KANSAS GEOLOGICAL SURVEY
OPEN-FILE REPORT 93-24

INCISED PALEOVALLEYS OF THE DOUGLAS GROUP IN NORTHEASTERN KANSAS: FIELD GUIDE AND RELATED CONTRIBUTIONS

by

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Disclaimer

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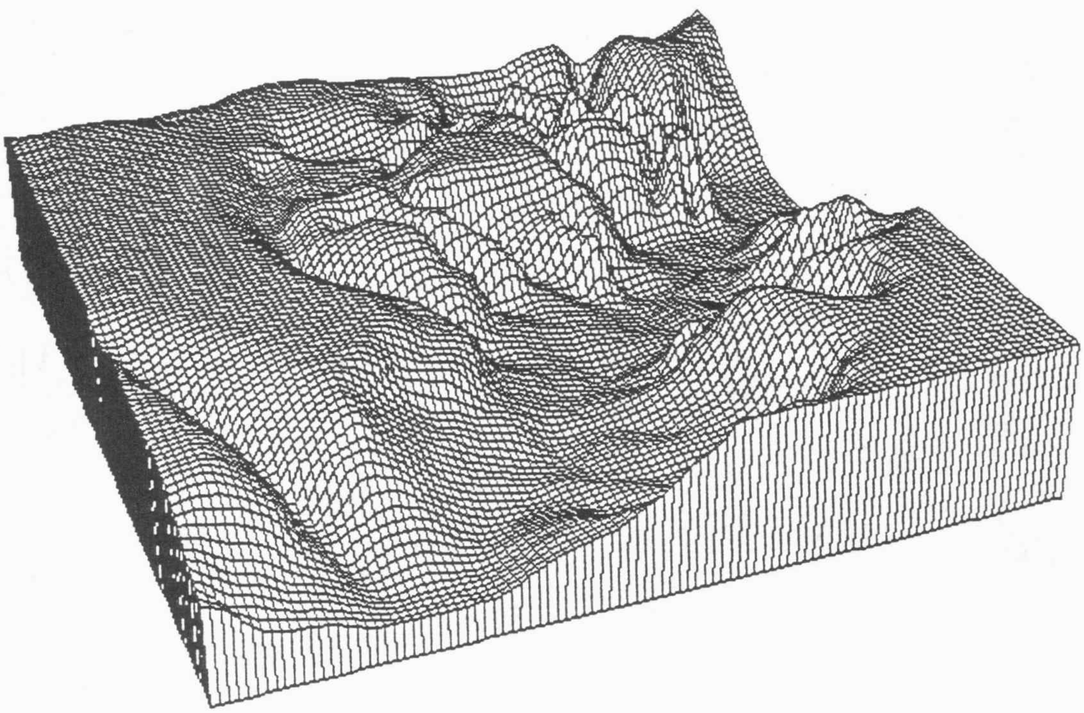
SEPM Midcontinent Section 1993 Fall Field Conference
Co-sponsered by the
Kansas Geological Society,
Department of Geology, Kansas State University
and the Kansas Geological Survey

Incised Paleovalleys of the Douglas Group in northeastern Kansas: Field Guide and Related Contributions



View looking northeast along the Tonganoxie paleovalley from Lawrence (near corner) to Leavenworth (far corner).

Kansas Geological Survey Open-File Report 93-24

Trip leaders and Field Guide Editors:
Allen W. Archer
Howard R. Feldman
William P. Lanier

October 9 and 10, 1993

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OVERVIEW

The trip leaders wish to thank all those who have assisted with the various aspects of this trip. The Department of Geology, Kansas State University, has provided vans for the trip. Tyler Sanders of the Kansas Geological Society was particularly helpful in arranging the various aspects of the co-sponsorship that society. Martin Gibling and Bernadette Tessier provided much assistance in the field recognition of various facies within the Douglas Group.

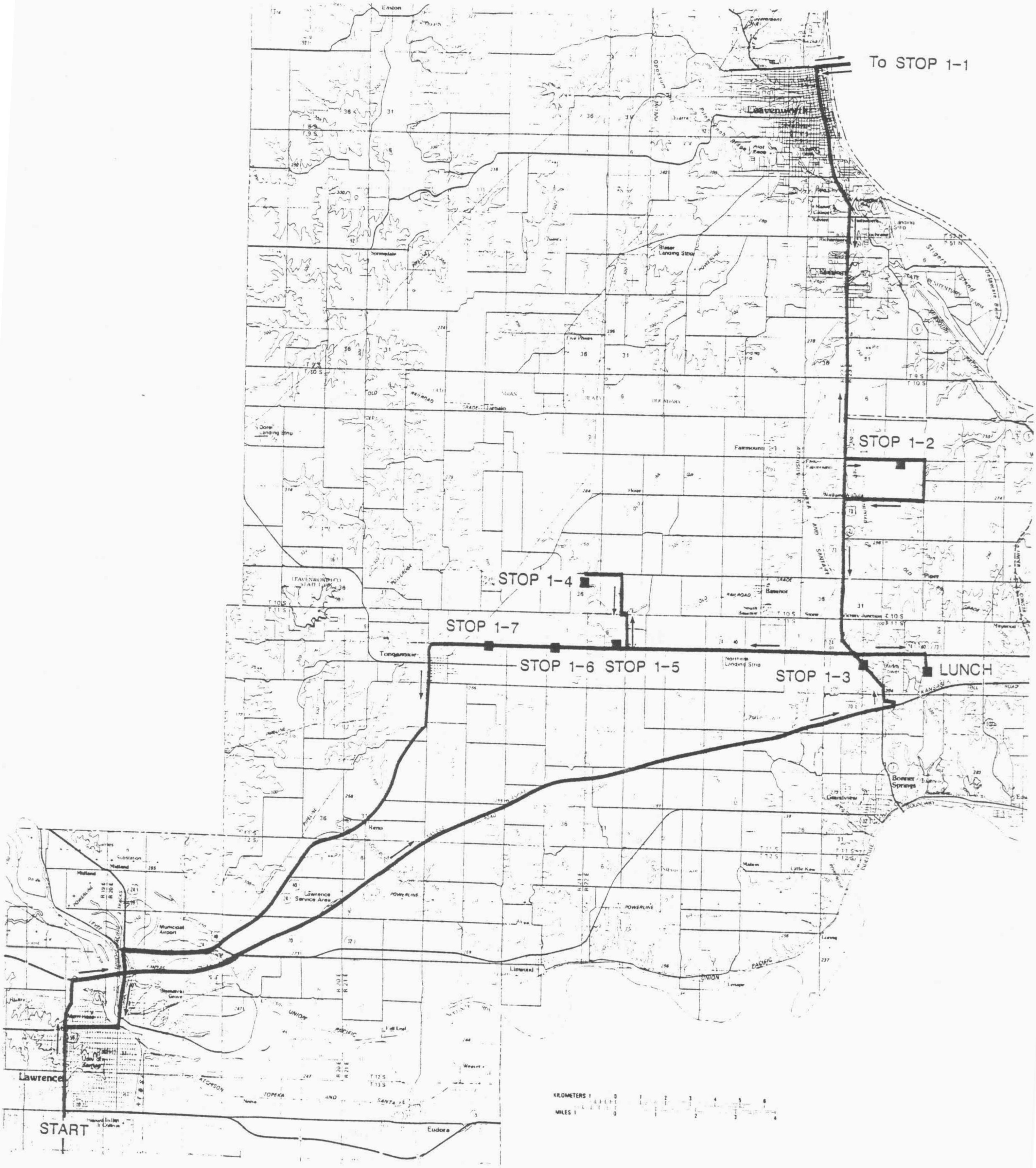
During this field trip we will examine incised valley-fill facies of the Douglas Group Pennsylvanian, Missourian-Virgilian) and will concentrate on exposures of the Tonganoxie Sandstone in the type area of Tonganoxie, Kansas, and tidal-rhythmite facies in members of the Douglas Group. We will observe the transition from coarse-grained braided fluvial facies at the base of the paleovalley to finer-grained fluvial and estuarine facies in the middle, to marine facies capping the sequence.

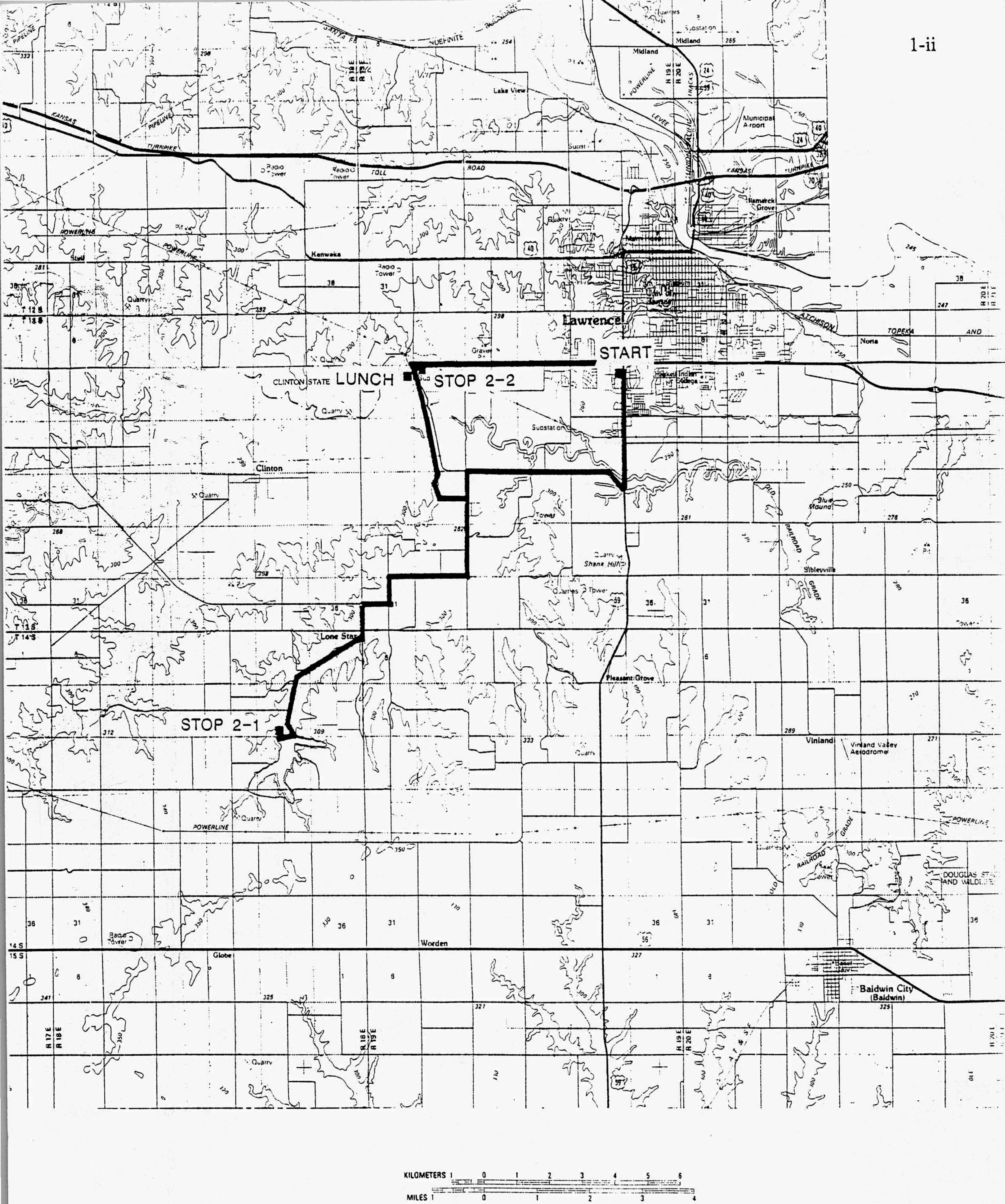
Specific goals of the field trip include: (1) Examining evidence of incisement of the paleovalley from outcrops and well-logs, (2) Recognition of characteristics used to distinguish fluvial and estuarine sandstone, (3) Studying the evidence of tide-dominated deposition, (4) Interpreting the succession in a sequence stratigraphic model, and (5) Discussing the implications of the Douglas Group and overlying and underlying cycles to basin evolution and sea level history.

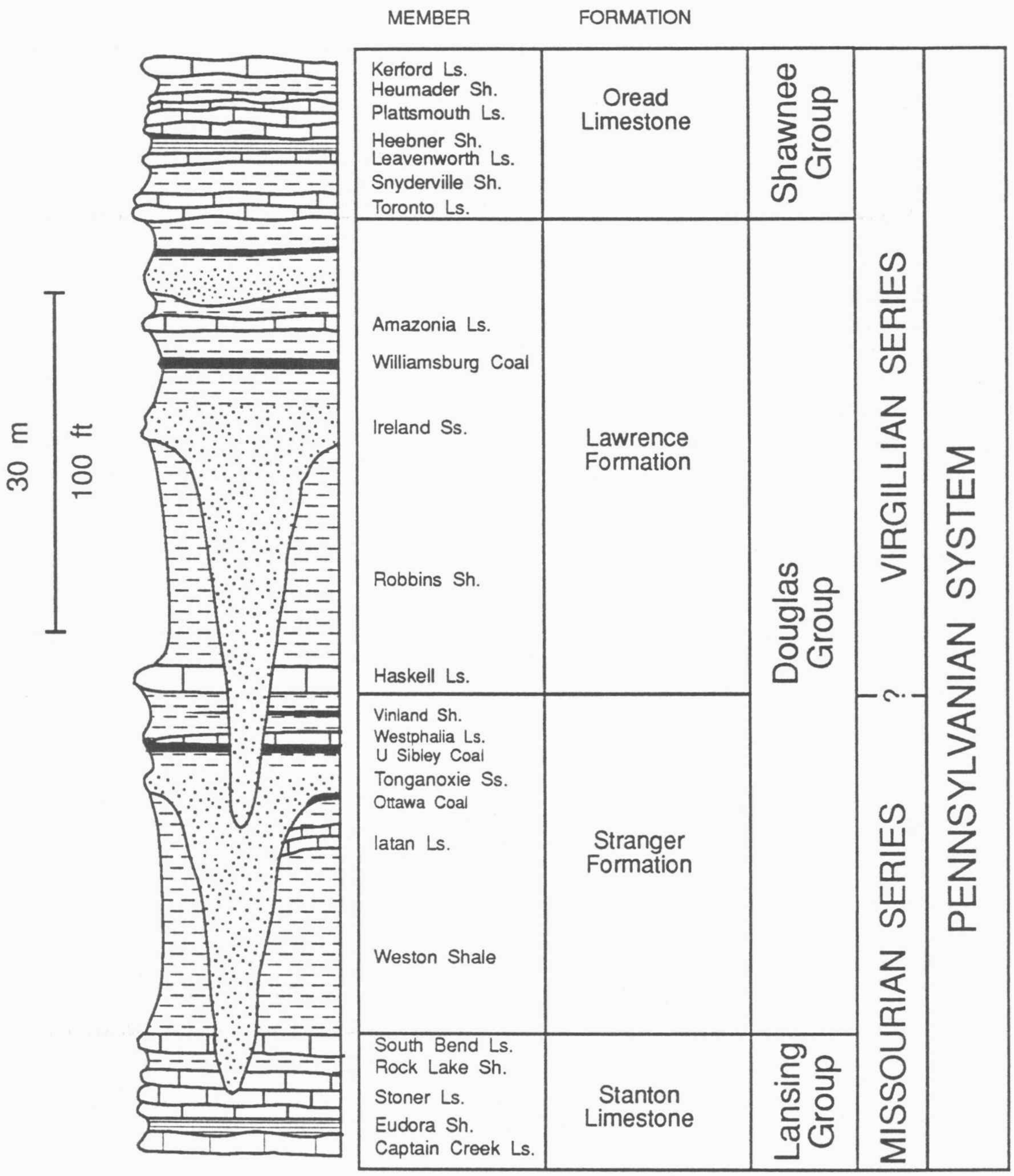
In addition we will examine cores of the Tonganoxie and other Pennsylvanian incised paleovalley sequences in an informal workshop on Saturday evening. During this time discussions will be presented regarding recognition of tidal and estuarine facies within siliciclastic facies of the midcontinent.

Schedule:

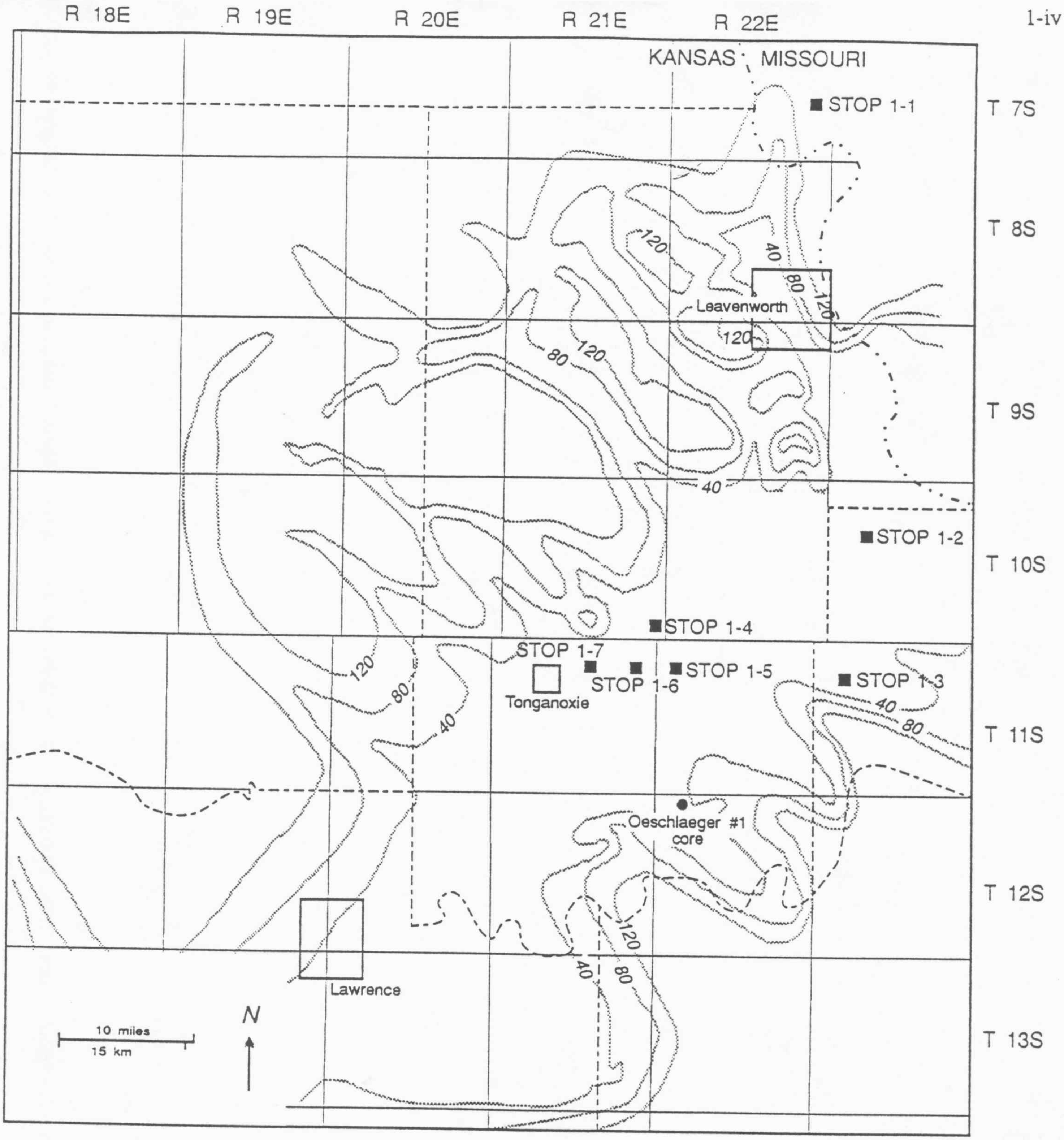
Friday, Oct. 8.	7:30PM.	Orientation session, Kansas Geological Survey.
Saturday, Oct. 9.	8:30AM.	Depart from Day's Inn for field trip.
	5:00PM	Return from field trip.
	6:00PM	Buffet dinner at Day's Inn
	7:00PM	Core workshop and specimen display at Day's Inn.
Sunday, Oct. 10.	8:30AM	Depart from Day's Inn for field trip.
	12:00PM	Return from field trip for those needing to depart for the AAPG Midcontinent meeting. Others may spend the early afternoon examining addition outcrops.


To STOP 1-1
Leavenworth
STOP 1-2
STOP 1-4
STOP 1-7
STOP 1-6
STOP 1-5
STOP 1-3
LUNCH
Tonganoxie
Bonner Springs
Lawrence
START
Eudora
KILOMETERS
MILES

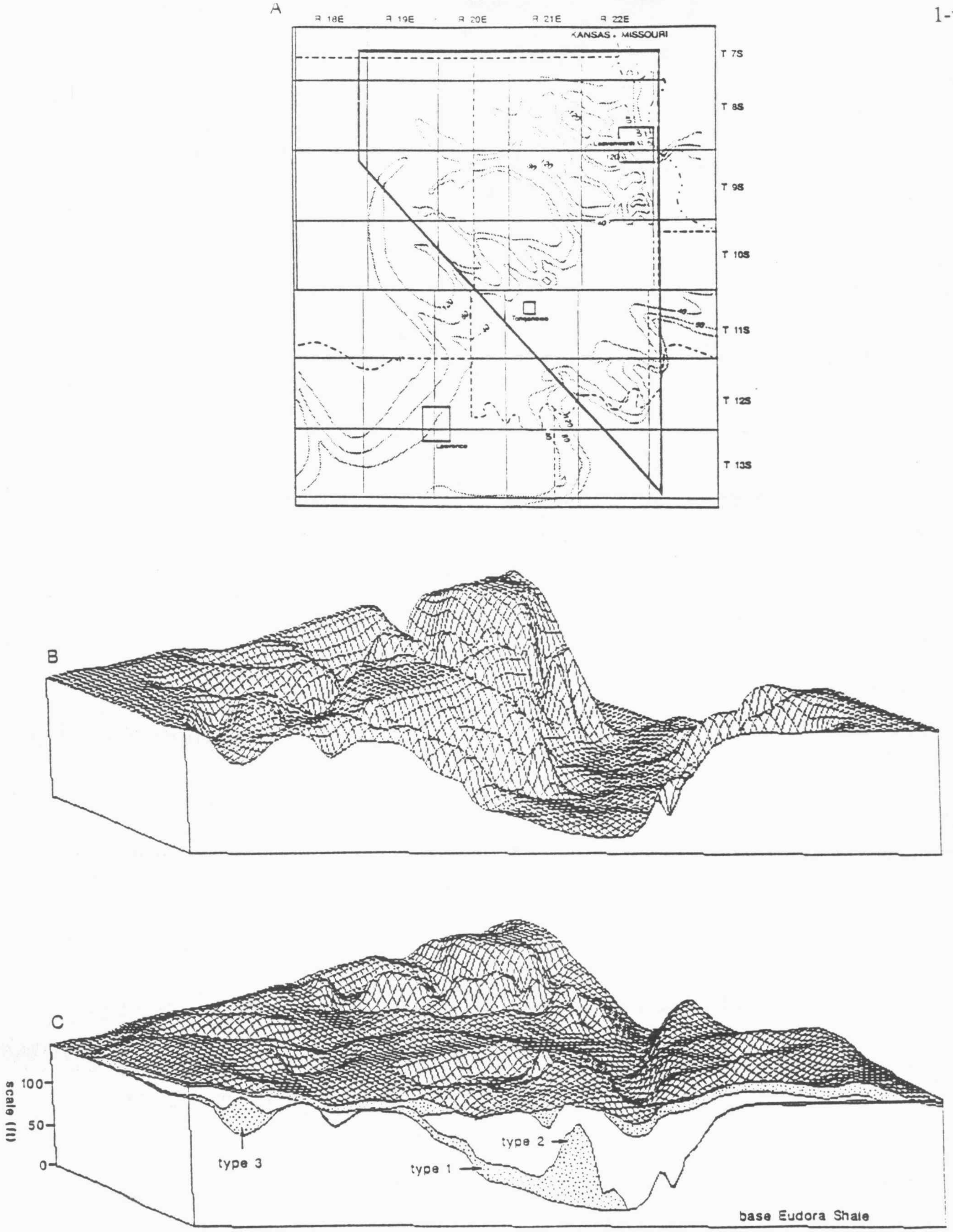

START
LUNCH
STOP 2-2
STOP 2-1
Lawrence
CLINTON STATE
Clinton
Lone Star
Pleasant Grove
Shank Hill
Kanwaka
Lake View
Midland
Municipal Airport
Bismarck Grove
Haskell Indian Jr. College
Blue Mound
Sibleyville
Vinland
Vinland Valley Aerodrome
Worden
Globe
Baldwin City
(Baldwin)
Noria
KANSAS TURNPIKE
TOLL ROAD
ATCHISON TOPEKA AND
OLD RAILROAD GRADE
POWERLINE
PIPELINE
LEVEE
Quarry
Radio Tower
Substation
KILOMETERS 1 0 1 2 3 4 5 6
MILES 1 0 1 2 3 4



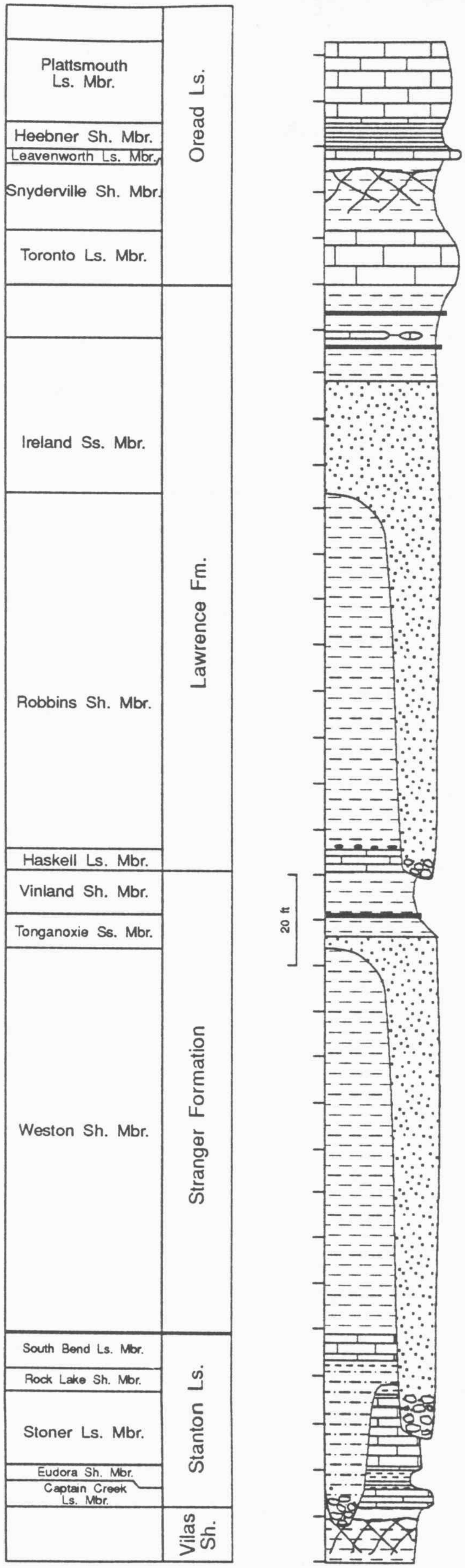
Stratigraphic nomenclature in the study interval in Leavenworth Co.



Map showing relationship between day 1 field trip stops and the Oeschlaeger # 1 core, and the Tonganoxie paleovalley. Isopach background map shows the thickness (in ft) of the interval from the base of the Eudora Shale to the base of the Tonganoxie Sandstone. This is presumed to approximate topography immediately prior to Tonganoxie deposition.



Cross section of the Tonganoxie paleovalley and a tributary valley. A, Reference map for location of block diagram. B, Block diagram showing surface at the base of the Tonganoxie Sandstone. C, Cross section extending from the base of the Eudora Shale to the top of the Haskell Limestone. The lower unit filled with sandstone pattern is the basal Tonganoxie Sandstone composed of type 1, 2, and 3 sandstones. Above this is shale (with minor amounts of sandstone and coal) of the Tonganoxie Sandstone and Vinland Shale. Upper unit with sandstone pattern is the combined upper Vinland Shale sandstone facies and Haskell Limestone. These units were combined for clarity.


Plattsmouth Ls. Mbr.
Heebner Sh. Mbr.
Leavenworth Ls. Mbr.
Snyderville Sh. Mbr.
Toronto Ls. Mbr.
Oread Ls.
Ireland Ss. Mbr.
Robbins Sh. Mbr.
Haskell Ls. Mbr.
Lawrence Fm.
Vinland Sh. Mbr.
Tonganoxie Ss. Mbr.
Weston Sh. Mbr.
Stranger Formation
South Bend Ls. Mbr.
Rock Lake Sh. Mbr.
Stoner Ls. Mbr.
Eudora Sh. Mbr.
Captain Creek Ls. Mbr.
Stanton Ls.
Vilas Sh.
20 ft

ROAD LOG: DAY 1

Miles

0.0 **START**: Days Inn parking lot, 2309 Iowa. Turn left (north) on Iowa Street.

0.6 Kansas Geological Survey on left.

0.9 Plattsmouth Ls. Mbr. of Oread Ls. on right (east).

1.1 Continue north past 15th St. Toronto Ls. Mbr of Oread Ls. on right (east).

2.3 Bear right on access road (McDonald Dr.) to I-70. Go under 6th St. bridge.

3.3 Kansas Turnpike toll booth. Proceed on I-70 east.

4.3 Cross Kansas River.

7.3 Enter Leavenworth County.

8.4 Tonganoxie Ss. Mbr. on left (north).

10.1 Lawrence Service Area.

10.9 Haskell Ls. Mbr. on right (south).

12.2 Cross Ninemile Creek.

13.1 Upper Lawrence Sh. on left (north).

13.4 Vinland Sh. Mbr. on left (north).

16.4 Stoner Ls. Mbr. on both sides.

17.5 Cross Stranger Creek.

22.4 Tonganoxie Ss. Mbr. on both sides.

22.6 Section of Stoner Ls. Mbr. through South Bend Ls. Mbr.

23.0 Section of Vilas Sh. through Stoner Ls. Mbr.

23.4 Cross creek.

24.0 Enter Wyandotte Co.

24.1 Exposure of Plattsburg Ls. on right (south).

24.5 Section of Stanton Ls. Mbr. through Tonganoxie Ss. Mbr.

25.6 Exit 224 on right.

26.1 Pay toll.

26.2 Turn right (north) on Ks. Hwy. 7.

26.5 Sandstone Amphitheater entrance.

26.9 Tonganoxie Ss. Mbr. on right (east).

27.1 Tonganoxie Ss. on both sides of road (Stop 1-3)

27.7 Cross U.S. Rts. 24-40.

28.7 Tonganoxie Ss. Mbr. on right (east).

34.1 Enter Leavenworth Co.

35.5 Cross Ninemile Creek.

37.2 Cross Sevenmile Creek.

38.4 Leavenworth City Limit.

40.2 Cross Fivemile Creek.

41.5 Junction of Ks. Hwy. 92. Continue north on Ks. Hwy. 7.

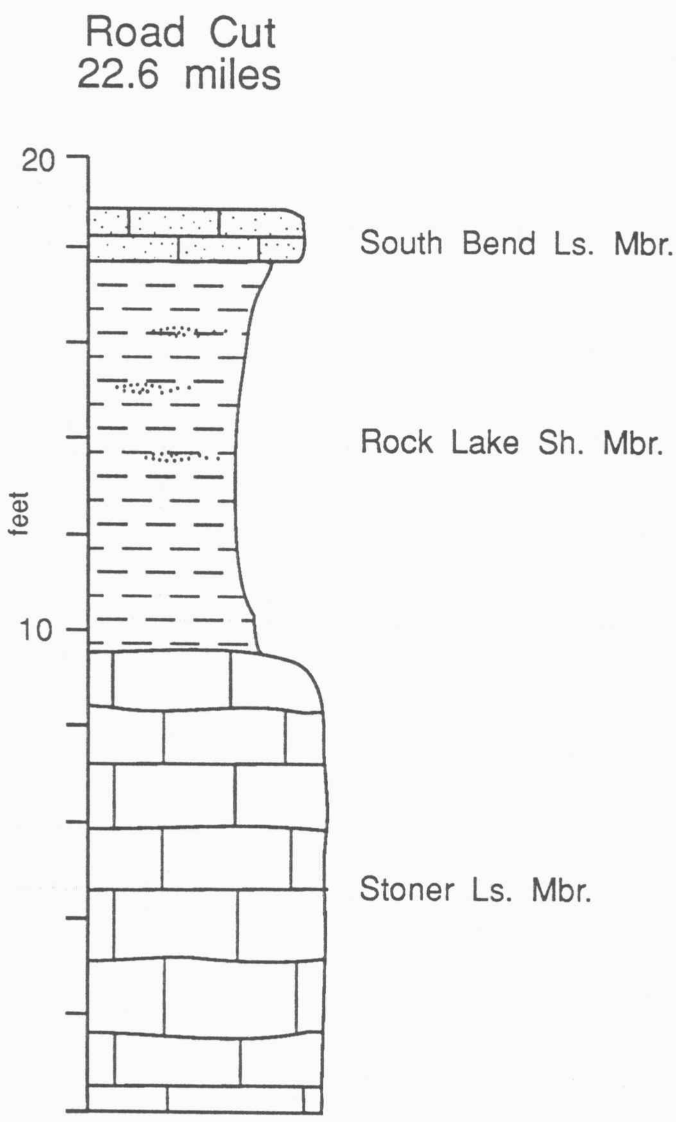
41.8 Cross Threemile Creek.

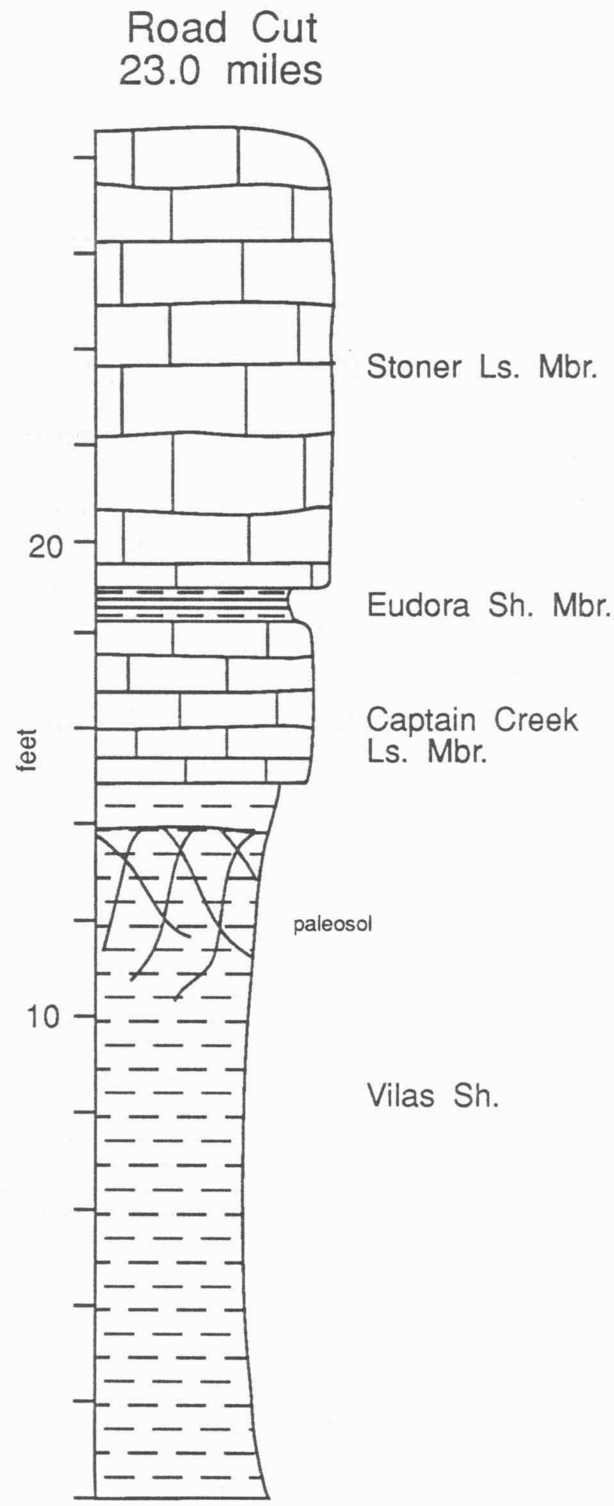
42.7 Turn right (east) on Rt. 92 at T.

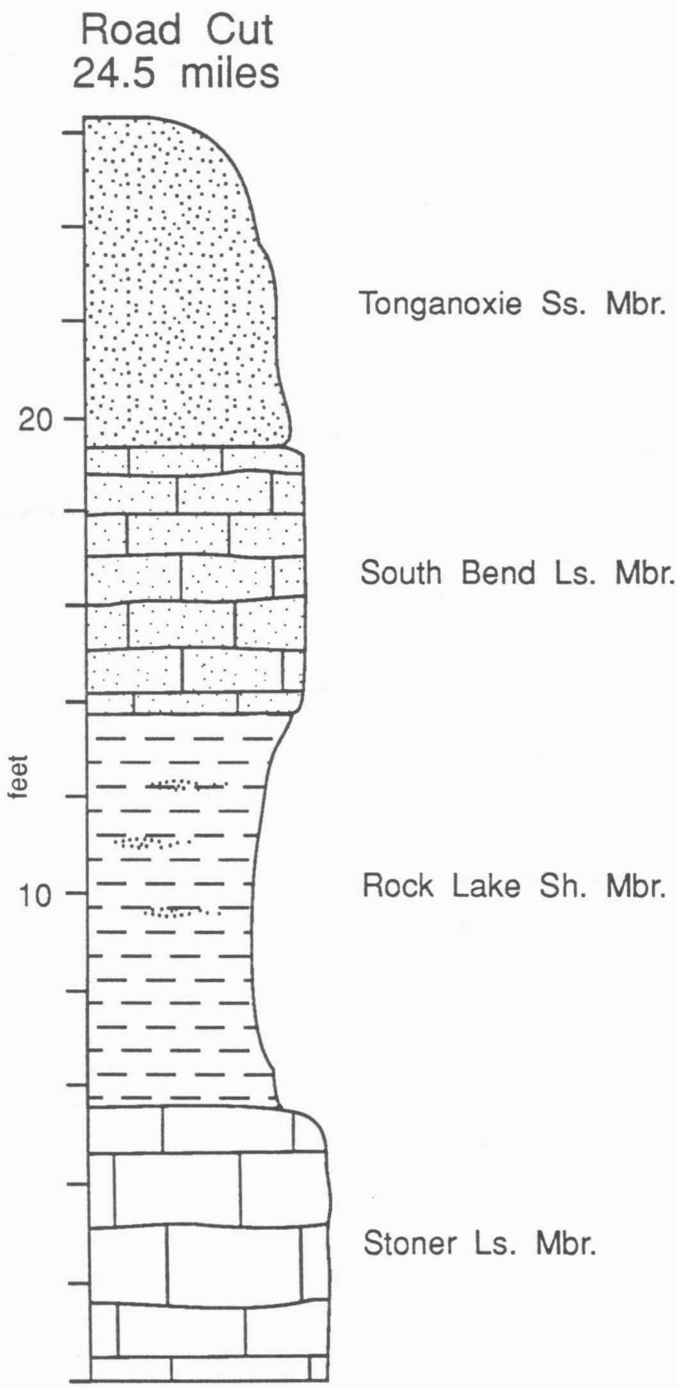
43.0 Enter Missouri, cross Missouri River.

46.7 Sign for Beverly.

47.0 Turn left on to access road to Platte Co. Rt. 45 at sign for Weston and then right onto Rt. 45 north.


Road Cut
22.6 miles
20
10
feet
South Bend Ls. Mbr.
Rock Lake Sh. Mbr.
Stoner Ls. Mbr.


Road Cut
23.0 miles
20
10
feet
Stoner Ls. Mbr.
Eudora Sh. Mbr.
Captain Creek
Ls. Mbr.
paleosol
Vilas Sh.


Road Cut
24.5 miles
20
feet
10
Tonganoxie Ss. Mbr.
South Bend Ls. Mbr.
Rock Lake Sh. Mbr.
Stoner Ls. Mbr.

48.1 Cross creek.

50.7 Weston city limit.

53.5 Loess.

54.1 Cross Bear Creek.

54.7 Cross RR tracks.

55.8 **STOP 1-1:** Turn right (east) onto access road to quarry. Drivers note: There is not much room for vehicles here. Be sure to leave enough room to turn around.

55.9 Leave Stop 1, return to Rt. 45 south.

57.0 Cross RR tracks.

58.2 Loess

59.4 Weston city limit.

64.6 Turn left onto access road and then right onto Mo. Rt. 92 west.

68.6 Enter Kansas, cross Missouri River.

69.0 Turn left (south) onto Ks. Hwy. 7.

70.0 Cross Threemile Creek.

71.6 Cross Fivemile Creek.

74.6 Cross Sevenmile Creek.

76.2 Cross Ninemile Creek.

77.9 Enter Wyandotte County.

79.0 Turn left (east) onto Polfer Rd. Rest stop at Total station. Then continue east on Polfer Rd.

79.8 Basal Tonganoxie Ss. Mbr. on left (north).

80.4 **STOP 1-2:** Road cut on south side of road. Drivers note: Park vehicles either east or west of the outcrop so that people can view the exposure from across the road to get an overview of the facies.

Continue east.

80.7 Cross Island Creek.

81.0 Turn right (south) onto 123rd St.

82.0 Turn right (west) onto Hollingsworth Rd.

84.0 Turn left (south) onto Ks. Hwy. 7.

86.2 Cross Piper Creek.

87.4 Tonganoxie Ss. Mbr. on right.

87.9 Cross U.S. Rts. 24-40.

89.4 **STOP 1-3:** Pull off Rt. 7 on right side just before 134th St. Drivers note: Do not pass 134th St. or you will have to drive further to turn around.

Return to Rt. 7 north.

89.6 Bear right onto Ks. Hwys. 24-40 east.

91.1 Turn right (south) onto 123rd St. at sign for Wyandotte Co. Park.

91.6 Turn right to park at shelter A. **LUNCH**
Return to Ks. Hwys. 24-40.

92.1 Turn left (west) onto Ks. Hwys. 24-40.

93.6 Tonganoxie conglomerate on Stoner Limestone Member on right (north).

94.4 Enter Leavenworth Co.

94.7 Tonganoxie on Rock Lake Shale on right (north)

95.3 Stoner Limestone and Rock Lake Shale members on right (north).

96.0 Road to Basehor on right.

99.4 Turn right (north) 182nd St.

100.3 Turn left (east) on Parallel.

100.4 Cross Stranger Creek and then turn right (north) on 183rd St.

100.8 Douglas Group sandstone on right (east). In this area the Ireland and Tonganoxie are amalgamated.

101.4 Turn left (west) on Leavenworth Rd.

101.6 Douglas Group sandstone on right.

102.4 **STOP 1-4:** Park vehicles on east side of bridge on north side of road.

Turn around in pull off at east side of bridge.

103.4 Turn right (south) on 183rd St.

104.4 Turn left (east) on Parallel Rd. and cross Stranger Creek.

104.5 Turn right (south) on 182nd St.

105.4 Turn right (west) on Ks. Hwys. 24-40.

105.6 **STOP 1-5:** Park on right.

Continue west on Ks. Hwys. 24-40.

105.9 Cross Stranger Creek.

107.1 **STOP 1-6A:** Park on right.

Continue west on Ks. Hwys. 24-40.

107.4 **STOP 1-6B:** Park on right.

Continue west on Ks. Hwys. 24-40.

108.6 **STOP 1-7:** Park on right.

Continue west on Ks. Hwys. 24-40.

109.1 Welcome to Tonganoxie!

109.8 Cross Tonganoxie Creek.

119.8 Enter Douglas Co.

Route into Lawrence may change with flooding.

122.5 Turn left (south) on Douglas Co. rt 9

Follow signs for detour or continue west on Ks. Hwys. 24-40.

124.9 Cross Kansas River.

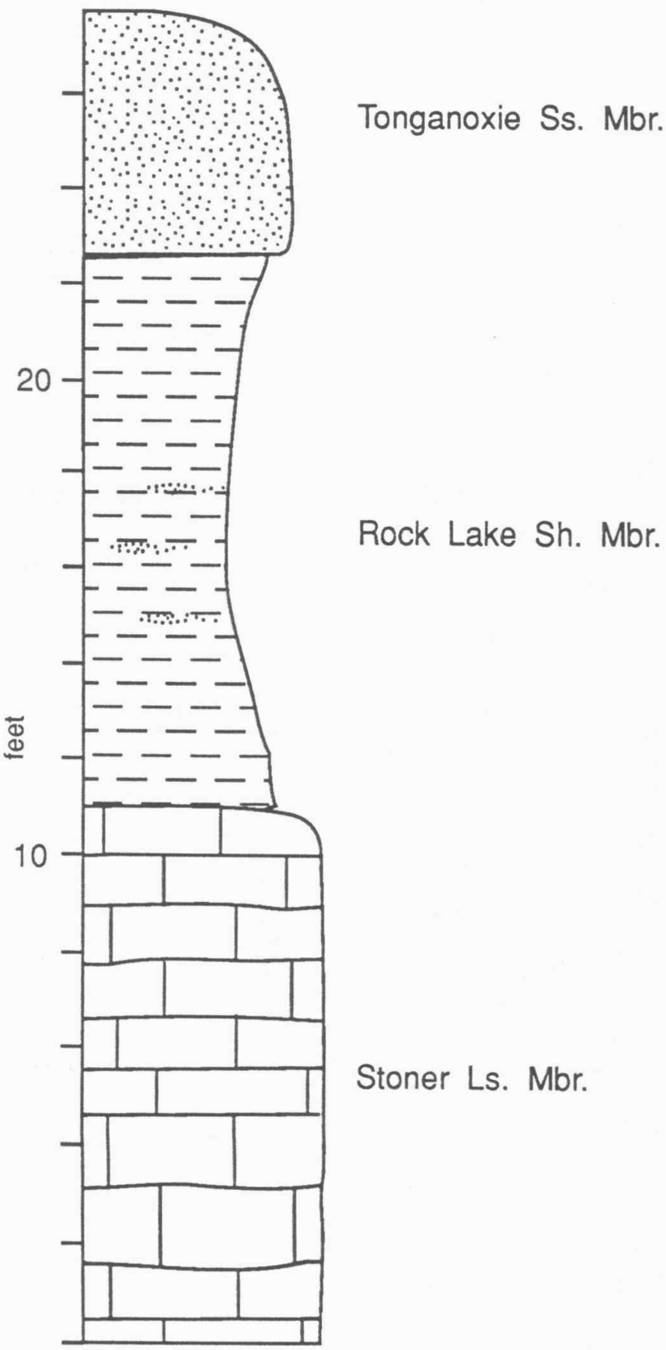
125.1 Turn right (west) on 6th St.

126.2 Uppermost Lawrence Shale and Toronto Limestone Member.

126.3 Turn right (south) on Iowa St.

128.5 Enter Days Inn parking lot.

Road Cut
94.7 miles



ROAD LOG: DAY 2

Miles	
0.0	**START**: Days Inn parking lot, 2309 Iowa. Turn right (south) on Iowa Street.
2.3	Turn right (west) on Douglas Co. 458.
5.5	Turn left (south) on Douglas Co. 1000E. Then stay on black top.
9.9	Turn left (south) on Douglas Co. 1039 at sign for Lone Star Lake.
10.6	Turn right (west) on Douglas Co. 1. Stay on black top.
13.2	Turn right (west) and cross dam.
13.5	**STOP 1-1:** Turn right (north) on gravel access road. Drive 100 ft and park.
13.5	Return across dam.
13.7	Left (north) at park exit. Follow Douglas Co. 1.
21.1	Turn left (west) to Clinton Lake.
21.7	Road cut of uppermost Lawrence Formation, Toronto Limestone, and Snyderville Shale.
	Continue north and Cross dam.
24.0	**STOP 2-2B:** Park on right by emergency spillway for Lake Clinton.
	Continue north.
24.3	Turn left (west) at entrance to Clinton State Park. Follow black top to left.
24.7	**LUNCH:** Park at picnic area 1.
	Return to park entrance.
25.1	Turn right (south) on Douglas Co. E900.
25.2	Turn left (west) on Clinton Parkway.
29.4	Turn right (south) on Iowa Street, and then enter Days Inn parking lot.

STOP DESCRIPTIONS

STRATIGRAPHY AND DELINEATION OF SEQUENCES: OVERVIEW OF FIELD TRIP DAY 1

The Douglas Group exhibits a high degree of lateral and vertical variability, in part because it includes incised valley-fill sequences, deltaic facies, and marine intervals. Unlike most upper Pennsylvanian deposits, coals are also unusually common within the Douglas Group. During the first day's excursion, we will examine a series of exposures that begin within deposits in a paleo-interfluvial area, and then proceed to the deepest part of the Tonganoxie paleovalley (lower Douglas Group) where fluvial facies are well developed. Based upon subsurface analyses (see Section 3), there are three types of valley-fill sandstone bodies. Type 1 sandstones fill the lower parts of the paleovalley, exhibit a sheet-like geometry, and range from 20 to 60 feet in thickness. The conglomerates and sandstone exposed at Stops 1-2 and 1-3 are part of the Type 1 sandstones. Type 2 sandstones are finer grained and exhibit arcuate geometries suggestive of point bars. Outcrop data indicates that these are probably, at least in part, estuarine fluvio-tidal point bars. These sands are as much as 60 feet thick. The top of a type 2 sandstone is exposed at stop 1-6A. The type 3 sandstones are the uppermost part of the valley-fill sequence and occur at the heads of the tributary valleys, but are not exposed.

During the trip we will view exposures from various parts of the valley-fill sequences that exhibit a transition from fluvial to tidal estuarine bedforms. We will also attempt to relate the various subsurface sandstone types to the outcrops.

During the second day, we will examine the uppermost parts of the Douglas Group, and see some of the complex inter-relations among coals and tidal facies that were formed in the non valley-confined part of the depositional system.

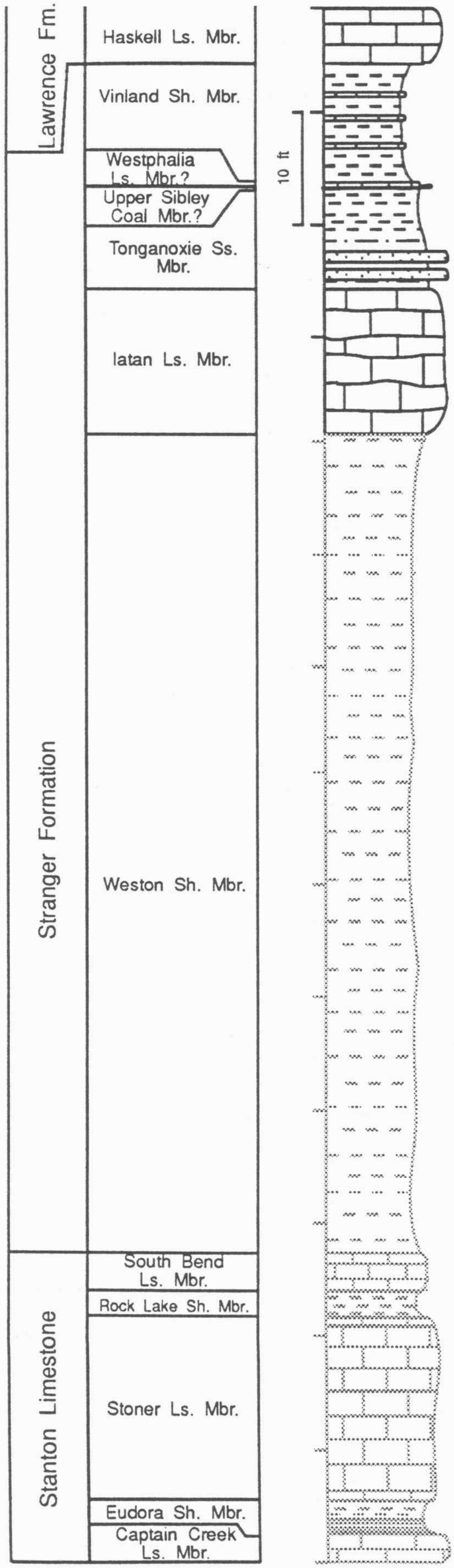
STOP 1-1: STRATIGRAPHIC OVERVIEW AND VALLEY GEOMORPHOLOGY

Location: Old quarry on east side of Missouri River Valley, located near Sadler siding. Locality P1 of Spriggs (1989).

Description: This stop provides a stratigraphic overview of the lower half of the Douglas Group in an paleo-interfluvial area (uneroded, upland area outside of the paleovalley). The top of the Iatan Limestone defines the base of the Douglas Group and is exposed at the base of the quarry. The Tonganoxie Sandstone is poorly developed here, and consists of thin, sandy beds with a shale-rich section. The Upper Sibley Coal(?) is exposed a few meters above the quarry floor. Directly above the coal is shale that contains abundant myalinid bivalves suggesting nearshore marine to brackish water. The limestone near the top of the quarry face is the Haskell Limestone.

Interpretation: A well developed paleosol has been described from the top of the Iatan Limestone and overlying shales (Goebel et al., 1989). This pedogenic episode was presumably related to the erosional period that formed the Tonganoxie paleovalley; however, it is difficult to correlate erosional and pedogenic events. The Tonganoxie sequence is very thin here and consists largely of shale with minor sandstone beds. It would be interpreted as late Tonganoxie deposition that followed the backfilling of the paleovalley. The Upper Sibley Coal is one of the more widespread coals and represents widespread peat accumulation; however continued transgression resulted in marine flooding of this peat field and deposition of the Westphalia Limestone.

STOP 1-1


Lawrence Fm.
Haskell Ls. Mbr.
Vinland Sh. Mbr.
Westphalia Ls. Mbr.?
Upper Sibley Coal Mbr.?
Tonganoxie Ss. Mbr.
10 ft
Stranger Formation
Iatan Ls. Mbr.
Weston Sh. Mbr.
Stanton Limestone
South Bend Ls. Mbr.
Rock Lake Sh. Mbr.
Stoner Ls. Mbr.
Eudora Sh. Mbr.
Captain Creek Ls. Mbr.

Sequence Stratigraphy: The following discussion of the stratigraphy summarizes the relationships illustrated in Figure 1. Delineation of sequence boundaries is relatively straightforward in these paleointerfluves. The lowstand surface of erosion (unconformity), which is the Iatan paleosol, can be relatively easily traced and correlated. Facies of the terrestrial[?] lowstand systems tract include the Tonganoxie up through Upper Sibley Coal. It should be noted that the lowstand tract includes the initial transgressive phases. The base of the transgressive systems tract is marked by the abrupt marine flooding at the base of the Westphalia Limestone. Locally, layers of coaly material ("coal clasts") have been incorporated into the base of the Westphalia; thus this surface appears to be a ravinement or transgressive surface of erosion. The transgressive systems tract continues up through the marine Vinland Shale to the Haskell Limestone, the top of which is probably one of the best developed and most convincing condensed sections that occur in the Pennsylvanian of the midcontinent. Phosphate nodules and fossils such as fish skulls with brain casts suggest an extended period of nondeposition, probably owing to deep-water conditions. Corals, brachiopods, and bryozoans occur in the shale overlying this phosphatic zone and indicate a return to open marine conditions. The marine Robbins Shale, which overlies the Haskell, probably resulted from the distal effects of a prograding, clastic coastal plain ("deltas"). The Robbins and underlying units, down to the level of the Tonganoxie, were erosionally truncated during the development of the next lowstand surface of erosion which forms the lower boundary of the Ireland Sequence.

STOP 1-2: BRAIDED FLUVIAL PART OF VALLEY-FILL SEQUENCES

Location: Roadcut on south side of country highway (1.5 miles east of Kansas Highway 7), this road turns east off of Kansas Highway 7 (at APCO Gasmart), approximately 9 miles north of junction of Kansas Highway 7 and Interstate 70.

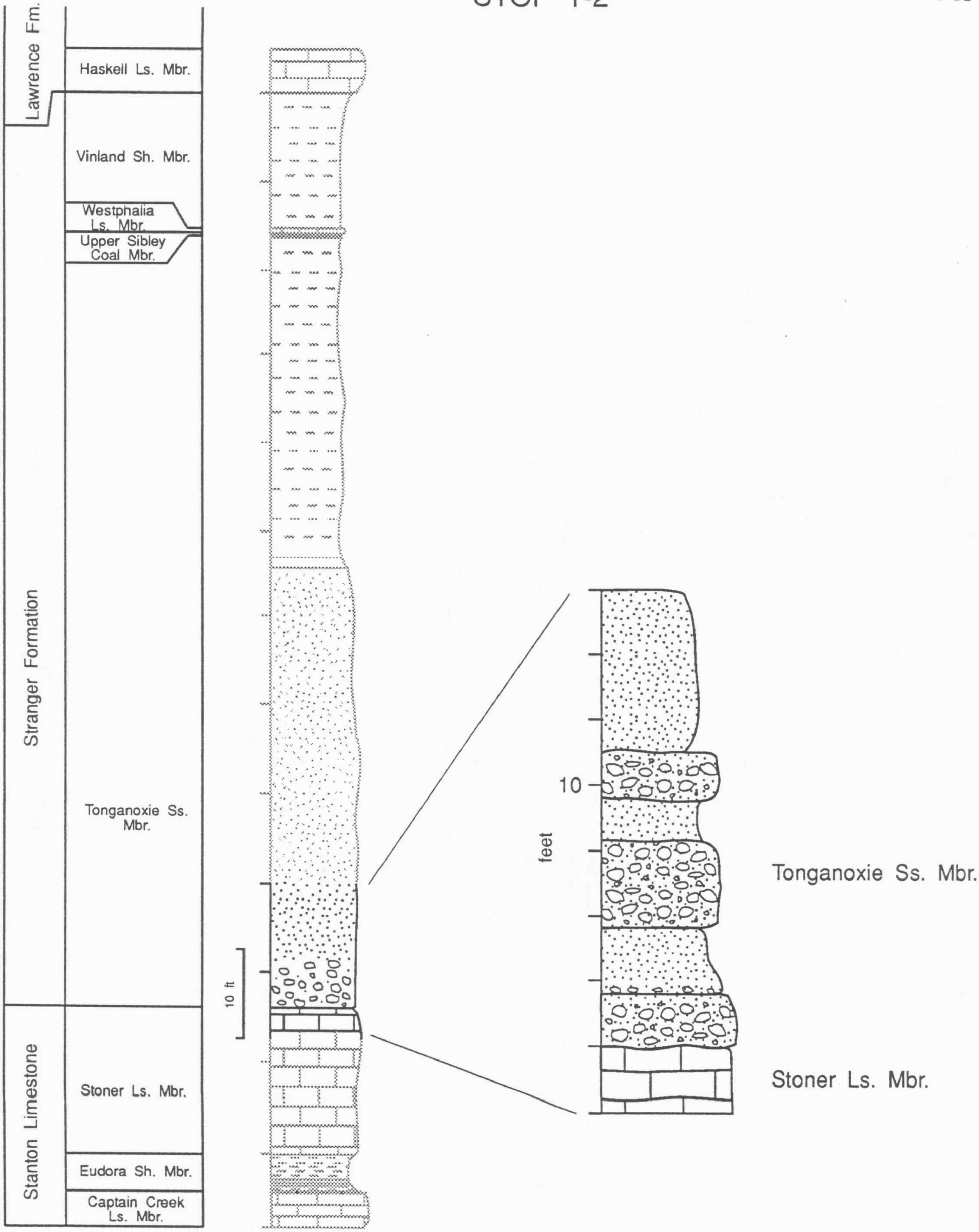
Description: Roadcut exhibits coarse, lower-part of valley-fill sequence (Type 1 sandstone) of the lowermost Tonganoxie Sandstone resting unconformably on the Stoner Limestone. Conglomerates contain clasts eroded from previously deposited limestones. Underlying limestone beds can be observed at west end of outcrop. Abundant coalified plant debris and wood impressions common within conglomerates. Paleoflow is unidirectional and generally to the west and southwest.

Interpretation: The conglomerate here is thick because we are situated near the main axis of the trunk paleovalley. Bedding types suggest a bedload-dominated braided fluvial system formed in a seasonal climate (see Section 3). The abundant woody material and large logs indicate that the area was forested. The degree of iron staining and abundance of clay within the conglomerates suggest a semi- to tropical climate with a high degree of chemical weathering.

The abundant log/branch debris at the base of the conglomerates appear to be from conifers (*Walchia*?). During the Pennsylvanian, conifers have been considered to be part of the upland, or climatically drier flora. Conversely, flora of wetter, swamp-forming communities, such as lycopods and calamites, are not as abundant (but are common at subsequent stops). Woody debris and macerated plant material is abundant throughout the section, and thin coaly layers appear to represent waterlogged wood and leaf-litter accumulations.

In the conglomerates, limestone clasts are only common in the lower part of section. For a coarse-grained facies, clays are unusually common throughout the section. A portion of

STOP 1-2



Lawrence Fm.
Haskell Ls. Mbr.
Vinland Sh. Mbr.
Westphalia Ls. Mbr.
Upper Sibley Coal Mbr.
Stranger Formation
Tonganoxie Ss. Mbr.
Stanton Limestone
Stoner Ls. Mbr.
Eudora Sh. Mbr.
Captain Creek Ls. Mbr.
10 ft
10
feet
Tonganoxie Ss. Mbr.
Stoner Ls. Mbr.

the clay component appears to be eroded clasts from the incised, stratigraphically older units (such as the Rock Lake Shale). However, clay chips apparently derived from mud-cracked clay layers are also common, especially within and throughout the upper part of the section.

Within the thinner conglomerate beds, there is a pronounced fining-upward trend and tops of beds become especially clay enriched. This may relate to flow variations that occurred during barform development, either as a short-term or seasonal component. If the paleoclimatic systems were tropical monsoonal, then pronounced seasonal variations in rainfall would result in extreme variations in flow velocities. As will be discussed in subsequent stops, "yearly" cycles in some of the more seaward estuarine facies also occur.

Sequence Stratigraphy: The locally derived gravels were eroded from lithified limestones and the lithification, exposure, and erosion of the marine carbonates indicate a profound drop in baselevel which presumably resulted from a significant lowering of relative sea level. Based upon experimental and theoretical constraints (Schumm, 1993), such pronounced incisement indicates relative proximity to the coastline, which was probably within a few hundred km to the south.

STOP 1-3: FLUVIAL DEPOSITS NEAR THE MOUTH OF A TRIBUTARY VALLEY

Location: Series of outcrops on both sides of Kansas Highway 7, immediately south of overpass with Kansas Highways 24-40.

Description: The Stanton Limestone forms the base of the outcrop and was the local source for the limestone conglomerates of the Tonganoxie Sandstone. The basal conglomerate is best exposed at the road cut at the southwest corner of the intersection of Highway 7 and 134th St. Bedding is poorly developed, but imbricated pebbles and trough cross bedding indicate northerly flow. Upper sandstones are best exposed at the northeast and northwest parts of these outcrops and indicate unidirectional paleoflows predominately to the southwest and west. The sandstone exposed at this outcrop probably represents much of the total thickness of the Type 1 sandstone.

Interpretation: There is a transition within the Tonganoxie Sandstone from a braided fluvial system at the base (bedload system) to a more suspended-load system (meandering?) fluvial system at top of the outcrops. This outcrop may be near the mouth of a tributary paleovalley that extended southwest from the trunk paleovalley. Bedform sedimentology of these sandstones is summarized in Section 3.

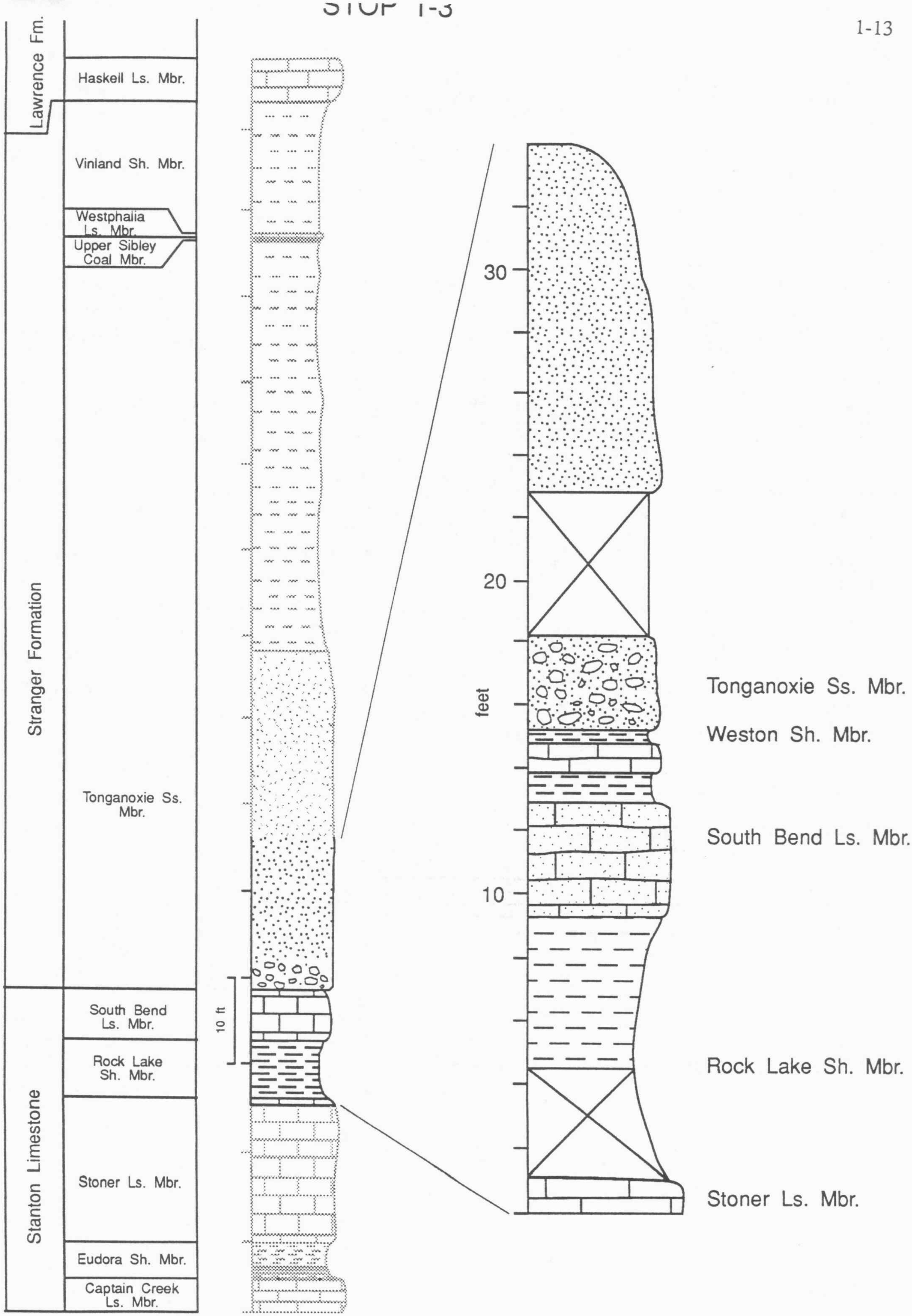
Sequence Stratigraphy: The conglomerate at Stop 1-3 is not as thick or as extensive as at Stop 1-2. In part, this decrease in thickness occurred because the site of deposition was likely located in a paleotributary valley instead of a paleotrunk valley, as was Stop 1-2.

