GEOLOGY OF THE KANSAS FLINT HILLS: ANCIENT ICE AGES, SEA LEVELS, AND CLIMATE CHANGE

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PALEOGEOGRAPHIC AND CLIMATIC CONTEXT

This fieldtrip focuses on a nearly continuous exposure of the lower Permian (Wolfcampian) stratigraphic interval that includes the entire Council Grove Group and the lower half of the overlying Chase Group. The outcrop exposures are all within the Manhattan area in Riley County, northeastern Kansas (Figures 1 and 2).

OUTCROP LOCALITIES

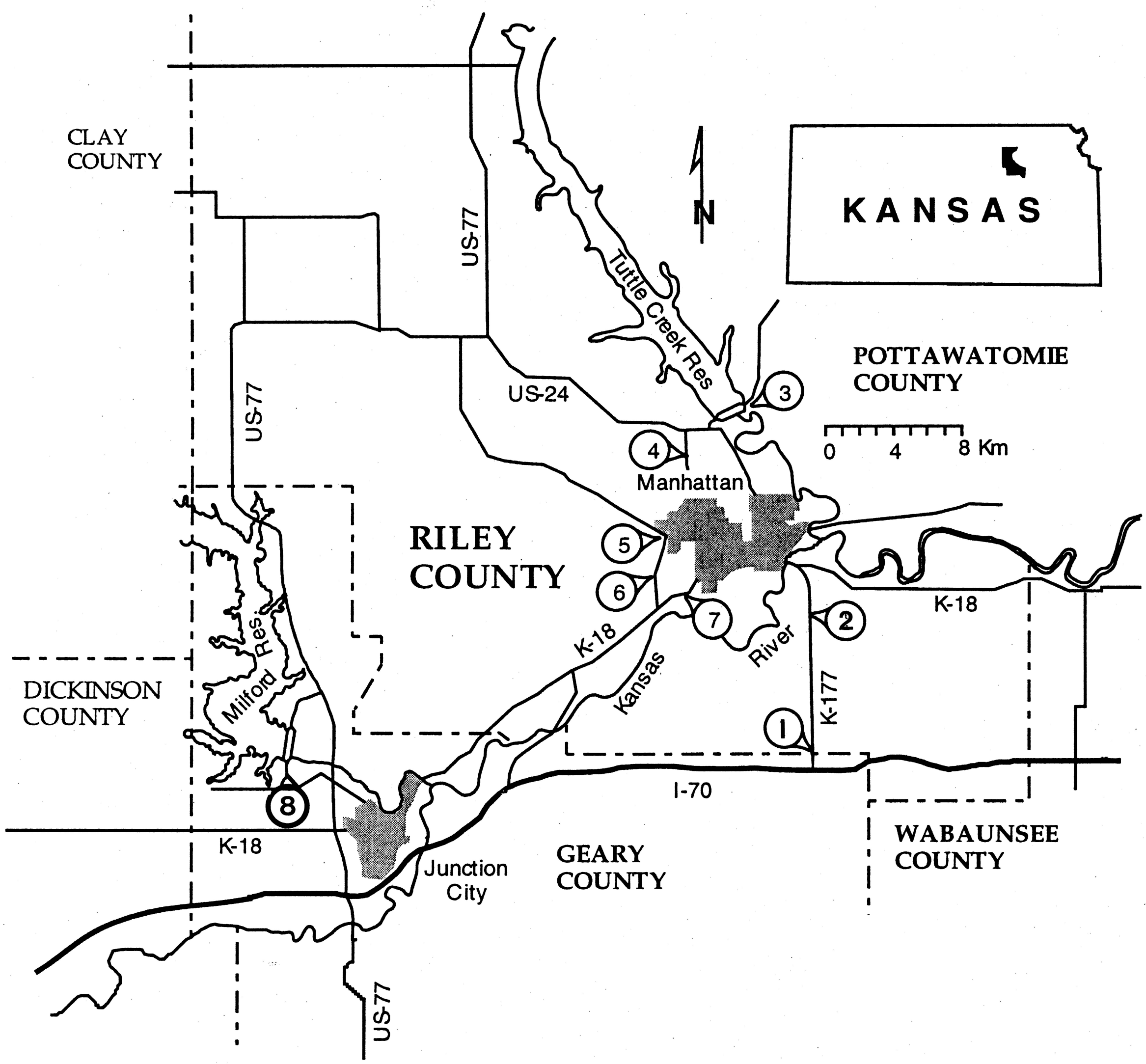


Figure 1. Map of the Manhattan and Junction city area of northeastern Kansas showing locations of fieldtrip stops.

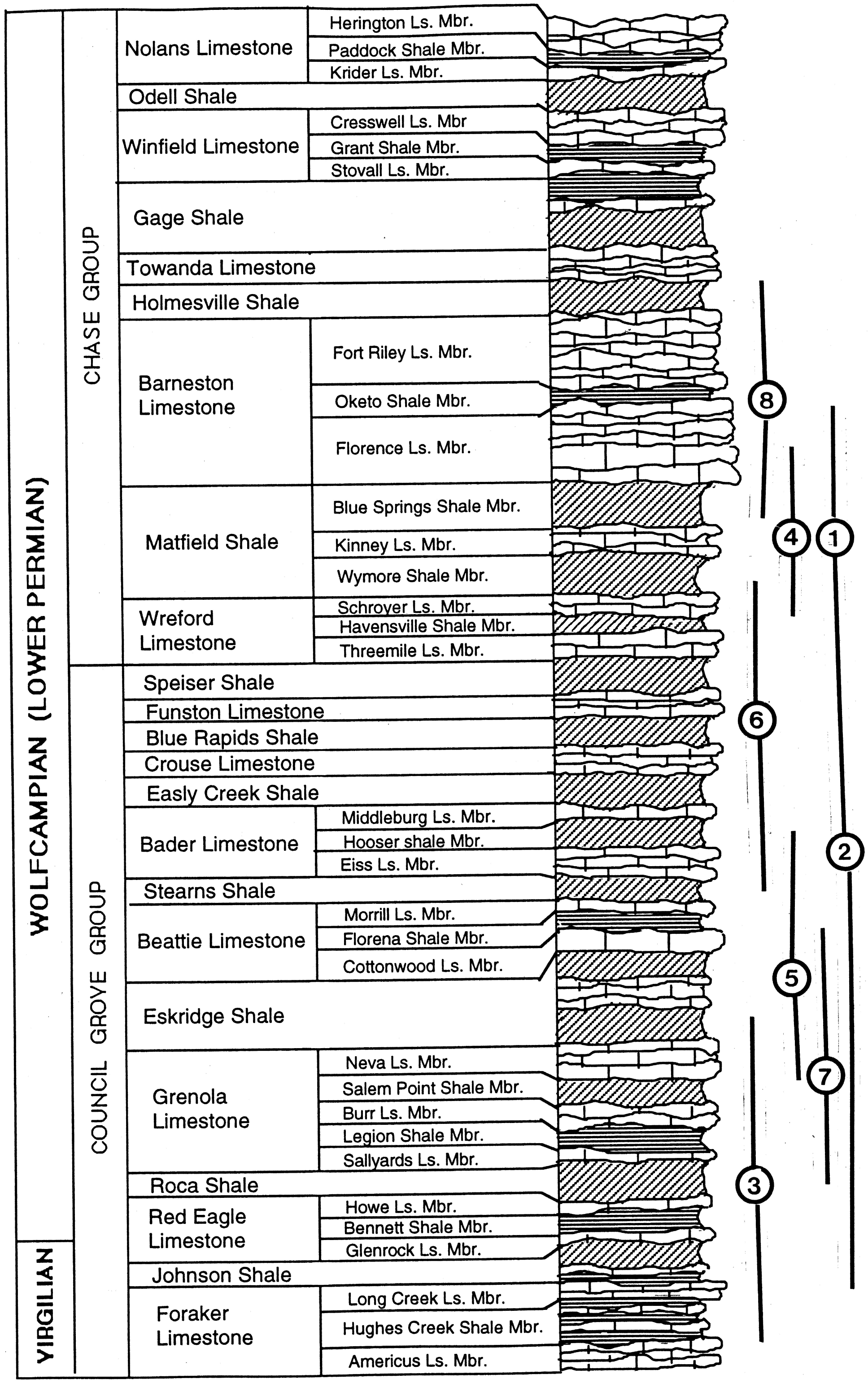


Figure 2. Stratigraphic column of the Council Grove and Chase Groups showing intervals exposed at the various stop locations.

During the Wolfcampian the mid-continent of North American lay within the low relief interior of the supercontinent Pangea in near equatorial latitudes. Throughout the Permian and into the Triassic this landmass drifted slowly to the north into higher latitudes (Rowley et al., 1985; Scotese, 1986; Witzke, 1990). In the Wolfcampian, the study area would have been relatively far from areas of active tectonism. The highlands of the ancestral Rockies lay ~500 km to the west and the Ouachita and Wichita uplifts were an approximately equal distance to the south. A broad low lying cratonic area probably lay to the north and east. The carbonate and fine clastic facies of the Council Grove and Chase Groups in northeastern Kansas suggest a vast shallow marine to marginal marine shelf periodically exposed during relative sealevel lowstands.

The facies of the Wolfcampian are in many ways transitional between those of the Late Pennsylvanian (Virgilian) and the later Permian. During this time black shales and coal beds decline, and red beds and evaporites increase in abundance (West et al. 1997). These facies changes reflect a long term climatic change from more humid to more arid conditions. The trend toward increased aridity begun in the Late Pennsylvanian can also be followed in the paleobotanical record (Phillips & Peppers, 1984; Phillips et al., 1985; Cross & Phillips, 1990; DiMichele & Aronson, 1992). In addition, the Pennsylvanian and Early Permian was a time of widespread continental glaciation that subsequently declined later in the Permian (Crowell, 1978; Veevers & Powell, 1987; Frakes et al., 1994). The waxing and waning of these glaciers, probably driven by cyclic changes in the Earth's orbital parameters (Denton & Hughes, 1983), is the likely cause for the repeated sedimentary cycles characteristic of the Pennsylvanian and Permian in the mid-continent.

CYCLE PATTERNS

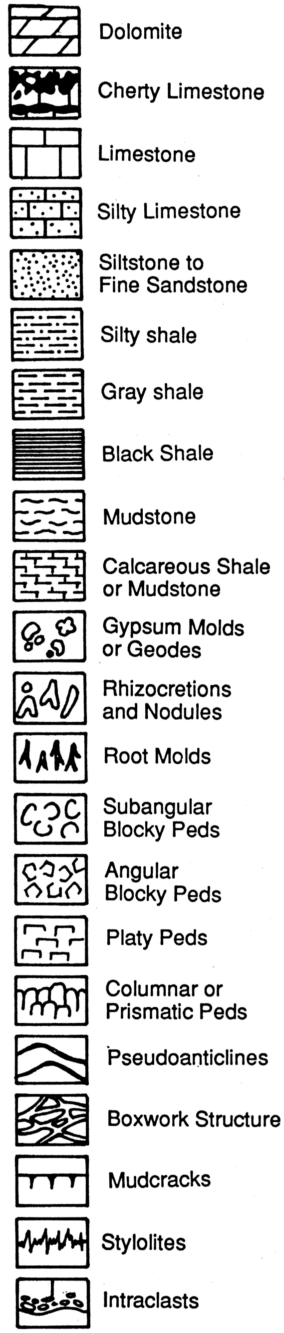
The term "cyclothem" was introduced by Wanless and Weller (1932) to describe Pennsylvanian cyclicity of the Illinois Basin. The term was subsequently applied to the description of Permian cyclicity within the mid-continent by Jewett (1933). This description was modified and elaborated by Elias (1937), who placed all the major facies encountered within Permian cycles into an idealized depth-related sequence. A number of detailed sedimentary and paleontological studies of individual Lower Permian cylothems and their member-scale lithologic units followed (Imbrie, 1955; Hattin, 1957; Lane, 1958; Laporte, 1962; McCrone, 1963; Imbrie et al., 1964).

