

KANSAS GEOLOGICAL SURVEY
OPEN-FILE REPORT 1994-47

Rocks of the Milford Lake Spillway:
Facies, Cycles, and Environments of Deposition

by

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1930 Constant Avenue
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**ROCKS OF THE MILFORD LAKE SPILLWAY:
FACIES, CYCLES, AND ENVIRONMENTS OF DEPOSITION**

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December 31, 1994

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ABSTRACT

The midwest floods of 1993 resulted in the erosion of both the Tuttle Creek Lake and Milford Lake spillways. These two sites now provide an excellent opportunity to examine rocks of Early Permian (Wolfcampian) age. Exposed in the Milford spillway are paleosols of the upper Matfield shale, the entire Barneston Limestone, and paleosols and other subaerial exposure features of the lower Doyle Shale. The suite of sedimentary features present within this stratigraphic interval strongly suggest semi-arid to arid climatic conditions in an environmental setting not much different from the modern Persian Gulf or Western Australian coast. Meter-scale sedimentary cycles are present throughout the interval and may be attributed to cyclic changes in climate as well as fluctuations in relative sealevel.

INTRODUCTION

The Milford Lake spillway area is located northwest of Junction City, Kansas, in western Geary County (Section 29, T11S, R5E) (Fig. 1). During the summer of 1993, exceptional precipitation within the midwest resulted in record flood-peak discharges at gaging stations throughout the upper Mississippi River Basin (Parrett et al., 1993). By the end of July the area of the Tuttle Creek and Milford reservoirs had received over twice the normal precipitation (Wahl et al., 1993). The sustained high rainfall within the Republican River watershed resulted in the filling of the reservoir to maximum pool and the release of water over the emergency spillway of the Milford Dam. From July 20th through August 3rd, water flowed over the spillway at rates of up to 19,000 cubic feet per second.

The flood waters eroded a narrow channel into the spillway, stripping off the overlying unconsolidated fill and Pleistocene loess and uncovering an ancient karst landscape. Sinkholes and solution channels, many following joints, can be observed within the eroded spillway area. Some of the Permian limestone bedrock was also

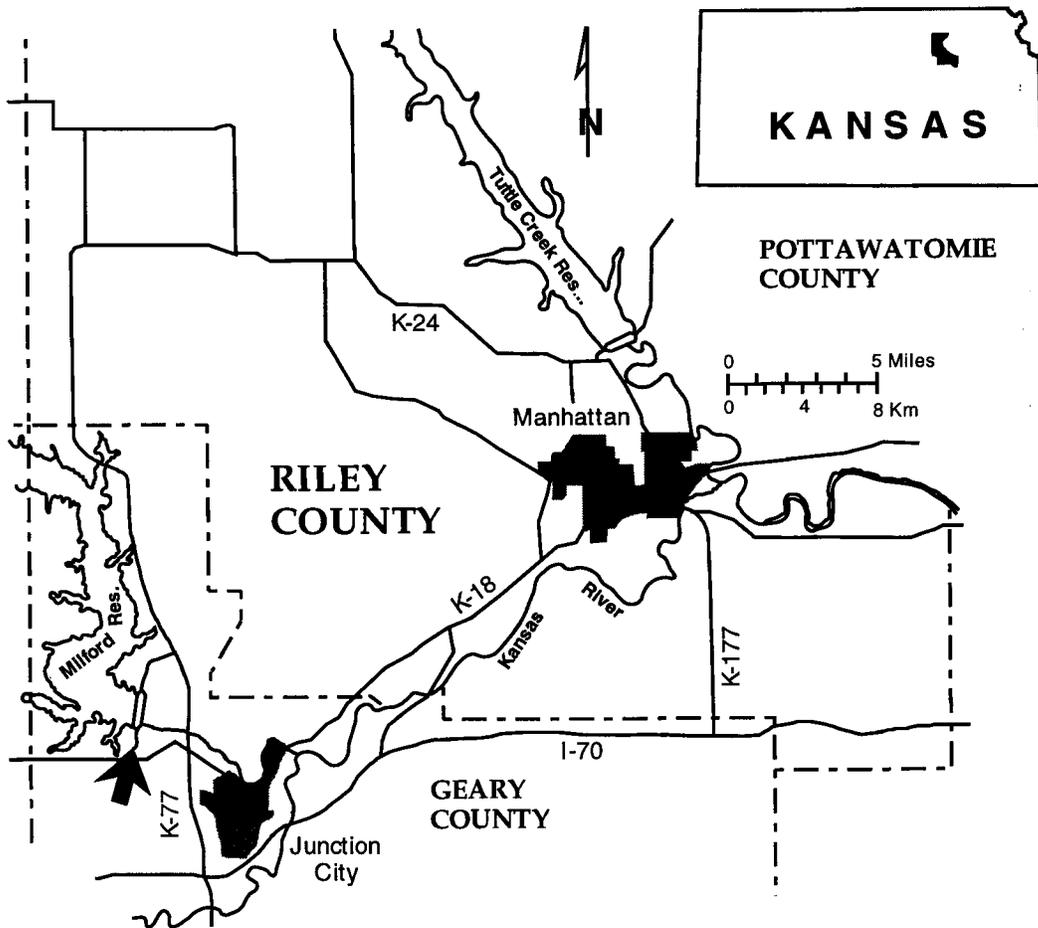


FIGURE 1. Locality map for Milford Lake spillway. The arrow marks the location of the Milford Lake spillway in northwestern Geary County (Section 29, T11S, R5E) northwest of Junction City. The eroded section is located on both sides of Spurr 244 south of the dam.

eroded, providing fresh exposures of bedding plane surfaces and layers of chert nodules. These surfaces provide the first opportunity to observe the three dimensional geometry of the chert layers that so characterize the Flint Hills region (Twiss, 1994).

STRATIGRAPHIC AND PALEOGEOGRAPHIC SETTING

The eroded Milford spillway exposes the Blue Spring Member of the Matfield Shale, the entire Barneston Limestone, and the lower part of the Holmesville Shale Member of the Doyle Shale (Fig. 2). These units are within the lower part of the Chase Group and are of Early Permian (Wolfcampian) age. The Barneston Limestone is the thickest carbonate unit within the Permian section in Kansas, and is the most prominent cliff-former in the Flint Hills region.

During the Wolfcampian the mid-continent of North America 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 (Archer & West, 1993). 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, is the likely cause for the repeated sedimentary cycles characteristic of the Pennsylvanian and Permian in the mid-continent.

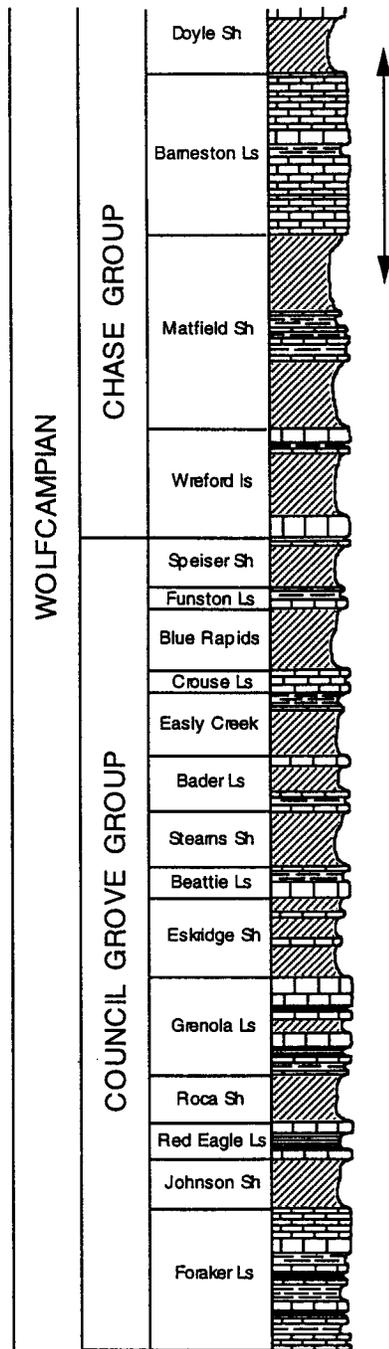


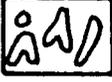
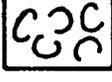
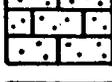
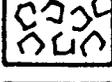
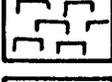
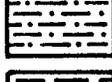
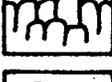
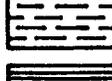
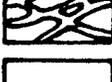
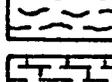
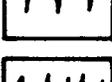
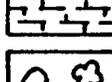
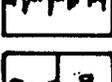
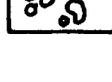
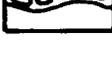
FIGURE 2. Stratigraphic section of the Council Grove and lower chase Groups. The arrowed line marks the top and bottom of the newly eroded spillway section that extends from the upper Matfield Shale to the lower Doyle Shale.