STOP 1-4: EXTENT OF SANDSTONE BODIES

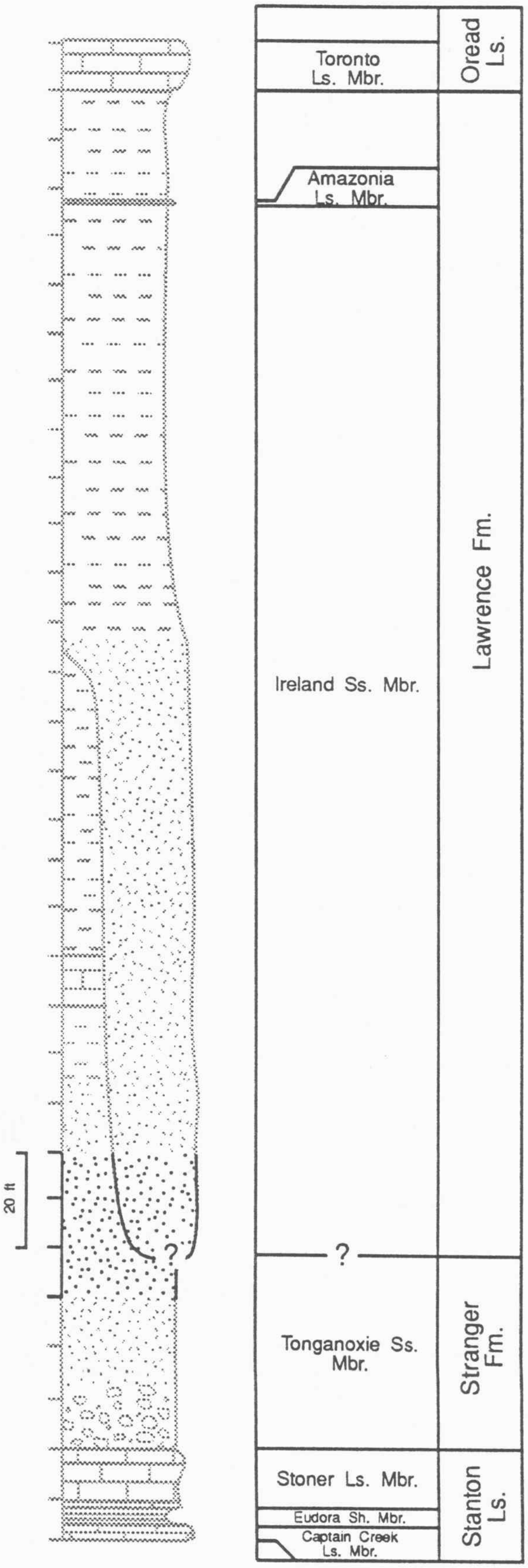
Location: Outcrops along the bluffs of Stranger Creek, accessible on graveled county road.

Description: This outcrop exhibits a very thick (>20 m) sandstone with a considerable lateral extent. Because of the lack of stratigraphic markers it is not clear if this is the Tonganoxie Sandstone, Ireland Sandstone, or an amalgamation of the two Douglas Group sandstones.

Interpretation: This is an obviously fluvial sandstone; attributes of the bedform sedimentology are summarized in Section 3. This outcrop is very similar to Morrowan-age


Lawrence Fm.
Haskell Ls. Mbr.
Vinland Sh. Mbr.
Westphalia Ls. Mbr.
Upper Sibley Coal Mbr.
Stranger Formation
Tonganoxie Ss. Mbr.
Stanton Limestone
South Bend Ls. Mbr.
Rock Lake Sh. Mbr.
Stoner Ls. Mbr.
Eudora Sh. Mbr.
Captain Creek Ls. Mbr.
10 ft
30
20
10
feet
Tonganoxie Ss. Mbr.
Weston Sh. Mbr.
South Bend Ls. Mbr.
Rock Lake Sh. Mbr.
Stoner Ls. Mbr.

STOP 1-4



20 ft
?
Toronto Ls. Mbr.
Oread Ls.
Amazonia Ls. Mbr.
Ireland Ss. Mbr.
Lawrence Fm.
?
Tonganoxie Ss. Mbr.
Stranger Fm.
Stoner Ls. Mbr.
Eudora Sh. Mbr.
Captain Creek Ls. Mbr.
Stanton Ls.

sandstones exposed in the Illinois Basin (Indiana and Kentucky) and Appalachian Basin. The scale of the exposure is similar to Morrowan sandstones of Indiana, which commonly attain such thicknesses. Conversely, age equivalent sandstones in the Appalachian Basin are thicker and attain thicknesses of 300 feet (100 m).

Sequence Stratigraphy: The thickness and extent of this sandstone are apparently related to the large-scale nature of the fluvial systems that occupied the paleovalleys incised prior to the deposition of the Douglas Group sandstones. As discussed at Stop 1-1, these trunk paleovalleys were approximately twice as wide as the current Missouri River Valley. The paleolatitudinal position of this area during the upper Pennsylvanian was approximately 10°, thus tropical, high rainfall paleoclimatic conditions probably resulted in paleoriver systems of considerable size. However, estimations of river sizes based upon sand-body geometry and paleovalley size is extremely difficult.

STOP 1-5: FLUVIO-ESTUARINE TRANSITION

Location: Outcrop on north side of Highway 24, approximately 6.5 miles west of junction with Highway 7 and about 4.5 miles east of Tonganoxie, Kansas. The area east of this town is the type area for the Tonganoxie Sandstone. Small stream immediately west of stop is Stranger Creek.

Description: This exposure is near the top of a type 1 sandstone. The exposure consists of large-scale, unidirectional foresets. Tangential lower contacts suggests large-scale trough cross bedding. Nearly all the cross bedding foresets exhibit thick clay drapes..

Interpretation: Well developed and common clay drapes are suggestive of tidal influences during deposition. The foresets were formed within the lower reaches of a fluvial system and the clay drapes indicate stillstands created by upstream tidal flow. The clay-draped, presumably fluvial cross bedding can be interpreted as having formed within the fluvio-upper estuarine transition.

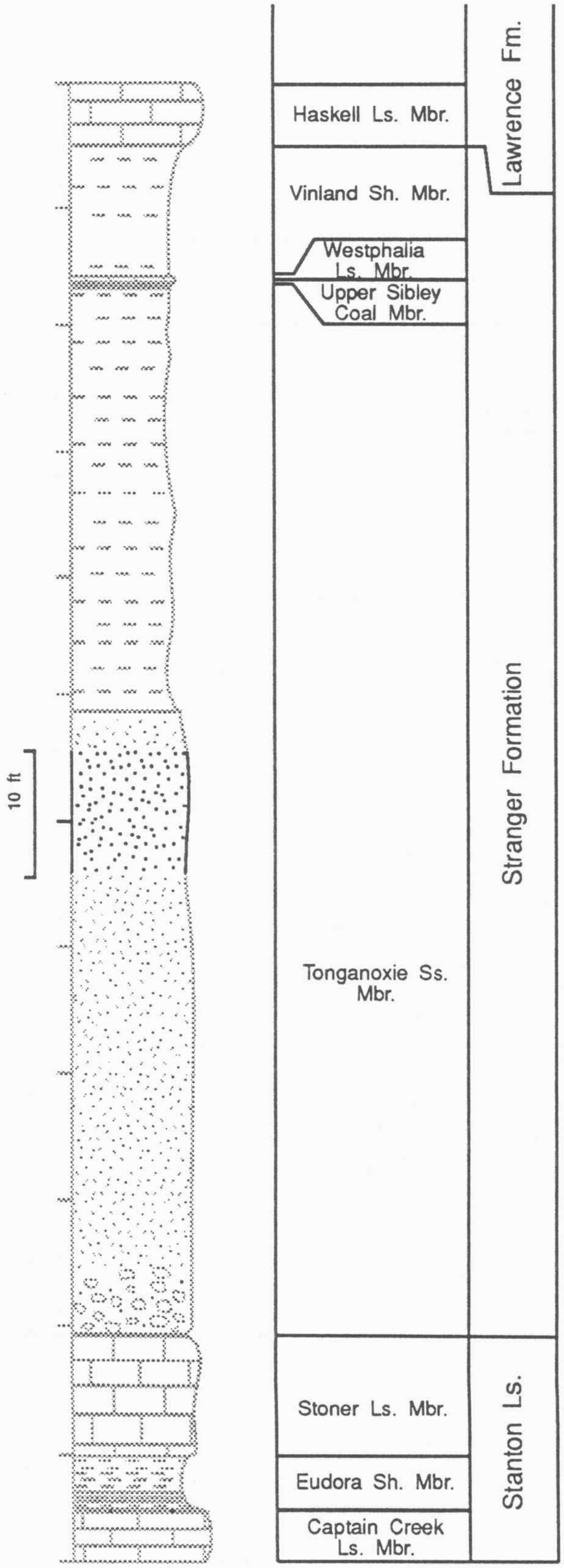
Sequence Stratigraphy: The tidal influences evidenced by the clay drapes indicates that the fluvial system was undergoing conversion to an estuarine depositional system. This was occurring during the initial rise in baselevel associated with the late phase of the lowstand systems tract. Although the facies are becoming "marine" influenced, this should not be confused with the marine flooding surface that forms the transgressive surface of erosion ("ravinement"). The transgressive surface of erosion is formed much later when the paleovalleys had been completely filled and rising sea level flooded the interfluve areas.

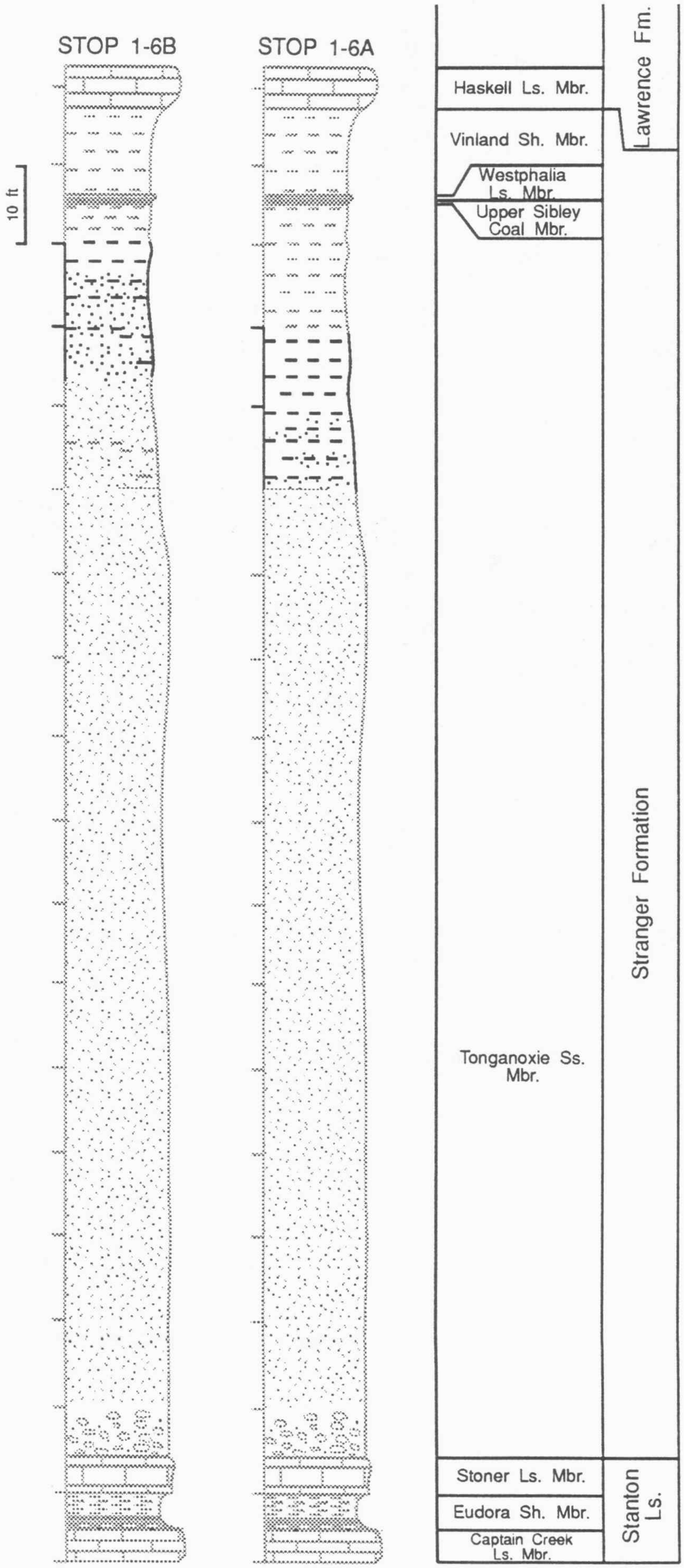
STOP 1-6a: MUDDY ESTUARINE DEPOSITS

Location: Outcrop on north side of Highway 24, approximately 8 miles west of junction with Highway 7 and about 3 miles east of Tonganoxie, Kansas. There are smaller exposures also on the south side of Highway 24.

Description: This outcrop exhibits the heterolithic (interlaminated sand and mud) facies of the upper part of Tonganoxie Sandstone. Sheet-like, parallel laminated sandstones are common and presumably represent the upper parts of a Type 2 sandstone. Poorly preserved, small bivalves that resemble *Carbonicola* are common. Such bivalves are commonly interpreted as nonmarine forms in the Carboniferous of Europe, the maritime provinces of Canada, and the Appalachian Basin.

STOP 1-5


10 ft
Haskell Ls. Mbr.
Vinland Sh. Mbr.
Westphalia Ls. Mbr.
Upper Sibley Coal Mbr.
Tonganoxie Ss. Mbr.
Stoner Ls. Mbr.
Eudora Sh. Mbr.
Captain Creek Ls. Mbr.
Lawrence Fm.
Stranger Formation
Stanton Ls.


STOP 1-6B
STOP 1-6A
10 ft
Haskell Ls. Mbr.
Vinland Sh. Mbr.
Westphalia Ls. Mbr.
Upper Sibley Coal Mbr.
Lawrence Fm.
Tonganoxie Ss. Mbr.
Stranger Formation
Stoner Ls. Mbr.
Eudora Sh. Mbr.
Captain Creek Ls. Mbr.
Stanton Ls.

Interpretation: The occurrences of *Carbonicola*-like bivalves, which are generally interpreted as indicators of freshwater conditions, suggest low-salinity conditions. The parallel laminated sandstones indicate upper flow-regime conditions during deposition interspersed with low energy conditions that deposited the mud layers. Although such conditions can occur in seasonal-climate fluvial systems, the common occurrence of the mud layers ("drapes") suggests tidal influences. As compared with the next stop (Stop 1-6b), this outcrop may represent the fringing mudflats and muddy bars developed laterally to sandy channels within the upper parts of an estuary.

Sequence Stratigraphy: This outcrop and the next stop are probably lateral facies within the uppermost estuarine system. These estuarine influences indicate that continued base-level rise (transgressive) has moved the fluvio-estuarine transition progressively upstream during the development of the latter phases of the lowstand systems tract.

STOP 1-6b: SANDY ESTUARINE DEPOSITS

Location: Roadcut on north side of Highway 24, about 0.3 mile west of Stop 1-6a.

Description: This outcrop is probably near the top of an arcuate type 2 sandstone body. It consists of sheet-like sandstone beds exhibiting parallel lamination, poorly developed cyclical tidal rhythmites, and abundant ripple bedding. Vertical *Lockeia*-related escape trace fossils are common and were apparently formed by bivalves similar to those that can be collected at Stop 1-6a.

Interpretation: These beds represent fresh- to brackish-water sandy tidal flats that developed within the uppermost estuarine limits, in the transitional to fluvial parts of the depositional system. The sands may be similar to the axial sands that form within the axial ("channelized") parts of macrotidal estuarine systems, such as the Bay of Fundy. Escape traces indicate rapid rates of vertical accretion.

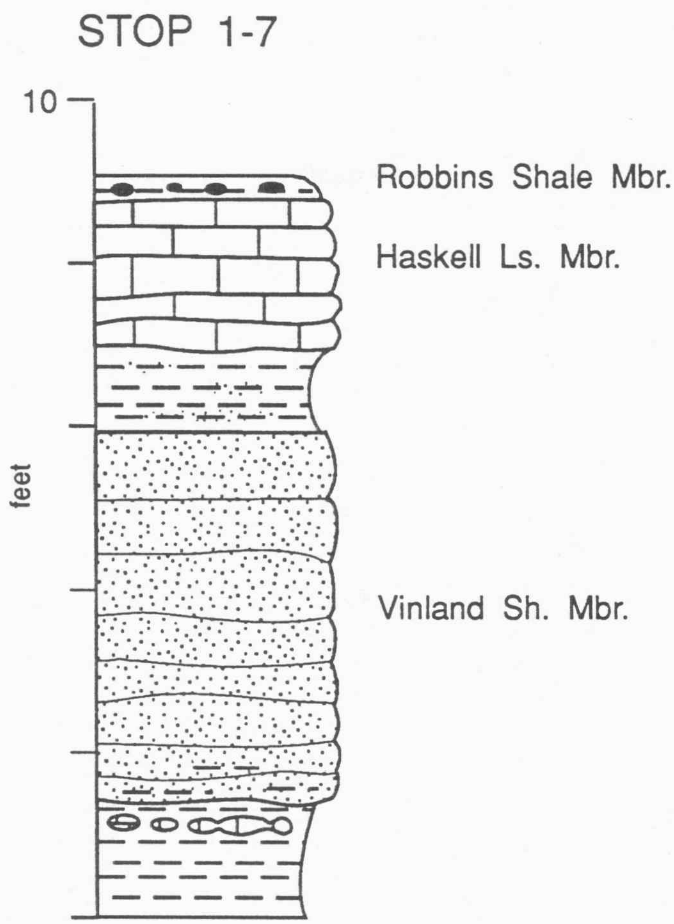
The section is dominated by ripple bedding and planar laminations. The *Lockeia*-related escape structures, which do not change in diameter from bottom to top, indicate that sedimentation was rapid relative to the growth of the clams. Although the planar lamina may be upper-flow regime bedforms, the grain size is generally finer than in the ripple-bedded zones. Thus, the planar lamination may be "sheet-wash" produced during late-stage emergent runoff that can occur in sandy tidally-influenced flats. In such a scenario, flow in very shallow water will preclude ripple formation and will result in planar lamination.

Sequence Stratigraphy: See discussion for Stop 1-6a.

STOP 1-7: MARINE DEPOSITS

Location: Road cut on Highway 24, approximately 9 miles west of Highway 7 and 1.5 miles east of Tonganoxie.

Description: The road cut exposes most of the Vinland Shale, the Haskell Limestone, and the lowermost Robbins Shale. The lower exposed part of the Vinland Shale is a grey shale. No macrofossils were observed in the shale. The upper part of the shale contains limestone wackestone concretions with fish(?) debris. Above a sharp contact is the upper Vinland Shale sandstone facies. This is a sheet of sand that averages 10 ft in thickness. The sandstone has a sharp lower contact and exhibits horizontal wavy bedding, ripple crossbedding, and extensive bioturbation. A variety of horizontal and vertical burrows can best be observed on weathered blocks. Above the shale is the fossiliferous Haskell


STOP 1-7
10
feet
Robbins Shale Mbr.
Haskell Ls. Mbr.
Vinland Sh. Mbr.

Limestone. Myalinid bivalves, brachiopods, crinoids and other marine fossils are present in abundance. Above the Haskell on the southern road cut is a few inches of lowermost Robbins shale that contains phosphate concretions.

Interpretation: This is the marine cap to the estuarine valley fill. The upper Vinland Shale includes a sheet of sandstone that was deposited across the paleovalley after it was substantially filled. In places, it thickens over buried tributaries, suggesting that some minor reflection of buried topography remained. The sandstone was deposited in a nearshore, marine environment. The overlying Haskell Limestone was deposited in open marine conditions. Although not present here, oolites are common in the Haskell in nearby areas.

The lowermost Robbins Shale is a condensed interval that was deposited slowly in relatively deep water. Common in this interval are phosphate concretions, phosphatic fossils, such as fish scales, fish skulls with brain casts, and orbiculoid brachiopods. Also present are cephalopods such as ammonites and nautiloids. Foul bottom water conditions are suggested by the rarity of benthic fossils.

Sequence Stratigraphy: The fully marine deposits exposed at Stop 1-7 represent the upper part of the transgressive systems tract. The condensed interval at the top of the exposure is the maximum flooding surface and the boundary between the transgressive systems tract below and the highstand systems tract above.

DAY TWO

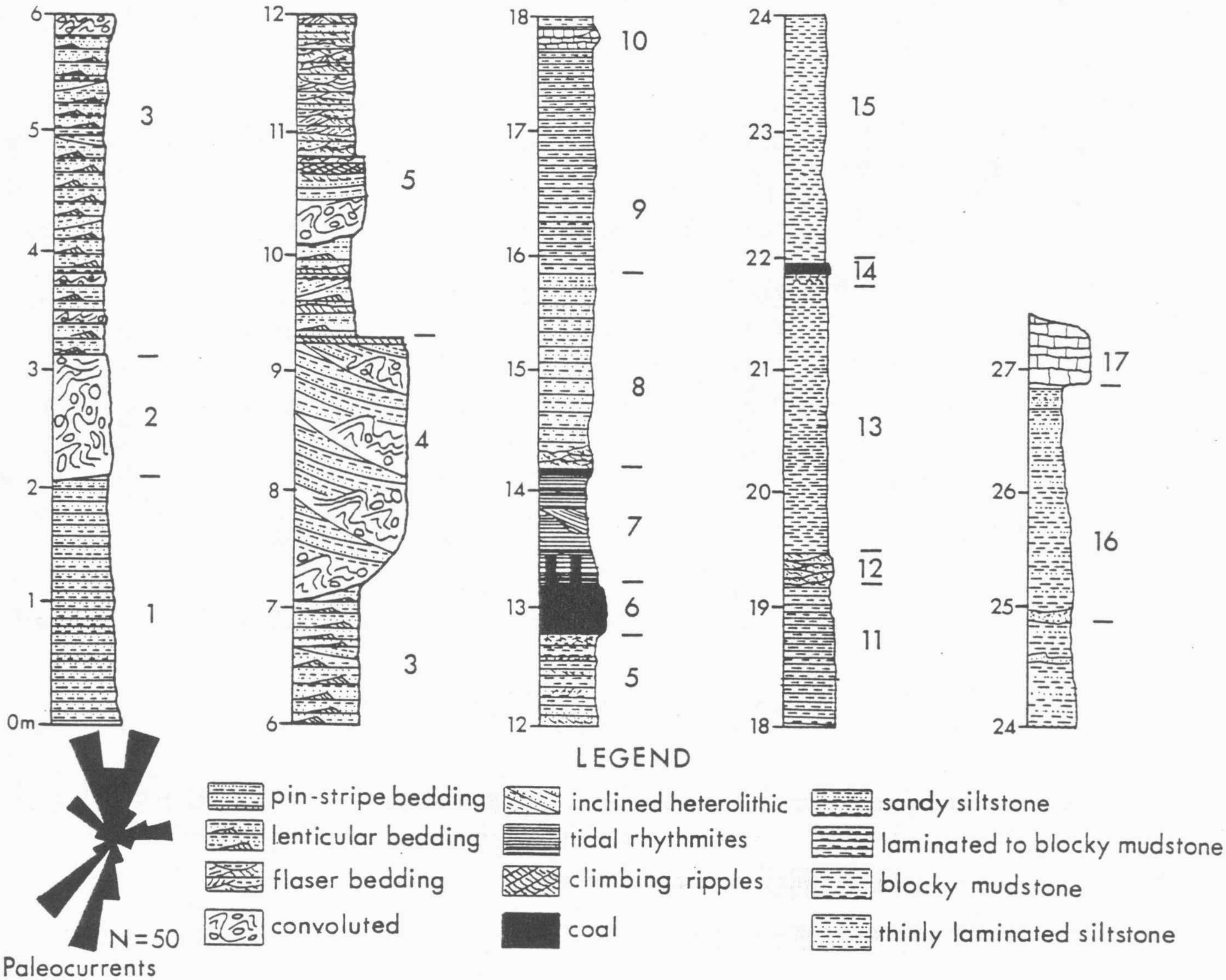
STOP 2-1: TIDAL ESTUARINE FACIES

Location: Spillway of Lone Star Lake Reservoir. Located about 9 miles southwest of Lawrence, Kansas. This locality was described by Rutan (1980), and is a tidal-rhythmite locality of Archer (1991).

Description: Because of flooding and erosion, this outcrop provides a rare exposure of laminated, heterolithic shales and thin-bedded sandstones that would otherwise be deeply weathered. Tidal rhythmites are common in the upper part of the section and occur directly over a thin coal (Lower Williamsburg Coal). Siderite concretions occur in the shale directly over the coal, and contain abundant well-preserved plant fossils, especially ferns. The concretions also contain rare cockroaches, limulids (horseshoe crabs), arachnids, and shrimp. Upright, in situ trees occur at the top of the coal and extend for as much as 2 meters into the overlying shales. Below the coal are channel-form sandstones exhibiting climbing ripple lamination in a finer-grained facies consisting of lenticular- and flaser-bedding heterolithic shales. In the water-washed gully, well laminated, rhythmic lamina occur about 1 m below the coal. Other than moderately extensive rooting, the shale under the coal is not extensively altered.

Interpretation: The upper part of the section (overlying the coal) shares many similarities with coal-bearing tidal facies in the Illinois and Appalachian basins (Archer and Kvale, in press; Archer et al, in press). Depositional environment can be interpreted as brackish-water tidal flats formed within the turbidity maximum portion of estuary.

Sequence Stratigraphy: The lower, tidally deposited parts of the section subsequently underwent subaerial exposure, development of a rooted zone, and accumulation of peat. Based upon decompaction estimates, the original peat was probably from 3 to 6 m (10 to 20 ft) in thickness. Based upon rates of accumulation of modern, tropical peats, 1000 to 2000 years would have been required to accumulate such a thickness of peat. The coal



Measured section of upper part of Lawrence Formation at Lonestar Lake spillway (Stop 2-1). See Section 4 for details of the sedimentology of this stop.

appears to be autochthonous because of extensive rooting below the seam; however, the seat earth is not an extensively leached underclay, such as those associated with the thicker, Desmoinesian (Westphalian) coal seams of southeastern Kansas and the Illinois Basin. The clayey parting and upper "paper coal" character of the coal seam suggest flooding of the peat-producing mire. Some of the upright trees are lycopods which could have grown in standing, low salinity waters. There are a general lack of indicators of subaerial exposure in the heterolithic rhythmites overlying the coal seam, which suggests that much of the deposition occurred within subtidal, or low intertidal conditions. However, the initial heterolithic facies overlying the coal probably formed within high intertidal conditions, unless structural subsidence or very rapid rise in sea level resulted in a "geologically instantaneous" transition from subaerial (peat-forming) to subtidal (rhythmite- forming conditions). The exact mechanism and timing of rhythmite progradation over peats with in situ trees is not well understood; however, compaction of the peat may have produced accommodation space that allowed the 3-m thick rhythmite section to have been accumulated in short periods of times (i.e., years).

Overall, despite the paleosol attributes of the seat earth and coal, the unconformable relationships at this outcrop may in part be autogenic, and related to sedimentation up to base level, subaerial exposure and peat accumulation, compaction of thick, underlying valley-fill sequence, flooding, and deposition of tidal rhythmites over a rapidly compacting peat. The Williamsburg Coal, of which the lower bench is exposed here, is relatively widespread and has been traced into Franklin County to the south. There is not enough data to delineate the exact relationships of the coal to the underlying paleovalley, but if the coal is more widespread, then allogenic processes (i.e., eustatic rise) would better explain the coal/rhythmite relationships.

STOP 2-2: OVERVIEW OF UPPER DOUGLAS GROUP AND OVERLYING UNITS

Location: Spillway of Clinton Lake Reservoir, located approximately 3.5 mi (5.5 km) west of Lawrence.

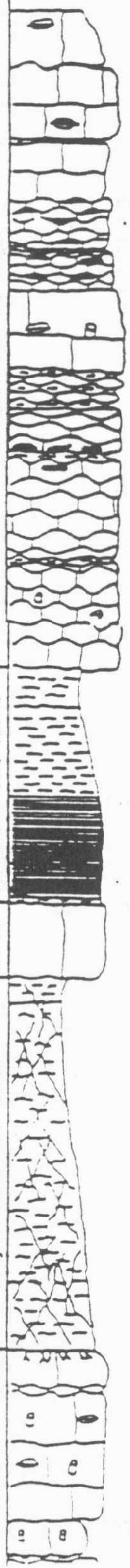
Description: This large exposure provides an excellent overview of gently eastward dipping strata of the uppermost Douglas Group and of the units that overlie the Douglas Group. The stratigraphic interval ranges from just below the Amazonia Limestone Member and unnamed upper shale member (containing the Upper Williamsburg Coal) of the Douglas Group up through the Plattsmouth Limestone Member of the Oread Limestone.

Interpretation: The range of environments expressed in the thick stratigraphic succession range from terrestrial (maroon shales and coals at base) to offshore carbonates.

Sequence Stratigraphy: This stop provides a stratigraphic overview of the transition from muddy, thick, Douglas Group cycles to the overlying relatively thin, carbonate-dominated "Kansas" cycles typical of Missourian and lower Virgilian rocks (Heckel, 1977). The cycles immediately below the Douglas Group in the Vilas Shale and Stanton Limestone are very similar to the Oread Limestone cycles. The cyclothems above and below the Douglas Group are bounded below by deeply weathered carbonate-rich paleosols (Vilas Shale and Snyderville Shale). The paleosols are overlain by thin transgressive deposits composed of thin limestones and black shales. These are overlain with thicker regressive carbonates. In contrast the Douglas Group cycles have thick transgressive portions, and little carbonate. Although changes in relative sea level probably generate the individual sequences, the

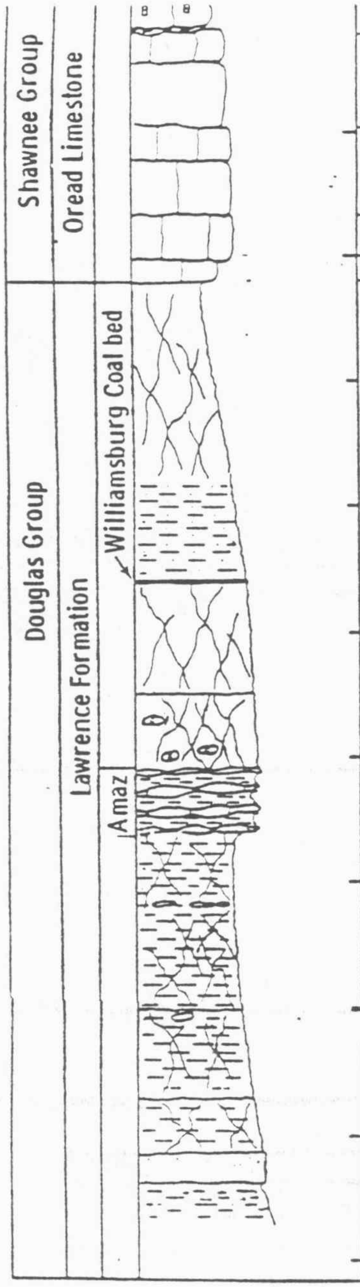
Measured Section of Clinton Spillway
Douglas Co., Kansas

Vertical Scale: 1 m



Group	Formation	Member	Sed. Struct.	Rock Name	Fossils Particles	Color Fresh/ Weathered	Grain Size	Diagenetic Features	Remarks
Shawnee Group	Oread Limestone	Plattsmouth Ls. Mbr.		fusulinid packstone					
				fusulinid packstone		brown-rusty orange			
				skeletal packstone		gray			
				algal packstone-wackestone		tan			thin wavy bedding shale interbeds
				cherty wackestone		gray		chert	
				fusulinid/crinoid packstone		gray-orange yellow			
				wackestone/packstone		rusty orange			rugose coral common
				skeletal packst.-wackestone		gray		(chert)	chert concentrated on bottom of bed
				skeletal packstone/wackestone		gray			whispy shale laminations
				skeletal packstone/wackestone		gray			whispy shale laminations
		Heebner Sh. Mbr.		clay shale		greenish yellow / dark gray brown	clay		softer and less platy than shale below
				black shale		black			hard platy phosphate nodules conodonts, sulfides 3 cm. soft shale at base
		Leav		Leavenworth Ls. wackestone		dark gray-brown			
Shawnee Group	Oread Limestone	Snyderville Sh. Mbr.		clay shale		dark gry-brn			
				clay shale		dark gray	clay		
		Toronto Ls. Mbr.		micrite		tan			tube-like structures at top of bed filled with shale, weather to tubes. pyrite
				crinoid/fusulinid packstone/wackestone		light gray			algal oncolites coated grains glauconite
				crinoidal wackestone		greenish gray			

FIGURE 6-3–Measured section of upper Lawrence and Oread at Clinton Lake Spillway.
From Stephens and Watney (1991).



	crinoidal packstone/ wackestone		light greenish gray			whispy shale laminations
	skeletal packstone		light gray -orange yellow			iron stains
	skeletal wackestone		light gray			iron stains
	wackestone		light gray			
	mudstone/ clay shale		gray			thin (1 cm.) silty laminations weathering to, yellow color
	coal smut		black			
	mudstone		greenish gray greenish gray with maroon mottling			clayey light brown calcareous nodules cylindrical and branching
	Amazonia Ls. Mbr. micrite, silty Ls. & clay shale		greenish gray/orange yellow			solution breccia sheet cracks fitted clasts
	slightly silty clay shale		greenish gray lt. gray			maroon lenses around iron rich nodules soft thinly laminated
	clay shale		red			some v. fine silt platy laminated
	clay shale		greenish gray			weathers blocky
	siltstone		pale green-gray			micaceous thinly laminated in places red, iron hardened burrows

KEY TO SYMBOLS

- brachiopods
- gastropods
- crinoids
- phylloid algae
- fusulinid forams
- bivalves
- rugose coral
- conodonts
- bryozoans
- oncolites
- coated grains
- vug
- pyrite
- shale interbeds
- burrows
- tubes
- shale interbeds
- phosphate nodules
- chert
- calcareous nodules
- iron rich nodules

differences between the Douglas Group cycles and overlying and underlying cycles may be attributable to climate (see Section 19). In dryer climates during periods of exposure deeply weathered dry-climate type paleosols (e.g. vertisols) may form, but there may insufficient runoff to form deeply incised paleovalleys. Lack of runoff will also result in little influx of terrigenous sediment to coastal areas. Deposition of carbonate sediments will dominate during times of flooding. Evidence that the cycles immediately overlying and underlying the Douglas Group were deposited in relatively dry climates include carbonate-rich paleosols, conifer-dominated vegetation (see Section 12), and the low ratio of siliciclastic to carbonate facies.

In contrast, Douglas Group cycles reflect wetter periods as indicated by the abundance of coals and the lack of carbonate-bearing paleosols (accept in the uppermost Lawrence Shale), the abundance of fern foliage and lycopods, and the deeply incised river valleys.

END OF OFFICIAL FIELD TRIP; RETURN TO DAY'S INN

ADDITIONAL STOPS BELOW ARE OPTIONAL BUT WILL BE VISITED BY TRIP LEADERS; INTERESTED INDIVIDUALS MAY ACCOMPANY THEM

STOP 2-3: FLUVIO-ESTUARINE TRANSITION

Location: Buildex Quarry, approximately 1 mile south of Ottawa, Kansas. Please note that access to the quarry proper is currently restricted, owing to liability problems.

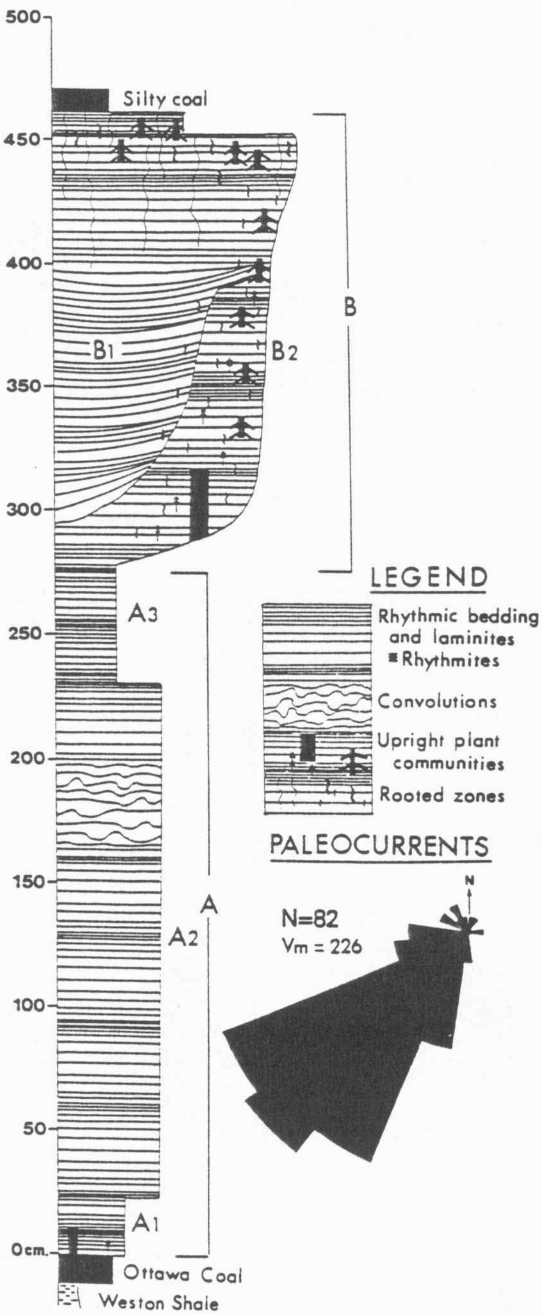
Description: This clay pit was operated for the extraction of ceramic-grade materials and removed materials from the Weston Shale Member of theStranger Formation. The upper parts of the pit expose the locally developed Ottawa Coal, which forms a low-angle discordance with the underlying shales. The Tonganoxie Sandstone immediately overlies the coal.

Depositional Environments: The shale in the lowest part of the pit contains little to indicate its environmental attributes. The shale is relatively massive, is not laminated, and does not exhibit anything useful in terms of sedimentological information. Macroinvertebrate fossils have not been recovered from this shale.

The Ottawa Coals rests disconformably on the underlying shale, that has been in part altered to an underclay. Abundant upright trees, including pteridosperms and calamites rise from the top of the coal and are encased in the silty rhythmites of the overlying Tonganoxie Sandstone.

The silty rhythmites have been intensively studied at this locality by W. Lanier and students from Emporia State University (see Section 4). In addition, extensive collection of plant fossils was undertaken by Gilbert Leisman, at Emporia State. This exposure contains a unique suite of physical sedimentary structures (see Lanier, this report) and a high diversity of trace fossils (see Archer and Lanier, this report). Paleocurrent analyses indicates bimodal flow with a stronger southwesterly component. This can be interpreted as an ebb-dominant, or as a fluvially dominated, tidally influenced depositional system. Modern analogs of such a system include fluvio-tidal point bars developed in the upper reaches of macrotidal estuaries, such as the Bay of Mont Saint Michel in France (see Tessier et al, this report) and Bay of Fundy in Canada (Dalrymple et al., 1991).

Sequence Stratigraphy: This site is east of the main paleovalley trend and appears to



Generalized section of the section at the Buildex Quarry near Ottawa (Stop 2-3). See Section 4 for details regarding the sedimentology of this area.

represent progradation of the upper valley-fill sequences out and over the surrounding valley sides or terraces. Erosional during valley incision produced the low-angle discordance that underlies the Ottawa Coal. During the upper part of the valley fill, the depositional system was no longer confined to a narrow valley. Flooding resulted in a broad, funnel-shaped estuary. Wetter microclimates resulted in localized mire development and formation of the Ottawa Coal. The funnel-shaped geometry resulted in strong tidal amplification, and development of localized macrotidal conditions in which the laminated siltstones that form the roof facies of the coal were deposited. Compaction of the underlying peat produced the accommodation space that allowed rapid vertical accretion of the silty rhythmites. As this generation of accommodation space was reduced, channeling and erosional reactivations became more prominent in the upper parts of the siltstone sequence. The silts accumulated to base level, extensive vegetation cover was re-established and organic accumulation was re-initiated although clastic flux was too great to have resulted in a coal seam.

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Tidal Processes in the Fluvio-Tidal Transition within Estuaries

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(adapted from Short Course Notes prepared for Energy Minerals Division of the American Association of Petroleum Geologists, April 1993)

Recognition of Tidal Controls on Sedimentation

Traditionally, tidal facies have been recognized on the basis of a few simple criteria. These criteria include physical sedimentary features that indicate bimodal flow conditions, such as herringbone crossbedding (Fig. 2-1), or biological indicators, such as characteristic biogenic structures or body fossils. Use of such criteria, however, can be problematic. For example, herringbone crossbedding is not restricted to tidal environments and has been reported from fluvial (Alam *et al.*, 1985) or storm-dominated lacustrine settings (Fraser and Hester, 1977). In addition, deposition within many tidal environments tends to be dominated by either ebb or flood tidal currents; thus strongly unidirectional flow is more common in tidal settings and bimodal-flow indicators would be rare.

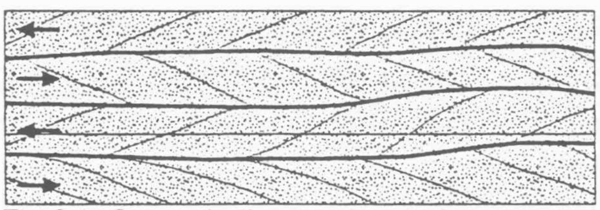

Fig. 2-1. Schematic diagram of herringbone crossbedding (cross-stratification) which has traditionally be used, because of bimodal current flow, as an indicator of tidal influences during deposition. As discussed in text, such crossbedding is rare and not necessarily confined to tidal settings.

Relying upon biological criteria can also be problematic because of a variety of factors. Bioturbation within certain tidally influenced settings can be minimized owing to very high rates of sedimentation or short-term fluctuations in salinity. Such factors tend to exclude habitation of the sediment by infaunal organisms. In terms of fossil content, some Carboniferous tidal estuarine facies can exhibit a wide range of terrestrial to marine forms (Feldman *et al*, in press). This mixing of marine, estuarine, and terrestrial fauna and flora can result in high diversity fossil assemblages that could readily be misinterpreted in terms of paleoenvironment if only selected elements of the diverse assemblage were used as a basis for an environmental assessment.

Related to the problems discussed above, there has been a lack of recognition of the importance of tidal processes in coal-bearing strata. There are useful criteria for delineating tidal facies that occur in association with coals. It appears that although tidal indicators are common within coal-bearing sections, these tidal facies were not generally formed in fully marine conditions. Because significant peat accumulations require generally wet climates, the high rates of freshwater flux in such environments can serve to reduce salinities in nearshore clastic depositional settings. This "freshening" serves to minimize the occurrence of "marine" indicators, such as characteristic trace- or body fossils.

In the following discussion, only a limited range of tidally influenced sedimentary environments are considered, and this range is restricted to settings which might normally be associated with peat-forming environments. This limits the discussion to fluvial, estuarine, and tidally-influenced deltaic settings. Because of sequence- stratigraphic considerations, the tidal influences recognized in coal-bearing sequences are most strongly developed in the roof facies and were developed during a rise in base level. This rise may be related to global factors, such as glacio-eustacy, or be more localized, such as subsidence related to growth faulting. Once the peats were flooded by a tidally influenced, clastic-depositional regime, there was commonly an abrupt termination of peat production and rapid accumulation of roof sequences exhibiting tidal bedforms.

Most of the tidal facies that occur as roof strata can apparently be considered as related to estuarine settings, which in this case refers to a sedimentational regime occurring within a zone of fresh- to saltwater mixing and a more detailed explanation of estuarine conditions will be considered in a later section. The relationships of the biological and sedimentological factors varies between differing types of estuarine systems. In estuarine settings where there is a high tidal range, however, rapid rates of sedimentation and highly fluctuating salinities can serve to reduce epi- and infaunal organisms and reduce or even eliminate significant amounts of bioturbation. It is this lack of obvious biological indicators that has lead to the interpretation as "nonmarine" of many ancient estuarine facies developed in coal-bearing sequences. A term such as "nonmarine" can become confusing and problematic in estuarine settings especially if it is considered to be synonymous with "terrestrial" or "lacustrine."

Biologic Indicators and Bioturbation

Sedimentation and biological activity on tidal flats with normal marine salinities has been widely discussed. However, the biogenic and physical sedimentary structures developed on brackish- and freshwater tidal flats has received less attention. Within meso- to macrotidal estuaries, significant tidal activity can extends for hundreds of kilometers landward from the estuary mouth. Within the upper parts of large estuaries, tidal flats can occur in fresh to brackish waters. When coupled with a high tidal range, these fresh- to brackish conditions can oscillate during a single semidiurnal tidal cycle. Although variations in salinity do not dramatically affect the development of physical sedimentary structures, such variations will profoundly affect the biological environment and the types of biogenic structures that are formed. Long-term habitation is greatly reduced in tidal flats that undergo extreme variations in both water level and water salinities. In such settings, the degree of bioturbation can be greatly reduced. Conversely, this lack of bioturbation leads to excellent potential for preservation of surficial trackways and physical sedimentary structures. This preservation potential is further increased in areas of rapid sedimentation that can occur within the turbidity maximum zone; such zones are commonly developed in the mixing zone of fresh- to brackish waters in well mixed, high-tidal-range estuaries.

In Carboniferous coal-bearing sections, silt-rich tidal rhythmites have been described from a number of settings in the U.S. (Kvale *et al.*, 1989; Kuecher *et al.*, 1990; Archer *et al*, 1992; Lanier *et al.*, in press). Laminated siltstones from these areas are essentially identical from sedimentological and ichnological standpoints. In general, the siltstones directly overlie thin, locally developed coals and encase upright trees that were rooted within the underlying coals.

Biogenic structures are common within the laminated siltstones and are restricted to surficial trails and trackways or very shallow (few mm) burrows. Hence the silt lamina of the tidal rhythmites are not bioturbated and burrows that penetrate deeper than a few mm are exceedingly rare. To date, biogenic structures from the Hindostan facies have been most extensively described (Archer and Maples, 1984; Maples and Archer, 1987); however, the most common forms also occur in abundance within the Tongonoxie Sandstone. The ichnogenera *Plangtichnus, Treptichnus*, and *Haplotichnus* are quite common and characterize such silt-rich tidal rhythmites. This suite of trace fossils is an uncommon and such forms have been interpreted to be formed by insect larva (Miller, 1889; Archer and Maples, 1984; Maples and Archer, 1987). A number of other invertebrate biogenic structures occur, some of the more significant are *Cochlichnus* and arthropod trackways such as *Kouphichnium.* Vertebrate biogenic structures include fish-fin drag marks and tetrapod trackways, both of which can be locally common.

Modern analogs for Carboniferous silt-rich tidal rhythmites have been reported from macrotidal estuarine settings. These settings include areas that have the highest tidal ranges in the world (greater than 15 m) and include the Bay of Fundy (Dalrymple et al., 1991) and the Bay of Mont Saint Michel (Tessier et al., 1989; Tessier, 1990). Because of its funnel-shaped geometry, tidal ranges within the Bay of Fundy are progressively amplified and tidal effects are propagated well up into the fluvial systems and many of the rivers connecting to the upper reaches of the Bay exhibit tidal bores.

Another well documented modern analog for tidal rhythmites is within the Bay of Mont Saint Michel in northwestern France. Preliminary comparisons between these tidal rhythmites and those associated with Carboniferous coal-bearing sections similar macrotidal conditions (Tessier *et al.*, 1992; in ed. review). Because of the extreme dominance of the tides in this bay, the sites of rhythmite deposition are not obviously "estuarine"; however, during high tides the flats are inundated by waters of essentially normal marine salinity whereas at low tides channels within the flats contains freshwater from fluvial sources. Thus at least the range of salinities that occur at the rhythmite sites follows variations typical of estuarine circulation patterns.

Diversity of preserved biogenic structures can be inversely related to amount of biological activity within the sediments during and post deposition. A high degree of activity serves to significantly disrupt the sediment-water interface; thus surficial trackways and trails and shallow burrows have a low degree of preservational potential in highly bioturbated sediments. The wide-range of salinity fluctuations in the tidal flats at the Bay of Fundy and Bay of Mont Saint Michel is related to the relatively small size of the fluvial flux as compared to the tidal range. Conversely, within estuarine systems with a larger fluvial flux, such as that developed within the St. Lawrence estuary (Quebec, Canada), tidal flat deposition occurs within more-or-less constant freshwater conditions with only minimized brackish incursions. Because of minimal, short-term variations in salinity, the intertidal flats can be significantly bioturbated.

Where tidal rhythmites are forming within the Bay of Fundy and Bay of Mont Saint Michel the sediments are not extensively bioturbated. This can be attributed to, among other factors, exceedingly high rates of sedimentation, extremely high turbidity, wide ranges in salinities, and significant periods of exposure during low tides. Although burrowing and bioturbation are absent, there are a variety of surficial trackways and trails produced by a mobile fauna. Because of the high tidal ranges, a variety of aqueous and terrestrial organisms can produce biogenic structures upon the same sediment layer. For example, deposition of a silt layer during flood tides can be subsequently marked by fins of bottom-hugging fish. During highest tides, water depths can exceed several meters, and a variety of swimming marine organisms can be producing biogenic structures as the high-stand clay drape if being deposited.

A number of features of macrotidal, silt-rich tidal flats that exhibit significantly ranges in salinities make such settings potentially useful analogs for understanding of facies such as the Carboniferous Hindostan Whetstone. The elevated tidal range that occurs on such tidal flats means that a variety of fresh- to brackish-water organisms may interact with the sediment during semidiurnal tidal cycles. In addition, a variety of terrestrial organisms will also interact with the same sediment layer as it become exposed during ebb.

Although all these biogenic structures are then subaerially exposed for periods ranging from hours to days (during neap-tidal periods), the cohesiveness of the silts readily maintains the structures until coverage by sedimentation during the next tidal cycle that will submerge the flat. Because of the low energies of the tidal flood and lack of erosive potential because of sediment saturation, there is a high degree of preservation of the all features that disrupted the surfaces of the preceding lamina. In addition, because tidal rise is quite rapid owing the elevated tidal range, the effects of wave reworking are minimized during flood tide. As an example of the rates of inundation, the flats of the Bay of Mont Saint Michel are approximately 15 km in width. Since the time period is about one-half tidal cycle from maximum exposure to maximum inundation, the lateral rates of inundation would average out to be about 64 cm/sec. Additionally, since the tidal range is about 15 m, the average vertical rate of inundation is about 0.64 mm/sec or about 3.9 cm/minute. These values assume a symmetrical tidal wave; however, in upper estuarine reaches, maximum flood commonly occurs within a few hours of maximum ebb. Thus the rates of inundation can be several times greater than those calculated above.

Tidal Currents and Paleoflow Analyses

Although the biological criteria needed to recognize tidal influence may be absent, a number of sedimentological criteria can be used. A traditionally used indicator of tidal influence is herringbone cross-stratification (Fig. 2-1); however, as discussed above this type of structure will not only probably be rare in many tidal settings, but more importantly, can occur in non-tidal environments. During a single rise and fall of the tides, current directions in open marine settings can continuous vary and make a complete 360 degree rotation during a single tidal cycle. Such settings are defined as having a "rotary" or "circumrotary" tide and in these situations, significant current velocities are maintained throughout the tidal cycle. Conversely, within restricted embayments and estuaries, current directions tend to be more linear with the flood-current directions being at 180 degrees to the ebb-current directions. In this type of setting velocities are maximized during incoming (flood) and outflowing (ebb) tides. During these times most of the sediment is transported and deposited. During highest reach of the tides, there can be a stillstand and fine-grained sediment that is being carried as aggregates in suspension will settle out of the water column and be deposited. Thus in intertidal environments, any bedforms produced during flood tides can be draped by a laterally persistent layer of mud. Such mud layers have been termed a "mud drape" or "clay drape." In subtidal settings, a mud drape can also accumulated during the stillstand associated with a low tide stillstand. Intertidal settings, because of subaerial exposure during low tide, do not form laterally continuous mud drapes during the low-tide stillstand. However, within locally ponded water, clays may settle out and form thin, discontinuous clay drapes during what is otherwise a period of subaerial exposure.

Bedform Development

Current velocities undergo marked variations in most tidal depositional regimes, and these variations can produce non constant rates of sediment accumulation and grain-size alternations. Tidal environments commonly exhibit specific types of reactivation surfaces, whereby previously deposited bedforms are modified and/or eroded by later deposition. Reactivation surfaces can be formed in steady-state systems owing to the development of erosional vortexes on the lee (down current) sides of larger-scale bedforms (Fig. 2-2). Such reactivations are common in many depositional systems that exhibit strongly unidirectional flow, including fluvial systems. Within tidal systems, however, more complex reactivations can be produced because of bedform modification during current reversal (de Mowbray and Visser, 1984). However, the types of tidal system that occur within estuarine systems commonly exhibit flood-tide velocities that are much more prominent than ebb-tide velocities. In this case, relatively simple reactivation surfaces are developed and consist of reworking of the toesets of larger-scale bedforms (Fig. 2-3). In a similar manner, near the upstream tidal limit, flood-tidal currents may modify larger-scale bedforms deposited through fluvial processes.

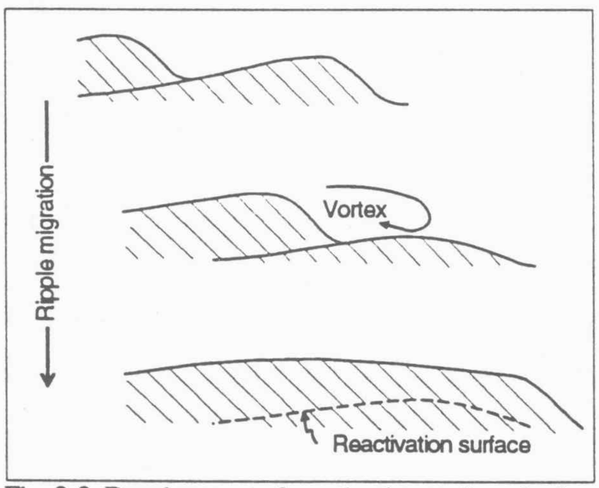

Fig. 2-2. Development of reactivation surfaces by lee-side current vortices (after McCabe and Jones, 1977). This type of reactivation forms in any setting where flow variations related to bedform development affect previously deposited sediment.

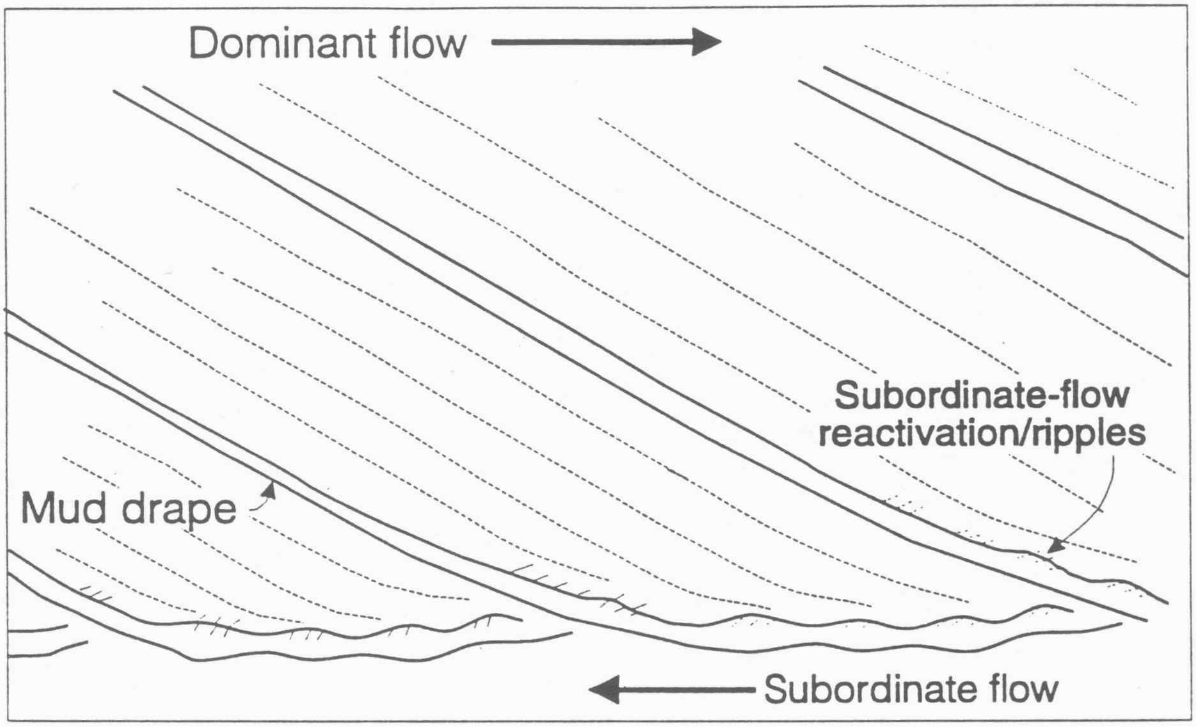

Fig. 2-3. Development of reactivation surface related to weak subordinate flow. Major crossbedding is produced by dominant flow; during subsequent lower-energy reverse flow, the toesets are reactivated and reworked into ripples. This type of reactivation occurs in settings where there is a strong asymmetry in the tidal-flow velocities, such as estuaries and tidally influenced fluvial systems. Adapted from de Mowbray and Visser, 1984).

On a smaller scale, specific ripple-sized bedforms can be indicative of tidal influences during sedimentation. There is a complex suite of interlayered sand and mud, rippled to planar laminations, which includes flaser, wavy, and lenticular bedding (Reineck and Wunderlich, 1968). These bedding types (Fig. 2-4) have been called "tidal bedding" because of a common occurrence in muddy tidal flats. Nonetheless, such bedding can occur in nontidal settings and has been reported from lacustrine and wave-dominated settings (Coleman and Pryor, 1982; Ridge and Larsen, 1990). This type of bedding, however, is extremely common in tidal environments and its pervasive occurrences strongly suggests tidal influence. Within the Illinois Basin, roof facies of many coals exhibit such tidal bedding and the bedform thicknesses commonly exhibit tidal periodicities (Kvale and Archer, 1990; Archer and Kvale, in press). This type of bedding, especially wavy and lenticular bedding is also common in the lignite mines of the Gulf Coast (Breyer, 1987) such as that visited during the accompanying field trip. The variations in flow velocities that occur during individual tidal cycles create the sand/mud alternations. For instance, high flow velocities produced during flood or ebb tides result in bedload deposition of sand. During stillstands (related to high- or low-water conditions), deposition from suspension will result in the formation of a clay or mud layer. This fine-grained layer, which can be termed a "mud drape," indicates that depositional system had periods of essentially zero velocity. Mud-draped, sand-dominated bedforms, ranging from ripple- to dune-sized, have been termed "heterolithic bedding" Although mud-drapes can form in many depositional settings, abundant

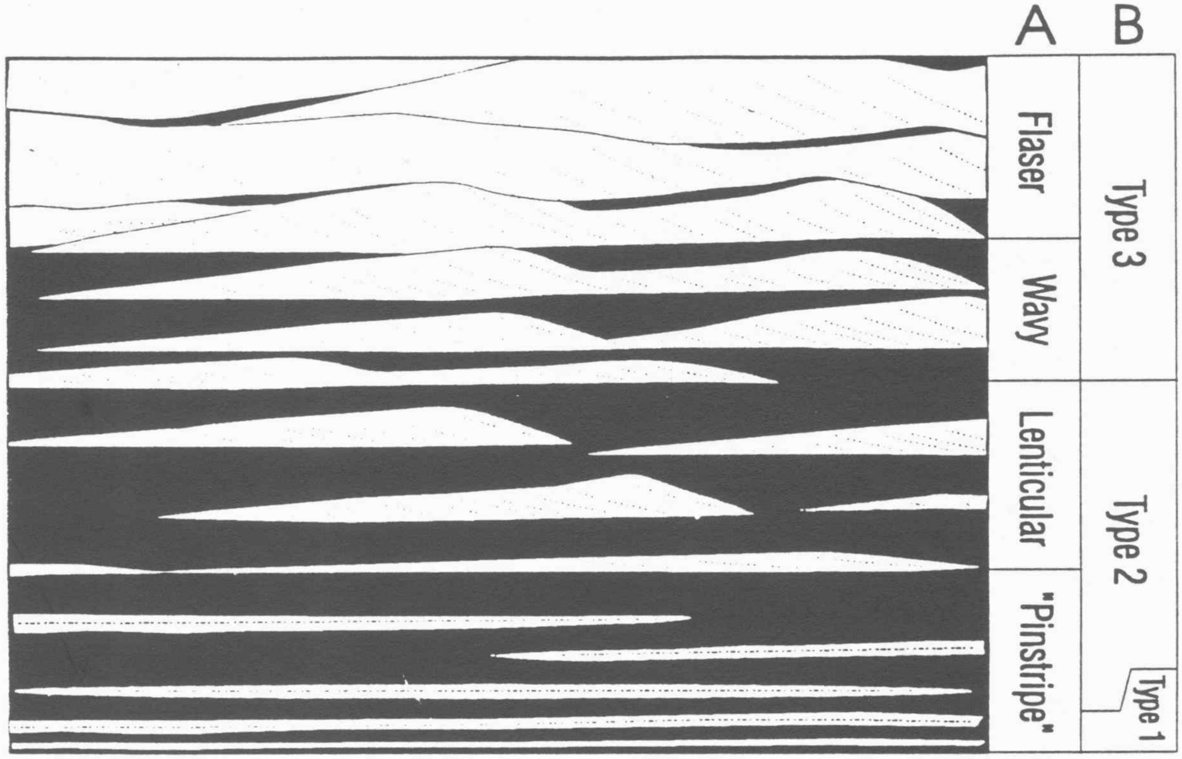

Fig. 2-4. Relationships of flaser, lenticular, and wavy bedding (Reineck and Wunderlich, 1968) to "pinstripe" bedding (Klein, 1977) to types described from roof strata of Carboniferous, Illinois Basin coals (Kvale and Archer, 1990). This bedding, which has been referred to as "tidal bedding" is not restricted to, but is characteristic of, tidal environments where sedimentation alternates between bed- and suspended-load deposition.

occurrences become very suggestive of tidal processes. The presence of mud-draped large-scale bedforms, or "inclined heterolithic bedding" in point-bars is a useful indicator of probable influence (Smith, 1988a,b,c). Large-scale, mud-draped lateral accretion surfaces are also a common feature of Gulf Coast Lignite mines (Breyer, 1989) and are useful indicators of estuarine point-bar deposition.

When mud-drapes occur in more-or-less consistently in pairs, a tidal origin is very strongly suggested. Many tidal rhythmites contain successive bedform thicknesses that exhibit a prominent thick-thin pairing. This pairing occurs in both vertically and laterally accreted forms. These pairs have been referred to as a variety of terms including "couplets" (Kvale *et al.*, 1989) Because each element of the pair can be clay draped, the pair has also been described as a "mud couplet" (Smith, 1988b). The development of these pairs has been interpreted in two ways, both of which are probably correct depending on the setting. Originally, there was a tendency to interpret the pairing in terms of a single flood-ebb tidal cycle. Because most tidal settings exhibit an pronounced asymmetry in flood versus ebb velocities, the thicker member of a pair would be formed during the "dominant" half of the cycle, and could be either flood or ebb related. The thinner member of the pair would then be formed during the "subordinant" half of the tidal cycle. In this case, the pairing could theoretically be formed in any tidal system, ranging from diurnal to semidiurnal (Fig. 2-5a).

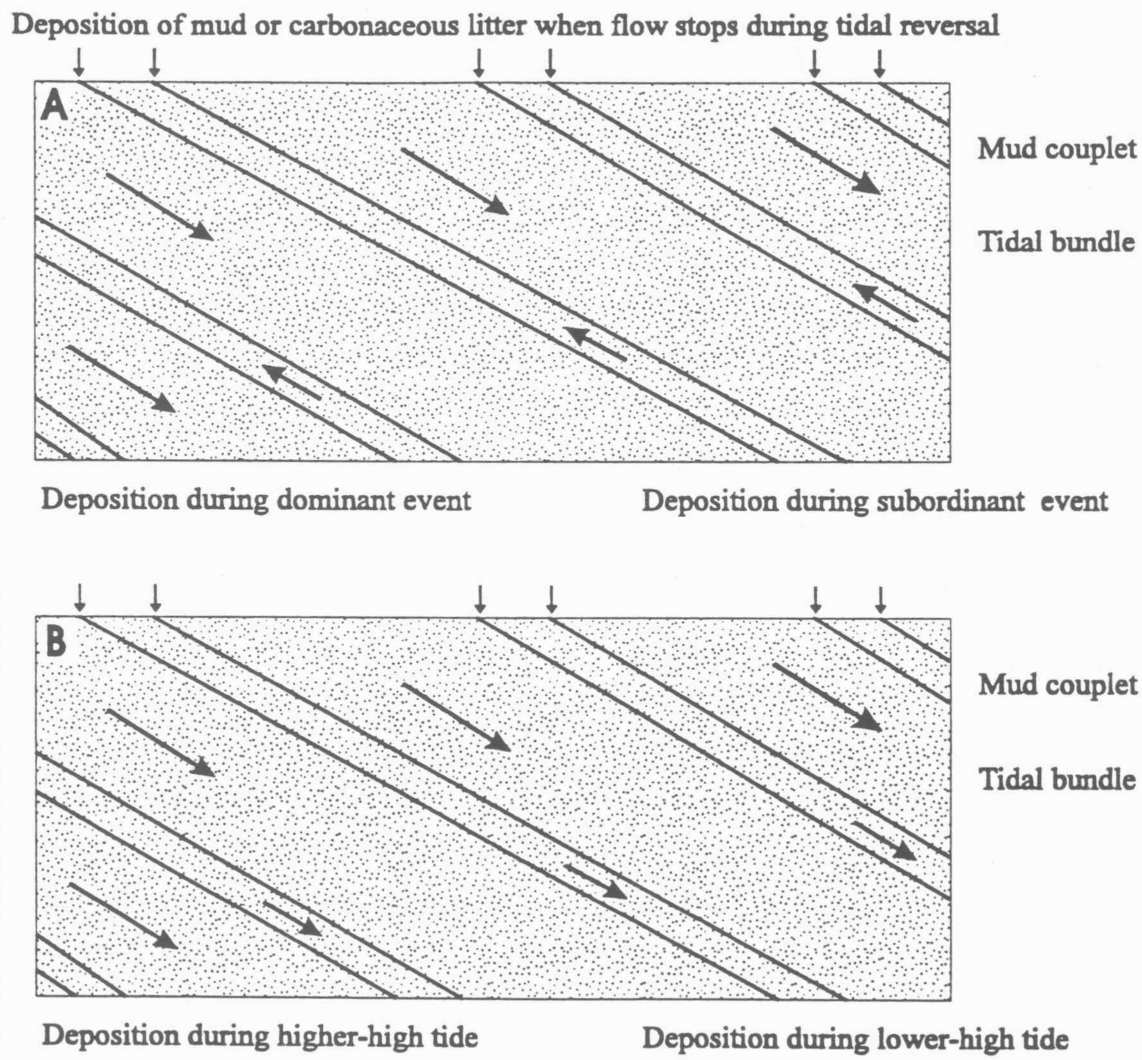

Fig. 2-5. Development of mud couplets in tidal settings by (A) dominant-subordinant ("flood-ebb") flow, or (B) by dominant flow in a semidiurnal tidal system with a marked diurnal inequality. (part A adapted from Smith, 1988b). Either system will generate mud-draped pairs of foresets; thus mud couplets are a useful indicator of tidal influences.

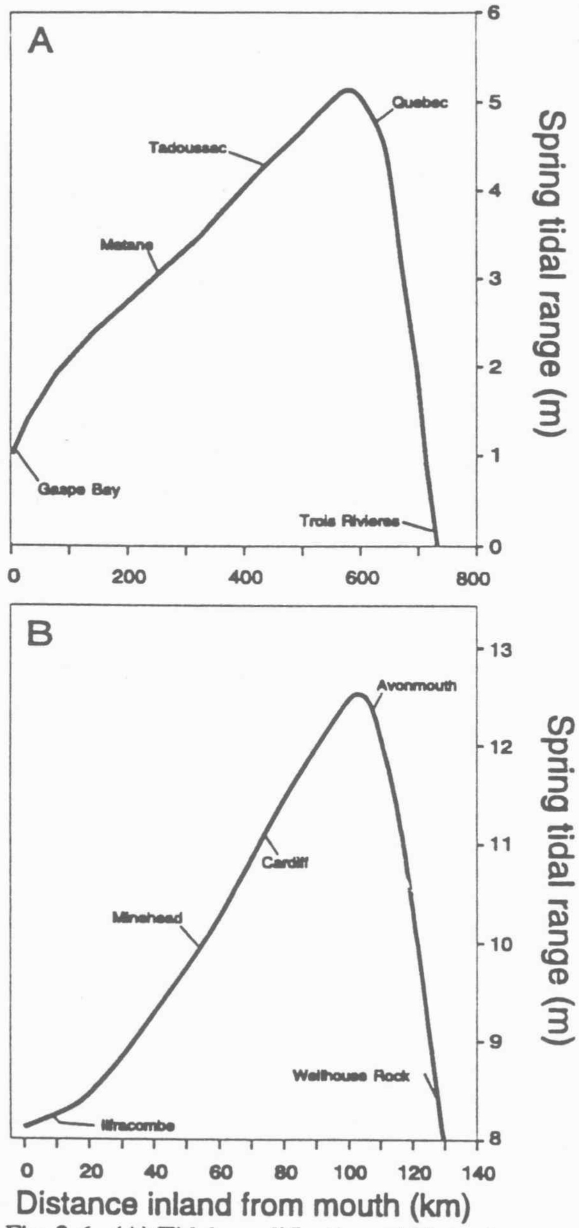

Fig. 2-6. (A) Tidal amplification within major estuarine systems. These diagrams were constructed by extrapolating spring-tidal ranges to a midline within the estuary. (A) Within the Severn Estuary of southwestern England, macrotidal coastal systems are amplified to a severely macrotidal system (data from Hoare and Haggett, 1979, p. 15 with additional information from NOAA, 1991a). (B) Amplification along St. Lawrence River Estuary increases coastal microtidal systems to a low macrotidal system. Note the amplification is maximized at a considerably distance from the "mouth" of the system (data from NOAA, 1991b).