The facies sequence of Lower Permian (Wolfcampian) cyclothems typically begins with a thin marine limestone overlain by a gray fossiliferous shale/mudstone. One or more additional limestone-shale (mudstone) alternations may follow. An interval of variegated red and green mudstones with extensive paleosol development lies above these shallow marine facies. Cyclothem boundaries are here recognized at the base of the stratigraphically lowest fossiliferous fully marine limestone occurring above a paleosol-bearing interval. Commonly, these marine limestones directly overlie and partially truncate the uppermost paleosol profiles. The contacts often appear to be erosive, although little or no relief is evident at an outcrop scale, and are typically overlain by intraclastic beds up to 20cm thick. As thus defined, the cyclothem-bounding surfaces are equivalent to the transgressive surfaces of depositional sequences (Van Wagoner et al., 1988). These sufaces thus provide a basis for understanding these cycles in a sequence stratigraphic framework (Miller & West, 1998).

Meter-scale cycles are both ubiquitous and prominent within the Wolfcampian cyclothems of eastern Kansas (Miller & West, 1993; Miller & West, 1998). These small-scale cycles are bounded by flooding surfaces and can be defined as parasequences (Van Wagoner et al., 1988) or punctuated aggradational cycles (Goodwin & Anderson, 1985). Flooding surfaces overlie paleosol profiles and other indicators of subaerial exposure, or mark sharp changes in depth as indicated by lithology and fossil content. Thin (<2 cm thick) skeletal and/or intraclastic lags mark these cycle-bounding flooding surfaces. The inferred positions of both flooding surfaces and transgressive surfaces are indicated on the stratigraphic columns provided (Figures 3 through 7).

Most of the meter-scale cycles throughout the Wolfcampian are capped by subaerial exposure surfaces. These range from well-developed paleosol profiles that may have required 100,000 yrs to form, to desiccation cracked surfaces. The criteria used to identify and classify ancient soil profiles are nicely summarized by Retallack (1988, 1990). Within the more carbonate-dominated parts of cyclothems, meter-scale cycles may be capped by tepee structures or boxwork structures. These latter features can be seen in the Johnson Shale, Morrill Mbr. of the Beattie Limestone, Eiss Mbr. of the Bader Limestone, Havensville Mbr. of the Wreford Limestone, and the Holmesville Shale.

Of particular interest is the consistent carbonate-to-siliciclastic pattern exhibited by the meter-scale cycles. Within the variegated mudstone intervals of cyclothems, flooding surfaces are typically overlain by thin micritic carbonates. Carbonate deposition thus follows inundation of the exposed land surface during relative sealevel rise and is replaced by the influx of siliciclastic sediments during subsequent sealevel fall. Pedogenesis begins with the subaerial exposure of these clastic sediments during sealevel lowstand. The carbonate-to-clastic pattern is also clearly apparent for meter-scale cycles within the dominantly marine part of cyclothems. Here, bioclastic marine wackestones are overlain by fossiliferous gray shales or calcareous mudstones. This meter-scale cyclicity is also apparent within the thick Barneston Limestone.



Key for Stratigraphic Columns: The key above provides the meaning of the various symbols used to show rock type and paleosol structures in the stratigraphic columns that follow.

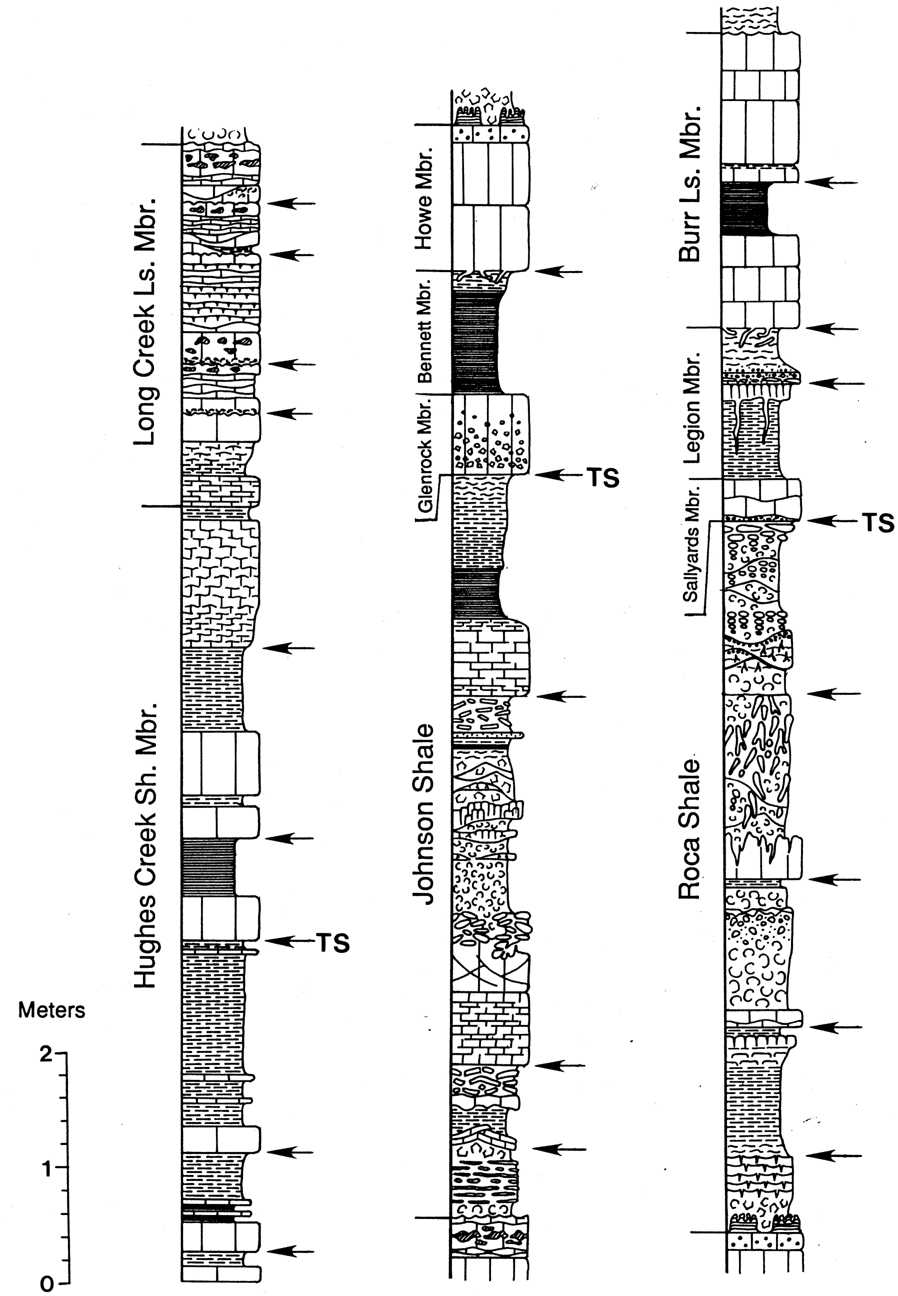


Figure 3. Stratigraphic section for rocks exposed in the Tuttle Creek spillway (STOP 3). Arrows mark flooding surfaces and (TS) marks transgressive surfaces and cyclothem boundaries.

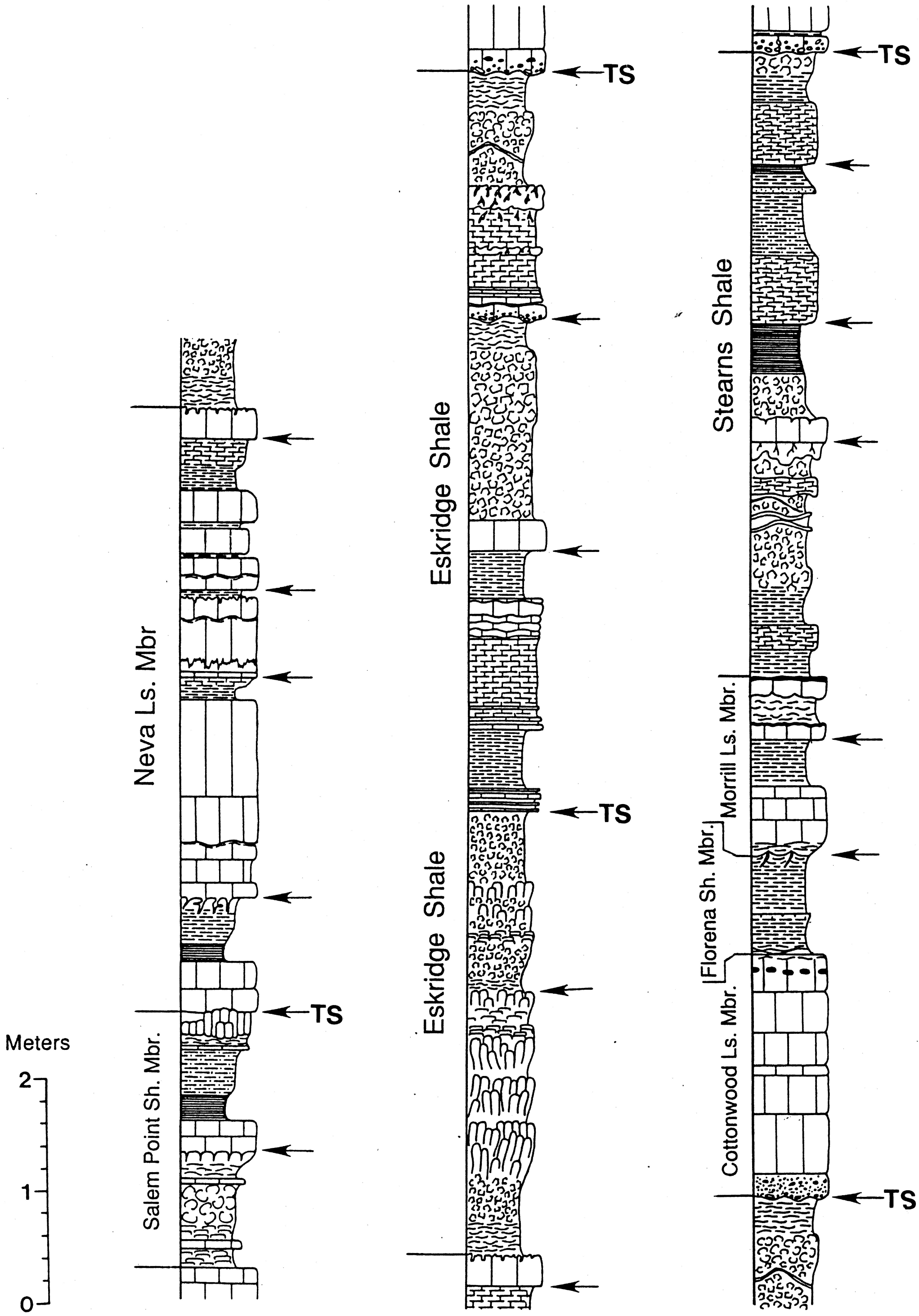


Figure 4. Stratigraphic section for rocks exposed on Fort Riley Blvd. (STOP 7) and at the intersection of Anderson Ave. and Scenic Drive (STOP 5). Arrows mark flooding surfaces and (TS) marks transgressive surfaces and cyclothem boundaries.

