped structure caps the last meter-scale cycle of this cyclothem.

Crouse cyclothem Marking the next cyclothem boundary is a 50-cm-thick (20-in.-thick) intraclastic limestone containing rounded granule- to pebble-size micrite clasts (fig. 9). These clasts occur in graded layers together with disarticulated and fragmented brachiopod shells, bivalves, and pyramidellid gastropods. The intraclastic limestone grades into interbedded limestone and shale containing abundant brachiopod shell debris (with articulated productids common), ramose bryozoans, small crinoid ossicles, algal-coated grains, and ostracodes. These grade into an interval of medium-gray shale with a low-diversity assemblage of lingulids and pectinid bivalves. The base of the Crouse Limestone begins the second cycle of this cyclothem.

The Crouse Limestone consists of three widely traceable stratigraphic units that have been interpreted as recording a shallowing-upward transition from a shallow subtidal to supratidal environment (West et al., 1972; Voran, 1975; West and Twiss, 1988). A lower wackestone to packstone interval is characterized by pyramidellid gastropods and bivalves. The middle Crouse is a calcareous, somewhat dolomitic, silty mudstone. Undulatory carbonate-filled fractures and a rubbly zone at the top of this interval may indicate a period of subaerial exposure. Beginning the next cycle, the upper interval of the Crouse is a thin-bedded, horizontally laminated, dolomitic micrite with pavements of ostracodes.

The variegated mudstone of the overlying Blue Rapids Shale is divided into cycles by three sharp flooding surfaces. These flooding surfaces have been recognized over tens of kilometers in Riley County (Miller, 1993). Resting on mudcracked and brecciated micrite from the Crouse, the lowest interval preserves a nearly complete paleosol profile with well-developed color horizonation, angular blocky ped structures, pedogenic slickensides, and carbonate rhizocretions. This paleosol is truncated by a flooding surface and is sharply overlain by a calcareous mudstone containing ostracodes and fish bone. This mudstone in turn lies at the base of another similar well-preserved paleosol profile, itself abruptly overlain by a laminated mudstone containing ostracodes, fish bone, and granule-size intraclasts. The next interval of greenish-gray mudstone, although different in appearance, also shows evidence of pedogenesis. The most prominent pedogenic structures are abundant pseudoanticlines. A horizontally laminated carbonate bed truncates this paleosol and is followed by an interval of dusky yellow-green shale with thin, wavy carbonate bands.

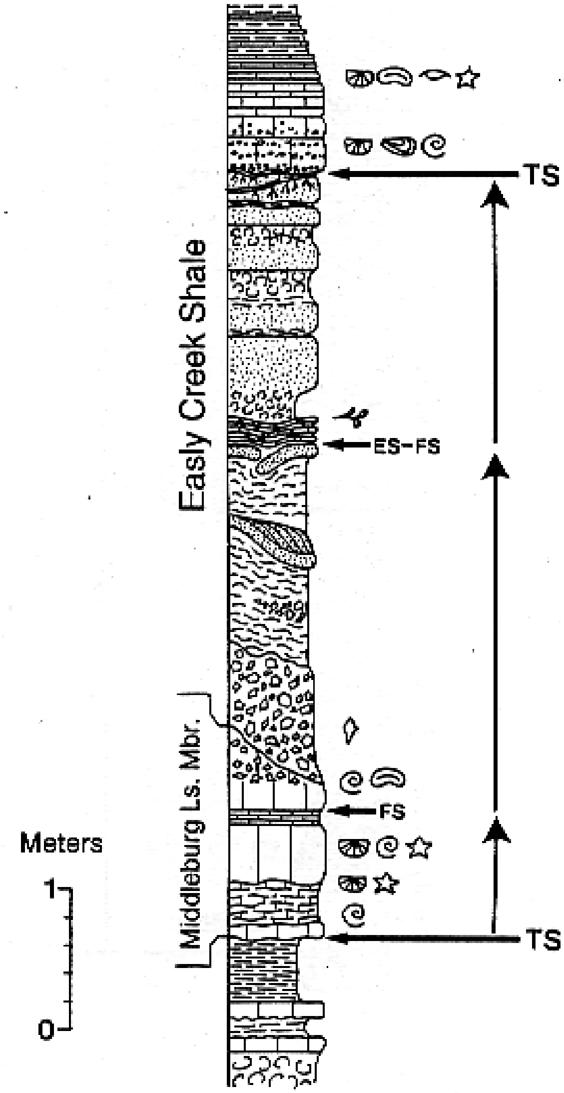

Figure 8. Detailed section of upper Bader cyclothem measured at locality 4 showing lithology, general fossil content, and position of discontinuity surfaces. Interpreted transgressive surfaces (cyclothem boundaries) and position of meter-scale cycles indicated by arrows to the right. See fig. 3 for key to lithology and fossil symbols.

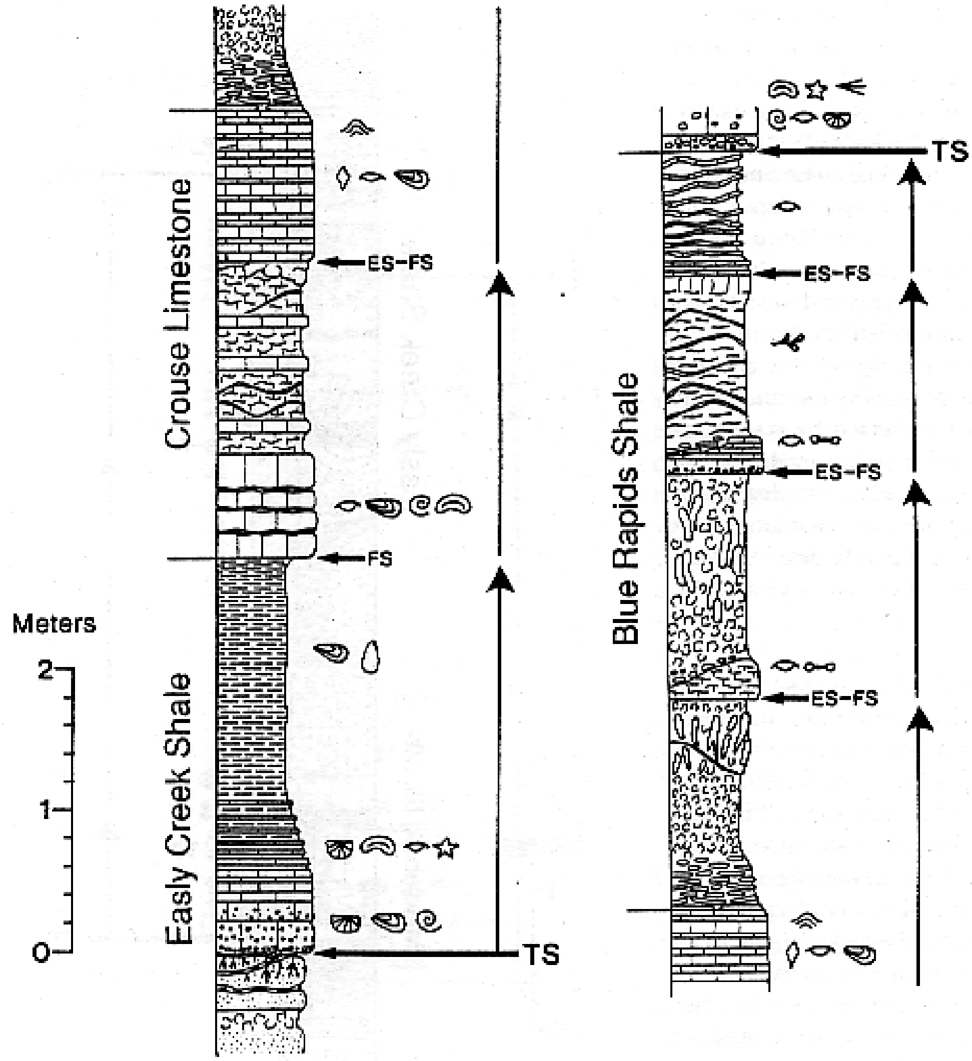

Figure 9. Detailed section of Crouse cyclothem measured at locality 4 showing lithology, general fossil content, and position of discontinuity surfaces. Interpreted transgressive surfaces (cyclothem boundaries) and position of meter-scale cycles indicated by arrows to the right. See fig. 3 for key to lithology and fossil symbols.

Funston cyclothem The base of the Funston Limestone is marked by a prominent transgressive surface (fig. 10). Resting on this surface is a 40-cm-thick (16-in.-thick) argillaceous packstone containing abundant granule-size mudstone clasts and fragmented and abraded skeletal debris. Fossils include pyramidellid gastropods, ostracodes, productid brachiopods, bryozoans, and crinoid ossicles. This limestone grades upward into an unfossiliferous grayish-yellow mudstone that is horizontally laminated in its lower part and contains botryoidal silica geodes. These geodes and those occurring elsewhere in the section are interpreted as silicified evaporite nodules (Chowns and Elkins, 1974). Marking the next flooding surface is a second wackestone to packstone unit with platy micrite intraclasts at its base. It is highly recrystallized with abundant moldic porosity and small solution voids. Identifiable fossils include ostracodes, pyramidellid gastropods, and algal-coated grains. Above this limestone is a light greenish-gray mudstone with well-developed pedogenic slickensides indicating subaerial exposure and incipient soil development. This is sharply overlain by a third argillaceous limestone with granule-size green mudstone clasts at its base. Above is another thin pedogenic interval that is in turn truncated by an ostracode-bearing argillaceous limestone that is extensively rooted. These four cycles in the Funston have been recognized as far as the Hugoton embayment in southwestern Kansas (Abdullah, 1985).