Another way in which pairing can be developed is in a semidiurnal system with a marked diurnal inequality, such as the system described above for Savanna, Georgia (Fig. 1-1). For simple pairing to be developed, the dominant (flood or ebb) flow velocities must be so much higher than the subordinant (ebb or flood) velocities that no sediment accumulation occurs during the subordinant flow. Because sedimentation is only occurring during dominant flow, the thickness inequality between the members of the pair is proportional to the diurnal difference in dominant flow velocities, which in turn is proportional to the diurnal inequality in tidal heights between the successive, semidiurnal high tides. Rhythmites with pairing formed in this manner can be expressed diagrammatically as in Figure 2-5b.

Tide-influenced Estuaries

The presence of clay draped bedforms indicates stillstands during deposition, as such stillstands are particular common in tidal environments. When bedforms are pervasively clay draped, it is also suggestive of high turbidity levels. Such high levels can be produced by a variety of ways, such as wave activity, but some of the highest levels of turbidity developed within tidal estuarine systems. Within tidal estuaries, a unique pattern of facies is a function of distinctive patterns of water circulation caused by the interaction of saline and fresh water and the opposing forces of tidal and fluvial currents (Dyer, 1973, 1979, 1988; McDowell and O'Conner, 1977).

Within estuarine and fluvial settings, tidal energies can be propagated for considerable distances up river. Within specific estuarine geometries, tidal heights can be significantly amplified upstream (Fig. 2-6). For example, coastal areas at the eastern end of the St. Lawrence seaway are only microtidal (tidal range less than 1 m in this case), but near Quebec, which is nearly 700 km inland, the tidal range become becomes macrotidal (Fig. 2-6a) and large-scale tidal flats are formed along the banks of the St. Lawrence estuary. Because of the great outflow of the St. Lawrence River, these macrotidal flats are formed in a dominantly freshwater setting. Many other examples of freshwater tidal flats occur within tidally influenced fluvio- estuarine settings. Even in areas of macrotidal coastal systems, such as southeastern England, tidal amplification within the Severn Estuary leads to very high tidal ranges (Fig. 2-6b). In general, a higher tidal range leads to more extensive tidal flats and marshes and a much more dynamic sedimentational system.

Ideally, an estuary is defined as having a salinity gradient occurring in an area of fresh- and saltwater mixing. However, an adequate and reliable assessment of paleosalinities is not always possible; thus we are forced to rely upon salinity proxies, such as specific sedimentological criteria (Fig. 2-7). In addition, biogenic sedimentary structures or body

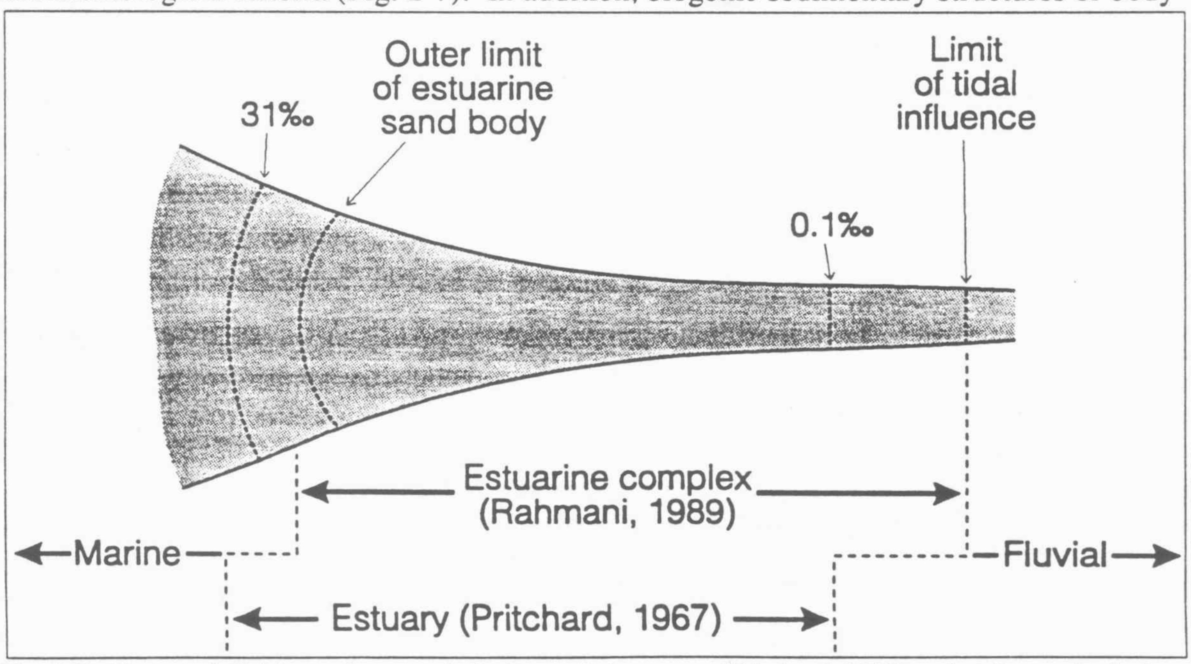

Fig. 2-7. Various definitions of estuary including salinity ranges (Pritchard, 1967) and sedimentological criteria (Rahmani, 1989). Adapted from Dalrymple and Zaitlin (1989, Fig. 2).

fossils can also be used as estimates of paleosalinities, although as discussed above, areas of highly fluctuating salinity, high turbidity, and rapid rates of sedimentation may serve to greatly reduce biotic activity within the sediment and curtail benthic habitation.

The complex fresh- and saltwater circulation patterns lead to the formation of a turbidity maximum in most estuaries. In stratified estuaries, water volumes introduced during a tidal cycle are small relative to the river-water volumes and the turbidity maximum is maintained near the toe of the salt-water wedge that intrudes into the estuary (Fig. 2-8). In well mixed estuaries vertical salinity stratification is absent; however, the turbidity maximum can be maintained by tidal currents (Allen *et al.*, 1980). Estuaries with high tidal ranges, such as the Bay of Fundy, Bay of Mont Saint Michel, Gironde Estuary, and Severn River Estuary, are commonly well mixed because of the tidal flux.

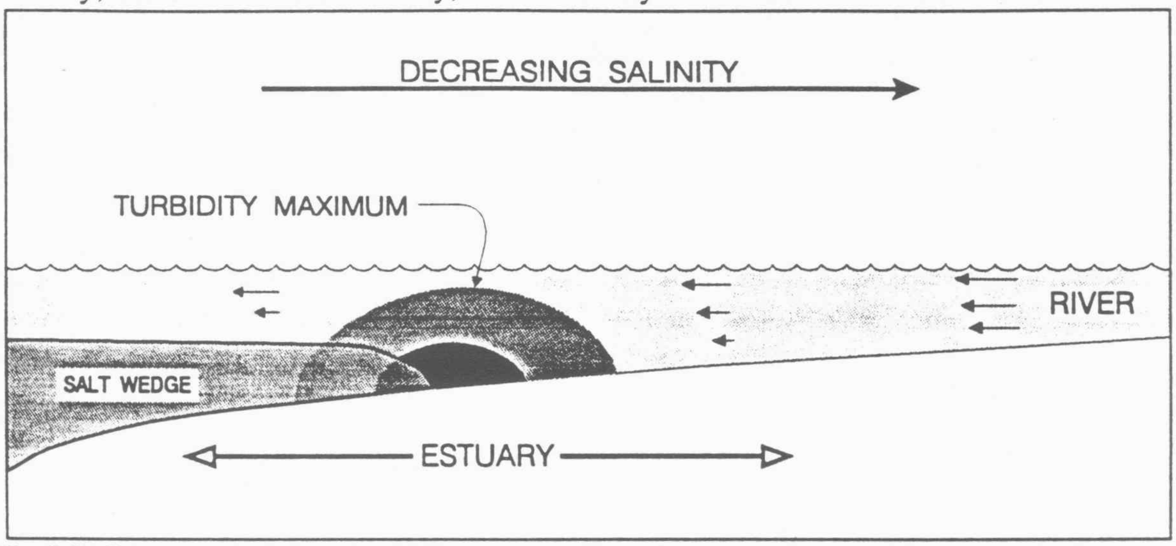

Fig. 2-8. Schematic depiction of turbidity maximum formed in meso- to macrotidal estuary related to position of salt- freshwater mixing zone. High turbidity levels within such an estuary will result in mud draping (via suspension deposition) of bedforms produced by bedload deposition during fluvial/tidal processes. After Rahmani (1989; originally from Allen, 1972).

Estuarine circulation and the presence of a turbidity maximum can result in a tripartite facies distribution that is characterized by a fluvial to marine coarse-fine-coarse pattern of sedimentation (Dyer, 1979; Rahmani, 1989; Nichols *et al.*, 1991; Dalrymple *et al.*, 1991) (Fig. 2-9). Coarse sediment is primarily deposited in the narrow upper parts of estuaries where cross-sectional areas are small and fluvial deposition is dominant. As the systems widens, fluvial processes begin to merge with estuarine processes and because of dechannelization, this is a area of rapid fluvio-estuarine deposition of the coarser, bedload sediments. Current velocity stillstands induced by tidal activity will result in large-scale clay draping of these fluvial bedforms. In the middle estuary bottom currents are weak, turbidity is high, and the sediment is generally muddy. Much of the suspended mud is deposited during slack water during high and low tide. As tidal velocity decreases suspended sediment is deposited as normally graded layers. Muddy tidal flats can be well developed in the middle estuary; such flats can contain heterolithic bedding consisting of sand layers deposited during maximum tidal velocities and clay drapes formed during stillstands that occur during the tidal maximum. In the bay mouth, bottom currents are higher, and marine processes such as waves and tides can deposit coarse marine sediment.

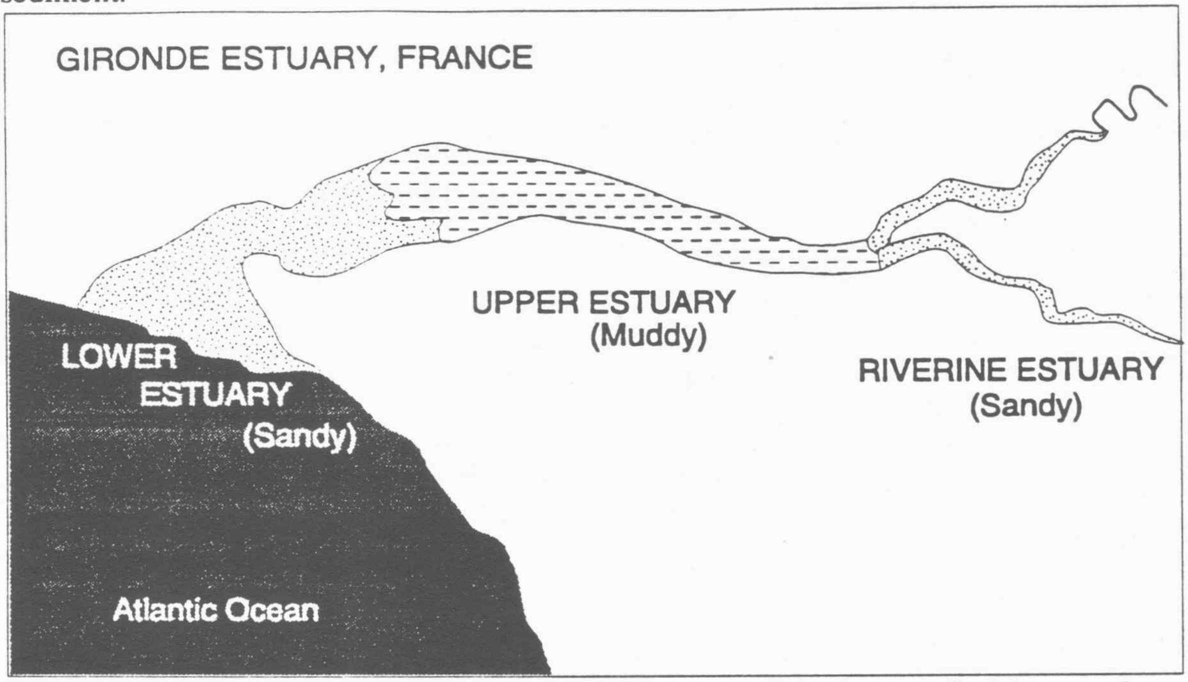

Fig. 2-9. Tripartite division of facies within Gironde estuary with sand dominance in fluvial part, mud dominance in estuarine part, and sand dominance in marine-influenced part. After Rahmani (1989; originally from Allen, 1972).

This tripartite facies distribution has been documented from several estuarine systems (Dalrymple *et al.*, 1991; Allen, 1991; Dorjes and Howard, 1975; Nichols *et al.*, 1991) and appears to be a useful criteria for recognition of ancient estuarine systems. This tripartite model has only recently been widely discussed in the sedimentological literature. Thus older environmental interpretations of some coal-bearing sections did not have access to such models. Without using this type of tripartite model, the sandy fluvial to muddy estuarine transition could easily be misinterpreted as a "deltaic" to "prodeltaic" transition and furthermore, the marine sands at the mouth of the estuary be misinterpreted as "offshore bars" or "barrier islands." Some older literature that invoked such traditional fluvio-deltaic interpretations could probably be re-evaluated in terms of the more recent tripartite estuarine models. In Carboniferous strata, the "muddy lacustrine delta" model is probably one that, in many cases, could also be interpreted within the context of a fluvio-estuarine transition.

Rates of Sediment Accumulation

Tidal energies are readily capable of pumping large amounts of fine-grained sediments of marine origin into inland estuarine depositional settings. For example, many of the estuaries formed by drowning of river valleys during the Holocene transgression have filled with decameters of tidally emplaced silts. Although the geological lifetime of an estuary is generally short, it capability to trap rapidly deposited sediments is high. Given the apparently episodic nature of the rock record, this is the type of coastal setting that will have a higher preservational potential than those settings that have a more continuous, but slower, rates of sedimentation. Thus these tidally emplaced sediments epitomize a feature of the rock record that can been characterized as consisting of extremely discontinuous sedimentation over long periods of time, but continuous for very short periods of time.

As compared to estimates of meter-scale sediment- accumulation rates of marine sediments in Carboniferous coal basins (Busch and Rollins, 1984; Busch and West, 1987), Carboniferous tidal rhythmites exhibit high rates of vertical accretion. For example, some sections exhibit apparently yearly cycles in which yearly rates of deposition approximated 1 m/yr (Kvale *et al.*, 1989). Estimates of such vertical accretion rates can be computed based upon the recognition of semidiurnal laminae, occurrence and thickness of neap-spring cycles, and the interpretation of larger-scale patterns as yearly in origin. Such high rates are supported by other observations, such as the occurrence of upright lycopod trunks (Kvale *et al.*, 1989). Other studies of similar marine- influenced coal-bearing strata have likewise suggested that very high rates of sedimentation were possible (Kuecher, 1983; Baird *et al.*, 1986; Kuecher *et al.*, 1990).

Tidal Periods

Before proceeding, a brief discussion of the various tidal periods is relevant. The various periodicities related to tides are complex and are only briefly summarized here. Relations of tidal periodicities that can be encoded in tidal sediments is presented in more detail in Archer *et al.* (1991). The important point is that successive bedform thicknesses may contain tidal-period information and if this occurs, the presence of such periodicities is a very reliable indicator of tidal influence during sedimentation.

The rise and fall of tides are related to tidal bulges created in the oceans by the gravitational attraction of the moon and sun (Fig. 2-10a). Because gravitational force is inversely related to distance, the moon, although it has a much smaller mass than the sun, exerts much greater tidal effects. Thus tides are constrained by moon, and it requires 24 hours and 50 minutes for the moon to return to the same relative position in the sky. In most coastal areas, there are two high tides per day and these are referred to as "semidiurnal" tides and have a period of 12 hours and 25 minutes. In partially enclosed seas and gulfs, a single high tide per day may occur, and this is termed a "diurnal" system. Diurnal tides characterize many tidal stations in the Gulf of Mexico, whereas more open coastal settings are characterized by predominantly semidiurnal tides.

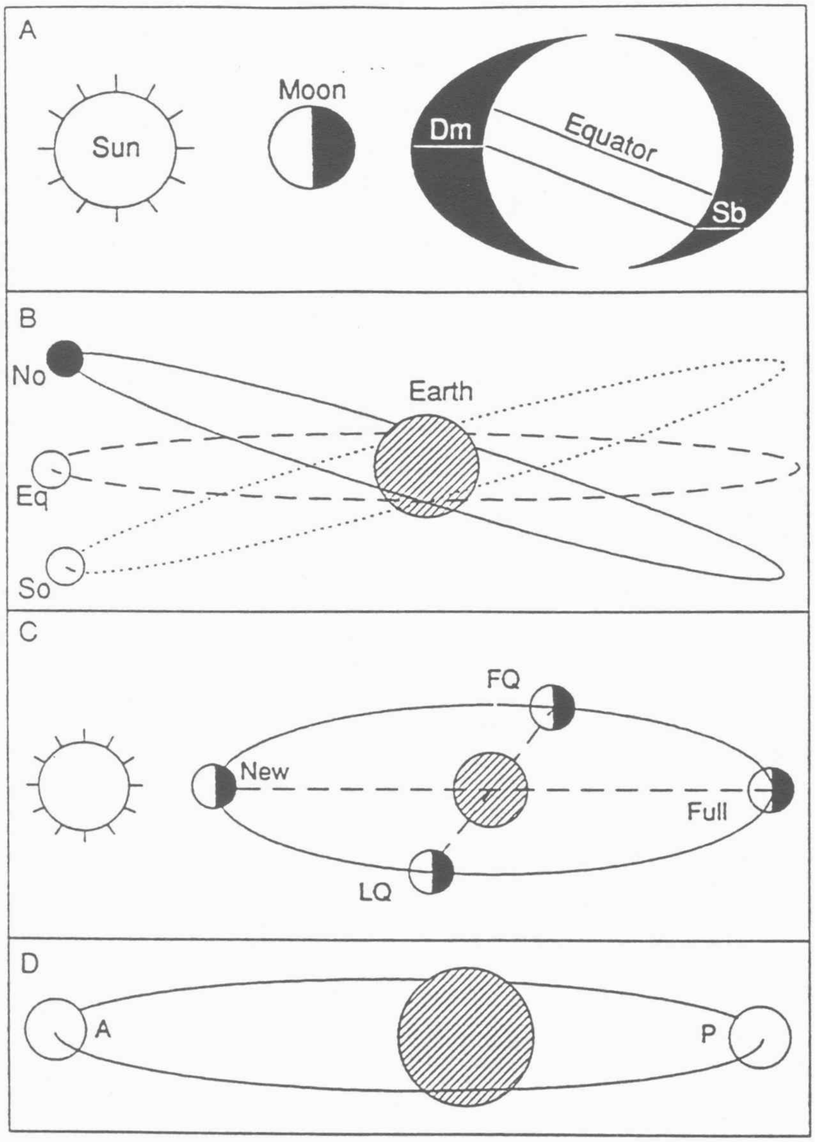

Fig. 2-10. Principal earth-moon interactions that produced various tidal cycles. (A) Diagrammatic tidal bulge as produced on the earth by the gravitational effects of the moon and sun and resultant semidiurnal (twice daily) tidal inequality that occurs in southern latitudes. During one day, a higher high, or dominant (Dm), tide and a lower high, or subordinate (Sb), tide are produced. (B) Effects of lunar declination which results in variations in the diurnal inequality. Moon diagrammed at maximum northerly declination ("No"), at equatorial passage ("Eq"), and at maximum southerly declination ("So"). (C) Synodic month, which is related to the phases of the moon. Phases include new and full moons as well as first quarter ("FQ") and last quarter ("LQ"). This is the principal cause of neap-spring tidal cycles, with highest (spring) tides occurring during either a new or full moon (syzygy). (D) Anomalistic month, which is related to lunar-orbital eccentricity. Spring tides during lunar perigee ("P") can be significantly higher than spring tides produced during lunar apogee ("A").

In semidiurnal systems, there may be a height difference between the two daily high tides. This difference is termed the "diurnal inequality" and is related to the inclination, or declination, of the moon's orbit to the earth's equatorial plane (Fig. 2-10b). Lunar declination varies over a 27.3 day period that is termed the "tropical" month. When the moon is directly over the earth's equator the diurnal inequality is minimized, conversely when the moon has a maximal northerly or southerly declination, the diurnal inequality is maximized. The period from minimal to maximal to minimal diurnal inequality is half the tropical month, or 13.66 days. In purely diurnal (single high tide per day) tidal systems, the tropical-month period is the dominant control on tidal heights.

Alignment of the sun, moon, and earth (syzygy) occurs when the moon is in new and full stages. During these times, the tidal bulges created by the gravitational effects of the moon and sun are additive and the highest, or spring, tides occur (Fig. 2-10c). During first and last quarters of the moon (quadrature), tidal bulges created by the moon and sun are out of phase and lowest, or neap, tides occur. During a single lunar orbit (synodic month), which is approximately 29.5 days, two periods and spring and two periods of neap tides occur. Thus a neap-spring cycle occurs every 14.75 days and this cycle characterizes semidiurnal tidal systems.

The lunar orbit is elliptical and tides are significantly higher during the closest approach (perigee) of the moon to the earth. Period of time between successive perigees is 27.55 days, and this is termed the "anomalistic" month (Fig. 2-10d). Note that the periods of the synodic, tropical, and anomalistic month also of the same magnitude, are significantly different, and are constantly varying in their phase relationships. When syzygy (new or full moon) and perigee coincide, unusually high tides occur.

Having defined the various small-scale tidal cycles, comparisons to Carboniferous tidal rhythmites can be made. In general, the ancient depositional systems that produced the deposits described herein were able to respond to sub-daily depositional events that apparently corresponded to the rise or fall of tides. In the Carboniferous systems studied, sedimentological analyses of small-scale tidal bundles of vertically accreted mudstone laminae and ripples indicate these deposits were forming within a dominantly unimodal current regime, with either flood or ebb dominance (Kvale and Archer, 1990). Laminae thicknesses are apparently related to flux of water and sediment during tidal cycles, this flux being directly related to tidal height. Because of this relatively simple relationship, plots of lamina thicknesses for a series of sequential, continuously deposited laminae exhibit patterns that can be directly related to the hierarchy of modern tidal cycles discussed previously. Such diagrams, based on analyses of the Hindostan facies in Indiana, exhibit systematic lamina- thickness variation (Fig. 2-11) that can be related to neap-spring tidal cycles produced during syzygy. In some cases, laminae are commonly conspicuously paired (see Kvale *et al.*, 1989) as a thicker and thinner set. These laminae pairs are apparently a response to a semidiurnal tidal system and their thickness inequality a reflection of the ancient diurnal inequality. The thickness inequality within laminae pairs exhibits variations that are similar to variations exhibited in the diurnal inequality during changes in lunar declination (tropical month). Thus, when the individual lamina in laminae pairs are approximately equal in thickness, this appears to reflect an ancient equatorial passage of the moon ("Eq" on Fig. 2-11). Conversely, when there is a marked inequality in laminae-pair thicknesses, a high declination of the ancient moon is suggested.

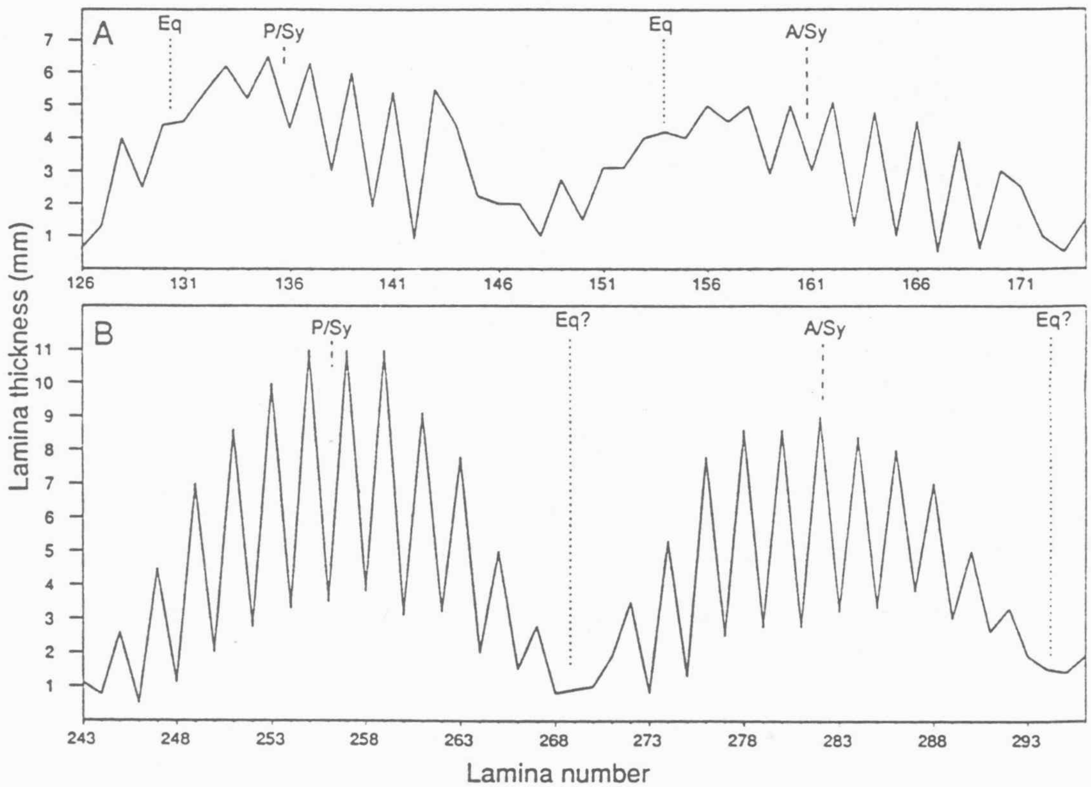

Fig. 2-11. Lamina-thickness measurements from Carboniferous tidal sequence in Hindostan Whetstone. Horizontal axes refer to sequential laminae number; these plots are part of a nearly continuous series of approximately 2000 laminae measurements. Thickness periodicities exhibit prominent thick- thin relationships that are interpreted as being the effect of semidiurnal tidal deposition. Longer term Periodicities are interpreted as neap-spring cycles and successive neap-spring cycles exhibit significant different in maximum laminae thicknesses. Thickest laminae probably correspond to spring tides produced during new or full moons, or syzygy (Sy). Higher spring tides probably produced during lunar perigee (P) and lower series of spring tides were probably produced during lunar apogee (A). Where successive laminae are approximately equal in thickness probably reflect reduced diurnal inequality produced during equatorial passage of the moon (Eq) during a tropical month. Upper diagram (A) illustrates thinner (less than 7 mm, laminations with reduced difference between subordinate and dominant laminae. Lower diagram (B) illustrates thicker laminae (as much as 11 mm, interspersed with thin subordinate laminae.

The changing distance of the ancient moon (apogee to perigee) is also apparently reflected in laminae-thickness series. Successive zones of thicker laminae (inferred spring tides) exhibit variations that are similar to modern tidal records. Thus the approximate occurrence of ancient lunar perigee ("P" on Fig. 2-11) and apogee ("A" on Fig. 2-11) can be estimated within a lamina- thickness series. As discussed previously for modern tides, spring tides tend to be higher during perigee than compared to spring tides occurring during apogee.

Apparently yearly cycles are evident when a number of neap-spring cycle thicknesses are plotted. Such cycles are expressed by a systematic increase and decrease in maximal neap-spring cycle thicknesses; the periodicity of these variations is on the order of hundreds of laminae (Fig. 2-12).

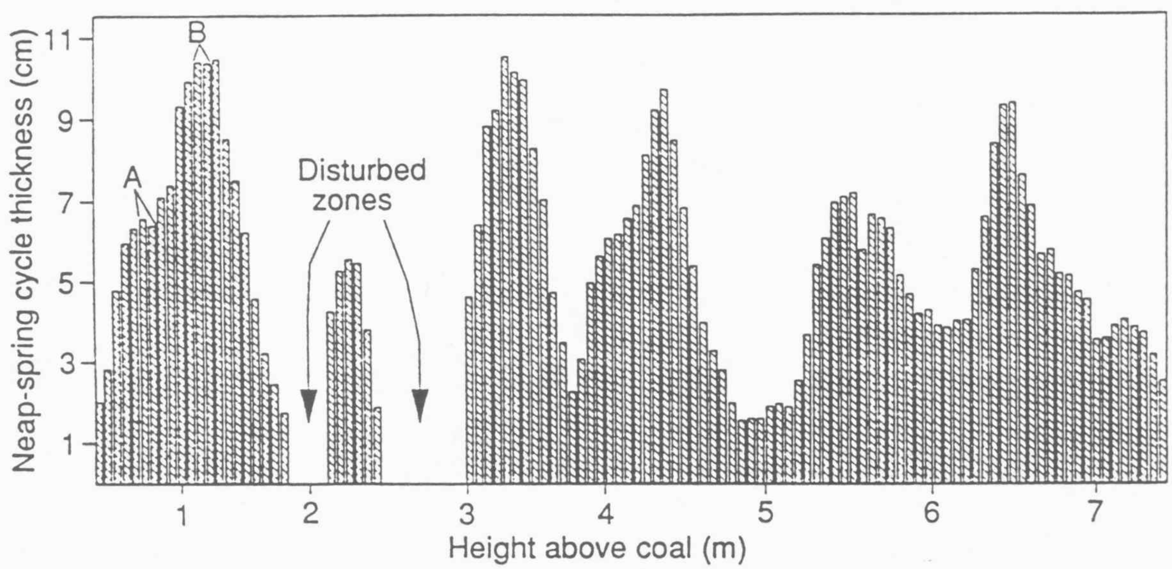

Fig. 2-12. Systematic thickness variations in neap-zone spacing within the Hindostan Whetstone as measured above the underlying coal (measured interval is "Td" of Fig. 2-13). These measurements are based upon the distance between two zones of closely spaced laminae, which were probably formed during neap tides. Six large-scale cycles are evident; the second cycle contains two disturbed zones containing highly convolute laminae in which neap-zone spacing were not measurable. Location of Figure 2-11a and 2-11b is indicating within first cycle as "A" and "B" respectively.

The apparently yearly cycles can be related to yearly variations in sea level. Yearly sea-level variations also occur across much of the earth; direct astronomical effects are in part responsible for yearly sea-level change. In addition, sea level is also affected by seasonally varying parameters such as temperature, salinity, and air pressure. In addition, these yearly cycles may related to variations in clastic influx into the tidal estuary related to seasonal fluvial flooding. To summarize, the presence of a variety of scales of depositional events that can be related to tidal periodicities provides a strong argument for an interpretation of paleotidal controls during sedimentation. The rapidity of paleodeposition of such tidal facies that directly overlie coals is undoubtedly a major factor in the original preservation of peat thickness and ultimately the quality of the coal.

Tidal Estuarine Model for Carboniferous Coals

Beyond "cyclothems"

The concept of repetitive cycles of sedimentation, or "cyclothems," has long been entrenched in discussions of Carboniferous coal-bearing sections, particularly those within the Interior Coal Basins (Illinois, Forest City, and other midcontinental depositional basins). The general cyclothem model was first widely applied within the Eastern Interior Coal Basin (Illinois Basin), but subsequently received widespread application throughout the midcontinent, particularly in Kansas (see Moore, 1930, 1936). There is nothing intrinsically wrong with the concept of cyclic sedimentation, and these original cyclothemic concepts helped pave the way for the development of sequence-stratigraphic concepts. Nonetheless, rigid application of "cyclothem" models can be problematic, especially when aspects of lateral variations are not taken into consideration. In the following discussion, some of the stratigraphy and sedimentological relationships of the Mansfield and Brazil formations in Indiana and Douglas Group of Kansas are discussed. Location and general stratigraphy of these areas is portrayed in Fig. 3-1.

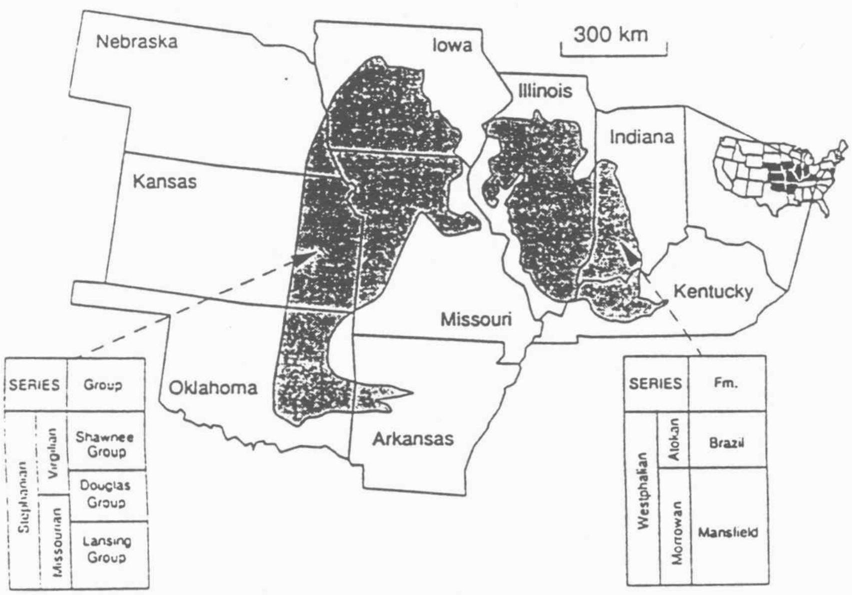

Fig. 3-1. General outlines of the Eastern Interior Coal Basin (Illinois Basin) and Western Interior Coal Basin and generalized stratigraphic framework for units discussed in text.

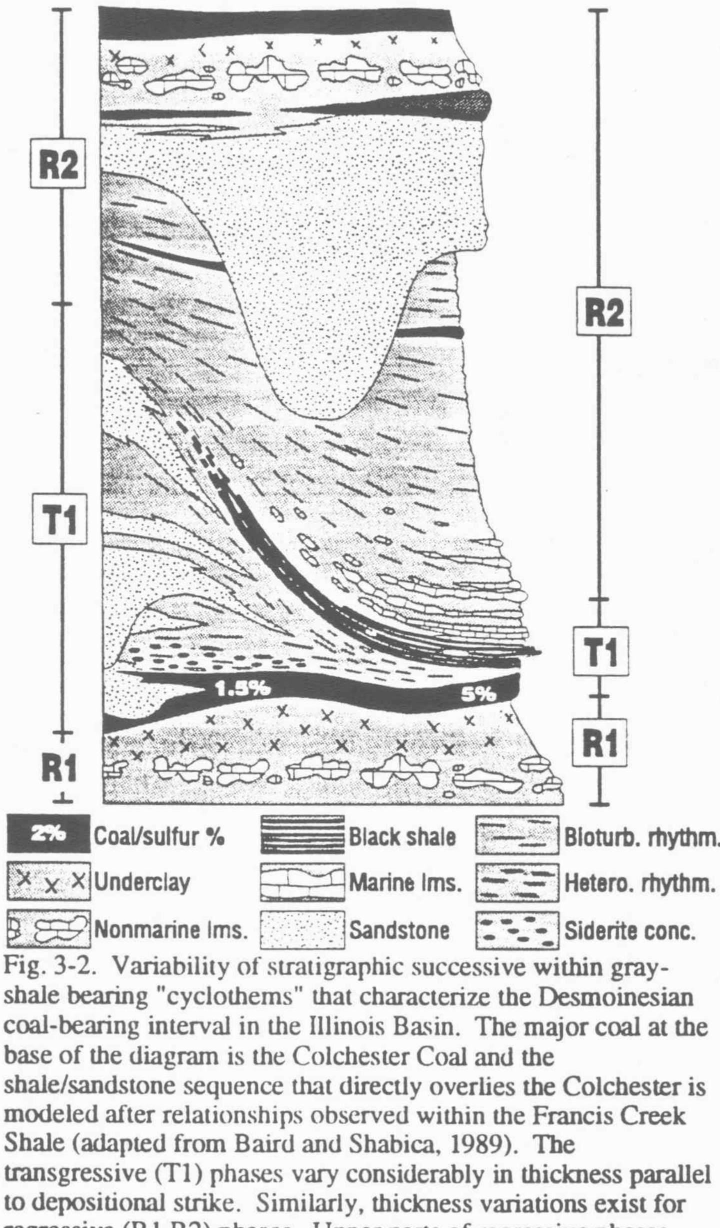

Fig. 3-2. Variability of stratigraphic successive within gray-shale bearing "cyclothems" that characterize the Desmoinesian coal-bearing interval in the Illinois Basin. The major coal at the base of the diagram is the Colchester Coal and the shale/sandstone sequence that directly overlies the Colchester is modeled after relationships observed within the Francis Creek Shale (adapted from Baird and Shabica, 1989). The transgressive (T1) phases vary considerably in thickness parallel to depositional strike. Similarly, thickness variations exist for regressive (R1,R2) phases. Upper parts of regressive phases undergo protracted periods of nonmarine deposition, erosion, pedagenesis, and peat accumulation. During this time a vast alluvial plain was formed that lead to the subsequent development of widespread mires. During transgression, mires overlain by estuarine sequences (left side) develop thicker, low-sulfur coals as compared to mires overlain by marine facies (right side). Sulfur value relationships adapted from Gluskoter and Hopkins (1970).

Attempts to create an idealized, or conceptually pure cyclothem model have always been doomed to failure because of the high degree of lateral variability that characterizes the Carboniferous coal measures of the midcontinental U.S. The basic nature of this variability (see Fig. 3-2) can be related to two primary controlling factors: 1) the precursor, erosional topography upon which the stratigraphic sequence was formed, and 2) the ongoing depositional topography that was created and maintained by the clastic-delivery system (fluvio-, estuarine, and deltaic complex). Once these types of factors are taken into consideration, then it becomes possible to separate their effects was the other processes that produced the thin, widespread, "layer-cake" components of the "cyclothems."

A glacio-eustatic control for large-scale patterns of sedimentation for the much of the upper Carboniferous appear to be well documented (Heckel, 1986). These dramatic changes in sea level, which were probably on the order of 100 meters, resulted in broad shifts in coastline positions. Because of large continental area and probable large drainage basins, and large amounts of freshwater flux owing to the wet tropical conditions, the midcontinental fluvial systems developed during the

Carboniferous were probably of a very large scale. During lowstands, these fluvial systems incised broad valleys into the previous deposited, but largely unlithified sediments. Subsequently, during highstands a clear-water carbonate depositional regime was established. This oscillations of sea level has produced the well developed cycles in the midcontinent (see Fig. 3-3), originally termed "megacyclothems" by R. C. Moore (1930, 1936) and as a concept simplified to a "cyclothem" by Heckel (1977). The more terrigenous parts of these cycles, which are stratigraphically complex, can contain significant coal-bearing sections (Fig. 3-4). Although these cycles are commonly considered to be the product simply of eustatic flux, there are climatic, structural, and valley-incisement factors that also need to be considered which affected local and regional clastic flux.

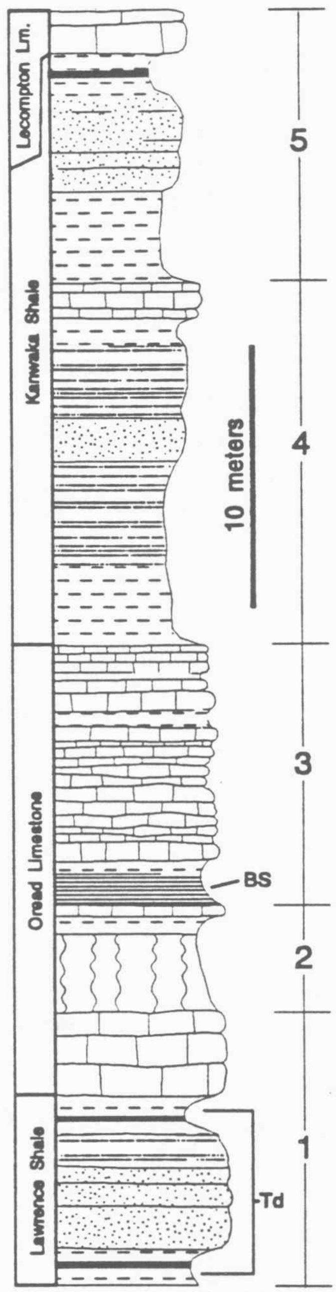

Fig. 3-3. Portion of lower Virgilian stratigraphic sequence from eastern Kansas (adapted from Moore, 1936). This "cycle of cyclothems", or "megacyclothem", has also been referred to as a "cyclothem" by Heckel (1977). Individual clastic-to-carbonate cycles (cyclothems) are numbered. Tidal-rhythmite-bearing Lawrence Shale (Td, and Fig. 3a) occurs in lower part of megacyclothem. Cyclothems 1 and 5 are more clastic rich and can contain coals. Conversely, cyclothem 3 is carbonate dominated and in addition contains organic-rich, black shale (BS).

Gray-shale wedges

At lamination scale of millimeters to centimeters, vertically accreted tidal rhythmites occur at a number of coal-bearing sections. Laminations include mud, silt, and sand-rich variants and in forms with progressively greater amounts of sand, lenticular, wavy, and ultimately flaser bedding is developed. Planar lamina that exhibit well defined tidal

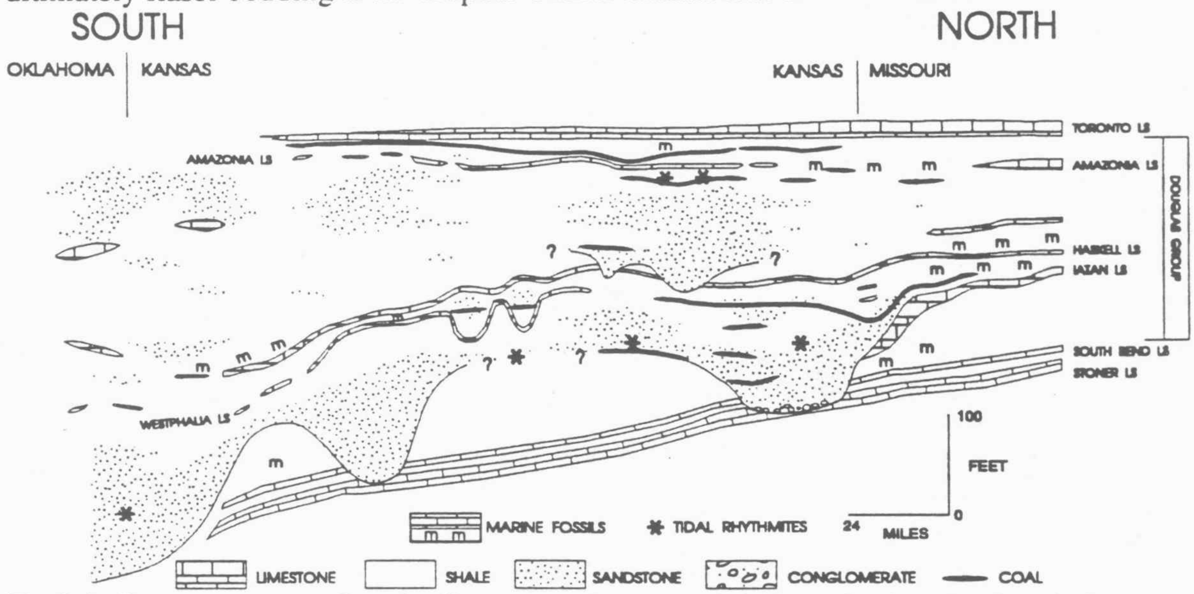

Fig. 3-4. Cross section of the Douglas Group along the outcrop belt illustrating lateral and vertical lithofacies variability and location of tidal rhythmites. The southern portion of the cross section extends westward into the subsurface in order to show the Stalnaker Sandstone. Modified from Bowsher and Jewett (1943) and based upon additional information from Ball (1964).

cycles have been reported most commonly in the Eastern Interior Coal Basin, or Illinois Basin (Kvale *et al.*, 1989; Kvale and Archer, 1990, 1991; Kuecher *et al.*, 1990). Similar tidal rhythmites occur in association with Carboniferous coals in Kansas and Colorado (Archer, 1991) and have now also been recognized in the Appalachian coal province (Greb and Chestnut, 1992; Martino and Sanderson, 1993). Within tidal rhythmite-bearing sections, however, these rates of accumulation only occurred for extremely short periods of time. The initial accommodation space, which could have been generated by compaction of the underlying peat (Kvale and Archer, 1990) or by rapid flooding, was filled and subsequent deposition would have been far less continuous.

In a typical stratigraphic sections (Fig. 3-5), the tidal rhythmites occur directly over a coal. The sequence commonly is capped by an underclay (paleosol) and coal. The coals and underclays can be described, using sequence-stratigraphic nomenclature, as "exposure surfaces". Because these zones embrace the tidal rhythmites, the sections begin with rapid flooding of a previously, subaerially exposed surface (the coastal peats), deposition of tidal rhythmites that exhibit a coarsening upward development, and a subsequent development of a fining upward sequence culminating in a rooted, subaerially exposed zone. In addition to the more obvious exposure surfaces delineated by coals, some sections contain additional non coal-bearing rooted zones (Fig. 3-5a). Relatively common occurrence of upright trees, rising from the lower coal and encased within tidal rhythmites, indicate rapid initial inundation of the coastal peat-producing areas (Kvale *et* *al.*, 1989, Kvale and Archer, 1990). As described above, the best developed rhythmicity occurs within a few meters above the coal. Above the rhythmically laminated zone, the section become sandier and commonly exhibits lenticular to flaser bedding; within such

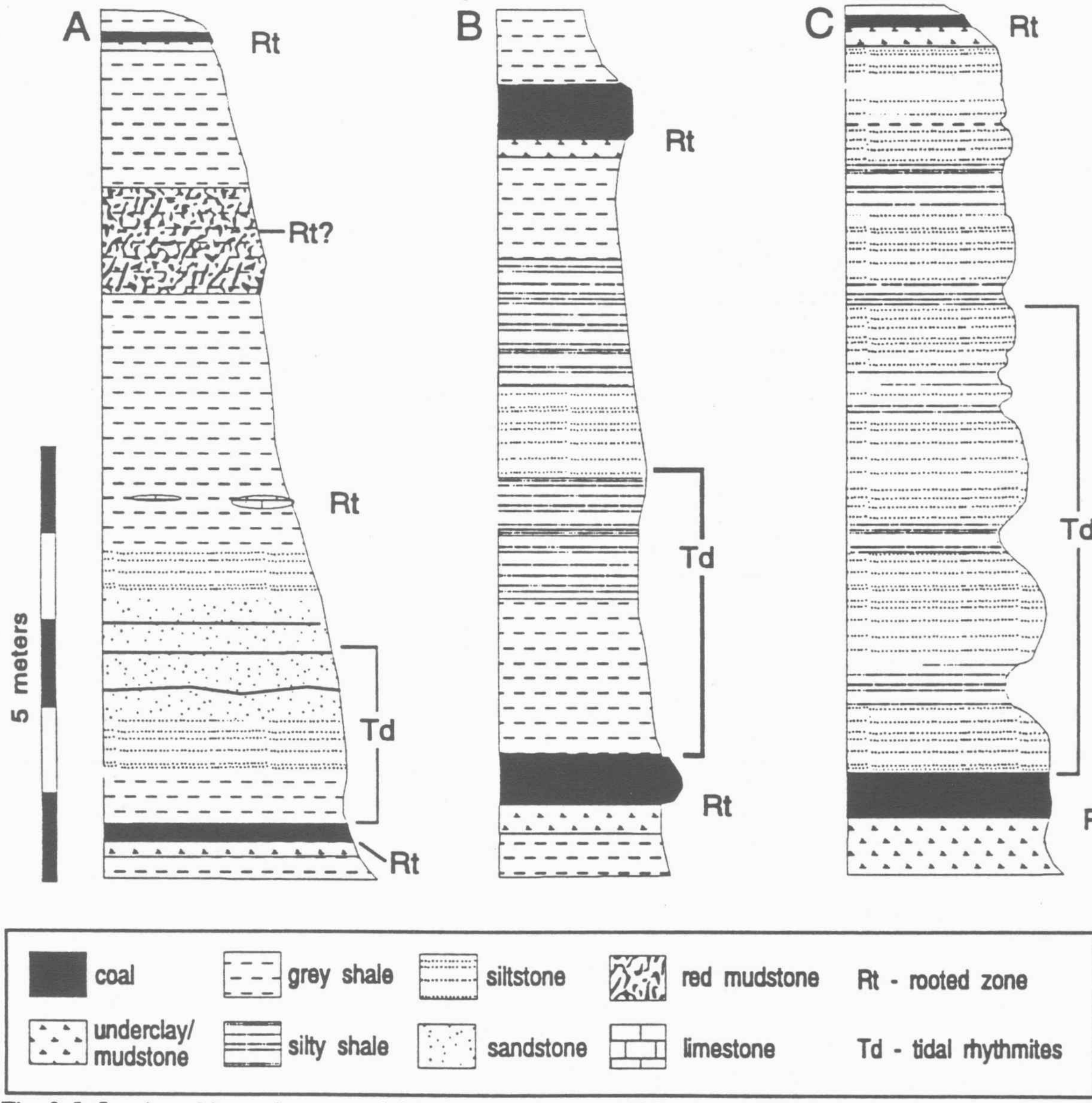

Fig. 3-5 Stratigraphic sections containing tidal rhythmites: (A) Lawrence Formation of Kansas (described by Archer, in press), (B) Brazil Formation of Indiana (described by Kvale and Archer, 1990), and (C) Hindostan Whetstone beds (Details of this sequence have been discussed in Kvale and others, 1989, and Kvale and Archer, 1990, in press.) In each section, the tidal rhythmites occur directly above lower coal. In sections A and B, the sequence exhibits a coarsening upward trend followed by a fining-upward trend, which is capped by an underclay and coal. Tidal deposits directly overlying the lower coal suggest a flooding event. The coarsening-upward sequence represents a deepening event concomitant with an increase in energy and/or sand influx. The overlying fining-upward sequence is terminated with another exposure surface, which includes the underclay (paleosol) and coal.

bedding the presence of erosional truncations and bioturbation tend to obscure the tidal cyclicity. Above the sand-rich zones, the section become progressively finer grained and is primarily composed of clay-rich laminae; however, unlike the laminae more or less directly above the coal, the clay-rich lamina in the upper part of the sequence are notably non continuous and do not readily exhibit tidal rhythmicity.

PALEOCLIMATIC CONSIDERATIONS

During eustatic lowstands, deep tropical weathering lead to the development of paleosols and underclays upon the low relief land surface and subsequent development of widespread peat-producing mires. During early transgressive phases, aggradation was initiated within the incised valleys. Because of everwet paleoclimates and the potential for a high degree of plant cover, the sediment flux within the fluvial systems, which occurred during peat accumulation in the surrounding highlands, may have been very low. Thus, clear- or black-water (organic rich but sediment poor) were flowing within the fluvial systems confined to the incised valleys. Thus, although rising base levels were produced during early transgression phases, the potential for aggrading sedimentation within the paleovalleys was reduced owing to a lack of sediment availability. With rising base level and sea level some significant climatic changes could have occurred. As the polar icecaps melted, the low latitude climatic belts, which had been contracted towards the equator, would begin to expand. The intertropical convergence zone (ITCZ) would become less pronounced, and low latitudes climates could become less wet and undergo an onset of seasonality, or even monsoonal, climatic regime. If these were the case, then a greater fluvial sediment flux could occur together with greater rates of aggradation within the valley-fill sequences. This increasing sediment flux may not be related to the local climatic conditions, but could be a reflection of the onset of seasonality in the headwaters of the drainage basin. Because of the large continental size, in part related to the ongoing accretion of Pangaea, the upper reaches of the drainage basin were theoretically some tens of degrees farther to the north of the depositional sites and thus would have been within a significantly different climatic belt. Some preliminary work on detailed sedimentology of valley-fill sequences in Indiana (Kvale *et al.*, 1992) and Kansas (Lanier *et al.*, in press) suggests that there may be evidence of monsoonal deposition within some roof-rock facies formed within valley-fill sequences. This increase in clastic flux would result in an increased potential for splaying and alluviation that would begin to overwhelm the surrounding peat fields. In near-coastal settings this alluviation could be tidally influenced and as transgression proceeded it could be expected to exhibit progressively greater degrees of tidal influence and ultimately of a greater degree of marine influence. Because of the large-scale nature of the river systems and the fact that the rivers had formed incised valleys during the preceding lowstand, it would be expected that many of the paleovalleys would undergo a conversion to estuaries during the following transgressive phase. Specific estuarine geometries lead to concentrations and amplifications of tidal energies. Such amplifications can occur at large distances upstream from the mouth of the estuary (see Fig. 2-3). These tidal energies can be readily propagated past the upstream limit of brackish-water influences, especially when rivers have a large freshwater outflow. For example, brackish waters do not invade the Amazon River and estuarine mixing occurs out upon the continental shelf. Nonetheless, tidal effects, such as tidal bores, propagate for hundreds of kilometers inland from the river's mouth. Similar, and potentially even more pronounced effects could be expected when large-scale tropical fluvial systems emptied into cratonic embayments, such as was the case during the deposition of the midcontinental Carboniferous sequences. Thus it is readily apparent that tidal energies could theoretically be propagated for considerable distances up through the fluvio-estuarine regime and it would not be unusually that such marine energies would be propagated into freshwater environments of deposition. This concept appears to be particularly important to an understanding of Carboniferous coal-forming settings and, as will be seen during the field trip, and may also relate to the depositional and preservational regime of Gulf Coast lignites.

Consequently because of either increased fluvial sediment flux, or inland transport of marine sediments via tidal processes, these incised paleovalleys were rapidly filled with aggrading sediments. Any peats formed along the valley sides had a tendency to be rapidly covered with sediments during this aggrading phase of deposition within the fluvio-estuarine facies complex. Once the paleovalleys were filled, then widespread marine transgression overwhelmed the laterally extensive peat fields that occurred outside of the confines of the paleovalleys resulting peats reworked by tidal and wave energies to form that laterally extensive black shale roofs. These widespread black shales, which characterize most of the widespread midcontinental coals, have long been a point of debate of midcontinental stratigraphers. One view, originally advocated for Illinois Basin occurrences and subsequently applied to the Western Interior coal region, is that these black shales are shallow water deposits formed during initial marine flooding of peat fields. Another view, advocated primarily by Heckel (1977), states that such shales represent condensed, deep-water facies. It is likely that there is some true to both of these views and that the black shales represent an extending period of time and were deposited beginning during early transgression and continuing until maximum flooding, or high-stand deposition. As long as transgression continued to flood coastal peats, then a high rate of organic influx into the seaway effectively precluded other forms of deposition, such as carbonates, from being initiated. The high acidity and organic toxins flushed from the peats. Ultimately, complete transgression of the peats and removal of this source of reworked organic would allow development of more clear water, normal marine facies, such as carbonates. It is not the intent herein to resolve the Carboniferous black-shale debate, but a step toward resolution of these organic-rich marine facies was presented by Coveney *et al.* (1991), in which significant differences were noted between nearshore (shallow-water) and offshore (deeper-water) black shales. Within the Illinois Basin, the black shales that lie directly over the major coals, and especially that part of the black shale that occurs directly overlying the coal, invariably appears to be a nearshore and therefore shallow-water variant of black shales. Despite a number of suggestions that biological indicators are useful for paleodepth determinations, there appears to be no unequivocal indicator of depths that occurs within these organic-rich facies (C. Maples, pers. comm., 1992). Detailed analyses, in part through the mapping of roof facies in underground mines in southern Illinois, indicates the presence of erosional discordances between the overlying black shales and underlying gray shales or coal beds. In particular, along the margins of gray-shale wedges, the gray shales are restricted to isolated pod-like occurrences, which appear to be erosional relicts of a once more widespread lithofacies (Archer and Kvale, in press). In these settings, the gray shales are restricted to small pods that are sharply overlain by black shales. In other cases, the black shales appears to have a disconformable relationship with the underlying coal (Bauer and DeMaris, 1982; Krausse *et al.*, 1979).

Some general statements regarding gray and black-shale deposition can be made. In many cases, upright that appear to have been rooted in the underlying peats extend up through the gray-shale roof facies. These upright trees extend for heights as great as 2 to 3 m above the coal. Therefore the gray shales represent a nonerosional, aggradational facies that formed subsequent to, and perhaps are related to the termination of, peat accumulations. On the contrary, black shales truncate not only the underlying gray shales, but also can truncate the underlying coal beds and appear to represent a low-energy ravinement surface formed during marine transgression. Locally, shelly lags and marine bioturbation occur at the lower surface of the black shales, but other than these restricted occurrences, the appearance of a transgressive limestone, as advocated by Heckel (1977), does not occur.

SEQUENCE STRATIGRAPHIC CONSIDERATIONS

During the Upper Carboniferous in the U.S. midcontinent, widespread marine marker beds, which include thin carbonates and black shales that are readily recognized on geophysical logs, were deposited during sea level highstands. These stratigraphic markers allow for a fairly accurate delineation of the coastlines and extent of the interior seaway during highstand (Fig. 3-6). Conversely, because of the more discontinuous geometries and lack of regional markers, it is much more difficult to delineate the mid- and lowstand coastlines. Because of these difficulties, a paleogeographic reconstruction during such times are more tentative and are, in part, based upon our understanding of the basinal geometries that would be necessary to produce: 1) the necessary incisements during lowstands, and 2) the necessary geometries for tidal amplification that apparently occurred during deposition of the tidal estuarine facies. Despite these limitations, an interpretive paleogeography (Fig. 3-6) for midstand and lowstands is useful for considering the hypothetical constraints of the depositional systems. In particular, our assessment of lowstand configurations are based upon similarities of the incised valley-fill sands of the Douglas Group with stratigraphic equivalents in Oklahoma and north-central Texas. Correlations and stratigraphic relationships of these more southerly units has been presented by Shelton (1973), Toomey (1964), and Brown and others (1990).

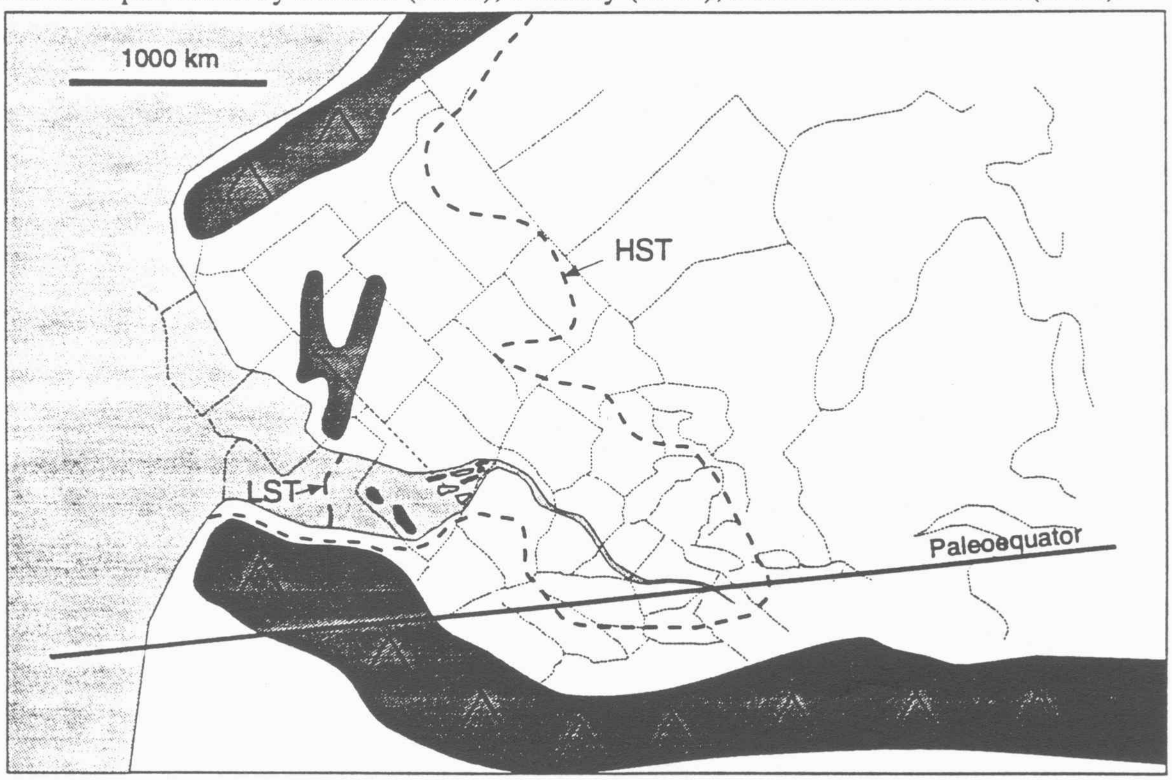

Fig. 3-6. Paleogeographic reconstructions for intervals encompassing Douglas Group deposition during various phases of transgression. Non-dotted outlines are interpreted geometries during early to mid transgression. Embayment and estuarine geometries south of the study area are in part hypothetical, but are based upon the theoretical geometries needed for tidal resonance and amplification needed to develop the tidal facies tracts observed within the Douglas Group. Paleogeography and highstand position (HST) modified from Witzke (1990). Lowstand positions (LST) based information in Shelton (1973), Toomey (1964), and Brown and others (1990).

Many of the facies within Carboniferous coal-bearing sequences are remarkably similar to late Holocene estuarine deposits within incised valleys along the North

American and European Atlantic coasts. Recent studies of Atlantic coast estuaries have revealed similarities of facies patterns (Nichols *et al.*, 1991; Rahmani, 1989; Dalrymple *et al*, 1991). Both the modern estuarine model based on the James River estuary and the thick Douglas Group cycles of Kansas start with fluvial sand resting erosionally on older rocks. The fluvial sandstone grades upwards into middle estuarine muddy sediment. The Douglas Group cycles are capped by marine shale and limestone whereas the James River estuary sequence is capped by marine sand. The Douglas Group does, however, contain marine sand facies within the valley fill sequence basinward to the south. Many of the details of the Douglas Group facies model have yet to be worked out, yet the similarities with modern estuarine facies are quite impressive.

A generalized model for the development of tidal rhythmite roof facies is readily explainable by use of a tidal estuarine model. During lowstands raised mires were developed on a broad alluvial plain formed within large, broad valleys (Fig. 3-7a). Lowstand deltaic systems could have developed along the coast and were probably tidal influenced, much as the modern Mahakam River Delta in Kalimantan, Indonesia (Allen *et al.*, 1979; Gastaldo and Huc, 1992). During rise in base level, related either to glacio-eustatically induced sealevel rise or basinal subsidence, flooding of the older fluvial valley result in an estuarine configuration (Fig. 3-7b). Concentration of tidal energies and development of turbidity maximum result in rapid progradation of tidal-rhythmite "splays" over the mires. In the upper reaches of the estuary, silt-rich rhythmites rapidly mantle the peats, whereas in the middle, muddy zone of the estuary, heterolithic rhythmites are developed. The silt-rich rhythmites correspond to laminated siltstones such as those described from the Illinois Basin (Kvale and Archer, 1991; Kuecher *et al.*, 1991) and from Kansas (Lanier *et al.*, in press). Because of the similarity to modern macrotidal analogs (Dalrymple *et al.*, 1991; Tessier *et al.*, 1989, in ed. review), silty rhythmites may indicate the development of a macrotidal regime. and form within the zone of maximum tidal amplification (see Fig. 2-6). Heterolithic rhythmites are those consisting of "tidal bedding" (Fig. 2-4) such as described by Kvale and Archer (1990) and occurring in the Gulf Coast lignites (Breyer, 1987, 1989). Heterolithic rhythmites probably do not require macrotidal ranges, and could also be formed in mesotidal and potentially microtidal settings. Lowered tidal range, however, would also result in lowered salinity fluctuations and generally lower sedimentation rates and the sediments would be characterized by greater degrees of bioturbation. Thus nonbioturbated heterolithic rhythmites, based upon modern analogs, appear to require at least mesotidal conditions.

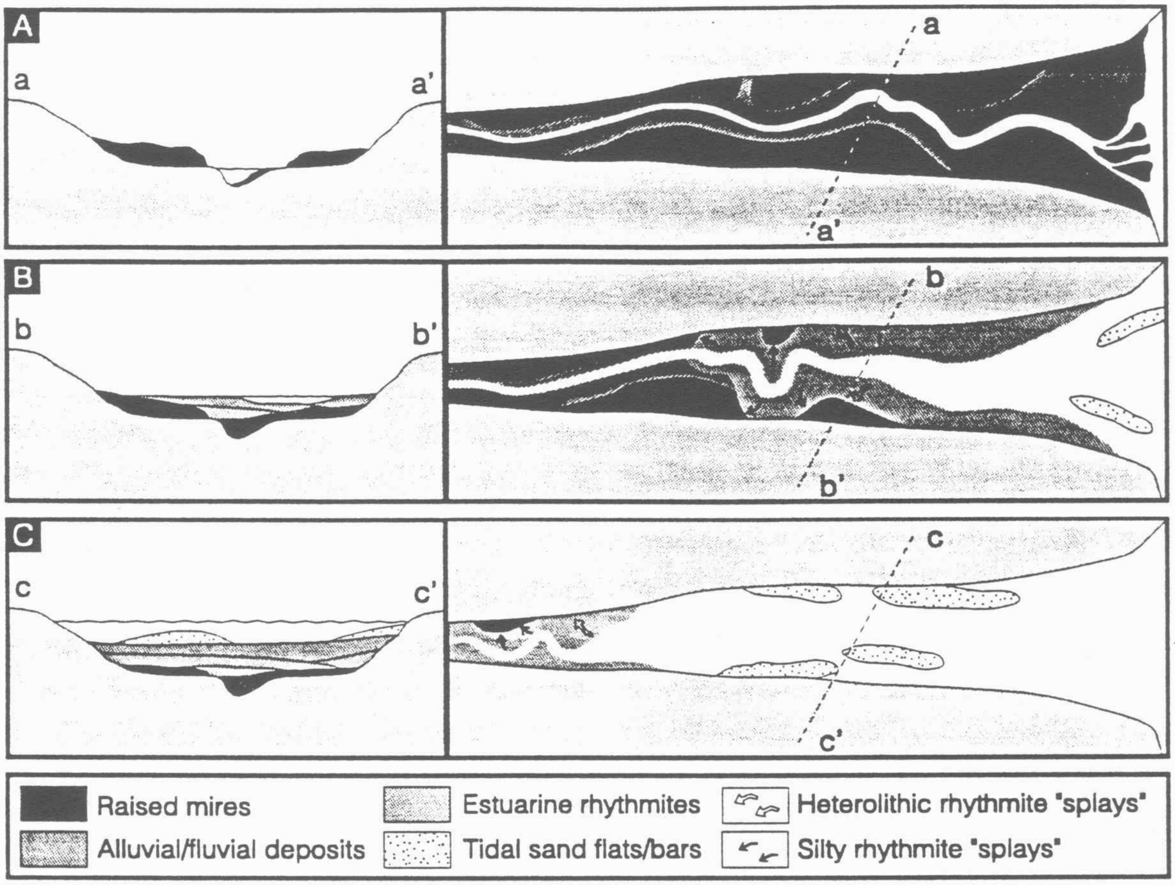

Fig. 3-7. Interpreted depositional setting and sequence of development for estuarine coals in the Carboniferous of the Mansfield Formation of Indiana and Douglas Group of Kansas. Cross sectional views on left based on transect labeled on map views on the right. (A) Lowstand: raised mires form within valley, tidally influenced deltaic system developed along the coast. (B) Initial transgression: Development of high-tidal-range estuary and flooding of peats with low-salinity rhythmites ("splays"). At fluvio-estuarine transition, silty rhythmites are produced. Within the muddy middle estuary, deposition of heterolithic rhythmites is related to development of turbidity maxima. Both forms of rhythmites rapidly "splay" from the upper reaches of estuarine system where tidal ranges and rates of sedimentation are maximized. (C) Later transgression: estuarine rhythmites continue to flood mires at the fluvio-estuarine transition. In seaward end of estuarine, tidal sand bars overlie the estuarine rhythmites. Near-normal salinities are achieved in seaward end of estuary and sediments become significantly bioturbated.