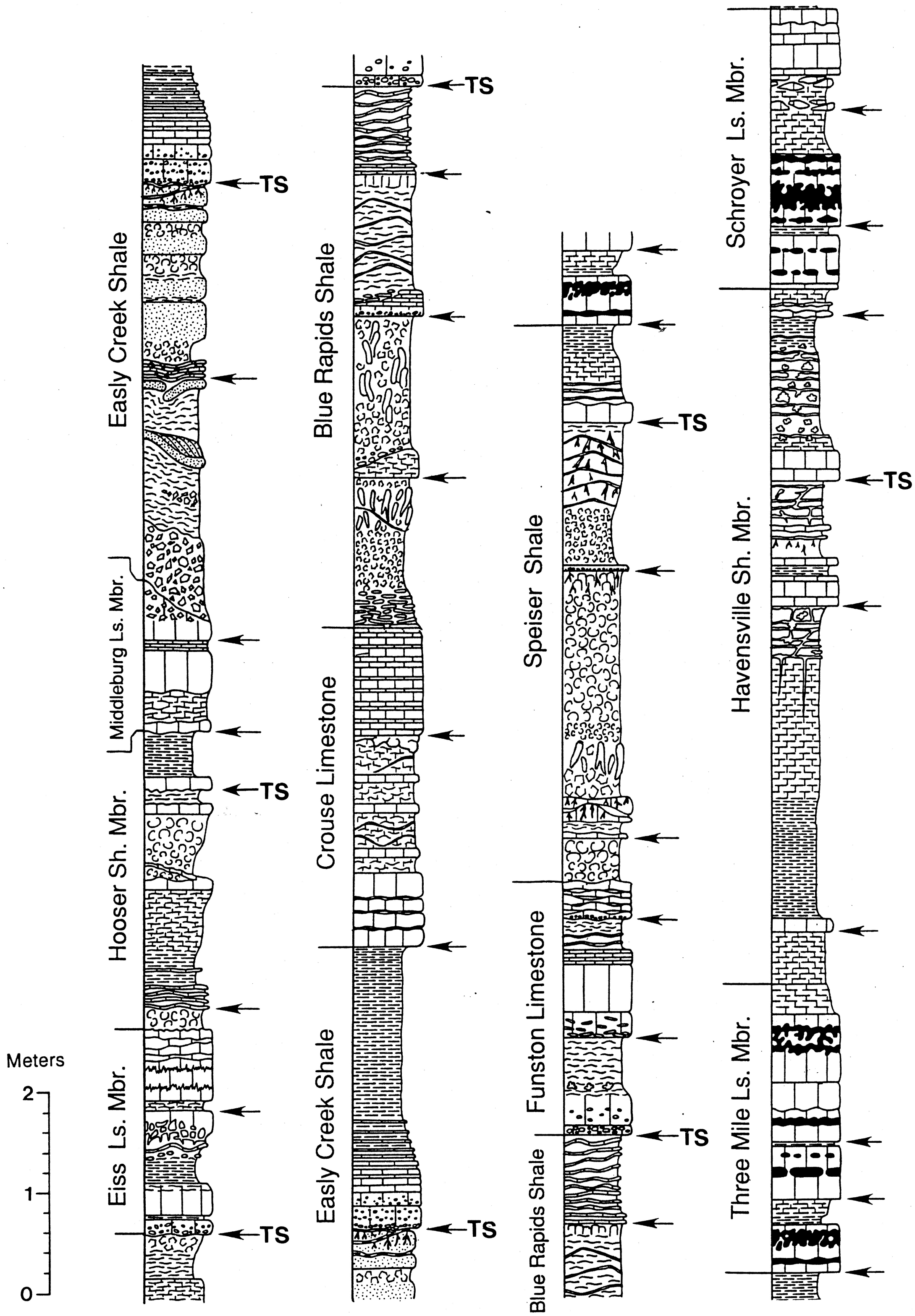


Figure 5. Stratigraphic section for rocks exposed along roadcuts of Scenic Drive (K-408) (STOP 6). Arrows mark flooding surfaces and (TS) marks transgressive surfaces and cyclothem boundaries.

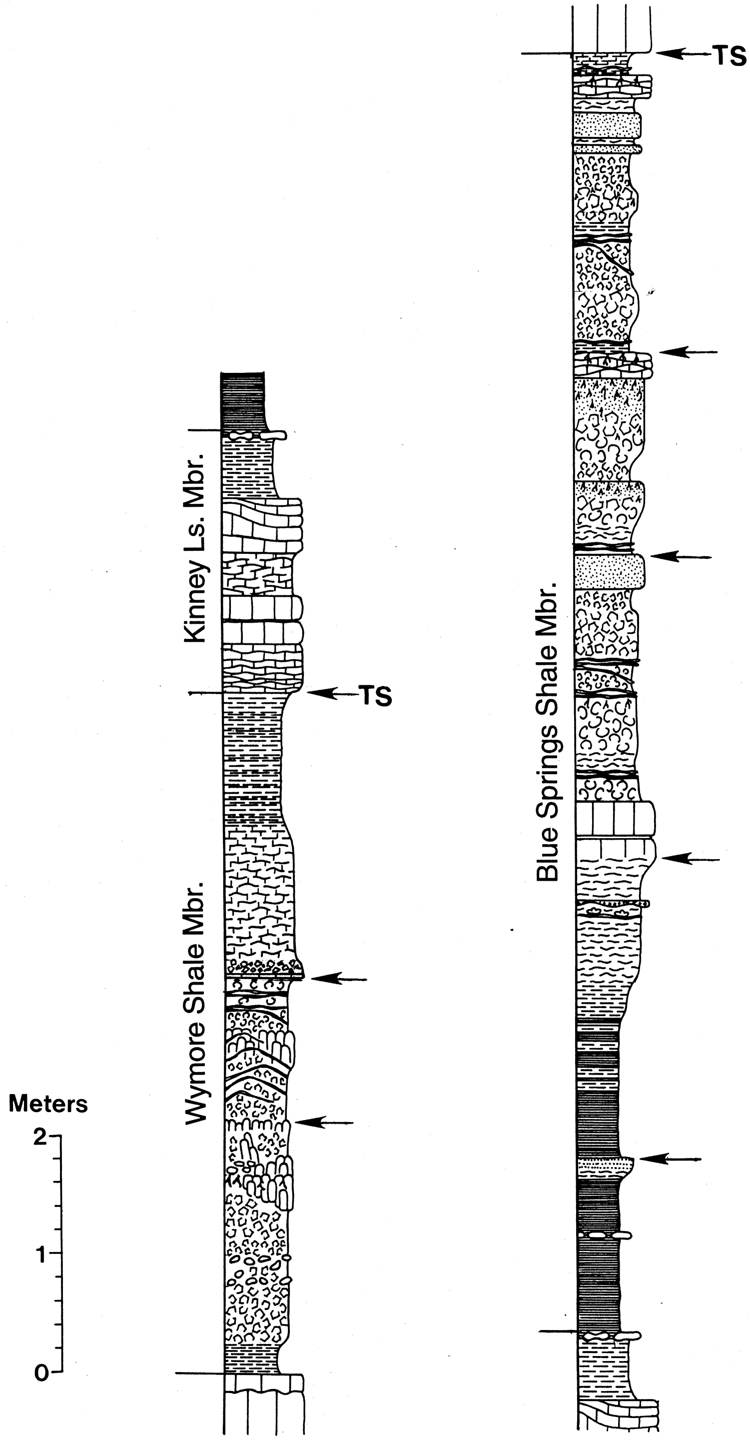


Figure 6. Stratigraphic section for rocks exposed in roadcuts along Seth Childs Blvd. (STOP 4). Arrows mark flooding surfaces and (TS) marks transgressive surfaces and cyclothem boundaries.

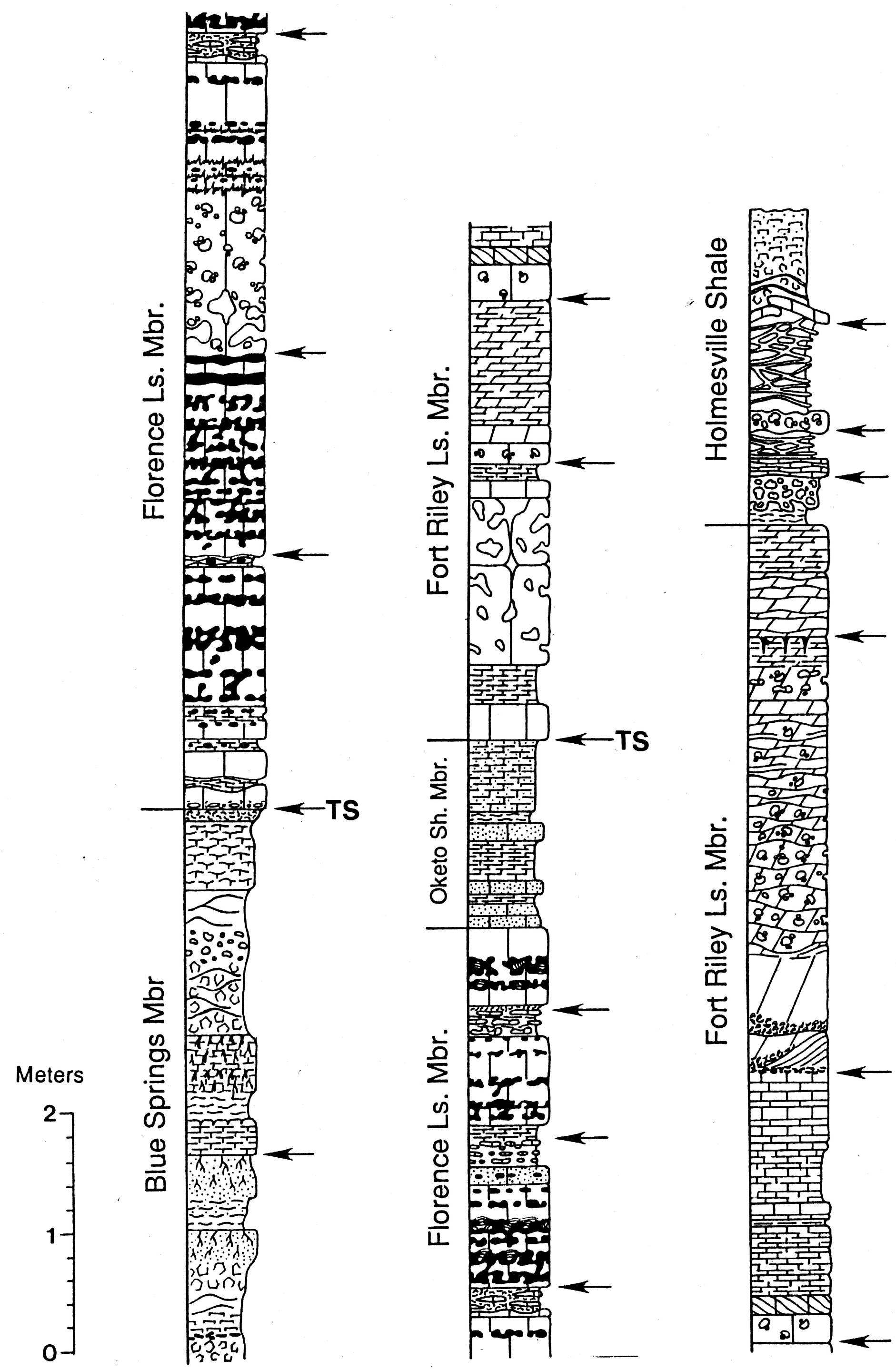


Figure 7. Stratigraphic section for rocks exposed in the Milford Reservoir spillway (STOP 8). Arrows mark flooding surfaces and (TS) marks transgressive surfaces and cyclothem boundaries.

DESCRIPTION AND INTERPRETATION OF PALEOSOLS

Stacked paleosol profiles comprise a substantial part of the variegated mudstone facies of Wolfcampian cyclothems in the mid-continent. Flooding surfaces within these mudstone intervals are marked by lags of intraclasts, fish bone, and ostracodes, and are overlain by thin beds of micrite or laminated calcareous mudstone. These surfaces divide the variegated mudstone intervals into laterally traceable meter-scale cycles. The paleosol-bearing cycles thus defined can be correlated for tens of kilometers or more (Miller & West, 1998). This has enabled time-equivalent packages of paleosol profiles to be compared from locality to locality. Lateral variations in paleosol development within correlated cycles have been found to be small relative to the differences among vertically stacked paleosol profiles at a single locality. Furthermore, the vertical succession of paleosol types observed within individual cyclothems are consistent from locality to locality.

For most of the thicker variegated mudstone units within the Council Grove and lower Chase Groups (ie. Roca Shale, Eskridge Shale, Blue Rapids Shale, Speiser Shale, Matfield Shale) a very similar vertical succession of paleosol profiles has been observed (Miller et al, 1996). Paleosols from the lower part of these units have calcic clay-rich profiles with carbonate nodules and rhizocretions. By contrast, the uppermost paleosols within these units are characterized by pseudoanticlines and other features of vertic paleosols.

Paleosols from the lowest cycles of the variegated mudstones have angular blocky to sub-angular blocky ped structure, root traces, and carbonate nodules, stacked nodules, and rhizocretions similar to those observed by Blodgett (1988). The lower paleosols are also characterized by distinct color horizonation, and have prominent grayish-red to reddish-brown horizons in the middle of the profiles. Clay cutans are well-developed around the blocky peds, indicating clay illuviation. These paleosols can be classified as calcic Argillisols according to Mack and others (1993), or as Alfisols in the USDA classification (Soil Survey Staff, 1992).