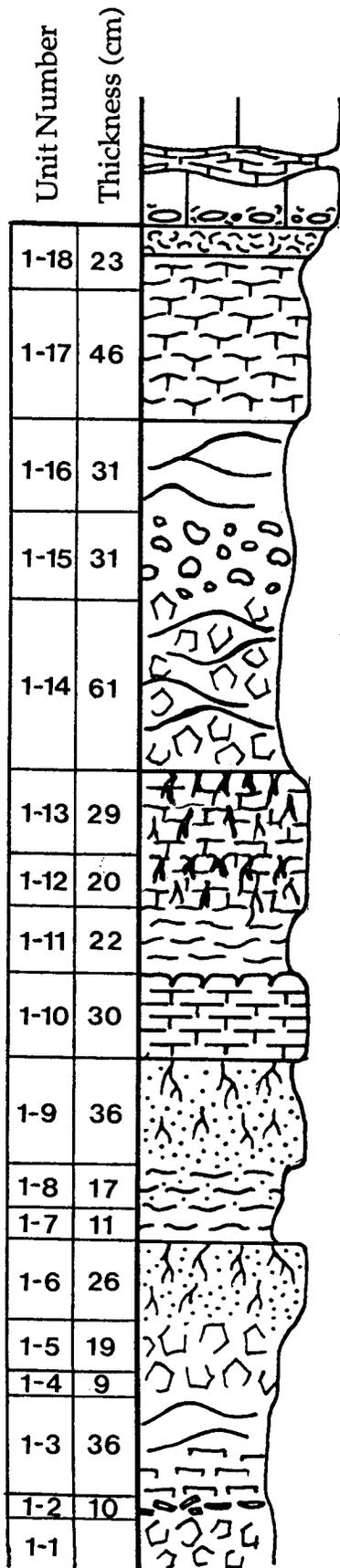
Results of global circulation models for Pangea (Parrish et al., 1982; Kutzbach & Gallimore, 1989; Crowley et al., 1989; Patzkowsky et al., 1991; Dubiel et al., 1991) have strongly indicated a monsoonal circulation pattern that intensified from the Early Permian to a maximum in the Triassic. The retrodictions of these numerical climate models have been tested primarily against the global distribution of coals, evaporites, red beds and eolian sands (Patzkowsky et al., 1991; Parrish, 1993). However, these geologic data are averaged over time periods that include multiple glacial and interglacial cycles. As a result, climate models are being tested by comparison with geologic data representing time intervals over which major shifts of climate likely occurred. What is needed is paleoclimate and paleoenvironmental data collected at a high level of stratigraphic resolution. The documentation of meter-scale cyclicity and detailed facies descriptions that follow are an effort toward that end.

DETAILED FIELD DESCRIPTIONS

Following are the detailed bed-by-bed descriptions of the stratigraphic interval exposed at the Milford spillway, from the upper Blue Springs Shale through the entire Barneston Limestone and into the lower Holmesville Shale. These field descriptions record vertical changes in lithology, texture, and skeletal content. Attention was also given to the recognition of discontinuity surfaces, particularly flooding surfaces and subaerial exposure surfaces. For paleosol profiles, every horizon distinguishable in the field by color or pedogenic structure was described separately. The morphological features of paleosols were described in the field according to Retallack (1988).

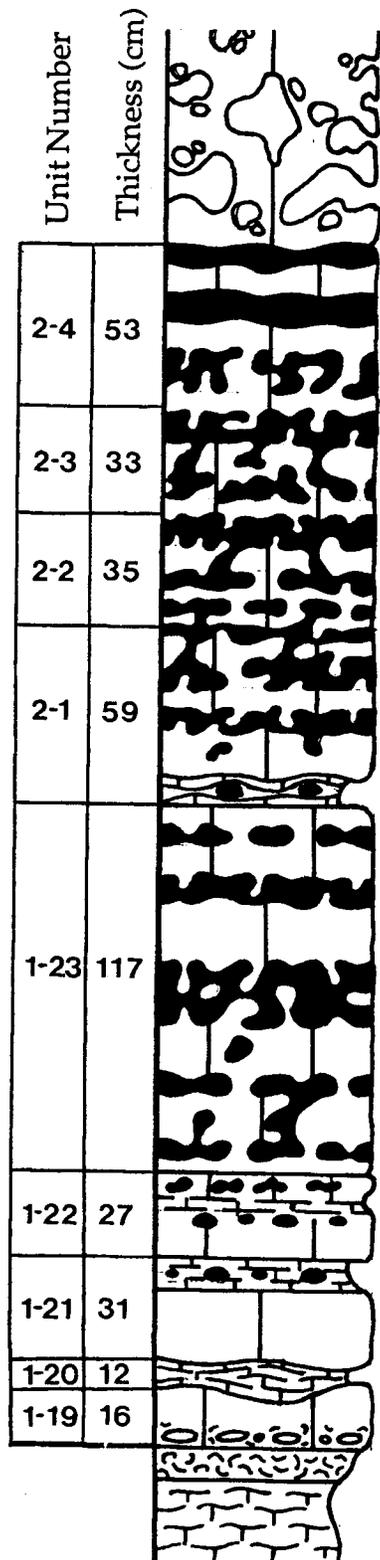
SYMBOL KEY
for
Lithologies and Sedimentary & Pedogenic Structures

	Dolomite		Rhizocreations and Nodules
	Cherty Limestone		Root Molds
	Limestone		Subangular Blocky Peds
	Silty Limestone		Angular Blocky Peds
	Siltstone to Fine Sandstone		Platy Peds
	Silty shale		Columnar or Prismatic Peds
	Gray shale		Pseudoanticlines
	Black Shale		Boxwork Structure
	Mudstone		Mudcracks
	Calcareous Shale or Mudstone		Stylolites
	Gypsum Molds or Geodes		Intraclasts



- 1-12. Calcareous mudstone (light greenish gray 5GY7/1)
Abundant root traces filled w/ clay (greenish gray 5GY5/1) traces up to 2mm in diameter
- 1-11. Variegated mudstone (pale reddish brown 10R5/4)
Clay coatings on horizontal surfaces
Dendritic green root mottles that increase upward
Mottled upper contact
- 1-10. Carbonate mudstone (light greenish gray 5GY7/1)
Mottled lower and diffuse upper contact
A few green clay wisps, no clay skins
Top 10cm with fine dendritic red mottles that increase upward
On upper surface 8-10cm diameter polygons (may be incipient ped development)
- 1-9. Very coarse siltstone (pale reddish brown 10R5/4)
Lower 26cm is coarser becoming finer upward
Abundant greenish gray (5GY5/1) root traces increase upward
Upper 8cm is mottled red and green claystone with very abundant root traces (greenish gray and weak red 10R4/2) and some carbonate development - very poorly developed blocky structure
- 1-8. Slightly silty mudstone (pale reddish brown 10R5/4)
Fine isolated greenish gray (5GY7/1) mottles
Massive, structureless
- 1-7. Variegated mudstone (greenish gray 5GY7/1)
Massive, structureless - abrupt lower and upper contacts
- 1-6. Medium to coarse siltstone (pale reddish brown 10R5/4)
Greenish gray (5GY7/1) root traces increase in density upward
Some very thin clay coatings in lower part
- 1-5. Very silty mudstone (reddish brown 10R4/4)
Very coarse blocky structure with clay coatings
- 1-4. Very silty mudstone (greenish gray 5GY7/1)
Slightly mottled lower contact and diffuse upper contact
Very poorly developed coarse subangular blocky structure
- 1-3. Variegated fine silty mudstone (pale brown 5YR5/2 wet)
Lower 5-6cm gradational into green unit below - platy to massive
Upper 16cm w/ gleyed root traces that increase in density upward. Clay-coated curved fracture surfaces become better developed toward top (wedge-shaped peds). Root traces up to 3-4mm thick and 14cm long
- 1-2. Variegated slightly silty mudstone
Lower 6-7cm grayish red (10R4/2) w/ fine dendritic mottling
Medium angular blocky peds
Upper part platy claystone (greenish gray 5GY6/1)
Variable in thickness laterally - locally brecciated
- 1-1. Variegated silty mudstone
Lower part grayish red (10R4/2) - slightly platy structure
Upper part reddish brown (10R4/4) with fine dendritic mottling toward top (light greenish gray 5GY7/1)

- 1-18. Carbonate mudstone (yellowish gray 5Y7/2)
 - More clay-rich and platy upward
 - Limonite blebs
 - Ostacode packstone in upper ~9cm (pale yellowish brown 10YR6/2)
- 1-17. Clayey carbonate mudstone (yellowish gray 5Y7/2)
 - Limonite blebs abundant, some vertically elongate (roots?)
 - Manganese spots (some dendritic) and fracture coatings
- 1-16. Mudstone (greenish gray 5GY5/5)
 - Gradational with unit below, upper contact sharp
 - Manganese coatings and limonite spots
 - Curved fracture surfaces w/o significant clay coatings
 - Subtle limonite root traces
- 1-15. Mudstone (mottled greenish gray 5GY5/5 and gray)
 - Manganese coated surfaces and limonite blebs or concentrations
 - Root traces common
 - Carbonate-rich nodules throughout (1-2cm diameter)
- 1-14. Mudstone to claystone (gray 5Y6/1)
 - Gradational boundary with unit below
 - Manganese dendrites, small limonite spherules and limonite-filled root traces
 - Pedogenic slickensides - breaks into curved plates with thin clay coatings, coarse (2-5cm) subangular blocky peds
- 1-13. Calcareous mudstone (greenish gray 5GY6/1)
 - Heavily rooted with root traces and matrix almost same color
 - Limonite brown spots



2-1. Skeletal wackestone (very pale orange 10YR8/2)

Lower ~8-10cm clayey skeletal wackestone, platy
Slightly dolomitic, little identifiable skeletal debris
(bryozoans, brachiopods)

Chert beds: 4-7cm irregular discontinuous bed, nodules elongated parallel to bedding, dark cores (N4) with light outer rims up to 2.5cm thick; 27-34cm irregular continuous bed (isolated irregular nodules below, sporatically distributed); 41-52cm irreg. discontinuous bed connected to bed above by galleries; 56-59cm irreg. cont. bed Possible monaxial sponge spicules in chert nodules, more common in darker cores.