The Speiser Shale, a variegated mudstone similar in many respects to the Blue Rapids Shale, is divisible into three prominent cycles (fig. 10) that have been correlated in outcrop for tens of kilometers (Miller, 1993). These cycles can

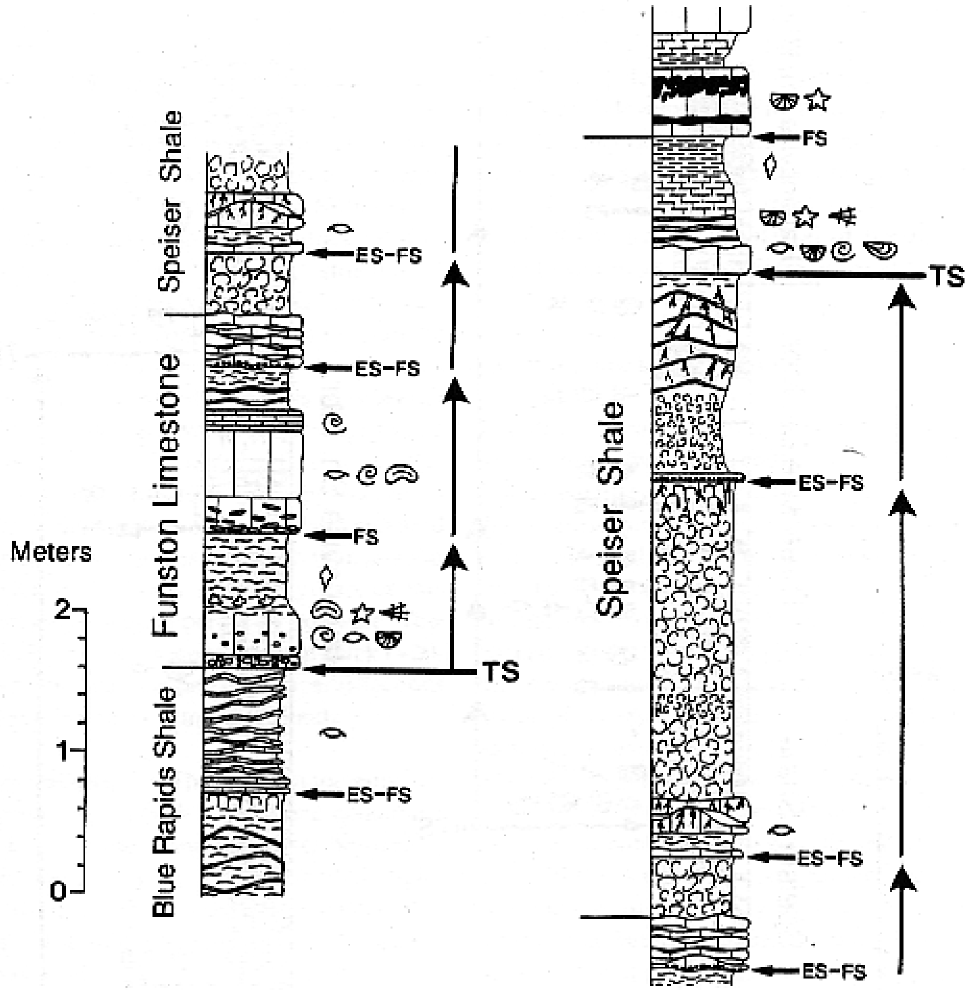

Figure 10. Detailed section of Funston cyclothem measured at locality 4 showing lithology, general fossil content, and position of discontinuity surfaces. Interpreted transgressive surfaces (cyclothem boundaries) and position of meter-scale cycles indicated by arrows to the right. See fig. 3 for key to lithology and fossil symbols.

also be recognized over a six-county area in northeast Kansas from the detailed descriptions of Cunningham (1989). Its lower part is a spectacular red and green banded interval of stacked and truncated paleosols (Miller et al., 1992). These paleosols have angular to subangular ped structures and abundant dendritic root mottles. This interval is sharply overlain by a thin-bedded mudstone with granule-size green mudstone clasts. Above this flooding surface is a light greenish-gray mudstone with prominent pseudoanticlines and abundant concertina (vertically compacted) root traces up to 3 cm (1 in.) in diameter. A packstone of comminuted skeletal debris, including ostracodes and gastropods, abruptly overlies this paleosol and marks the next cyclothem boundary.

Lower Wreford cyclothem A detailed study of the Wreford Limestone was made by Hattin (1957), who recognized two nearly symmetric cyclothems that together were designated the Wreford megacyclothem. Hattin did not specifically identify meter-scale cycles within these cyclothems, but many of those described here can be recognized from his detailed correlations along the Kansas outcrop belt. Similarly, Cuffey (1967) subdivided the Wreford into 22 widely traceable stratigraphic units from which meter-scale cycles can be readily identified [see also Lutz-Garihan and Cuffey (1979)]. More recent work on the genetic stratigraphy of the Wreford in Riley and Geary counties (T. Barrett, 1989) has defined cycles similar to those of this study, although the positions of some cycle boundaries have been chosen differently.

The lower Wreford cyclothem includes the uppermost part of the Speiser Shale. Overlying the cyclothem boundary is a highly fossiliferous medium light-gray calcareous mudstone that grades upward into a more fissile and less fossil-rich shale (fig. 11). Fossils include brachiopods (particularly

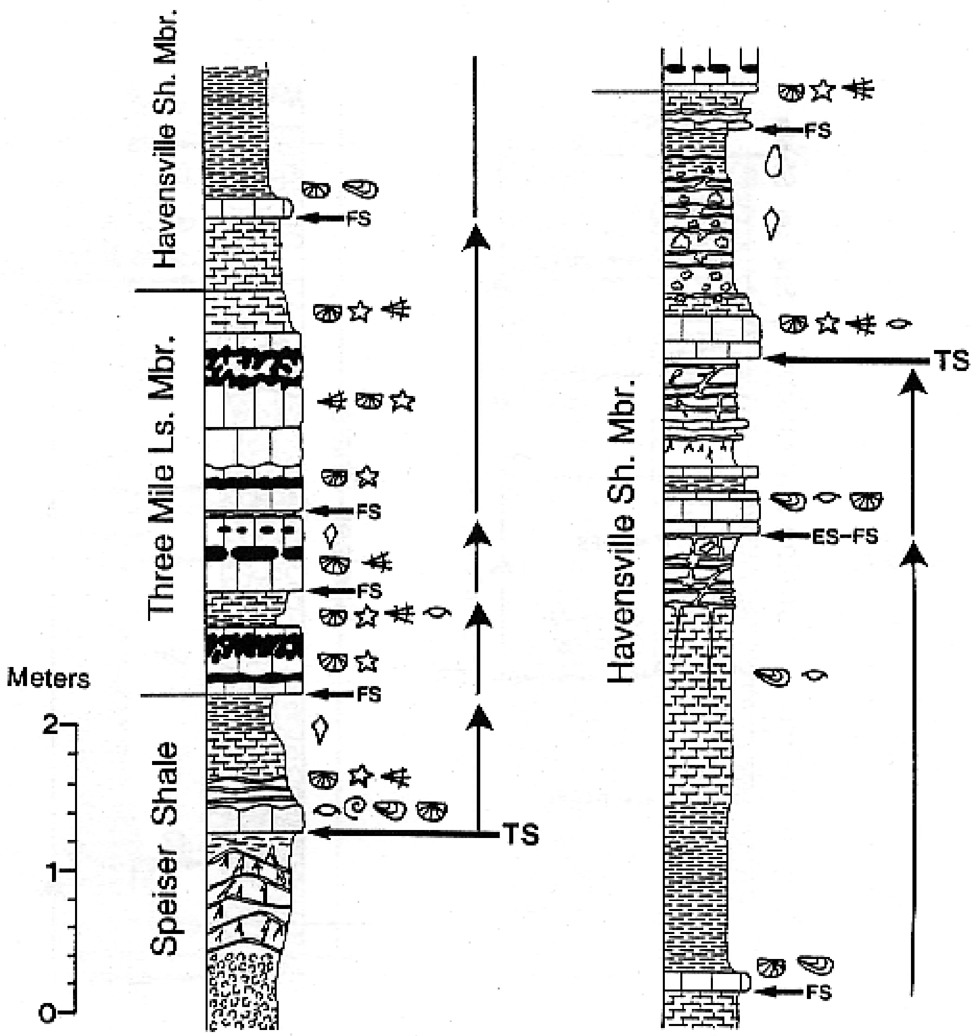

Figure 11. Detailed section of lower Wreford cyclothem measured at locality 4 showing lithology, general fossil content, and position of discontinuity surfaces. Interpreted transgressive surfaces (cyclothem boundaries) and position of meter-scale cycles indicated by arrows to the right. See fig. 3 for key to lithology and fossil symbols.

productids, which can be found articulated and in life position), bivalves, ramose and fenestrate bryozoans, and crinoid ossicles. Carbonate nodules with quartz-lined vugs and thin chert bands occur within this unit, and at some localities tepeelike structures occur at the top with large botryoidal masses of chert associated with their crests (Miller et al., 1992). This uppermost unit of the Speiser is abruptly overlain by the basal bed of the Threemile Limestone Member.

The Threemile Limestone Member of the Wreford Limestone is the first prominent chert-bearing limestone in the Council Grove Group. At the bottom is a wackestone to packstone containing irregular beds of chert. Productid shell debris and crinoid ossicles are abundant. This is overlain by a fissile calcareous shale that contains brachiopods (including articulated productids), crinoid ossicles, fenestrate and ramose bryozoans, and ostracodes. A second cherty wackestone begins the next cycle. Near the top of this bed are isolated chert nodules with radial length-slow chalcedony formed by the replacement of gypsum nodules (West et al., 1987; Twiss, 1991). A thin clay parting marks the top of this thin cycle. The next limestone unit contains little chert but abundant small solution cavities. Fossils within this wackestone include bryozoans, brachiopods, small bivalves, and crinoid ossicles. Hattin (1957) found that this part of the Threemile Member thickens to 7.5 m (25 ft) in central Kansas, where it contains abundant fenestrate and ramose bryozoans. At the top of this unit is a highly cherty wackestone that grades upward into an argillaceous packstone with a diverse fossil assemblage that includes crinoid ossicles, ramose and fenestrate bryozoans, and chonetid brachiopods.

The next meter-scale cycle begins with a thin limestone near the base of the Havensville Shale Member. Overlying this wackestone is a thick interval of medium-gray calcareous shale to mudstone that is poorly fossiliferous except for pectinid bivalves and ostracodes. Correlative with this stratigraphic interval over the axis of the Nemaha structural high is a 3.5-m-thick (11-ft-thick) packstone to grainstone with a diverse brachiopod and mollusk fauna and abundant large plant fragments and charcoal (T. Barrett, 1989; Miller et al., 1992). At the top of this interval is a 50-cm-thick (20-in.-thick) calcareous mudstone with a "boxwork" structure of irregular botryoidal carbonate bands and vertical carbonate-filled fractures, some extending up to 60 cm (24 in.) into the underlying mudstone. This structure probably developed as a result of desiccation during extended periods of subaerial exposure. Above this boxwork is a wackestone with a graded layer of shell debris marking a flooding surface at its base. This wackestone is overlain by medium light-gray calcareous shale and mudstone with abundant ostracodes and chonetid brachiopods. Root traces and the development of an angular blocky ped structure in the upper olive-gray part of this interval indicate another extended period of exposure. This rooted horizon is followed by a second ≈50-cm-thick (≈20-in.-thick) boxwork interval capped by an argillaceous wackestone overlying the next cyclothem boundary.

Upper Wreford cyclothem The final cyclothemic sequence described here begins with a limestone containing brachiopod shell debris, ramose and fenestrate bryozoans, crinoid ossicles, and ostracodes (fig. 12). The medium light-gray calcareous mudstone above contains abundant thin irregular bands of silica, silica nodules, and large quartz-filled, cauliflower-shaped geodes. The shape of these silica bands and nodules suggests formation by the replacement of gypsum, which is found in some geodes. Tiny lath-shaped molds of gypsum crystals are also locally abundant. The flooding surface above this evaporitic interval is marked by the base of the Schroyer Limestone Member of the Wreford Limestone. The bottom unit is a micrite with layers of ellipsoidal chert concretions, abundant small solution voids, and fine skeletal debris. A new cycle is interpreted to begin above a thin shale layer at the base of a massive wackestone with prominent irregular chert beds. Fossils include brachiopods (productids and *Composita* occur as articulated specimens), ostracodes, crinoid ossicles, and ramose and fenestrate bryozoans. Above this is a fossiliferous calcareous mudstone that becomes rubbly and nodular toward the top.