Continued base-level rise pushes the tidal estuarine system landward (Fig. 3-7c). The rhythmites which initially mantled the underlying mires, now become overlain by tidal sand flats or ridges. Continued rise in base level will result in more marine influences, such as bioturbation. Finally, transgression may result in open marine lithofacies, such as carbonates, capping the sequence. Regressive phases are not diagrammed, but could constitute fluvio-deltaic systems, probably tidal influenced, prograding back seaward through the flooded embayment. Fluvial components of the regressive system could incise into the underlying, older fluvio-estuarine system and result in a highly complex facies mosaic. Subsequent development of a regressional alluvial plain would then set the stage for subsequent re-establishment of widespread mires. This sequence would complete the "cyclothem."

The model presented above is based upon coal occurrences, such as those in the Douglas Group of Kansas and Mansfield Formation of Indiana. In such settings, the coals are laterally restricted and seem to be more-or-less confined to the wetter paleovalleys. Conversely, wetter climatic conditions occurred during development of the more widespread Carboniferous coals, such as the Colchester, Springfield, and Herrin coals of the Illinois and Indiana parts of the Illinois Basin. It is apparent that these types of coals were not valley confined but were produced by laterally extensive mire. Nonetheless, the generalized model as presented above is potentially appropriate. There are gray-shale wedges associated with localized occurrences of low-sulfur coal in these more widespread high-sulfur coal. These gray-shale wedges have commonly been interpreted as nonmarine fluvial, overbank, and lacustrine settings. However, the gray shales that directly overlie the coals commonly contain silty or heterolithic rhythmites (Archer and Kvale, in press). The gray-shale sequences can thus be interpreted as the product of fluvio- to estuarine- to marine transitions developed within low-relief valley-fill sequences (Fig. 3-8). There are a number of details which need to further refined regarding these models; however, depositional interpretations for any coastal-plain coal-bearing sections must consider the potential importance of tidal influences and tripartite estuarine models.

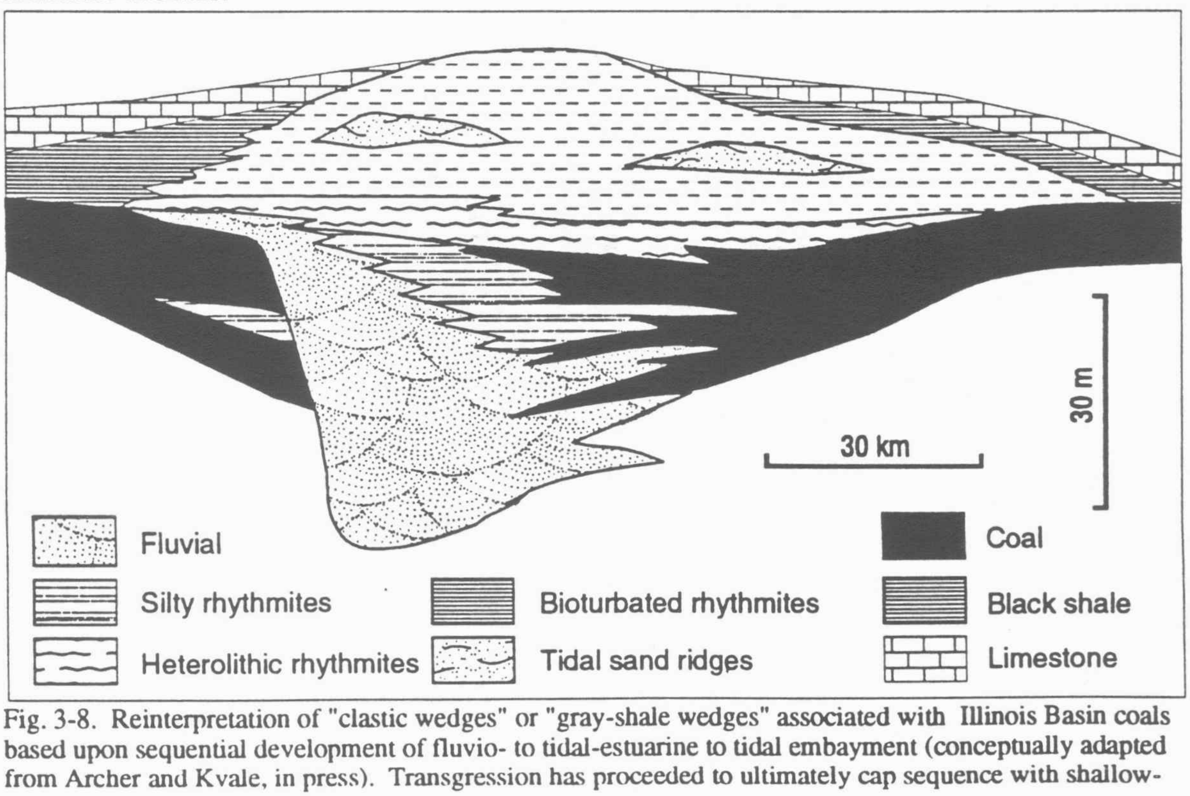

Fig. 3-8. Reinterpretation of "clastic wedges" or "gray-shale wedges" associated with Illinois Basin coals based upon sequential development of fluvio- to tidal-estuarine to tidal embayment (conceptually adapted from Archer and Kvale, in press). Transgression has proceeded to ultimately cap sequence with shallow-

marine facies (black shale) and offshore facies (carbonate). As discussed in text, both these marine facies can have ravinement-type relationships with the underlying fluvio-estuarine facies. Geometry of major facies adapted from Nelson (1983).

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SEDIMENTOLOGY, STRATIGRAPHY, AND PALEOFLOW PATTERNS OF THE TONGANOXIE SANDSTONE MEMBER AND RELATED STRATA IN NORTHEAST KANSAS AND SOUTHWEST MISSOURI

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ABSTRACT

The Tonganoxie Sandstone Member of the Stranger Formation (basal Virgilian-Stephanian) occupies a NE-SW oriented paleovalley that was incised during lowered sea-level and filled during the subsequent transgression. The fill records a complete fluvial to estuarine to marine sequence. The main paleovalley is approximately 130 ft (40 m) deep, 7 miles (11 km), wide and >90 miles (140 km) long, and was fed by tributary valleys oriented roughly normal to the main valley. The strata are amalgamated in places with the Ireland Sandstone Member of the Lawrence Formation, a younger paleovalley fill.

The basal strata of the Tonganoxie Sandstone Member consist of trough cross-bedded sandstones and clast-supported conglomerates with abundant plant material, and were deposited in southwesterly flowing rivers that occupied shallow channels which were subject to episodic discharge. Planar cross-bedded sandstones with clay drapes, rare thick-thin pairs on foresets and locally rhythmic variation in foreset thickness rest locally on thin valley-base conglomerates or thicker fluvial strata. They also show southwesterly paleoflows and formed in an ebb-dominated, tidal (estuarine) sandwave complex. Flaser-bedded siltstones overlie cross-bedded sandstones at most localities and formed in the subaqueous part of an estuary that contained tidal channels. Northwesterly paleoflow in some flaser-bedded strata suggests a reversal in sediment-transport direction and a change to a flood-dominated tidal system as transgression proceeded. Flow was commonly deflected into the tributary valleys or embayments of the main valley.

Subsurface analysis reveals three types of sandstone bodies in the Tonganoxie Sandstone Member. Type 1 sandstone consist of a sheet of sandstone that is 10 to 60 ft (3 to 18.3 m) thick, and confined to the basal portions of the trunk valley and wider tributary valleys. It was deposited in fluvial, and perhaps estuarine settings. Type 2 sandstones occur in arcuate to sinuous bodies up to 60 ft (18.3 m) thick, are 1 mile (1.6 km) wide and up to 5 miles (8 km) long. Type 2 sandstones were probably deposited in tidal point bars. Type 3 sandstones are thick (80 to 100 ft, 24.4 to 30.5 m) elongate pods that occur at the upstream limits of tributary valleys. These may represent deltas that formed during the late stages of valley flooding.

A widespread capping paleosol and thin coal (the Upper Sibley Coal) may reflect a relative lowering of sea-level after most of the paleovalley was filled. The marine Vinland Shale Member and Haskell Limestone Member overlie the coal and extend across the paleovalley margin.

INTRODUCTION

The Tonganoxie Sandstone Member of the Stranger Formation is an unusually thick but areally restricted formation of Virgilian (or latest Missourian) age that crops out in northeast Kansas and northwest Missouri. In a classic study, Lins (1950) demonstrated that the member occupies a paleovalley cut through shales and carbonates, thus explaining its unusual geometry, and was laid down by the southwest-flowing "Tonganoxie River". The Tonganoxie Sandstone Member is of some economic importance. It forms an important aquifer (O'Connor, 1960) and, according to local residents, yielded well water throughout the drought of the 1930s. Thin, discontinuous coals within the unit, as well as the overlying Upper Sibley Coal, have been mined (Bowsher & Jewett, 1943), and the hydrocarbon-bearing Stalnaker Sand of northern Oklahoma is probably contiguous with the Tonganoxie Sandstone Member (Winchell, 1957).

The present paper describes the geometry of this classic Pennsylvanian paleovalley, and documents the facies and paleoflow patterns of the paleovalley fill and overlying strata. The study is based on 180 wireline well logs, 203 water-well logs, 49 outcrops for stratigraphic data, and 44 outcrops for paleoflow measurements Leavenworth, Wyandotte and Douglas Counties, Kansas, and Platte County, Missouri (Figs. 1, 2; Appendix 1). In addition a core was obtained in Leavenworth Co. Our field data was supplemented with outcrop data from Bowsher and Jewett (1943), Lins (1950) and Howe (1986).

STRATIGRAPHY

The Tonganoxie Sandstone was defined by Moore et al. (1934) and Moore (1936) as the basal member of the Stranger Formation of the Douglas Group. O'Connor (1963) subsequently redefined the Stranger Formation to include the underlying Iatan Limestone and Weston Shale, and these units, as well as the Tonganoxie Sandstone, are presently considered as separate members (Fig. 3). Detailed stratigraphic and mapping studies of the Tonganoxie Sandstone Member in Kansas and Missouri were carried out by Newell (1935), Lins (1950), Ball et al. (1963) and Howe (1986). The type locality of the Tonganoxie Sandstone lies along Kansas Highway 40 about 7 miles (11 km) east of Tonganoxie, and on Stranger Creek and its tributaries north of Linwood, Leavenworth County, within the study area. The sedimentology of parts of the Tonganoxie Sandstone has been studied recently by Spriggs (1989), Archer et al. (in press), and Lanier et al. (in press).

Lins (1950) originally suggested that the Tongonoxie Sandstone occupied a southwesterly oriented paleovalley with a maximum width of 20 miles (32 km), and mapped the paleovalley along the outcrop belt from the Kansas-Missouri border to Lawrence, Kansas. Sanders (1959) used subsurface data to extend the paleovalley to Geenwood County, Kansas. This study focuses on the area originally mapped by Lins where outcrop and subsurface data were used to add detail to the originally mapped paleovalley. For the purposes of subsurface mapping the base of the Tonganoxie was identified as the lowest thick (over 10 ft, 3 m) sandstone above the Stanton Limestone. The stratigraphically lowest unit that is at least partially truncated by the Tonganoxie paleovalley is the Stoner Limestone Member of the Stanton Limestone. The Weston Shale consists of beds above the Stanton and below the Iatan Limestone, or where the Iatan is absent, below the Tonganoxie. However, subsurface mapping has demonstrated that in Kansas the Weston Shale thins westward and southward to a feather edge at about R 20 E, and T 10 S (Fig. 4), where the Iatan merges with the South Bend Limestone. Above the Iatan and below the Tonganoxie is a unit of shale up to 140 ft (42.7 m) thick. For the purposes of this report, the term "Weston Shale" is used to refer to shale above the South Bend, and below the Tonganoxie where the Iatan is absent.

An isopach map of the interval from the

base of the Eudora Shale to the base of the Tonganoxie Sandstone (Fig 5) is assumed to approximate the morphology of the land surface prior to valley filling. The Eudora was chosen as a datum because it is the youngest unit not truncated by palleovalley erosion and it is easily identified in well logs and outcrops. The morphgology of the surface at the base of the Tonganoxie was mapped assuming that the base of the Eudora was flat during early Tonganoxie deposition. If there was any regional dip at the time, it is not reflected in the maps and cross sections that follow. This surface was also potentially modified by wave erosion during transgression, but no direct evidence of wave-cut benches was identified. The iopach map indicates that the U-shaped trunk valley is approximately 7 miles (11 km) wide, and has a maximum incision of 130 ft (39.6 m). The sides of the paleovalley are bounded by shale and have slopes of up to 80 ft per mile (15.2 m per km). The base of the paleovalley is subhorizontal to gently sloping with relief less than 20 ft per mile (3.8 m per km) and is underlain by the Stanton Limestone. In most well logs and outcrops the base of the paleovalley is underlain by either the South Bend Limestone or the Stoner Limestone members of the Stanton Limestone. These limestones were resistant units that prevented deeper incision. The South Bend Limestone may have formed minor benches and small hills within the trunk valley.

Feeding into the trunk valley is a series of tributary valleys that extend to the northwest and southeast. These minor valleys were probably incised by tributary streams that drained into the trunk valley. Tributary valleys on the south edge of the paleovalley are poorly defined because they are near the erosional limit of the Tonganoxie, but are apparently 2 to 3 miles wide, and have subhorizontal bases mostly on the South Bend Limestone and include possible narrow, deeper incisions that cut down to the Stoner Limestone. Tributary valleys extending north are better defined because of on dense oil-well log control. Northern tributary valleys are 0.5 to 1 mile (0.8 to 1.6 km) wide at their mouths, are V-shaped (especially upstream), taper upstream, and can be traced 10 to 15 miles (16 - 24 km) to the northwest. Tributary paleovalleys truncate progressively younger strata upstream. In the area near Leavenworth, the subsurface data suggest that the Iatan Limestone formed benches on valley walls, and may have formed falls or rapids in the valleys. Minor, short (under 2 miles [3.2 km] long) valleys apparently fed into the tributary valleys.

The valleys are filled with a generally fining-upward succession of conglomerate, sandstone, and shale (Lins, 1950). Conglomerate is a common lithology at the base of the Tonganoxie Sandstone in outcrop, but was not identifiable from water well or wireline logs. These logs suggest a pattern of generally increasing shaliness upwards, but sandstone beds may occur anywhere within the Tonganoxie interval. In most well logs the thickest sandstone bed is at the base of the Tonganoxie Sandstone. The thickness of this basal valley sandstone was mapped in order to determin the geometry of sandstone bodies. For the purposes of mapping the thickness of the basal sandstone, the top of the sandstone was picked at the point above which more than half the succession is shale. Three types of sandstone bodies can be identified within the Tonganoxie paleovalley (Fig. 6, 7): (1) a broad basal sheet of sandstone, (2) arcuate to sinuous sandstone bodies above the basal sheet, and (3) pods of sandstone near the upstream limits of tributary valleys.

Type 1 sandstone forms a broad basal sheet that is confined to the trunk valley and wider portions of tributary valleys. It ranges from 10 to 60 ft (3 to 18.3 m) thick and displays a broad undulating upper surface. In outcrop it is composed of poorly sorted conglomerate and sandstone ranging to well-sorted sandstone. Type 2 sandstone bodies are arcuate to sinuous sand bodies up to approximately 60 ft (18.3 m) thick, 1 mile (1.6 km) wide and up to 5 miles (8 km) long. These sand bodies are underlain by the sandstone sheet (type 1 sandstone bodies), and have shale above and adjacent to them. Type 3 sandstone bodies are elongate, thick (up to 40 ft or 12.2 m) pods of sandstone that occur near the heads of minor and major tributaries (Figs., 6, 8). Type 3 sandstones tend to occur near the updip limits of the tributaries where the bases of tributaries are 80 to 100 ft (24.4 - 30.5 m) above the base of the Eudora Shale. See below for outcrop characterizations of type 1 and 2 sandstones. Type 3 sandstones are not exposed.

Based on analysis of gamma-ray, neutron, and density well-log patterns, and the Oeschlaeger core, the unit overlying the basal Sandstone of the Tonganoxie consists mostly of shale, with thin sandstone beds and coal. The Upper Sibley Coal Member overlies the Tonganoxie Sandstone Member in the study area. At Localities 33 and 34 (Stop 1-1) in Platte County, Missouri, at the paleovalley margin (Fig. 1), the Upper Sibley Coal Member rests on a thin (7.9 ft or 2.4 m) unit of shale, probably the Tonganoxie Sandstone Member (see below). The peat now represented by the Upper Sibley Coal was deposited after the paleovalley was substantially filled, and extended across the adjoining inter-valley area. Density logs can be used to correlate the Upper Sibley Coal across the paleovalley and into interfluvial areas in the subsurface, where the Tonganoxie is represented by thin shaly sandstone (Fig. 8). Where density logs are not available the contact between the Tonganoxie Sandstone and the Vinland Shale cannot be picked because the lower Vinland Shale and upper Tonganoxie Sandstone members are not substantially different. In the upper Vinland Shale there is a sheet of sandstone that ranges up to 30 ft (9.1 m) thick, but averages approximately 10 ft (3 m) thick (Fig. 9). This sandstone is not present in approximately half the well logs. The upper Vinland sandstone extends beyond the limits of the paleovalley but is thickest along the northeasternmost, tributary suggesting that the topographic expression of the paleovalley was still reflected in topography of the seafloor shortly after marine flooding. On outcrop (Day 1, Stop 1-7) the sandstone consists of horizontally bedded shaly, fine-grained sandstone with abundant horizontal and vertical burrows.

The Haskell Limestone caps the Tonganoxie paleovalley-fill sequence and is a widespread marine marker. In the field trip area it averages 5 to 10 ft (1.5 - 3.0 m) thick and consists of fossiliferous wackestone and packstone, and oolitic grainstone. Directly above the Haskell in the lowest 1 ft (30.5 cm) of the Robbins Shale is a phosphatic zone that contains phosphate nodules, and phosphatic fossils such as fish skulls, cephalopods, and phosphatic brachiopods (Miller and Swineford, 1957).

In parts of Leavenworth, Wyandotte, and Douglas Counties, the Ireland Sandstone Member occupies a paleovalley cut through the Stranger Formation and is amalgamated with the Tonganoxie Sandstone Member (Lins, 1950). The two valley fills are not readily distinguished in these areas.

In northeastern Kansas, the Douglas Group dips WNW at less than 1°, and its outcrop belt is about 19 miles (30 km) wide, trending in a SSW-NNE direction. The orientation of the paleovalley is approximately SW-NE (Fig. 5). Consequently, the paleovalley fill runs obliquely across the outcrop belt. It has been eroded away updip in Missouri, and lies deep in the subsurface in central-southern Kansas.

THE OELSCHLAEGER #1 CORE

No complete section of the Tonganoxie Sandstone Member was available prior to this study. In consequence, the Oelschlaeger #1 core was drilled in the type area at Linwood (Fig. 10) and logged with gamma ray and neutron tools in order to determine the thickness and facies of the Tonganoxie Sandstone and to provide a basis of comparison for interpreting geophysical log signatures in uncored wells. A full descriptive log is given in Appendix 2 and illustrated in Figure 10. The hole was drilled to 168.3 ft (51.3 m) below ground surface and all but the top 7.8 ft (2.3 m) was cored. Core recovery was virtually complete.

The Tonganoxie Sandstone at the drill site is 68.4 ft (20.8 m) thick and is underlain by 1 foot of shale that may be the Weston Shale, beneath which are the Stanton Limestone and Vilas Shale. A thin basal conglomerate is overlain by a thick unit of trough or planar cross-bedded, fine-grained sandstone, about 54 ft (16.5 m) thick. Thin conglomerate layers (locally cross-bedded) and ripple cross-laminated and plane-bedded sandstones are present, and plant fragments are common in the lower part.

The overlying 14 ft (4.2 m) is predominantly ripple cross-laminated siltstone but includes several concretionary calcareous layers, with many concretions oriented normal or oblique to bedding. The concretions reach their maximum concentration just below the Upper Sibley Coal. They may represent development of a calcareous paleosol within the siltstone, with cementation related to roots or zones of shrinkage, or possibly paleosol development within a pre-existing limestone.

The sandstone undergoes a pronounced change in appearance at 97.9 ft (29.8 m) varying from a tough, calcareous-cemented gray sandstone below this level to a soft, yellow-brown sandstone above. The upper sandstone contains iron oxide/hydroxide layers and "knots" of calcareous-cemented grains. The change probably corresponds to the prevailing level of the water table, based on a pronounced change in the neutron log signature at a similar level. Most calcareous cement apparently has been removed from the sandstone above this level and ferruginous material added.

The Tonganoxie Sandstone Member is overlain by the Upper Sibley Coal Member, (11.5 inches, 0.29 m thick). The Westphalia Limestone Member (3.5 inches or 9 cm thick), which has been studied in detail across midwestern U.S.A. by Ball (1971), and the Vinland Shale Member (37.4 ft or 11.4 m thick) which is bioturbated and coarsens in its upper part. The fossiliferous Haskell Limestone is >8.5 ft (2.6 m) thick and is sandy in its lower part; its top was not cored.

FACIES ASSEMBLAGES

Strata of the Tonganoxie Sandstone Member below the Upper Sibley Coal were divided into four facies assemblages based on the studied outcrops, with each assemblage named for a prominent feature of the strata (Table 1). These assemblages could not be identified with certainty in the drill core where trough and planar cross-beds are difficult to distinguish. Paleoflow patterns are mentioned briefly with the descriptions below and discussed more fully later in the paper.

CONGLOMERATIC ASSEMBLAGE

Description

Interbedded conglomerate and sandstone up to 15 ft (4.5 m) thick is present at the base or within the basal 26 ft (8 m) of the paleovalley fill, typically where the erosional surface has cut into the Stanton Limestone. Good exposures are present at Localities 4 (Stop 1-2) and 10. The strata are organized into sediment bodies 1.5 - 6.5 ft (0.5-2 m) thick separated by sub-planar to concave-up erosional surfaces that extend least 130 ft (40 m) in the downflow direction, and which cut into underlying units. Paleoflow patterns at any one locality are unidirectional.

The conglomerates form discrete beds up to 6.5 ft (2 m) thick. They are composed of clasts typically 0.2 - 2 inches (0.5-5 cm) in maximum dimension, with one 6.7 inches (17 cm) siltstone slab observed. The clasts are predominantly micritic limestone, altered ferruginous material, and gray claystone and siltstone. Abundant fragments of bryozoa, pelmatozoa, brachiopods, corals, and vascular plants (including Calamites stems 1 ft (30 cm) long) are present, with sparse bone fragments. The clasts are poorly sorted and set in a sparry calcite cement. The conglomerates are clast-supported and clasts are generally flat-lying with weak grain-size banding but little indication of graded bedding. Cross-bed sets 4-12 inches (10-30 cm) thick are common, and apparent imbrication of clasts probably reflects deposition on poorly developed foresets. At one locality, a conglomerate bed 3.3 - 6.6 ft (1-2 m) thick contains low-angle surfaces that run from the top to the base of the bed and dip at 2-4° in the paleoflow direction. One smaller convex-up accumulation of pebbly sandstone is about 33 ft (10 m) long and is composed of two superimposed, sigmoidal cross-sets.

The conglomerate beds contain thin sandstone lenses and are capped by thin, tabular sandstones that are trough cross-stratified or contain lineated plane beds. Thicker beds of fine- to very fine-grained sandstone are associated with the conglomerates. They are mainly trough cross-bedded, with sets 2-20 inches (5-50 cm) thick (average 8 inches (21 cm), 13 measurements). Some beds are ripple cross-laminated with both 2D and 3D ripple forms present, and ripple-drift cross-laminated sandstones cap some scour fills. Plane-bedded sandstone with primary current lineation forms sheets up to 2.5 ft (75 cm) thick.

Thin (up to 2.6 ft (80 cm) thick) conglomerate sheets that extend for >50 ft (15 m) rest on the erosional base of the paleovalley at many localities (11 [Stop 1-3], 13, 15, 30), principally where the erosional surface cuts into limestones. Thin conglomerate lags are present at the base of sandstone storeys at higher levels in the paleovalley fill (Localities 1,5; Oeschlaeger No. 1 core).

Interpretation

The clast-supported conglomerates and sandstones were deposited as sediment sheets and bars within channels, the bases of which are marked by the prominent erosional surfaces. A few virtually complete channel fills about 1 m (3 ft) thick were observed, but most fills are truncated. Based on the maximum thickness of strata preserved between erosional surfaces, channels are inferred to have been a few meters deep in most cases. This inference is supported by the relatively small scale of cross-beds (mean of 8 inches or 21 cm), which suggests water depths in the range of 3-16 ft (1-5 m) based on data presented by Allen (1984, Fig. 8.20). Within the thicker conglomerate units, the presence of low-angle surfaces with a vertical extent of 3.3-6.6 ft (1-2 m) and inclined downflow suggest that large gravel bars occupied the channels. One fully preserved barform probably represents a small transverse bar.

Thick units of plane-bedded sandstone capped locally by ripple-drift cross-laminated sandstone indicate periods of upper regime flow, probably flood events, with rapid deposition as flow waned. Discharge was thus episodic. The abundant, large plant fragments indicate that vegetation was probably established within or closely adjacent to the channels. The fragmentary and abraded marine fossils were probably reworked from the underlying Stanton Limestone and possibly from the Iatan Limestone Member.

Many of the features of this facies association can be matched in modern braided rivers and braidplains subject to strongly episodic flow (Williams & Rust, 1969; Stear 1985). The channels probably formed a shallow, braided network within the Tonganoxie paleovalley.

TROUGH CROSS-BEDDED ASSEMBLAGE

Description

Sandstone bodies with trough cross-beds as the predominant sedimentary structure are widely distributed within the paleovalley fill. They form units up to 23 ft (7 m) thick associated with the Conglomeratic Assemblage in areas where the Tonganoxie Sandstone Member rests on the Stanton Limestone near the paleovalley axis (Localities 1-3, 5, 10, 26, 44). They also form the bulk of the sandstone facies of the paleovalley fill southwest of Leavenworth (Localities 36, 38-41) where the valley is cut to shallower levels into the Weston Shale. The sandstones are mainly fine- to very fine-grained, locally medium-grained.

Larger outcrops at these localities show sandstone storeys up to 10 ft (3 m) thick separated by erosional surfaces lined with mudstone intraclasts up to 2 inches (5 cm) in diameter, plant fragments and (rarely) limestone fragments. The storeys consist of cosets of trough cross-beds mainly less than 1.7 ft (50 cm) and up to 2.6 ft (80 cm) thick (Fig. 11A). In a few instances, large trough cross-sets pass upward into smaller-scale sets which in turn pass up into finer-grained, ripple cross-laminated sandstone. Cross-beds are commonly diffuse and convoluted, with foresets locally picked out by mica flakes, plant fragments, and silty layers. Plane-bedded sandstone with primary current lineation forms sheets up to 3.2 ft (1 m) thick. Large-scale, inclined surfaces ("epsilon" cross-strata) were not observed. Paleoflow at individual localities is unidirectional.

A series of outcrops near Stranger Creek northeast of Tonganoxie (Localites 22-24 [Stop 1-4], 27) lie within an where the Ireland Sandstone is amalgamated with the Tonganoxie Sandstone (Lins, 1950). It is unclear at present which stratigraphic unit is represented by the outcrops. At least 43 ft (13 m) of cross-bedded sandstone form spectacular bluffs on the west side of Stranger Creek (Locality 22, Stop 1-4) where the outcrop runs slightly oblique to the paleoflow direction. The strata here are cut by prominent erosional surfaces with up to about 10 ft (3 m) of relief. These erosional surfaces have local concave-up segments and extend for at least 330 ft (100 m) in the downflow direction. Some are lined with cavities that probably represent eroded mudstone blocks. The surfaces delineate storeys up to about 20 ft (6 m) thick that consist of cosets of cross-beds. The three dimensional form of the cross-sets is not certain. Some cross-sets, which show curved set bases and wedge out within about 33 ft (10 m) in the downflow direction, are probably trough cross-beds. Other cross-sets up to 6.5 ft (2 m) thick have relatively planar basal surfaces and can be traced for tens of meters in the downflow direction. They are probably planar cross-sets, and their bounding surfaces commonly show a systematic dip in the downflow or upflow direction, suggesting that they form components of larger scale sediment accumulations. "Epsilon" cross-strata were not observed.

Interpretation

Where occurrences of the facies association can be attributed unequivocally to the Tonganoxie Sandstone Member, the presence of erosionally based storeys a few meters thick composed primarily of trough cross-bedded sandstone suggests that the strata were laid down in shallow, bedload channels floored by 3D dunes. Lower regime flow predominated (dunes, ripples), but plane beds indicate periodic upper-regime flow. The scarcity of fining-upward trends and the lack of indication of larger scale barforms suggests that the paleovalley contained a network of shallow, braided channels, similar (apart from the scarcity of gravel) to those inferred for the Conglomeratic Assemblage.

The outcrops of Tonganoxie or Ireland Sandstone near Stranger Creek show thicker storeys and cross-sets. The systematic dip direction shown by some groups of set-bounding surfaces suggests that large-scale barforms were present within the channel (cf. Banks, 1973), who used downstream dips of set and coset boundaries to infer the presence of larger scale barforms). The channels appear to have been deeper and to have contained more common larger scale macroforms.

PLANAR CROSS-BEDDED ASSEMBLAGE

Description

Units of planar cross-stratified, fine- to very fine-grained sandstone >12 ft (3.5 m) thick rest on thin conglomerate sheets directly above the Stanton Limestone on the southeast side of the paleovalley axis (Localities 7-9, 11 and 12 [Stop 1-3], 17 [Stop 1-5], 29 and 31, at the edge of the outcrop belt). Planar cross-sets are associated with trough cross-bedded sandstones at several localities. The planar cross-sets are up to 4 ft (1.2 m) thick (Fig. 11B) and, where outcrops are good, can be traced in the downflow direction for at least 115 ft (35 m).

Cross-bed surfaces are commonly sigmoidal, and maximum dips range from 12-24°, averaging 17° (11 measurements). Cross beds are 0.4-1.2 inches (1-3 cm) thick, and in at least one instance show rhythmic variation in thickness (Archer et al., in press). Their surfaces commonly, but not universally, are defined by red-brown, ferruginous and silty laminae which are probably original fine drapes enhanced by cementation during diagenesis. These laminae are prominent at the base of the cross-bed surfaces but die out updip. Paired silty laminae (Visser, 1980) are common, and sands between some paired laminae contain ripple sets generated by flows that moved up the cross-bed surfaces. Many cross-beds are convoluted, especially where silty drapes are lacking. Bioturbation was not observed in any occurrence of the facies association. Foreset dip is strongly unidirectional.

At several localities, planar cross-set boundaries dip systematically in the upflow or downflow direction, with a maximum relief of 5 ft (1.5 m). Upflow-dipping surfaces appear more regular and extensive.

Associated strata are trough cross-bedded, ripple cross-laminated and lineated, plane-bedded sandstones in units up to 3.3 ft (1 m) thick. A few reddish siltstone layers up to 6 inches (15 cm) thick are present.

Interpretation

The planar cross-sets formed from 2D dunes that had a maximum height of at least 4 ft (1.2 m). The systematic inclination of set-bounding surfaces suggests that the cross-sets are components of barforms several meters high with a spacing greater than 165 ft (50 m). The presence of fine-grained drapes, paired laminae, and rhythmic variation in cross-bed thickness suggests a tidal origin for at least part of the facies association (Visser, 1980; Archer et al., in press). Associated trough cross-beds indicate the presence of 3D dunes, and periodic upper-regime flow is indicated by plane-bedded sandstones.

Planar cross-sets generated from 2D dunes are prominent in the deposits of many shallow, sand-bed streams (Smith, 1971). They are also common in sandflats and sandwave complexes of estuarine and shallow-marine systems (Kumar & Sanders, 1974; Visser, 1980; Dalrymple et al., 1990). Paleoflow for Tonganoxie planar cross-sets is unidirectional and sub-parallel with that of the fluvial assemblages discussed earlier, suggesting a fluvial origin. However, the good sedimentological evidence for tidal influence suggests deposition in an ebb-dominated estuarine system.

RIPPLE CROSS-LAMINATED ASSEMBLAGE

Description

Ripple cross-laminated sandstone and siltstone overlies cross-stratified sandstones in both the Tonganoxie and Ireland outcrop areas mapped by Lins (1950) (Localities 16, 18 [Stops 1-6a, b], 25, 27, 36, 37 and 41-43). The thickness of strata assigned to the assemblage is 67 ft (20.45 m) at Locality 25 (which may be part of the Ireland Sandstone

Member) and 20-43 ft (6-13 m) at five other localities.

The strata are organized into erosionally based, fining-up units 3.3-15 ft (1-4.5 m) thick (Fig. 12). Basal surfaces of the units are planar but locally scoured into the underlying strata. The lowermost few decimeters of each unit consists of very fine-grained sandstone with stacked, truncated rippled sets and a lack of clay drapes. Trough cross-sets up to 4 inches (10 cm) thick are present in some layers. The sandstones fine upward into ripple cross-laminated siltstone. The ripples in these finer grained beds are asymmetric (current-formed), linguoid, or lunate in planform, and commonly climbing. Most are preserved as formsets 0.4-1.2 inches (1-3 cm) thick with minimal truncation of the cross-laminae. Clay laminae drape foresets and entire ripples, and the stratification can be assigned to the category of flaser-bedding (Reineck & Wunderlich, 1968) with some wavy and lenticular bedding. A few ripples are apparently symmetric in cross-section and plan view but show a preferred foreset dip; they may be combined-flow ripples. Plane-bedded sandstone layers and a few ferruginous layers up to 2 inches (5 cm) thick are present. Paleoflow is bimodal but predominantly northeasterly (Fig. 12).

In the basal 30 ft (9 m) of strata at Locality 25 (Fig. 12), discrete beds of ripple cross-laminated sandstone 0.8-6 inches (2-15 cm) thick are intercalated with rippled siltstones. Some sandstone beds have scoured bases lined with mudstone intraclasts.

Sparse vertical and horizontal burrows were noted at most localities. One fining-up unit contains abundant bivalves (Carbonicola) in the basal part, with the both articulated and splayed out, and disarticulated valves. Vascular plant fragments up to 4 inches (10 cm) long are common.

Features indicative of subaerial exposure or very shallow water were observed in ripple cross-laminated strata at two localities where the stratigraphic attribution is uncertain. At Locality 28, the strata were mapped as Ireland Sandstone by Lins (1950) but could also be part of the Vinland Shale just below the Haskell Limestone. A distinctive suite of sedimentary structures includes planed-off ripples, mudcracks in ripple troughs, groove casts, primary current lineation, and runzel marks. The ichnogenera Arenicolites, Lockeia and Scalarituba are present, along with numerous plant fragments. Paleoflow was towards the southwest. At Localities 33 and 34 in Platte County, Missouri (Fig. 13), the Iatan Limestone is overlain by 4.6 ft (1.4 m) of rippled siltstone with sandstone interbeds, syneresis cracks, plant fragments and Lockeia. A meter-thick rooted seat earth above the siltstone is overlain by a thin dark limestone under the Upper Sibley Coal. These strata were assigned to the Tonganoxie Sandstone by Howe (1986) and Spriggs (1989) but could also be part of the Weston Shale.

Interpretation

The abundance of flaser bedding indicates a prevailing tidal influence (Reineck & Wunderlich, 1968), an inference supported by the bimodal paleoflow of some units. Bivalves and burrows were noted only within this assemblage, suggesting marine or brackish influence. The erosionally based, fining-up units are interpreted as tidal channel deposits. Unusually powerful tidal or fluvial flow events are represented by the discrete sandstone beds and rare plane-bedded layers. The common occurrence of plant fragments suggests proximity to a vegetated terrain. The overall setting was probably a tidal embayment or subaqueous estuarine zone. Features indicative of subaerially exposed tidal flats or very shallow tidal waters were noted only in two problematic outcrops.

OTHER FACIES OF THE TONGANOXIE SANDSTONE

Several facies not discussed above are present in the Tonganoxie Sandstone Member. Lins (1950) noted that shales are an important component of the member, but few exposures were found in the study area. Thin, discontinuous coals were reported at several levels below the Upper Sibley Coal by Bowsher & Jewett (1943) and lie entirely within the paleovalley fill (Lins, 1950). They were not encountered during the present study. At the Buildex Quarry near Ottawa, Franklin County, about 25 miles (40 km) south of Lawrence, tidal rhythmites with upright trees, rain prints, and tetrapod trackways are well developed at the base of the Tonganoxie Sandstone (Lanier et al., in press). The rhythmites rest on the Ottawa Coal which in turn overlies an erosional surface cut into the Weston Shale, and the strata occupy a valley-marginal position. Tidal rhythmites were not identified in outcrop or core during the present study.

A calcareous paleosol is developed beneath the Upper Sibley Coal in the Oelschlaeger No. 1 drill hole (Fig. 10). However, no exposures at this level were found in the study area, and the extent of the calcareous layer is not known, although a well-developed but apparently non-calcareous seat earth underlies the Upper Sibley Coal in the Platte County localities (33, 34; Fig. 13).

PALEOFLOW PATTERNS

A total of 115 paleoflow measurements were obtained in the study area. About 60% of the measurements are considered accurate to within 5°. These comprise orientation data for large-scale cross-sets and barform surfaces in large, 3D outcrops, and for ripple cross-lamination, current lineation and groove casts in smaller outcrops. The remaining measurements represent partial exposures of trough and planar cross-sets in small or 2D outcrops. Such measurements are strongly biased by outcrop orientation and may be tens of degrees from the true cross-bed orientation, particularly in the case of trough cross-sets. Additionally, it is not always clear whether trough or planar cross-sets were measured. However, such measurements can provide a supplementary source of information about these important, large-scale structures when data from several outcrops are grouped. In a few cases, exposure was adequate to yield a generalized paleoflow direction accurate to within about 20°.

Figure 14 shows paleoflow data for each assemblage according to the type of sedimentary structure and by geographic location within the paleovalley fill. Important conclusions are:

1) Across most of the study area, the conglomeratic and trough cross-bedded assemblages show a unidirectional, southwesterly to westerly paleoflow sub-parallel to the paleovalley axis (Fig. 14A,B,C). This indicates the presence of a southwesterly oriented fluvial drainage system along the valley axis during early stages of valley filling, as suggested by Lins (1950). A similar paleoflow pattern was obtained for the planar cross-bedded assemblage, interpreted above as an estuarine sandwave system, and suggests that tidal flow was ebb-dominant.

2) Southeasterly to southerly paleoflow was obtained for all three assemblages towards the southern paleovalley margin in southeast Leavenworth County and southwest Wyandotte County. This paleoflow trend was documented both from thick fluvial conglomerates and from thin conglomerates underlying planar cross-sets at the valley base. This local paleoflow at right angles to the paleovalley axis corresponds approximately with a tributary valley or embayment defined from drill-log data.

3) Sparse northwesterly paleoflow data were obtained from trough cross-bedded sandstones resting on the Weston Shale towards the northern paleovalley margin in northern Leavenworth County. A tributary valley was documented also in this area (Fig. 14B).

4) Current ripples of the ripple cross-laminated assemblage show a bimodal pattern at Locality 25 northeast of Tonganoxie (Fig. 14D), supporting a tidal origin for these strata. The predominant northeasterly paleoflow represents

a pronounced reversal from that of the underlying fluvial strata, and suggests that flood-dominant tidal flows along the paleovalley axis controlled deposition during later stages of valley filling. This outcrop, however, may be part of the Ireland Sandstone. A few measurements from ripple-bedded strata mapped as Tonganoxie Sandstone suggest southwesterly and northeasterly paleoflow in southern and northern Leavenworth County, respectively, in accord with paleoflow data from other assemblages. This could reflect ebb-dominant tidal flow into embayments of the main paleovalley or flood-dominant flow into tributary valleys.

VINLAND SHALE AND HASKELL LIMESTONE MEMBERS

Sparse data only were obtained for this stratigraphic interval in the study area, from the Oelschlaeger #1 core, Localities 20 and 32 in Leavenworth and Douglas Counties, and Localities 33 and 34 in Platte County. The Vinland Shale is 37 ft (11.4 m) thick in the core and 13 ft (3.95 m) thick in the Platte County localities where it is a gray-to-tan clayshale with resisant calcareous layers and an open-marine biota (Spriggs, 1989). A thick-bedded, sandy facies is present in the topmost Vinland Shale in the core (Fig. 10) and at Locality 32 (Fig. 15). The strata are cross-bedded and ripple-laminated, and include an erosionally based, fining-up sequence (Fig. 15). The topmost meter of strata at Localities 20 (Stop 1-7) and 32 is a ripple cross-laminated, very fine-grained sandstone to siltstone with scour fills and plant fragments. The Haskell Limestone is sandy in its lower part and contains an abundant shelly marine fauna (Miller & Swineford, 1957).

EVOLUTION OF THE TONGANOXIE PALEOVALLEY AND SEA LEVEL HISTORY

The base of Tonganoxie paleovalley was incised approximately 130 ft (19.6 m) during a major fall in sea level. Paleosols are not well represented on the surface underlying the Tonganoxie Sandstone, but at the Buildex quarry (Stop 2-4) the Tonganoxie Sandstone rests on a rooted coal overlying the "Weston Shale." A paleosol developed on the Iatan Limestone and overlying shale in Missouri may also be contemporaneous with valley incisement. The surface underlying the Tonganoxie Sandstone is a sequence boundary because it occurs at a major basinward shift in facies (see Van Wagoner et al., 1990). The Tonganoxie paleovalley was a major topographic feature, and is similar in scale to the modern Missouri River valley in the field trip area; the Tonganoxie trunk paleovalley had approximately the same relief as the modern Missouri River valley, and was twice as wide. The transition from a dominantly erosional stream to a dominantly depositional one can result from many causes, such as climate, tectonics, and changes in baselevel, and is not easily related to sea level (Schumm, 1993; Wescott, 1993). The initial deposits in the paleovalley comprise the type 1 sandstone and consist mostly of the conglomeratic and trough cross-bedded assemblages. These coarse lithologies were deposited primarily by braided streams.

The rest of the Tonganoxie Sandstone in the trunk valley is composed of type 2 sandstones, shale, and coal. Where type two sandstones are exposed they are composed of planar cross-bedded and ripple cross-laminated assemblages, and contain evidence of tidal, estuarine conditions, including clay drapes, increased diversity of trace fossils, and reversals in paleoflow. The arcuate shapes of type 2 sandstones suggest that they were formed in point bars, perhaps in tidal creeks surrounded by mudflats. Type 3 sandstones occur at the upstream limits of tributaries, where the bases of tributaries are 80 to 100 ft (24.3 to 30.5 m) above the Eudora Shale. These sandstone bodies may be deltas that prograded during a stillstand after most of the paleovalley was flooded. Type 3 sandstones are not exposed.

Following Tonganoxie deposition the area was exposed and the Upper Sibley Coal was deposited. The paleovalley was mostly filled with sediment prior to development of the Upper Sibley Coal, and the coal extends far beyond the limits of the paleovalley. This coal may represent a small fall in relative sea level. Abrupt marine inundation after coal deposition is recorded by the Westphalia Limestone. The Vinland Shale above the Westphalia Limestone consists of marine shale and sandstone and is overlain by clear water deposits of the Haskell Limestone. The presence of oolites in the Haskell indicate shallow water. The lowermost Robbins Shale is a condensed interval that was deposited slowly in relatively deep water. Common in this interval are phosphate concretions, phosphatic fossils, such as fish scales, fish skulls with brain casts, and orbiculoid brachiopods (Miller and Swineford, 1957). Also present are cephalopods such as ammonites and nautiloids. Foul bottom water conditions are suggested by the rarity of benthic fossils. This interval represents maximum flooding surface. The top of the Tonganoxie sequence is at the base of the Ireland Sandstone.

CONCLUSIONS

The Tonganoxie Sandstone Member occupies a paleovalley cut through the Iatan Limestone and Weston Shale members into the Stanton Limestone in northeast Kansas. It is locally amalgamated with a paleovalley fill of the younger Ireland Sandstone Member. The Tonganoxie sandstones and siltstones represent an upward transition from a braided-fluvial system with episodic flow to a subaqueous estuary with tidal channels. A tidal sandwave complex is present locally. Paleoflow was southwesterly during early stages of valley filling but changed to northeasterly during the later, estuarine stage (possibly of the Ireland Sandstone). Systematic paleoflow deflections correspond to tributary valleys or embayments documented from drill-log analysis.

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APPENDIX 1: OUTCROP LOCATIONS

1. NW 1/4 SW 1/4, sec. 21, T12S, R21E; Leavenworth Co. Two small outcrops 75 m apart on E side of N section road, about 200 m downhill from outcrop of Haskell Ls. near hillcrest. Tonganoxie Sandstone. Elevation of section base 880'.

2. NW 1/4 NE 1/4, sec. 21, T12S, R21E; Leavenworth Co. Outcrops 20 m long on both sides of E-W section road, outcrop mainly on S side of E-facing hill. Tonganoxie Sandstone. Elevation of section base 880'.

3. NE 1/4 NE 1/4, sec. 21, T12S, R21E; Leavenworth Co. Outcrops 30 m long along both sides of E-W section road, up W-facing hill and into driveway on the N side of road. Tonganoxie Sandstone. Elevation of section base 880'.

4. NE 1/4 NW 1/4, sec. 17, T10S, R23E; Wyandotte Co. Excellent outcrop 5 m high for 100 m along S side of E-W section road, along crest of small hill. Tonganoxie Ss.on Stanton Lst, with good exposures of limestone above stream on N side of road. Elevation of section base 870'.

5. NW 1/4 NE 1/4, sec. 17, T10S, R23E; Wyandotte Co. Outcrop 20 m long on N side of E-W section road, below driveway on E-facing hill. Section commences in ditch. Tonganoxie Ss. Elevation of section base 900'.

6. NW 1/4 NE 1/4, sec. 16, T10S, R23E; Wyandotte Co. Outcrop 20 m long on S side of E-W section road, on W-facing hill, in ditch and bank. Stanton Ls. only. Elevation of section base 830'.

7. NW 1/4 NW 1/4, sec. 34, T10S, R23E; Wyandotte Co. Outcrops 20 m long around NE and SE corners of road intersection, 1 mile E of Piper. Tonganoxie Ss. Elevation of section base 935'.

8. NE 1/4 NE 1/4, sec. 33, T10S, R23E; Wyandotte Co. Outcrops 80 m long on both sides of E-W section road, 120 m W of intersection (outcrop 7). Tonganoxie Ss. Elevation of section base 935'.

9. NE 1/4 NW 1/4, sec. 34, T10S, R23E; Wyandotte Co. Outcrops 150 m long on both sides of E-W section road, 200 m E of intersection (outcrop 7). Tonganoxie Ss. Elevation of section base 935'.

10. NW 1/4 NE 1/4, sec. 36, T10S, R22E; Leavenworth Co. Outcrops for 100 m along both sides of E-W section road on E-facing hill. Also in small bluff above Wolf Creek on S side of road and in tributary creek 100 m S of section road. Roadside outcrop commences just W of bridge 200 m W of intersection with Hwy. 73. Tonganoxie Ss. on Stanton Ls. Elevation of section base 870' (Stanton Ls.).

11. NW 1/4 NW 1/4, sec. 8, T11S, R23E; Wyandotte Co. Outcrops for 100 m on both sides of Hwy. 73 near hillcrest about 300 m SE of Hwy. 24/40. Tonganoxie Ss. on Stanton Ls. Elevation of section base 980'.

12. NW 1/4 NW 1/4, sec. 8, T11S, R23E; Wyandotte Co. Outcrop 100 m long on E side of Hwy 73, 200 m S of outcrop 11. Tonganoxie Ss. Elevation of section base 970'.

13. NE 1/4 NE 1/4, sec. 7, T11S, R23E; Wyandotte Co. Outcrops on both sides of Hwy. 24/40 just E. of underpass below Hwy. 73. Outcrop on N side is along access road onto Hwy. 24/40. Tonganoxie Ss. on

Stanton Ls. Elevation of section base 940'.

14. SW 1/4 SW 1/4, sec. 6, T11S, R23E; Wyandotte Co. Small outcrops in ditch and bank on N side of Hwy. 24/40, for 100 m up W-facing hill immediately E of Leavenworth Co. line and side road. Tonganoxie Ss. Elevation of section base 950'.

15. SW 1/4 SE 1/4, sec. 1, T11S, R22E; Leavenworth Co. Outcrops for 100 m down both sides of Hwy. 24/40 on W-facing hill 300 m E of Wolf Creek. Tonganoxie Ss. on Stanton Ls. Elevation of section base 920'.

16. SW 1/4 SW 1/4, sec. 1, T11S, R21E, Leavenworth Co. Outcrop 100 m long on E-facing hill, N side of Hwy. 24/40 and 2 km W of Stranger Creek crossing. Tonganoxie Ss. Elevation of section base 880'.

17. SW 1/4 SE 1/4, sec. 6, T11S, R22E; Leavenworth Co. Outcrop 100 m long on N side of Hwy. 24/40, 200 m E of Stranger Creek. Tonganoxie Ss. Elevation of section base 830'.

18. SW 1/4 SW 1/4, sec. 1, T11S, R21E; Leavenworth Co. Outcrops 100 m long on N side and 20 m long on S side of Hwy. 24/40. At hillcrest 300 m W of outcrop 17. Tonganoxie Ss. Elevation of section base 910'.

19. SE 1/4 SW 1/4, sec. 2, T11S, R21E; Leavenworth Co. Outcrops 50 m long on both sides of Hwy. 24/40, at crest of hill with major W-facing slope, 500 m W of outcrop 18. Tonganoxie Ss. Elevation of section base 930'.

20. SW 1/4 SE 1/4, sec. 3, T11S, R21E; Leavenworth Co. Outcrops 40 m long on both sides of Hwy. 24/40, on hillcrest E of Tonganoxie and 1.5 km W of outcrop; 19. Tonganoxie Ss. below Haskell Ls. Elevation of section base 915'.

21. NW 1/4 NW 1/4, sec. 5, T11S, R22E; Leavenworth Co. Outcrop 50 m long on E side of N-S section road, just S of right-angle bend above stream, along N-facing hill. Tonganoxie Ss. Elevation of section base 850'.

22. NE 1/4 NW 1/4, sec. 36, T10S, R21E; Leavenworth Co. Near-continuous excellent outcrop, 5-10 m high, for 500 m along W bank of Stranger Creek below bridge on E-W section road. Tonganoxie or Ireland Ss. Elevation of section base 810'.

23. NE 1/4 NW 1/4, sec. 31, T10S, R22E; Leavenworth Co. Outcrop 20 m long on N side of E-W section road, along E-facing hill 1 km E of bridge over Stranger Creek; small outcrop on S side of road. Tonganoxie or Ireland Ss. Elevation of section base 880''.

24. NW 1/4 SW 1/4, sec. 20, T10S, R22E; Leavenworth Co. Outcrop 20 m long on W side of small N-facing hill above Little Stranger Creek, on N-S road. Tonganoxie Ss. Elevation of section base 890'.

25. SW 1/4 SW 1/4, sec. 25, T10S, R21E; Leavenworth Co. Outcrop 50 cm high for 200 m in roadside ditch running all the way up a N-facing hill, on N-S road above creek. Tonganoxie or Ireland Ss. Elevation of section base. 830'.

26. SW 1/4, NE 1/4, sec. 26, T10S, R21E; Leavenworth Co. Small outcrop at hillcrest on E-W section

road, 300 m W of Tonganoxie Rd. Tonganoxie Ss. Elevation of section base 850'.

27. NE 1/4 NW 1/4, sec. 36, T10S, R21E; Leavenworth Co. Outcrop in bank and ditch on E-W road starting 20 m W of bridge over Stranger Creek and 30 m from outcrop 22. From base of E-facing hill to driveway on S side of road near hillcrest. Tonganoxie or Ireland Ss. Elevation of section base 820'.

28. SW 1/4 SE 1/4, sec. 10, T10S, R21E; Leavenworth Co. Outcrop for 100 m along E side of N-facing hill above Jarbalo Creek, along paved section road. Tonganoxie or Ireland Sst, at level a little below Haskell Ls. (if formerly present). Elevation of section base 850'.

29. NW 1/4 NW 1/4, sec. 35, T10S, R23E; Wyandotte Co. Outcrops 100 m long on both sides of E-W running Hwy. 5, 200 m W of overpass of Hwy. 435. Outcrops above rip-rap. Tonganoxie Ss. Elevation of section base 980'.

30. NE 1/4 NW 1/4, sec. 35, T10S, R23E; Wyandotte Co. Outcrop just on W side of Hwy. 435 overpass, by access road onto Hwy. 5. Stanton Ls. along access road, Tonganoxie Ss. in bank of overpass. Elevation of section base 980'.

31. NE 1/4 NW 1/4, sec. 35, T10S, R23E; Wyandotte Co. Outcrop 50 m long, above rip-rap on N side of Hwy. 5 along Northwood exit, 150 m of Hwy. 435 overpass. Tonganoxie Ss. Elevation of section base 980'.

32. NE 1/4 NE 1/4, sec. 5, T13S, R20E; Douglas Co. Outcrops 50 m long towards crest of E-facing hill on 15th St., Lawrence, and into driveway on N side of road. Tonganoxie Ss. below Haskell Ls. Elevation of section base 850'.

33. NW 1/4 NW 1/4, sec. 29, T54N, R36W; Platte Co., Missouri disused quarry with face 300 m long on E side of highway and railroad, opposite road to powerplant and 2.5 km S of Iatan. Iatan Lst, to Haskell Ls. interval. Elevation of section base 920'.

34. NW 1/4 NW 1/4, sec. 33, T54N, R36W; Platte Co., Missouri disused quarry on E side of highway and railroad, accessed by track where railroad divides S into two tracks. 800 m S of outcrop 33. (Outcrop 1 of Spriggs, 1989). Section from just above Iatan Ls. to Haskell Ls. Elevation of section base 840'.

35. SW 1/4 NE 1/4, sec. 3, T8S, R22E; Leavenworth Co. Disused quarry S of railroad and 300 m SE of E-W section road that crosses the tracks. Just S of Salt Creek. Iatan Ls. only. Elevation of section base 820'.

36. NW 1/4 SW 1/4, sec. 1, T9S, R22E; Leavenworth Co. Disused quarry just SE of Firemile Creek and 300 m E of Hwy. 73 on E outskirts of Leavenworth, S side of Marion Rd., Tonganoxie Ss.on Weston Shale. Elevation of section base 820'.

37. SE 1/4 SE 1/4, sec. 9, T9S, R22E; Leavenworth Co. Outcrop 100 m long, on NW side of Hwy 5. Tonganoxie Ss. Elevation of section base 890'.

38. SW 1/4 SW 1/4, sec. 10, T9S, R22E; Leavenworth Co. Outcrop 30 m long

on S bank of NE-running stream, S of Hwy. 5, and extending for 30 m up tributary stream. 200 m SE of outcrop 37. Tonganoxie Ss. Elevation of section base 860'.

39. SE 1/4 NW 1/4, sec. 10, T9S, R22E; Leavenworth Co. Outcrop 75 m long in bank on NW side of Hwy 5, 300 m NE of outcrop 38. Tonganoxie Ss. Elevation of section base 870'.

40. NW 1/4 NE 1/4, sec. 10, T9S, R22E; Leavenworth Co. Outcrop 50 m long on N side of Hwy 5, more scattered on S side, at hillcrest 0.8 km NE of outcrop 39 and just inside Leavenworth city limits. Tonganoxie Ss. Elevation of section base 900'.

41. NW 1/4 SW 1/4, sec. 23, T9S, R22E; Leavenworth Co. Outcrop 200 m long in ditch and bank up E side of N-S section road, starting at base of N-facing hill and running to near hillcrest at driveway. Tonganoxie Ss.on Weston Shale. Elevation of section base 860'.

42. SW 1/4 SW 1/4, sec. 23, T9S, R22E; Leavenworth Co. Outcrop 20 m long on W side of road, 0.8 km S of outcrop 41. Tonganoxie Ss. Elevation of section base 950'.

43. NW 1/4 NW 1/4, sec. 10, T9S, R22E; Leavenworth Co. Outcrop 100 m long up hill on E-W road running W from Hwy 5, in bank and ditch. Tonganoxie Ss. Elevation of section base 865'.

44. NE 1/4 SW 1/4, sec. 5, T13S, R21E; Douglas Co. Outcrop 50 m long, 2 blocks W of old Kaw Valley Bank, Eudora, in bank on S side of E-W road just W of bridge. Originally measured by N.D. Newell. Tonganoxie Ss.visible. Elevation of base of Tonganoxie Ss. exposure 815'.

TABLE 1: Tonganoxie Sandstone facies descriptions.

FACIES ASSEMBLAGE		POSITION IN PALEOVALLEY FILL	MAX. THICKNESS OBSERVED IN OUTCROP	LITHOLOGY
1.	CONGLOMERATIC ASSEMBLAGE	In basal 8 m of fill in central outcrop belt. Thin conglomerate on Stanton in SE part of outcrop belt.	4.5 m	Pebble conglomerate, Fine-medium sandstone
2.	TROUGH CROSS-BEDDED ASSEMBLAGE	Overlies Assemblage 1 locally. At base of fill on Weston Shale in NW part of outcrop belt.	13 m	Fine-sandstone, rarely medium-grained.
3.	PLANAR CROSS-BEDDED ASSEMBLAGE	Overlies thin conglomerate (Assemblage 1) in SE part of outcrop belt.	3.5 m	Fine sandstone, minor siltstone.
4.	RIPPLE CROSS-LAMINATED ASSEMBLAGE	Overlies Assemblages 2 + 3 across outcrop belt.	20 m	Siltstone, with fine-very fine sandstone, claystone.

SEDIMENTARY FEATURES	STRATAL ORGANIZATION	FOSSILS	DEPOSITIONAL SETTING
Clast-supported, cross-bedded Trough cross-beds, ripple cross-lam, plane beds.	Channel fills up to 2 m thick with bar forms and surfaces.	Large plant fragments; bone and marine shell fragments reworked from Stanton Ls.	Fluvial (braided?) channels with episodic discharge.
Trough cross-sets upto 80 cm thick, with planar cross-sets, ripple cross-lam, plane beds.	Channel-based storeys up to 3 m thick. Upward succession of bedforms rare. Large-scale barforms.	Plant fragments	Fluvial (braided?) channels with episodic discharge.
Planar cross-sets up to 1.2 m thick, with lower foreset drapes, paired drapes, rhythmic variation in foreset thickness. Minor trough cross-sets, ripple cross-lam, plane beds.	Barforms > 3.5 m high inferred from systematic dip of set boundaries.	Plant fragments	Tidal sandwave complex, ebb-dominated.
Flaser and lenticular bedding, asymmetric ripple formsets. Minor plane beds.	Fining up, erosionally based units up to 4.5 m thick.	Sparse burrows, bivalves (Carbonicola), plant fragments.	Tidal embayment with subaqueous channels.

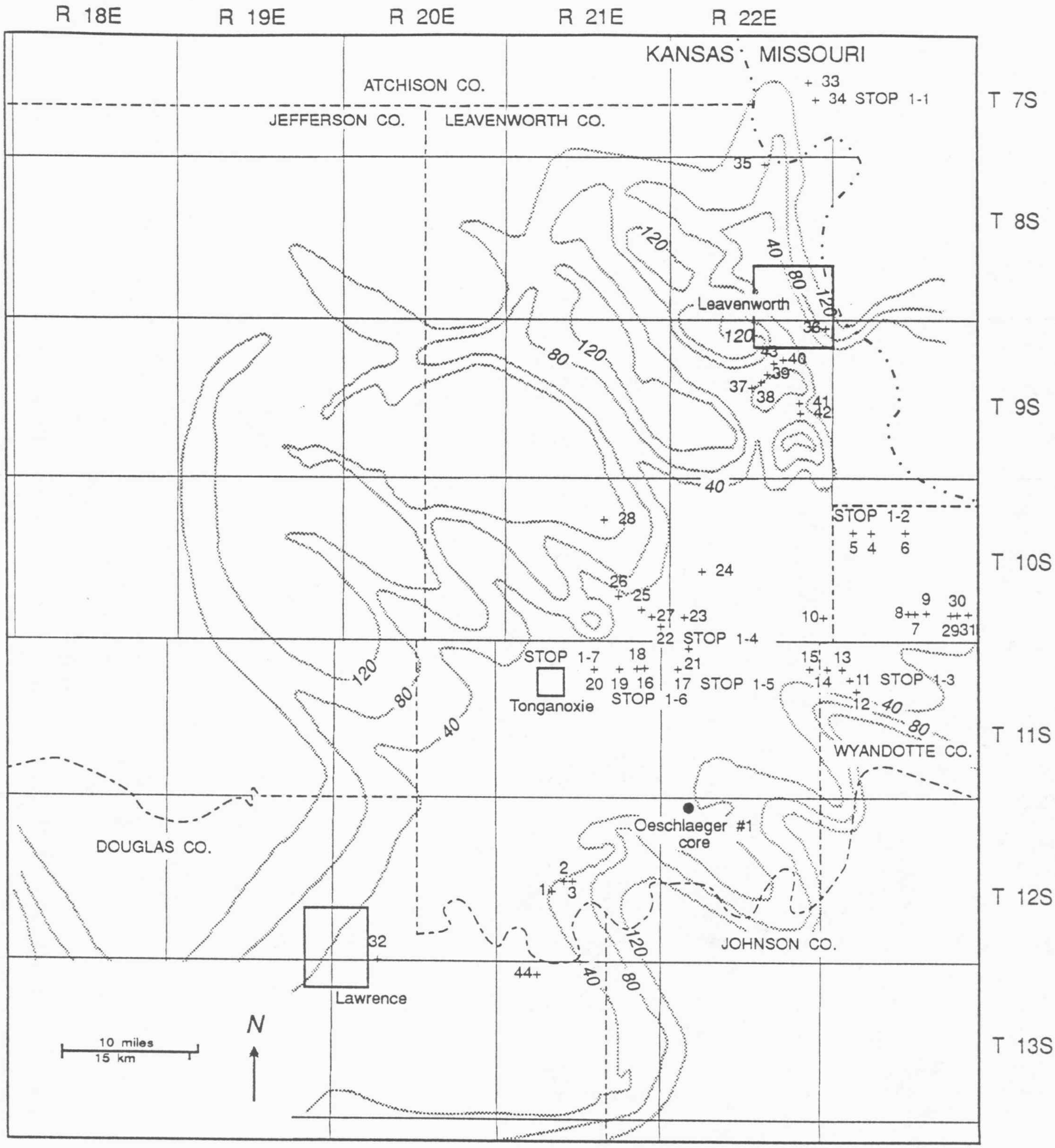


Figure 1. Map of outcrop localities used for facies descriptions and to measure paleoflow directions. Base map includes township lines, county and state boundaries, and contour lines of the thickness from the base of the Eudora Shale to the base of the Tonganoxie Sandstone in ft.

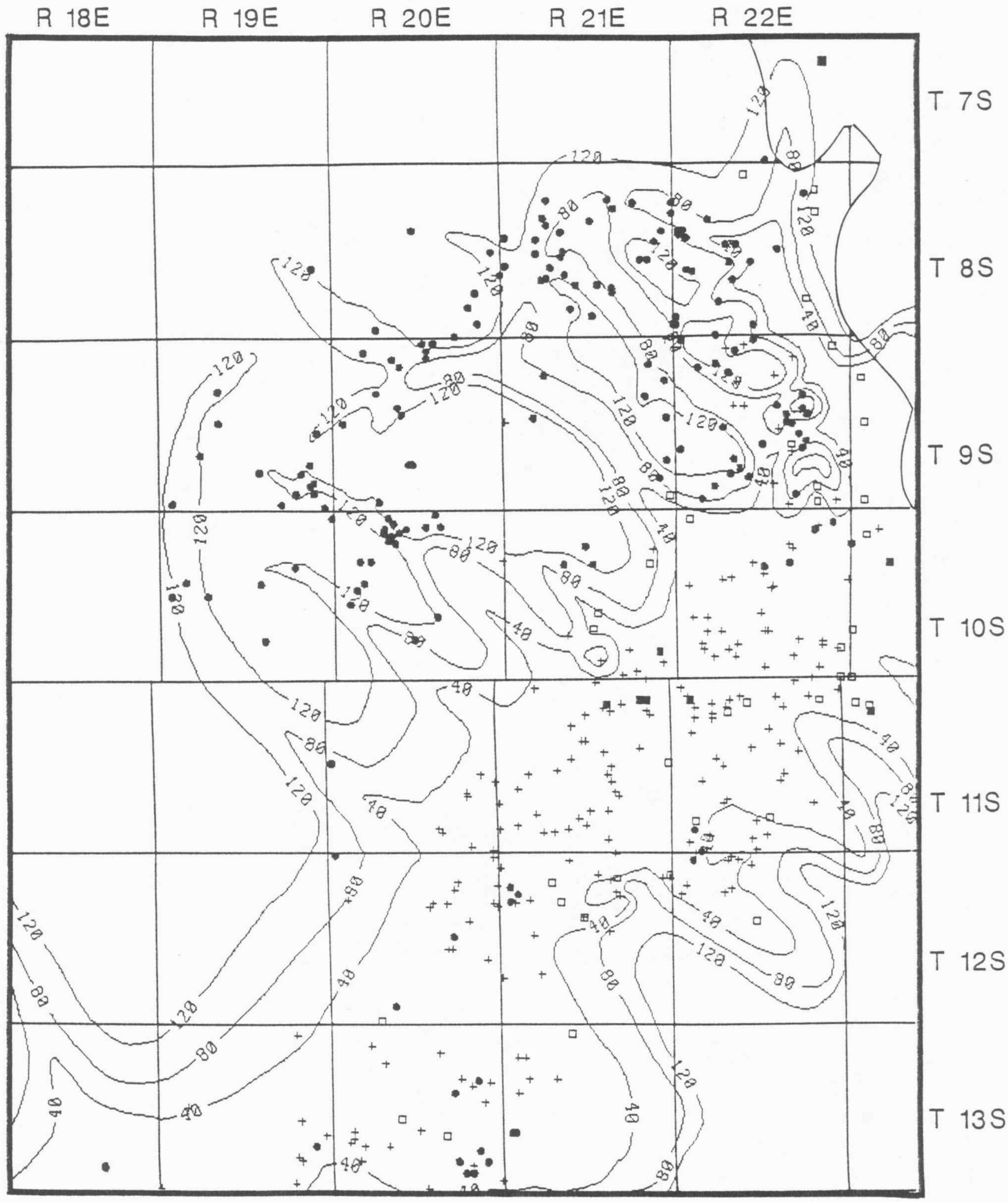


Figure 2. Map of the localities used to construct isopach maps. Solid circles are oil well wireline logs, pluses are water well drillers logs, open squares are outcrops, and filled squares are field trip stops. Base map shows contour lines of the thickness from the base of the Eudora Shale to the base of the Tonganoxie Sandstone in ft.