Skeletal content appears to increase upward: fenestrate bryozoans abundant and dominant component, ramose bryozoans, echinoid spines, productids (?Reticulatia), chonetids.

1-23. Skeletal wackestone

Chert beds: 4-9cm discontinuous bed; 24-29cm discontinuous bed w/ some pathways to bed below; 45-67cm thick gallery; 84-93cm continuous bed; 105-111cm discontinuous bed. Chert nodules have med dark gray (N4) cores and very light gray (N8) rims. Top of unit is platform at top of falls - no chertified burrow galleries cross this surface.

Fossils: fenestrate bryozoans abundant, productid brachiopod spines, crinoid ossicles, large brachiopods uncommon, lophophyllid coral, fusulinids in upper 30cm together with echinoid spines and plates.

1-22. Skeletal wackestone

Pale yellowish brown (10YR7/2), weathers very pale orange (10YR8/2)

Lower 14cm - silicified and unsilicified brachiopod fragments (productids) abundant, ramose bryozoans, crinoid ossicles. A few scattered lenticular chert nodules at top

Middle 8cm clayey, weathers platy - abundant brachiopods (chonetids, productids, ?Composita), fenestrate bryozoans

Upper 5cm - fenestrate and ramose bryozoans, brachiopod debris. Irregular chert nodules common

1-21. Skeletal wackestone

Upper 10cm clay-rich interval

Chert horizon in upper 6-8cm, horizontal gallery, skeletal debris in silicified burrows same as in matrix, burrows elongate in cross-section.

Fossils: large Reticulatia on upper surface w/ marginiferids, Derbyia, ?Aviculopinna. Skeletal debris includes small crinoid ossicles, ramose and fenestrate bryozoans, brachiopod debris, echinoid spines

1-20. Argillaceous carbonate mudstone

Lenticular at outcrop scale - both top and bottom contacts gradational

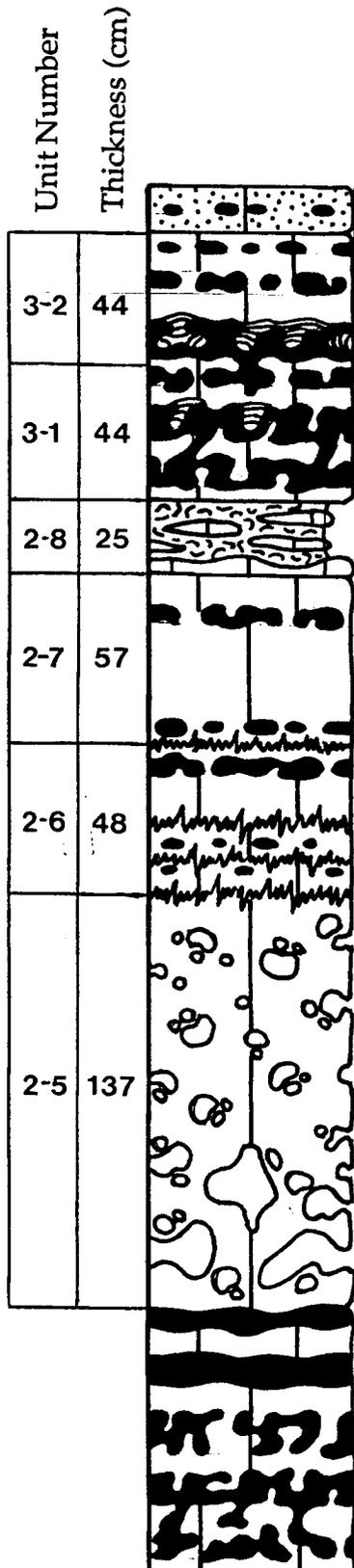
Fine skeletal debris

1-19. Packstone to wackestone (light gray N7 to yellowish gray)

Lag at base with rounded intraclasts (~3cm long, 1.5cm thick) surrounded by ostracode & pyramidellid gastropod packstone

Skeletal debris above include: brachiopods (?Reticulatia, Derbyia, chonetids), echinoid spines - fines upward.

- 2-4. Skeletal wackestone (pale yellowish brown 10YR7/2)
Recrystallized, sugary texture and very slightly dolomitic
Chert beds: 5-21cm very irregular discontinuous bed; 28-38cm undulatory continuous bed; 47-53cm undulatory bed, continuous.
No connecting galleries between chert beds.
Evaporite (gypsum rosettes) molds below upper chert bed.
Clusters of rosettes ~3cm diam and linear series of lath shaped molds (2-5mm wide) up to 15cm long.
Interval becomes less fossiliferous and skeletal debris becomes finer toward top: fenestrate bryozoans, echinoid spines, scattered fusulinids in lower part, large productids (Reticulatia) at base and within uppermost chert bed.
- 2-3. Skeletal wackestone
Chert beds: 4-11cm irregular discontinuous bed; 14-17cm small irregular nodules, part of connecting networks; 20-33cm highly irregular continuous bed w/ vertical galleries extending downward. Dark gray probably spiculitic centers to chert nodules. Few, if any, upward connecting galleries at top.
Top surface forms eroded platform.
Fossils: fenestrate bryozoans dominate, echinoid spines, ramose bryozoans, fusulinids near top. Fossil debris less fragmented toward top
- 2-2. Skeletal wackestone
Chert beds: 4-7cm very irregular discontinuous bed, connects to horiz below and possibly to overlying bed; 12-17cm irregular discontinuous bed connected by galleries to overlying bed; 24-35cm irregular continuous bed. Very few upward connections of silicified burrow network into overlying unit. Diameter of silicified burrows of top horizon ~3-8cm w/ lattice-like network on horizontal surface.
Fossils: fenestrate bryozoans abundant (some relatively unfragmented), ramose bryozoans (up to 6mm diam), echinoid spines.



3-2. Skeletal wackestone

Chert beds: 0-10/15cm highly irregular continuous bed w/ connecting galleries to bed below, romanenichite developed on upper surface of chert and has botryoidal morphology with zebraic cross-section; 25-30cm discontinuous bed w/ irregular to ellipsoidal nodules; 38-42cm scattered ellipsoidal nodules. Bryozoan debris and spicules within chert.

Fossils: large Derbyia and ?Linoproductus at top of lower chert bed, fenestrate and ramose bryozoans, echinoid spines, crinoid ossicles, Aviculopinna in life position at top.

3-1. Skeletal wackestone

Chert beds: 4-32cm two irregular continuous beds connected by numerous galleries, some zebraic romanenichite present in upper bed; 38-44cm irregular discontinuous bed at top. Dark cores of chert nodules show some spiculitic debris, but not as abundant as in cherts that are lower in Florence.

Fossils: fenestrate bryozoans (some unfragmented), ramose bryozoans, Derbyia, crinoid ossicles, Aviculopinna in life position, scattered articulated productids near top.

2-8. Argillaceous clayey wackestone

Lower ~6cm w/ crinoid ossicles, bryozoans, brachiopod debris. Upper part skeletal hash with small carbonate lenses: crinoid ossicles, fenestrate & ramose bryos, Derbyia, Reticulatia, ostracodes

2-7. Skeletal wackestone (very pale orange 10YR9/2)

Chert beds: 2-8cm discontinuous bed, ellipsoidal nodules (5-13cm max. dimension), 42-48cm somewhat irregular and nearly continuous, dense Thalassinoides network.

Sparsely fossiliferous interval.

2-6. Skeletal wackestone

Styliolitic contact ~12cm from base w/ few isolated chert nodules just below; styliolitic contact at ~23cm not as well developed, chert nodules up to 8cm diam in middle of interval; nearly continuous 4-8cm thick chert bed at top capped by styliolitic surface. Limonite staining on styliolite surfaces.

Partly silicified gypsum rosettes near styliolites

Fossils: very fine unident. debris, Neospirifer, Derbyia, fenestrate & ramose bryozoans.