The upper unit of the Schroyer begins the next cycle. This limestone is a dolomitic wackestone to packstone with abundant solution voids and moldic porosity. A thin packstone of ellipsoidal osagid grains marks the top. Above the Schroyer, at the base of the Wymore Shale Member of the Matfield Shale, is a very thin dark-gray to black shale with abundant terrestrial plant debris and spiral fish coprolites (Williams, 1972). Above, the Wymore can be divided into two paleosol intervals representing two meter-scale cycles. The lower interval consists of variegated red and green paleosol profiles with calcic horizons of caliche nodules and closely packed rhizoconcretions. These aridic profiles are followed by olive-gray vertic paleosols with abundant pseudoanticlines and locally well-developed prismatic ped structure. This second paleosol interval is truncated by another flooding surface marked by a mudstone breccia with granule- to pebble-size angular clasts. The final meter-scale cycle of the upper Wreford consists of an interval of horizontally laminated olive to yellowish-gray calcareous mudstone.

Interpreting cycle patterns

Detailed measurement of the lower Wolfcampian of Kansas demonstrates that the cyclothems first described by Jewett (1933) and Elias (1937) are actually generalized facies trends that disguise a complex internal cyclostratigraphy. Using the sequence model, one can define boundaries of these Permian cyclothems clearly and for the most part unambiguously, despite this complexity. However, sequence-stratigraphic concepts are not as easily applied to the interpretation of the internal stratigraphy of these cyclothems. The repeated alternation of carbonate and clastic facies at the meter scale is not implied by sequence models of cyclothem development. Similarly, the predominance of shallow-water paralic facies and the ubiquitous occurrence of subaerial exposure surfaces limit the probable extent of eustatic sea-level change (Miller et al., 1991). A realistic model for the origin of cyclothemic sequences must adequately explain the origin of the meter-scale cycles that so dominate the stratigraphy. The process of selecting an appropriate and widely applicable model for these subcyclothemic-scale cycles will certainly greatly refine, if not alter, our present understanding of midcontinent cyclothems. For this reason three approaches to interpreting meter-scale cycles are discussed in what follows and tested against the facies patterns of the cycles described. Two cyclothems are given particular attention: the lower Grenola cyclothem, because it is most similar to the extensively studied Missourian cycles; and the Crouse cyclothem, because it displays the features of a more typical Wolfcampian cycle.

Kansas-type cyclothem model The Kansas-type cyclothem model proposed by Heckel (1977) provides one context within which to interpret smaller-scale cycles. The original model explicitly incorporated the multiple limestone-clastic cycles included in Moore's (1936, 1949) megacyclothems but focused primarily on the core shale and the immediately over- and underlying limestone units (Heckel and Baesemann, 1975; Heckel, 1984a). Only those carbonates associated with the black phosphatic core shales were recognized as transgressive or regressive units. Outside this facies triplet, carbonates were interpreted as minor deepening events within generally shallow-water to terrestrial clastic intervals. These cycles were understood by both Heckel

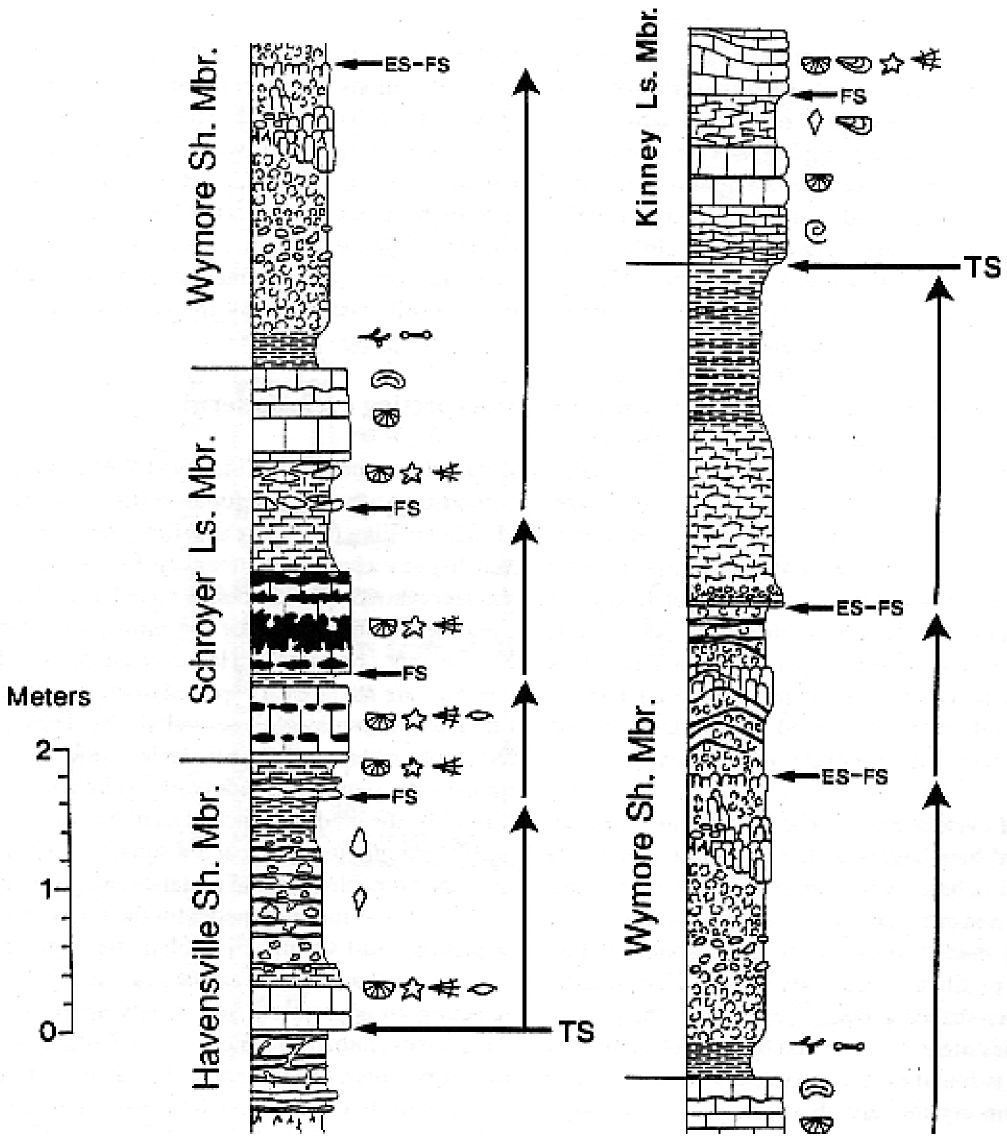

Figure 12. Detailed composite section of upper Wreford cyclothem measured at localities 2 and 4 showing lithology, general fossil content, and position of discontinuity surfaces. Interpreted transgressive surfaces (cyclothem boundaries) and position of meter-scale cycles indicated by arrows to the right. See fig. 3 for key to lithology and fossil symbols.

and Moore as essentially shallowing-upward cycles or parasequences. More recently, small-scale cycles within the generally thicker multistoried regressive limestones have been similarly interpreted as parasequences (Heckel and Watney, 1985). Because parasequences are not the focal point of the Kansas cyclothem model, they are discussed separately.

The central cycle of a Kansas-type cyclothem, consisting of transgressive limestone, core shale, and regressive limestone, is interpreted as a cratonic depositional response to global glacio-eustatic sea-level change (Boardman and Heckel, 1989; Watney et al., 1989). The asymmetry of the cycle reflects the asymmetry of the glacio-eustatic sea-level curve as recorded in the Pleistocene. The thin transgressive carbonate is deposited during initial rapid eustatic sea-level rise and is followed by a condensed lag formed by non-deposition and reworking during the time of maximum sea-level rise. The overlying black shale is then interpreted to represent slow deposition under anoxic conditions in deeper water and is equivalent to the condensed section of a sequence. As sea level slowly falls, carbonate production resumes, resulting in the formation of a thicker regressive limestone within which shallow marine to intertidal facies are commonly developed. The top of the regressive limestone