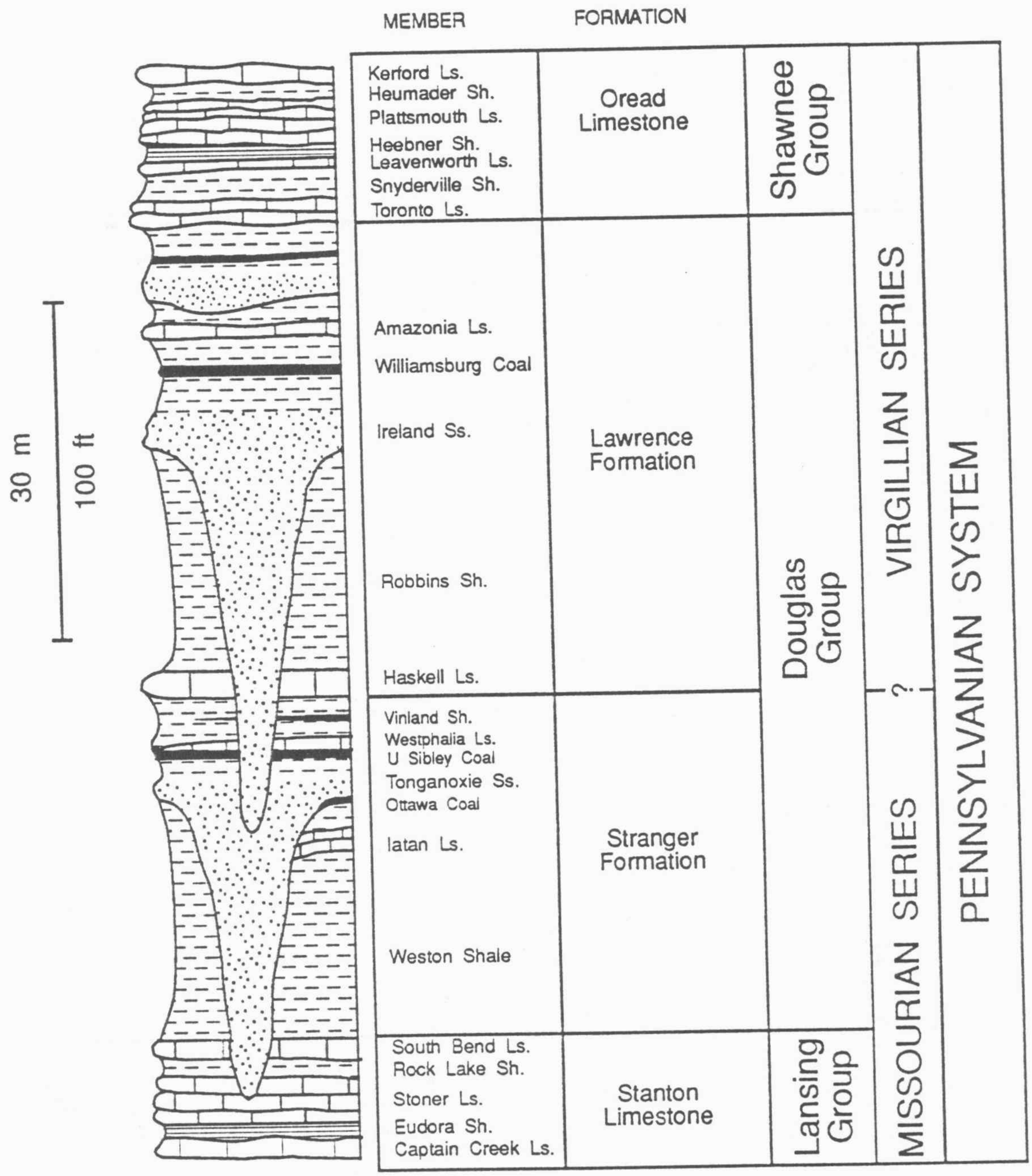


Figure 3. Stratigraphic nomenclature of the study interval in Leavenworth Co.

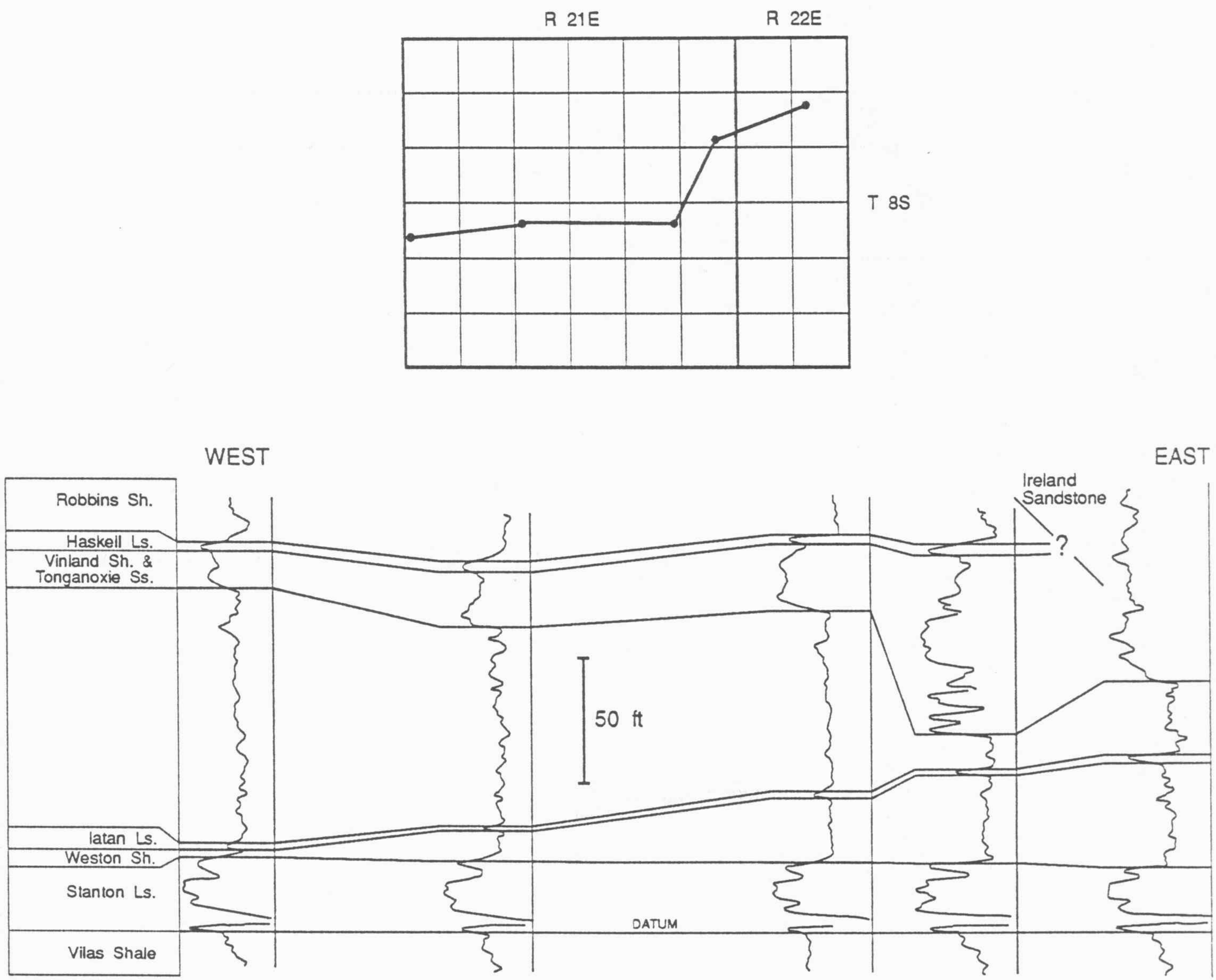


Figure 4. Cross section showing the relationship between the Iatan Limestone and the Stanton Limestone. Datum is base of Stanton Limestone.

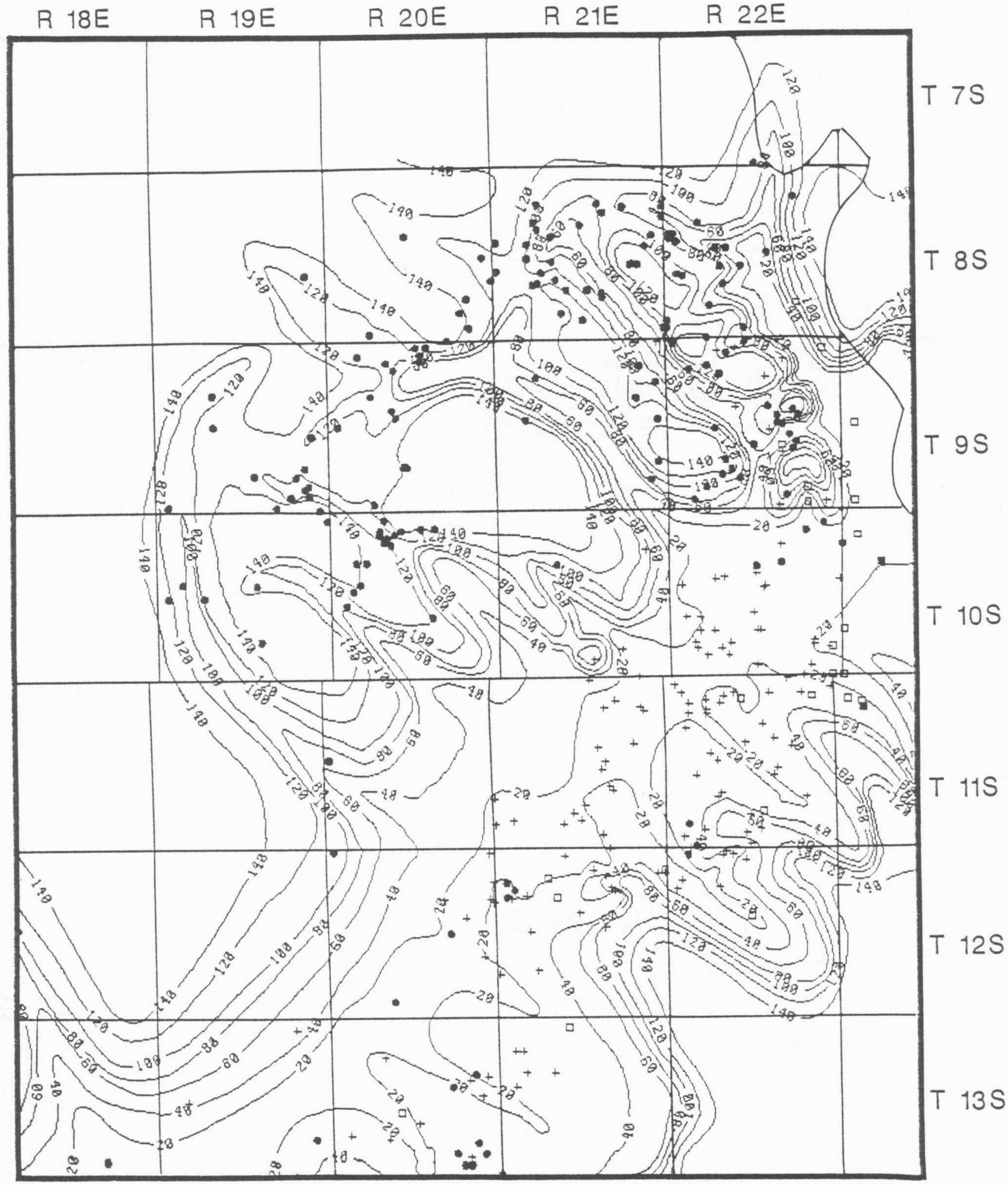


Figure 5. Isopach map of the interval from the base of the Eudora Shale to the base of the Tonganoxie Sandstone. Contour interval is 20 ft. See Fig. 2 for explanation of types of data points.

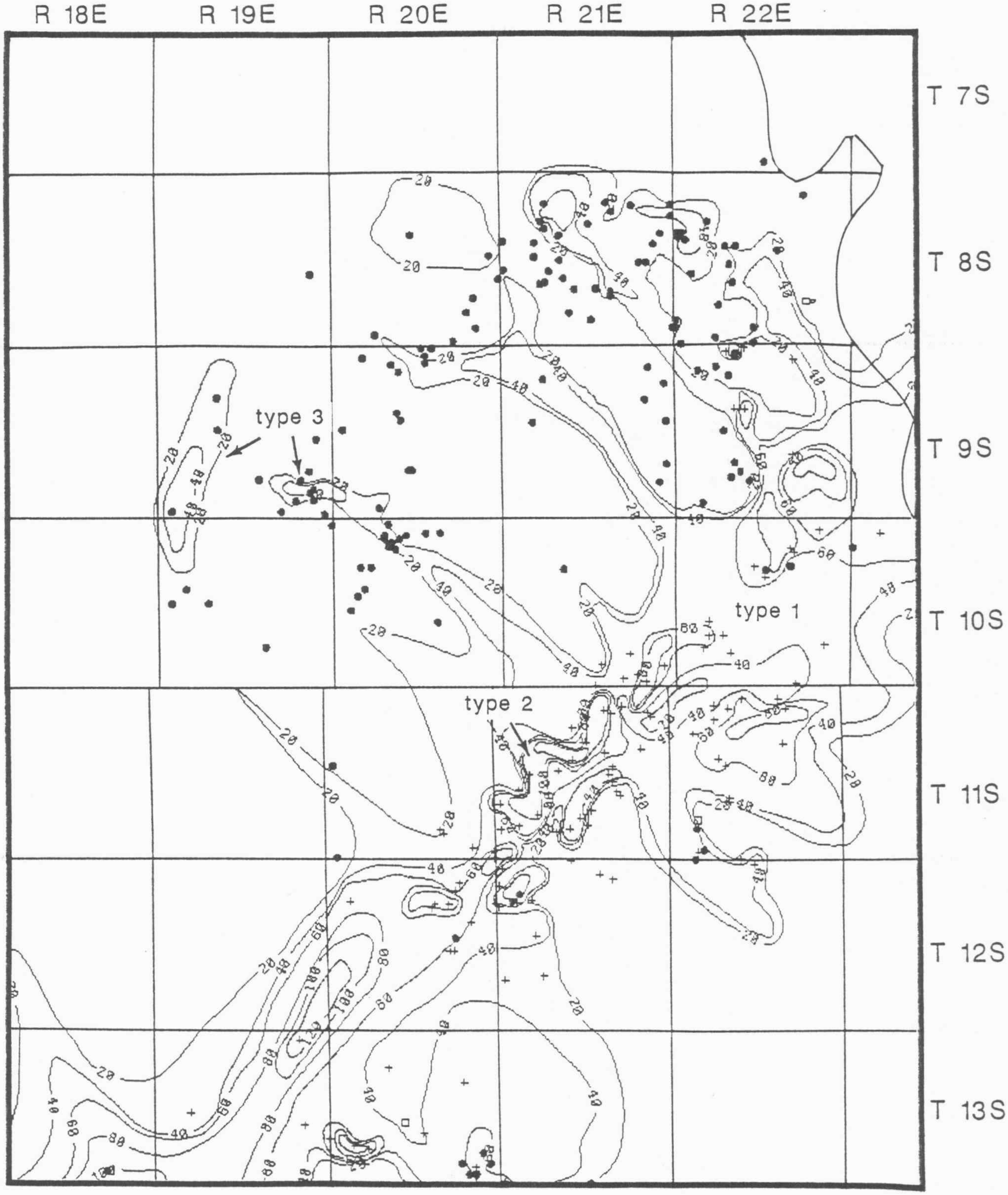


Figure 6. A, Isopach map of the basal sandstone of the Tonganoxie Sandstone showing type 1, 2, and 3 sand bodies. B, Detail from A showing arcuate sand bodied (type 2). Contour interval is 20 ft. See Fig. 2 for explanation of types of data points.

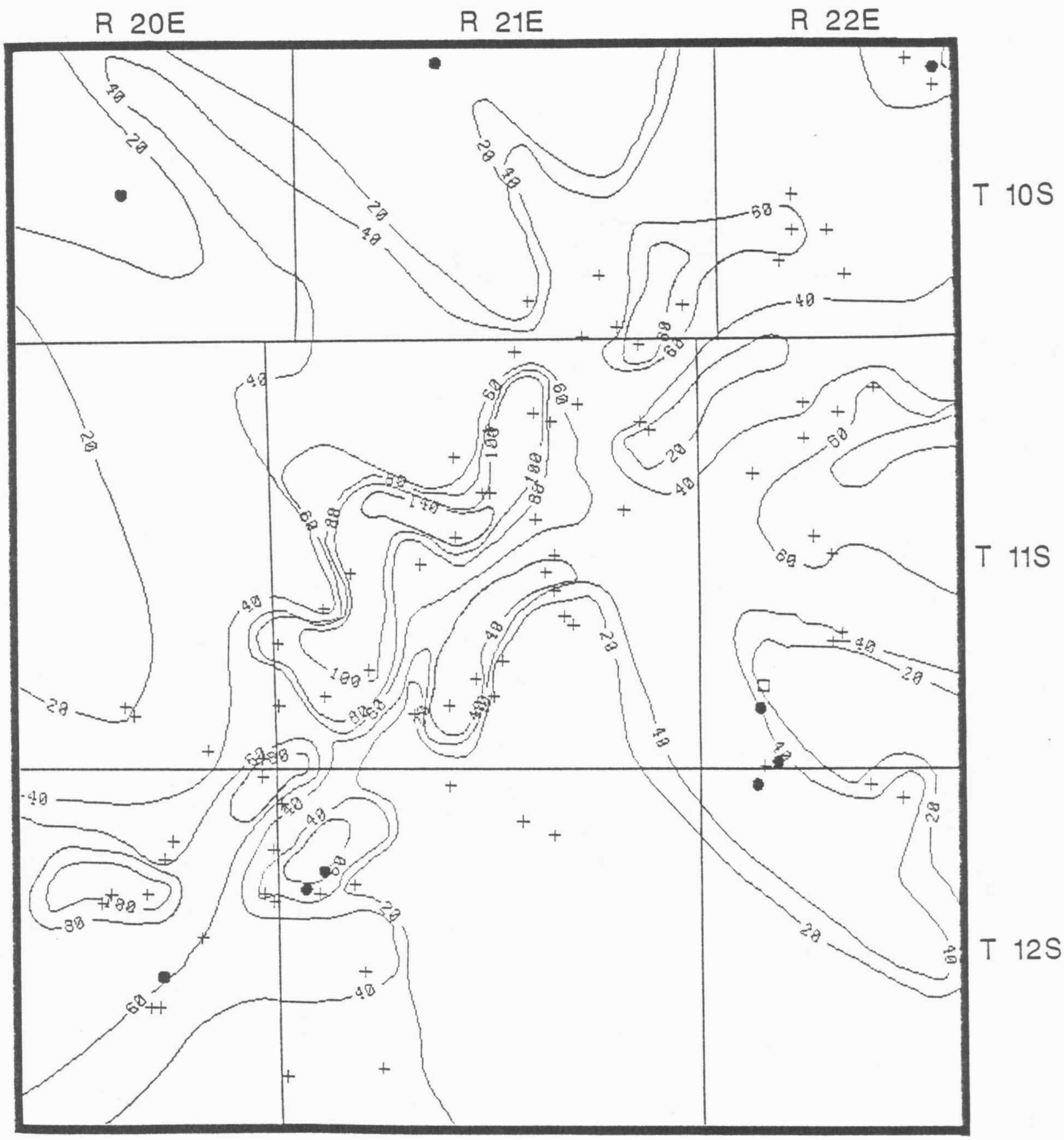


Figure 6B.

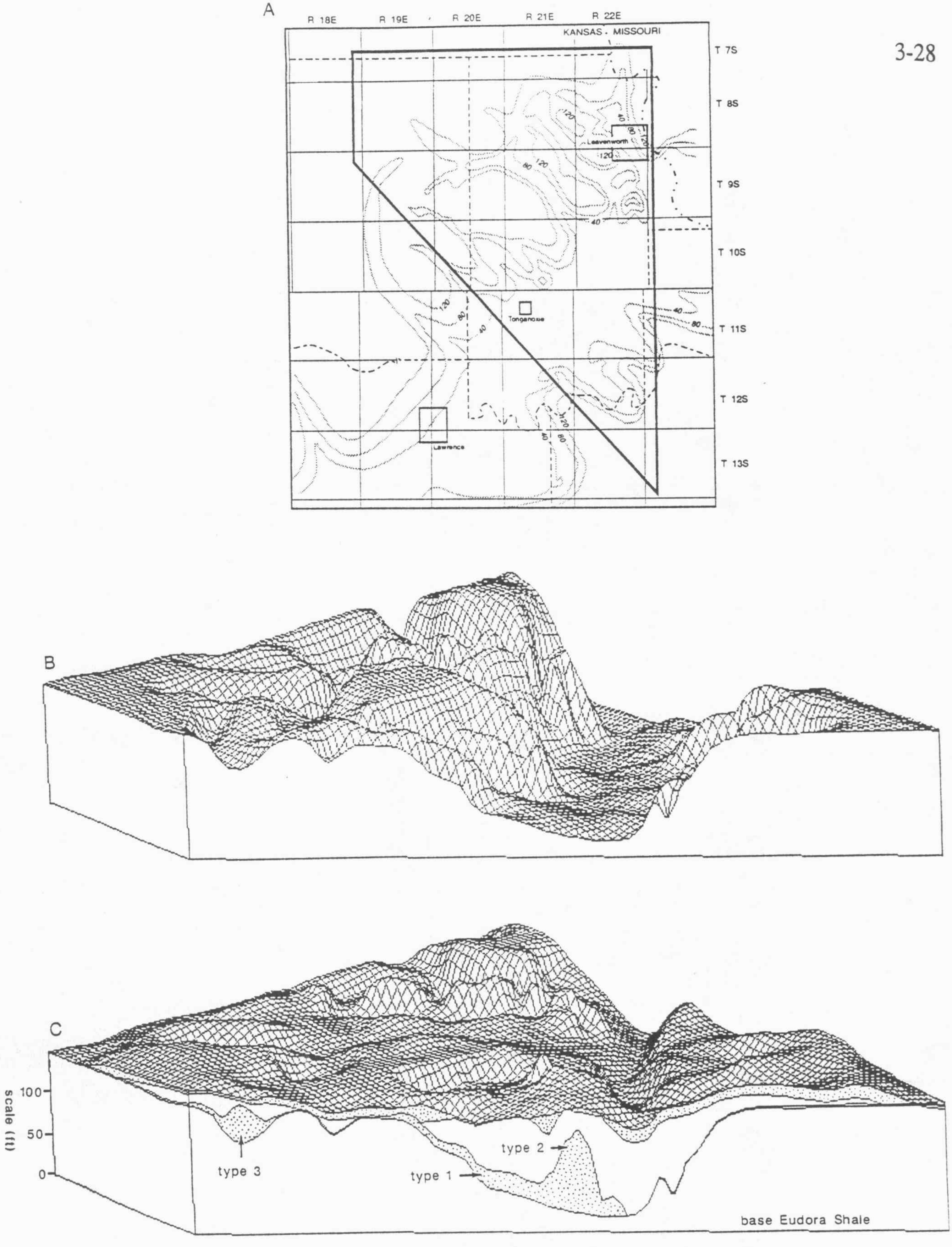


Figure 7. Cross section of the Tonganoxie paleovalley and a tributary valley. A, Reference map for location of block diagram. B, Block diagram showing surface at the base of the Tonganoxie Sandstone. C, Cross section extending from the base of the Eudora Shale to the top of the Haskell Limestone. The lower unit filled with sandstone pattern is the basal Tonganoxie Sandstone. Above this is shale (with minor amounts of sandstone and coal) of the Tonganoxie Sandstone and Vinland Shale. Upper unit with sandstone pattern is the combined upper Vinland Shale sandstone facies and Haskell Limestone. These units were combined for clarity.

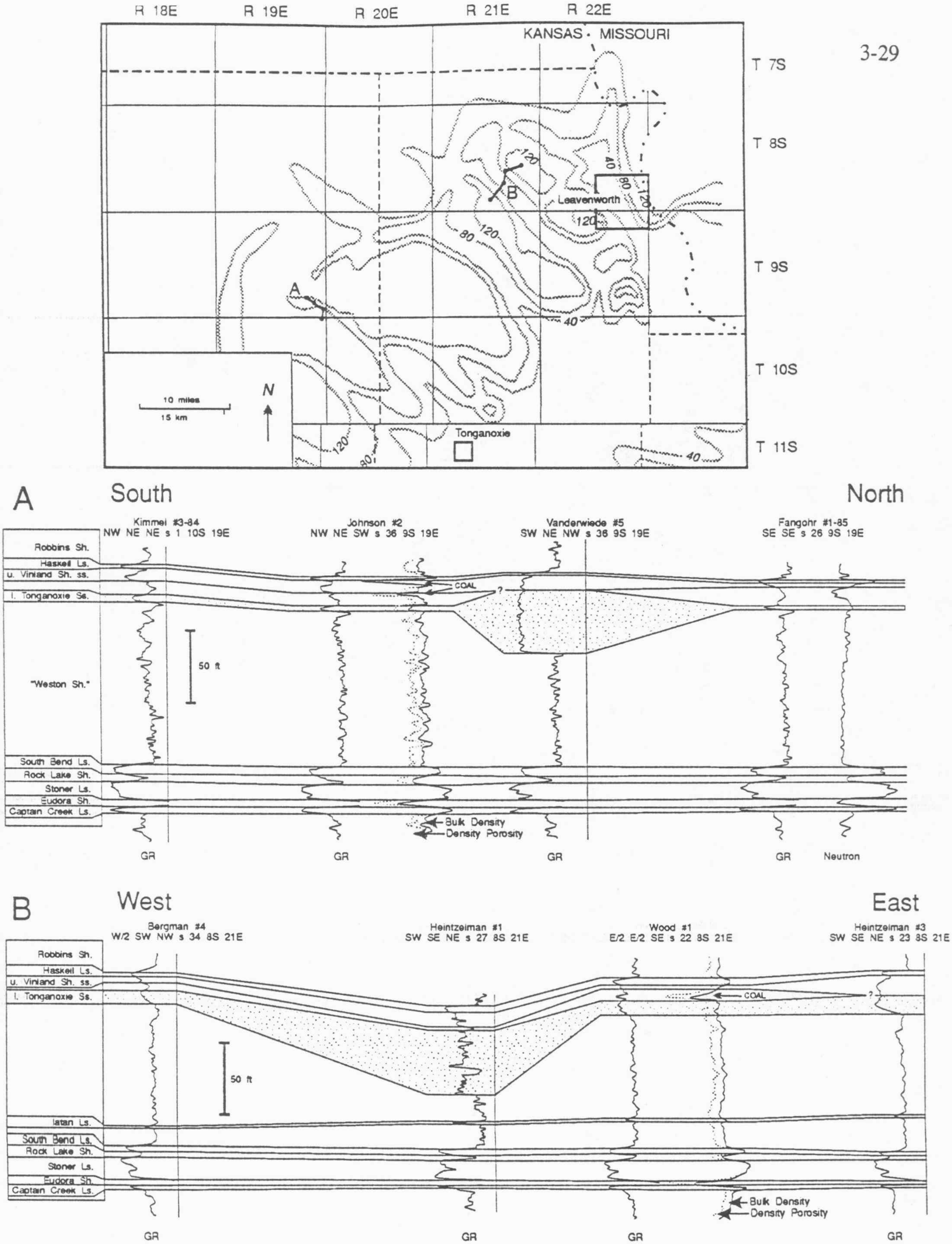


Figure 8. Cross sections through tributaries to the Tonganoxie paleovalley. Lower coal in Johnson #2, and coal in Wood #1 are probably both the Upper Sibley Coal.

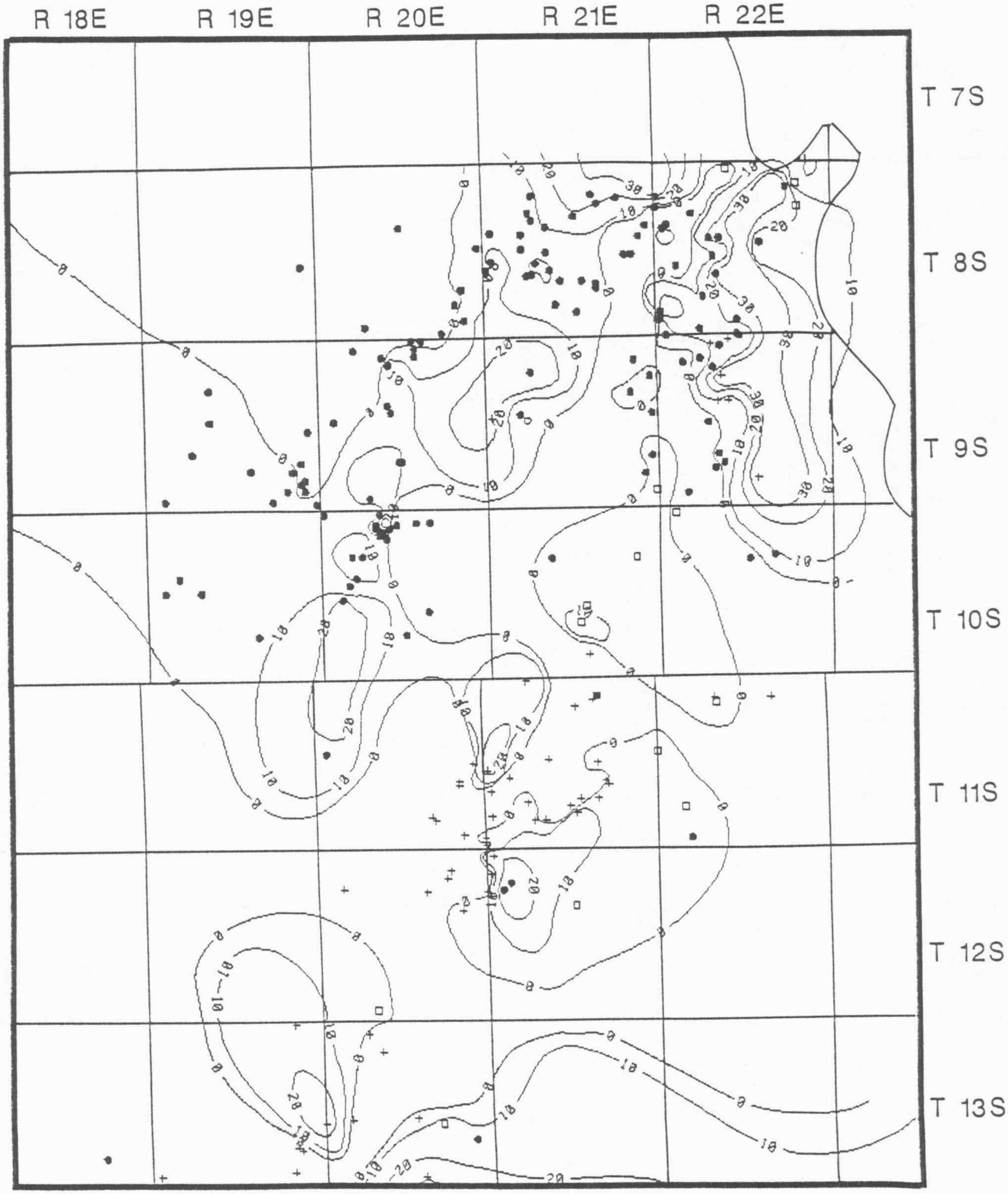


Figure 9. Isopach map of the upper Vinland Shale sandstone facies. Contour interval is 10 ft. See Fig. 2 for explanation of types of data points.

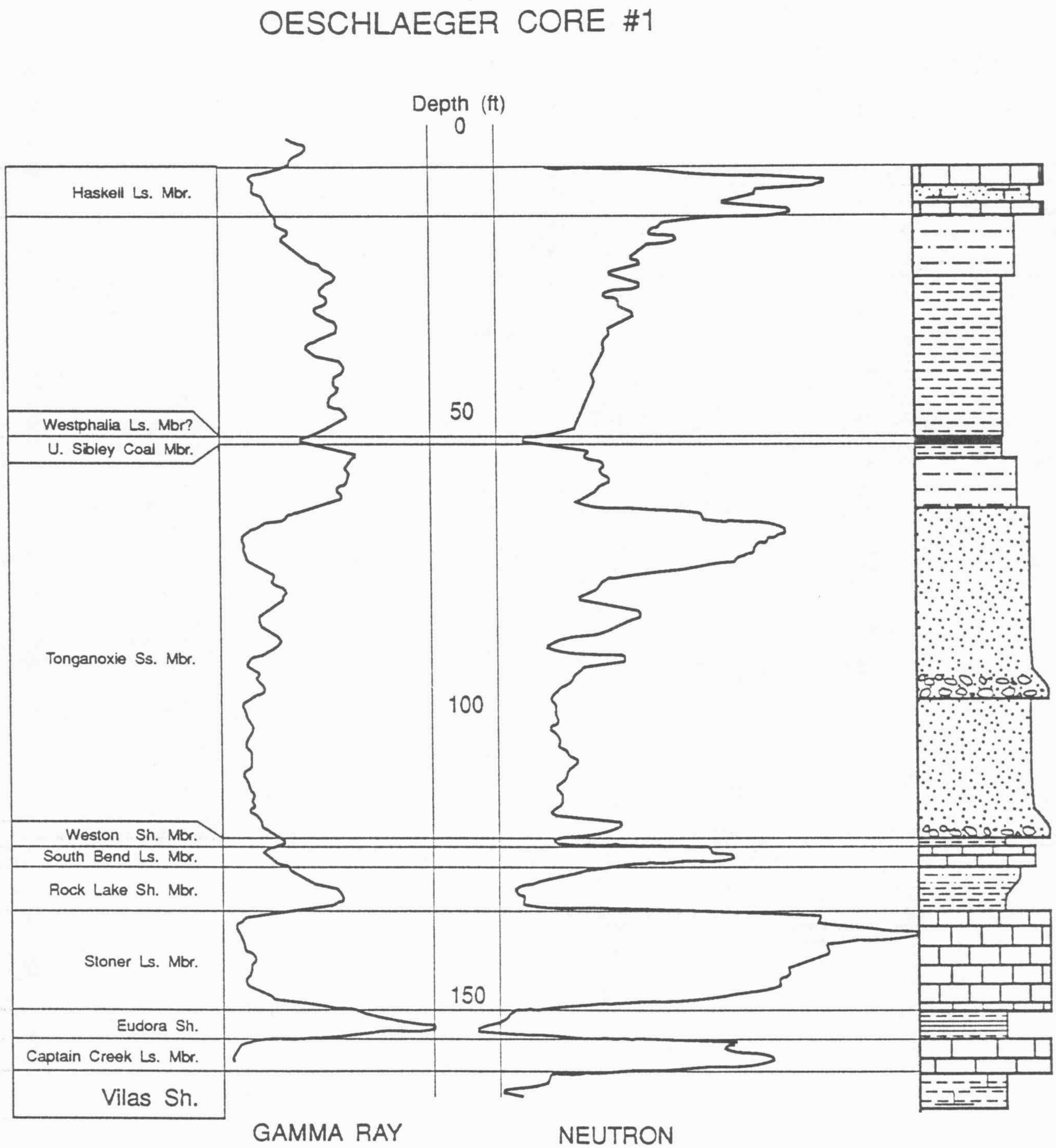


Figure 10. Lithologic and wireline logs for the Oeschlaeger #1 core. See Fig. 1 for location of core.

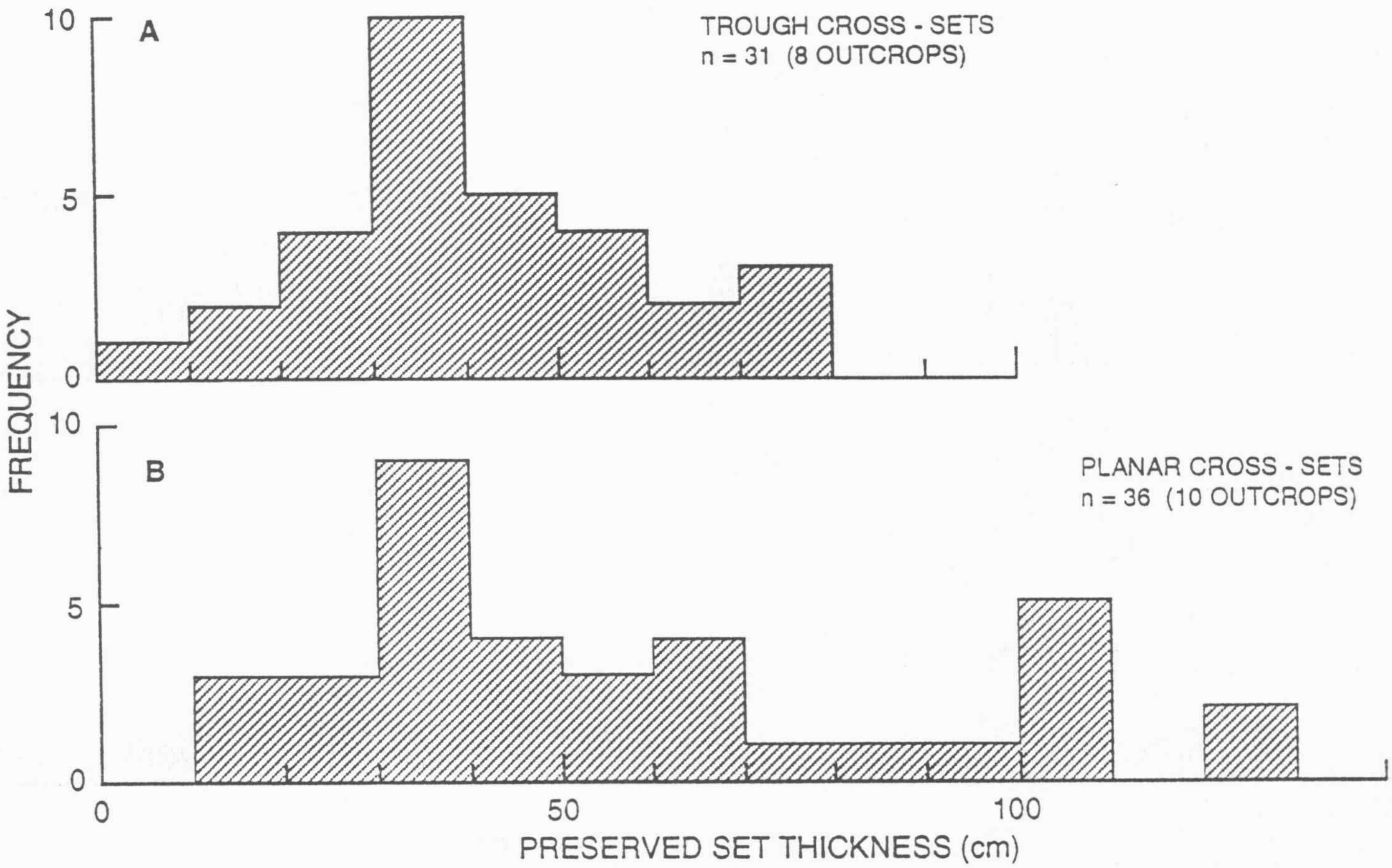


Figure 11. Frequency distribution of cross-set thicknesses in the basal Tonganoxie Sandstone. A, Trough cross-sets in the Trough Cross-bedded Sandstone Assemblage, not including possible outcrops of Ireland Sandstone (see text). B, Planar cross-sets in the Planar Cross-bedded Sandstone Assemblage.

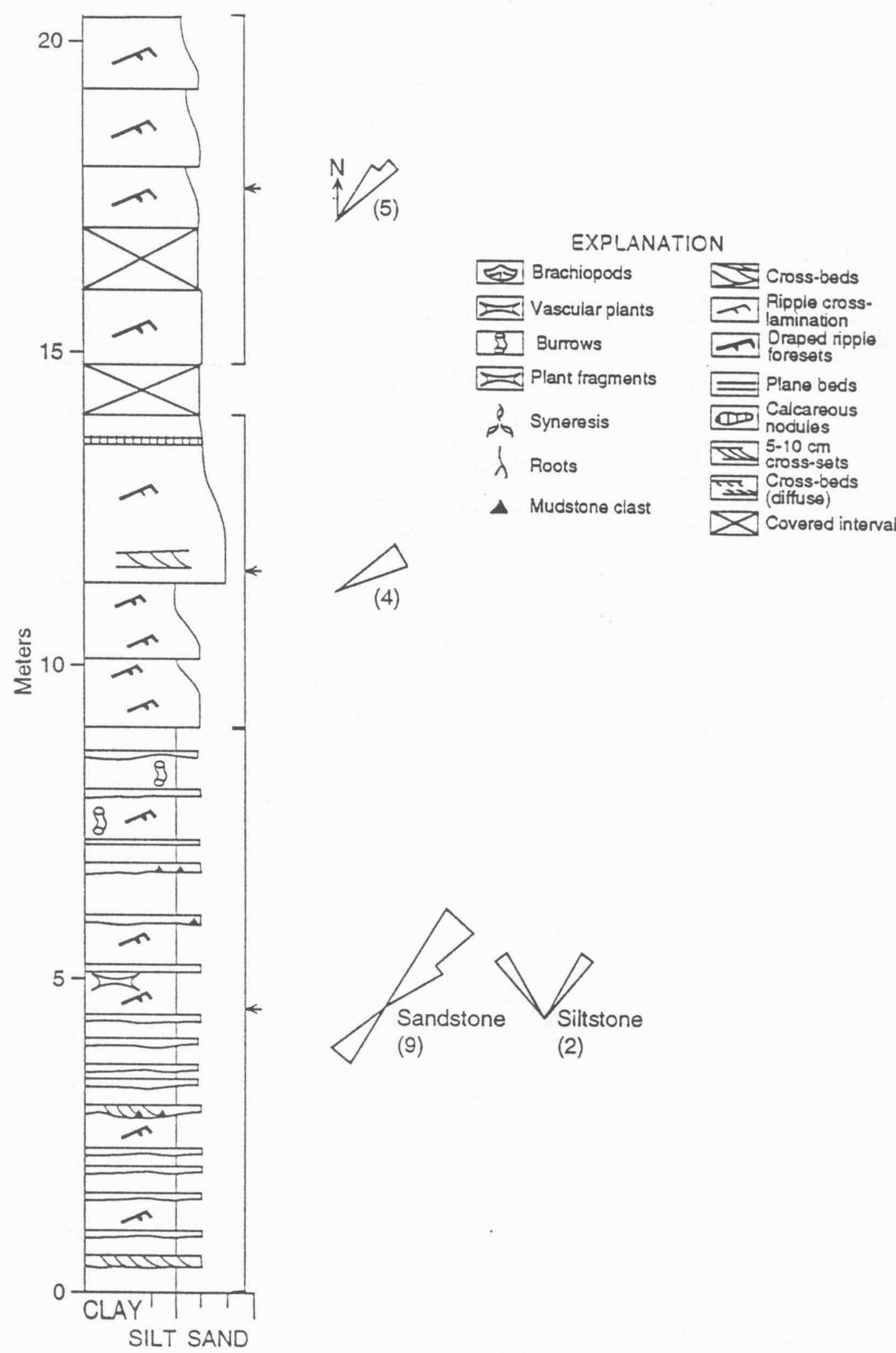


Figure 12. Stratigraphic log and paleoflow data for the Ripple Cross-laminated Siltstone assemblage, Locality 25. Paleoflow data are plotted as the square root of the percentage of total readings in each class to reduce visual bias.

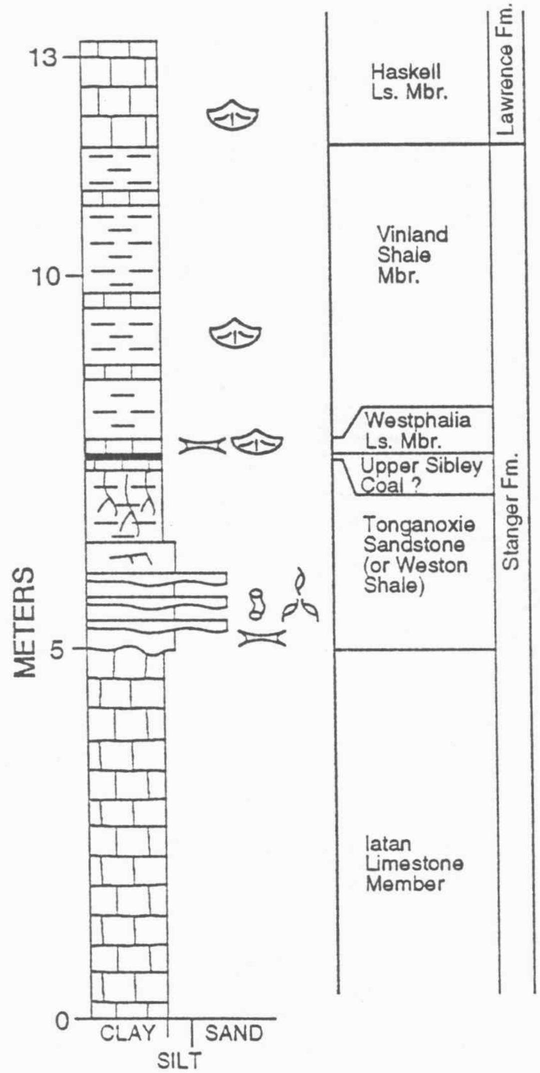


Figure 13. Stratigraphic log for strata overlying the Iatan Limestone at Locality 33, Platte County, Missouri, where the Tonganoxie Sandstone is thin because it is in a paleointerfluvial position. See Fig. 12 for key to symbols. Some data from Spriggs (1989, Locality P1).

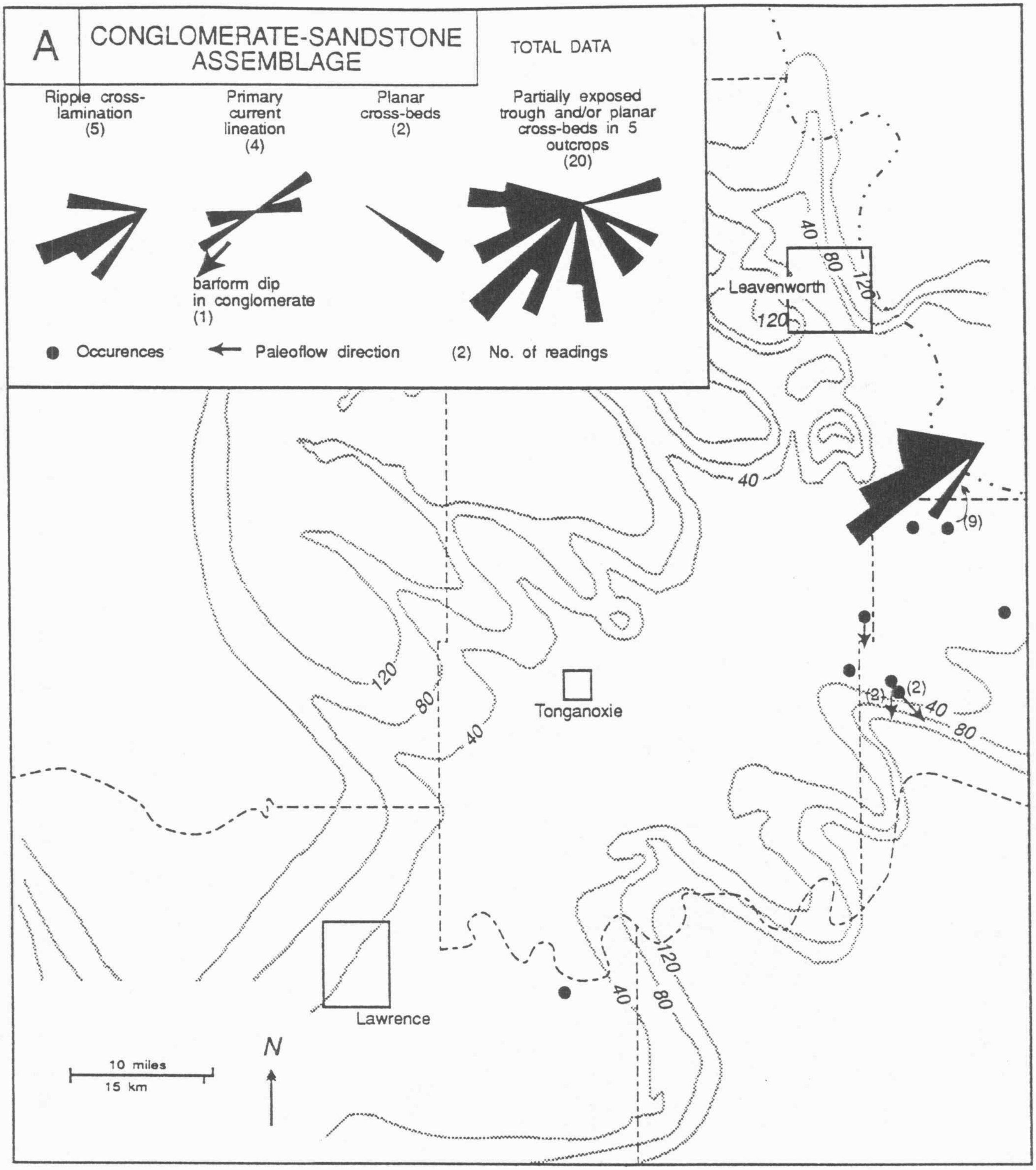
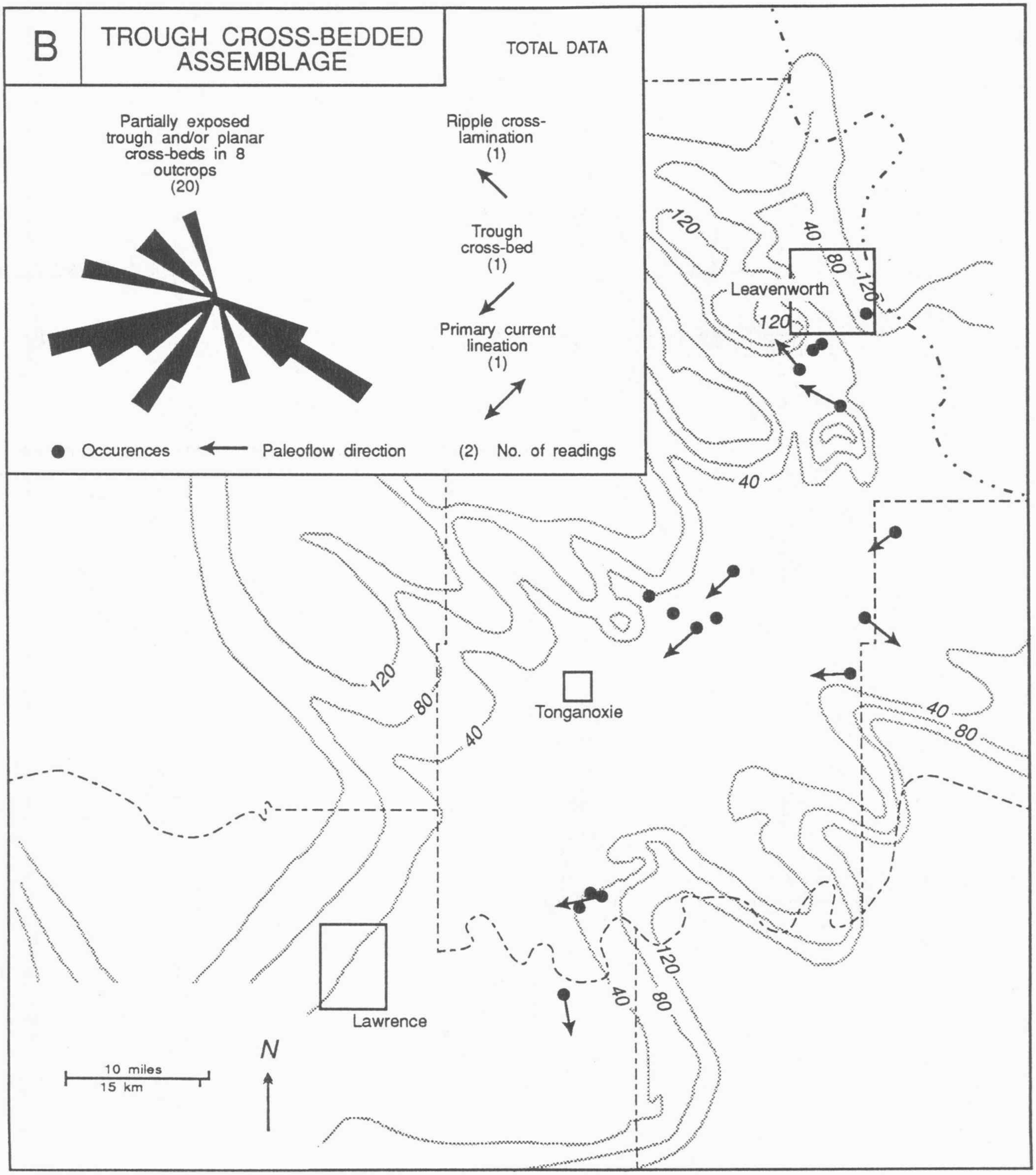
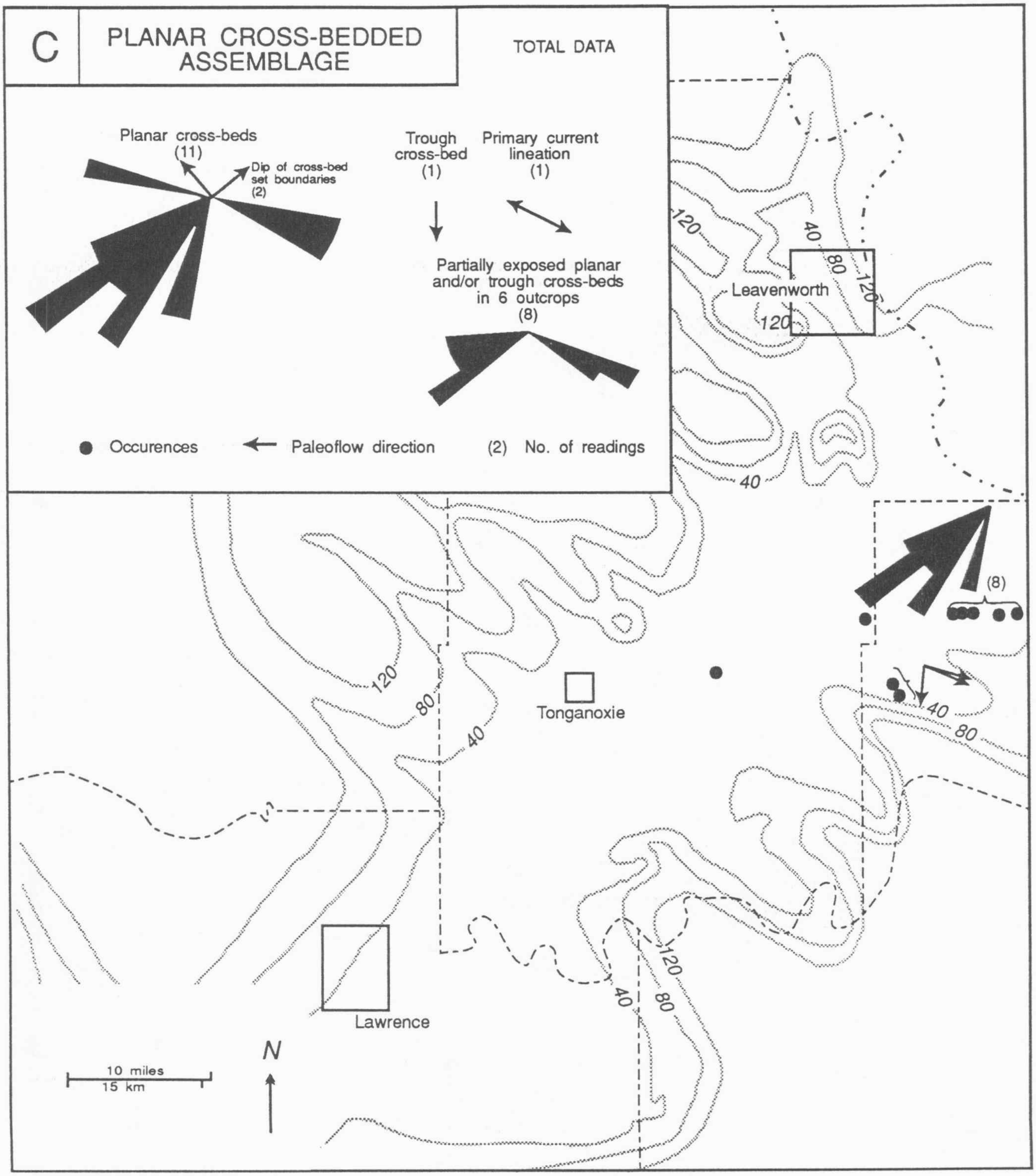
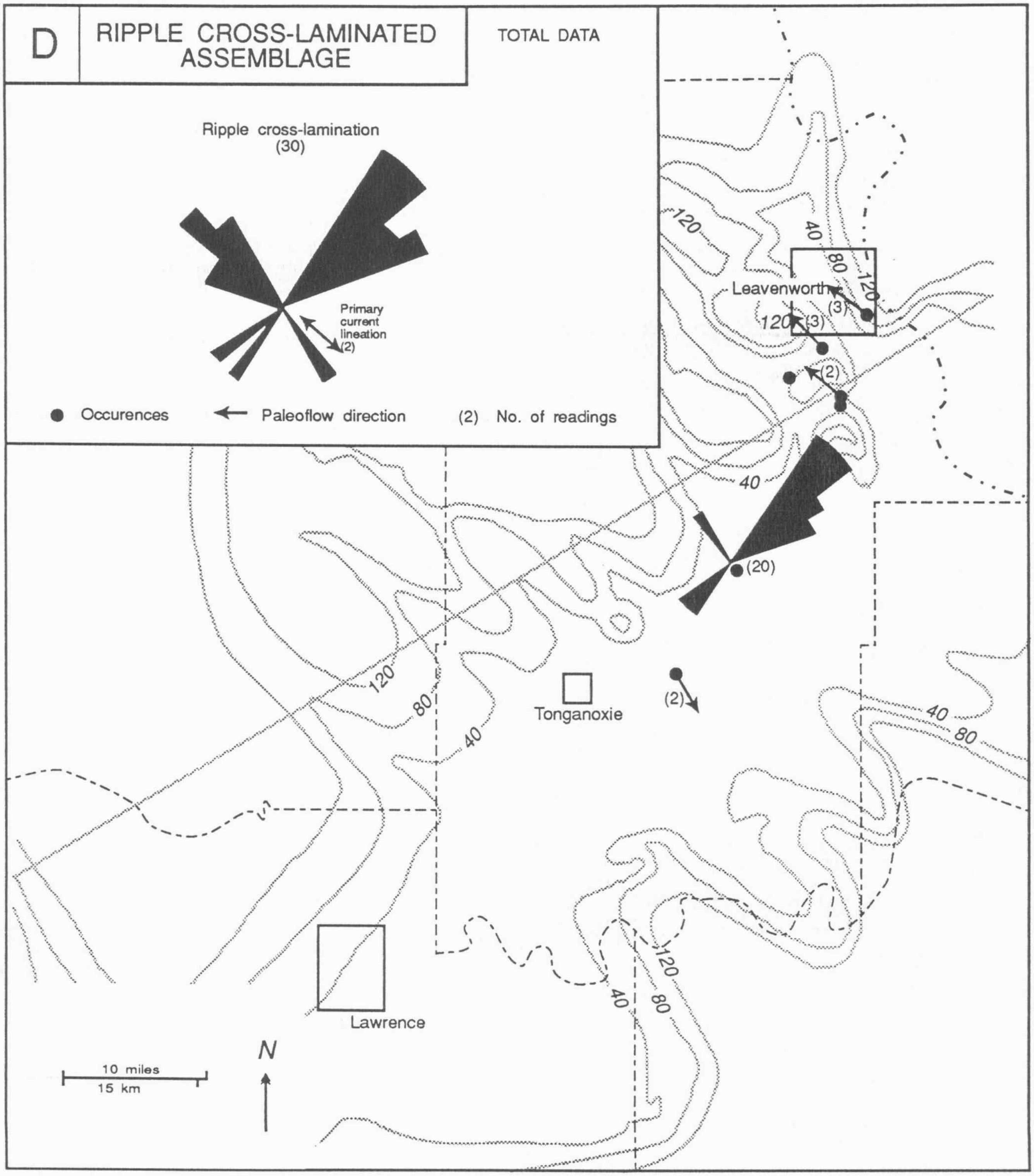


Figure 14. Paleoflow data for facies assemblages of the Tonganoxie Sandstone. Paleoflow data for individual localities include measurements accurate to within 5° and a few generalized paleoflow directions accurate to within about 20° (see text). To reduce visual bias, rose diagrams are plotted using the square root of the percentage of total readings in each 10° class. A, Paleoflow data for the Conglomeratic-sandstone Assemblage. B, Paleoflow data for the Trough cross-bedded Assemblage. C, Paleoflow data for the Planar Cross-bedded Assemblage. D, Paleoflow data for the Ripple Cross-laminated Assemblage.


B
TROUGH CROSS-BEDDED ASSEMBLAGE
TOTAL DATA
Partially exposed trough and/or planar cross-beds in 8 outcrops (20)
Ripple cross-lamination (1)
Trough cross-bed (1)
Primary current lineation (1)
Occurences
Paleoflow direction
(2) No. of readings
Leavenworth
Tonganoxie
Lawrence
120
80
40
N
10 miles
15 km


C
PLANAR CROSS-BEDDED ASSEMBLAGE
TOTAL DATA
Planar cross-beds
(11)
Dip of cross-bed set boundaries
(2)
Trough cross-bed
(1)
Primary current lineation
(1)
Partially exposed planar and/or trough cross-beds in 6 outcrops
(8)
Occurences
Paleoflow direction
(2) No. of readings
Leavenworth
Tonganoxie
Lawrence
120
80
40
(8)
10 miles
15 km
N


D
RIPPLE CROSS-LAMINATED ASSEMBLAGE
TOTAL DATA
Ripple cross-lamination (30)
Primary current lineation (2)
Occurences
Paleoflow direction
(2) No. of readings
Leavenworth
(3)
(2)
(20)
Tonganoxie
Lawrence
40
80
120
10 miles
15 km
N

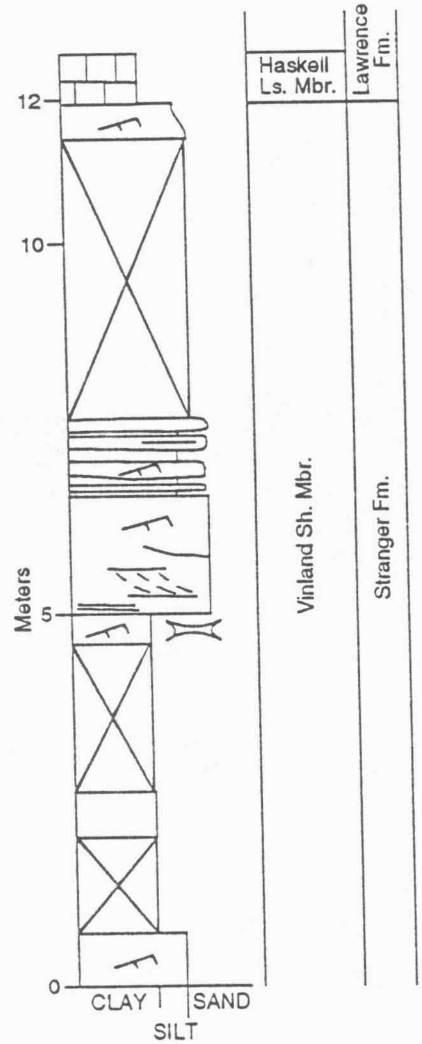


Figure 15. Stratigraphic column for the Vinland Shale Member at Locality 32 east of Lawrence. See Fig. 12 for key to symbols.

BEDFORM SEDIMENTOLOGY OF THE LONESTAR SPILLWAY AND BUILDEX QUARRY STOPS

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INTRODUCTION

An estuary is defined as the seaward portion of a drowned river valley system which receives sediment from both fluvial and marine sources, and contains sedimentary facies influenced by tidal, wave and fluvial processes (Dalrymple et al. 1992). According to the definition of Dalrymple et al. (1992), the estuary extends from the landward limit of tidally influenced facies at its head to the seaward limit of coastal facies at its mouth. Studies of modern estuarine systems (e.g. Allen 1991; Nichols et al. 1991; Dalrymple et al. 1992) have identified a tripartite distribution of sedimentary facies: (1) a fluvial dominated upper estuarine facies, (2) a mid-estuarine facies, and (3) a marine-dominated facies located towards the seaward limit of the system. This tripartite facies distribution pattern can be equally well expressed in micro- through macrotidal systems which are wave or tidally dominated (Dalrymple et al. 1992). These sediments should have a high preservation potential in the geologic record, as estuaries are excellent traps for sediments deposited during the transgression that follows valley incisement.

The Douglas Group (Stephanian) of eastern Kansas contains several paleovalleys that were eroded during sea-level lowstands and filled during the subsequent transgressions. Detailed studies of bedform-scale sedimentary structures have contributed greatly to our understanding of these paleovalley-fill sequences. Both the Stranger (lower Douglas Group) and Lawrence (upper Douglas Group) Formations are characterized by tripartite sedimentological facies distribution patterns that record the fluvial-estuarine-marine transitions within these systems. These facies are differentiated on the basis of lithology, sedimentary structures, paleocurrent distributions, and trace and body fossil content. Facies within the proposed fluvial-estuarine-marine transition include: facies 1, basal conglomerate and fluvial sandstones; facies 2, horizontally bedded, very fine-grained sandstones and siltstones of the fluvial to estuarine transition; facies 3, mid-estuarine "gray shales" characterized by lenticular and flaser bedded (heterolithic) mudstones and siltstones; facies 4, cross-bedded and horizontally bedded sandstones representing estuarine sandflats; and facies 5, interbedded sandstone and mudstone with marine body and trace fossils representing the estuarine to marine transition.

These facies are exposed within the Douglas Group rocks in a generally northeast to southwest trending outcrop belt that roughly parallels the eastern margin of the Douglas Group paleovalleys. The fluvial components of these Douglas Group systems are best developed and exposed in Wyandotte and Leavenworth Counties of northeastern Kansas (see Gibling and Feldman, this volume). The fluvio-estuarine transition of the Stranger Formation, which contains silt-dominated tidal rhythmites (facies 2), is particularly well exposed at the Buildex Quarry in Franklin County. The mid-estuarine heterolithic facies (facies 3) of the Lawrence Formation is exposed at the Lonestar Lake spillway in Douglas County. Estuarine sandflat and marine sandbar sediments (facies 4 and 5) within the Lawrence Formation are well exposed around the Toronto Resevoir in Woodson and Greenwood Counties, and marine-influenced sands (facies 5) occur along a series of road-cuts in Chautauqua County, Kansas. This article describes the bedform-scale sedimentology of the Buildex Quarry and Lonestar spillway localities, which contain units deposited within upper- to mid-estuarine facies, respectively.

BUILDEX QUARRY (Stop 2.2)

The outcrop of Stranger Formation in the Buildex Quarry (Franklin County, NW1/4, Sect. 23, R19E) exposes the Weston Shale, disconformably overlain by the Ottawa Coal and about 9 m of Tonganoxie Sandstone. The Ottawa Coal is thin, laterally discontinuous and likely accumulated relatively high along the valley wall within floodplain of the Tonganoxie fluvial system. The lower 5 m of the Tonganoxie Sandstone Member are considered in the present description. It consists of a well-defined package of gently inclined (ca. 2-3° SW) planar beds to flat, planar laminae of poorly indurated, carbonate-cemented siltstone and mudstone (facies 2). The sequence is bounded above and below by thin coals and paleosols with upright plant remains. A striking feature of the exposure is the lateral continuity of bedding throughout the approximately 400-m-long exposure in the quarry and the apparently systematic fashion in which the beds thicken and thin.

Exposures of the Tonganoxie are found on the north and west quarry walls. While the steep, vertical face of the north wall precludes detailed inspection, a bench on the west wall of the quarry does provide access to the exposure, although the lower approximately 2 m of the section are covered. One complete and ten partial sections were measured along the west quarry wall by dismantling the outcrop bed by bed. Over 300 samples have been collected for the analyses of physical and biogenic sedimentary structures, paleocurrents, and sediment grain-size.

The lower 5 m of the Tonganoxie Sandstone Member at the Buildex Quarry is composed entirely of siltstones with a maximum of about 10% very fine-grained, slightly micaceous, quartz sand. This section can be subdivided into two units (Fig. 1) on the basis of bed and laminae thickness variations and lateral continuity of stratification, primary sedimentary structures, and the presence of upright plants and rooted horizons. Unit A consists of planar bedded and planar laminated strata (PBL facies of Lanier et al 1993)), while unit B represents a tidal channel and an associated channel levee complex (CL facies of Lanier et al 1993). The sedimentological units which comprise the lower 5 m of the Tonganoxie at Buildex are illustrated in Figure 1 and described below.

Unit A in Figure 1 is the planar bedded/laminated (PBL) facies of the Buildex Quarry (Lanier et al 1993). It is 2.8 m thick and consists of vertically accreted planar, locally convoluted, beds to flat planar laminae of lithologically homogeneous gray (buff weathering) siltstones. Bed and laminae thicknesses range from 0.05 mm to 12.5 cm. Each bedform is normally graded and thicker units are laterally continuous. This unit is divided into three subunits on the basis of systematic changes in strata thicknesses and primary sedimentary structures.

Unit A_1 This unit consists of medium gray to buff, sandy siltstones to mudstones with a well-developed, rhythmic thickening and thinning of normally graded strata ranging in thickness from 0.05-1.37 cm. Thicker strata have silty climbing ripples or climbing silt-waves. Small-scale erosional surfaces are common. This unit overlies the Ottawa coal, and small upright plants and trees rooted in the coal are inclined at various angles relative to stratification. Stems of upright plants are commonly mud-draped. Penecontemporaneous normal microfaults with mm- to cm-scale are common.