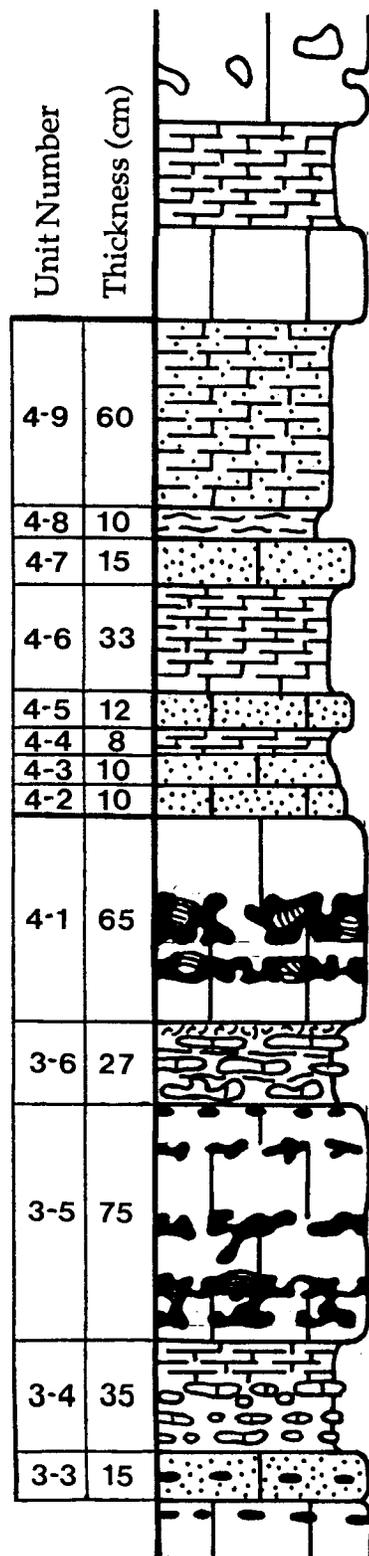
2-5. Vuggy skeletal wackestone (very pale orange 10YR9/2)

Recrystallized, sugary texture - slightly dolomitic.

Solution voids decrease in size and abundance upward w/ connected solution channels in lower ~60cm forming cavernous porosity. Many molds of gypsum rosettes (2-4cm diam) and small lath-shaped molds (1-2cm long).

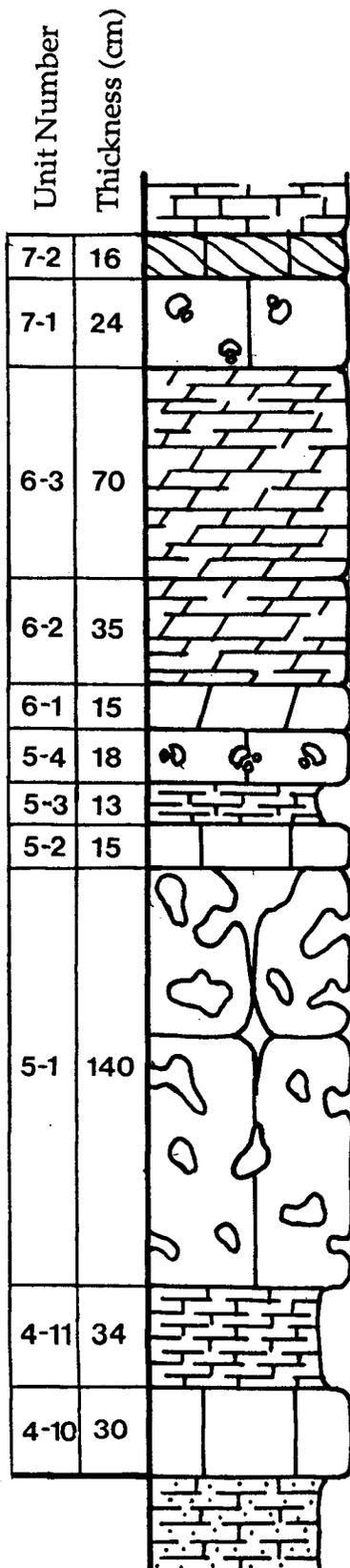
Fossils: fenestrate bryozoan fragments abundant, echinoid spines common, brachiopod shell debris and a few large articulated specimens

Upper contact styliolitic



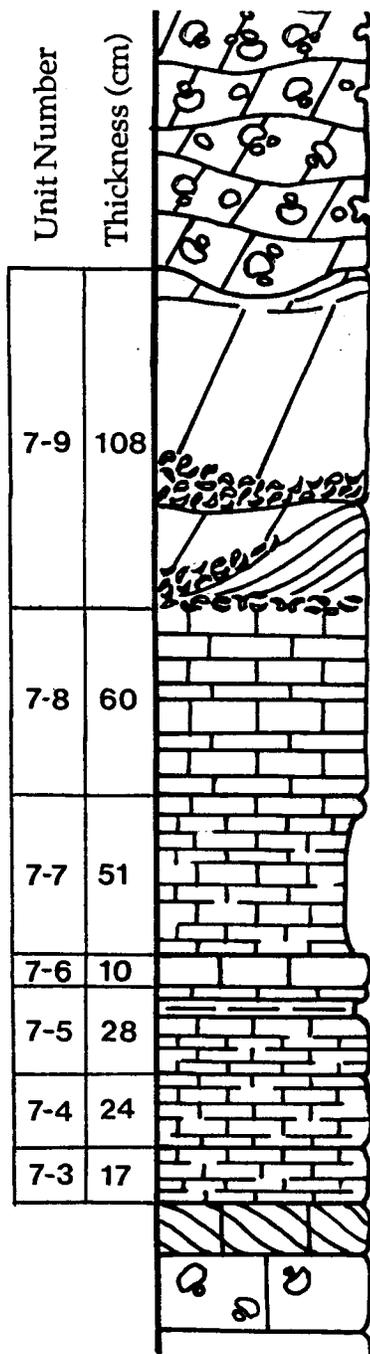
- 3-6. Muddy nodular carbonate (matrix 2.5Y8/3 pale yellow)
 Nodule beds: 0-6cm irregular discontinuous bed, chert cores and dolomitic rinds; 12-14cm thin, nearly continuous bed; 18-21cm nearly continuous bed. Nodules dolomitic and silicified, porous and punky (10YR9/2).
 Matrix between nodule beds: ramose & fenestrate bryozoans, Derbyia, large articulated Reticulatia at top of upper chert bed w/ Meekella, and in fossil layer ~8cm from base.
 Upper 6cm fossil hash approaching packstone: fenestrate & ramose bryozoans, crinoid ossicles, echinoid spines, articulated productids (Reticulatia), Derbyia, Composita, Meekella. Skeletal-filled Thalassinoides burrows at base of fossil hash. Rhizocorallium burrows on top surface - up to 8cm across w/ 2cm wide marginal burrows, 15cm long.
- 3-5. Argillaceous skeletal wackestone
 (Pale yellowish brown 10YR7/2)
 Chert beds: 4-8cm irregular discontinuous bed; 16-20cm irregular continuous bed (medium light gray N6 with thin light rims), lower two beds connected by galleries, upper bed has a few, irregular masses of romanenichite on top and bottom, silicified Linoproductus & Reticulatia common on upper surface of upper chert bed, Composita and ?Meekella also present; 34-40cm irregular discontinuous bed with prods extending downward but no clear connections, no gray cores in nodules, punky porous chert (10YR9/2); 58-64 scattered irregular nodules (medium light gray N6 cores); 73-75cm isolated nodules.
 Fossils: fenestrate & ramose (1cm diam) bryozoans, crinoid ossicles, echinoid debris (esp abundant on upper surface), scattered articulated Derbyia, Linoproductus, ?Iuresania. Skeletal debris abundant at top and bottom of interval.
- 3-4. Silty argillaceous wackestone and nodular carbonate
 Matrix slightly dolomitic, shaley, light yellowish gray (2.5Y7/2). Irregular nodules (5cm diam.) dolomitic and slightly silicified, very pale orange (10YR9/2). Part of discontinuous burrow network.
 Wackestone-nodule couplets: 7cm thick, 5cm thick, 10cm thick
 Fossils associated with nodular layers: scattered Linoproductus, Composita, ?Wilkingia, bryozoan and brach hash within burrows and in patches.
 Upper 13cm abundant skeletal hash in silty shaley carbonate: Brachiopod fragments, fenestrate & ramose bryozoans, a few crinoid ossicles and echinoid spines, Derbyia, small burrows (3-4mm diam). Scattered dolomitic burrows (5cm diam) up to 18cm long in lower half.
- 3-3. Silty wackestone
 Slightly dolomitic
 Bed of isolated flattened elliptical nodules 7-9cm from base.
 Nodules dolomitic and silicified, form discontinuous burrow network.
 Layer of abundant silicified and articulated brachiopods at top: Linoproductus, Composita, Reticularia, Derbyia, Meekella.
 Within unit: ?Wilkingia common, a few fenestrate bryozoan fragments and encrusting bryozoans.