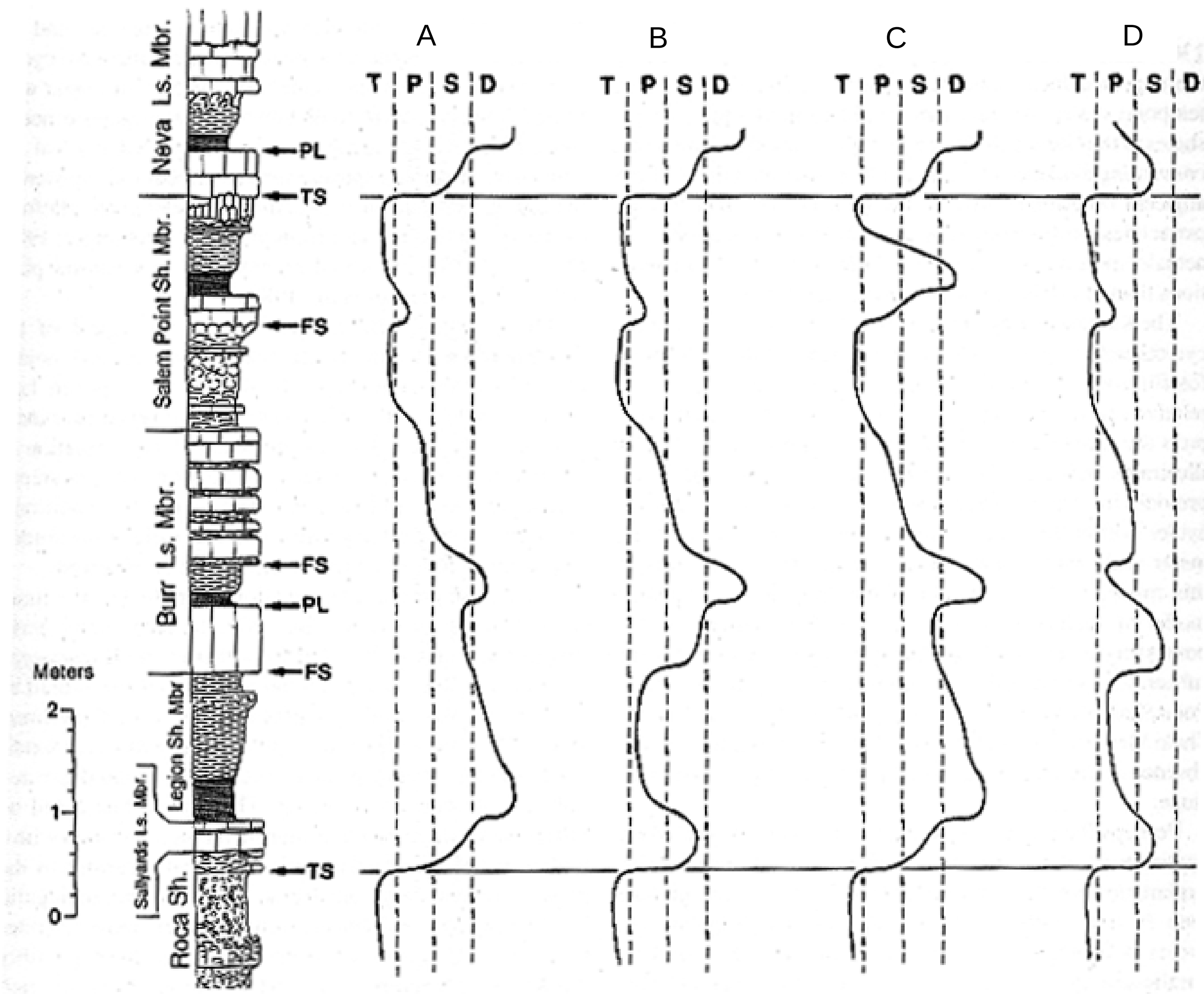

Figure 13. Stratigraphic section of lower Grenola cyclothem, broadly similar to the much studied Missourian cycles, with four alternative relative sea-level curves. Arrows mark transgressive surfaces (TS), flooding surfaces (FS), and phosphatic lags (PL). Depth zones indicated are terrestrial (T), paralic (P), shallow marine (S), and deep marine (D). The four curves are: (A) Relative sea-level curve drawn based on Kansas-type cyclothem model of Heckel (1977) interpreting Sallyards limestone as a transgressive limestone and Legion shale as a core shale. (B) Relative sea-level curve based on Kansas-type cyclothem model interpreting lower limestone unit of Burr as transgressive limestone and overlying black shale as core shale. (C) Relative sea-level curve based on Kansas-type cyclothem model interpreting all black shale intervals as core shales. (D) Relative sea-level curve based on parasequence model of shallowing-upward cycles with limestones interpreted as representing deeper water. Compare with Moore's (1936) model of megacyclothems.

may contain evidence of subaerial exposure and may be overlain by paleosols.

The model can be best applied to the Grenola Limestone, which is the only limestone formation of this study to contain black shale units analogous to those of the Missourian cyclothems. The lower Grenola cyclothem has four meter-scale cycles, three of which include black shale intervals (fig. 3). The application of Heckel's (1977) cyclothem model to these cycles is not unambiguous, however. The Sallyards limestone could be considered a transgressive limestone with the Legion Shale Member representing the core shale and the Burr interpreted as a regressive unit (fig. 13A). Alternatively, the lower Burr limestone could be designated the transgressive limestone, the black shale above the core shale, and only the upper Burr considered regressive (fig. 13B). Still another approach would be to recognize each black shale, including the one underlying the Neva, as equivalent to a core shale (fig. 13C). Identification of cycle phases is complicated because the expected facies pattern is actually present at different temporal scales. An additional problem in identifying core shales in the Grenola is that none of the black shales provides *convincing* evidence of water depth greater than those of the adjacent limestones. In fact, the presence of plant fossils, ostracodes, pectinid bivalves, and inarticulate brachiopods is actually more suggestive of nearshore brackish-water conditions than of offshore marine conditions (fig. 3).

The Kansas-type cyclothem model can also be extended to cyclothemic sequences that include meter-scale cycles with fossiliferous gray or olive-gray shales. Figure 14A shows a relative sea-level curve for the Crouse cyclothem that interprets the upper Easly Creek Shale as a core shale. As fig. 14 illustrates, however, the Kansas-type cyclothem model only provides interpretive guidance for one of the six meter-scale cycles within this cyclothemic sequence. For most of the meter-scale cycles in the Wolfcampian, the predictions of this model are not distinguishable from a parasequence model of shallowing-upward cycles. Even among cycles possessing a core shale analogue, some show evidence of subaerial exposure at the tops of the shales (e.g., upper Salem Point Shale Member, lower Neva Limestone Member, Florena Shale Member, Eiss Limestone Member), thus implying the absence of the usually substantially thicker regressive limestone.

Perhaps the greatest weakness of Heckel's model when applied to the Permian is that it does not provide an adequate explanation for the consistent carbonate-to-clastic pattern seen in essentially all meter-scale cycles. Why should cycles developed in both open-marine and terrestrial or paralic settings show the same pattern? This question cannot be answered by reference to the Kansas-type cyclothem model. According to the model of limestone deposition for the Pennsylvanian (Heckel, 1984b), carbonate precipitation was limited seaward by deep, cold, poorly lit bottom waters and landward by the influx of terrigenous clastic sediment. Carbonate-to-clastic alternations are thus understood as the result of the lateral migration of depth-controlled facies belts in response to glacio-eustatic sea-level change. However, the common occurrence of shallow subtidal to supratidal indicators (e.g., algal-coated grains, laminated micrites, fenestral fabric, desiccation cracks) in carbonates of the Wolfcampian section indicates that carbonate precipitation extended into coastal and paralic settings. These same environments were at other times accumulating fine clastic sediments. This observation requires that some non-depth-related factor periodically cut off clastic sediment supply from the coastal environment.

Meter-scale cycles as parasequences The most straightforward interpretation of the meter-scale cycles is as parasequences (Van Wagoner et al., 1988). These shallowing-upward cycles are bounded by flooding surfaces and are essentially equivalent to the punctuated aggradational cycles (PACs) of Goodwin and Anderson (1985). Consistent with the shallowing-upward prediction of the parasequence model, most of the cycles recognized in the studied interval are capped by subaerial exposure surfaces. Subaerial exposure at the top of parasequences is common in carbonate platform cycles (Goldhammer and Elmore, 1984; Grotzinger, 1986; Strasser, 1988) and would be expected in a coastal plain setting (Van Wagoner et al., 1988).

The mudstone and paleosol cycles so typical of the Wolfcampian can be easily understood as shallowing-upward cycles (fig. 14B). Flooding of an exposed land surface during rapid transgression would result in truncation of underlying paleosol profiles and the formation of intraclastic and skeletal lags. Deposition of calcareous mudstones would follow under shallow paralic conditions. With the subsequent regression and exposure of the muddy sediments, paleosol development would be renewed.

If a parasequence interpretation is applied to the limestone–black shale cycles (fig. 13D), the bathymetric position of the facies is reversed from that of the Kansas-type cyclothem model. A rapid relative sea-level rise would be recorded by the flooding surface at the base of the limestone. The limestone would represent deepest water conditions with the overlying black to dark-gray shales deposited during subsequent shallowing. The shales thus could be interpreted as lagoonal or estuarine facies associated with a high influx of terrestrial organic matter, as suggested by the presence of abundant plant debris. The occurrence of lingulid brachiopods, pectinid and myalinid bivalves, and ostracodes in these shales is also consistent with a nearshore, possibly brackish-water setting. This interpretation of organic-rich shales as nearshore or paralic facies is similar to that proposed by Moore (1936) for the black shales of Pennsylvanian cyclothems.

Gray to olive shales overlying marine limestones can also be understood in terms of the parasequence model. As stated in the previous section, several of the limestone-shale cycles are capped by probable subaerial exposure surfaces. Many of the shales also contain biotic or lithologic evidence suggestive of deposition at depths shallower than the associated limestones, such as decreases in the abundance and diversity of macrofossils. However, limestone-shale cycles do not always show persuasive evidence of shallowing-upward conditions. The limestone-shale couplets in the Threemile (fig. 10) and Schroyer Limestone Members (fig. 11) are examples of cycles for which a shallowing-upward interpretation is not strongly supported. There are also carbonate-clastic cycles, such as those in the upper Stearns Shale (fig. 6), whose description as parasequences is uncertain.

As with the Kansas-type cyclothem model, the parasequence model alone does not provide an adequate basis for understanding the carbonate-to-clastic alternation that is a

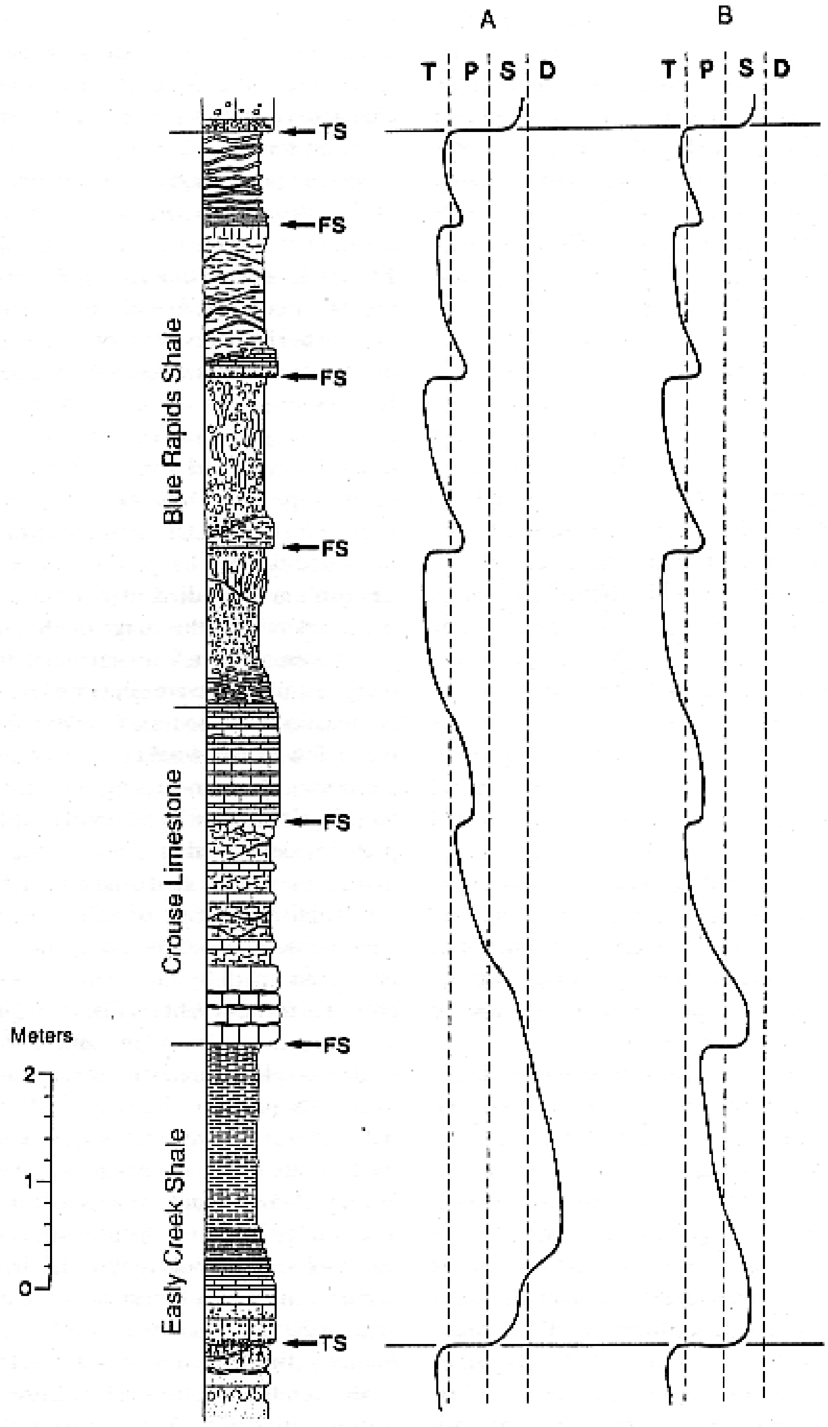

Figure 14. Stratigraphic section of Crouse cyclothem, a typical Wolfcampian cycle, showing two alternative relative sea-level curves. (A) Relative sea-level curve drawn based on Kansas-type cyclothem model of Heckel (1977) interpreting upper Easly Creek Shale as a core shale. (B) Relative sea-level curve based on parasequence model of shallowing-upward cycles. Note that the two curves differ only in the interpretation of one of the meter-scale cycles. Arrows mark transgressive surfaces (TS) and flooding surfaces (FS).

fundamental characteristic of the meter-scale cycles. Carbonates always appear associated with sea-level rise and clastics with sea-level fall, regardless of actual water depths. If depth were the primary control over facies development, then a bathymetric facies model should be able to be constructed. However, both carbonate and clastic units exhibit a wide range of facies representing subaerial to open-marine conditions. A simple onshore-offshore Waltherian facies model is thus clearly inadequate to explain the periodic change from carbonate-to-clastic deposition.