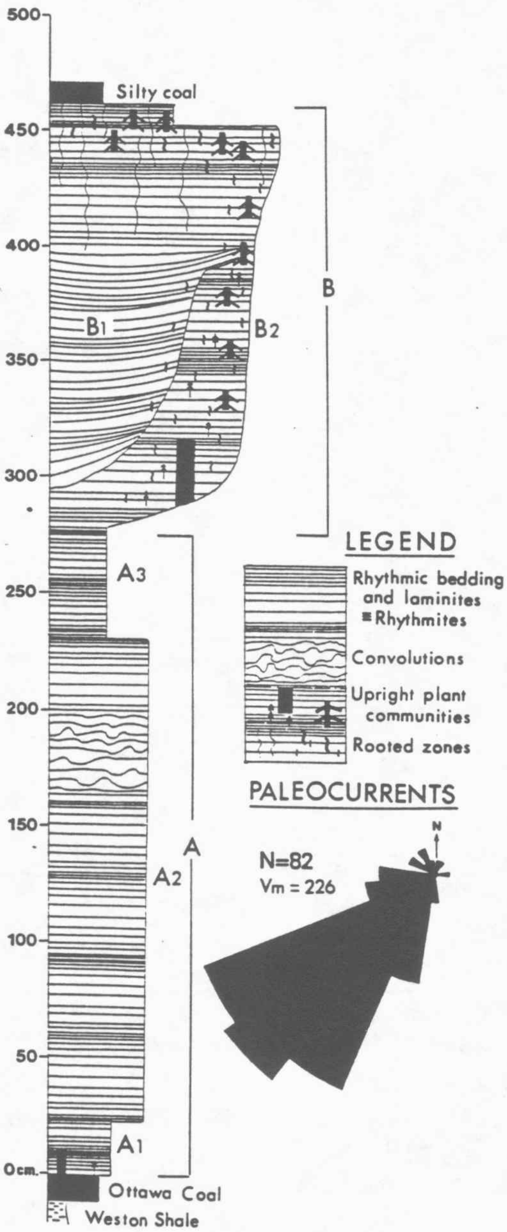

Fig. 1. Generalized section of the complete excavation of the Tonganoxie at Buildex from the west wall of the quarry. Rhythmic bedding (tidal rhythmites) within the section are not drawn to scale. Paleocurrent rose diagram measurements is from sections along the west wall of the quarry.

Unit A2 Unit A2 consists of medium gray, very fine-grained sandy siltstones to siltstones with well-developed, rhythmic thickening and thinning of normally graded beds, ranging from 1.4 cm to 12.5 cm in thickness. Thicker beds have a basal, massive to graded and parallel laminated zone with ripple-drift, cross-lamination at the top of the unit. Beds within the convoluted zone contain abundant water escape structures. Physical sedimentary structures preserved on upper and lower bedding plane surfaces include stick-drag tool marks, microload (sag) marks, and rain drop imprints. Plant materials are very common. Biogenic sedimentary structures include the trace fossils *Haplotichnus*, *Treptichnus*, arthropod tracks, fish-fin drag marks, and tetrapod footprints.

Unit A3 This unit has gray to buff-brown sandy siltstone with well developed, rhythmic thickening and thinning of normally graded strata, ranging from 0.1 to 1.8 cm in thickness. Thinner strata have parallel laminations while thicker beds contain climbing siltwaves. Physical sedimentary structures preserved on upper and lower bedding plane surfaces include drag marks, rain drop impressions, rill marks, strandline and "falling water" marks. Biogenic sedimentary structures include the trace fossils *Haplotichnus*, *Treptichnus*, *Plangtichnus*, arthropod traces, fish-fin drag marks, tetrapod footprints, and swimming tetrapod tail drag marks.

The transition from Unit A (Fig. 1) to the overlying 1.8 m of section of Unit B (Fig. 1) may appear to be gradational, conformable, and characterized by increasing siltstone bed thicknesses. When traced laterally, however, many beds thin and pinch-out, defining a channel-form geometry with a width of approximately 10-12 m and a thickness of 1 m (B1 in Fig. 1). The axis of the channel is towards the southwest (215°) and is roughly parallel to the axis of the Tonganoxie paleovalley. Lateral excavations of Unit A3 exposes beds and laminae that dip inwards towards the channel axis. Where lateral contacts have been exposed, these channel siltstones onlap, and may erosionally truncate, a channel levee sequence (B2 in Fig. 1) of vertically accreted, planar bedded and laminated siltstones that contain upright plants with attached leaves (largely pteridosperms and small lycopods). Rooted horizons are very common. Channel strata near the B_1/B_2 contact also contain roots. The top of Unit B is a thin (5-8 cm thick), laterally discontinuous, silty coal. The siltstone beds beneath the coal contain upright, 2-6 cm diameter lycopods at a minimum density of 28 plants per square meter. These strata are pervasively rooted and solitary roots can extend down as deep as 50-75 cm into Unit B. Descriptions of Unit B (Fig. 1) are given below.

Unit B_1 This unit consists of buff to brown, silty, very fine-grained normally graded sandstones to siltstones. This appears to be an accretionary infilling of a channel with a relief of about 1 meter. There is a moderately well-developed to poorly developed cyclicity in bedding thickness; beds near the channel axis are commonly amalgamated with erosional bases. Thicker sedimentation units contain a basal zone of sinusoidal ripple lamination and an upper zone of ripple-drift cross-lamination. Bed surfaces have sinuous-crested asymmetric ripples or linguoid ripples. Vertical root traces are very common near the margin of the channel. Biogenic and physical sedimentary structures preserved on upper and lower bed surfaces include *Haplotichnus*, *Plangtichnus*, *Treptichnus*, arthropod traces, fish-fin drag marks, rain drop imprints, foam marks, rill marks, and strandline "standing water" marks.

Unit B_2 This unit consists of buff to brown, normally graded, sandy siltstones ranging in thickness from 0.1 to 3 cm. The internal structuring of strata may be poorly defined due to extensive rooting. Upright ferns are abundant with occasional upright lycopods. Physical and biogenic sedimentary structures include rain drop imprints, rill marks, strandline marks, drip marks from upright plant leaves, *Haplotichnus*, *Plangtichnus, Treptichnus*, arthropod traces, and tail-drag marks from swimming tetrapods.

Interpretation of the Tonganoxie Strata at the Buildex Quarry

The rhythmic variations in strata thicknesses throughout the vertical sequence (Fig. 2), in conjunction with associated physical and biogenic sedimentary structures that indicate repetitive exposure of bed surfaces, strongly support a tidally influenced depositional setting for the Tonganoxie Sandstone Member in the Buildex Quarry (Lanier et al. 1993). Bedforms which range through three orders of magnitude (from less than 1 mm to over 12 cm) systematically thicken and thin throughout the vertical sequence. Thicker laminae and beds (maxima) would correspond to spring tides, when tidal heights, flow velocities and the capacity of the system to transport sediments was maximized. Thinner laminae and beds (minima) would correspond to neap portions of the tidal cycle. The 257 strata thickness measurements for the entire sequence contain a range of 6 to 14 bedsets per tidal cycle, with an average of 9.9. The maximum of 14 sedimentation events per tidal cycle corresponds closely to the present-day, semi-lunar cycle of 14 days between neap-spring tidal cycles in a predominantly diurnal tidal system. The paleocurrent distribution pattern (Fig. 1) for the sequence shows a dominant southwest mode, roughly down the long axis of the Tonganoxie paleovalley. This suggests that the system may have been ebb dominant. An estimated 29 complete and partial tidal cycles for the lower 5 m of the Buildex se

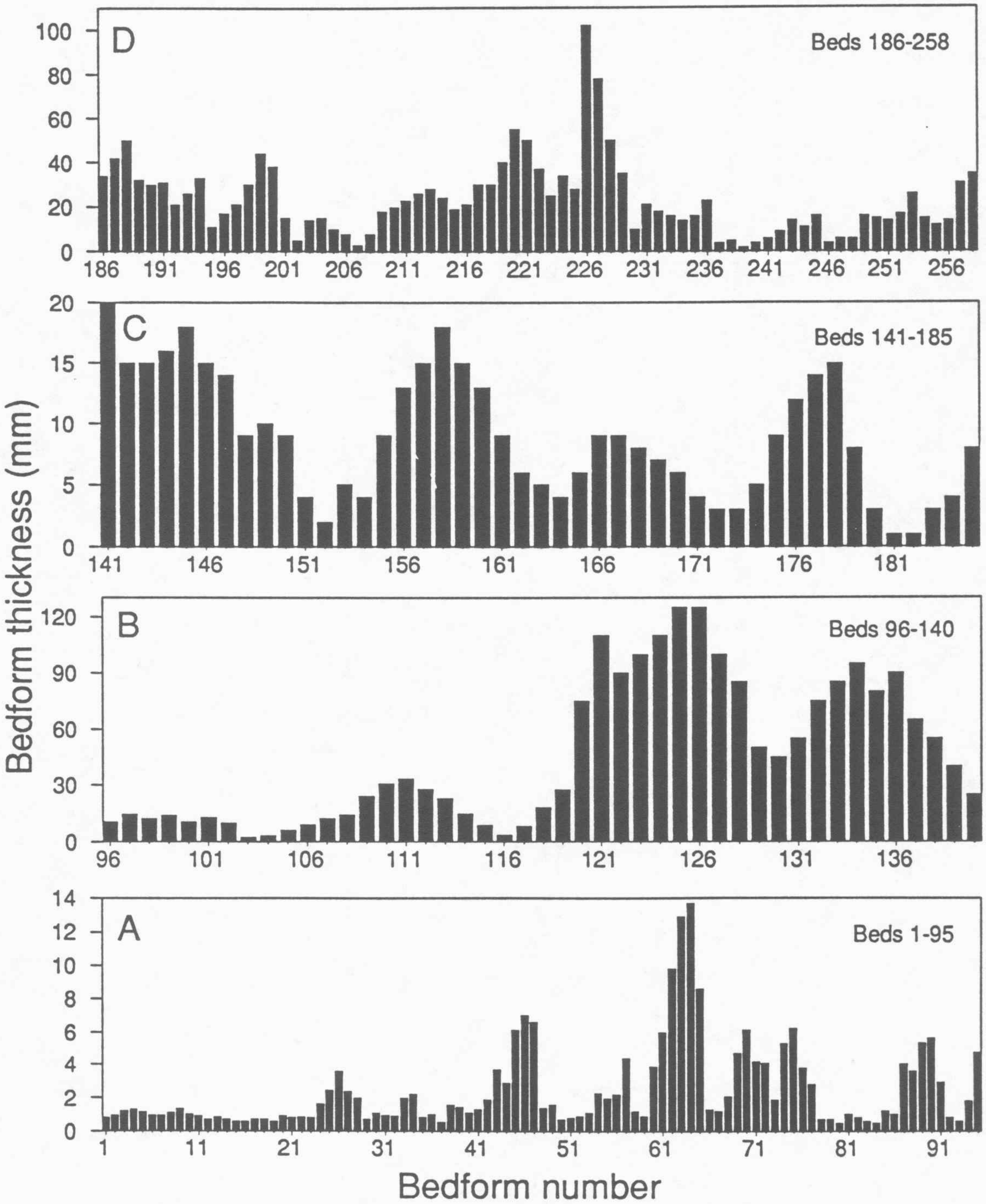

Fig. 2. Bedform thicknesses vs. bedform number through the Tonganoxie succession at the Buildex Quarry. Bedform numbers increase upwards. (A) Unit A_1 (of the PBL facies, Lanier et al. 1993); (B) Unit A_2 (within PBL facies); (C) Unit A_3 (within PBL facies); (D) Bed-thickness measurements from Unit B (CL facies).

quence would indicate an averaged sedimentation rate of approximately 3.8 m/year.

Modern depositional settings that appear analogous to the Tonganoxie at Buildex, in terms of the suggested rate of vertical aggradation and characteristic physical and biogenic sedimentary structures, are upper tidal flat facies of fluvial-estuarine transitions in macrotidal settings. Specific examples include the Bay of Fundy, Canada, and Bay Mont Saint-Michel, France. Both are funnel-shaped estuarine basins where the maximum tidal amplification occurs towards the fluvial-estuarine transition, which results in unusually high sedimentation rates. For example, depositional rates for upper tidal flats of the Bay of Fundy are estimated at a maximum of 7 m/year (Dalrymple et al. 1991). Dalrymple et al. (1991) suggest that these unusually high vertical aggradation rates may be a common feature of inner-estuary tidal flats. Both modern depositional settings have strikingly similar physical and biogenic sedimentary structures on bedding surfaces to those preserved in the Tonganoxie at Buildex.. These include rain drop imprints, foam marks, rill marks, runnel marks, standing water marks, falling water marks, insect trackways, tetrapod trackways, and a wide variety of invertebrate surface grazing traces. Recent work by the author in the Bay of Fundy indicates that the entire suite of physical and biogenic structures which occur on these bedding plane surfaces have a very high preservation potential.

LONESTAR SPILLWAY (Stop 2.1)

The approximately 27 m thick outcrop of the upper Lawrence Shale exposed in the Lonestar Lake spillway (Center/South line, Sect. 11, T14S, R18E) provides one of the few good exposures of mud-rich, heterolithic, mid-estuarine facies (facies 3) of the upper Douglas Group. The lower 13 m of section below the Lower Williamsburg Coal is a shoaling- and coarsening-upwards succession of pin-stripe- and lenticular-bedded mudstones; flaser-bedded, fine-grained, micaceous sandstones; thin, laterally discontinuous, current- and wave-rippled, fine-grained micaceous sheet sandstones; and channels with accretionary infillings of inclined, heterolithic bedding and convoluted bedding. Tidal rhythmites are common in the upper part of the section and occur immediately above the Lower Williamsburg Coal. A detailed description of the units identified in the measured section (Fig. 3) is given below.

Unit 1 An approximately 2 m thick unit of laterally continuous, gray, pin-stripe bedded, silty mudstone. Light colored, horizontal laminae of coarse silt or very fine-grained sand, range from a few grain diameters to 1 mm in thickness. These alternate with dark, clay-rich laminae up to 8 mm in thickness. Laminae may be normally or reversely graded. Some thin sand layers are convoluted and form micropillow structures. The few very low-angle, cross laminations suggest transport towards the south or southwest. There are several 2-5 cm thick, convoluted horizons with sharp upper and lower contacts. Laminae within these zones are completely disturbed, with silt and sand layers contorted into wispy stringers or deformed into small ball and pillow structures. Bioturbation is minimal and trace fossils consist of small, horizontal, tubular burrows, and a few vertical burrows and escape structures.

Unit 2 A 1 m thick unit of highly convoluted mudstone and fine-grained, micaceous sandstone. This unit has a wedge-shaped, perhaps channel-form, geometry with a roughly north-south elongation. Thicker convoluted sand "balls" within the unit similarly have a north to south elongation and cross-lamination within these sands

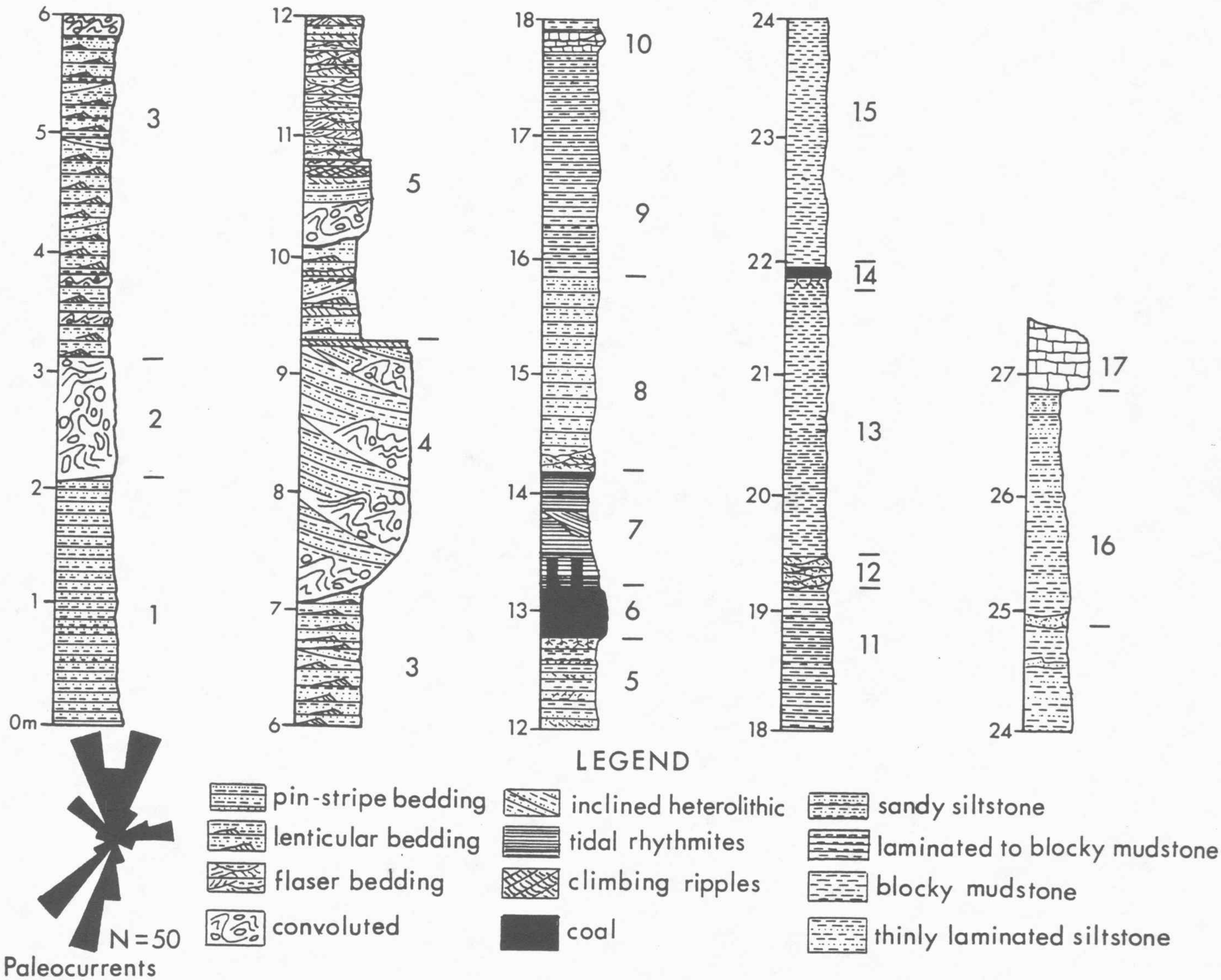

Fig. 3. Measured section of Lawrence Formation at the Lonestar spillway locality. See text for descriptions of the units. The descriptions for units 8-17 are from Archer and West (1991).

indicates transport towards the south.or southwest.

Unit 3 This unit consists of about 4 m of lenticular- and pin-stripe bedded, heterolithic, mudstones. Both the fine-grained sand and the organic content of these mudstones increase relative to the underlying units. The internal stratification of the mudstones throughout the unit is organized into packages, ranging up to 1.5 cm thick, which contain pin-stripe bedding grading into lenticular bedding and back to pin-stripe bedding. Small-scale loading convolutions are common at the bases of sand laminae. Lenticular, very fine-grained sands formed by the migration of small-scale current ripples, and ripple crests were commonly beveled by the succeeding current event and may appear flat-topped. Paleocurrents are bidirectional (north and south), with transport becoming predominantly northwards towards the top of the unit. Tool marks, largely stick drag marks, on bedding plane surfaces give a similar indication of paleoflow. Plant materials also are preserved on bedding plane surfaces. A few thin channel-forms, 5-10 cm thick and up to 2 m across, contain accretionary infilling of heterolithic mudstones, and commonly contain small ball and pillowed sands at their bases. Unit 3 also contains three, laterally continuous, convoluted beds up to 20 cm in thickness, and smaller wedge-shaped slump structures. The heterolithic mudstones have minimal bioturbation. Trace fossils include small vertical and horizontal burrows, and mm-scale vertical escape structures which can extend vertically for over 8 cm.

Unit 4 Unit 4 is the major channel complex of the Lonestar outcrop. It has a depth of about 2.1 m and extends for approximately 46 m along the west face of the exposure. The channels downcut into, and are encased in, the heterolithic mudstones of Unit 3. The channel complex had at least four phases of asymmetric, accretionary infilling. The bounding surfaces slope northward between 8° and 35°. Overall orientation of the channel complex appears to be north-south. The base of each infilling is invariably convoluted and commonly has an almost "homogenized" appearance, characterized by load, slump, and ball and pillow structures. The balance of the channel fill is largely inclined heterolithic bedding. Thin, fine-grained, micaceous sandstone beds within the channels are not bioturbated and contain unidirectional and bidirectional cross-lamination, rare unidirectional climbing ripple cross-lamination, and a few climbing wave ripples. Paleoflow reversals are very common within individual sandstone beds, however, transport directions were predominantly towards the north. Trace fossils from the unit include *Locheia*, which was apparently produced by small burrowing bivalves, *Uchirites*, *Planolities*, *Scalarituba*, and *Gordia*.

Unit 5 Unit 5 contains sand-rich, heterolithic mudstones, thin, laterally discontinuous, sheet sands, and flaser-bedded, fine-grained, micaceous sandstones. There are six channels exposed in Unit 5, smaller than those in Unit 4. Four of the channels are similar in infilling to the main channel complex, but range from 8-13 m in width and up to 1.5 m in depth. Two other small channels have accretionary infillings of laminated mudstone, and are located towards the southern end of the spillway exposure. A laterally continuous, 1-1.5 m thick, oxidized horizon within a flaser-bedded, fine-grained sandstone lies about 1.7 m below the Lower Williamsburg Coal. This may be related to pedogenesis. Upwards , near the coal, Unit 5 grades into sandy siltstones, which are light gray to brown, with horizontal to flaser laminations. These siltstones are moderately to highly bioturbated and contain rhizoliths.

Unit 6 Unit 6, the Lower Williamsburg Coal, has a blocky basal unit with a sharp lower contact. It has abundant disarticulated plant fragments, and pyrite dendrites along blocky edges. Gradationally upwards, the coal becomes shaley, very dark gray, horizontally laminated and friable. It contains the disarticulated plant materials *Annularia*, *Calamites*, *Cordaites*, *Neuropteris*, *Spenopteris*, *Asterophyllites* and *Pecopteris*. The fossils *Myalina* and *Aviculopecten* are also common. Prior to the most recent flooding and erosion within the spillway (summer, 1993), three large upright trees rooted in the coal were found along the west wall near the southern end of the exposure. The trees extended about 1 m upwards into the overlying rhythmically bedded mudstones.

Unit 7 This unit consists of rhythmically bedded, muddy siltstones and silty mudstones (tidal rhythmites) with a well-defined, cyclic thickening and thinning of laminae. It is approximately 1.5 m thick, and lies above the coal. Individual strata consist of thin silt or very fine sand, pinstripe laminae overlain by organic-rich mudstone. Thicker sand or silt-mudstone laminations have thicker basal sand layers. The detailed fabric of these lamina packages is complex, although larger scale variations in thickening and thinning through the unit indicate neap-spring tidal cycles which range from 0.7 cm to about 4 cm in thickness. Channel-like features are infilled by inclined, rhythmically bedded mudstones. Early diagenetic siderite nodules within this unit contain abundant well-preserved plant fossils, especially ferns, and rare cockroaches, limulids (horseshoe crabs), and shrimp. Mudstone laminae which can be traced laterally into these early diagenetic siderite nodules suggest an approximately 63% compaction of the unit. Invertebrate fossils include nuculoid bivalves, *Myalinia*, and *Aviculopecten*.

Unit 8 This unit consists of a basal flaser- bedded, fine-grained, micaceous sandstone layer overlain by sandy siltstone. The lower sandstone contains the trace fossils *Locheia*, *Scalaratuba*, *Scolicia* and *Planolites*. The upper, medium light gray, sandy siltstone has thin, horizontal laminations with no fossils and highly bioturbated zones with *Planolites*, *Lockeia*, *Aulichnites* and *Isopodichnus* (?).

Unit 9 A gray, laminated to blocky mudstone containing *Phestia*.

Unit 10 A 15 cm thick, cross-bedded calcarenite containing abundant myalinids. This is a possible Amazonia limestone equivalent in this sequence.

Unit 11 An 120 cm thick, bioturbated gray mudstone with horizontal laminations and siderite nodules and concretions.

Unit 12 A 20 cm thick, flaser-bedded, fine-grained micaceous sandstone containing the starfish trace *Asteriacites*.

Unit 13 A 218 cm thick, purple to brown gray, blocky mudstone (218 cm thick).

Unit 14 A thin (3 cm) blocky coal. This is most likely the Upper Williamsburg Coal.

Unit 15 Approximately 250 cm of gray, finely laminated, silty mudstone.

Unit 16 About 230 cm of gray-green, thinly laminated siltstone. The lower meter contains several flaser-bedded, micaceous, fine-grained sandstone lenses.

Unit 17 The approximately 60 cm thick, basal Toronto Limestone is a yellowish-brown, slabby calcarenite (packstone to wackestone) with crinoids, bivalve and brachiopod fragments, and fusulinids.

Interpretation of the Lawrence Formation at the Lonestar Spillway Locality

The approximately 12 m section of the Lawrence Formation beneath the Lower Williamsburg Coal is interpreted as a shoaling upwards, prograding, muddy tidal flat sequence. The section coarsens upwards, with a repetitive depositional style characterized by a continuum of punctuated (waning energy) sedimentation events.

The lower mudstones with pin-stripe tidal bedding were probably deposited on shallow, subtidal mudflats. The lack of extensive bioturbation suggests relatively continuous sedimentation. Lenticular bedded, heterolithic mudstones of unit 3 are interpreted as shallow subtidal to intertidal mudflat deposits. Lenticular bedding is formed by pulsations in current strength, in which traction transport alternates with suspension sedimentation. The continuum of pin-stripe bedding to lenticular bedding and back to pin-stripe bedding, which characterizes the heterolithic mudstones throughout this unit, indicates repetitive, longer term alternations of lower- to higher- to lower-energy conditions. These can be interpreted in a tidal model as neap-spring-neap tidal sequences. This unit also lacks significant bioturbation which is consistant with relatively rapid deposition. The convoluted horizons and wedge-shaped slumps within this interval may have formed through small-scale mass movements along the relatively gentle slopes of the subtidal to intertidal transition of the mudflat environment.

Unit 4 is interpreted as a large-scale, meandering, tidal channel complex. Prevailing northward transport directions within the thicker sandstone packages of the channel complex indicate these channels were flood dominant. Slumping along the channel margins produced the highly convoluted, "homogenized" sand bodies at the bases of the accretionary channel infillings. The smaller-scale channels in Unit 3 of the lenticular-bedded heterolithic facies probably are smaller drainage channels which connected to the channel complex. Climbing-ripple cross-lamination in the channel sandstones indicates rapid deposition from suspension-laden, currents of declining velocity.

The part of the section overlying the coal shares many similarities with coal-bearing tidal facies in the Illinois and Appalachian basins (Archer and Kvale, in press; Archer et al. in press). The depositional environment is interpreted as brackish-water tidal flats formed within the turbidity maximum portion of an estuary.

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REAPPRAISAL OF PENNSYLVANIAN TRACE-FOSSIL ASSEMBLAGES IN THE EASTERN INTERIOR COAL BASIN, U.S.

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ABSTRACT

Previous attempts to establish a nonmarine-to-marine gradient of trace-fossil distributions in Pennsylvanian strata have tended to rely upon fluvio-deltaic depositional models. A growing amount of evidence, however, indicates that a significant degree of tidal influences exists in Pennsylvanian sections in the eastern interior of the U.S. In addition, a number of facies and sequence stratigraphic models have recently been developed for modern estuaries and such models seem to have particular applicability to some Pennsylvanian strata. Herein, an attempt is made to reconcile older models of trace-fossil distributions with the newer evolving concepts of depositional environments. Although some of the older notions of a gradient of "nonmarine" to marine trace fossils are generally correct, the previous interpretations of paleoenvironments are in need of significant revision.

INTRODUCTION

Location and Stratigraphy

In the eastern interior of the U.S., lower Pennsylvanian strata (Fig. 1) are dominated by a siliciclastic motif that consists of a variety of sandstone types associated with heterolithic facies. The sandstones are related to fluvial, estuarine, and marine environments and include "channel" and "barform" geometries. Stratigraphically, this siliciclastic facies is particularly common in the Morrowan and Atokan (Westphalian) and is the predominant lithofacies in the Eastern Interior Coal Basin (Illinois Basin) and surrounding areas in this stratigraphic interval. Conversely, in the younger Desmoinesian strata of this basin, this facies become less common and is more laterally restricted. In the younger interval, the facies has been termed a "clastic wedge" (Wanless, 1964) because it punctuates the commonly developed vertical sequence of underclay, coal, black shale, and limestone. In such sequences, the "clastic wedge" occurs locally between the coal and the black shale. In the Morrowan and Atokan of Eastern Interior Basin and extending into northwestern Arkansas, similar lithofacies of the clastic wedges are predominant, but because limestones and black shales are not common, boundaries of the individual "wedges" cannot be readily delineated and become amalgamated into thick, siliciclastic sequences that exhibit a high degree of lateral variability. Within these amalgamated sequences, the lateral variability and lack of widespread markers, such as coals or limestones makes it problematic to apply formalized lithostratigraphic nomenclature. Within the Eastern Interior Basin, ongoing attempts are currently being made to standardize the lithostratigraphy. Nonetheless, correlations (Fig. 1) within the study area have been reasonably well established (Shaver *et al.*, 1984; Mankin *et al.*, 1986).

Changing Concepts

Over the past decade, there has been a significant reappraisal of the depositional environments of Pennsylvanian coal measures. Historically, these paleoenvironments have been commonly interpreted as fluvial-dominated deltas within tideless cratonic seaways. Renewed understanding of these paleoenvironments is related to the following concepts which are discussed more fully below: (1) a major reappraisal in modern analogs for peat accumulation, (2) understanding the high frequency eustatic flux that occurred throughout much of the Pennsylvanian, and (3) recognition of fine-scale sedimentological features that indicate tidal influences within presumably estuarine environments.

Deltaic models and peat accumulation.- Regarding coal-forming environments in general, and the associated siliciclastic facies, there have been major shifts in understanding of modern analogs. The extensive work on the delta of the Mississippi River and discussion of deltaic peats (originally by Fisk, 1960 subsequently by Kosters, 1989) greatly influenced the interpretation of ancient coal-bearing environments. In particular, coal-bearing siliciclastic sequences within the study area have commonly been modeled following the general outlines of the Mississippi River delta. Peats formed in the Mississippi River delta, however, have a relatively high siliciclastic content (see McCabe, 1984) and thus would not be transformed into coals but would form organic-rich shales. More suitable modern analogs have now been documented in near equatorial coastal-plain settings, such as Indonesia (Cecil *et al.*, 1988; Staub *et al.*, 1991). One of the important aspects of the Indonesian analogs is the recognition of the importance of wet, equatorial climates, rather than depositional setting, in controlling peat accumulations. Similarly to these Indonesian analogs, the depositional basins of the study area had a near-equatorial paleolatitude during deposition of the coals and related siliciclastic facies. In addition, comparison of these modern analogs to Pennsylvanian coals indicate the close association of tidally influence coasts and tidal-estuarine facies to modern peat-forming environments (Staub and Esterle, 1992).

Cyclothem models.--Pennsylvanian coal-bearing strata in the Eastern Interior Coal Basin have long been recognized as having an intrinsic, decameter-scale cyclicity. A number of models have been proposed in attempts to explain these cycles, or "cyclothems" (Wanless, 1964; Heckel, 1984). Cyclothem models that merely portray simple vertical sequences tend to be problematic because they attempt to characterize the uniformity rather than the variability of the cyclical stratigraphic sequences. Conversely, models that incorporate lateral as well as vertical variability are much more realistic. In addition, the evolving concepts of sequence stratigraphy also provide models for paleovalley incision and valley-fill sequences that are readily applicable to these Pennsylvanian strata. This renewed understanding of the sedimentological controls, in conjunction with application of sequence stratigraphy, now allows a more precise delineation of the related ichnofacies.

Tidal estuarine models.--Related to this high frequency of eustatic flux, there were repeated occurrences of eustatic lowering. During falling sealevel, fluvial systems developed incised paleovalleys and a dissected erosional topography. In the study area, the Mansfield Formation was deposited overlying the Mississippian-Pennsylvanian unconformity and paleovalley incision on the order of 30 m was common (Bristol and Howard, 1974; Droste and Keller, 1989). During subsequent sealevel rise, these incised paleovalleys were converted into estuaries, in which were deposited a variety of tidally influenced sedimentation, especially tidal rhythmites (Kvale *et al.*, 1989; Archer and Kvale, 1989; Kvale and Archer, 1991). Understanding of these ancient tidally influenced facies is now facilitated because of studies of suitable modern analogs of tidally influenced estuaries (Allen, 1991; Nichols *et al.*, 1991; Dalrymple *et al.*, 1992). In particular, these modern-analog studies provide a generalized, tripartite model for tidally influenced estuaries (see Section 2) that appears to be particularly useful for understanding the roof strata of Pennsylvanian coal-forming environments. Many aspects of the sedimentological features within these modern analogs can be favorably compared with Pennsylvanian features (Tessier *et al.*, 1992).

Paradigm shift.--Following from these new perspectives on Carboniferous depositional environments, a shift in emphasis is needed away from the older deltaic models onto fluvio-estuarine to marine models. In order to accomplish this shift in paradigms, it is useful to discuss the depositional model originally used, when a deltaic model appeared to be applicable, by Archer and Maples (1984) to explain trace-fossil distributions. This model (Fig. 2a, Table 1), because of manuscript shortening for publication, was not originally figured in the 1984 publication, but was based upon a fluvio-deltaic interpretation. Current understanding of this depositional system, however, would suggest that a fluvio-estuarine to marine model is more appropriate (Fig. 2b). The general

TABLE 1

	LITHOFACIES	MAJOR TRACE FOSSILS	DELTAIC MODEL	EST. MODEL
8	Limestone	*Chondrites, Planolites, Zoophycos*	Outer interdistributary bay, marine	Offshore marine
7	Gray mudstone	*Chondrites*, looping burrow, *Zoophycos, Planolites*	Middle interdistributary bay	Offshore marine
6	Black shale	*Chondrites, Zoophycos*	Upper interdistributary bay	Offshore marine
5	Ripple-bedded sandstone	*Diplocraterion*	Marine tidal flat	Marine sands
4	Heterolithic rhythmites (gray shale)	*Lockeia*, escape burrows, *Palaeophycus, Rhizocorallium*	Distributary channel	Mid estuarine sand flats
3	Laminated sandstone	bilobed trails, *Lophoctenium*	Crevasse splay	Outer estuarine sand flats
2	Silty rhythmites (laminated siltstone)	*Treptichnus, Plangtichnus, Kouphichnium*, tetrapod trackways	Proximal floodplain, lacustrine	Fluvio-tidal bars
1	Crossbedded sandstone	*Cochlichnus, Palaeophycus*	Fluvial channel- and pointbars	same

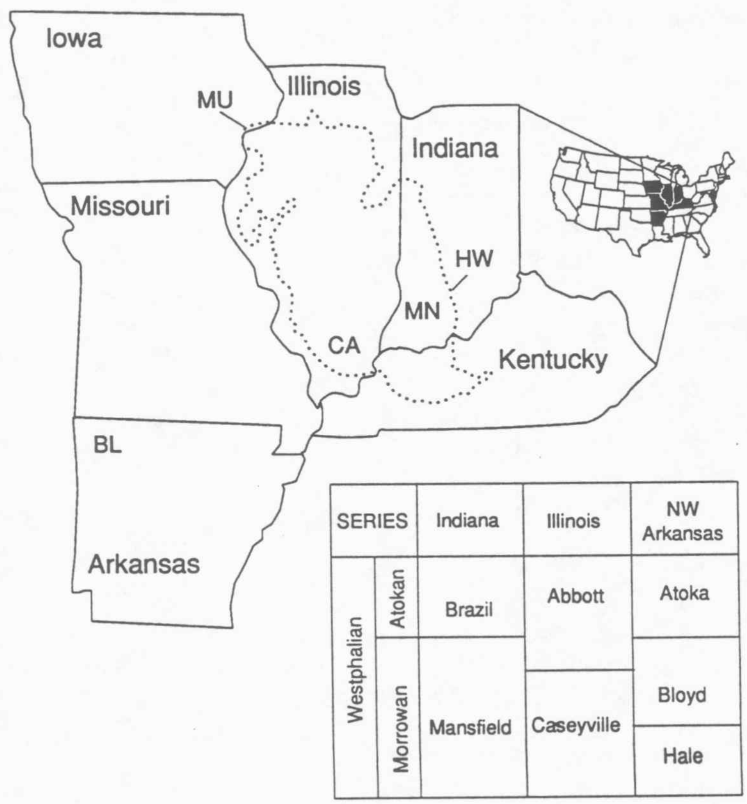

Fig. 1. Location and correlations of Morrowan and Atokan strata in the eastern and midcontinental U.S. Correlations from Shaver *et al.* (1984) and Mankin *et al.* (1986).

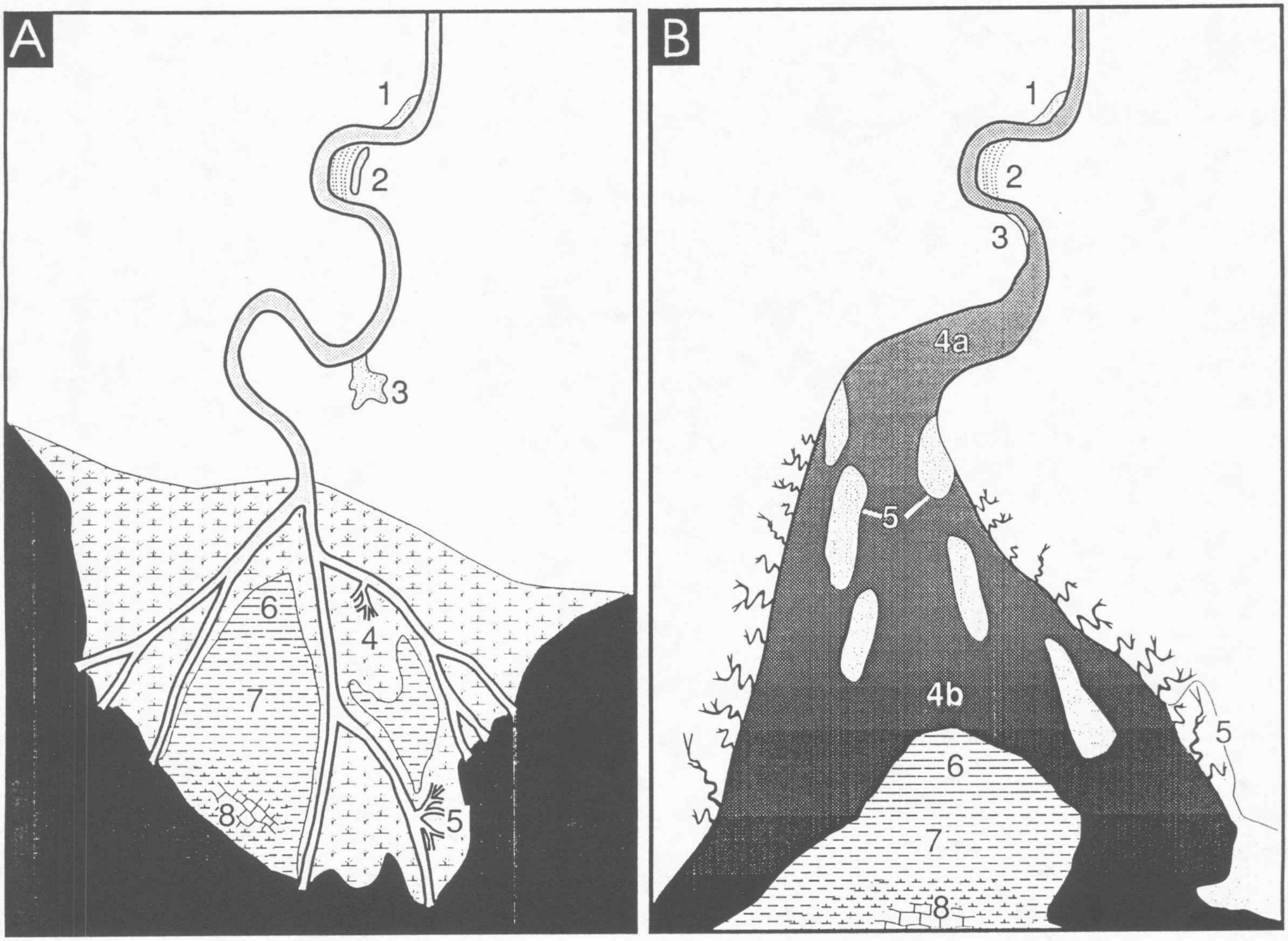

Fig. 2. Comparison of depositional model used by: (A) Archer and Maples (1984, unpublished diagram) with: (B) fluvio-estuarine marine model. Relative positions of various litho- and ichnofacies (listed in Table 1) shown on each diagram.

spectrum of litho- and ichnofacies shares a number of similarities between the older and newer models; however, the newer model more adequately accounts for the sedimentological information that has been recognized since 1988 (see Kvale *et al.*, 1989). The generalized interpretations of the depositional system are summarized in table 1. The following sections will delineate some of the relevant background information of the litho- and ichnofacies that has been used to generate this newer model. The most marine aspects of these lithofacies are currently considered not so much to be lateral facies of the fluvio-estuarine system, but to reflect lithofacies developed during highstand conditions. Therefore, the following discussion will concentrate on the interpretations of the fluvio-estuarine components of the system.

BIOTURBATION IN UPPER ESTUARINE SETTINGS

Degree of Bioturbation

Sedimentation and biological activity on tidally influenced settings with normal marine salinities has been widely discussed. However, the biogenic and physical sedimentary structures developed on brackish- and freshwater tidal flats has received less attention. Within meso- to macrotidal estuaries, significant tidal activity can extend for hundreds of kilometers landward from the estuary mouth. Within the upper parts of large estuaries tidal ranges can be quite high. In such estuarine settings, tidal flats can occur in brackish to freshwater settings. When coupled with a high tidal range, fresh- to brackish conditions can oscillate during a single semidiurnal tidal cycle. Although variations in salinity do not dramatically affect the development of physical sedimentary structures, such variations will profoundly affect the biological environment and the types of biogenic structures that can potentially be formed. Long-term habitation and infaunal activity can be greatly reduced in tidally influenced settings that undergo extreme variations in both water level and water salinities; thus the degree of bioturbation will be minimal. Preservation potential of both biogenic and physical sedimentary structures is further increased in areas of rapid sedimentation that can occur within zones of high turbidity, which are commonly developed in the mixing zone of fresh- to brackish waters in well mixed, high-tidal-range estuaries.

PENNSYLVANIAN FACIES

Lithofacies

In the siliciclastic facies motif, a variety of overlapping and inter-related facies can be recognized. These are described below in order of a landward to seaward distributions that can be interpreted from vertical-stacking patterns. These facies are (1) thick, crossbedded sandstones, (2) silty rhythmites, (3) laminated sandstones, (4) heterolithic rhythmites, and (5) ripple-bedded sandstones. Details of each of these lithofacies are presented below.

Thick, crossbedded sandstones (facies 1).-- Preceding Morrow deposition throughout the study area and well documented in the Illinois Basin (Bristol and Howard, 1974; Droste and Keller, 1989), a ridge and valley topography had been created upon the extensive erosional unconformity developed on the underlying Mississippian bedrock. Within these paleo-valleys, incised valley-fill sequences were deposited during early phases of transgressive and the basal parts of these sequences include a variety of fluvial facies. These include thick, crossbedded sandstones, in which the magnitude of barforms indicates that water depths during flood stages must have been at least as deep as 20 m (Kvale and Eggert, 1988; Fishbaugh *et al.*, 1989). Quartzite granules and pebbles can be common within the bases of the larger-scale trough sets and occur less commonly within the planar sets. Although initially valley confined, these sands can form more extensive sheets, especially where they are developed overlying the valley-fill sequences.

Paleogeographic reconstructions suggest these sandstones were formed in lowland, near-coastal settings. In Arkansas, where more laterally extensive outcrops are available for study, there is a downdip change in dominant style from trough to tabular-planar crossbedding (Zachry, 1977, 1979). In outcrops with dominance of tabular-planar crossbedding, successive foresets commonly exhibit a pronounced development of thick-thin pairs. Measurements of successive foreset thicknesses indicate cycles (Fig. 3a,b) that suggest degraded tidal cyclicities such as those that occur in the upper reaches of the St. Lawrence estuary and such cycles indicate tidal influences during sedimentation.

Silty rhythmites (facies 2).-The silty rhythmites facies consists of planar laminae and beds, most commonly of silt, although fine-grained sands are locally present. Very thin clay drapes mark the upper surfaces of the laminae and thin beds. Features indicative of subaerial exposure or very shallow-water conditions are common, including raindrop imprint, drain features, and runzel marks. Vertical accretion characterizes this facies and upright, *in situ* trees are common where this facies directly overlies a coal bed. Well developed tidal periodicities can be detected in successive laminae thicknesses (Fig. 3c,d). In Indiana, this facies has been informally termed the "Hindostan Whetstone" and several reports have discussed the trace fossils (Archer and Maples, 1985; Maples and Archer, 1987) and sedimentology (Kvale et al., 1989; Kvale and Archer, 1991).

Laminated sandstones (facies 3).--At some localities, the upper parts of the thick, crossbedded sandstones exhibit sandstones that are thinly laminated (1- to 3-mm thick) or locally exhibit current ripples. Lamina boundaries may exhibit very thin, discontinuous clay drapes or more commonly are marked by drapes of finely macerated plant materials and/or muscovite mica. This facies also occurs as isolated, m-thick sandstone bodes encased within nonbioturbated heterolithic rhythmites (Facies 4).

Heterolithic rhythmites (facies 4).- Commonly overlying or encasing silty rhythmites and laminated sandstones, occurs the heterolithic rhythmite facies. A variety of lenticular, wavy, and flaser bedding occurs in this facies. In the updip, apparently more inland depositional area, the heterolithic rhythmites are nonbioturbated (Facies 4a) and exhibit well developed tidal periodicities (Kvale and Archer, 1990). The degree of bioturbation generally increases in a downdip direction and extensively bioturbated aspects of this facies occur (Facies 4b).

Ripple-bedded sandstones (facies 5).-- Within individual coal mines, broad channels filled with ripple-bedded sands (Facies 5) occur within the heterolithic rhythmites (Facies 4). A variety of ripples occur in this facies and many exhibit wave reworking. Relatively thin (0.5- to 2-m-thick), crossbedded bar-form sandstones also occur within the ripple-bedded sandstones. Measurements of successive foreset thicknesses can exhibit well developed tidal cyclicities (Fig. 3e,f). Such localized crossbedded sandstones within the ripple-bedding sandstones might represent development of ebb- or flood-tidal deltas in an outer estuarine to marine setting.

Ichnofacies

Each of the above described lithofacies contains a more-or-less unique assemblage of trace fossils (table 1). Trace-fossil diversity and abundance is low in some facies, such as the thick, crossbedded sandstones (facies 1) and laminated sandstones (facies 2, and trace fossil descriptions for these facies are of the types that do occur. Other facies, such as the silty rhythmites (facies 3) and ripple-bedded sandstones (facies 5), contain a high diversity and variability of trace fossils. In these facies, only the forms considered to be the most diagnostic are discussed and a complete listing of all forms that occur is not attempted. Within the heterolithic rhythmites (facies 4), the trace-fossil content is exceedingly variable, ranging form varieties that are nonbioturbated (facies 4a) to extensively bioturbated (facies 4b). This facies is extremely variable and herein attempts are made only to summarize the extent of the variability.

Thick, crossbedded sandstone (facies 1).- Trace fossils are exceedingly rare in such coarse-grained facies. Because of the coarse grain size most biogenic structures are only poorly preserved; however, forms such as *Cochlichnus* do occur and are the biogenic structure that most characterizes these sandstones. More rarely forms such as *Palaeophycus* also occur. These sandstones commonly contain large amounts of plant debris and drag marks produced by sticks and logs are difficult to separate from animal bioturbation. In addition, water-escape pipes and other soft-

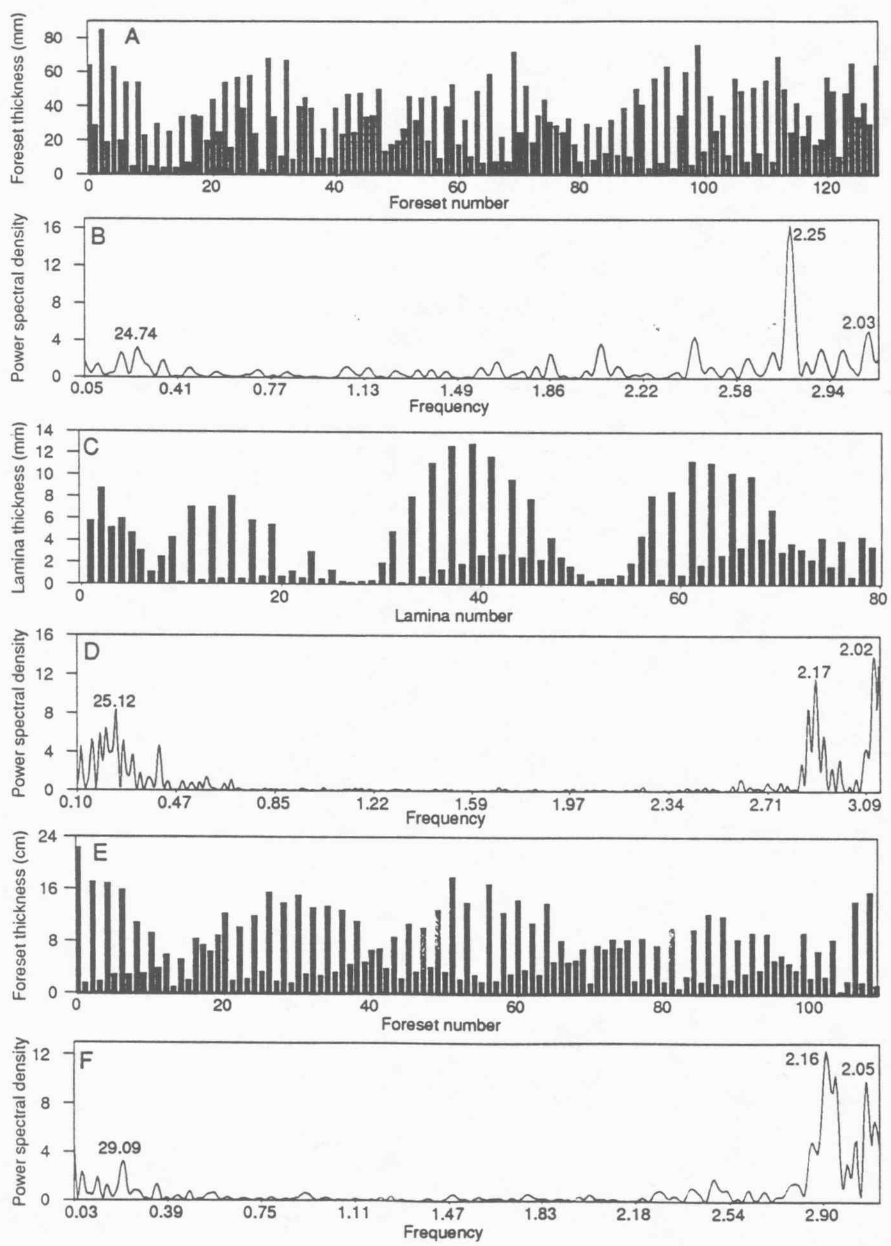

Fig. 3. Comparison of bedform thicknesses and harmonic analyses of various lithofacies. Harmonic analyses based on FFT algorithm of Horne and Baliunas (1986). (A) Sequential foreset thicknesses of the Bloyd Sandstone of northwestern Arkansas exhibiting poorly developed cyclicity, (B) FFT analyses of Bloyd data indicating weak cycles of 24.74 foresets and 2.03 foresets and more strongly developed cycle of 2.25 foresets. (C) Sequential laminae thicknesses from siltstone (Hindostan Whetstone) from Indiana, (D) FFT analyses of Hindostan data indicates well developed periodicities of 25.12, 2.17, and 2.02 laminae per cycle. (E) sequential foreset thicknesses from Abbott Sandstone in southern Illinois, (F) FFT analyses illustrates weak cycle of 29.09 and stronger periodicites of 2.16 and 2.05 foresets/cycle.

sediment deformation is common and easily confused with biogenic activity.

Silty rhythmites (facies 2).--This facies contains a unique assemblage of trace fossils and most commonly includes the forms *Treptichnus, Plangtichnus,* and *Haplotichnus,* which were originally described from the study area (Miller, 1889). These three ichnogenera are approximately equally abundant, but *Treptichnus* is probably the most characteristic form. Because of the obscure nature of this original publication, the holotypes of these ichnogenera were redescribed by Maples and Archer (1987). Since the work in southern Indiana by Archer and Maples (1984), the distribution of this "nonmarine" ichnofacies has been verified by subsequent work in the U.S. midcontinent (Archer *et al.* 1992; Lanier *et al.*, in press). In the Douglas Group of Kansas, litho- and ichnofacies occur that are essentially identical, both in terms of trace fossils and tidal rhythmites, to that of the silty rhythmites (Hindostan whetstone) of Indiana. Other trace fossils that occur in Kansas as well as the original sites in Indiana include fish-fin drag marks (*Undichna*), *Cochlichnus*, and moderately abundant tetrapod trackways. This lithofacies is rare; however, a similar litho- and biofacies has been reported from the Warrior Basin of Alabama (Rindsberg, 1990) and these trace fossils also occur in association with tidally influenced sedimentary structures. Subsequent to the publication of descriptions of trace fossils from the Hindostan whetstone (Archer and Maples, 1984; Maples and Archer, 1987), other ichnogenera have been recorded. Probably the most important is *Kouphichnium*, which is presumably the trackway of a limulid. *Kouphichnium* has also been reported from finely laminated siliciclastic facies in the Pennsylvanian of Tennessee (Miller and Knox, 1985).

Laminated sandstone (facies 3).--The trace fossil to occur in greatest abundance in this facies is *Lockeia* and its associated vertical components, which are *"Skolithos"*-like escape burrows. This group of trace fossils, which is termed the vertical-*Lockeia* assemblage, indicates repeated vertical movements of the *Lockeia*-producing bivalves. *Lockeia* and the associated vertical tubes are commonly the only trace fossil that occurs in outcrops of this facies. More rarely, *Palaeophycus* and very rarely, *Lophoctenium*, also occur.

Heterolithic rhythmites (facies 4).--This facies contains nonbioturbated, partially bioturbated, and extensively bioturbated variants. Nonbioturbated expressions of this facies commonly exhibit tidal rhythmites. In the partially bioturbated expressions, various forms of *Lockeia* occur, but these lack the vertical components that occur in the laminated sandstones (facies 2). *Lockeia* and its associated forms in this facies exhibit more horizontal movements, and include *Uchirites* and *Palaeophycus*. *Uchirites* appears to represent repeated horizontal translation of *Lockeia*, a relationship that has been described by Maples and West (1988).

The extensively bioturbated expressions of the heterolithic rhythmites exhibit a variety of trace fossils and suggest a greater marine influence during deposition. Within the Mansfield/Caseyville interval, there are traceable "marine bands" which can be used for regional correlation (Devera, 1989; Kvale and Eggert, 1988). Although commonly lacking abundant body fossils, these zones contain a variety of "marine" trace fossils. The most consistently occurring form is *Asterosoma;* thus this ichnofacies is herein termed the *Asterosoma* ichnofacies. Other characteristic forms include *Conostichus* and *Teichichnus*.

Ripple-bedded sandstone (facies 5).-These sandstones contain a great variety of subfacies and as a result, a great diversity of trace fossils. Various types of snail-like grazing and shallow burrowing forms are probably the most common throughout the variety of sands in this facies. The ichnogenus *Scolicia* appears to best fit most of the recorded forms; thus this lithofacies can be described as the *Scolicia* ichnofacies. In the thicker sandstones, forms such as *Eione* and *Rhizocorallium* are also common. The association of these three traces are similar to the *Curvolithus* ichnofacies described from Colorado by Lockley *et al.* (1987). In the thinner-bedded sandstones of this facies, large forms of *Lockeia* occur as well as trilobite-type trackways referable to *Cruziana*.

ESTUARINE DEPOSITIONAL MODEL

Facies interpretations.--These lateral facies relationships indicate a progression from fluvial systems to tidally influenced facies, and ultimately facies that reveal significant marine influence (Fig. 2b). It appears that the thick, crossbedded sandstones (facies 1) were probably deposited in a fluvial system that was experiencing distal tidal influence. As the fluvial depositional belt spread out across the coastal plain, the sheet-like sands were formed that characterize much of the Bloyd Sandstone in Arkansas and Mansfield and Caseyville sandstones in the Illinois Basin. In braided channel systems, the bar head is the part of the bar-form that is most affected by fluctuations in flow discharge (Bluck, 1980, 1986). Zones of planar foresets within the thick, crossbedded sandstones (facies 1) appear to be influenced by modulation of fluvial flow via tidal fluctuations. Thus the thick-thin pairings of foresets and apparent cycles (Fig. 3a,b) may be indicative of tidal influence. Because of the equatorial proximity during the Morrow, it would be expected that the tropical fluvial systems were of significant size. This can be confirmed by the bar-form heights that suggests channel depths of 20 m. Because of the size of these fluvial system and the presence of tidal-estuarine facies to the south, tidal energies may have propagated for considerable distance up into the fluvial system.

Silty rhythmites (facies 2) formed at the fluvio-estuarine transition. At such locations the fluvial system was dechannelized and largescale upper-estuarine, "mouth-bar" type forms were produced. These were subaerially exposed at low tides and were formed lateral to the low-water fluvial channels. Because of exposure, as evidenced by abundant raindrop imprint, drain features, and runzel marks, low-water clay drapes are not formed on these bars. During flood tides, rapid deposition of fine sand and silt from suspension produced the vertically accreted bedforms; however, because of location in the fluvio-estuarine transition, ongoing fluvial flow during tidal highstand reduces the potential for clay-drape deposition during maximum tides. This mode of deposition resulted in rapidly deposited and vertically accreted silty rhythmites. Well developed tidal cyclicities ("tidal rhythmites") are developed in this facies (Fig. 3c,d). Although mid-channel bars could have been produced in this way, this facies is commonly observed encasing upright trees that are rooted in underlying coals (Kvale et al., 1989; Kvale and Archer, 1991). This relationship suggests lateral barforms that accumulated along the banks of the fluvio-estuarine systems and prograded out and over surrounding peatfields.

Within the laminated sandstones occurs the vertical-*Lockeia* ichnofacies; such trace-fossil occurrences have commonly been interpreted as "nonmarine" in the eastern U.S., Nova Scotian, and British coal measures. Such interpretations would suggest that the bivalves are escaping from brackish water conditions that periodically interrupted their preferred freshwater environments. The vertical movements of the *Lockeia*-producing bivalves were apparently both to keep pace with rapid vertical aggradation and to escape variations in salinity. Whether the bivalves were attempt to escape from too fresh or too saline waters or merely from rapid sedimentation is not easily resolvable at this time.

Heterolithic rhythmites (facies 4) commonly overlie the laminated sandstones of facies 3); however the heterolithic rhythmites occur locally occur interbedded with laminated siltstones (facies 2). Such facies apparently formed on the seaward end of the silty rhythmite facies and represents the upper reaches of movement of the turbidity-maximum zone that resulted in the deposition of the silty rhythmites. This marks the transition of the fluvial-dominant facies to the tidal-estuarine heterolithic facies and delineates a transition from the sand- and silt-rich upper, fluvial estuarine to mud-rich, middle estuarine settings. The nonbioturbated components of the heterolithic rhythmites can exhibit well developed tidal periodicities (Kvale and Archer, 1990, 1991). In the more landward depositional sites of the heterolithic rhythmites, the potential occurrence of lowered salinities and fluctuating salinities, together with rapid rates of vertical accretion, could have served to preclude bioturbation. Within these muddy facies, the general downdip increase in bioturbation and wave reworking probably reflect greater marine influence and increases in salinity. The bioturbated portions of the heterolithic rhythmites, exhibit generally thinner clay drapes and both because of reduced rates of sedimentation and increased bioturbation, exhibit only poorly developed tidal rhythmites.

The most updip occurrences of the heterolithic rhythmites are commonly nonbioturbated, however bioturbated parts of this facies include the horizontal-*Lockeia* assemblage. Toward the more marine part of the system, the heterolithic rhythmites become progressively more bioturbated; herein occurs the *Asterosoma* assemblage, which includes the forms *Teichichnus* and *Conostichus*. This trend in increasing bioturbation and trace-fossil diversity is probably most simply explained as a gradual increase in marine influence within these estuarine to marine depositional systems. The twelve-fold symmetry of *Conostichus* has been well documented for Illinois Basin examples (Devera, 1989) and suggests production by sea anemones; modern descendants of such organisms generally require more-or-less normal salinities. This particular ichnogenus may be one of the more reliable indicators of deposition within, or beyond the estuary mouth, or even in a lateral coastal position away from the estuarine system. A variety of environments have been suggested for such ichnofacies, including bay fill (Devera, 1989) and transgressive fills of channels (Greb and Chesnut, 1992). These forms can occur in heterolithic facies, but in general the degree of bioturbation is such that sedimentary structures, such as tidal rhythmites, are obscured by the intense infaunal activity of the burrowing organisms. Highly bioturbated tidal rhythmites containing these ichnogenera, however, have been described in eastern Kentucky (Martino and Sanderson, 1993); however, most occurrences of these ichnogenera are associated with a degree of bioturbation that serves to obscure the original sedimentary fabric.

Ripple-bedded sandstones (facies 5) occur at the seaward margin of the depositional system and the thickest sands in these facies do not acquire clay drapes. Feeding and grazing burrows that typify high-energy coastal systems, such as *Eione* and *Scolicia*, are common in the thicker sandstones of this facies. Other typical marine trace fossils, such as *Rhizocorallium* and *Cruziana*, are common in the thinner sandstone beds. This trace-fossil assemblage is similar to the *Curvolithus* assemblage described from high-energy, siliciclastic coastal facies in Colorado (Lockley *et al.*, 1987). Finally, another marine ichnofacies occurs within southern Indiana and Illinois that shares many similarities with the *Curvolithus* ichnofacies described from the Pennsylvanian of Colorado (Lockley *et al.*, 1987; Maples and Suttner, 1990). In the study area this assemblage is characterized, however, not by *Curvolithus*, but by similar forms such of *Scolicia*. Other common trace fossils include *Eione* and large (3 to 4 cm in length) forms of *Lockeia*. These traces occur within sandstones that are encased in shales that contain marine ichnogenera including *Cruziana* and *Rhizocorallium*. Thus these sandstones appear to represent the most marine parts of the coarser-grained siliciclastic component of the system. Preliminary analyses suggests that an offshore bar or spit interpretation may be appropriate (E. Kvale, pers. comm., 1991) although work in ongoing on these sands.

It is noteworthy that starfish-resting traces have not been reported from the study area. Such forms have been reported from Pennsylvanian sandstones of Tennessee (Miller and Knox, 1985) and from Kansas (Hakes, 1985; Archer *et al.*, 1992). Because the rocks of the study area have been relatively intensively studied, this lack is apparently not related to limited sampling. Perhaps conditions in the study area never achieved the fully marine or nonbrackish conditions required for the presence of such echinoderms.

CONCLUSIONS

A clearly definable lateral gradient exists in lower Pennsylvanian trace-fossil assemblages and this gradient appears to relate to a freshwater to marine transition. Previous models that suggested fluvio-deltaic depositional settings did not recognize the significance and degree of tidally influenced sedimentation. The common occurrence of tidal rhythmites in facies that otherwise contain no evidence of marine influences, but that contain abundant "nonmarine" indicators (e.g., coals, upright trees, well preserved plant fossils, insect and tetrapod trackways) suggests that tidal effects were propagated into inland settings. Additional evidence to constrain the Pennsylvanian paleoenvironments comes from modern analogs of tidal rhythmites, which have been reported from high tidal range estuarine settings. Thus, based upon sedimentological data, the trace-fossil bearing Pennsylvanian siliciclastic facies would suggest that deposition occurred with a tidal-estuarine facies mosaic.

The gradient from most freshwater to marine conditions includes a variety of lithofacies and trace-fossil assemblages. The most fluvial and freshwater components include (1) thick, crossbedded sandstones that contain *Cochlichnus*, (2) silty rhythmites that include *Treptichnus, Haplotichnus, Plangtichnus, Kouphichnium*, and tetrapod trackways, (3) laminated sandstones that exhibit *Lockeia* and associated vertical-escape tubes (vertical-*Lockeia* assemblage). These facies suggest a transition from fluvial to uppermost estuarine facies. These three lithofacies contain abundant plant fossils and commonly overlie coals. Upright trees are commonly encased within these facies, particular by silty rhythmites.

Moving seaward, the components include (4) heterolithic rhythmites, which can be nonbioturbated and exhibit well- developed tidal cyclicities to completely bioturbated forms. The nonbioturbated variants commonly directly overlie coals and contain upright trees. As the degree of bioturbation increases, there first occurs a horizontal-*Lockeia* assemblage consisting of *Lockeia* and *Uchirites*. Increasing levels of bioturbation were produced with the occurrence of forms such as *Asterosoma* and *Conostichus*. This lithofacies can be interpreted as having been deposited within a mid-estuarine settings where high levels of turbidity were maintained. At the marine end of the system, (5) ripple-bedded sands were deposited; these sands include a wide variety of trails and burrows, the most common of which include *Scolicia*. Other diagnostic forms include *Eione, Rhizocorallium*, and *Cruziana*.

The gradient of trace fossils and lithofacies may in some ways be unique to study area and thus may not be readily applicable to other Carboniferous basins. In particular the common occurrence of tidal rhythmites suggests an elevated (macrotidal?) paleotidal range. This is presumably related to paleogeographic configurations that resulted in significant amplification of tidal ranges. This would have resulted in tidal influences within significantly inland settings that might otherwise be considered as "nonmarine." In other areas that lacked significant tidal influences, the gradient of litho- and ichnofacies described herein could probably not have been developed.

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Depositional Environments of the Tonganoxie Sandstone Member of the Stranger Formation (Upper Pennsylvanian) in northeastern Kansas

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[Editors note: this is an shortened version of the thesis abstract from Spriggs, 1989, M.S. thesis.]

Analysis of the Tonganoxie Sandstone Member of the Stranger Formation of the Douglas Group (Virgilian Stage, Lower Pennsylvanian Series) in northeastern Kansas ... has provided insight into depositional conditions on a finer scale than cyclothems.

Studies of 27 measured sections utilizing stratigraphic, sedimentologic, and paleontologic observations provide the basis for interpretation of the depositional environments of the Tonganoxie Sandstone Member. This study suggests the Tonganoxie is a confined valley-fill deposit in the northern portion of the study area. The shale units above the sandstone section represent abandoned channel-fill and post-fluvial estuarine deposits, whereas mudstones with root traces and mottles, and very weakly- to moderately-developed horizons represent paleosols. Coals were deposited in relatively humid, swamp-like, subaerial environments as a result of climate change. Most sandstones in the southern portion of the study area represent shoreline deposits. Shale associated with these shoreline sandstones was deposited in an alluvial (possibly low lying-coastal plain) or shallow water marine environment.

PALEOECOLOGY OF THE DOUGLAS GROUP (PENNSYLVANIAN, KANSAS): STATUS

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INTRODUCTION

Rocks of the Douglas Group range from the conglomerates in the lower part of the channelloid sandstones (Tonganoxie and Ireland) to the Williamsburg and Sibley coals and Iatan, Westphalia, Haskell and Amazonia limestones; as well as the intervening mudrock units (Robbins, Vinland, Weston, and an unnamed mudrock unit above the Amazonia limestone and below the Toronto limestone, herein referred to as the Wathena). The name Wathena was proposed by Ball (1964, p.158) for this mudrock unit and is commonly used, informally, by others. Thus, the Douglas Group (see Section 1 for stratigraphy) is a vertical smorgasbord of different types of sedimentary rocks. Not only is their vertical variety, but the lateral relationships of these different stratigraphic units are often times staggering. Such abrupt changes vertically from one lithology to another coupled with drastic changes in thickness and facies over relatively small lateral distances is no doubt one of the reasons that the Douglas Group has challenged, and continues to challenge, the abilities of stratigraphers, sedimentologists, paleontologists, and others interested in the geologic history of the northern midcontinent.