- 4-9. Silty calcitic wackestone
 Medium light gray (N6), weathers (2.5Y7/2)
 More calcitic than below, but still a pseudo-shale w/ irregular interbeds of more pure limestone
 More fossiliferous toward top: Aviculopinna (some in vertical position), large Derbyia, Reticulatia, crinoid ossicles, fenestrate and ramose bryozoans. Thalassinoides-like burrows (3.5-4cm diam), burrow fillings contain pyramidellid gastropods, crinoids, brachiopod fragments.
 Sharp upper contact with Fort Riley Limestone Mbr.
- 4-8. Shaley calcitic clay mudstone (light yellowish gray 2.5Y7/2)
 Fossiliferous: Aviculopinna, Reticulatia, crinoid ossicles.
 Fossil diversity and abundance increases upward.
- 4-7. Very fine silty wackestone
 Massive w/ irregular fracture. Mottled white (2.5Y8/1) to pale yellow (2.5Y7/4).
 Slightly fossiliferous: crinoid ossicles, echinoid plates, ramose bryozoans, thin-shelled brachiopod fragments (?Derbyia, ?Meekella) occurring in 3cm layer about 8cm from top.
- 4-6. Clayey calcitic carbonate mudstone
 Light yellowish gray (2.5Y7/2)
 Non-fossiliferous, locally more calcitic
 Weathers to shale-like slope w/ horizontal partings and vertical fractures
- 4-5. Silty calcitic wackestone (light yellowish gray 2.5Y7.5/2)
 Finely sucrose texture
 Sparsely fossiliferous w/ crinoid ossicles. Brachiopod fragments and crinoids on upper surface.
- 4-4. Clayey calcitic carbonate mudstone
 Med light gray (N6), weathers light yellowish gray (2.5Y7.5/2)
 Weathers to thin plates (2-4mm thick), shale-like slope
 Non-fossiliferous - Grades laterally into more calcitic siltstone
- 4-3. Silty calcitic carbonate mudstone (2.5Y7.5/2)
 Slightly laminated, massive, poorly fossiliferous (small Composita). Slightly dolomitic.
- 4-2. Silty calcitic wackestone (light yellowish gray 2.5Y7.5/2)
 Sparsely fossiliferous: crinoid columnals, partly silicified thin-shelled brachiopods (?Derbyia)
 Platy, irregular limonite stains in upper part.
 Sharp irregular contact with underlying Florence Ls Mbr.
- 4-1. Skeletal wackestone (very pale orange 10YR7/2)
 Chert beds: 15-21cm irregular continuous bed w/ zebrachite romanenichite filling depressions and cavities (N4-N6), chert (N7-N8) w/ thin light rind; 25-40cm very irregular complex bed, discontinuous w/ a few occurrences of zebrachite romanenichite filling cavities. Some bryozoan and brachiopod debris within chert.
 Higher concentration of fossil debris in upper several cms: crinoid ossicles, echinoid spines, fenestrate & ramose bryozoans, Derbyia, Composita, Straparolus, Rhizocorallium burrows at top.



- 6-2. Dolomitic carbonate mudstone
Light gray (10YR7/1), weathers mottled light gray (10YR7/3) to pale brown (10YR6/3).
More dolomitic than bed below, thin bedded, non-fossiliferous
- 6-1. Calcitic dolomitic carbonate mudstone
Very light brownish gray (10YR7.5/1.5), weathers light gray (10YR7/2).
Microgranular, non-fossiliferous.
- 5-4. Calcitic wackestone
Very light brownish gray 10YR7/2 to very pale brown (10YR8/3), weathers to pale yellow (2.5Y8/3).
Contains very small skeletal debris: crinoid ossicles (2mm diam), echinoid spines, thin-shelled brachs (?*Derbyia*), possible *Meekella*, *Aviculopinna* in life position at top.
Nearly hollow, poorly developed geodes that probably were gypsum rosettes, now with thin rinds of calcite and quartz.
Some gypsum rosette molds within burrows.
Becomes somewhat platy near top.
- 5-3. Clayey calcitic wackestone
Weathers to form shale-like break.
- 5-2. Calcitic wackestone
Very light brownish gray (10YR7/2), weathers (10YR6/2).
Very finely crystalline, pin point vugs.
Abundant echinoid spines and plates, some thin-shelled brachiopod fragments, burrowed.
Much less porous than unit below with no large solution channels. Prominent vertical joints oriented N70°E
- 5-1. Silty calcitic dolomitic wackestone
Pale grayish brown (10YR8/2) with vugs up to 3cm lined with yellowish brown (10YR5/6) limonite.
Massive ridge former - "rimrock" of Fort Riley Limestone.
Well-developed karst - some solution channels developed from base upward and some from top downward largely by groundwater solution. Well-developed east trending joints have been greatly widened by solution. Many solution channels filled with loess.
Very porous, finely crystalline
Skeletal debris: crinoid columnals, thin-shelled brachiopods (?*Derbyia*). Highly disturbed, randomly oriented skeletal debris suggests bioturbation - probable horizontal burrows represented by channels up to 4-5cm diam.
Unit weathers into two beds with vague boundary about 85cm from base.
- 4-11. Platy clayey wackestone (color as below)
Shale-like outcrop, sharp upper contact with Fort Riley rimrock
Highly bioturbated: upper surface has large interpenetrating *Rhizocorallium* burrows (10cm across, marginal burrows up to 3cm diam). Skeletal debris similar to unit below.
- 4-10. Finely crystalline wackestone
(2.5Y7/2, weathers very pale brown 10YR7/4).
Massive, ledge former
Abundant skeletal debris: crinoid columnals, echinoid spines & plates, *Composita*, large *Derbyia*, *Reticulatia*, fenestrate & ramose bryozoans. A few burrow fillings.

- 7-2. Slightly dolomitic calcitic carbonate mudstone (10YR7/2)
Cross bedded (S70°W), tangential toward base
(dip angle up to 25°)
Scattered horizontal to inclined burrows
- 7-1. Slightly dolomitic calcitic carbonate mudstone (10YR7/2)
Finely crystalline, non-fossiliferous
Scattered burrows up to 2cm diam, contain abundant lath-shaped
molds (evaporitic?), burrow fills calcitic and light gray
(10YR7/1).
- 6-3. Dolomitic carbonate mudstone
Light gray (10YR7/1), weathers to mottled light gray (10YR7/3)
to pale brown (10YR6/3).
Very finely crystalline - a few pin head vugs that could have
been halite inclusions.
Poorly-developed very thin bedding. Non-fossiliferous.



- 7-8. Clean calcitic carbonate mudstone (very light gray 10YR8/1)
 Horizontal bedding ~5-12cm thick w/ weak internal lamination
 Pinpoint and tiny lath-shaped vugs. Top ~3cm very abundant small vugs giving spongy appearance.
 Small (2mm diam) burrows up to 3cm long - horizontal to slightly inclined
 Skeletal lag ~8cm from top - Permorphus, Aviculopecten common to abundant, burrows up to 6mm diam and 6cm long.
- 7-7. Argillaceous carbonate mudstone
 Medium light gray (10YR6/1), weathers (10YR7/2).
 Thin bedded to platy, weakly laminated and finely crystalline.
 Several bivalve pavements/lags subdivide interval: lower 14cm, Permorphus, Aviculopecten pavement at top; 7cm, Permorphus pavement at top with many articulated and splayed valves, possible mudfilled scour 14X7cm (2.5cm thick); 9cm, two Permorphus pavements in upper 2cm; 14cm, skeletal lag 1-2cm thick ~1cm from top, Permorphus, pectinids, unidentified gastropods (bellerophontids?), possible Rhizocorallium burrow.
 Top 7cm massive layer with skeletal lag up to 2cm thick at top.
- 7-6. Slightly dolomitic calcitic carbonate mudstone
 Light gray (10YR7/1)
 Massive unit, tiny lath-shaped voids
 Bivalve lag at 2-5cm from base, and at top (~1cm thick): Permorphus, scattered pectinids (Aviculopecten).
- 7-5. Slightly dolomitic calcitic carbonate mudstone (N6-N7)
 Horizontally thin-bedded, tiny lath-shaped voids
 Lower 18cm: bivalve lag at base (up to 2cm thick) and 3-4 closely-spaced lags in top ~4cm (Permorphus, some pectinids, Septimyalina; horizontal surfaces coated w/ manganese oxide; polygonal fracture pattern at top, 50-70cm diam polygons.
 Shaley interval 7cm: unfossiliferous
 Hard cap bed at top 3-4cm thick: bivalve skeletal lag at top up to 3cm thick, Permorphus, pectinids.
- 7-4. Slightly dolomitic calcitic carbonate mudstone
 Pale yellow (2.5Y8/3)
 Horizontally thin-bedded
 Tiny (1mm) iron oxide lined vugs, a few scattered ~1cm diam vugs cross-cut bedding (gypsum rosettes?)
 Discontinuous bivalve skeletal lag ~16cm from base (lenticular, up to 4cm thick, pods ~36cm long), some fine vertical to inclined burrows ~2mm diam and 2.5cm long, well-defined burrowed surface at top.
- 7-3. Slightly dolomitic calcitic carbonate mudstone
 Lower ~5cm shaly, clayey calcitic mudstone.
 Upper ~12cm medium crystalline (10YR7/2 to 10YR6/1), weakly horizontally bedded, scattered crinoid ossicles.