Meter-scale cycles as climate cycles If relative sea-level change alone is insufficient to explain the observed facies transitions and cycle patterns, climate change may provide an important forcing mechanism. Orbitally forced climate cycles have been invoked by, among others, Barron et al. (1985), Fischer et al. (1985), Hattin (1985), and Kauffman (1986) to explain decimeter- to meter-scale periodicities in the Cretaceous. A model for climatic control over facies development in Carboniferous cycles has been proposed by Cecil (1990) based on a comparison of Mississippian and Pennsylvanian cycles in the Appalachian basin (Cecil et al., 1985; Donaldson et al., 1985; Cecil and Eble, 1992). 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) and Perlmutter and Matthews (1989)]. Carbonates and evaporites accumulate during arid and semiarid conditions, and mappable coal beds form in relatively wet climates when clastic influx is low. These climate-driven depositional processes may function at more than one temporal scale, responding to long-term climatic changes during the Permian-Carboniferous and to short-period Milankovitch climatic oscillations.

The climate model of Cecil (1990) can be applied to the meter-scale cycles of the Wolfcampian. Wet-dry climate fluctuations could account for the observed cycle pattern, with the transport of terrigenous clastics into the basin during wetter intervals and the precipitation of carbonate during drier intervals. For example, the black to gray shale intervals of the Grenola Limestone (fig. 3) could record the influx of clastic sediments and terrestrial organic matter during a seasonally wet climatic period, shutting down carbonate production and locally reducing salinities. With a return of more uniformly dry conditions, sediment influx would be greatly reduced. Carbonate production would resume with the return of normal salinities and clear water.

The climate model also provides a useful basis for understanding the mudstone and paleosol cycles. During periods of seasonally wet climate, a relatively rapid influx of sediment into the nearshore and paralic environments would rapidly aggrade the bottom to base level. Paleosol development would then follow on the exposed muddy coastal plain. Continued episodic sediment supply combined with gradual subsidence would result in stacked paleosol profiles. With drier conditions and reduced sediment influx, subsidence would result in the flooding of the coastal plain and the reworking and erosion of the uppermost paleosol profiles. Calcareous shallow-water facies would then be deposited over this transgressive lag.

Paleoclimate models for western North America during the Late Pennsylvanian and Permian indicate the existence of a strong monsoonal climate (Parrish and Peterson, 1988; Kutzbach and Gallimore, 1989; Patzkowsky et al., 1991). Global circulation models also predict significant fluctuations in the intensity of monsoonal circulation in response to orbital forcing (Kutzbach and Guetter, 1984). Climate records for the Pleistocene similarly indicate periodic fluctuations in the intensity of monsoons during glacial and interglacial times (Crowley and North, 1991, ch. 6). Perhaps fluctuations of this type in the monsoonal climate of Pangea generated short-term oscillations between semi-arid and seasonal wet-dry conditions. The predominance of calcic and vertic paleosols in the studied interval (Miller and McCahon, 1992) is consistent with this range of climate change.

As presented, the climate model implies that relative sea-level fluctuations were generated only by basin subsidence, compaction, and sediment aggradation. Depth changes of only a few meters would then have been associated with the generation of meter-scale cycles. This is not unreasonable for those cycles capped by paleosol profiles. The paleosols were probably developed on low-relief coastal plains never more than a meter or two above the water table (or above sea level). The reddish horizons of paleosols, probably representing well-drained conditions above the water table, are rarely more than 1 m (3 ft) thick. There is also a striking absence of erosional fluvial channels that would be expected if there was a significant sea-level lowstand. In addition, the laminated or thin-bedded ostracode-bearing carbonates that typically overlie the paleosols (see especially figs. 9 and 10) indicate only shallow paralic conditions following flooding. By contrast, the abrupt facies change at sequence boundaries would seem to demand depth changes of more than a few meters. The establishment of open-marine conditions over a wide geographic area would require depths of perhaps 10 m (33 ft) or more. Similarly, limestone-shale cycles capped by probable subaerial exposure surfaces [e.g., lower Neva Limestone Member (fig. 3), Cottonwood Limestone Member to Florena Shale Member (fig. 6), and Eiss Limestone Member (fig. 7)], may require depth changes greater than those predicted by climatic change alone.

Discussion

Detailed measurement of stratigraphic sections in northeast Kansas has documented that the Wolfcampian cyclothems of the midcontinent can be divided into prominent meter-scale cycles that are commonly capped by paleosols and other subaerial exposure surfaces. These cycles show a consistent change from carbonate to clastic deposition. In addition, shallow-water paralic facies dominate both carbonate and clastic intervals. Because of the constraints they place on possible eustatic interpretations, these observations have profound implications for our understanding of cyclic processes during this important time of climatic and paleogeographic change.

Sea-level changes of the magnitude proposed for the Pennsylvanian cyclothems of Kansas [in excess of 100 m (330 ft) (Heckel, 1977)] are clearly difficult to justify for the Permian. The absolute magnitude of sea-level fluctuation recorded by Lower Permian cycles has always been a matter of dispute. Elias's (1937, 1964) original estimate of 60 m (200 ft) for the deepest water facies of Permian cycles was questioned by Imbrie et al. (1964) and McCrone (1964). These researchers placed maximum water depth at less than 20 m (66 ft) based primarily on a reinterpretation of fossil evidence and the recognition of abundant sedimentary indicators of shallow water. We suspect that even this estimate of relative depth change may be higher than necessary to account for the range of facies observed in Wolfcampian cyclothems (Miller et al., 1991). Although the magnitude of relative sea-level fluctuation was probably not great, glacio-eustasy was still likely an important factor in cycle formation, especially considering the presence of waning Gondwana glaciation at this time. However, the extent of its control over facies development was probably considerably less than that usually assumed. Most important, the Waltherian stacking of laterally migrating depth-controlled facies is inadequate to explain the observed carbonate-to-clastic alternations. Climate change, probably forced by Milankovitch orbital periodicities, through its control over sediment supply and transport, does appear to provide such a mechanism [see also Soreghan (1992)].

Meter-scale cycles seem best understood as responses to orbitally forced fluctuations in a monsoonal climate. The cyclothem pattern, on the other hand, was probably more influenced by glacio-eustatic sea-level change. The observed cycle pattern is thus interpreted as the result of regional climate oscillations superimposed on longer-term, low-amplitude glacio-eustatic sea-level change. We are not arguing, however, for an exclusive mechanism at each scale of cyclicity. Climatic control over sedimentation within a depositional basin and global eustatic sea-level change are in fact logically linked (Perlmutter and Matthews, 1989). Soreghan (1992) recently completed a study that applies the coupling of glacio-eustasy and climate change to the interpretation of Pennsylvanian stratigraphic cyclicity. Alternating eolian and fluvial facies in Pennsylvanian to Lower Permian sediments of the Ancestral Rockies were earlier interpreted by Johnson (1989) as responses to climate cycles coincident with global glaciations. Many more such field studies are

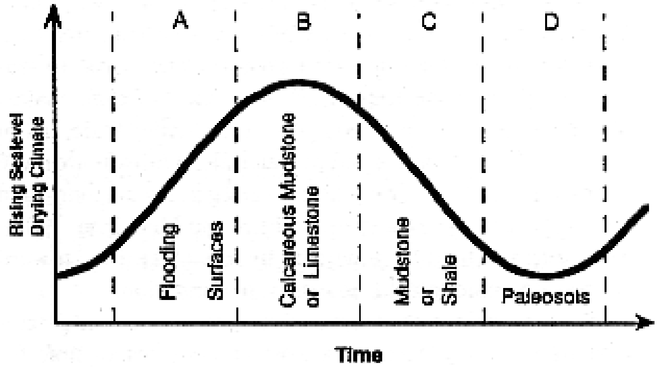

Figure 15. Illustration of climatic-eustatic model proposed here for the generation of meter-scale cycles within the Wolfcampian. The combined sea-level/climate curve is divided into four parts: (A) rising sea level and drying climate, (B) sea-level highstand and driest climate phase, (C) falling sea level and increasing rainfall, and (D) sea-level lowstand and wet climate phase. The times of carbonate and clastic deposition and nondepositional periods are indicated below the curve [based in part on Cecil's (1990) climate model]. This model explains the pervasive carbonate to clastic pattern of the cycles.

needed to provide a database for understanding the dynamics of climate cyclicity, sea-level change, and sedimentation on the Pangean supercontinent.

Although we believe climate fluctuations to have been the dominant factor in the formation of meter-scale cycles, climate alone cannot account for water-depth changes greater than the decompacted thickness of these cycles. Because relative depth changes exceeding this may be needed to explain at least some cycles, short-term climate change probably was accompanied by eustatic sea-level change. Flooding surfaces and the carbonate facies overlying them would record both eustatic sea-level rise and an increasingly arid climate. Conversely, shale and mudstone deposition would record sediment aggradation and sea-level fall under more seasonally wet conditions. Paleosols would develop at sea-level lowstands during these wetter climate periods and during any subsequent drying that preceded inundation. These relationships are illustrated in fig. 15.

As wet-dry climate fluctuations alone may not explain the meter-scale cycles, glacio-eustasy likewise does not appear adequate to fully explain the cyclothem pattern. Evidence of climatic change at the scale of the cyclothemic sequences is recognized in the studied interval. Indicators of the driest climatic conditions tend to be associated with the limestone formations of sequences. Gypsum crystal molds and silica pseudomorphs after gypsum are common in limestones and associated mudstones, and massive gypsum beds immediately overlie some limestone units (i.e., the Burr Limestone Member and the Middleburg Limestone Member) in the subsurface. By contrast, the extensive rooting and presence of plant debris and charcoal fragments that characterize many mudstone units indicate significant vegetation cover and at least seasonally wet climates. Consistent vertical changes in paleosol morphology upward through several shale formations (e.g., the Blue Rapids, Speiser, and Wymore shales) also suggest climatic trends at a cyclothemic scale, given relatively homogeneous parent materials. Aridisols are more characteristic of the lower parts of variegated mudstones, and Vertisols occur near their tops (Miller and McCahon, 1992). Such a trend could be generated by a climate trend toward increasing, although still seasonal, precipitation.