Certain enigmatic features of the lower calcic paleosols indicate that they are polygenetic profiles. The carbonate nodules and rhizocretions are concentrated in the upper part of the profiles, and overlie argillic horizons with well-developed clay cutans. This pattern is the reverse of what would be expected in a typical calcic soil, where carbonate precipitation occurs below the zone of seasonal leaching and clay illuviation (Birkeland, 1984; Marriott & Wright, 1993; Smith, 1994). Climates wet enough to translocate clay downward through the profile would also leach soluble salts from the upper soil horizons. It is therefore inferred that these Wolfcampian paleosols developed first under humid to subhumid conditions. The precipitation and preservation of the carbonate then occurred under semi-arid conditions later in pedogenesis, when rates of evapotranspiration greatly exceeded mean annual precipitation (Mack, 1992). A diagram illustrating the proposed climatic changes associated with the formation of these complex paleosol profiles is shown in Figure 8.

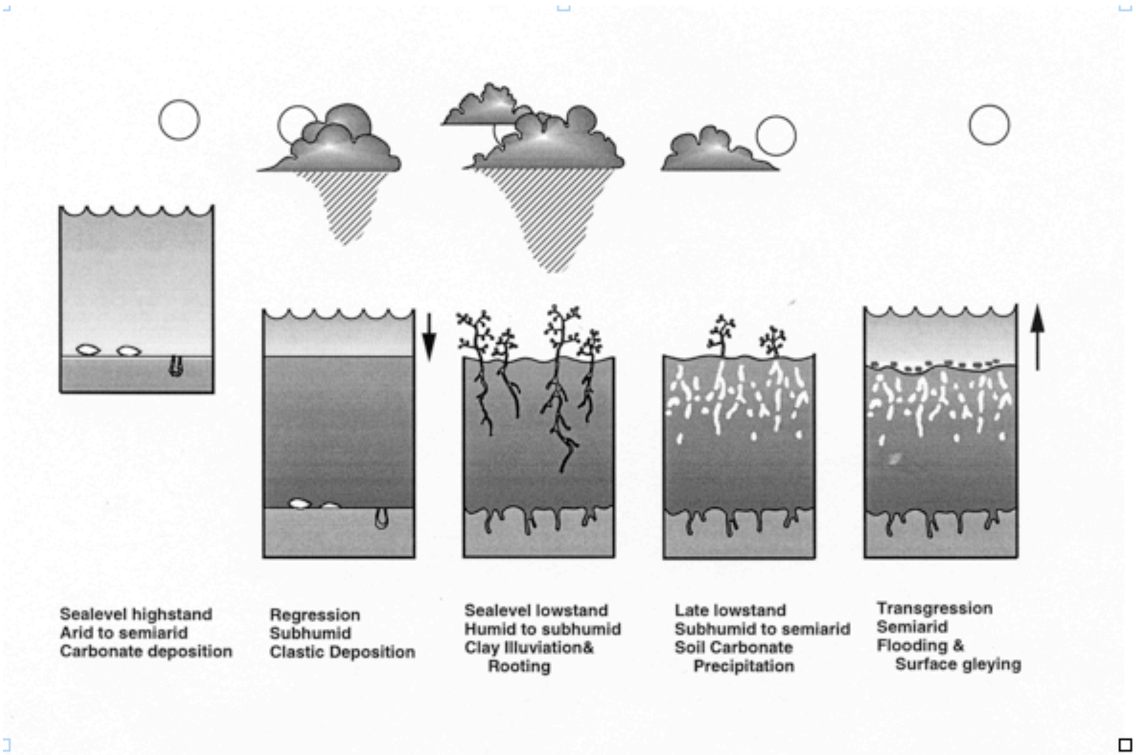


Figure 8. Diagram showing interaction of sealevel change and climate change on the formation of paleosols as interpreted by the model described herein. Arid to semi-arid conditions prevailed during sealevel rise and highstand. Seasonally wet climates were associated with falling sealevel and deposition of siliciclastic muds. Pedogenesis followed first under humid conditions resulting in illuviated clays, and subsequently under sub-humid to semi-arid conditions producing carbonate nodules and rhizocretions.

Within some cyclothems, rooted reddish-brown siltstones are preserved at the tops of silty paleosol profiles. Some siltstone beds are also distinct lithologic units. They weather spheroidally and bear a striking resemblance to loessites described from the Ancestral Rockies and elsewhere. The silts of the midcontinent may have been derived from the extensive Permian eolian dunefields to the west. Wind directions determined from both eolian dune crossbeds and paleoclimate models indicate winds from the northwest during the Wolfcampian (Johnson, 1989; Soreghan, 1992). If these silts were windblown, their occurrence at the top of paleosol horizons is consistent with sediment trapping by a vegetated surface. Relatively high rates of sediment aggradation would also account for only the early stages of pedogenic development being present in the upper silty horizons. Siltstones also increase in abundance upsection coincident with other lithologic indicators of increased aridity during the course of the Permian (West et al, 1997).

Another paleosol type is commonly found within cyclothems of the Council Grove Group. These paleosols are characterized by columnar-shaped ped structures with rounded tops, and typically occur in underlying or overlying carbonate units with evaporitic features. In modern soil-forming environments, these columnar peds occur only under the influence of sodium domination, and are referred to as natric horizons (Birkeland, 1984). The columnar peds in the Wolfcampian paleosols of northcentral Kansas all display the typical morphology found in extant natric horizon soils (McCahon & Miller, 1997). Columnar peds are distinguishable from argillic prismatic peds, also present in the paleosols, by the presence of domed rather than flat surfaces at the top of the peds in the B horizons.

The paleosols occurring at the top of the variegated mudstone intervals are dominated by vertic features. These paleosol profiles lack clearly developed horizonation and have a uniform greenish gray to yellowish gray color. Their most prominent features are pseudoanticlines (mukkara structure) with pedogenic slickensides. The hummocky surface relief (gilgai) associated with these structures are especailly well-displayed if horizontal exposures are available (see Miller et al., 1996). In some profiles the curved fractures of the pseudoanticlines are enhanced by carbonate precipitation along the fractures. The carbonate is generally micritic with a botryoidal surface texture, although it may also be sparry calcite. Carbonate nodules, isolated or less commonly stacked, and small (<5mm) sesquioxide nodules are also present in the matrix. Root traces are abundant and sometimes take on a "concertina" appearance. These paleosols can be classified as Vertisols (Soil Survey Staff, 1992) or calcic Vertisols (Mack et al., 1993).

The pseudoanticlines and pedogenic slickensides of the vertic paleosols were produced by the shrinking and expansion of clay-rich soils in response to wetting and drying in a markedly seasonal or monsoonal climate. The uniform green to yellowish color of these profiles suggests saturation of the soil during part of the year, and the lack of horizonation is consistent with the extensive turbation characteristic of Vertisols. The relatively high organic carbon contents (~1-2%) and presence of disseminated charcoal also reflect high rates of soil turbation, and an extended dry season. As for the calcic soils, the abundant carbonate nodules found in the upper part of some vertic soil profiles, such as in the Roca Shale, suggest a trend toward drier conditions during later phases of soil development.

CLIMATIC-EUSTATIC MODEL

As stated above, the early Permian was a time of continental galciation in the southern Hemisphere continents of Gondwana. Glacial advance and retreat would be associated with both global cyclical sealevel fluctuation and climate change. The consistent carbonate to siliciclastic pattern of meter-scale cycles, within both the open marine facies and paleosol-bearing intervals of cyclothems, indicates that glacio-eustatic seaelvel change alone is not adequate to explain the observed cyclicity. A model for climatic control over facies development proposed by Cecil (1990) provides a basis for developing a more complete model of cyclothem formation. In this model, clastic sediment transport is predicted to be highest in seasonal wet-dry climates and lower in both arid and tropical wet climates (see also Wilson, 1973; Perlmutter & Matthews, 1989). Carbonates and evaporites accumulate during arid and semiarid conditions, and mappable coal beds form during relatively wet climates when clastic influx is low. Because carbonates typically overlie the flooding surfaces of meter-scale cycles, acceptance of Cecil's model would indicate that drier conditions were associated with sealevel rise (interglacials) and wetter climates associated with sealevel fall (glacials).

Combining the climate model of Cecil (1990) with the paleosol evidence gives the following scenario for cycle formation. Arid to semi-arid conditions prevailed during sealevel rise and highstand resulting in carbonate precipitation. Falling sealevel was associated with a transition to seasonally wet climates that initiated the influx of siliciclastic muds. These siliciclastic muds were subaerially exposed with continued sealevel fall. Pedogenesis followed first under humid conditions resulting in clay illuviation, and subsequently under semi-arid conditions producing carbonate nodules and rhizocretions. Flooding of the land suface by rising sealevel truncated the soils and formed the thin intraclastic and skeletal lags. At the cyclothem-scale, a general trend toward wetter conditions is recorded by the change from calcic to vertic paleosols. The proposed relationship between cycles formation and sealevel climate change is illustrated in Figure 9.

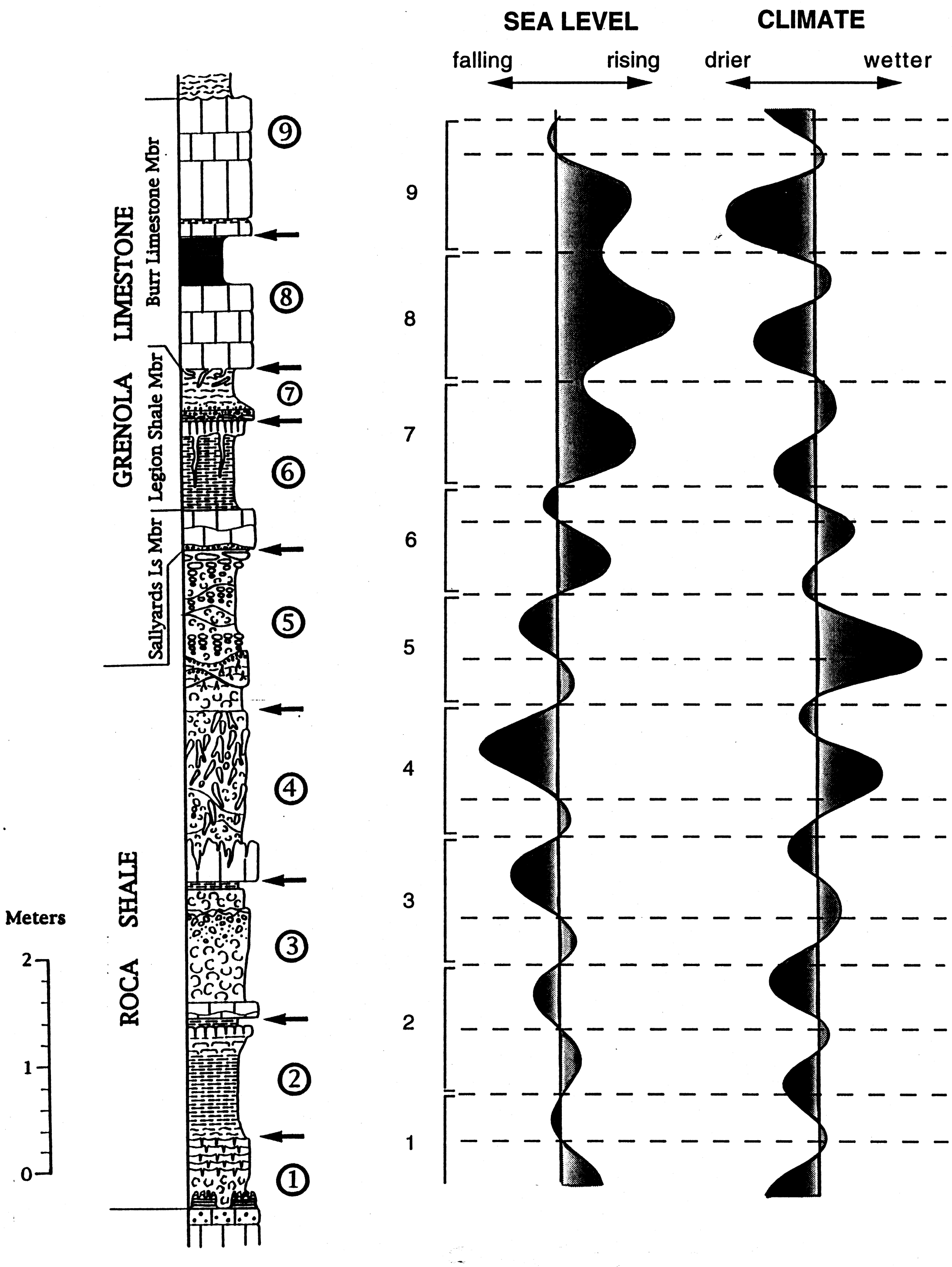


Figure 9. Stratigraphic section for Tuttle Creek spillway with interpreted sealevel and climate curves. Note the short-term climatic fluctuations superimposed on the cyclothem-scale pattern.