7-9. Calcitic carbonate mudstone (pale yellow 2.5Y8/3)

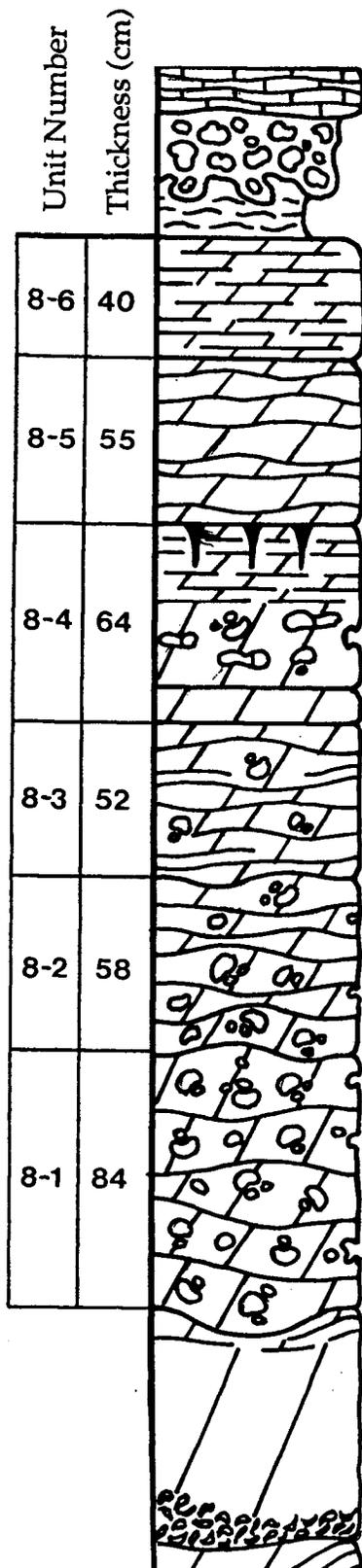
Vuggy: tiny iron oxide-lined vugs and large voids up to 6cm diam (gypsum rosette molds)

Lower ~33cm consists of overlapping large lenticular beds. 33cm thick unit at base pinches out toward N40°W over ~9m lateral distance. Locally 16cm thick cross-bed set evident (dip up to 33° approx N60°W), cross beds become asymptotic at base.

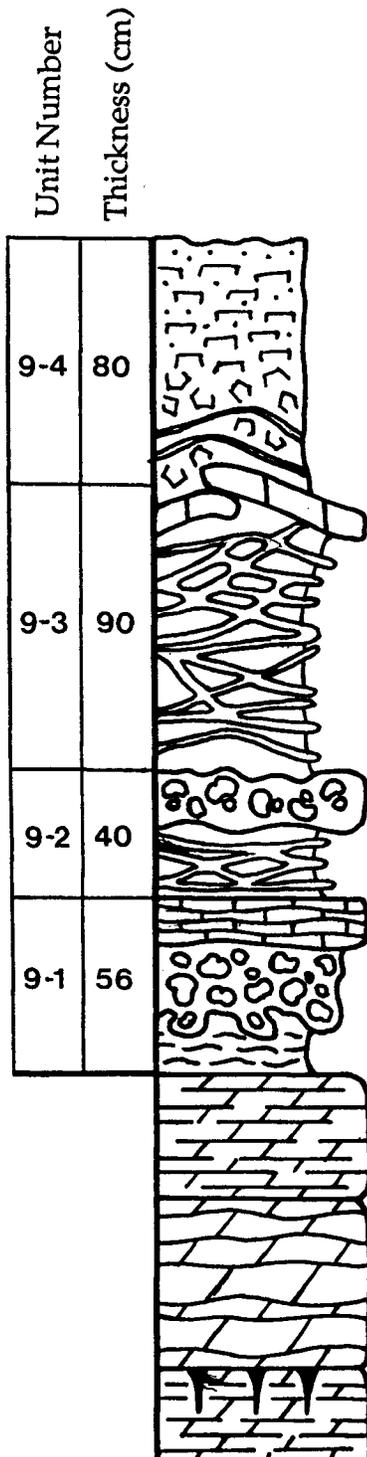
Overlying unit to NW thickens toward the N40°W up to 33cm thick. Lower 1/3 to 2/3 of this unit porous and highly vuggy (bivalve coquina) with dolomitic cap above. A few large (5-6cm diam) horizontal to slightly inclined burrows in this lower part.

Middle 60cm thick interval - Lower part (up to 20cm) porous and highly vuggy (bivalve coquina including nuculids), and upper part dolomitic.

Upper 15cm dolomitic and porous, locally platy. Pinches and swells with undulatory upper surface, "wavelengths" of about 5 meters.



- 8-6. Laminated dolostone (white 2.5Y9/2)
 Horizontally laminated
 Scattered calcite spar-lined vugs ~1-3cm diam - abundant locally in lower 26cm.
 Two distinct beds 11cm and 23cm thick
- 8-5. Calcitic dolomitic carbonate mudstone
 Significantly more calcitic than unit below - result of sparry calcite vug fillings.
 Wavy horizontal bedding 2-5cm thick w/ irregular botryoidal surfaces.
 Very porous with very abundant tiny lath or ellipsoidal-shaped vugs giving spongy appearance under magnification.
- 8-4. Slightly calcitic dolomitic carbonate mudstone
 Pale yellow (2.5Y8/2)
 Lower ~12cm more dense w/ fewer voids
 Middle part highly vuggy, abundant gypsum rosette molds. Lighter and somewhat denser patches with burrow-like morphology.
 Upper ~24cm horizontally bedded and laminated, fine-grained with few voids. Polygonal fracture system (desiccation cracks) at top. Polygons 30-50cm diam in one area and 10-20cm diam in another. Cracks may extend ~10cm or more downward, with calcitic crack fillings up to 4cm wide at top.
- 8-3. Slightly calcitic dolomitic carbonate mudstone (10YR8/2)
 Undulatory beds 2-3cm thick
 Porous - some voids secondarily filled with coarsely crystalline calcite, gypsum molds not as abundant as below.
 Calcite nodules with concretionary appearance, 1-3cm diam spheroidal nodules w/ internal voids, some occur in aggregates. Finely crystalline haloes around some gypsum voids.
 Patches with radial or cross hatched patterns of linear voids ~5-6cm diam.
- 8-2. Slightly calcitic dolomitic carbonate mudstone (10YR8/2)
 Porous: pin point vugs, abundant gypsum rosette molds up to 4cm diam. (esp. in lower part)
 Undulatory beds ~10-20cm thick, locally ~2cm thick beds evident. Vague relict disrupted laminae, possible cross lamination.
- 8-1. Slightly calcitic dolomitic carbonate mudstone
 Very pale orange (10YR8/2)
 Interval ranges from 66-84cm thick: beds ~18-25cm thick and broadly undulatory (dip ~5° at N65°E and ~2° at S50°W), bedding surfaces wavy with locally "shaly" breaks.
 Finely crystalline, vague relict disrupted laminae.
 Porous: pin point vugs, gypsum rosette molds up to 3cm common.
 Unfossiliferous, possible fine burrows (<1mm diam).



9-4. Variegated mudstone

Lower ~30cm light olive gray (5Y7/1) at base to light brownish gray (10YR6/1) upward. Medium angular blocky peds, abundant spar-filled fractures.

Upper part is light brown (7.5YR6/3).

Silty, platy, diffuse gray mottles.

Top is modern disturbed vegetated surface.

9-3. Calcareous mudstone (white 5Y8/1)

Lower ~70cm (+ or - 10cm) calcareous mudstone w/ abundant calcite spar-filled horizontal, inclined and vertical fractures. Well-developed boxwork structure.

Massive undulatory cap of calcitic dolomitic carbonate mudstone ~10 thick. Some spar-filled curved fractures extend through cap. Tepee structures.

9-2. Mudstone and carbonate mudstone

Lower 20-25cm mudstone, pale yellow (5Y8/2).

Abundant wavy calcite spar plates, inclined and horizontal forming boxwork structure.

Upper part calcitic carbonate mudstone, light gray (10YR7/1).

Abundant spar-lined gypsum molds up to 20cm diam, locally giving honeycomb appearance. Iron oxide staining of vugs.

Very irregular upper surface

9-1. Mudstone and carbonate mudstone

Lower ~14cm slightly calcitic mudstone (olive gray 5Y5/2).

Manganese oxide coatings on some fracture surfaces.

Upper ~7cm more calcitic, chalky texture (light yellowish gray 5Y9/1)

Middle ~27cm solution zone w/ sparry calcite lining gypsum solution cavities. Cavities abundant and up to 7cm or more in diam., interval becomes honeycomb network of crystalline calcite. Medium crystalline, sucrosic (light olive gray 5Y6/1).

Upper ~15cm calcitic carbonate mudstone (very pale yellow 2.5Y9/2). Wavy, irregular laminations (algal?)

GENERAL DESCRIPTION OF STRATIGRAPHIC SECTION AND ENVIRONMENTAL INTERPRETATIONS

Matfield Shale Blue Springs Shale Member

Only the upper 4.6 meters of the Blue Springs Shale is exposed in the face of the waterfall at the east end of the spillway. Close examination of the red and green mudstones and siltstones and greenish-gray carbonate mudstones reveals several stacked paleosol profiles. Recognized pedogenic features include blocky peds, curved fracture surfaces and wedge-shaped peds, gleyed and limonite root traces, manganese dendrites and coatings, and carbonate nodules. The lower reddish brown paleosols profiles coarsen upward and commonly become massive siltstones that exhibit abundant drab haloed root traces. The uppermost profile is separated from the reddish silty profiles below by bedded carbonate mudstone. It is primarily olive gray and contains curved fracture surfaces and wedge-shaped peds.