Some combination of regional climatic change and glacio-eustatic sea-level fluctuation was probably responsible for the generation of both cyclothemic sequences and meter-scale cycles. If so, and if Cecil's (1990) climate model is correct, then eustatic sea-level rise was associated with increasingly arid climate conditions, and sea-level fall was associated with an intensification of seasonal rainfall (see fig. 15). This implies that glacial advance was accompanied by an increase in precipitation across the midcontinent and that glacial retreat was accompanied by a return to more arid to semi-arid conditions. Much more paleoclimatic data are needed on the stratigraphic and geographic distribution of climatically sensitive facies and paleosols to determine the generality of this pattern.

The apparent association of falling glacio-eustatic sea level with wetter climate phases and rising sea level with drying climate phases inferred from this study is the reverse of that generally expected. The timing of sediment influx into a basin relative to sea level is a function of latitude and geographic position (Perlmutter and Matthews, 1989). The midcontinent, on the western half of northern Pangea, was still at low paleolatitudes (<10°) during the Wolfcampian (Parrish and Peterson, 1988). Because of the equatorward shift of midlatitude high-pressure atmospheric circulation cells during glacial periods, low latitudes would be expected to experience drier conditions during sea-level lowstands. Similarly, the expansion of the equatorial low pressure cell (ITCZ) during interglacial periods would bring wetter conditions during sea-level highstands (Perlmutter and Matthews, 1989). The Quaternary paleoclimate record shows just this pattern. Evidence of changing lake levels, vegetation changes, and the expansion and contraction of sand seas reveals that at low latitudes drier conditions prevailed during glacial periods than during the interglacial periods (Crowley and North, 1991). This association of drier climate with falling glacio-eustatic sea level has also been inferred for the Pennsylvanian in the southern Ancestral Rockies region (Soreghan, 1992).

The unexpected results for the midcontinent Permian may be explained by the monsoonal circulation resulting from Pangean paleogeography. Monsoonal conditions would have strengthened as Pangea moved northward and the Appalachian highlands were eroded during the Permian (Rowley et al., 1985). The Pangean monsoon would have disrupted the global zonal circulation pattern, diverting the moisture-laden equatorial easterlies flowing from the Tethys to the north or south and drying the equatorial region (Parrish et al., 1982; Parish and Peterson, 1988). In addition, the rainshadow effect produced by the equatorial Appalachian highlands and the size of the continental mass would have made western Pangea, including the midcontinent, generally dry regardless (Patzkowsky et al., 1991). However, fluctuations in the intensity of monsoonal circulation may have produced oscillations between semi-arid and seasonal wet-dry conditions. Both climate models (Kutzbach and Guetter, 1984) and paleoclimate data (Fairbridge, 1986; Crowley and North, 1991) indicate that monsoons are strengthened during interglacial periods and significantly weakened during glacial episodes. A weakened monsoon during the Permian may have permitted a return to more zonal circulation (Parrish and Peterson, 1988) with more moisture brought in by the equatorial easterlies (J. T. Parrish, personal communication, 1993). Thus in the midcontinent strong monsoons during interglacial highstands would have been associated with more arid conditions, and weakened monsoons during glacial lowstands would have been associated with relatively wetter conditions. Orbitally controlled changes in the intensity of the monsoon may therefore have overwhelmed the effects of shifting zonal circulation patterns and rising and falling sea levels, resulting in the pattern observed in this study.

The Wolfcampian may record a time during which the influence of zonal circulation and glacio-eustasy was giving way to monsoonal circulation and Milankovitch climate oscillations. With the waning of Gondwana glaciation in the early Permian, the extent of glacio-eustatic sea-level fluctuation would also have declined. Predominantly sea-level-controlled cyclothems of the Pennsylvanian would then have given way to more directly climate-controlled cyclothems in the Permian. Relative depth changes of the order of perhaps 10 m (33 ft), accompanied by fluctuations in the monsoonal climate, could have generated both the observed facies patterns recognized by Jewett (1933) and Elias (1937) and the superimposed meter-scale cycles described here. Wetter climate phases, associated with small glacio-eustatic base-level falls, generated an influx of clastic material into the depositional basin. Conversely, decreases in precipitation and reduced sediment transport favored chemical precipitation during times of sea-level rise. This proposed general model provides a viable and testable alternative to the predominant paradigm for midcontinent cyclothemic deposition.

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References

Abdullah, T. Y., 1985, Depositional facies in the Funston cycle (Lower Permian) of southwestern Kansas; *in*, Core studies in Kansas—sedimentology and diagenesis of economically important rock strata in Kansas, Watney, W. L., Walton, A. W., and Doveton, J. H., eds.: Kansas Geological Survey, Subsurface Geology Series 6, p. 161–171

Ager, D. V., 1981, The nature of the stratigraphical record, 2d ed.: Wiley & Sons, New York, 122 p.

Aigner, T., 1985, Storm depositional systems—dynamic stratigraphy in modern and ancient shallow-marine sequences: Lecture Notes in Earth Sciences 3, Springer-Verlag, New York, 174 p.

Algeo, T. J., and Wilkinson, B. H., 1988, Periodicity of mesoscale Phanerozoic sedimentary cycles and the role of Milankovitch orbital modulation: Journal of Geology, v. 96, p. 313–322

Assereto, R. L. A. M., and Kendall, C. G. St. C., 1977, Nature, origin and classification of peritidal tepee structures and related breccias: Sedimentology, v. 24, p. 153–210

Baars, D. L., 1990, Permian chronostratigraphy in Kansas: Geology, v. 18, p. 687–690

Baars, D. L., Maples, C. G., Ritter, S. M., and Ross, C. A., 1990, Redefinition of the Upper Pennsylvanian Virgilian Series in Kansas: Geological Society of America, Abstracts with Programs, v. 22, no. 7, p. A44

Barrett, F. J., 1989, Hierarchal genetic (T–R unit) stratigraphy of the Lower Permian (Gearyan Stage) Foraker Formation in northeastern Kansas: M.S. thesis, Kansas State University, Manhattan, 329 p.

Barrett, T. R., 1989, Hierarchical genetic stratigraphy of the Wreford Limestone Formation (Lower Permian, Gearyan) in northeastern Kansas: M.S. thesis, Kansas State University, Manhattan, 251 p.

Barron, E. J., Arthur, M. A., and Kauffman, E. G., 1985, Cretaceous rhythmic bedding sequences—a plausible link between orbital variations and climate: Earth and Planetary Science Letters, v. 72, p. 327–340

Birkeland, P. W., 1984, Soils and geomorphology: Oxford University Press, New York, 372 p.

Boardman, D. R., II, and Heckel, P. H., 1989, Glacio-eustatic sea-level curve for early Late Pennsylvanian sequence in north-central Texas and biostratigraphic correlation with curve for midcontinent North America: Geology, v. 17, p. 802–805

Bogina, M. A., 1986, Hierarchical genetic stratigraphy of the Neva Limestone Member of the Grenola Limestone and Eskridge Shale (Lower Permian) in northeastern Kansas: M.S. thesis, Kansas State University, Manhattan, 187 p.

Bown, T. M., and Kraus, M. J., 1981, Lower Eocene alluvial paleosols (Willwood Formation, northwest Wyoming, USA) and their significance for paleoecology, paleoclimatology, and basin analysis: Palaeogeography, Palaeoclimatology, Palaeoecology, v. 34, p. 1–30

Brett, C. E., and Baird, G. C., 1986, Symmetrical and upward shallowing cycles in the Middle Devonian of New York State and their implications for the punctuated aggradational cycle hypothesis: Paleoceanography, v. 1, p. 431–445

Brett, C. E., Goodman, W. M., and LoDuca, S. T., 1990, Sequences, cycles, and basin dynamics in the Silurian of the Appalachian basin; *in*, Process and patterns in epeiric basins, Aigner, T., and Dott, R. H., eds.: Sedimentary Geology, v. 69, p. 191–244

Busch, R. M., and Rollins, H. B., 1984, Correlation of Carboniferous strata using a hierarchy of transgressive-regressive units: Geology, v. 12, p. 471–474

Busch, R. M., and West, R. R., 1987, Hierarchical genetic stratigraphy—a framework for paleoceanography: Paleoceanography, v. 2, p. 141–164

Busch, R. M., Rollins, H. B., and West, R. R., 1989, Recognition of genetic surfaces and genetic units in late Paleozoic stratigraphic sequences; *in*, Middle and Late Pennsylvanian chronostratigraphic boundaries in north-central Texas—glacial-eustatic events, biostratigraphy, and paleoecology, Boardman, D. R., II, Barrick, J. E., Cocke, J., and Nestell, M. K., eds.: Texas Tech University, Studies in Geology 2, p. 325–331

Busch, R. M., West, R. R., Barrett, F. J., and Barrett, T. R., 1985, Cyclothems versus a hierarchy of transgressive-regressive units; *in*, Recent interpretations of late Paleozoic cyclothems: Proceedings of the Third Annual Meeting and Field Conference, Midcontinent Section, Society of Economic Paleontologists and Mineralogists, p. 141–153

Cecil, C. B., 1990, Paleoclimate controls on stratigraphic repetition of chemical and siliciclastic rocks: Geology, v. 18, p. 533–536

Cecil, C. B., and Eble, C. F., eds., 1992, Paleoclimate controls on Carboniferous sedimentation and cyclic stratigraphy in the Appalachian basin: U.S. Geological Survey, Open-File Report 92-546, 186 p.

Cecil, C. B., Stanton, R. W., Neuzil, S. G., Dulong, F. T., Ruppert, L. F., and Pierce, B. S., 1985, Paleoclimate controls on late Paleozoic sedimentation and peat formation in the central Appalachian basin: International Journal of Coal Geology, v. 5, p. 195–230

Chowns, T. M., and Elkins, J. E., 1974, The origin of quartz geodes and cauliflower cherts through the silicification of anhydrite nodules: Journal of Sedimentary Petrology, v. 44, p. 885–903

Clark, M. H., 1989, Hierarchal genetic stratigraphy of the Red Eagle Limestone and Roca Shale Formations (Lower Permian) in northeast Kansas: M.S. thesis, Kansas State University, Manhattan, 207 p.

Condra, G. E., and Busby, C. E., 1933, The Grenola Formation: Nebraska Geological Survey, Paper 1, 31 p.

Cross, A. T., and Phillips, T. L., 1990, Coal-forming plants through time in North America: International Journal of Coal Geology, v. 16, p. 1–46

Crowell, J. C., 1978, Gondwanan glaciation, cyclothems, continental positioning, and climate change: American Journal of Science, v. 278, p. 1,345–1,372

Crowley, T. J., and North, G. R., 1991, Paleoclimatology: Oxford Monographs on Geology and Geophysics 18, Oxford University Press, New York, 339 p.

Cuffey, R. J., 1967, Bryozoan *Tabulipora carbonaria* in Wreford megacyclothem (Lower Permian) of Kansas: University of Kansas, Paleontological Contributions, Bryozoa, art. 1, 96 p.