Because both eustacy and climate are intimately connected to the dynamics of glacial advance and retreat, some consistent relationship should be expected. A model incorporating both climate change and glacio-eustatic sealevel fluctuation has been proposed for the Wolfcampian of the mid-continent (Miller et al., 1996). Global circulation models (Parrish & Peterson, 1988; Kutzbach & Gallimore, 1989; Patzkowsky et al., 1991; Parrish, 1993) indicate a change from the dominance of zonal circulation in the Late Pennsylvanian, to the increasing influence of monsoonal circulation in the Permian, diverting the moisture-laden equatorial easterlies flowing from the Tethys, and resulting in a drying of equatorial Pangea. Furthermore, both climate models (Kutzbach & Guetter, 1984) and paleoclimate data (Fairbridge, 1986; Crowley & North, 1991) indicate that monsoons are strengthened during interglacial periods and significantly weakened during glacial periods.

The proposed climatic/eustatic model assumes that the climate of the mid-continent was strongly affected by a Pangean monsoon, and that fluctuations in the intensity of the monsoon produced oscillations between wetter and drier conditions. During interglacial periods when the monsoon was strong, the wet equatorial air would have been diverted to the north or south, resulting in a dry midcontinent. However, the weakening of the monsoon during glacial periods would have permitted the equatorial easterlies to penetrate into the continental interior. This model predicts that strong monsoons during sealevel highstands would have been associated with more arid conditions resulting in the precipitation of pure carbonates and evaporites, and weakened monsoons during sealevel lowstands would have been associated with wetter conditions resulting in argillaceous and silty carbonates and mudstones (Miller et al., 1996). Figure 10 shows the contrasting atmospheric circulation patterns associated with glacial maximums and interglacials according to our model.

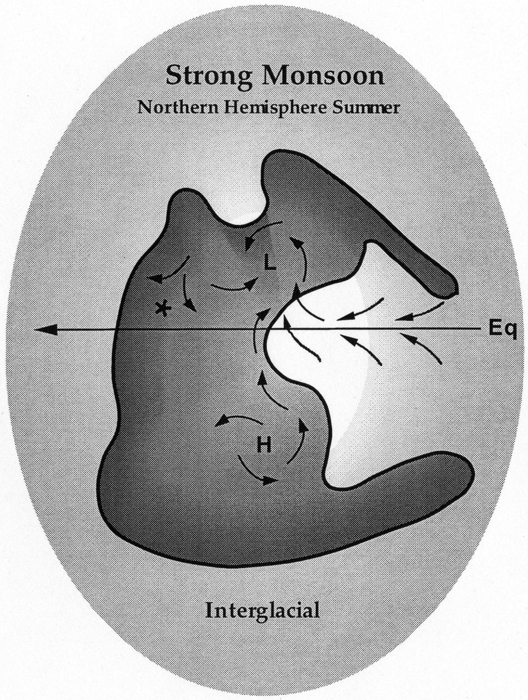


Figure 10. Changes in equatorial circulation patterns across Pangea between glacial and interglacial periods during the Lower Permian. According to the model presented here, low pressure cells over the supercontinent intensified during interglacials deflecting moisture-laden equatorial easterlies. This monsoonal circulation weakened during glacials allowing more moisture to reach the continental interior.

Ice volume changes during the Pleistocene have been attributed to variations in solar insolation resulting from periodic changes in the Earth's orbit and axial tilt. the five primary "Milankovitch periodicities" are 413,000, 100,000, 41,000, 23,000, and 19,000 years (Crowley & North, 1991). Time estimates for the duration of Pennsylvanian and Permian cyclothems are not well constrained, varying between 250,000 and 400,000 years. Although probably falling with the range of 40,000 to 150,000 years (Heckel, 1986; Busch & West, 1987), the absolute time duration of meter-scale cycles is at present impossible to obtain. Most time within a cycle is represented by paleosols, exposure surfaces and flooding surfaces. Some individual paleosol profiles could easily have developed over time periods of several tens of thousands of years. Cycle periodicities thus will tend to be overestimated by an order of magnitude or more by a simple division of stage duration by number of cycles (Algeo & Wilkinson, 1988). Thus, while estimated cycle periods fall within the Milankovitch band, there is no way at present to identify specific Milankovitch orbital periodicities.

STOPS AND STRATIGRAPHIC DESCRIPTIONS

A composite stratigraphic section from the base of the Council Grove Group through the lower half of the Chase Group is shown in Figures 3 through 7. The lithologies and prominent paleosol features are represented by symbols that can be interpreted using the key provided. Flooding surfaces marking the boundaries of meter-scale cycles are marked by arrows on the stratigraphic columns, and the transgressive surfaces defining cyclothem boundaries are indicated by the letters TS. For a thorough discussion of the entire Permian section in Kansas please see the Kansas Geological Survey Bulletin by West and others (2010).

STOPS 1 and 2

Roadcuts along K-177 between the Kansas River and I-70 provide a nearly continuous exposure of the Lower Permian section from the Johnson Shale, near the base of the Council Grove Group, to the Florence Limestone Mbr. of the Barneston Limestone of the Chase Group. Of particular interest along this extended series of roadcuts, are the exposures of the Easly Creek Shale, the Blue Rapids Shale, the Speiser Shale, and the Matfield Shale.

The Easly Creek Shale (Fig. 11) is a very silty variegated mudrock unit with poorly-developed paleosols. The silt content may be eolian in origin. An interesting feature of this interval is that throughout northeastern Kansas it is marked by a mudstone breccia of variable thickness at its base. At this locality, clasts are up to a meter across. Above the breccia, the unit is locally highly faulted. These are predominantly normal faults, but some also show reverse movement. Significantly, the base of the Easly Creek is marked by a meter-thick gypsum bed in the subsurface. The breccia and faulting could be a result of solution collapse, or, alternatively, it may be tectonic deformation localized by the gypsum bed.

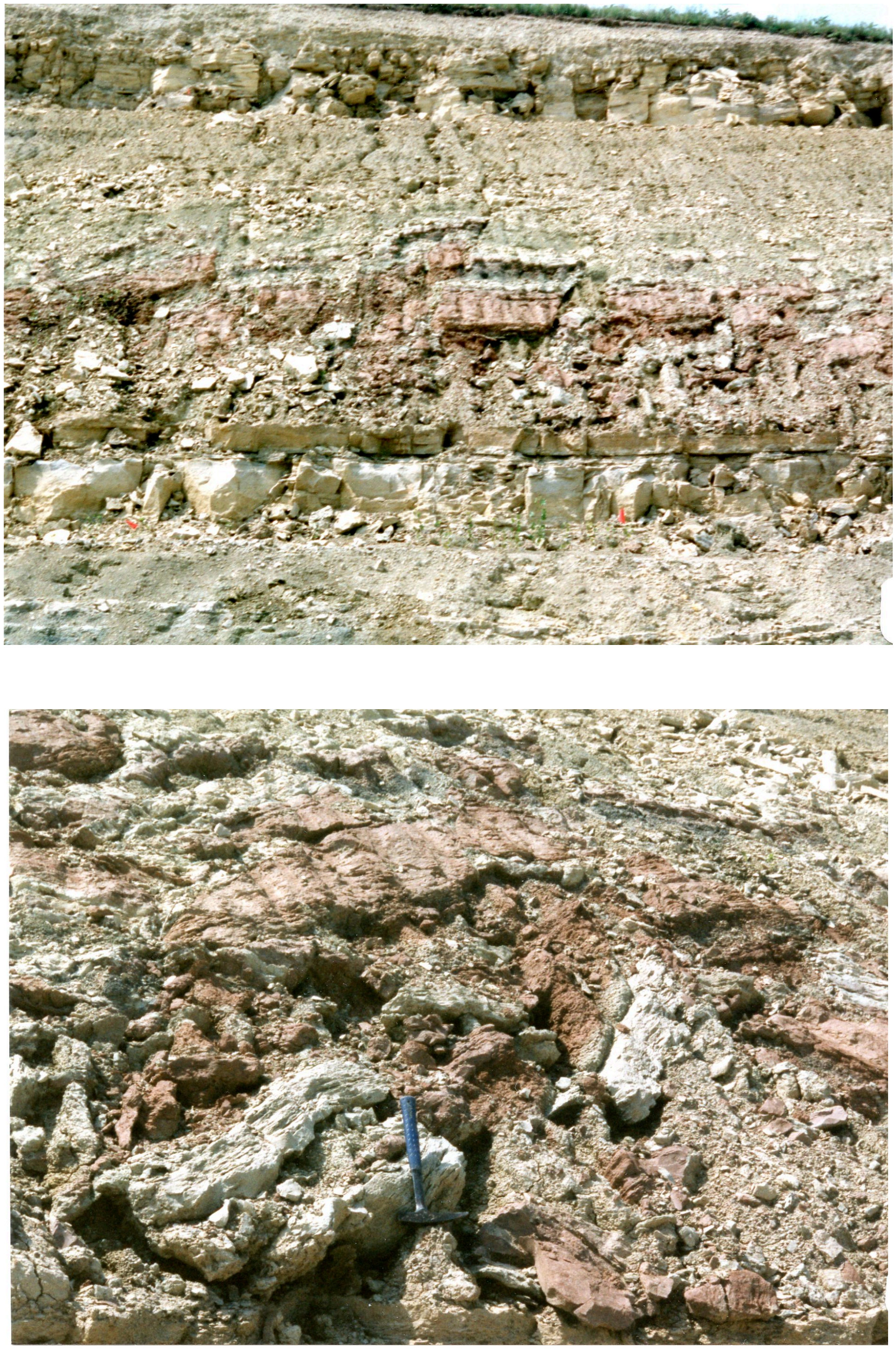


Figure 11. Easly Creek Shale showing faulted and brecciated mudstone of lower part. The breccia at the base correlates to a gypsum layer in the subsurface.

The Blue Rapids Shale (Fig. 12) is an excellent unit for examining complex polygenetic paleosol profiles. This interval also illustrates well the transition from calcic paleosols at the base of the variegated mudrock interval, to vertic paleosols at the top. The Blue Rapids also rests on the Crouse Limestone -- the top of which is a platy, somewhat dolomitic, fine-grained limestone with gypsum crystal molds and a restricted mollusk fauna. A climatic trend from relatively arid, to subhumid, to monsoonal is suggested by the sequence from the Crouse through the top of the Blue Rapids (see Miller et al., 1996). The next variegated mudstone interval is the Speiser Shale (Fig. 13) that overlies the intervening Funston Limestone. This paleosol interval shows the same pattern from calcic paleosols with caliche nodules, overlain by mottled paleosols and finally a greenish gray vertic paleosol profile.

Figure 12. The lower Blue Rapids Shale displays the typical stacked and polygenetic paleosols of the lower Permian. Also shown is the transition from a calcic paleosol at the base with caliche nodules to a greenish gray vertic paleosol at the top.