The rooted reddish brown siltstones weather spheroidally and bear a striking resemblance to the loessites described by Johnson (1989) from the contemporary Eagle Basin of Colorado. Paleosol profiles with similar siltstone caps can also be seen in the lower Roca Shale (Miller, 1994) and in the lower Blue Rapids Shale at some localities (McCahon & Miller, 1993). These silts may have been derived from the extensive eolian dunefields to the west (Loope, 1985; Peterson, 1988; Johnson, 1989; Soreghan, 1992). Wind directions determined from both eolian dune crossbeds and paleoclimate models indicate winds from the northwest during the Wolfcampian (Parrish & Peterson, 1988). 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.

The upper olive gray paleosol profile may be equivalent to that of a modern Vertisol. Wedge-shaped peds bounded by curved fractures and pedogenic slickensides are indicative of Vertisols. These features form as a result of the expansion and contraction of clay-rich soils in a seasonal wet/dry climate (Retallack, 1990). The transition from reddish silty paleosols below to clay-rich vertic paleosols above is consistent with the pattern seen in nearly all variegated mudstone intervals of the Wolfcampian in northeastern Kansas (Miller & West, 1993; McCahon & Miller, 1993; Miller, 1994). Within a series of stacked paleosols, reddish profiles with silty or calcic horizons are

typically overlain by greenish profiles with vertic features. This pattern may reflect changes from semi-arid to seasonally wet climates associated with cyclic glacio-eustatic sealevel fluctuations (Miller & West, 1993).

Barneston Limestone Florence Limestone Member

The Florence Limestone Member is the uppermost and thickest chert-bearing unit of the Flint Hills Physiographic Province that extends southward into Oklahoma. The flood waters removed the softer carbonate mudstone leaving the beds of chert exposed in relief on bedding plane surfaces. For the first time the three dimensional geometry of the numerous chert layers within the 10.5 meters of the Florence Limestone Member can be examined over extensive areas in the field. The morphology of the chert nodule layers resembles that of complex burrow systems similar to *Thalassinoides* (Bromley, 1990). Commonly, two or more of the chert layers are joined by vertical and inclined chert masses to form multi-storied networks. The chert seems to occur only in relatively pure fine-grained carbonates. A few silicified rosettes of gypsum occur in some chert bands.

Associated with some of the chert layers in the upper Florence is botryoidal, or mammillary romanenchite, formerly called psilomelane. This mineral is a complex hydrated barium manganese oxide that seems to fill spaces between raised chert masses. The romanenchite forms several thin crusts in silicified rock that developed in the depressions between, and in some places, under the chert. Cross-sections of the intergrowth of romanenchite and microquartz show a "wood-grained" structure that consists of thin black layers within the lighter brownish matrix. Both the chert and romanenchite contain silicified skeletal debris similar to that occurring in the adjacent carbonate mudstone and wackestone. The romanenchite may have an organic origin in which bacteria have oxidized some humic residue. These botryoidal masses also occur in the Threemile Limestone of the lower Wreford Limestone along its outcrop belt.

The bedded and nodular chert formed early and by silica replacement of the bioturbated skeletal carbonate mudstone and wackestone. The silicification of burrows as seen in the Florence Limestone has also been observed within Cretaceous cherts in Europe (Bromley & Ekdale, 1984) and within peloidal sandstones of the Permian San Andres Formation of New Mexico (Sonnenfeld, 1991). The apparent localization of silica replacement within burrow networks in the Florence may have been a result of higher porosity and permeability within the skeletal burrow fills. Silicification began

with the selective replacement of skeletal debris. Crinoid and brachiopod fragments were first to be replaced, followed by phylloid algae, fusulinids, and bryozoans. Replacement of the carbonate mud matrix and of gypsum rosettes completed the process. Silicified gypsum nodules, which also occur in the Threemile Limestone Member of the Wreford Limestone, are characterized by length -slow chalcedony (Folk & Pittman, 1971; Milliken, 1979).

The source of silica still remains unresolved. Monaxial sponge spicules do occur in the dark gray cores of chert nodules in a few layers in the lower Florence, and Jim Chaplin (pers. com., March 1994) of the Oklahoma survey has identified siliceous sponge spicules in the Florence Limestone in the subsurface of Oklahoma. However, it seems questionable whether siliceous sponge spicules alone would have been sufficient to provide the large amount of silica required. No fresh or weathered volcanic ash has been identified.

The Florence Limestone is the most faunally diverse member of the Barneston. Brachiopods, fenestrate, ramose and encrusting bryozoans, crinoid ossicles, echinoid spines and plates, fusulinids, bivalves, gastropods, and ostracodes occur throughout. The density and diversity of skeletal debris seems to increase upward. Burrowing by the *Thalassinoides* producing organism was obviously extensive throughout the interval. The tiering of burrow galleries would suggest episodic rapid sediment aggradation. The trace fossil *Rhizocorallium* occurs at the upper contact and continues into the overlying Oketo shale.

The Florence Limestone Member at the Milford spillway is very similar in lithology and thickness to its occurrence along I-70 about 18km to the east (Twiss & Underwood, 1988). Based on lithology and chert distribution these sections can be correlated at a meter-scale.

Barneston Limestone Oketo Shale Member

The Oketo shale Member is 1.6 meters thick and consists of clayey and silty calcitic carbonate mudstone and wackestone that weathers more like a shale or mudstone. The lower boundary with the Florence Limestone is sharp. The lower half contains only a few crinoid ossicles and thin-shelled brachiopods. The marine fauna becomes more abundant and diverse upward and consists of brachiopods, fenestrate and ramose bryozoans, crinoid ossicles, and *Aviculopinna* (some in life position).

Rhizocorallium is especially abundant on bedding planes in the upper part of the Oketo, and some *Thalassinoides* -like burrow systems occur in a few beds. These two burrow systems are filled with skeletal debris that is coarser than that of the matrix. Skeletal debris-filled burrows occurring within both the Oketo shale and Florence limestone are probably similar in origin to the tubular tempestites described from modern shallow marine environments (Wanless et al., 1988). These formed by the storm infilling of open *Callianassa* burrows, very similar in morphology to *Thalassinoides* burrow systems (Bromley, 1990), with skeletal debris.

The Oketo Shale Member is recognized in northern Kansas but is absent further to the south and into Oklahoma (Toomey, 1992). In northern Oklahoma, the boundary between the Florence limestone and the Fort Riley limestone is recognized by a transition from bryozoan and foram wackestones to coated-grain packstones (Toomey, 1992).

Barneston Limestone Fort Riley Limestone Member

At the Milford spillway, the Fort Riley Limestone is 10.6 meters thick and begins with an open marine limestone and ends with a laminated dolostone. The biologic diversity and abundance decreases upward and the percentage of dolomite and evaporites increase upward (Twiss, 1991). The whole Fort Riley probably represents not only a general shallowing trend but also a climatic trend toward increasingly arid conditions.

The Fort Riley can be subdivided into lower, middle, and upper intervals. The lower interval is a 2.3 meter-thick calcitic wackestone that contains echinoid spines and plates, crinoid ossicles, thin-shelled brachiopods, and *Aviculopinna*. A prominent 1.4 meter thick bioturbated "rimrock" is a key bed that is mappable throughout the region. The base of the "rimrock" is marked by many *Rhizocorallium* burrows. At the upper surface are vertical burrows that have been enhanced by solution.

The middle interval is light gray to pale brown calcitic and dolomitic carbonate mudstone that is 3.7 meters thick. The thin bedded to laminated dolomitic limestone probably records an intertidal environment. Many thin beds contain dense bedding plane accumulations of bivalve molds. These internal molds are in hydrodynamically stable positions and may represent storm lags.

The upper 4.6 meters of the Fort Riley begins with carbonate dune forms locally showing internal cross lamination and having thick bivalve coquinas at their base.

Above is an interval of undulatory and thin-bedded dolomitic mudstone with abundant pin-point vugs and large voids that appear to be molds of gypsum rosettes. Other than some possible burrows the interval is non-fossiliferous. The uppermost part of the Fort Riley consists of thin-bedded to laminated dolostone with a well-developed mudcracked surface near the top. The polygonal crack fillings are vertically laminated suggesting repeated expansion and filling of the cracks. They are very similar in appearance to polygonal cracks described from the Coorong region of South Australia that result from groundwater being forced upward through fractures in indurated dolomitic crusts (Muir, et al., 1980).

Doyle Shale Holmesville Shale Member

Only the lower 2.6 meters of the Holmesville Shale Member occurs in the spillway. The calcareous mudstone contains many calcite-filled polygonal fractures and tepee structures. Boxwork structures are very well displayed and are suggestive of evaporite dissolution. In an Amoco core, some 30 miles to the northeast, the upper Fort Riley contains increasing quantities of gypsum nodules and lenses grading into a two-foot thick bed of gypsum that marks the base of the overlying Holmesville shale (Twiss, 1991). At the Milford spillway, boxwork structures and large geodes mark the position of these gypsum nodules and beds in the subsurface. These evaporites serve as a prelude to the extensive evaporite deposits of the Late Permian rocks of the mid-continent (Archer & West, 1993).

The association of laminated dolomite, desiccation polygons, gypsum nodules, boxwork structures, and tepee structures strongly indicate that the upper Fort Riley limestone and lower Holmesville shale formed in a sabkha environment. As discussed by Warren and Kendall (1985), sabkhas are characterized by shoaling-upward peritidal sequences. These facies successions include flat-laminated algal mats, desiccation polygons, tepee structures, and sulfates occurring as replacive and displacive diagenetic nodules. Tepee structures are a particularly prominent feature of the sabkhas along the present day Trucial Coast of the Persian Gulf (Evamy, 1973) and are common in peritidal carbonates throughout the geologic record (Assereto & Kendall, 1977).