Cunningham, C. R., 1989, Genetic stratigraphy, depositional environments, and vertebrate paleontology of the Speiser Shale (Gearyan Stage, Lower Permian Series) in northern Kansas: M.S. thesis, Kansas State University, Manhattan, 205 p.

DiMichele, W. A., and Aronson, R. B., 1992, The Pennsylvanian-Permian vegetational transition—a terrestrial analogue to the onshore-offshore hypothesis: Evolution, v. 46, p. 807–824

Donaldson, A. C., Renton, J. J., and Presley, M. W., 1985, Pennsylvanian deposystems and paleoclimates of the Appalachians: International Journal of Coal Geology, v. 5, p. 167–193

Dott, R. H., Jr., 1983, Episodic sedimentation—How normal is average? How rare is rare? Does it matter? (1982 SEPM presidential address): Journal of Sedimentary Petrology, v. 53, p. 5–23

Elias, M. K., 1937, Depth of deposition of the Big Blue (late Paleozoic) sediments in Kansas: Bulletin of the Geological Society of America, v. 48, p. 403–432

________, 1964, Depth of late Paleozoic sea in Kansas and its megacyclic sedimentation; *in*, Symposium on cyclic sedimentation, Merriam, D. F., ed.: Kansas Geological Survey, Bulletin 169, p. 87–106

Evamy, B. D., 1973, The precipitation of aragonite and its alteration to calcite on the Trucial Coast of the Persian Gulf; *in*, The Persian Gulf, Purser, B. H., ed.: Springer-Verlag, New York, p. 329–341

Fairbridge, R. W., 1986, Monsoons and paleomonsoons: Episodes, v. 9, no. 3, p. 143–149

Fischer, A. G., Herbert, T., and Silva, I. P., 1985, Carbonate bedding cycles in Cretaceous pelagic and hemipelagic sequences; *in*, Fine-grained deposits and biofacies of the Cretaceous Western Interior Seaway—evidence of cyclic sedimentary processes, Pratt, L. M., Kauffman, E. G., and Zelt, F. B., eds.: Society of Economic Paleontologists and Mineralogists, 2d Annual Midyear Meeting, Field Trip Guidebook 4, p. 1–10

Galloway, W. E., 1989a, Clastic facies models, depositional systems, sequences, and correlation—a sedimentologist's view of the dimensional and temporal resolution of lithostratigraphy; *in*, Quantitative dynamic stratigraphy, Cross, T. A., ed.: Prentice Hall, Englewood Cliffs, New Jersey, p. 459–477

________, 1989b, Genetic stratigraphic sequences in basin analysis—I, architecture and genesis of flooding-surface bounded depositional units: American Association of Petroleum Geologists Bulletin, v. 73, p. 125–142

Goldhammer, R. K., and Elmore, R. D., 1984, Paleosols capping regressive carbonate cycles in the Pennsylvanian Black Prince Limestone, Arizona: Journal of Sedimentary Petrology, v. 54, p. 1,124–1,137

Goldhammer, R. K., Dunn, P. A., and Hardie, L. A., 1990, Depositional cycles, composite sea-level changes, cycle stacking patterns, and the hierarchy of stratigraphic forcing—examples from Alpine Triassic platform carbonates: Geological Society of America Bulletin, v. 102, p. 535–562

Goldhammer, R. K., Oswald, E. J., and Dunn, P. A., 1991, Hierarchy of stratigraphic forcing—example from Middle Pennsylvanian shelf carbonates of the Paradox basin; *in*, Sedimentary modeling—computer simulations and methods for improved parameter definition, Franseen, E. K., Watney, W. L., Kendall, C. G. St. C., and Ross, W., eds.: Kansas Geological Survey, Bulletin 233, p. 361–413

Goodwin, P. W., and Anderson, E. J., 1985, Punctuated aggradational cycles—general hypothesis of episodic stratigraphic accumulation: Journal of Geology, v. 93, p. 515–533

Grotzinger, J. P., 1986, Cyclicity and paleoenvironmental dynamics, Rocknest platform, northwest Canada: Geological Society of America Bulletin, v. 97, p. 1,208–1,231

Hattin, D. E., 1957, Depositional environment of the Wreford megacyclothem (Lower Permian) of Kansas: Kansas Geological Survey, Bulletin 124, 150 p.

________, 1985, Distribution and significance of widespread, time-parallel pelagic limestone beds in the Greenhorn Limestone (Upper Cretaceous) of the central Great Plains and southern Rocky Mountains; *in*, Fine-grained deposits and biofacies of the Cretaceous Western Interior Seaway—evidence of cyclic sedimentary processes, Pratt, L. M., Kauffman, E. G., and Zelt, F. B., eds.: Society of Economic Paleontologists and Mineralogists, 2d Annual Midyear Meeting, Field Trip Guidebook 4, p. 28–37

Heckel, P. H., 1977, Origin of phosphatic black shale facies in Pennsylvanian cyclothems of midcontinent North America: American Association of Petroleum Geologists Bulletin, v. 61, p. 1,045–1,068

________, 1984a, Changing concepts of midcontinent Pennsylvanian cyclothems: IX International Carboniferous Congress 1979, Compte Rendu, v. 3, p. 535–553

________, 1984b, Factors in Midcontinent Pennsylvanian limestone deposition; *in*, Limestones of the midcontinent, Hyne, N. J., ed.: Tulsa Geological Society, Special Publication 2, p. 25–50

Heckel, P. H., and Baesemann, J. F., 1975, Environmental interpretations of conodont distribution in Upper Pennsylvanian (Missourian) megacyclothems in eastern Kansas: American Association of Petroleum Geologists Bulletin, v. 59, p. 1,058–1,074

Heckel, P. H., and Watney, W. L., 1985, Stop 5A—US–69 Roadcut by Jingo-Swope and Dennis cycles; *in*, Recent interpretation of late Paleozoic cyclothems, Watney, W. L., Kaesler, R. L., and Newell, K. D., eds.: Proceedings of the 3d Annual Meeting and Field Conference, Midcontinent Section, Society of Economic Paleontologists and Mineralogists, p. 44–51

Imbrie, J., 1955, Quantitative lithofacies and biofacies study of Florena Shale (Permian) of Kansas: Bulletin of the American Association of Petroleum Geologists, v. 39, p. 649–670

Imbrie, J., Laporte, L. F., and Merriam, D. F., 1964, Beattie Limestone facies (Lower Permian) of the northern midcontinent; *in*, Symposium on cyclic sedimentation, Merriam, D. F., ed.: Kansas Geological Survey, Bulletin 169, p. 219–238

Jewett, J. M., 1933, Evidence of cyclic sedimentation in Kansas during the Permian Period: Kansas Academy of Science Transactions, v. 36, p. 137–140

Joeckel, R. M., 1989, Geomorphology of a Pennsylvanian land surface—pedogenesis in the Rock Lake Shale Member, southeastern Nebraska: Journal of Sedimentary Petrology, v. 59, p. 469–481

________, 1991, Paleosol stratigraphy of the Eskridge Formation—Early Permian pedogenesis and climate in southeastern Nebraska: Journal of Sedimentary Petrology, v. 61, p. 234–255

Johnson, S. Y., 1989, Significance of loessite in the Maroon Formation (Middle Pennsylvanian to Lower Permian), Eagle basin, northwest Colorado: Journal of Sedimentary Petrology, v. 59, p. 782–791

Kauffman, E. G., 1985, Cretaceous evolution of the Western Interior basin of the United States; *in*, Fine-grained deposits and biofacies of the Cretaceous Western Interior Seaway—evidence of cyclic sedimentary processes, Pratt, L. M., Kauffman, E. G., and Zelt, F. B., eds.: Society of Economic Paleontologists and Mineralogists, 2d Annual Midyear Meeting, Field Trip Guidebook 4, p. IV–XIII

________, 1986, High-resolution event stratigraphy—regional and global bio-events; *in*, Global bio-events, Walliser, O. H., ed.: Lecture Notes in Earth History, Springer-Verlag, Berlin, p. 279–335

________, 1988, Concepts and methods of high-resolution event stratigraphy: Annual Review of Earth and Planetary Science, v. 16, p. 605–654

Kraus, M. J., and Bown, T. M., 1986, Paleosols and time resolution in alluvial stratigraphy; *in*, Paleosols—their recognition and interpretation, Wright, V. P., ed.: Princeton University Press, Princeton, New Jersey, p. 180–207

Kutzbach, J. E., and Gallimore, R. G., 1989, Pangean climates—megamonsoons of the megacontinent: Journal of Geophysical Research, v. 94, p. 3,341–3,357

Kutzbach, J. E., and Guetter, P. J., 1984, The sensitivity of monsoon climates to orbital parameter changes for 900 years B.P.—experiments with the NCAR general circulation model; *in*, Milankovitch and climate, Berger, A. L., Imbrie, J., Hays, J., Kukla, G., and Saltzman, B., eds.: D. Reidel, Dordrecht, The Netherlands, pt. 2, p. 801–820

Lane, N. G., 1958, Environment of deposition of the Grenola Limestone (Lower Permian) in southern Kansas: Kansas Geological Survey, Bulletin 130, pt. 3, p. 117–164

________, 1964, Paleoecology of the Council Grove Group (Lower Permian) in Kansas, based upon microfossil assemblages: Kansas Geological Survey, Bulletin 170, 23 p.

Laporte, L. F., 1962, Paleoecology of the Cottonwood Limestone (Permian), northern midcontinent: Geological Society of America Bulletin, v. 73, p. 521–544

Lutz-Garihan, A. B., and Cuffey, R. J., 1979, Stratigraphy of the Lower Permian Wreford megacyclothem in southernmost Kansas and northern Oklahoma: Kansas Geological Survey, Bulletin 216, 19 p.

McCrone, A. W., 1963, Paleoecology and biostratigraphy of the Red Eagle cyclothem (Lower Permian) in Kansas: Kansas Geological Survey, Bulletin 164, 114 p.

________, 1964, Water depth and midcontinent cyclothems; *in*, Symposium on cyclic sedimentation, Merriam, D. F., ed.: Kansas Geological Survey, Bulletin 169, p. 275–281

Miller, K. B., 1993, Meter-scale cycles of the Lower Permian (Wolfcampian) of Kansas—flooding surfaces as a basis for high-resolution correlation within paleosol-dominated intervals: Geological Society of America, Abstracts with Programs, v. 25, no. 1, p. 38

Miller, K. B., and McCahon, T. J., 1992, Paleosol sequences within Lower Permian cyclothems of Kansas—evidence of climatic cyclicity: Geological Society of America, Abstracts with Programs, v. 24, no. 7, p. A287

Miller, K. B., McCahon, T. J., and West, R. R., 1992, Introduction to Lower Permian (Wolfcampian) cycles of Kansas; *in*, Project PANGEA workshop fieldtrip guidebook: Global Sedimentary Geology Program, IUGS, Lawrence, Kansas, p. I-1–I-47

Miller, K. B., McCahon, T. J., Archer, A. W., West, R. R., Oviatt, C. G., and Twiss, P. C., 1991, Lower Permian "cyclothems" of Kansas—evidence for facies transitions within a shallow water to supratidal environment: Geological Society of America, Abstracts with Programs, v. 23, no. 4, p. 49

Moore, R. C., 1931, Pennsylvanian cycles in the northern midcontinent region: Illinois Geological Survey, Bulletin 60, p. 247–257

________, 1936, Stratigraphic classification of the Pennsylvanian rocks of Kansas: Kansas Geological Survey, Bulletin 22, 256 p.