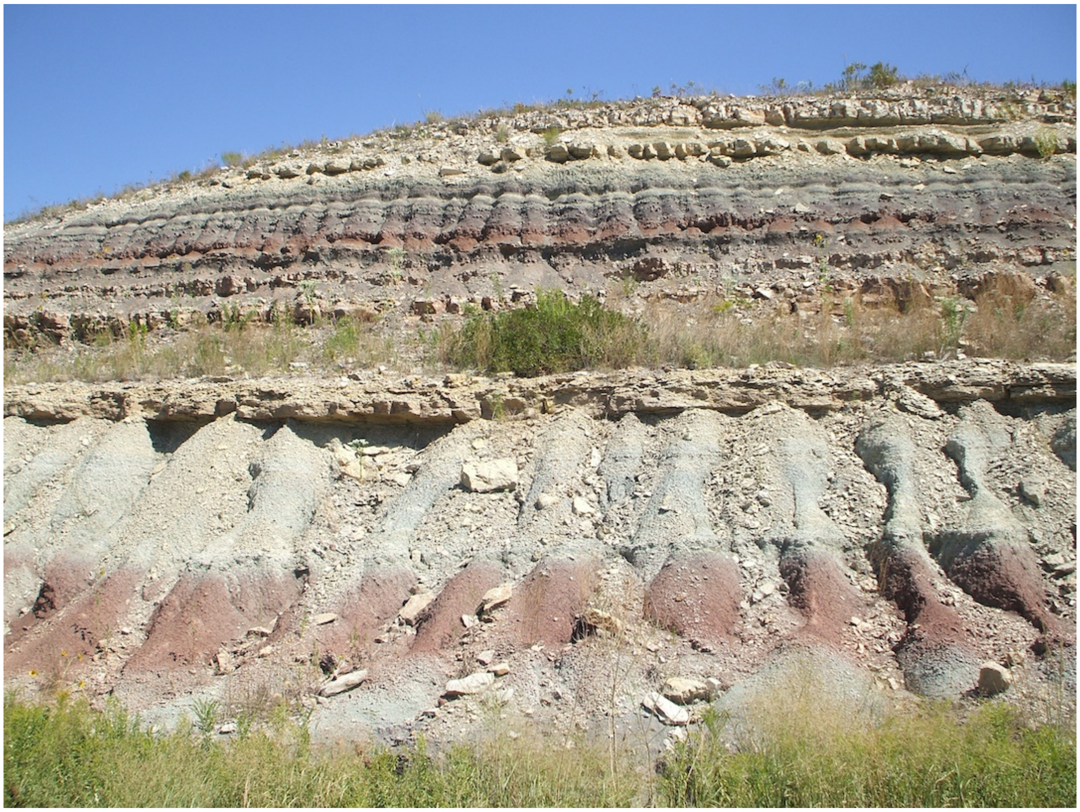


Figure 13. Roadcut showing the top of the Blue Rapids Shale, the Funston Limestone, and the overlying Speiser Shale. The Speiser Shale is characterized in this area by its "barber pole" appearance of stacked thin palsosols horizons.

The Blue Springs Member (Fig. 14) at the top of the Matfield Shale has numerous intriguing features. It is a rather silty interval with numerous stacked and truncated paleosol profiles. Within the Blue Springs paleosols the upper siltstone horizons are highly rooted but other pedogenic features are largely lacking suggesting that the silt may have accumulated later in soil development during drier climatic conditions. Of special note is that one of the paleosol horizons is marked by locally dense lungfish burrows (Fig. 15). This is consistent with the interpretation that these units represent highly seasonal wet/dry environments. A particularly puzzling feature of the Blue Springs at this locality is the presence of 1 to 2 cm thick carbonate cemented zones that crosscut all lithologic and pedogenic features. The timing and origin of these diagenetic features remains an open question. The Blue Springs is overlain by the massive and cherty Florence Limestone that acts as a prominent terrace former throughout the Flint Hills.

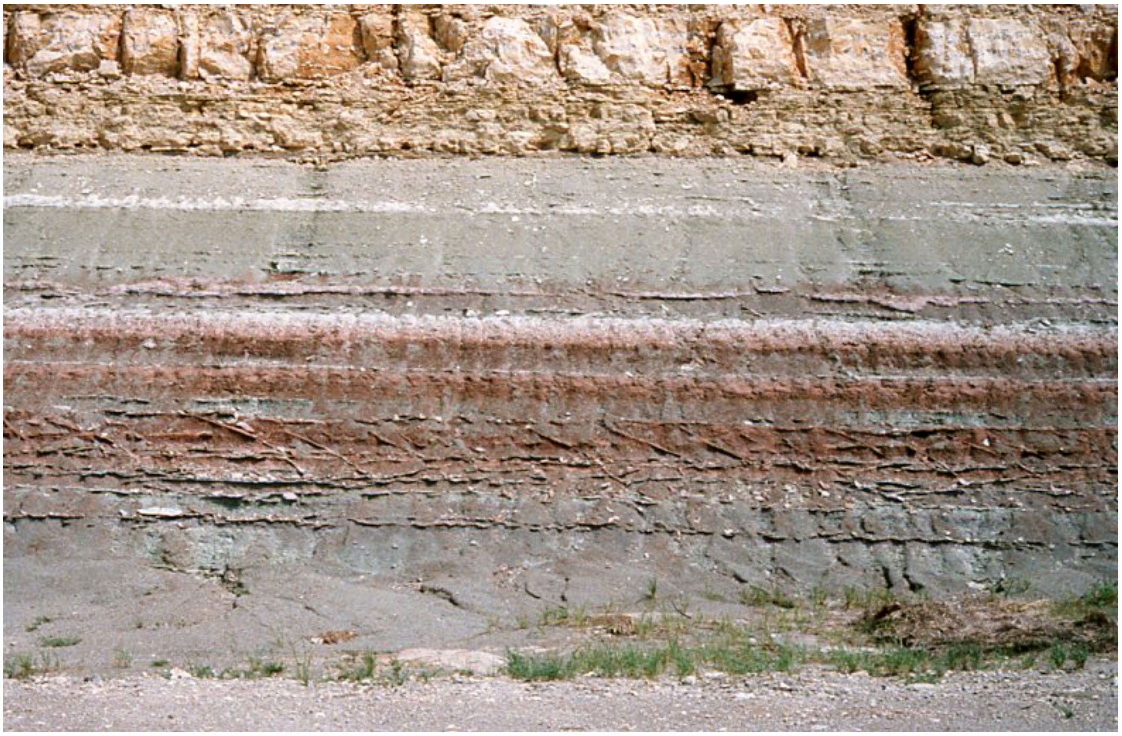


Figure 14. The upper photo shows the Blue Spring Member of the Matfield Shale with its stacked siltstones. These siltstones and silty mudstones typically display abundant root traces. The most prominent of the siltstone beds (shown below) also contains closely packed lungfish burrows.

Figure 15. A close-up of the lungfish burrows in the Blue Springs siltstone. These are closely packed and a high percentage of them contain lungfish bone fragments. This suggests that this population of aestivating lungfish may have died in their burrows as a result of the failure of wet season rains.

STOP 3

This stop is the emergency spillway of the Tuttle Creek Reservoir. This site is under the jurisdiction of the U.S. Army Corps of Engineers and collection of in-situ geological samples is by permit only. During the midwest floods of 1993, water was released over this spillway at rates as high as 60,000 cfs. This water flow extensively eroded the spillway, and resulted in fresh, unweathered exposures. These exposures provided an unprecedented opportunity to examine bedding plane surfaces and paleosol profiles over broad areas. Much of the upper part of the spillway has been subsequently covered, but good exposures remain along the spillway walls. The spillway exposes the stratigraphic interval from near the base of the Hughes Creek Mbr. of the Foraker Limestone, to the top of the Neva Limestone Mbr. of the Grenola Limestone. A detailed description of this interval is available from the Kansas Survey (Miller, 1994).

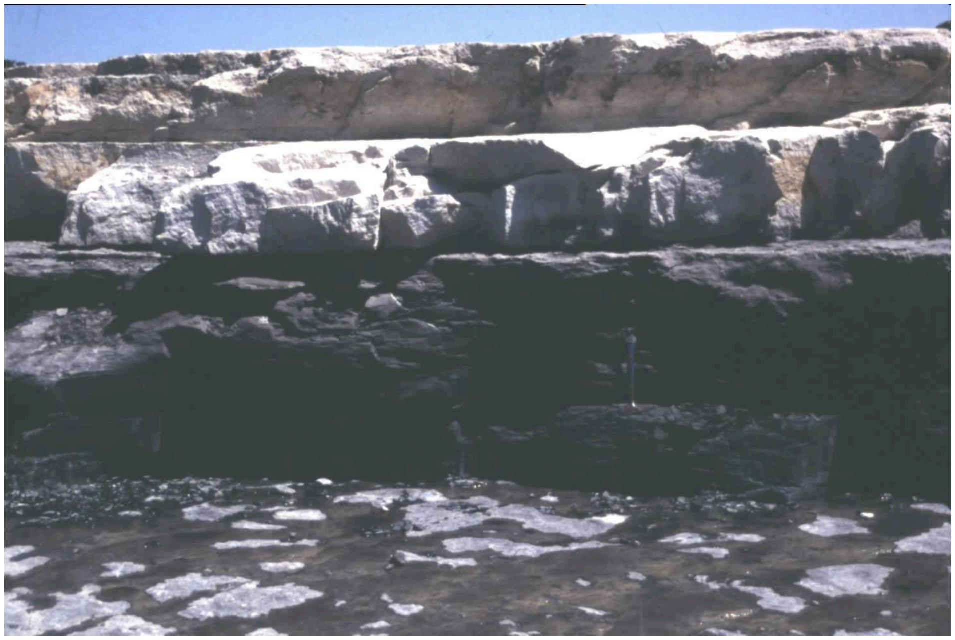


Figure 16. Exposure of the Bennet Shale Member and the Howe Limestone Member of the Red Eagle Limestone at the Tuttle Creek Spillway. The black Bennet Shale contains abundant orbiculid inarticulate brachiopods and shark teeth. The base of the Bennet and top of the Glenrock Limestone Member marks the base of the Permian.

The spillway provides an excellent exposure of the newly-recognized Pennsylvanian-Permian boundary (Fig. 16). Recent conodont work (Ritter, 1995) has placed the boundary at the top of the Glenrock Limestone Member of the Red Eagle Limestone. The stratigraphic sequence of conodont species in Kansas was found to be the same as that across the type boundary in Russia. This boundary placement was subsequently confirmed by the decision of the International Subcommission on Permian Stratigraphy to formally propose the first occurrence of the "isolated-nodular" morphotype of Streptognathus "wabaunsensis" as the base of the Permian System . The Virgilian/ Wolfcampian boundary of the midcontinent section is thus now precisely defined as the top of the Glenrock.

Underlying the Red Eagle Limestone is the Johnson Shale. This yellowish gray mudstone interval is noteworthy in that it displays an excellent example of a natric paleosol profile (Fig. 17). As mentioned above, these paleosols are characterized by a distinctive pedogenic structure called columnar peds. Natric horizons are suggestive of highly evaporitic environments and are commonly associated with coastal settings. This interpretation is supported by the presence of replaced evaporitic nodules, tepee structures and a low-diversity restricted mollusk fauna in the underlying units. A detailed description of the Johnson Shale paleosol profile can be found in McCahon and Miller (1997).

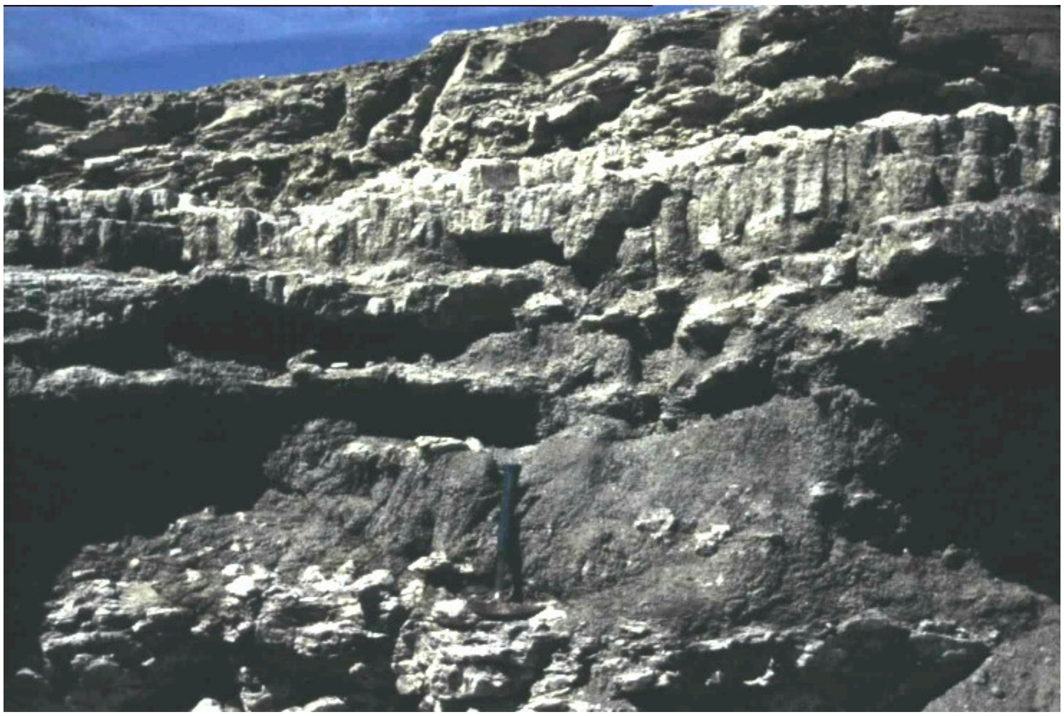


Figure 17. Johnson Shale displaying the characteristic columnar ped structure of natric, or sodium-influenced, soil formation.