This vertical and lateral variability records a wide variety of sedimentological (physical and chemical) and biological processes and environments, and our purpose in this short contribution is to point out the extent of the biological variation during deposition of the Douglas Group and from this, and associated sedimentological aspects, summarize the status of our paleoecological knowledge of these rocks. To set the stage for this summary the following are important.

1) The most comprehensive study, to date, of the Douglas Group was by Ball (1964) and it contains much useful paleoecological data.

2) The lower contact of the Douglas Group is the boundary between the Missourian Stage (below) and the Virgilian Stage (above) as recognized by the Kansas Geological Survey (Zeller,1968). As yet unpublished studies of conodonts suggest that a more appropriate boundary might be at the base of the Haskel limestone (lowest most member of the Lawrence Formation).

3) Using the climate model proposed by Cecil (1990), Archer, West, & Maples (1990) and Archer & West (1992) suggested that there was a shift from relative dry climates in the Missourian to wetter (more seasonal) climates in the lower Virgilian.

4) In terms of Heckel's 1977 model, the Douglas Group can be considered as two separate "outside shales" between the Stanton cyclothem below and the Oread cyclothem above. That is, the lower formation of the Douglas Group, the Stranger, is one outside shale, and the upper

formation of the group, the Lawrence, is the other.

5) Careful examination of most "outside shales" indicates that they contain one or more sequences that closely resemble the classical Illinois cyclothem as defined by Weller (1931). For example, consider the upper part of the Stranger Formation of the Douglas Group, the sequence from the Tonganoxie sandstone, upward through the mudrocks and Sibley coal to the overlying mudrocks and siliciclastics below the Westphalia limestone to the Vinland shale (mudrocks) at the top, represents an incomplete, but clearly recognizable Illinois cyclothem (this sequence would be units 1, 2, 4. 5, 6, 7, and 10 or units 1, 2, 4, 5, 6, 9, 10, see Figure 1).

PALEOECOLOGY

A useful place to start any consideration of the paleoecology of Upper Paleozoic (Pennsylvanian and Permian) rocks of the northern midcontinent is Moore's 1964 summary paper on this subject. In that paper Moore defined twenty two different biotic assemblages based on the dominant taxon and the rock unit in which the assemblage was best developed. Of these twenty two, three were non-marine assemblages and the remaining nineteen were marine. Moore recognized that there was a certain amount of overlap between his different marine assemblages and following his suggestions and using our experience we can consolidate the nineteen marine assemblages into eleven marine fossil assemblages as follows:

1) Chonetid, orthotetid, orthid brachiopod assemblage = Moore's Speiser (*Derbyia*), Snyderville (*Neochonetes*), Florena (*Neochonetes -Derbyia*), and Captain Creek (*Enteletes*) Assemblages.

2) Productid brachiopod and bryozoan assemblage = Moore's Beil (*Pulchratia*), Threemile (*Fenestrellina -Composita*), Leavenworth (*Isogramma*), Kereford (*Fenestrellina*), and Doniphan (*Rhombopora*) Assemblages.

3) Inarticulate brachiopod assemblage = Moore's Red Eagle (*Orbiculoidea -Lingula*) Assemblage.

4) Coral assemblage = Moore's Plattsmouth (*Caninia*) Assemblage.

5) Sponge assemblage = Moore's Avoca (*Amblysiphonella*) Assemblage.

6) Snail assemblage = Moore's Ozawkie (*Knightites*) and Drum (*Euconospira*) Assemblages.

7) Fusulinid assemblage = Moore's Tarkio (*Triticites*) Assemblage.

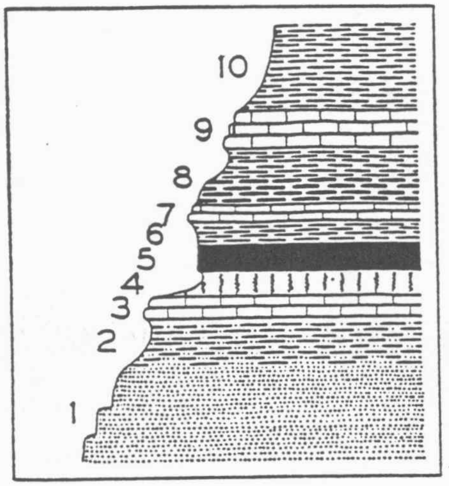
8) Algal-foraminiferid and productid brachiopod assemblage = Moore's Wakarusa (*Ottonosia -Reticulatia*) Assemblage.

9) Algal-foraminiferid assemblage = Moore's Morrill (*Osagia*) Assemblage.

10) Algae assemblage = Moore's Spring Hill (*Archaeolithophyllum*) Assemblage.

11) Fish assemblage = Moore's Heebner (*Listracanthus*) Assemblage.

Add to these eleven the three assemblages [Stranger (*Asterophyllites*), Rock Lake (*Garnettius*), and Elmo (*Sellardia*); for simplicity we are designating these **(12)** plant, **(13)** amphibian, and **(14)** insect respectively] designated non-marine by Moore and we have a total of fourteen.
It is immediately obvious that these are all body fossil assemblages and that Moore did not recognize any trace fossil assemblages. Additionally, it is important to note that at the time of Moore's study taphonomy was not an integral part of invertebrate paleoecology. These are both important paleoecologically. First, trace fossils are generally not subjected to transportation and record biological activity where it occurred. Additionally, the association of certain trace fossils with specific body fossils provides very useful information, not only about who



10	Shale	(upper shale)
9	Limestone	(upper limestone)
8	Shale	(middle shale)
7	Limestone	(middle limestone)
6	Shale	(lower shale)
5	Coal	
4	Underclay	
3	Limestone	(lower limestone)
2	Shale	(sandy shale)
1	Sandstone	

Figure 1. Complete sucession of members of an Illinois Cyclothem (from Weller, 1957, p. 330 and 331, fig. 2).

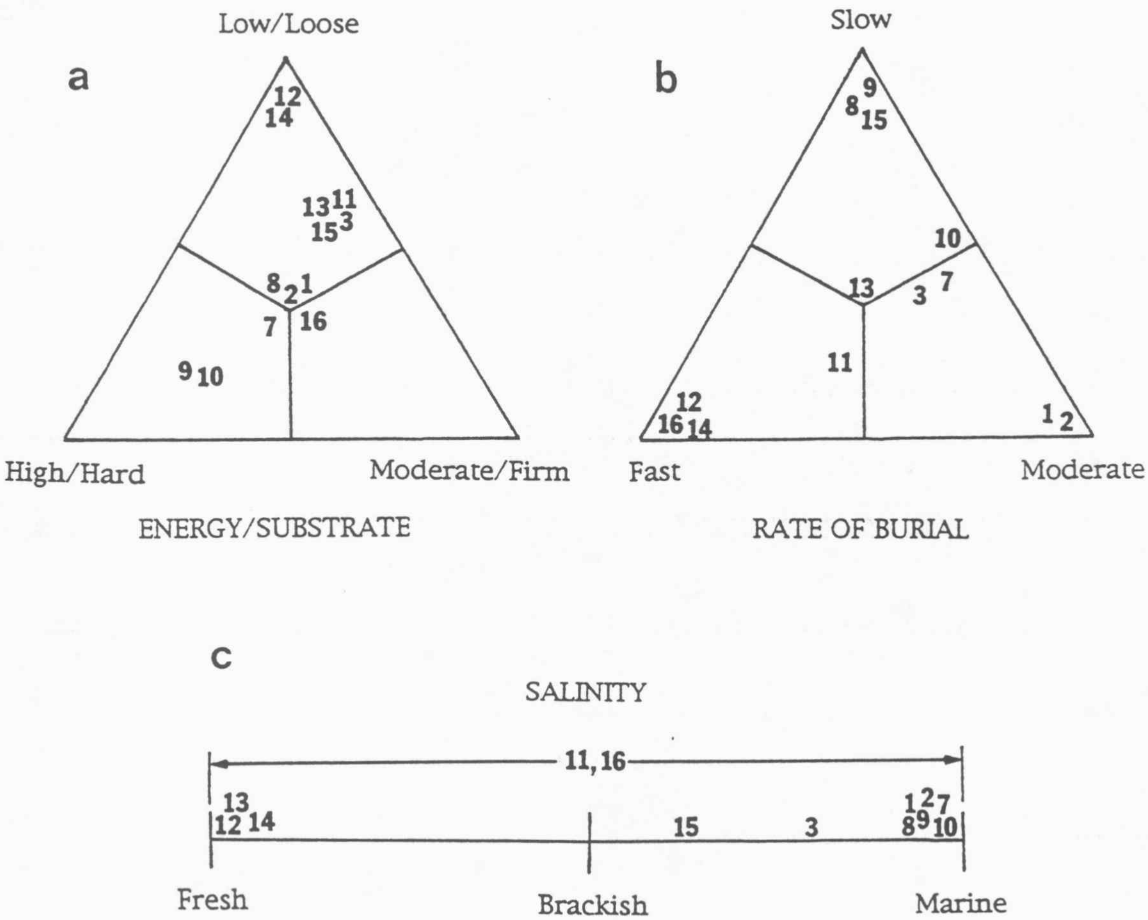


Figure 2. Inferred position of fossil assemblages encountered in the Douglas Group relative to (a) relative amounts of energy and relative degree of substrate consistency, (b) relative rates of burial (sedimentation), and (c) relative stability. Refer to text for the fossil assemblages denoted by these numbers.

made what, but also helps narrow the options for possible depositional environments. Second, without a taphonomic analysis of each body fossil assemblage it is impossible to know whether the organisms lived at the site of collection or were transported there after death. Obviously, such information is vital for any meaningful paleoecological assessment. Because taphonomic studies are lacking for the above groups of fossils it is only appropriate to indicate that they OCCUR in certain rock units NOT that they are the remains of what lived there during the deposition of the particular unit. Unfortunately, taphonomic assessment is lacking for the biotic assemblages for most of the rock units in the Douglas Group, however there are a few exceptions that will be discussed below. The lack of taphonomic data is demonstrated by referring to the groups of fossils as assemblages, and more that one assemblage may occur in any particular rock unit and the assemblages can and do change as one traces some units laterally.

The importance of trace fossil assemblages in the Lawrence Formation and other "outside shales" has been recognized by Hakes (1976, 1977) and Trace Fossil Assemblages are herein designated by the number **16**. Relative to the Douglas Group Hakes (1977, p. 215) stated that "Trace fossils within the Lawrence Shale are characteristic of a marginal marine environment."

A few strictly paleoecological studies have been made of biotic assemblages preserved in rocks of the Douglas Group. One such study was done by Miller & Swineford (1957) on a nodular zone just above the Haskell limestone. Nodules in this zone contains fish debris of both marine and freshwater forms, well preserved fish skulls in nodules, inarticulate brachiopods, cephalopods (rare), arthropods, and fossil wood; a Fish Assemblage. Articulate brachiopods, bryozoans, pelecypods, gastropods, cephalopods, trilobites, ostracodes, foraminiferids, conodonts, and corals occur in the interval 10 to 15 cm above the nodular bed. Most of the biotic elements in the nodular bed and interval above had been transported and the area of occurrence is interpreted as a very nearshore marine to marginally marine area that was above sea level during or shortly after deposition. Such an environment occurs along the outer parts of present day estuaries.

The most conspicuous fossil assemblage in the entire Douglas Group requires an additional designation, namely a Pelecypod Assemblage (**15**). Extending from Missouri and Nebraska into Oklahoma across all of Kansas (it is absent in Anderson County, Kansas) in the upper part of the Vinland shale, is a shell bed in which the pelecypod *Myalina* (*Orthomyalina*) is the most conspicuous component. This shell bed was described in general by Ball, S. M. (1964), in more detail by Ball, D. S. (1985), and recognized as an event bed by West, *et al.*(in press). Commonly the pelecypods are disarticulated, bored (barnacles and probably polychaete worms), and encrusted (bryozoans). Although most of the myalinids occur as single valves in a hydrodynamically stable position there are some localities were they are articulated and in inferred life orientation. In the classification scheme of Kidwell (1991, fig. 6) most exposures of this shell bed would plot near the "within habitat reworking" apex, but exposures of inferred *in situ* myalinids would plot near the "behaviour of shell-producers" apex. As pointed out elsewhere (West, *et al.*, in press) "within habitat reworking" can largely obscure "behaviour of shell-producers" Rollins, *et al.* (1979) have interpreted similar occurrences of myalinid shell beds in the Pennsylvanian of the Appalachians as being analogous to the extensive oyster biostromes that occur along tidal creeks in modern day salt marshes. Certainly, tides, currents, and waves, along with the occasional storm, can produce such shell beds along strand-lines and in shallow subtidal environments in, and along, the mouths and edges of estuaries and more open marine coast lines. Given the associated sedimentological features in the rocks above and below this shell bed an outer estuarine setting for this shell bed seems reasonable.

Current, as yet unpublished, studies by Archer and colleagues suggest than another Pelecypod Assemblage occurs in the upper part of the Tonganoxie and Ireland sandstones. The upper parts of these valley fill sequences contain a moldic assemblage of some pelecypods that resemble *Carbonicola*. Other types of pelecypods also appear to be present and although *Carbonicola,* and related forms have been considered as "...inhabitants of Carboniferous forest swamps..." (Newell, 1969, p. N406), that is as non-marine, the assemblages, and associated features, we have seen suggest marginal marine conditions.

Another paleoecological study of the Douglas Group was compiled by Robb (1991) and was produced by a group of students and faculty from Kansas State University and the University of Kansas. This Field Paleoecology problem focused on the Wathena shale, the informally named mudrock unit at the top of the Lawrence Formation, and, in part, on the underlying Amazonia limestone. In terms of the fossil assemblages listed above the Fish, Algal-Foraminiferid and Productid Brachiopod, and to some extent the Pelecypod Assemblages occur together in the Amazonia. In addition, there is evidence of both burrowing in the loose sediment and boring into shell fragments, thus Trace Fossil assemblages are present. Some of the trace fossil assemblages from this interval have been described by Hakes (1976, 1977). The Wathena contains beds of nearshore, brackish water ostracode valves as well as Plant, Pelecypod, Fish, and Trace Fossil Assemblages. As might be expected trace fossils occurred with plants, with a number of different marine invertebrates (Pelecypod Assemblage), and with both plants and marine invertebrates and are the only assemblage that characteristics *in situ* activity, in general the plants, invertebrates, and vertebrates were transported in from other areas. Additionally, Feldman (personal communication, 1992) has found insect remains (Assemblage **14**) in ironstone concretions from the Wathena near Lawrence, Kansas. Overall, paleoecological and sedimentological, data support an interpretation of shallow subtidal, nearshore marine (Amazonia) to more marginal marine (brackish) and possibly fresh water in the Wathena, a regressive sequence. Because of the lateral relationships between some of these different biotic assemblages a facies mosaic from outer estuary to inner estuary is reasonable.

Although these are some of the more recent and strictly paleoecological studies on the Douglas Group it is important to point out the biotic assemblages that occur in the other rock units in this interval. The following list uses numbers (**1** through **16,** as identified above) for the different biotic assemblages and goes from the oldest to youngest rock unit in the Douglas Group.

Weston shale - **1&2**, also with ironstone concretions in the lower part with molluscs (Ball, 1964).

Iatan limestone - **1, 2,&10.**

Tonganoxie sandstone - **12&16.**

Sibley coal beds - **12.**

Westphalia limestone - **7&9.**

Vinland shale - **1** in Nebraska, **8, 9, 15,&16** in Kansas, and **15&16** in Oklahoma.

Haskell limestone - **1, 2, 8, 9, 11,&16.**

Robbins shale - **2, 3, 11,&12,** also with ironstone concretions in the lower part that could contain well preserved fossils.

Ireland sandstone - **12,15,** and with reworked marine fossils in the conglomeratic beds that occur near the base of the sandstone (Ball, 1964).

Amazonia limestone - **8, 11, 15,&16;** appears to become more marine southward (Ball, 1964).

Wathena shale - **11, 12, 15,&16,** with some insect remains (**14**) in ironstone nodules (Feldman, personal communication, 1992); appears to become more marine southward (Ball, 1964).

Williamsburg coal - **12.**

Of the 16 different fossil assemblages listed, all of them except four (**4, 5, 6,&13**) occur somewhere in the Douglas Group (it seems reasonable that **13** should be there somewhere, we just have not found it yet) and illustrate a biological smorgasbord as one would except given the different sedimentary rocks that make it up. Eventhough careful taphonomic studies have not yet been made of all of these assemblages it is possible to provide some general approximation of some of the conditions under which they might have accumulated. In a very general sense it is possible to relate relative energy levels in the environment of accumulation to the degree of firmness of the substrate such that a loose, soft, fine grained substrate indicates low water energy and a hard substrate indicates high water energy. The degree of preservation of the fossils suggest something about the rate of sedimentation (burial); well preserved, *in situ* specimens suggest rapid (fast) burial and rounded, abraded, non-*in situ* specimens suggest transport and/or slow burial. Using associated sedimentological features and the sequence of such features we obtain some idea of the types of environments in which the fossil assemblages accumulated and from this we can inferred something of the water salinity. Inferences as to where the fossil assemblages of the Douglas Group may have accummulated relative to these three variables is shown in Figure 2. In using this figure remember that the positions of the different assemblages in this figure are sort of averages, and that there are instances when a given fossil assemblage would occupy more than one position on the three diagrams. For example, the Pelecypod Assemblage dominanted by myalinids accummulated under different conditions than did the Pelecypod Assemblage dominanted by *Carbonicola*.

If we now combine what we know about the vertical and lateral changes in sedimentological and biological data it is reasonable to suggest that the Douglas Group represents a range of environments from nearshore marine to freshwater and terrestrial; a series of stacked estuarine complexes punctuated by marine transgressions and valley fills?

SUMMARY

There is no general paleoecology, or paleontology, of the Douglas, it is varied and complex. Because of (1) this biological variation and complexity, (2) the occurrence of lithologic sequences like those of the classic Illinois cyclothems, and (3) because these rocks record a time when major climate changes are inferred the strata of the Douglas Group are "ripe" for paleoecological "picking".

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RELATIONSHIPS OF FLUVIO-DELTAIC AND TIDAL ESTUARINE FACIES WITHIN THE DOUGLAS GROUP (MISSOURIAN-VIRGILIAN) OF EASTERN KANSAS

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STRATIGRAPHY AND SAND DISTRIBUTIONS

There are two major sequences within the Douglas Group (Missourian-Virgilian) in Kansas, each of which starts with valley incision and delta formation during lowstand and ends with widespread marine deposition. The sequence boundaries can be placed at the contact between incised fluvial sandstones and eroded underlying, commonly marine, strata. During valley incision in northern and central eastern Kansas (Linns, 1950), deltas were being deposited in southern Kansas (Walton and Griffith, 1985) (Fig. 1). The delta complex of the Tonganoxie Sequence (lower Douglas Group) has an east- to-west lateral extent of approximately 250 km and the facies indicate significant tidal influences. North of the deltas, incised paleovalleys were filled during lowstands and subsequent transgressions (Linns, 1950). One paleovalley exhibits 34 m of incision, is approximately 32 km in width, and can be laterally traced along outcrop and into the subsurface to the south for approximately 140 km. Paleovalleys are filled with a succession of (base to top) fluvial to estuarine to marine facies (Fig. 2) and in one of the paleovalley, marine influence increases significantly to the south. The valley-fill fluvial and estuarine facies were deposited during lowstand and subsequent sea-level rise. Marine shales and limestones were deposited during highstand and were partly eroded during subsequent fall in sealevel. During valley incision, lithified carbonates in the eroded stratigraphic units impeded downcutting of the paleovalleys resulting in a benched paleotopography of some paleovalleys in which lithified carbonates formed valley-wall erosional terraces and valley floors. Evidence for subaerial exposure of the valley walls includes the presence of in situ coals and paleosols (Goebel et al., 1989).

The Tonganoxie Sandstone and its southern equivalent, the "Stalnaker" sandstone, form the main sandstone bodies in the lower sequence of the Douglas Group in Kansas (Fig. 1). The Tonganoxie in the northern part of Kansas is largely confined to paleovalleys and is part of a valley-fill succession. Conversely, the "Stalnaker" is not valley confined and forms a widespread, tabular geometry apparently reflecting deposition in a lowstand deltaic system which was apparently penecon-temporaneous with valley incision to the north. The upper parts of the valley-fill facies and deltaic facies exhibit tidally influenced sedimentation; however, such influences were most strongly developed within estuarine portions of the valley-fill system (Archer, 1991; Lanier et al., in press).

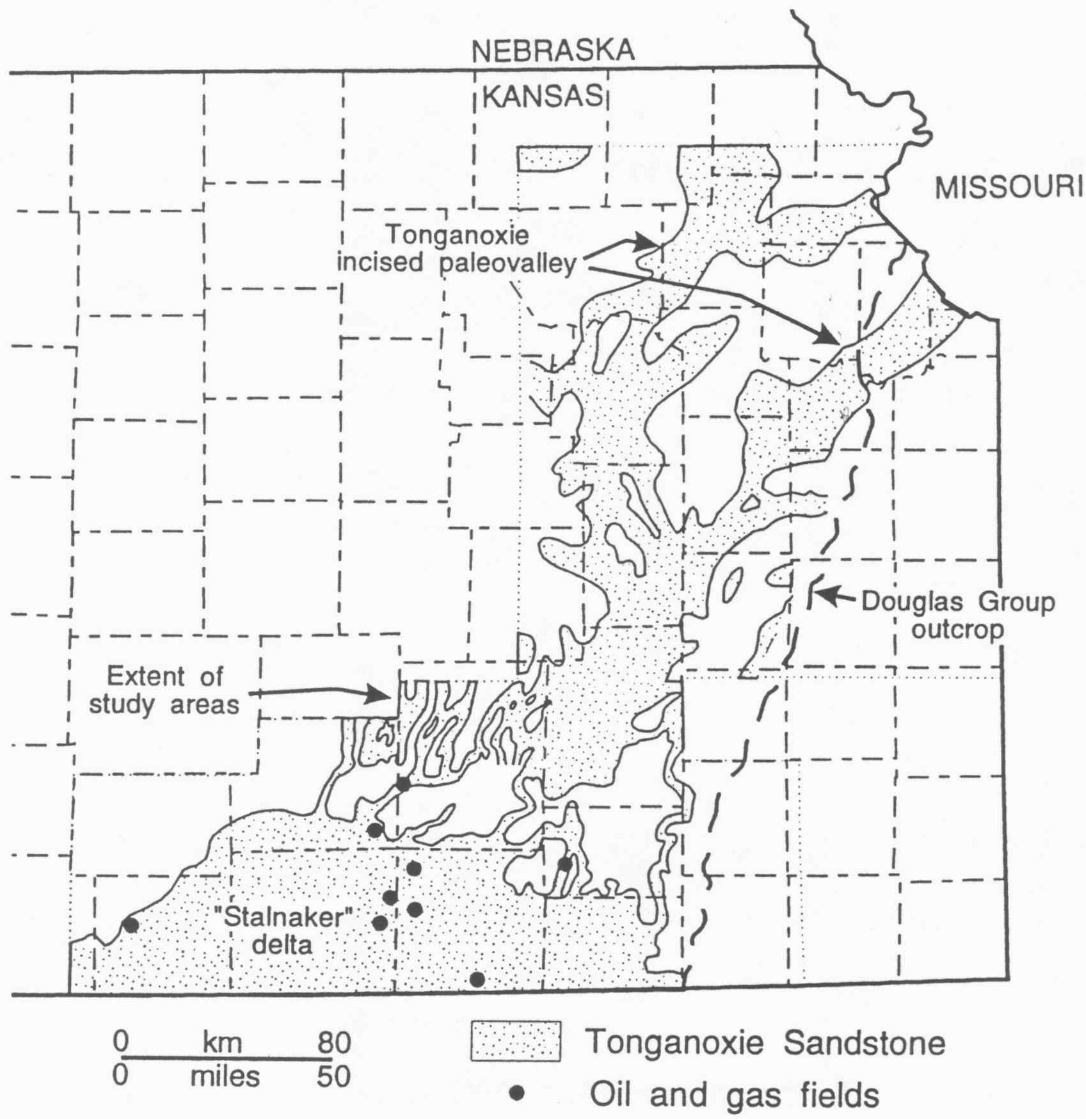

Figure 1. Map of eastern Kansas showing approximate outcrop of the Douglas Group and the extent of the Tonganoxie Sandstone. In northern Kansas, the Tonganoxie occurs within paleovalleys (from Lins, 1950 and Sanders, 1959). In southern Kansas, the Tonganoxie is a widespread unit that has been termed the "Stalnaker" sandstone (from Winchell, 1957) or delta (Walton and Griffith, 1985). Intervening areas exhibit transition from incised valley to deltaic phase (Griffith, 1981).

VERTICAL SEQUENCES

Paleovalleys were filled with a fining upward succession of facies (Fig. 2) with the lowest facies composed of cross-bedded conglomerate and sandstone. The conglomerate contains rock fragments and fossils eroded from older units exposed within the paleovalley and also contains abundant plant fossils. Sandstone beds exhibit large scale (up to 1 m thick) trough and tabular-planar cross beds. Paleocurrent directions (Fig. 3) are generally southwest and indicate deposition via large-scale fluvial systems that were constrained within the paleovalleys.

Overlying the fluvial sandstone is a diverse suite of lithofacies including planar-bedded sandstones and siltstones, heterolithic facies, sheet-like sandstones, bioturbated sandstones, and marine facies. The planar-bedded sandstones and siltstones can exhibit neap-spring tidal cycles, which were formed in high-intertidal settings (Lanier et al., in press). Heterolithic facies are typically laminated and contain pinstripe laminations, starved ripples, and well-developed tidal cycles, or cyclical tidal rhythmites (Archer, 1991). Neap-spring tidal cycles are common and range from 1 cm in thickness in heterolithic facies to as much as 1 m in thickness in planar-bedded siltstones. An interpretation invoking very high localized de-positional rates is substantiated by the presence of buried upright trees, some of which have attached foliage. The heterolithic facies, which includes estuarine and bay-fill paleoenvironments, can be very organic rich. Such facies in the Douglas Group have a number of similarities to modern macrotidal systems (Tessier et al., 1992).

The sheet-like sandstone bodies are dominated by small-scale trough crossbedding and ripple- and planar laminations. Paleocurrents are bimodal to the southwest and northeast (Fig. 3), reflecting ebb and flood tidal currents. Features such as flat-topped ripples, rain-drop imprints, and tetrapod trackways indicate deposition within the intertidal zone. "Flaggy" bioturbated sandstones indicate significant marine influences. These sandstones are capped by widespread marine shales and limestones that extend far beyond the limits of paleovalleys. Shales can be extensively bioturbated, lack laminations, and locally contain marine body fossils. Limestones form wide-spread lithostratigraphic mark-ers, and contain abundant marine fossils such as bivalves, fusulinids, brachiopods, crinoids, and bryozoans. Some of the limestones consist of shell lags which indicate the development of trans-gressive surfaces of erosion.

FACIES MODEL AND RESERVOIR CHARACTERIZATION

The facies within the valley-fill succession of the Douglas Group share many similarities with Morrowan sandstones of Indiana (Archer and Kvale, in press; Archer et al., in press) and of eastern Colorado and western Kansas (Wheeler et al., 1990). To the north, the lower valley-fill facies are dominated by thick, quartz arenitc to subarkosic, medium- to fine-grained sandstone with an underlying, thinner, crossbedded conglomerate (Fig. 2). The fluvial facies, although too shallow in northern Kansas for oil accumulation, probably has the greatest reservoir potential of the various sandstones developed within the Douglas Group. Strong tidal influences occurred within upper estuarine parts of the paleovalley-fill facies (Fig. 3) and have a number of effects on reservoir potential. During falling and low

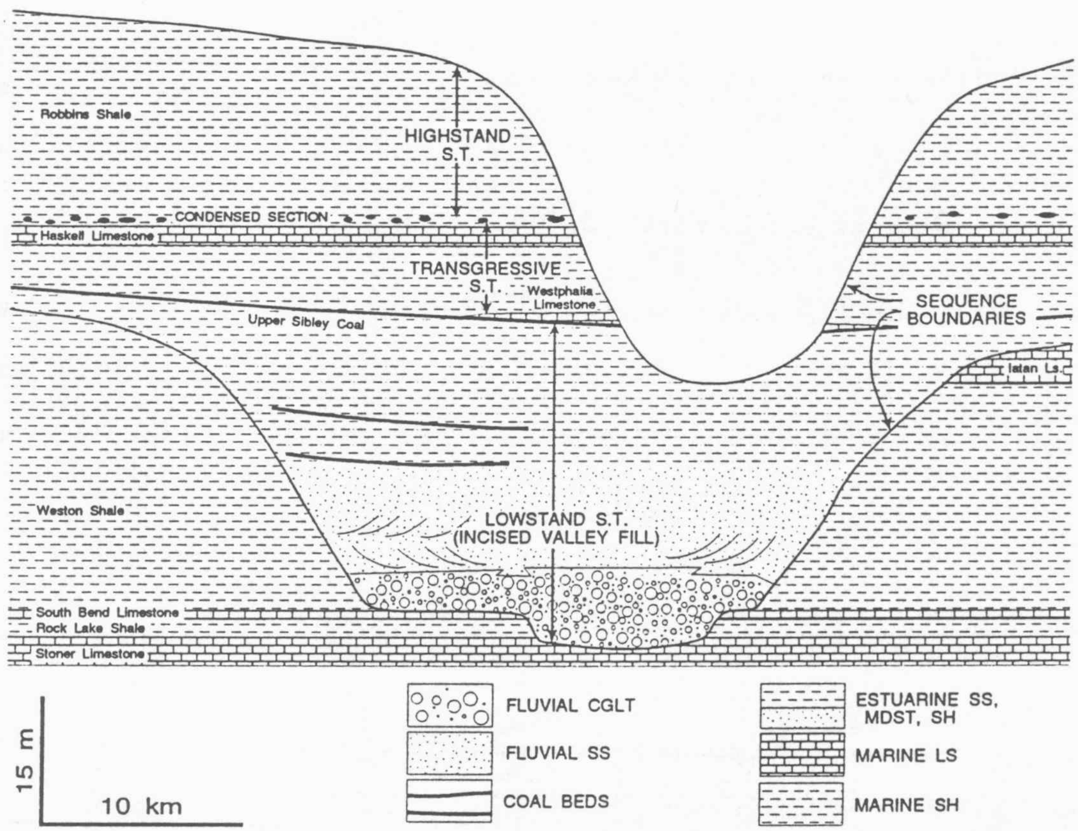

Figure 2. Sequence stratigraphic model for incised valley-fill sequences developed within the Tonganoxie Sequence (lower Douglas Group) of Kansas. Placement of systems tract boundaries is shown based upon the definitions proposed by Van Wagoner *et al.* (1990). Depending on criteria used to establish the transgressive surface, the incised valley fill can be placed into either the lowstand or transgressive systems tract.

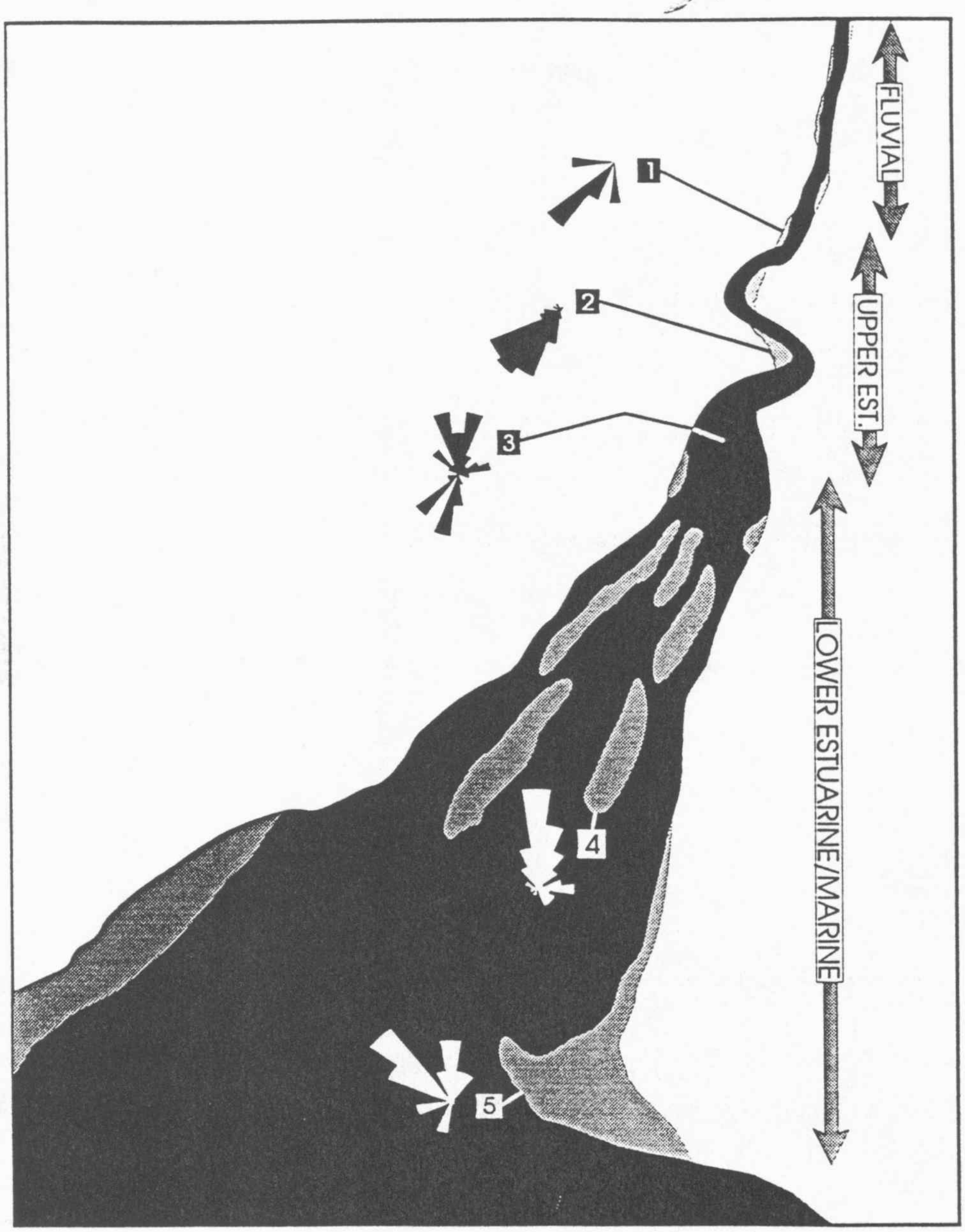

Figure 3. Facies model for valley-fill, estuarine-to-marine depositional sequences developed within the incised valleys in the Douglas Group of eastern Kansas. Numeric codes for facies are the same as used in the text. Paleoflow roses for the various facies are based upon the following counties in Kansas (1) Leavenworth, (2) Franklin, (3) Douglas, (4) Greenwood and Woodson, and (5) Chautauqua. This reconstruction is intended to represent the lateral relationships of the lithofacies developed during early to mid transgression. Adapted from models of Dalrymple *et al.* (1992).

sealevel stands, the paleovalleys contained fluvially dominated facies. However, during base-level rise, these fluvial valleys were transformed into estuarine depositional systems. Funnel-shaped estuarine geometries can significantly amplify tidal ranges and thus enhance tidal velocities and tidally influenced sedimentation. Within such systems, estuarine tidal ranges can be macrotidal (>4m) although open-coastal ranges may be only microtidal (<2m). The transition from channelized fluvial systems to nonchannelized estuarine systems is a major locus of sand deposition. Sands at the fluvio-estuarine transition are essentially analogous, in terms of depositional environment, to distributary mouth bars or channel-mouth bars, but are more strongly tidally influenced. The most important effects of tides in terms of reservoir heterogeneity is the deposition of extensive clay-draped beds and barforms. Clay draping of sandy bedforms becomes most pronounced in the middle parts of estuaries where high rates of turbidity, in part related to fresh/saline water mixing, result in high depositional rates for fine-grained siliciclastics. Clay drapes in the Douglas Group can extend for hundreds of meters and could be potentially important barriers to flow within reservoirs. Increased marine influence, fluvial influence, or bioturbation reduces the lateral continuity of clay drapes and increases reservoir homogeneity.

Towards the seaward end of the estuary, a number of depositional settings were potentially developed, including lower estuarine tidal sand flats, bars, subtidal sand ridges, and other marine sandstones (Fig. 3). These sandstones are generally fine grained and have a substantially greater degree of marine influence and may exhibit substantial degrees of bioturbation. Because of lowered turbidity and decreased rates of clay deposition and resuspension of fines via wave reworking, these outer estuarine to marine sands will be cleaner and exhibit fewer and less continuous clay partings as compared to upper estuarine sands. Absence of clay partings and vertical bioturbation will reduce vertical permeability barriers in outer estuarine sands that will be present in sands deposited further within the estuarine system.

CONCLUSIONS

A strong emphasis needs to be placed upon the transgressive context of the fluvio-estuarine sequences where various types of sand bodies (potential reservoir facies) will be intercalated with finer-grained, commonly heterolithic, organic-rich estuarine and bay-fill sediments (source rocks). These fine-grained facies will be characterized by tidal rhythmites formed in the intertidal and subtidal zones and offshore mud-dominated facies, which can develop the trapping facies overlying the estuarine sands.

Traceable discontinuities within sandstone facies are extremely important for reservoir characterization and are potentially traceable using well logs, especially when cores are available to adequately characterize the well-log signatures. Marked heterogeneity will occur within valley-fill successions because of both the depositional variability that will occur within the valley-fill deposits and the localized and irregular erosion of older, pre-incision deposits. In the Douglas Group, the presence of at least two stacked, valley-fill sequences creates a complex reservoir, especially where the younger Ireland sequence erosionally truncates the older, Tonganoxie sequence.

In general, it can commonly be difficult to adequately constrain the nature of incised paleovalleys and paleovalley-fill sequences because it cannot always be determined if the incision was due to base-level lowering (e.g., eustatic lowstand or uplift) or was related to autogenic processes (e.g., upper-delta plain incision). However, within the Douglas Group of Kansas, it is clear that base level was significantly lowered because paleovalleys were incised into marine units with well-defined stratigraphic markers. In fact, it is the presence of the underlying marine markers that allow delineation of the paleovalleys even when they are not primarily sand filled. Without the "layer cake" stratigraphy of the pre-Douglas Missourian-age units, it would not readily be possible to differentiate between allogenic processes of lowstand valley incision and the autogenic processes developed during deltaic sedimentation (e.g., channel shifting).

Insofar as the Douglas Group was formed during lowstand and was deposited overlying an erosional surface developed upon highstand, marine sequences, delineation of incised valley fills is particularly easy. This contrasts with older Pennsylvanian sandstones, such as Morrowan, Atokan, and Desmoinesian units, that were formed during a protracted transgression (Absaroka Sequence). Valley incision, except where it cut down into Mississippian bedrock, is more difficult to delineate in these rocks because the incised strata have a more terrestrial and less of a marine character. In addition, Illinois and Appalachian basin sand-stones, particularly those of Morrowan and Desmoinesian age, also share many similarities with a depositional model that can be generalized from our ongoing studies of the Douglas Group.

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Regional geological perspective for Virgilian Douglas Group in Kansas

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Introduction

This section is a short review of some current studies of the regional stratigraphy of the late Pennsylvanian interval encompassing the Douglas Group. The views are preliminary and are being presented here for the sake of discussion and feedback.

The Douglas Group is currently included in base of the Virgilian Stage of the Upper Pennsylvanian (Figure 1). It is divided into a lower Stranger Formation and an overlying Lawrence Formation. The Haskell Limestone, located at the base of the Lawrence Formation, is a significant regional marker that is extends from eastern Kansas to the western part of the state and into adjoining Nebraska and Oklahoma. The Missourian-Virgilian boundary is currently recognized at the top of the South Bend Limestone (currently in the Stanton Formation of the Lansing Group) in Kansas, Nebraska, and Iowa, but is placed at the base of the Tonganoxie Sandstone in Missouri. New conodont and ammonoid information suggest that the Missourian-Virgilian boundary may actually be in the Douglas Group. The only faunal change in the interval between the Eudora Shale (Stanton Limestone) and the Heebner Shale (Oread Limestone) occurs in the thin dark marine shale called the Little Pawnee Shale associated (as the core shale) with the Haskell Limestone. This change has been recognized throughout the Mid-Continent, Texas, and Illinois. The Little Pawnee shale contains the first appearance of the distinctive idiognathodid conodont Streptogathodus zethus (Heckel and Watney, 1991). Boardman and Heckel (1989) proposed that the base of the Virgilian Stage be placed at the base of the Haskell Limestone.

The Douglas Group is a thick siliciclastic-dominated interval in eastern Kansas presenting a marked contrast to the underlying carbonate-dominated Lansing and Kansas City Groups and the overlying Shawnee Group. The cyclothemic succession also undergoes a marked change at this position evolving from simple marine cyclothems of the Marmaton, Lansing, and Kansas City groups (four component -- transgressive limestone, core shale, regressive limestone, and outside shale) to the more complicated megacyclothem of the Shawnee Group (Moore, 1936).

The following two regional cross sections, extending some 125 mi (200 km) from central Kansas into northern Oklahoma, and several regional isopach maps provide broad perspectives of the Douglas Group in conjunction with adjoining strata. Key observations based on the analysis of these data and supporting study described in Watney et al. (1993) include:

1) several orders of cyclicity are recognized in the mid to late Pennsylvanian.
2) the Douglas Group was deposited at the boundary of two longer-term cycles. The underlying cycle is referred to as the Lansing cycle, incorporating 5 cyclothems: Iola, Wyandotte, Plattsburg, Stanton, and Iatan.
3) this longer-term Lansing cycle, approximately two million years (m.y.) long, is a transgressive-regressive (T-R) cycle

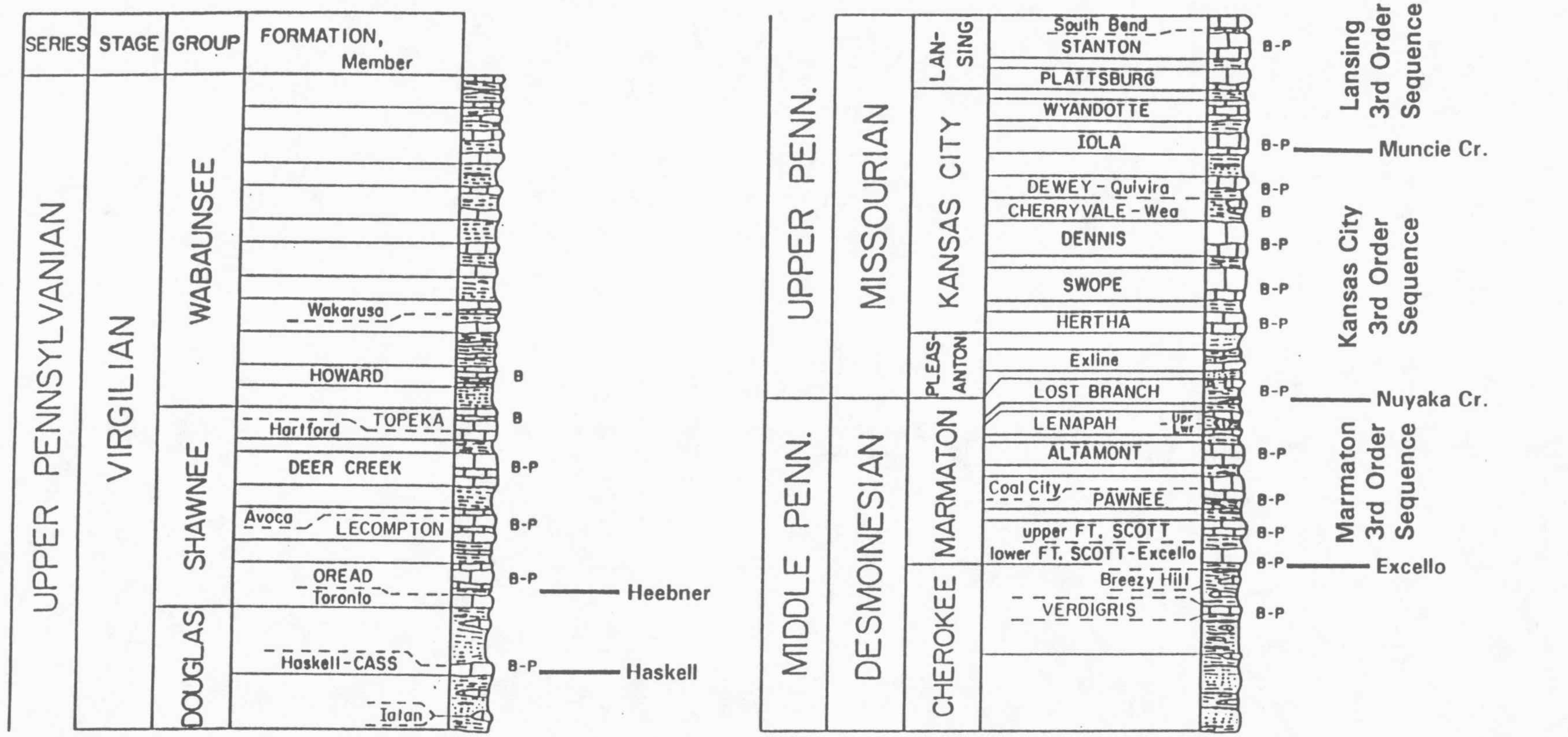


Figure 1. Stratigraphic section of Middle and Upper Pennsylvanian in Kansas adapted from Heckel (1991). Each formation corresponds roughly to a single cyclothem. Positions of widespread phosphatic black shales are delimited by "B-P", black shales by "B". In addition to formal stratigraphic nomenclature, a new subdivision of 3rd-order sequences is identified. These third-order sequences are distinguished by name -- Marmaton, Kansas City, and Lansing and major bounding marine markers -- Excello Shale, Nuyaka Creek Shale, and Muncie Creek Shale. The Heebner and Haskell shales are both noted because upper boundary of the Lansing 3rd-order appears to be transitional between them.

beginning with marked backstepping (drowning) of the lower carbonate shelf in southern Kansas. Cyclothems succeeding this drowning surface prograded basinward into the drowned shelf and suggest a general regression or falling sea level.

4) The thin, but very widespread Haskell Limestone that divides the Douglas Group defines the base of another regional, long-term T-R cycle that extends into the Shawnee Group.
5) The Douglas Group in eastern Kansas is thicker (5 to 6 times) and contains considerably more diverse facies than in western Kansas. In western Kansas, particularly over the Central Kansas uplift (CKU), the Douglas Group is under 50 feet (16 m) thick and contains evidence of more frequent and prolonged subaerial exposure. This suggests that the west presented significantly reduced sediment accommodation space due to its more positive location than to the east. The lower shelf in the east (particularly east of the Nemaha uplift) provided a fairway for siliciclastic progradation.
6) The Tongonoxie Sandstone fills a valley system incised into both the underlying southerly prograding terrigenous clastics of the Stranger Formation and the upper portions of the underlying Stanton Limestone. These lowstand conditions were significant, but not unusual during the Pennsylvanian. Lowstand and accompanying incisement are inferred for other late stages of other longer-term cycles: 1) Morrowan and Atokan during initial Pennsylvanian sea level rise in southwestern and northeastern Kansas, 2) mid Cherokee during time of "Bartlesville sandstone" valley formation and backfilling, 3) end of Marmaton (pre Nuyaka Creek Shale), 4) Chanute Shale and associated sandstones, and 5) the Douglas event. Apparent fall in longer-term sea-level during the late Pennsylvanian and early Permian led to a series of valley incisements as described primarily from surface exposures by Mudge (1956).
7) long-term T-R cycles result in major reconfiguration of the shelf. Characteristics are pronounced with extended drowning of the lower shelf during transgressions and large-scale incisement and prolonged subaerial exposure on upper shelves during regressions.

Cross sections

Two north-south cross sections from similar locations in southern Kansas and northern Oklahoma are described, one a gamma ray section derived from the regional database of wireline logs (Figure 2) and another a re-interpretation of an older published section (Figure 3). The original well-log cross section of Figure 3 is also included in Figure 4. Correlation of the older section Lukert established many of the regional markers, but use of new gamma ray-neutron-density log suites and results of detailed stratigraphic correlations from cores and outcrop from near-surface and surface studies helped to refine correlations.

The sections reveal details about the shelf-to-basin transition that have important implications about sea-level history. These regional sections are approximately 125 mi (200 km) long, are indexed on late Missourian and early Virgilian paleogeographic maps (Figure 5). The cross sections illustrate the stacking pattern of Middle and Upper Pennsylvanian strata along a profile extending from south-central Kansas into northern Oklahoma. The interval extends from the base of the Pennsylvanian to the Heebner Shale. Thickness ranges from 900 feet (300 meters) thick on the north to nearly

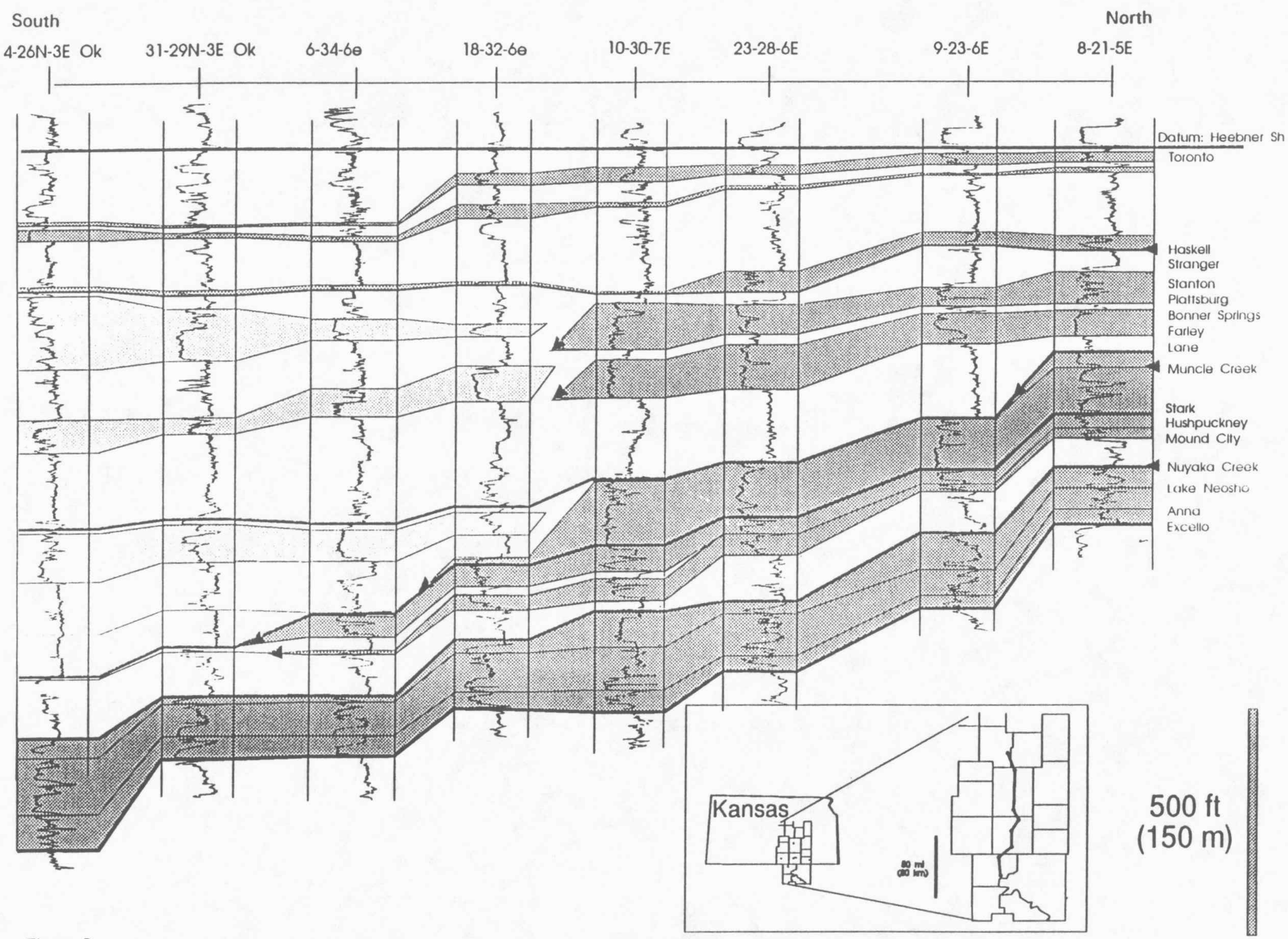


Figure 2. South-to-north regional stratigraphic cross section datumed on the Heebner Shale for the Middle and Upper Pennsylvanian interval running approximately 125 miles (200 km) from northern Oklahoma to central Kansas Gamma ray log traces and correlations of wells selected from regional sequence stratigraphic database showing shelf (right) to basin (left) transition where carbonate-dominated section gives way to siliciclastic rich section. Major continuous marine markers bounding 3rd-order cycles correspond to marked changes in shelf margin. Sandstones are interpreted as lowstand deposits based on analogies with the analog areas in surface exposures and shallow subsurface. Dark screen = limestone; light screen = sandstone; white = shale and thin sandstone.

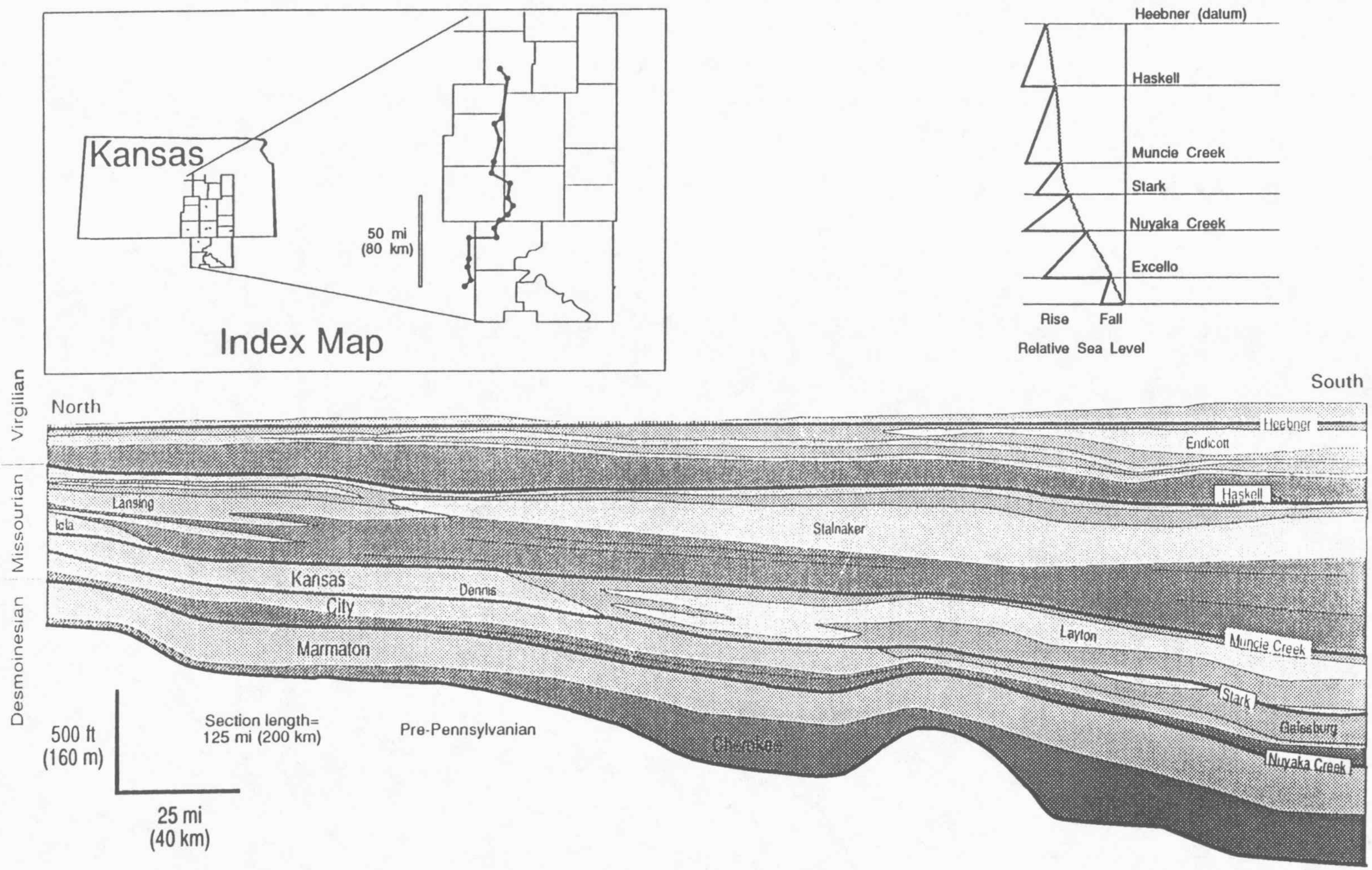


Figure 3. North-to-south stratigraphic cross section datumed on Heebner Shale for the stratigraphic interval from the base of the Pennsylvanian to the top of the Oread Limestone. Cross section is approximately 125 mi.(200 km)long. Section is approximately 20 miles west and parallel to the gamma ray log cross section. Section is a re-interpretation of a wireline log section prepared by Lukert (1948). Interpretation is assisted by use of wireline log database using gamma ray neutron-density logs that permit lithologic interpretation. Furthermore, stratigraphic model developed from near-surface analog study provided framework to support correlation development. The continuous marine shale markers delineate major changes to the shelf margin. Relative sea-level curve is depicted in inset based on a framework of the marine markers.

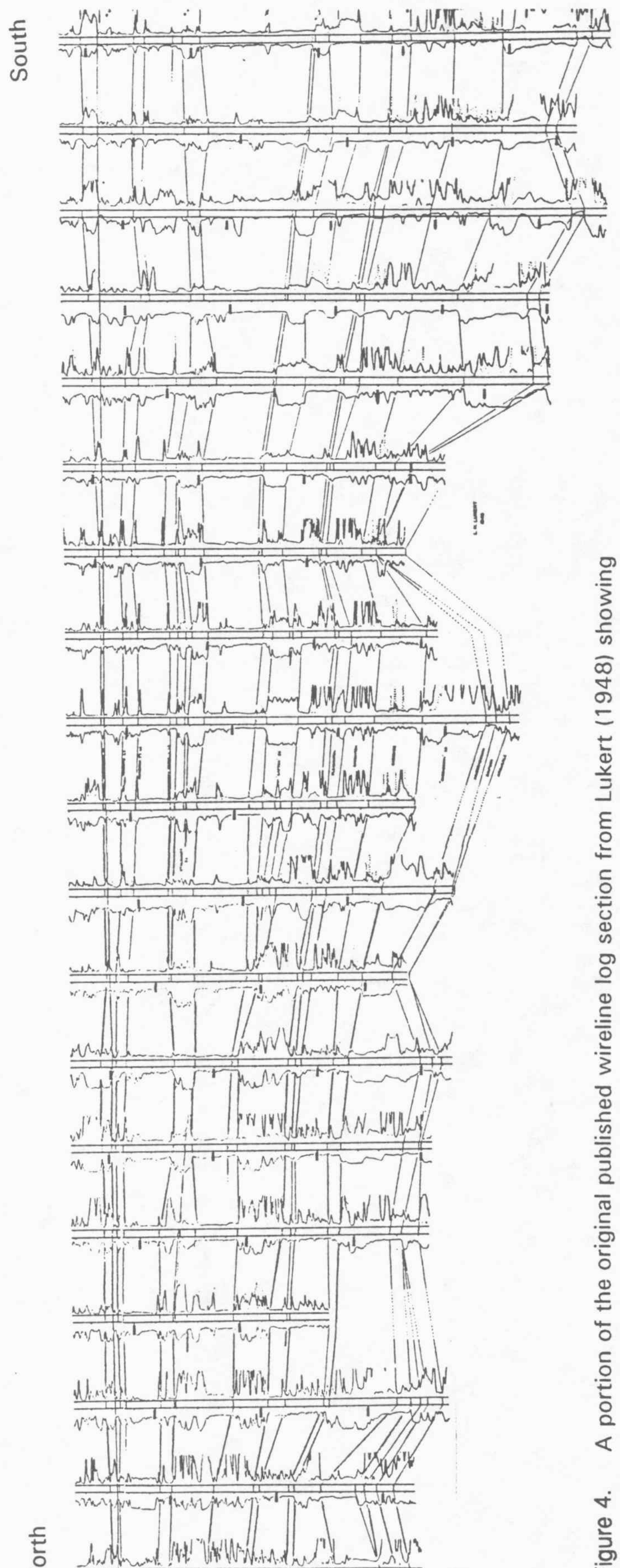


Figure 4. A portion of the original published wireline log section from Lukert (1948) showing framework correlations. Basic correlations have not changed, only more detail has been added, including identification of marine shale markers based on nearby gamma ray log control.

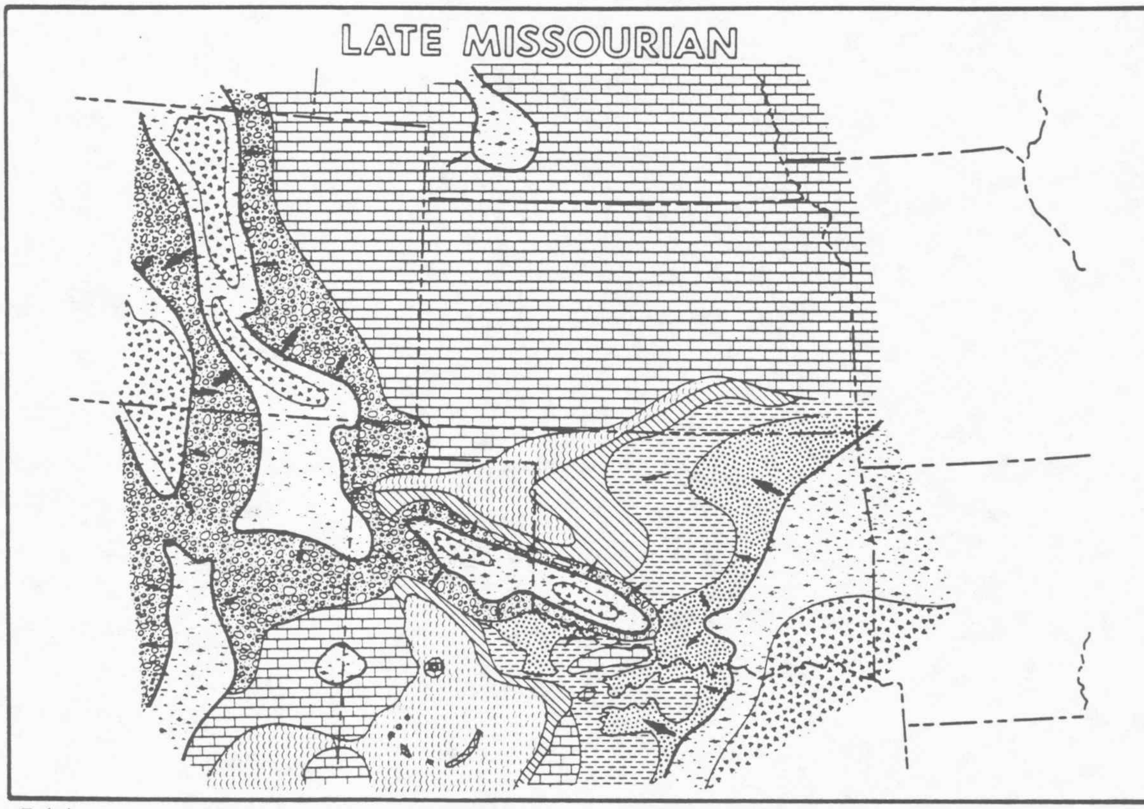


Figure 5 (a).-Generalized paleogeography and paleoenvironments of the late Missourian.

Figure 5 (b).-Generalized paleogeography and paleoenvironments of the early Virgilian.

1800 feet (600 meters) on the south. Both stratigraphic cross sections are hung (datumed) on the Virgilian Heebner Shale.

Major flooding surfaces and stratigraphic dislocations delimit stratigraphic bundles (long-term cycles) that each include from five to seven cyclothems. The flooding events resulted in drowning of the lower shelf and major readjustment of the facies patterns. In addition, progradation of superjacent cyclothems included within the long-term cycles along the shelf margin suggests a relative fall in sea level approximated by the relative sea-level chart included in Figure 3.

Major flooding events delimiting the long-term cycles are the heralded by the Excello Shale, Nuyaka Creek Shale, Muncie Creek Shale, and the Haskell Limestone (Figures 2 and 3). Each long-term cycle ranges from 300 ft (90 m) to in excess of 500 ft (150 m) thick. Each major flooding event results in initial landward (backstepping) shift of the carbonate shelf margin of up to 50 miles (80 km) suggesting relative sea-level rise. Following initial drowning, succeeding stratal geometries along the shelf margin indicate overall lateral, basinward accretion. The boundaries coincide closely with formal stratigraphic groups due to abrupt changes in stratigraphy lithofacies.

The cross sections show that significant landward (northward) backstepping (43 mi, 70+ km) of the carbonate shelf occurred at the Muncie Creek Shale horizon, the beginning of a long-term cycle (Lansing cycle) culminating in deposition of the Stranger Formation (Figure 3). The carbonate margin along the lower shelf retreated to central Kansas in the Sedgwick and Cherokee basins. This carbonate margin slowly accreated laterally southward during deposition of successive cyclothems. Depositional topography along this front is estimated to be on the order of 300 ft (100 m). According to wireline-log correlations, major siliciclastic infilling of the lower shelf did not occur until significant bypass of clastics occurred on the upper shelves. This siliciclastic progradation was probably facilitated by the relative sea level fall associated with the long-term cycle, possibly coupled with climate change to more wet conditions.

The front of the carbonate banks was believed to have received minor clastic influx while water exceeded photic depths eliminating significant carbonate production and resulted in considerable depositional topographic relief. Subsidence rates increased southward as they had throughout the Pennsylvanian including regions of sediment starvation further accentuating the relief along the carbonate shelf-to-basin transition (e.g., five cyclothems each approximately 300 ka duration, with subsidence of 0.035 m/ka = 52 meters of subsidence during the span of the long-term cycle). As longer-term sea level fell, more competent siliciclastic influx returned to the area and eventually filled in much of the space in front of the carbonate banks.

Regional studies indicate that siliciclastics from the Ouachita thrust belt episodically prograded into the area from the southeast (Wanless and Wright, 1978). However, significant siliciclastics were supplied from the north during accumulation of the Douglas Group at the close of the Lansing cycle. Recent studies by Archer et al. (in press) have described 140 ft deep by in excess of 15-mile-wide incised valleys that have been cut into pre-Haskell Limestone strata in the Douglas Group as deep as the Lansing Group in northeastern Kansas. These valleys run southward through eastern Kansas and exit across the shelf margin in southeastern Kansas (Winchell, 1957; Sanders, 1959). Sediment was apparently bypassed through the valley to reach a regional base level in southern Kansas on the lower shelf, beyond the shelf margin. This bypassed sediment is interpreted as shallow water deposits, consistent with the lowstand interpretation. The commonly coarsening-upward succession of the Stalnaker interval is furthermore consistent with a progressively lowering relative sea level. This pattern of inundation of the shelf, carbonate progradation, incised valley formation, and clastic influx is very similar to that observed in the proceeding long-term cycles (developed in the Marmaton and lower Kansas City groups) (Figure 3).

What was once a prominent shelf margin was nearly filled in by the time of Haskell Limestone deposition (Figure 3). The Heebner Shale, the datum of the cross section, is overlain by cyclothemic carbonates and siliciclastics representing shelf deposition in the region once part of the basin (northern reaches of the Arkoma basin). The interplay between subsidence and sea-level change is believed to have produced this changing shelf configuration.

Regional Mapping

Muncie Creek Shale to Heebner Shale.