________, 1949, Divisions of the Pennsylvanian system in Kansas: Kansas Geological Survey, Bulletin 83, 203 p.

________, 1964, Paleoecological aspects of Kansas Pennsylvanian and Permian cyclothems; *in*, Symposium on cyclic sedimentation, Merriam, D. F., ed.: Kansas Geological Survey, Bulletin 169, p. 287–380

Mudge, M. R., and Yochelson, E. L., 1962, Stratigraphy and paleontology of the uppermost Pennsylvanian and lowermost Permian rocks in Kansas: U.S. Geological Survey, Professional Paper 323, 213 p.

Parrish, J. T., and Peterson, F., 1988, Wind directions predicted from global circulation models and wind directions determined from eolian sandstones of the western United States—a comparison: Sedimentary Geology, v. 56, p. 261–282

Parrish, J. T., Ziegler, A. M., and Scotese, C. R., 1982, Rainfall patterns and the distribution of coals and evaporites in the Mesozoic and Cenozoic: Palaeogeography, Palaeoclimatology, Palaeoecology, v. 40, p. 67–101

Patzkowsky, M. E., Smith, L. H., Markwick, P. J., Engherts, C. J., and Gyllenhaal, E. D., 1991, Application of the Fujita-Ziegler paleoclimate model—Early Permian and Late Cretaceous examples: Palaeogeography, Palaeoclimatology, Palaeoecology, v. 86, p. 67–85

Perlmutter, M. A., and Matthews, M. D., 1989, Global cyclostratigraphy—a model; *in*, Quantitative dynamic stratigraphy, Cross, T. A., ed.: Prentice Hall, Englewood Cliffs, New Jersey, p. 233–260

Phillips, T. L., and Peppers, R. A., 1984, Changing patterns of Pennsylvanian coal-swamp vegetation and implications of climatic control on coal occurrence: International Journal of Coal Geology, v. 3, p. 205–255

Phillips, T. L., Peppers, R. A., and Dimichele, W. A., 1985, Stratigraphic and interregional changes in Pennsylvanian coal-swamp vegetation—environmental inferences: International Journal of Coal Geology, v. 5, p. 43–110

Prather, B. E., 1985, An Upper Pennsylvanian desert paleosol in the D-zone of the Lansing–Kansas City Groups, Hitchcock County, Nebraska: Journal of Sedimentary Petrology, v. 55, p. 213–221

Read, J. F., 1974, Carbonate bank and wave-built platform sedimentation, Edel province, Shark Bay, Western Australia; *in*, Evolution and diagenesis of Quaternary carbonate sequences, Shark Bay, Western Australia, Logan, B. W., ed.: American Association of Petroleum Geologists, Memoir 22, p. 1–60

Retallack, G. J., 1983, Late Eocene and Oligocene paleosols from Badlands National Park, South Dakota: Geological Society of America, Special Paper 193, 82 p.

________, 1984, Completeness of the rock and fossil record—some estimates using fossil soils: Paleobiology, v. 10, p. 59–78

________, 1988, Field recognition of paleosols; *in*, Paleosols and weathering through geologic time—principals and applications, Reinhart, J., and Sigleo, W. R., eds.: Geological Society of America, Special Paper 216, p. 1–20

________, 1990, Soils of the past—an introduction to paleopedology: Unwin Hyman, Boston, Massachusetts, 520 p.

Riding, R., and Wright, V. P., 1981, Paleosols and tidal-flat/lagoon sequences on a Carboniferous carbonate shelf—sedimentary associations of triple disconformities: Journal of Sedimentary Petrology, v. 51, p. 1,323–1,339

Rowley, D. B., Raymond, A., Parrish, J. T., Lottes, A. L., Scotese, C. R., and Ziegler, A. M., 1985, Carboniferous paleogeographic, phytogeographic, and paleoclimatic reconstructions: International Journal of Coal Geology, v. 5, p. 7–42

Sadler, P. M., 1981, Sediment accumulation rates and the

completeness of stratigraphic sections: Journal of Geology, v. 89, p. 569–584
Schutter, S. R., and Heckel, P. H., 1985, Missourian (Early Late Pennsylvanian) climate in midcontinent North America: International Journal of Coal Geology, v. 5, p. 111–140
Scotese, C., 1986, Atlas of Paleozoic base maps—paleoceanographic mapping project: University of Texas (Austin) Institute for Geophysics, Technical Report 66, 23 p.
Soreghan, G. S., 1992, Sedimentology and process stratigraphy of Upper Pennsylvanian Pedrogosa (Arizona) and Orogrande (New Mexico) basins: Ph.D. dissertation, University of Arizona, Tucson, 278 p.
Strasser, A., 1988, Shallowing-upward sequences in Purbeckian peritidal carbonates (lowermost Cretaceous, Swiss and French Jura mountains): Sedimentology, v. 35, p. 369–383
Suchy, D. R., and West, R. R., 1991, Genetic stratigraphy of the Fort Scott Limestone (Pennsylvanian: Desmoinesian) southeastern Kansas; *in*, Sedimentary modeling—computer simulations and methods for improved parameter definition, Franseen, E. K., Watney, W. L., Kendall, C. G. St. C., and Ross, W., eds.: Kansas Geological Survey, Bulletin 233, p. 195–206
Twiss, P. C., 1988, Beattie Limestone (Lower Permian) of eastern Kansas: Geological Society of America, South-Central Section, Centennial Field Guide, p. 35–41
________, 1991, Nodular and bedded chert in the Florence Limestone (Lower Permian) of east-central Kansas: Geological Society of America, Abstracts with Programs, v. 23, no. 4, p. 101
Udden, J. A., 1912, Geology and mineral resources of the Peoria Quadrangle, Illinois: U.S. Geological Survey, Bulletin 506, 103 p.
Vail, P. R., Todd, R. G., and Sangree, J. B., 1977, Seismic stratigraphy and global changes of sea level—pt. 5, Chronostratigraphic significance of seismic reflections; *in*, Seismic stratigraphy—applications to hydrocarbon exploration, Payton, C. E., ed.: American Association of Petroleum Geologists, Memoir 26, p. 99–116
Van Wagoner, J. C., Posamentier, H. W., Mitchum, R. M., Vail, P. R., Sarg, J. F., Loutit, T. S., and Hardenbol, J., 1988, An overview of the fundamentals of sequence stratigraphy and key definitions; *in*, Sea-level changes—an integrated approach, Wilgus, C. K., Hastings, B. S., Kendall, C. G. St. C., Posamentier, H. W., Ross, C. A., and Van Wagoner, J. C., eds.: Society of Economic Paleontologists and Mineralogists, Special Publication 42, p. 39–45
Veevers, J. J., and Powell, C. M., 1987, Late Paleozoic glacial episodes in Gondwanaland reflected in transgressive-regressive depositional sequences in Euramerica: Geological Society of America Bulletin, v. 98, p. 475–487
Voran, R. L., 1975, Fossil assemblages, stratigraphy, and depositional environments of the Crouse Limestone (Lower Permian) in north-central Kansas: M.S. thesis, Kansas State University, Manhattan, 208 p.
Walls, R. R., Harris, W. B., and Nunan, W. E., 1975, Calcareous crust (caliche) profiles and early subaerial exposure of Carboniferous carbonates, northeastern Kentucky: Sedimentology, v. 22, p. 417–440
Wanless, H. R., and Shepard, F. P., 1936, Sea level and climatic changes related to late Paleozoic cycles: Bulletin of the Geological Society of America, v. 47, p. 1,177–1,206
Wanless, H. R., and Weller, J. M., 1932, Correlation and extent of Pennsylvanian cyclothems: Bulletin of the Geological Society of America, v. 43, p. 1,003–1,016
Warren, J. K., 1982, The hydrological significance of Holocene tepees, stromatolites, and boxwork limestones in coastal salinas in South Australia: Journal of Sedimentary Petrology, v. 52, p. 1,171–1,201
Warren, J. K., and Kendall, C. G. St. C., 1985, Comparison of sequences formed in marine sabkha (subaerial) and salina (subaqueous) settings—modern and ancient: American Association of Petroleum Geologists Bulletin, v. 69, p. 1,013–1,023
Watney, W. L., French, J., and Franseen E. K., 1989, Sequence stratigraphic interpretations and modeling of cyclothems in the Upper Pennsylvanian (Missourian) Lansing and Kansas City Groups in eastern Kansas: Kansas Geological Society, 41st Annual Field Trip, 211 p.
Weller, J. M., 1930, Cyclical sedimentation of the Pennsylvanian Period and its significance: Journal of Geology, v. 38, no. 2, p. 97–135
West, R. R., and Busch, R. M., 1985, Sixth-order transgressive-regressive units in the Wewoka Formation (Anna Shale member) of Oklahoma; *in*, Recent interpretation of late Paleozoic cyclothems, Watney, W. L., Kaesler, R. L., and Newell, K. D., eds.: Proceedings of the 3d Annual Meeting and Field Conference, Midcontinent Section, Society of Economic Paleontologists and Mineralogists, p. 155–170
West, R. R., and Twiss, P. C., 1988, The Crouse Limestone in north-central Kansas—lateral changes and paleoecological analysis: Geological Society of America, South-Central Section, Centennial Field Guide, p. 29–34
West, R. R., Barrett, T. R., and Twiss, P. C., 1987, Chert in the Lower Permian of the northern midcontinent: Geological Society of America, Abstracts with Programs, v. 19, no. 3, p. 180
West, R. R., Jeppesen, J. A., Pearce, R. W., and Twiss, P. C., 1972, Crouse Limestone—its stratigraphy and depositional environments; *in*, Stratigraphy and depositional environments of the Crouse Limestone (Permian) in north-central Kansas, West, R. R., ed.: Field Trip Guidebook, Sixth Annual Meeting, South-Central Section, Geological Society of America, p. 81–90
Williams, M. E., 1972, The origin of "spiral coprolites": University of Kansas, Paleontological Contributions, paper 59, 19 p.
Wilson, L., 1973, Variations in mean annual sediment yield as a function of mean annual precipitation: American Journal of Science, v. 278, p. 335–349
Witzke, B. J., 1990, Palaeoclimatic constraints for Palaeozoic palaeolatitudes of Laurentia and Euramerica; *in*, Palaeozoic palaeogeography and biogeography, McKerrow, W. S., and Scotese, C. R., eds.: Geological Society of London, Memoir 12, p. 57–73
Wright, V. P., 1982, Calcrete paleosols from the lower Carboniferous Llanelly Formation, South Wales: Sedimentary Geology, v. 33, p. 1–33
Zeller, D. E., 1968, The stratigraphic succession in Kansas: Kansas Geological Survey, Bulletin 189, 81 p.