At the base of the Roca Shale, on the top surface of the underlying Howe Limestone Member of the Red Eagle, a surface covered by algal stromatolites (Fig. 18) was exposed following the '93 flood. Although this bedding plane exposure of stromatolites has subsequently been destroyed, stromatolites can still be found on the cut sides of the spillway. The '93 flood also formed exceptional three-dimensional exposures of the paleosol profiles of the overlying Roca Shale. The lower red-and-green variegated profiles contained extensive pedogenic carbonate in the form of both nodules and rhizocretions (carbonate precipitated around roots) (Fig. 19). The upper greenish-gray paleosol displayed the characteristic undulatory pseudoanticlines or gilgai of modern Vertisols (Fig. 20). These bowl-shaped undulatory surfaces were complete with clay-coated and slickensided surfaces. Detailed descriptions of these Roca paleosols are given in Miller and others (1996).

Figure 18. Stromatolite-covered surface at the top of the Howe Limestone Member. Desiccation cracks are common the shales that immediately overlie this stromatolitic layer.

Figure 19. Lower Roca Shale calcic paleosol profile displaying the abundant caliche nodules and calcareous rhizocretions characteristic of semi-arid climates.

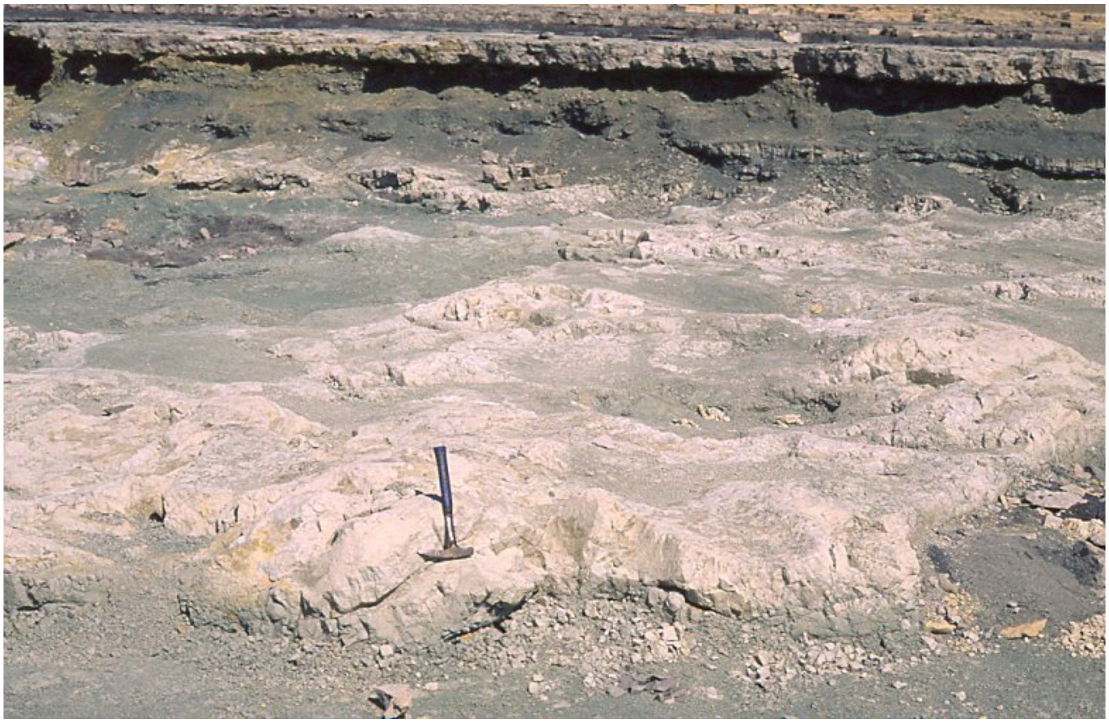


Figure 20. Exceptional exposures of vertic paleosols in the upper part of the Roca Shale. The upper image shows the undulatory surfaces, called gilgae, typical of Vertisols. The lower image illustrates the striated and clay-coated slickensides formed by the repeated expansion and contraction of the soil in monsoonal climates.

STOP 4

Roadcuts on Seth Childs Blvd. north of Manhattan provide good exposures of the Matfield Shale and the terrace-capping Florence Limestone.

The Wymore Shale Mbr. at the base of the Matfield displays very well-developed polygenetic paleosols. This unit again illustrates the repeated pattern of red and green variegated calcic paleosols being overlain by greenish-gray vertic profiles (Fig. 21).

The Blue Springs Shale Mbr. at the top of the Matfield consists largely of a stacked series of paleosol profiles giving a "barber pole" appearance to the outcrop (Fig. 22). These paleosols have well-developed pedogenic structures in their lower parts but are capped by massive rooted siltstone layers. As discussed above, the silts in these paleosols may have had an eolian origin, accumulated during drier climates phases near the end of paleosol formation.

Figure 21. The Wymore Shale showing the transition from mottled and calcium carbonate-rich paleosols at the base and greenish gray vertic paleosols at the top.

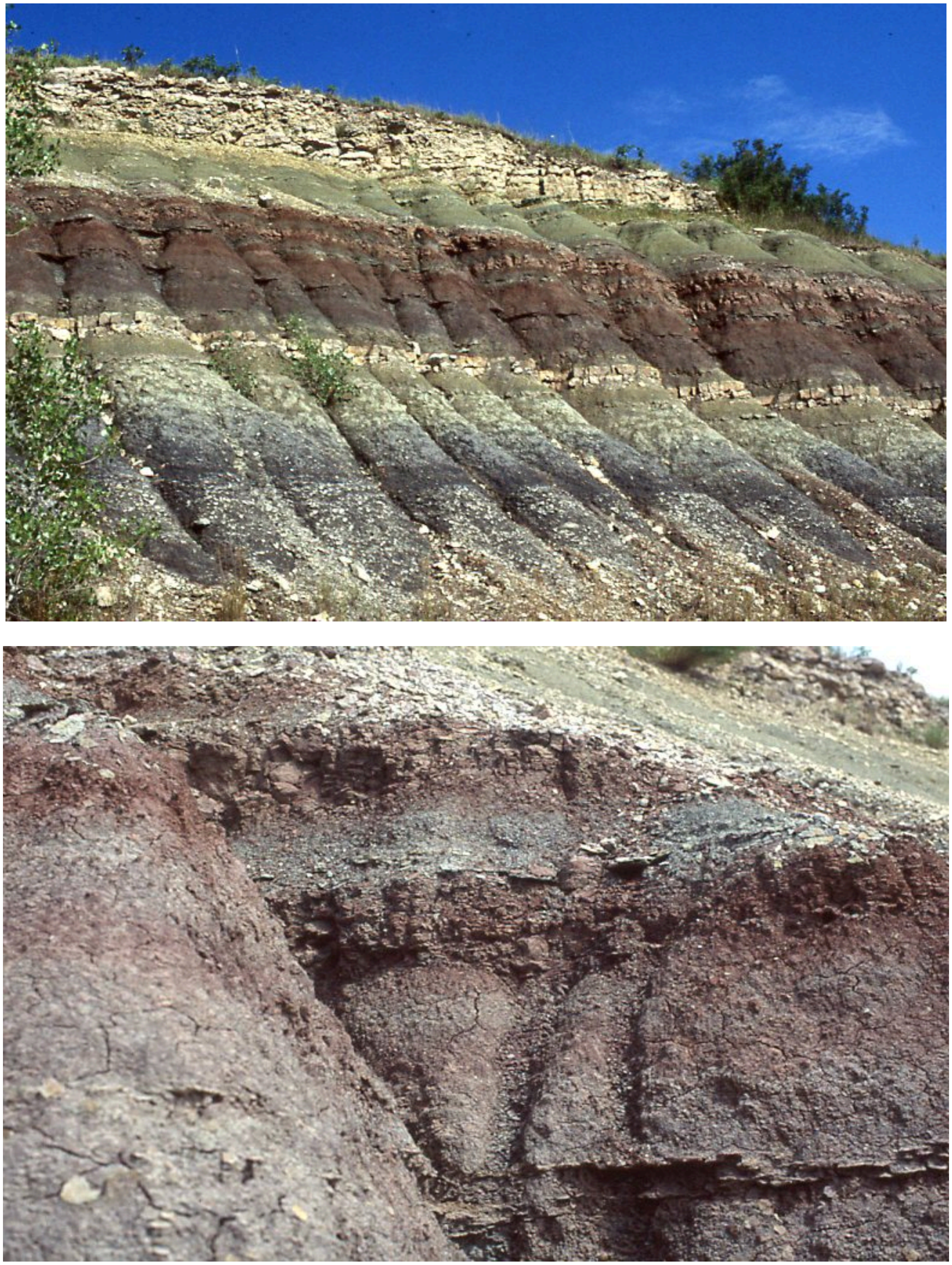


Figure 22. Exposure of Blue Spring Shale on Seth Childs Blvd showing gray shales at base and stacked paleosols at the top overlain by the Florence Limestone. The photo below shows the stacked paleosols with caps of rooted siltstone of possible eolian origin.

STOP 5

Excellent roadcut exposures are available at the intersection of Anderson Ave. and Scenic Drive. This locality displays the stratigraphic interval from the top of the Neva Limestone Mbr. of the Grenola Limestone through the Bader Limestone. Of special interest is the Eskridge Shale and the Beattie Limestone. Detailed descriptions of this stratigraphic section can be found in Miller and West (1993).

The Eskridge is a variegated mudstone with extensive paleosol formation, interrupted by two intervals of shallow marine calcareous facies. Joeckel (1991) described the same pattern of paleosol development and marine flooding in southern Nebraska. The lower paleosol interval of the Eskridge is characterized by the spectacular development of stacked horizons of elongated carbonate nodules (Fig. 23). These are locally tightly packed and take on the appearance of a prismatic ped structure. The carbonate precipitation was likely controlled primarily by roots (ie. the nodules represent rhizocretions), but the influence of burrowing cannot be discounted (Fig. 24). Lungfish and other vertebrate burrows have been recognized at other localities within the lower Eskridge. The thin limestone beds that overly this paleosol interval are characterized by a molluskan fauna dominated by pectinid and myalinid bivalves.

Figure 23. Lower Eskridge Shale displaying paleosol horizons with prominent elongated carbonate nodules overlain by thin shallow marine molluscan limestones.

Figure 24. Close-up closely packed elongated carbonate concretions associated with paleosol horizons of the Eskridge Shale. These were likely influenced by roots or possibly burrows.

Above the Eskridge is the prominent Beattie Limestone. The transgressive surface at the base of the Beattie is marked by a well-developed intraclastic bed with phosphate nodules, bone fragments, and skeletal debris. The Beattie Limestone has been intensively studied across the Kansas outcrop belt (Imbrie, 1955; Laporte, 1962; Imbrie et al., 1964). The Cottonwood Limestone member has a lower bioclastic facies with abundant algal-coated grains and an upper fusulinid facies. Overlying the Cottonwood is the Florena Shale Mbr. with abundant Derbyia and Neochonetes brachiopods.