The term "boxwork structure" has been applied to a variety of highly porous carbonates representing probably more than one mode of genesis. Irregular boxwork fabrics formed by "interlocking and interpenetrating filaments and small, curved plates to flat plates of micritic aragonite" are associated with coastal salinas in South Australia

(Warren, 1982). These porous limestones are interpreted by Warren (1982) to be the result of aragonite precipitation from upwelling marine-influenced groundwaters. Boxwork structures have also been described from supratidal flats in Shark Bay, Western Australia (Read, 1974). These structures are constructed of adjoining polygons of vertical aragonite plates that enclose soft sediment, and are interpreted by Read (1974) as forming by precipitation of carbonate along fractures. In the above examples, the boxworks were associated with either cemented veneers and tepee structures (Warren, 1982), or crust pavements and intraclast breccias (Read, 1974).

Pleistocene deposits

Light, yellowish brown silt filled the irregular karst topographic surface of the Permian rocks. Loess-filled sinkholes and solution channels are common. Some loess has even penetrated some of the burrow cavities and evaporite solution voids within the carbonates. Near the waterfall in the east end of the spillway the loess has covered a pre-Pleistocene hill of Florence Limestone. The waterfall is probably the original valley wall of the Republican River before the loess filled the old valley.

CYCLE PATTERNS AND CLIMATE CHANGE

While most studies Lower Permian of Kansas have focused on the generation and correlation of cycles at the cyclothem-scale (Elias, 1937; Hattin, 1957; Lane, 1958; McCrone, 1963; Imbrie et al., 1964), smaller-scale cyclic patterns are also prominent features of mid-continent stratigraphy. Meter-scale cycles are readily recognized within the cyclothem of the Lower Permian (Miller & West, 1993; Miller, 1994). 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 (see references in Miller & West, 1993). Correlation of such higher-order cycles provides a very fine time-stratigraphic framework for the reconstruction of lateral facies relationships and the evaluation of models of cycle generation and climate change.

Meter-scale shallowing-upward cycles within the stratigraphic interval exposed in the Milford Lake spillway are typically represented by carbonate-to-clastic alternations (Fig. 3). Within the upper Blue Springs shale, flooding surfaces truncate silty paleosol profiles and are overlain by carbonate mudstones that form the base of overlying paleosol profiles. Alternations between relatively pure fine-grained carbonates and

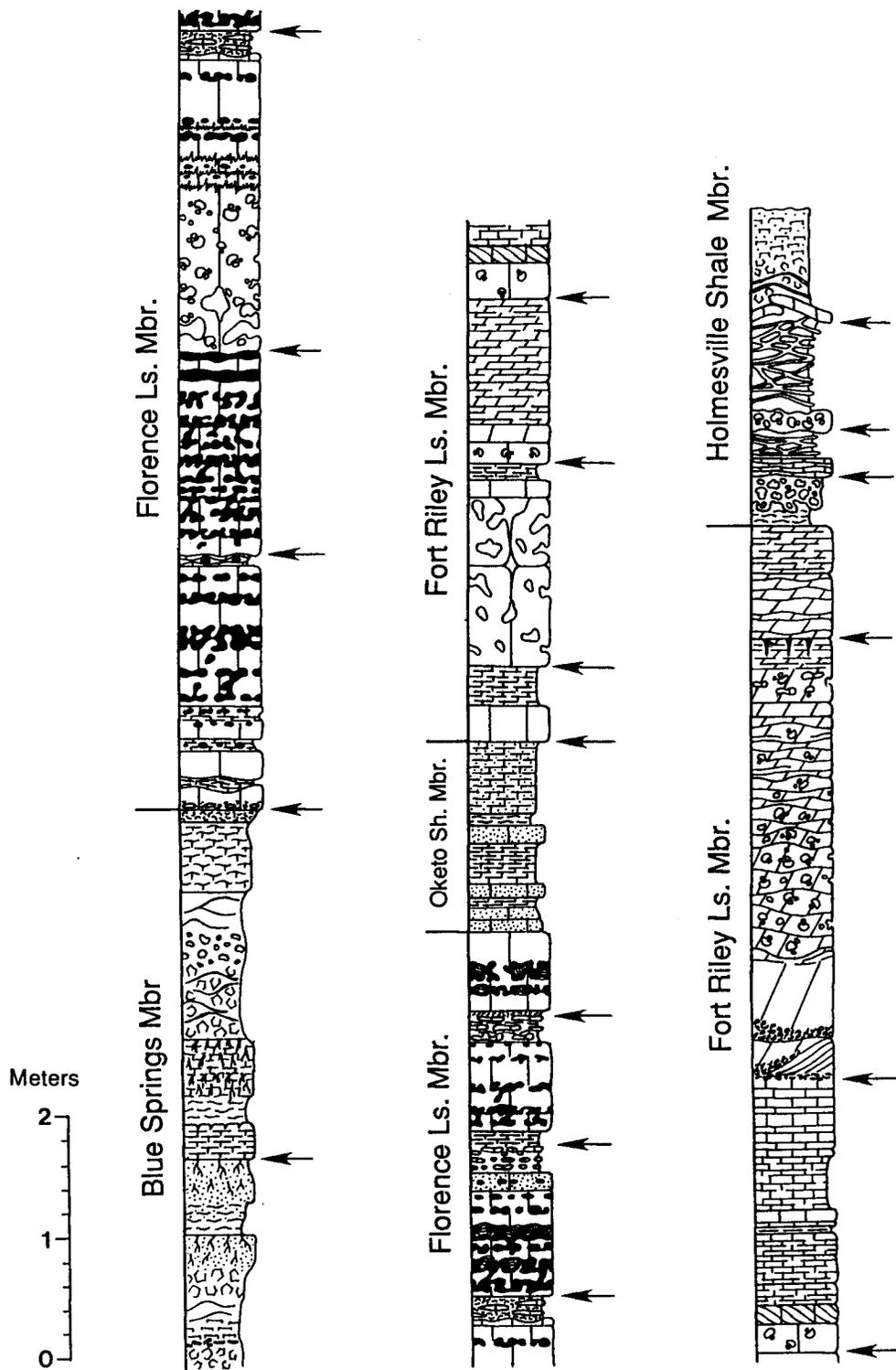


FIGURE 3. Meter-scale cycles of the Milford spillway stratigraphic section. Detailed stratigraphic section for the Blue Springs Member of the Matfield Shale, Florence, Oketo, and Fort Riley Members of the Barneston Limestone, and Holmesville Member of the Doyle Shale. Arrows indicate the position of interpreted flooding surfaces that separate meter-scale cycles. Note the carbonate-to-clastic pattern of many of the meter-scale cycles.

clayey or silty carbonates characterize the meter-scale cyclicity of the cherty Florence limestone. In many cases, the inferred flooding surfaces are associated with skeletal debris layers. These cycles appear similar to those described from cherty facies of the Permian San Andres Formation in New Mexico. There, glauconitic siltstones alternate with cherty peloid-rich sandstones that become increasingly micritic and dolomitic upward (Sonnenfeld, 1991).

Carbonate-to-clastic alternations are not as apparent within the Fort Riley except in the lower part. Within the middle part of the Fort Riley, the interpreted cycles begin with cross-bedded or cross-laminated units that are succeeded by thin-bedded, horizontally laminated or undulatory-bedded dolomitic carbonates. The laminated dolomite of the uppermost cycle rests on a well-developed mudcracked surface. The cycles of the Holmesville are represented by alternations between laminated or gypsiferous carbonates and mudstones.

Much of the stratigraphic interval described here clearly records very shallow marine conditions. Evidence of subaerial exposure is present within both carbonate and mudstone facies. A simple glacio-eustatic model based on an offshore-onshore facies gradient is inadequate to account for the diversity of facies represented. A model for climatic control over facies development has been proposed by Cecil (1990) that, if applied to the Wolfcampian, would interpret the carbonate-to-clastic pattern characteristic of the meter-scale cycles as a record of cyclic climate fluctuations. In this model, clastic sediment transport is predicted to be highest in monsoonal climates and lower in both arid and tropical wet climates. Chemical sediments such as carbonates and evaporites accumulate during arid and semiarid conditions, and siliciclastic units are deposited in response to seasonally wet climates.

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 by Miller and West (1993) for the Wolfcampian of the mid-continent. Recent global circulation models (Parrish & Peterson, 1988; Kutzbach & Gallimore, 1989; 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 cycle model of Miller and West (1993) 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. 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, 1994).

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 cyclothem are not well constrained, varying between 250,000 and 400,000 years. Although probably falling within 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 already described could easily have developed over time periods in excess of 100,000 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 and Wilkinson, 1988). Thus, while estimated cycle periods fall within the Milankovitch band, there is no way at present to identify specific Milankovitch orbital periodicities.

ACKNOWLEDGMENTS

Field work was carried out with the permission of the Corps of Engineers under Kansas City District Paleontological Permit No. *OF-MI-001*. We particularly wish to acknowledge the help and support of Brad Myers and Cynthia Dierks from the Milford Project Office.

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