STOP 6

The Scenic Drive roadcuts provide a continuous exposure from the Bader Limestone of the Council Grove Group through the Wreford Limestone of the Chase Group. This locality provides an excellent opportunity to see five uninterrupted cyclothems and their internal meter-scale cycles. The intraclastic beds marking the cyclothem-bounding transgressive surfaces are easily recognized. A detailed description of this complete stratigraphic section is provided in Miller and West (1993). The brief discussion below will focus on the interval from the Crouse Limestone through the Wreford Limestone.

The Crouse Limestone has been interpreted as recording a shallowing-upward transition from a shallow subtidal to a supratidal environment (West & Twiss, 1988). The lower Crouse is a wackestone to packstone characterized by pyramidellid gastropods and bivalves. By contrast, the upper Crouse is a thin-bedded, horizontally laminated, dolomitic micrite with small evaporite molds and pavements of ostracodes.

Figure 25. Lower paleosol horizons of the Blue Rapids Shale. In this photo can be seen the reddish B horizon with carbonate caliche nodules and rhizocretions, and the C horizon below. The paleosol is sharply truncated at the top by laminated calcareous shales deposted by a marine flooding event.

Above the Crouse is the Blue Rapids Shale with three stacked paleosol profiles each truncated by a flooding surface (Fig. 25). These paleosols show again the common pattern of calcic paleosols overlain by vertic profiles. Separated from the Blue Rapids by the thin Funston Limestone is the Speiser Shale. The Speiser at this locality consists of a series of stacked and truncated paleosol profiles giving the outcrop a striking "barber pole" appearance (Fig. 26). These red and green stacked horizons are followed by a greenish-gray vertic profile with well-developed pseudoanticles and large root molds. Interestingly, when the Speiser is traced to the east toward the axis of the Nemaha Anticline it thins and the lower stacked paleosols are replaced by a single well-developed profile. This suggests that the Nemaha was a stable topographic feature at the time with periodic sediment influx burying soils in slightly lower areas. Lateral changes in the Speiser and Blue Rapids Shales are illustrated in Miller and West (1998). Importantly, in both cases the meter-scale cycles can still be traced over at least tens of kilometers.

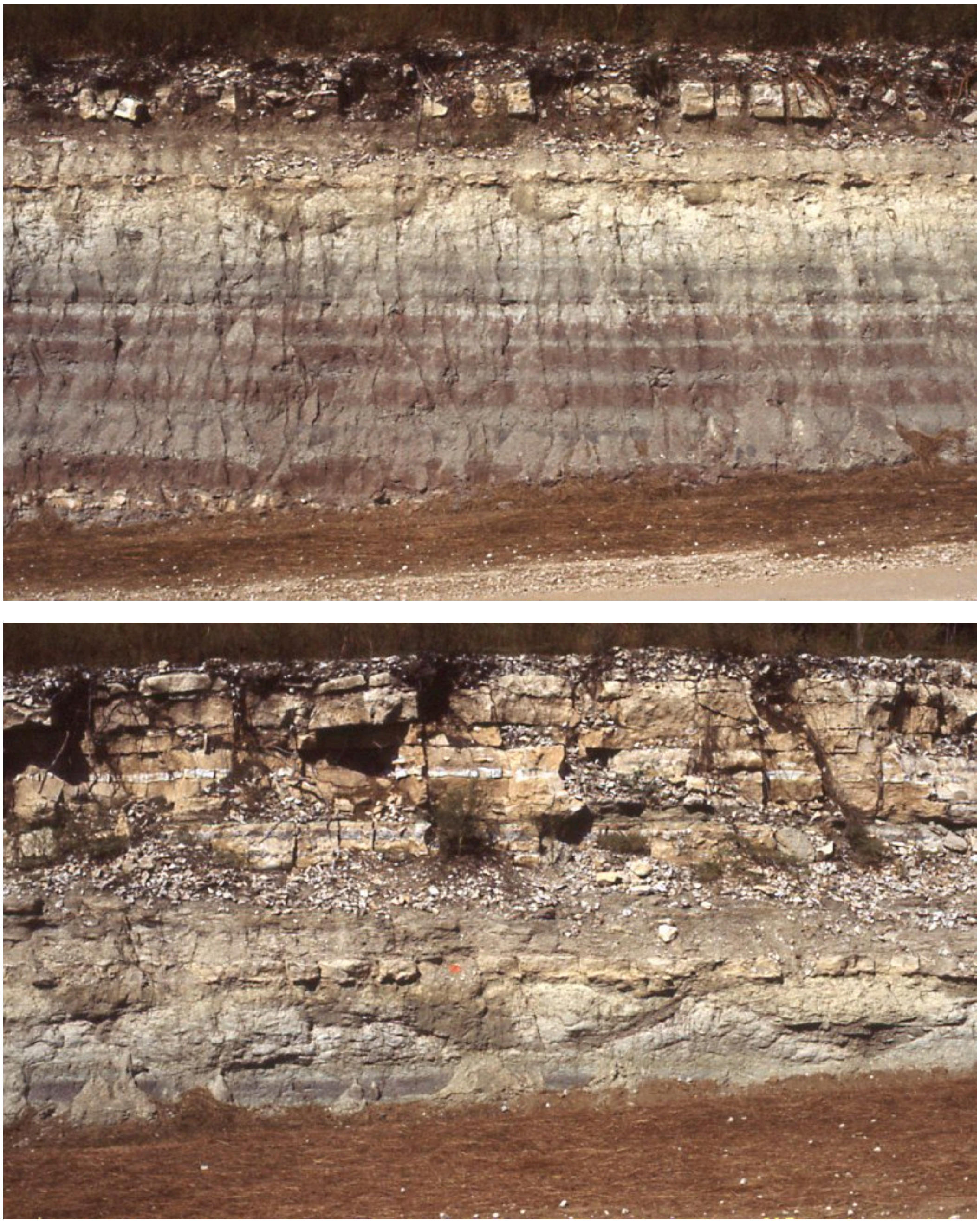


Figure 26. The upper image shows the Speiser Shale with the lower "barber pole" interval of thin truncated paleosols overlain by a vertic paleosol. The undulatory pseudoanticlines of the vertic paleosol are well displayed in the lower image. The vertic paleosol is overlain by the cherty Three Mile Limestone member at the base of the Wreford Limestone.

The facies of the Wreford Limestone have been studied in detail by Hattin (1957) along the full extent of the Kansas outcrop belt. The Wreford has regionally prominent cherty limestone members at its top and bottom. These limestones contain diverse marine faunas including productid brachiopods, bryozoans and crinoids. The origin of the chert remains unresolved, although some appears to have replaced burrow structures and some has replace evaporite nodules. The latter are represented by isolated nodules of radial length-slow chalcedony (Folk & Pittman, 1971). Between the two cherty limestones is the Havensville Shale Mbr., an interval of gray to yellowish-gray mudstone (Fig. 27). This unit is noteworthy for two reasons. Firstly, very well-developed boxwork structures are present near the middle of the unit (Fig. 28). These structures are rather common within the Lower Permian section and usually appear to record periods of subaerial exposure under rather evaporitic conditions. Secondly, overlying the boxworks is an interval with abundant large cauliflower-shaped geodes. These appear to be the result of the replacement of anhydrite nodules (Chowns & Elkins, 1974).

Figure 27. The Havensville Shale Member and overlying Shroyer Limestone Member of the Wreford Limestone.

Figure 28. The middle of the Havensville Shale Member displaying well-developed boxwork structures. These calcite-filled fractures are likely related to arid evaporitic conditions.

STOP 7

This roadcut along Fort Riley Blvd. southwest of Manhattan exposes the interval from the top of the Roca Shale to the Eskridge Shale. This locality provide easy access to the complete thickness of the Grenola Limestone. A detailed description can be found in Miller and West (1993).

The Grenola is significant in that it contains the highest stratigraphic occurrence of a conodont-rich black shale in the Lower Permian. Such black shales are common within the upper Pennsylvanian where they typically contain abundant non-skeletal phosphate nodules. The loss of such facies in the Lower Permian is one of the lithologic trends associated with both a general shallowing and increasing aridity throughout the Permian. The two "true" black shales in the sequence are the thin black shales in the Burr Limestone and at the base of the Neva Limestone. Both of these shales have skeletal phosphatic lags at their bases with abundant fish bone.

This locality also provides a good opportunity to examine a natric paleosol horizon at the top of the Salem Point Shale Mbr (see McCahon & Miller, 1997 for descriptions and photos) (Fig. 28). The columnar peds are prominently developed and their domedshaped tops can be viewed on fallen blocks. Significantly, a meter-thick gypsum bed is present at the base of the Salem Point in the subsurface.

Figure 28. The upper Salem Point Member of the Grenola Limestone includes two natric paleosol horizons. The diagnostic rounded columnar ped structures shown in the lower photo are produced by subaerial exposure under the influence of high sodium concentrations.

STOP 8

Like the Tuttle Creek spillway, the emergency spillway at the Milford Reservoir also experienced significant erosion during the floods of 1993. In this case, the erosion extensively exposed the entire Barnestone Limestone. A detailed description of this exposure is available from the Kansas Survey (Miller & Twiss, 1994). The U.S Army Corps of Engineers supervises this site, and collection of in situ geological samples is by permit only. The area west of K 244 is designated "No Trespassing" because it is an impact zone for small-arms fire. For personal safety, previous arrangements must be made with the Geary County Gun Club before proceeding west of K-244.

The Barneston is the thickest (22 meters) carbonate unit within the Permian section of Kansas, and is the most prominent cliff-former in the Flint Hills Physiographic Province. The Florence Limestone Member, comprising the lower 10.5 meters of the Barneston, contains closely-spaced nodular chert layers in a skeletal wackestone to packstone (Fig. 29). It is the faunally most diverse member and dominated by productid brachiopods, fenestrate, ramose and encrusting bryozoans, crinoids, and echinoids.

Figure 29. Irregular chert layers within the Florence Limestone Member. These chert nodule layers appear to form burrow-like networks.

The morphology of the nodular chert layers of the Florence Limestone resembles that of complex burrow systems similar to Thalassinoides (Fig. 30). On many surfaces they are joined to form continuous polygonal networks. Commonly, two or more of the chert layers are joined by vertical and inclined chert masses to form multi-storied networks. The apparent localization of silica replacement within burrows may have been a result of higher porosity and permeability within the skeletal burrow fills. Unsilicified Rhizocorallium and some Thalassinoides-like burrow systems occur in a few beds. These burrow systems are filled with skeletal debris coarser than the matrix and are probably similar in origin to the "tubular tempestites" described from modern shallow marine environments.

Figure 30. Bedding plane view of nodular chert horizon within Florence Limestone Member. Note the borrow-like geometries.

Vertically connected nodular chert layers form multi-storied galleries that are consistently 20 to 30 cm thick. These galleries are stacked, and although typically separated by less than 10 cm, do not appear to be interconnected. This would seem to suggest relatively rapid sediment aggradation followed by the development of extensive burrow networks. Filling of pre-existing burrow networks by skeletal debris may have accompanied these sedimentation events. The stacked silicified burrow networks are in turn organized into meter-scale cycles that are separated by clayey units of a few tens of centimeters or less. Based on previous work on Lower Permian cyclicity, these meter-scale cycles may record climatic fluctuations in which clean limestones record arid or semi-arid conditions, and the clay-rich carbonates record somewhat wetter climates when terrigenous clastics were flushed into the basin.

Above the Florence Mbr. is the thin argillaceous Oketo Shale Mbr that is in-turn overlain by the Fort Riley Limestone Mbr. At the base of the Fort Riley is a massive limestone bed that is a prominent ridge-forming unit in the area. The Fort Riley Mbr becomes less fossiliferous and more dolomitic upward. A variety of sedimentologic features, including abundant molds of anhydrite nodules and gypsum rosettes (Fig. 31), laminated dolomitic mudstone (Fig, 32), polygonal desiccation cracks, tepee structures and boxwork structures (Fig. 33), strongly suggest upward shallowing and the development of evaporitic sabkha conditions.

Figure 31. Pseudomorphs after nodular anhydrite indicating evaporitic conditions.

Figure 32. Laminated dolomitic mudstones of the upper Fort Riley Member. Bedding plane surfaces may have nearly monospecific pavements of small Permorhus bivalves.

Figure 33. Tepee structures near the base of the Holmesville Shale Member overlying the Fort Riley Limestone Member. These structures are associated with boxwork structures and anhydrite nodule molds all indicating evaporitic sabkha-like environments.

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