A series of maps further illustrate some the regional changes in the paleogeology that occurred during the late Missourian and earliest Virgilian. The interval isopach from the Muncie Creek Shale to the top of Lansing (lower 2/3rd of the Lansing long-term cycle) indicates abrupt thickens of 50% immediately east of the inferred shelf in central Kansas in the Sedgwick and Cherokee basins (Figure 6). This reflects increased accommodation, probably associated with increased subsidence in the vicinity of the tectonically active Arkoma basin (a foreland basin). Little change in thickness occurred across this same area during the proceeding long-term cycle (Nuyaka Creek to Muncie Creek). Moreover, a linear hinge line of thickness change suggests sites of basement weakness. The southern margin of the Lansing Group carbonates abruptly terminate along a large carbonate bank system represented by an adjoining blanked (unmapped) area between Ranges 8 East and 15 West in southeastern mapped area. The shelf margin turns southwestward at an "elbow" in southern Sedgwick County (probably of structural origin). The position of the carbonate bank margin of the Lansing Group is thought to have resulted from previous backstepping and drowning of the underlying Marmaton carbonate shelf at the beginning of the long-term Lansing cycle.

A northeasterly trending lineament paralleling one side of the shelf margin (delimited on map in Figure 6) cuts across the Central Kansas uplift in central Kansas situated 50 miles (80 km) northwest of the linear front of the shelf margin, forming a distinctive rhombic block of thinning. The northern edge of this rhombic area of thinning corresponds to prominent northeast-trending faulting on the Central Kansas Uplift paralleling the Midcontinent Rift System.

In general, the Central Kansas uplift is delimited by a broad northwesterly-trending thinning of the Muncie Creek to Heebner Shale interval indicating that it was not subsiding as rapidly as the adjoining shelf area. Southwestern Kansas was a broad area of pronounced thickening with the thicker region opening toward the Anadarko basin. The blank area west of Range 19 West in southwestern Kansas is unmapped and does not represent a basinal area as did the blank area to the east (Range 10 East to 17 West).

Top Lansing to Heebner Shale and Haskell Limestone to Heebner Shale Isopachs

The interval isopachs from top of Lansing to Heebner (Figure 7) and Lansing to Haskell (Figure 8), Haskell to Heebner

(Figure 9) represent the upper portions of the long-term Lansing cycle. Further evolution of the shelf from the previous configuration in the Muncie Creek to Lansing interval is noted, a prominent northeast-trending flexural hinge bisecting the Central Kansas uplift along the faulted region paralleling the Midcontinent Rift System. The southerly positive rhombic area is no longer present, but the northern edge of the hinge corresponds with the northern edge of the earlier developed rhombic block. Farther north there is a very broad, attenuated region covers much of western Kansas where the Douglas Group is under 50 feet thick.

North of the hinge, the Douglas Group siliciclastics are very thin, but still include the carbonate units such as the Iatan and Haskell limestones. In addition, cores from this broad, thin region in northwest Kansas indicate that portions of the Douglas Group are red and oxidized. This evidence suggests less sediment accommodation space and more prolonged emergence of this region than areas east and south; either the area was structurally uplifted or sea level fell. Regional cross sections shown earlier indicate infilling of the lower shelf and basin by siliciclastics at this time suggesting a lower sea-level stand late in this longer-term cycle. The increased oxidation at the level of the Douglas also corresponds with relatively higher redox levels based on Th/U ratios from other shelf positions in Kansas for this interval (Watney et al., 1993), indicating more oxidizing conditions and thus suggesting greater emergence during the later portion of this long-term cycle at the close of the Missourian. Also valley incision supports lower sea level during this time period.

Lansing to Haskell Isopach

The Lansing to Heebner isopach is divided into two intervals: 1) the Lansing to Haskell isopach (Figure 8) and the 2) Haskell to Heebner isopach (Figure 9). The Lansing to Haskell isopach, although restricted to central Kansas, reveals that the lower half of the Lansing-Heebner interval was extremely thin (less than 30 ft [10 m] thick) and particularly uniform throughout the area of the Central Kansas Uplift extending to the northern edge of the northeast-trending Lansing Group bank margin (Figure 8). The northeastern edge of the thinning is linear, bounding a contrasting thickened area extending to the east (exceeding 200 ft thick in the depositional fairway east of the Nemaha Uplift). This linear edge parallels the eastern faulted margin of the Central Kansas Uplift. The overall attenuated nature of this interval suggests reduced accommodation and further supports lowstand conditions associated with the waning stage of the long-term Lansing cycle analogous to that observed on the cross sections.

Haskell Limestone to Heebner Shale

The isopach of the interval from Haskell to Heebner (Figure 9) accounts for all of the prominent hinge or ramp-like thickening observed on the Lansing-to-Heebner isopach (Figure 7). The downwarping of the shelf to form this hinge is restricted to this narrow time interval and coincides with the initiation of the next long-term cycle. Further increases in accommodation and return to marine carbonate deposition on the higher shelf did not occur until after Heebner Shale deposition, suggests that the transgression associated with this particular long-term cycle was transitional, extending from post

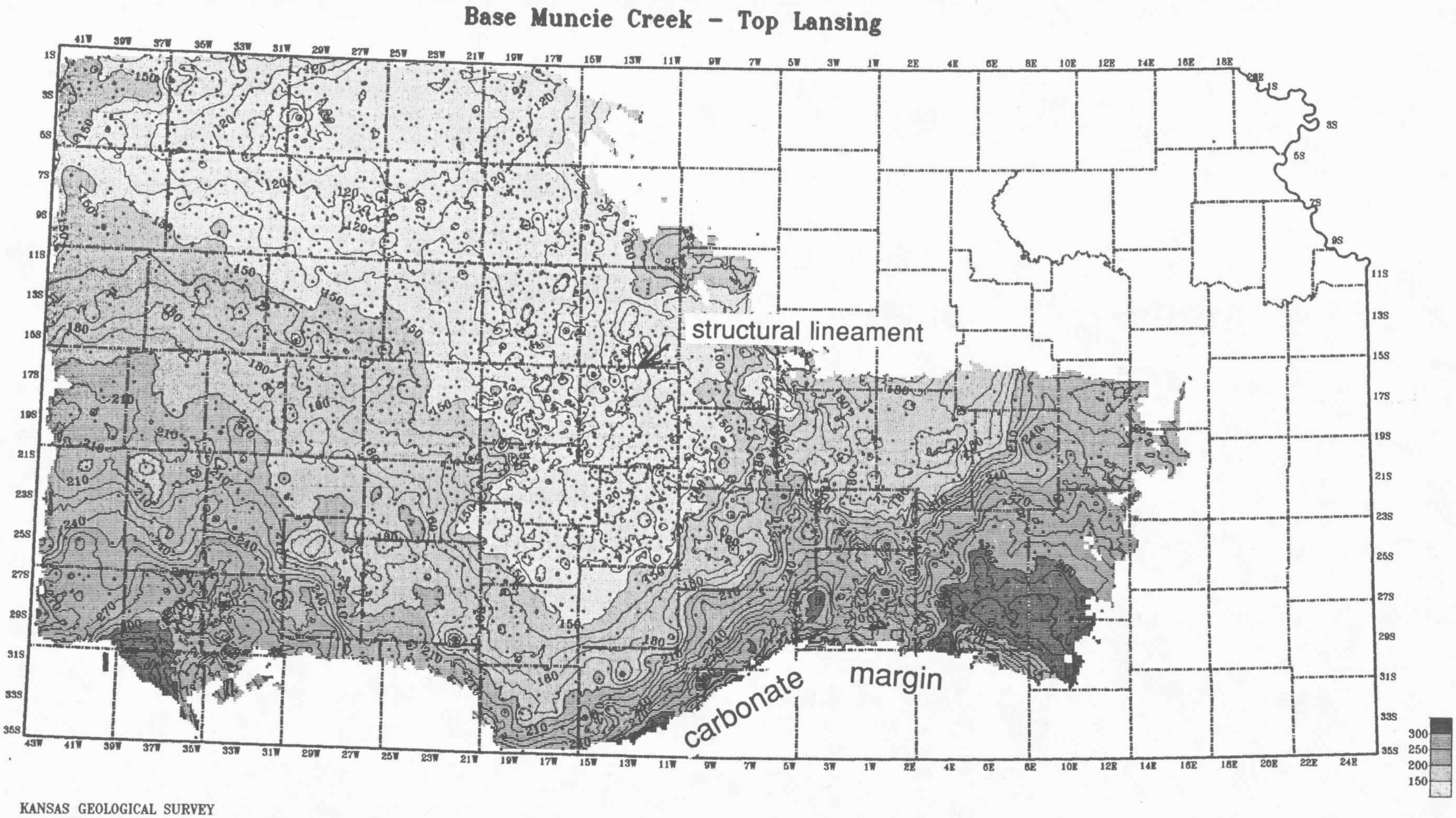


Figure 6. Isopach map, base of Muncie Creek Shale to Top of Lansing Group. Contour interval equals 10 feet.

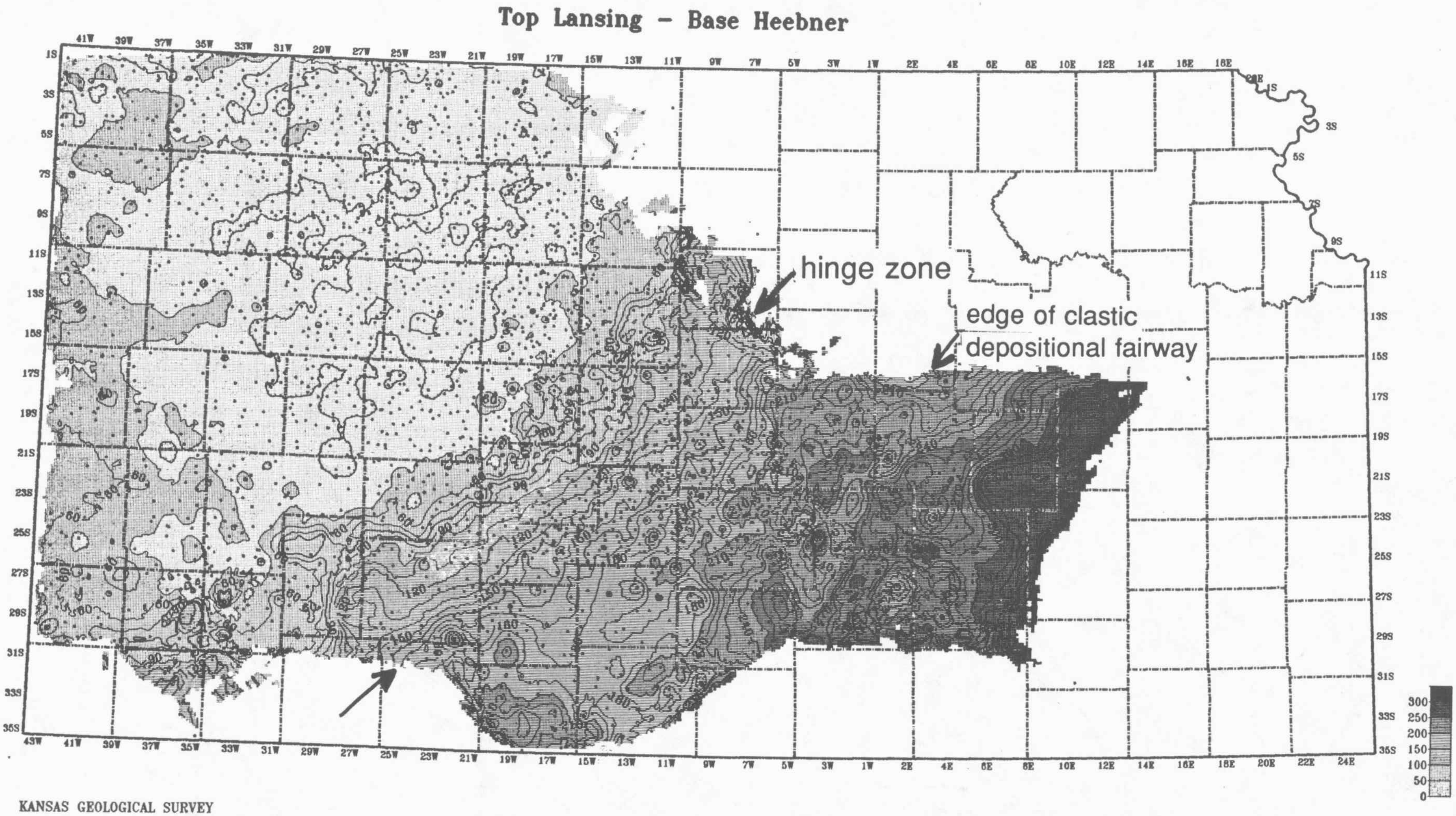
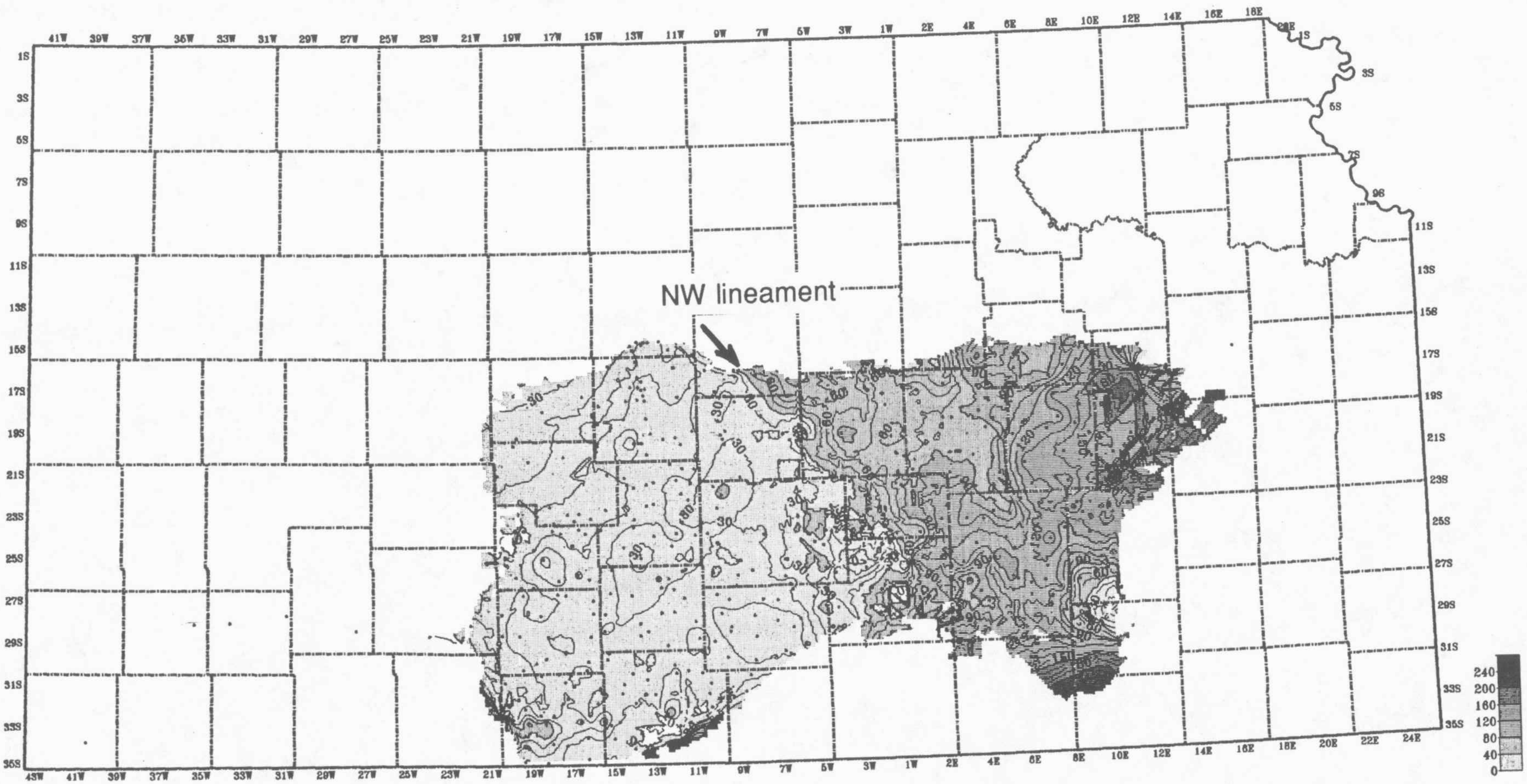
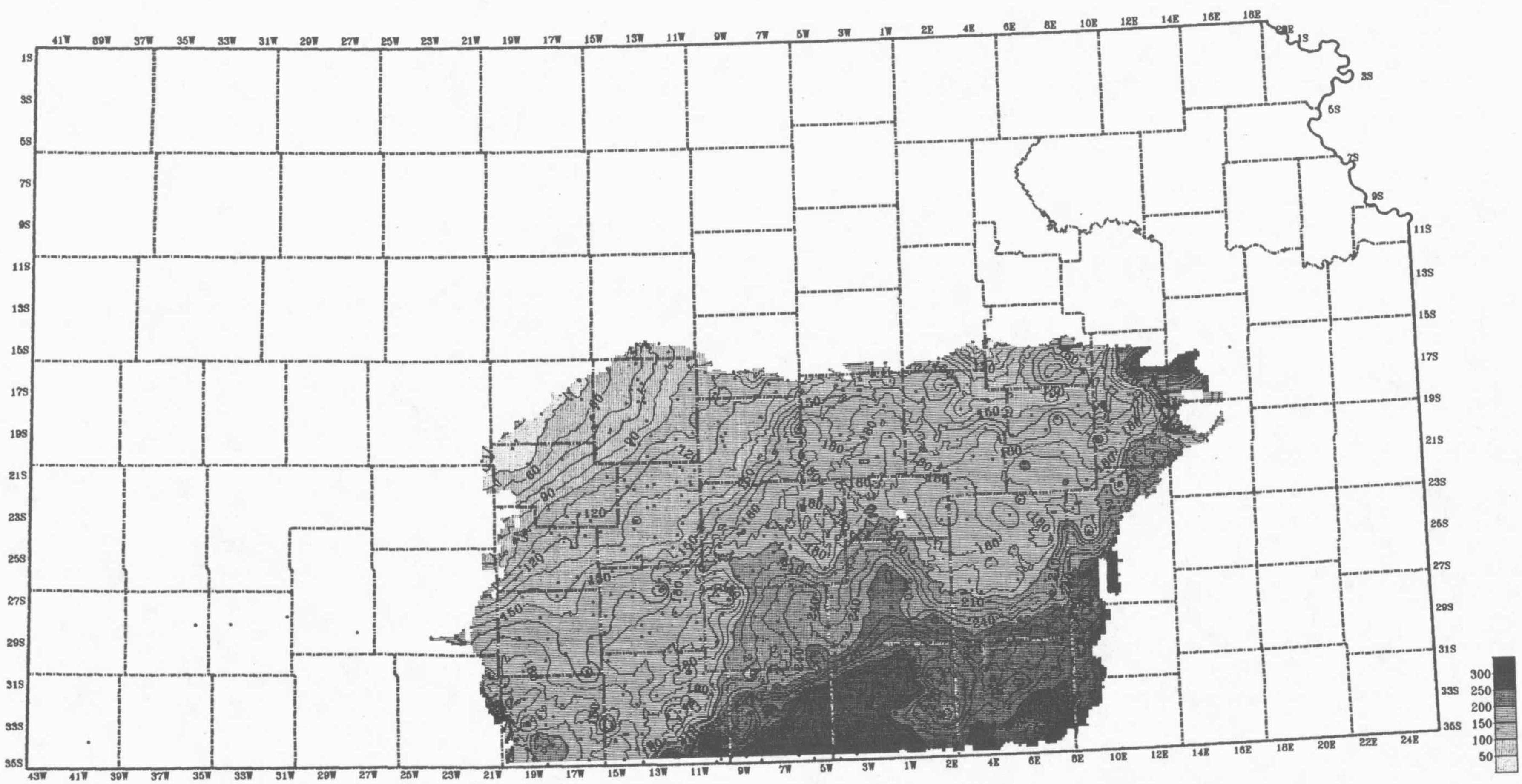


Figure 7. Isopach map, base of Top of Lansing Group to base of Heebner Shale. Contour interval equals 10 feet.



KANSAS GEOLOGICAL SURVEY

Figure 8. Isopach map, Top of Lansing Group to top of Haskell Limestone. Contour interval equals 10 feet.



KANSAS GEOLOGICAL SURVEY

Figure 9. Isopach map, Top of Haskell Limestone to base of Heebner Shale. Contour interval equals 10 feet.

Haskell to Heebner time. In fact, the lower shelf was again drowned beginning with the Heebner Shale deposition leading to renewed sediment starvation in southern Kansas and development of what is called the "double Heebner" (Heebner + Queen Hill shales adjacent to each other without intervening carbonate).

Winchell (1957) mapped the Tonganoxie ("Stalnaker") Sandstone in south-central Kansas in the interval below the Haskell Limestone (Figure 10). He identifies several narrow sinuous trends of sandstone on the carbonate shelf north of a large mass of sandstone to the south, basinward beyond the Lansing bank margin. The sinuous trends likely correspond to incised valleys. The sandstone was deposited during lowstand and rising sea level associated with the onset of the succeeding long-term cycle. Clastic deposition was focused in this region from both northerly (cratonic) and southerly sources (Ouachitas) during lowstand.

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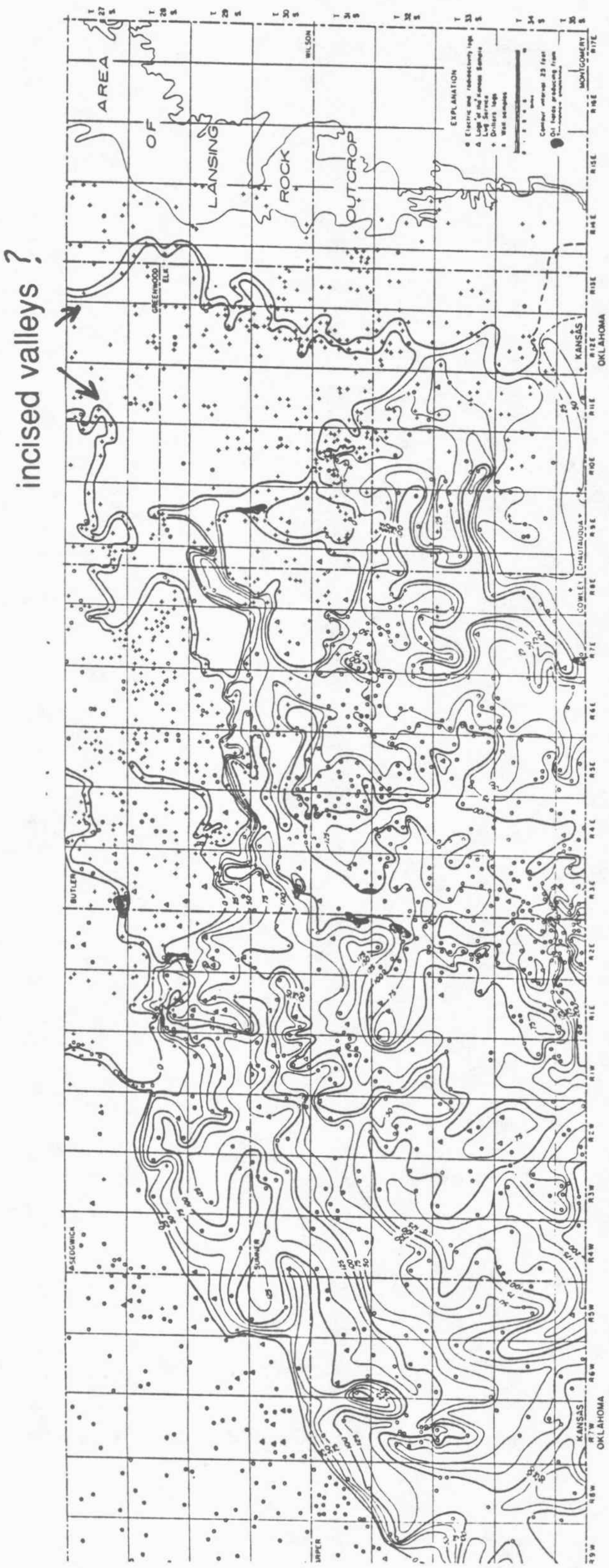

Figure 10. Isopach map of Tonganoxie ("Stalnaker") Sandstone in south-central Kansas from (Winchell, 1957).

Carbonate-clastic shelfedge changes in southern Kansas; lower Douglas Group, "Stalnaker" - (Tonganoxie or Tonkawa?) Sandstone

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Introduction

Many controversies have developed among Kansas geologists concerning southern Kansas Upper Pennsylvanian Virgilian-Missourian shelfedge changes from an open marine carbonate platform in the north to southern siliciclastic dominated environments. The Lansing Group carbonates and Tonganoxie-"Stalnaker"-Tonkawa clastic section, with numerous published studies in several local areas, is an excellent example of these conceptual differences. These studies offer many interpretations of depositional environments and sediment source area (northern-craton or southern-Ouachita mountains). The "Stalnaker" sandstone of south-central Kansas is herein proposed to be genetically related to the Tonkawa Sandstone of Oklahoma and is probably the fluvial-deltaic filling of a foreland basin. The direction and contribution of clastic sources is still debated. The relationship of the carbonate-clastic transition is also unresolved - erosional, facies change, or carbonate downlap with later clastic onlap? A regional synthesis and consensus, which must include the vast subsurface realm, has not yet been accomplished.

Review of Some Previous Studies

The eminent State geologist, R.C. Moore (1936, 1949) summarized data concerning the Pennsylvanian of Kansas, including the Tonganoxie Sandstone. Moore (1936, p.148) stated that the outcrop sandstones *in far southern Kansas* "...are continuous with certain persistent beds in Oklahoma, probably much of the sand was derived from the south." He later (1949, p.131) repeated his interpretation of a southern source for these sands in southern Kansas. The detailed study areas described below which soon followed Moore's overviews are outlined in Fig.1.

A petroleum geologist employed by The Texas Company presented (44 years ago!) the current author's thesis; that the "Stalnaker" should be genetically correlated to the Tonkawa Sandstone of Oklahoma, not the Tonganoxie of northeast Kansas. Lukert (1949) published an exceptional pioneering and very detailed subsurface (electric log) cross section including southern Kansas to northern Oklahoma shelfedge changes. He clearly understood the above thesis, plainly illustrating this relationship on his classic cross section, and used the term "Stalnaker-Tonkawa" (p.145). He correlated the Tonkawa Sandstone into its type area, the Tonkawa field of Noble and Kay Counties, Oklahoma, and to outcrop Bigheart Sandstone in Osage County, Oklahoma.

Unusual northeast Kansas outcrops attracted further study by Lins (1950, and references therein). He mapped a 14-20 mile wide paleovalley with 80-95 feet of erosion into underlying rocks, including the upper portion of the Lansing Group carbonates (Stanton Formation). This was definite evidence of post-Missourian sea level fall and resulting exposure and erosional episode.

He concluded that the sandstone within this large southwest trending Tonganoxie Valley was derived from the northeast and deposited in fluvial environments as channel or valley fill.

Winchell (1957) studied the south-central Kansas transition from Lansing Group carbonates to the southern "Stalnaker" sandstone section and contributed 13 insightful conclusions; including correlations from surface to subsurface of the Haskell limestone ("brown lime"), showing that the "Stalnaker" and outcrop belt Tonganoxie were both directly below this marker horizon. He concluded that the southward transition from Lansing Group carbonates to the "Stalnaker" did not represent a facies change. Winchell stated that the Lansing Group carbonates once extended farther southward (a layer-cake model) and using Lins' northeastern outcrop model of post-Missourian erosion, reasoned (*incorrectly*) that the entire Lansing Group was regionally "truncated by erosion" during post-Missourian exposure and the "Stalnaker" deposited in this eroded area.

A later study (Sanders, 1959) of the Tonganoxie extended Lins' work into the subsurface to the southwest, but did not "tie" into Winchell's study area; thus eliminating any problems which would have resulted. Sanders concluded that the sand trends of his study area were extensions of the north-easterly sourced channel - valley fill system described at the outcrop by Lins.

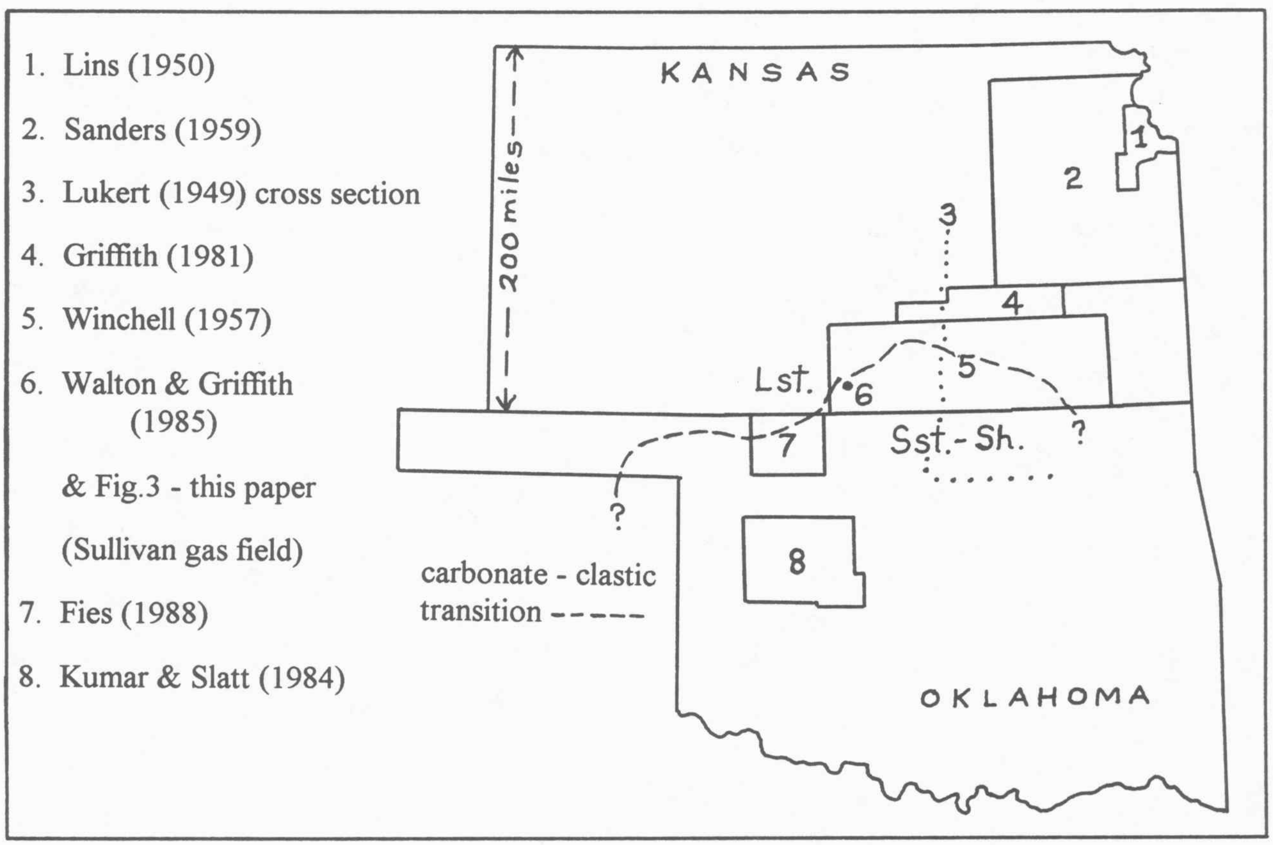

Figure 1. Index map, including referenced previous studies of the Tonganoxie-"Stalnaker"-Tonkawa interval.

In his excellent summary of Kansas geology, Merriam (1963) includes a north-south cross section (his Fig.61, p.124) showing the Lansing Group to "Stalnaker" changes. He references Winchell's conclusions of an eroded Lansing and later deposition of the "Stalnaker" in the eroded basin. A footnote (p.125) states that there is a controversy about these changes and that other data suggest "the 'Stalnaker' and Tonganoxie are not equivalent, but the 'Stalnaker' is a southern facies of Lansing beds farther north. The relationships are still open to interpretation and further work needs to be done on the problem." *Today, 30 years later, this last statement remains true.*

The best regional study of the Douglas Group is the dissertation completed by Ball (1964). His conclusions differed from Lins, Sanders, and Winchell, because he documented southern thickening and coarsening of Douglas Group clastics and correctly noted the importance of southern source areas in an overview Midcontinent context. Unlike Winchell, he believed Lansing Group limestones had not been eroded, but underwent a southward facies change to sand-shale.

Griffith (1982) provided long missing continuity between Lins and Sanders' study areas in northeast Kansas with Winchell's southern Kansas study. Griffith concluded (like Lins and Sanders) that in his thesis area, sediment source was to the northeast. He confirmed Winchell's correlation; stating that the "Stalnaker" correlates with the Tonganoxie as "a continuous unit from northeast to south-central Kansas." He had earlier noted a key problem with this statement by describing a Lansing Group "band of marine [carbonate] banks" immediately south of his study area (in Winchel's northern map area, centered on T.27-28S). He illustrates this bank (his Fig.8, p.26) overlain by a regionally thin Haskell to Lansing interval, separating his and Sanders' Tonganoxie from the "Stalnaker" of Winchell.

Walton and Griffith (1985) presented detailed description of a "Stalnaker" sandstone subsurface core (from Harper County, Kansas - in Winchell's study area) and determined the sand was deposited by a prograding delta. Previous reports were briefly reviewed, but no additional data or interpretations were offered concerning direction of progradation or sediment source areas.

In Oklahoma, two recent studies have been published concerning the equivalent rock unit in that state; the Tonkawa Sandstone. Fies (1988) studied the subsurface Tonkawa "format" along the north border of Oklahoma on the Anadarko basin's northern flank (adjoining Winchell's study on the south). He believed the sand-shale section was deposited in a "high-constructive lobate delta environment" with implied sediment input from the northeast. Like Merriam, He acknowledged longstanding controversies, stating that "the relationship...*to the adjacent limestones on the shelf...is not understood at this time.* Extensive studies are needed to completely resolve the question of age and stratigraphic relations to these units." Fig.3 is a local cross section in southern Kansas which partly illustrates this complex shelfedge carbonate-to-clastic change.

Kumar and Slatt (1984) studed a local area farther southwest, in west-central Oklahoma in the deeper portion of the Anadarko basin. They described three sandstone units below the Haskell Limestone, within a clastic section 1,000 feet thick, at depths of 6,300-10,000 feet. They interpreted the lowest sand bodies as basinal submarine-fans (up to 500 feet thick) deposited in water depths of 400-1,500 feet. The overall section exhibits shallowing upward (regressive) conditions, with the upper sandstone (up to 350 feet thick, directly below the Haskell) interpreted to be prograding, shallow water, deltaic (distributary or barrier island) deposits. Petrographic and paleogeographic data suggested eastern sediment sources in the Ouachita mountains. The author's attempt to illustrate the above studies and his own subsurface interpretations is shown as Fig.2.

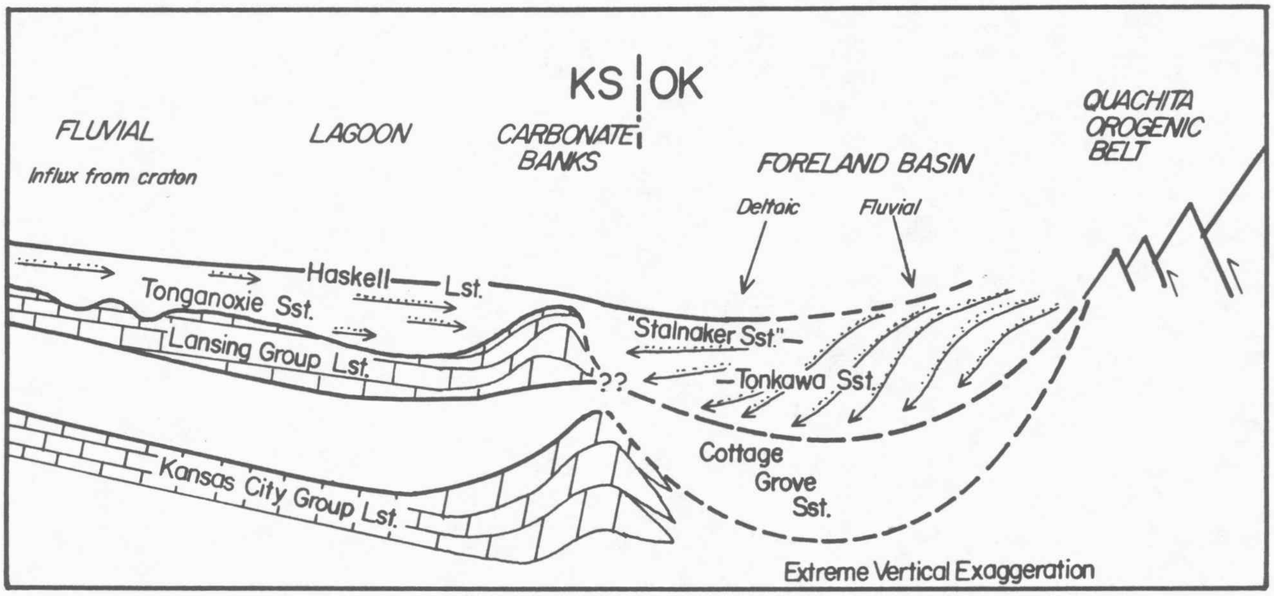

Figure 2. Preliminary stratigraphic cross section "cartoon" of lower Douglas Group from northeast to south-central Kansas, then to Ouachita mountains (southeast Oklahoma).

An interesting historical note to (new?) sequence stratigraphy interpretations of Kansas geology concerns an early-day petroleum geologist who began studying the subsurface of Kansas, including the "Stalnaker" (Rich, 1931). This brilliant and controversial geologist, John L. Rich (1951), published his insightful overview of depositional topography, introducing his terms unda-, clino-, and fondo-form for shelf, slope, and basin. He used these new terms for application to basins - bodies of water - of any size or depth, including epeiric seaways, because the familiar shelf-slope-basin connoted continental edge environments to most geologists. His paper is one, of probably two main articles, that have provided underpinnings for a revival of sequence concepts. Rich's unda-, clino-, and fondo- prefixes and diagrams can easily be interchanged with modern sequence terminology of highstand, lowstand or shelf-margin wedge, and lowstand systems tracts. These concepts were later applied in a landmark study by Van Siclen (1958) for Permo-Penn. carbonate-to-clastic shelfedge changes in rocks of north Texas. Rascoe (1978) applied these same concepts to interpret Virgilian shelfedges in the Anadarko basin.

The Arkoma-Anadarko Foreland Basin

The author believes the thin Haskell to Lansing Group interval near T.27-28S. (see Fig. 2 and Winchell, 1957) is evidence of physical division between two separate prograding fluvial-deltaic systems, one sourced from the northeast (cratonward) and one from the southeast (Ouachita mountains). As the title of this paper implies, the "Stalnaker" clastic section may be more closely genetically linked to Oklahoma equivalent Tonkawa, than to northeastern Kansas Tonganoxie (as also shown in paleogeographic maps referenced below). Winchell's study was a classic example of "stateline" limitations to regional understanding. The extreme southern Kansas transition from Lansing Group limestone to clastics of the "Stalnaker" section is a very small portion of an extensive foreland basin shelfedge system.

An important consideration in studying this limestones to sand-shale change is the realization that the Pennsylvanian age "basin" to the south of Kansas was a *foreland* basin, *often rapidly filled above base-level* by siliciclastic influx from rising Ouachita orogenic highlands along the south edge of the basin. These clastics were swept northwestward by fluvial-deltiac systems, resulting in a northwestward progression of carbonate-clastic transitions, through Desmoinesian, Missourian, and Virgilian time. The mud and sand spread northward to extinquish the carbonate factory that was building southward prograding shelfedges. As the cross section (Fig. 2) illustrates, the northward portion of these clastic wedges were primarily filling in accommodation space; not scouring into underlying cyclothems like northeast environments described by Lins. To understand these stratigraphic changes, they must be placed in the plate tectonics framework of a cratonward side of a foreland basin, with subsidence (accommodation space) and shelfedge position probably being affected by tectonic forces; including episodic uplift-thrusting of source areas, a widening basin, and a migrating fore-bulge (Beaumont, 1981). Excellent Missourian-Virgilian paleogeographic maps, including tectonic elements of the Midcontinent, may be found in Moore (1979) or Rascoe and Adler (1983).

Unsolved (Subsurface) Mysteries

To date, only local studies have been published concerning the entire Midcontinent three-dimensional stratigraphic framework of Tonganoxie and "Stalnaker"-Tonkawa clastic wedges. Perhaps Midcontinent-Anadarko basin subsurface stratigraphers may reach the understanding of Bennison's (1984, 1985, 1989, and at field conferences) cross sections representing carbonate-to-clastic transition for the Arkoma basin. His schematic north-south transect across the Arkoma trough for one complete cyclothem (Bennison, 1985, his Figure 4, p.224) is an excellent example illustrating clastic wedges sourced from different sides of the basin. The typical "overview" cross section often presented in many Anadarko-Arkoma basin publications is usually a simple cartoon (see Kumar and Slatt, 1984, their Figure 2) which inspires little insight into complex stratigraphic mysteries. The author has found Bennison's cross sections a very elucidating conceptual model for south-central Kansas Virgilian-Missourian rock changes.

In the science of stratigraphy, three-dimensional rock data presented as descriptive studies should precede interpretations. The previous studies of local subsurface areas or simple two-dimensional slices of eastern outcrops of time equivalent units, have already offered many regional interpretations. This has preceded any regional descriptions of the morphology (shape in *both* cross section and map view) of carbonate-clastic interfaces. What are the stratigraphic relationships of the many lower Virgilian-Missourian-Desmoinesian shelfedge changes - facies changes or carbonate downlap with later clastic onlap? Rascoe (1978) has admirably presented an example study for middle-upper Virgilian age rocks above the Heebner Shale. Descriptive studies of these carbonate-to-clastic tracts completed at three-dimensional, Midcontinent-Anadarko basin scale (*which must include the subsurface realm*) are lacking. They would aid a synthesis of Midcontinent Pennsylvanian stratigraphy - the rock record faithfully recording earth history with the interaction of: tectonics; basin subsidence; shelfedge position; eustacy - fluctuations, stillstands, and ancient shorelines; clastic influxes from different directions; carbonate factory vitality, and climate. Discovery of future oil and gas reserves would also be aided, a fair return for the petroleum exploration industry which has provided the subsurface data necessary for this type of study.

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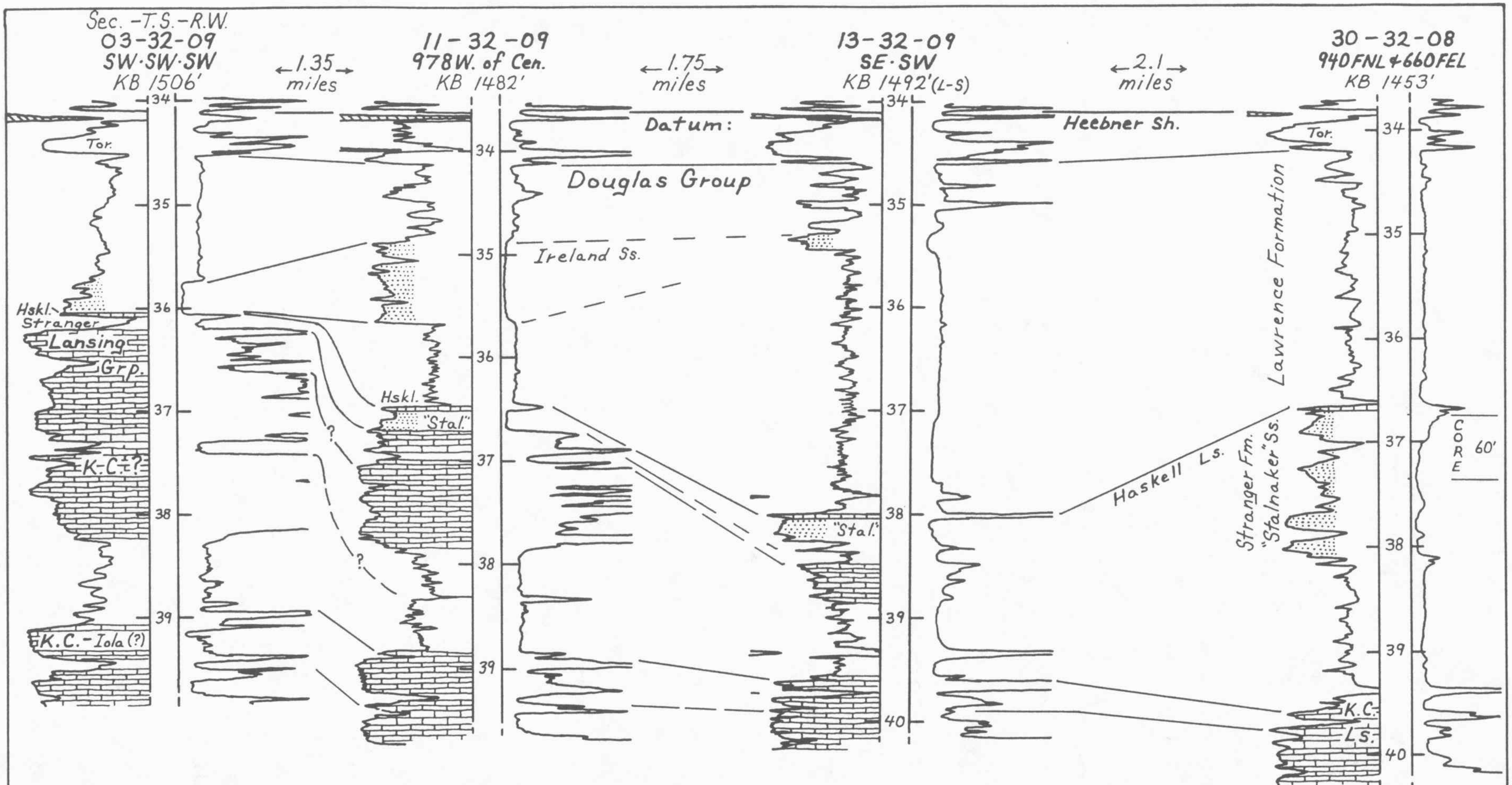

Preliminary - comments welcome !
Vertical exaggeration: 23 X
Vertical scale: 1 inch = 100 feet
Horizontal scale: 1 inch = 2300 feet
(total distance: 5.2 miles)
Depths: X 100
All logs are gamma ray - resistivity

Figure 3. NW-SE trending stratigraphic cross section illustrating Lansing Group carbonates to "Stalnaker"-Tonkawa siliciclastics in Harper County, KS (see Fig.1 for location). The shelfedge slope is very gentle (true scale), usually less than one degree. The "downlap?" between the wells on the left is "oversteepened" by vertical exaggeration of 23X. This is the Sullivan gas field area (primarily "Stalnaker" sand pay) in T. 32 S. R. 8-9 W., centered on US highway 160 at Attica, KS. Walton and Griffith (1985) described the core from the well on the right. The "Stalnaker" pay was discovered in 1961, but not developed until successful extensions were drilled beginning in 1977. Almost reminiscent of early wild days of unregulated close well spacing, the field was "overdrilled". This is the largest *gas* accumulation in the "Stalnaker" sandstone of KS. Churchill and Oxford fields along the Nemaha uplift in east-central Sumner County, KS, are by far the largest two *oil* fields.

Seasonal Thermal Energy Storage and Retrieval in the Tonganoxie Aquifer Beneath the University of Kansas Campus

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INTRODUCTION

The cost of cooling and heating public buildings has put stress on the budgetary capabilities of public institutions such as the University of Kansas. The energy costs for cooling and heating the buildings of the University of Kansas are listed in table 1. This cost is expected to increase in coming years because the demand for energy is likely to increase while the supply decreases.

The use of seasonal thermal energy storage (STES) of heated and chilled water in the Tonganoxie aquifer that is directly below the University of Kansas campus has the potential to reduce these cooling and heating costs by about $1,000,000 annually, according to preliminary studies executed by a senior mechanical engineering design class at the University of Kansas (L. Burmeister, personal communication, 1991).

The unusual location of the University of Kansas atop a suitable aquifer for STES and the availability of hydrogeologic scientists and engineers interested in evaluating the potential of the Tonganoxie aquifer for seasonal thermal energy storage and retrieval should justify university and state support for this project. A site in West Campus was selected for a proposed STES demonstration project.

SEASONAL THERMAL ENERGY STORAGE

The methodology of aquifer energy storage and retrieval consists of injecting either heated or chilled water into an aquifer during one season and retrieving this water during another season. An approximate representation of the lithology beneath the University of Kansas campus is shown in fig. 1. A process of injection and retrieval of water from the Tonganoxie aquifer for the purpose of assisting in meeting the cooling and heating needs of a surface application is also illustrated. The native water has a constant temperature of about 60° F. This temperature can be altered by adding or withdrawing heat. In a dual purpose approach, the system can be used for both cooling and heating purposes. This approach, generally known as the doublet configuration, is represented in more detail in Fig. 2. During the summer season, water chilled during the winter season is pumped out of the first well and delivered to a building on the surface. There the water is warmed by heat removed from the building by a heat pump and possibly by heat from the environment and by waste heat from power plants and processes. Finally, the heated water is injected into the second well. During the winter season, heated water from the second well is pumped out to provide heat to the building on the surface through the agency of the heat pump. After it is cooled by that process, with further cooling possibly provided by giving heat to the environment, the water is injected into the first well from which chilled water was withdrawn during the summer season. The use of a heat pump enables heat transfer to be effected without requiring heat source temperatures to exceed heat sink temperatures, a major design convenience.

GEOLOGIC SETTING OF TONGANOXIE SANDSTONE AQUIFER

The Tonganoxie Sandstone occurs in definite channel-like form, which is interpreted as an ancient alluvium-filled river valley that in places is more than 140 ft deep. The Tonganoxie Sandstone was deposited during the Pennsylvanian in a southwest-trending alluvial valley that was cut into the Weston Shale Member and Stanton Limestone and is 10–12 mi wide in the Lawrence area (O'Connor, 1960) (fig. 4). The plant remains that are found in outcrops and the shape of the sand bodies in long, branching, and relatively narrow trends, the crossbedding, and the disconformable relation to older strata seen in surface exposures all indicate a paleovalley-fill origin (see Sections 3 and 8, this volume). Four samples collected from Douglas and Leavenworth counties (Sanders, 1959) were all predominantly well-sorted fine sand (1/4–1/8 mm) with about 9% silt and clay. The hydraulic conductivities of these samples, as determined in the laboratory using the air permeability and variable head water permeameter methods, are listed in table 2. As expected, cores cut parallel to the bedding are more permeable than those cut perpendicular to the bedding. The hydraulic conductivity and the predominant size grade seem to depend where samples were obtained with respect to main channel deposition. The hydraulic conductivity of a part of the Tonganoxie Sandstone core from a depth of 201.5–210.5 ft collected from a West Campus test hole (next to Foley Hall) was found to be 1.5 ft/day. The values given in table 2 are the same order of magnitude as hydraulic conductivities obtained by means of pumping tests of wells that get water from the Tonganoxie Sandstone in northeastern Kansas. Such tests have given results for hydraulic conductivity ranging from

6.7–40.2 ft/day (O'Connor, personal communication, 1980).

The Tonganoxie Sandstone aquifer is bounded above by the Vinland Shale Member and below by the Stanton Limestone and other stratigraphic units. The Vinland Shale Member contains variable thicknesses of clayey to sandy shale and sandstone. Except locally, the Vinland deposits are entirely marine. The thickness of the Vinland Member in northeast Kansas ranges form 7 ft to 25 ft. The Stanton Limestone, which directly underlies the Stranger Formation in the area of West Campus, contains three limestone and two shale members. The upper member, the South Bend Limestone Member, is easily distinguishable on electric well logs and serves as a good subsurface marker bed. It is about 50 ft thick.

Groundwater movement in the aquifer system, which may include sandstones in the Vinland Shale Member, is toward the Wakarusa and Kansas River valleys in the Lawrence area. A composite potentiometric-surface map of the Douglas Group sandstone from unpublished KGS 1980–82 measurements is shown in fig. 5. In the Lawrence area composite head data from sandstones in the Vinland Shale and Tonganoxie Sandstone Members were used to make this map. It is inferred from this map and from what is known about hydraulic conductivities and water quality in the Tonganoxie Sandstone Member in the Lawrence area that the rate of movement of water through this part of the system is slow to stagnant.

LOCATION AND HYDROGEOLOGIC DESCRIPTION OF THE PROPOSED STUDY SITE

The location of the proposed study site is shown in fig. 4. It is situated in sec. 2, T. 13 S., R. 19 E., in West Campus of the University of Kansas, near the center of the southwest-trending erosional paleovalley in which the Tonganoxie Sandstone Member was deposited.

The proposed storage aquifer is a part of the Tonganoxie Sandstone Member of the Stranger Formation (figs. 3 and 6). This aquifer is a confined system bounded above by the Vinland Shale Member of the Stranger Formation and below by the Stanton Limestone (fig. 3), as mentioned previously. Depth of wells at the proposed site would range from about 200 ft to 300 ft. Thickness of the Tonganoxie Sandstone Member in the vicinity of the proposed site ranges from 100 ft to 130 ft (figs. 3 and 6). The permeable sandstone beds that compose the Tonganoxie aquifer are about 80 ft thick.

Limited information is available concerning the hydrogeology of the Tonganoxie Sandstone in West Campus. Two test holes have been drilled by the Kansas Geological Survey in 1950 and 1964, respectively, and the logs of these holes are shown in fig. 6. The lithologic log of another test hole drilled by the KGS in 1985 next to Foley Hall in West Campus is shown in Appendix A. One pump test was also conducted on the test hole in SWNESE sec. 2, T. 13 S. R. 19 E., located near the southern end of West Campus. The initial static water level was 84 ft below land surface (February 1964), and after 3 hr of pumping at 15 gpm, the water level in the pumped well had declined 21.5 ft. From this one test the initial estimate of hydraulic conductivity is calculated to be approximately 1 ft/day. The low hydraulic conductivity of the aquifer may be improved in the vicinity of the well field by hydrofracturing or other well stimulation techniques. Assuming a porosity of 20%, a hydraulic gradient of 7 ft/mi (O'Connor, 1960), and the calculated hydraulic conductivity, the calculated horizontal regional fluid velocity in the Tonganoxie aquifer in this area is a little less than 2.5 ft/yr. No information is available on the storativity of this aquifer.

Groundwater quality in the Tonganoxie Sandstone Member is highly variable. In 1950 a water sample from a well drawing water from the Tonganoxie Sandstone Member in northeast Lawrence (NWNE sec. 26, T. 12 S., R. 19 E.,) was reported to contain 12,800 mg/*l* chloride and 21,400 mg/*l* total dissolved solids. The results of chemical analyses on water samples taken from test wells in West Campus are presented in table 3. Clearly, the samples represent low-quality waters not suitable for domestic purposes. Problems related to scaling and corrosion could occur because of the presence of iron, the high concentrations of sodium and chloride, and the high hardness on the native water. Further study of these phenomena will be important in determining project feasibility.

REQUIREMENTS FOR AQUIFER ENERGY STORAGE AND RETRIEVAL

The successful process of energy storage and retrieval in a aquifer is subject to several factors. Among these are the gradient of the potentiometric surface, the hydraulic and thermal conductivities of the porous medium, the extent and thickness of a confined aquifer and its confining layer, and the sustainable pumping rate. The storage and retrieval of any liquid in a porous medium requires relatively high porosity and low groundwater flow velocity. A high porosity provides storage space, and a low groundwater flow velocity in the areas away from the storage site slows down the rate of convection and dispersion. A relative flat potential surface in the aquifer creates a low ambient velocity, which results in higher efficiency of the retrieval of the stored energy. The existence of confining layers with low thermal conductivity can reduce the rate of heat loss to adjacent layers, whereas a high heat capacity and reasonably high thermal conductivity of the aquifer will maximize storage and retrieval of energy.

Other factors also play important roles in the overall evaluation of a site. Some of these factors, such as the depth to the aquifer and willingness of the site owners to participate financially or otherwise in the project, are of economic nature, and others, such as the quality of the native waters and source of energy, are of a technical nature.

Based on a careful analysis of these factors, the Tonganoxie Sandstone aquifer, which underlies the land surface of West Campus of the University of Kansas, Lawrence, at a depth of about 130–225 ft, is proposed for consideration for aquifer thermal energy storage. For the Tonganoxie Sandstone aquifer it seems that locally there is a reservoir of about 90 ft of sandstone of low hydraulic conductivity with a confining layer of about 10 ft thickness. Furthermore, the temperature of native water is about 60°F from the data collected by the KGS from the experimental well near Foley Hall.

PROPOSED WORK PLAN FOR STES IN WEST CAMPUS

It is proposed that the work plan for this project be carried out in two phases. The second phase will be undertaken if the results of the first phase are promising.

In Phase 1, a geohydrologic investigation needs to be carried out to characterize the Tonganoxie aquifer in the vicinity of Foley Hall on West Campus, University of Kansas. This site is proposed because there already is a well about 50 ft from Foley Hall drilled into the Tonganoxie aquifer (see the lithologic units of this well in Appendix A), data on water level and quality in this well have been collected by the KGS, and the 5,000-ft^2 Foley Hall can be cooled and heated by one auxiliary heat pump with a capacity of about 120,000 Btu/hr from about 30 gpm of water from the Tonganoxie aquifer. Foley Hall has simple plumbing and HVAC systems so that the modifications needed for incorporation of an auxiliary heat pump would involve low cost. Furthermore, the proximity of Foley Hall to the existing well eases monitoring of the system. Observation of possible fouling of heat exchange surfaces exposed to the aquifer water and of the operation of water treatment equipment for prevention of such fouling would be readily observed.

In Phase 2, there will be two major elements. First, a geohydrologic and geochemical investigation of the Tonganoxie aquifer around the entire campus of the University of Kansas needs to be conducted to firmly establish the ability of the Tonganoxie aquifer to support an STES project for the entire campus. A campus-wide assessment of the cooling and heating needs of the campus and an environmental impact study of such a system need to be made. Second, a prototype of a feasible heat pump–aquifer system for meeting the needs of the entire University of Kansas campus needs to be constructed.

The feasible system design and installation plan devised in Phase 2 should be used in a follow-on implementation phase. In this follow-on phase, professional contractors would develop a final design for implementing the STES system based on the work accomplished in Phases 1 and 2.

CONCLUDING STATEMENT

A scheme is proposed for helping to meet the heating and cooling needs of Kansas communities and institutions, especially the University of Kansas, whose budgetary capabilities have been stressed by the costs of meeting those needs. Inasmuch as these costs will only increase in coming years in response to increasing demand on a decreasing supply of fossil fuels, the economy of the state of Kansas would be benefitted by such a scheme if the feasibility of such a scheme can be demonstrated now.

ACKNOWLEDGMENTS

Several individuals contributed time and effort on this proposed project. In particular I would like to acknowledge Manouch Heidari, former KGS Geohydrology section chief, Thomas McClain, KGS Technical Information Services section chief, and Howard O'Connor, retired KGS senior scientist, among others at KGS, and Louis Burmeister, Mechanical Engineering Professor at KU.

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Table 1. Energy Costs of Lawrence KU Campus excluding Jayhawker Towers and Daisy Hill residence halls.

Year	Total cost
FY1993	$5,173,116
FY1992	4,987,335
FY1991	5,102,367

Source: KU Facilities and Operations

Table 2. Hydraulic Conductivity of Samples of Tonganoxie Sandstone

Sample Location	Sample No.	Air Permeameter: Parallel to Bedding	Air Permeameter: Perpendicular to Bedding	Water Permeameter (disaggregated sand samples)
		ft/day (meinzer units)		ft/day (meinzer units)
Leavenworth Co.	2A	13.8 (103)	7.1 (53)	20.0 (149)
	2B	7.2 (54)	3.9 (29)	7.6 (57)
Douglas Co.	3	19.7 (147)	7.8 (58)	6.3 (47)
	4	–	–	4.1 (31)

Table 3. Chemical Analysis of Water Samples Collected From the Tonganoxie Sandstone Member

Constituent	NWNE sec. 26 T. 12 S., R. 19 E. 1950 (mg/*l*)	SWNESE sec. 2, T. 13 S., R. 19 E. 1964 (mg/*l*)	Well NE of Foley 1989 (mg/*l*)
Ca	615	606	52
Mg	257	222	21
Na + K	7,340	4,291	1,600
HCO_3	237	310	565
SO_4	279	122	303
C*l*	12,000	8,150	2,158
F	0.9	0.4	3.4
NO_3	8.8	1.1	1.9
Total Hardness as $CaCO_3$	2,590	2,424	216.3
Carbonate Hardness as $CaCO_3$	194		222
Non-carbonate Hardness as $CaCO_3$	2,400		0
SiO_2	15	9.5	9.0
Fe	20	2.4	26
Total dissolved solids	21,400	13,600	4,431
Specific conductance (µS/cm)		23,200	7,380

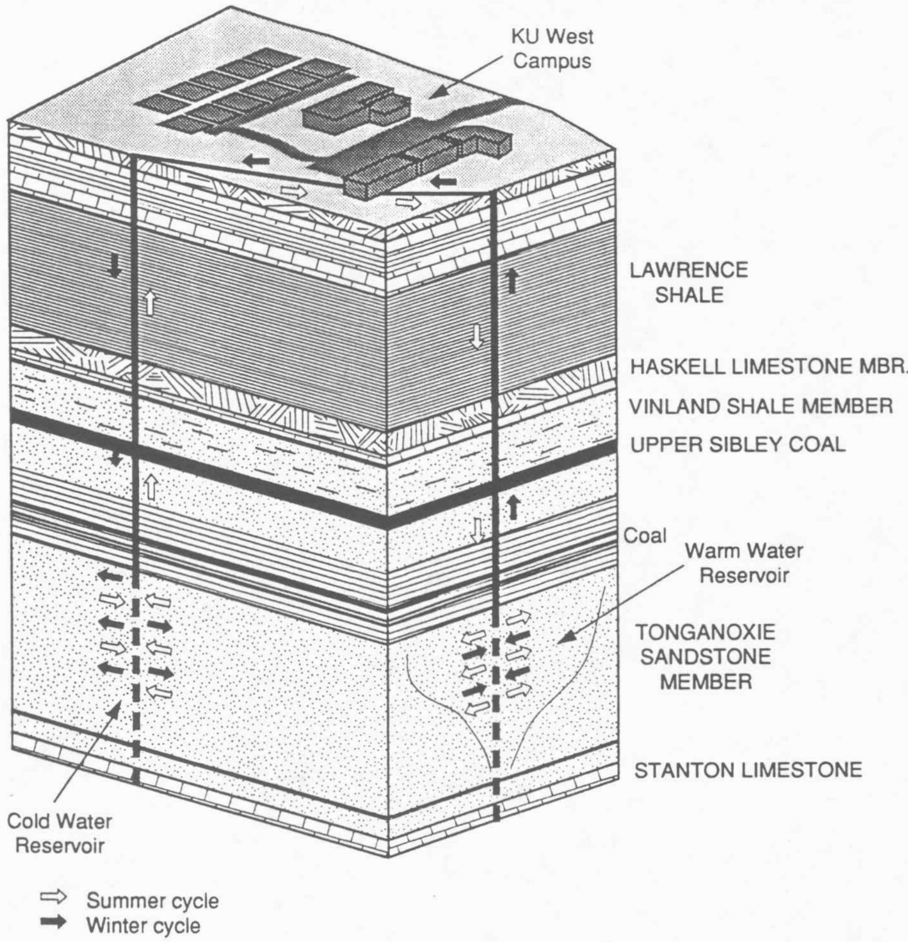

Figure 1. Representation of the Tonganoxie aquifer underneath the KU campus and summer and winter cycles of energy storage and retrieval.

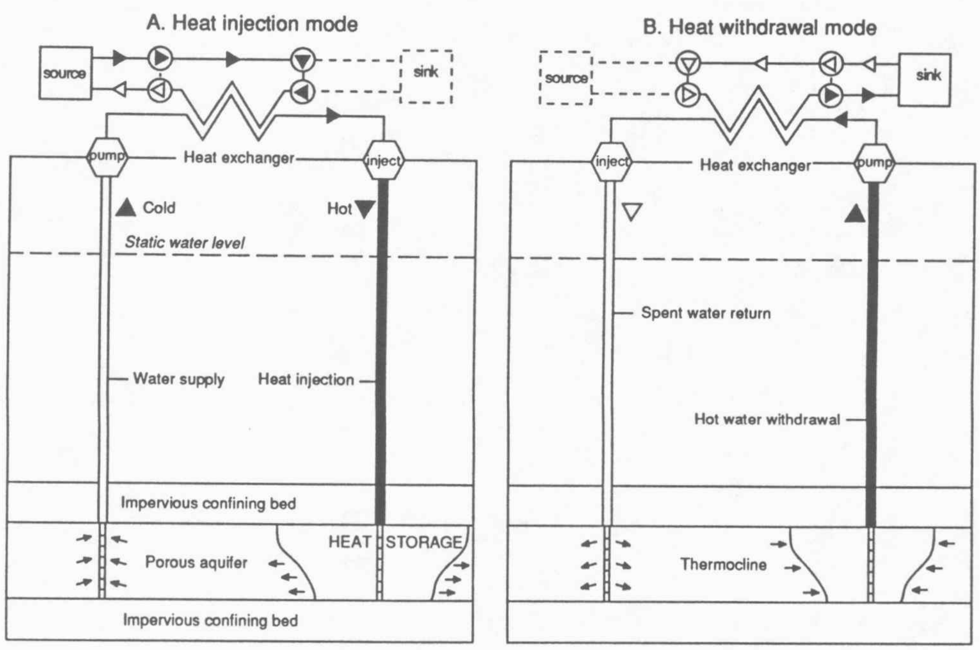

Figure 2. Representation of hot water storage and retrieval in an aquifer.

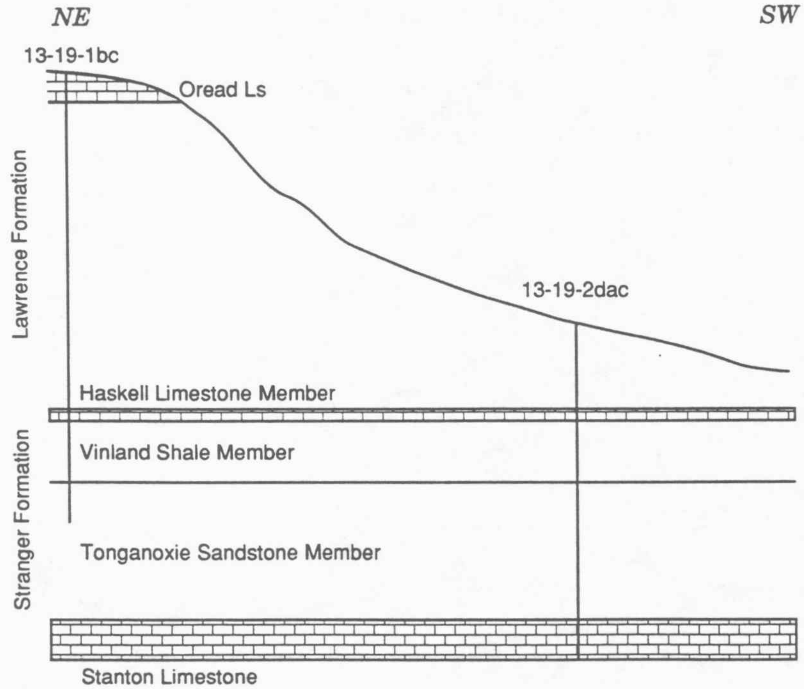

Figure 3. Schematic cross section between two test wells located on West Campus.

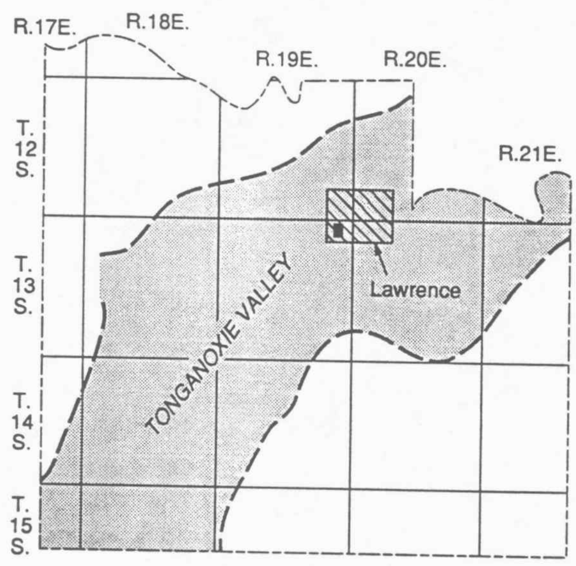

Figure 4. Approximate boundary of the Tonganoxie Valley and the location of Lawrence in Douglas County. Black area shows the proposed site on the University of Kansas campus.

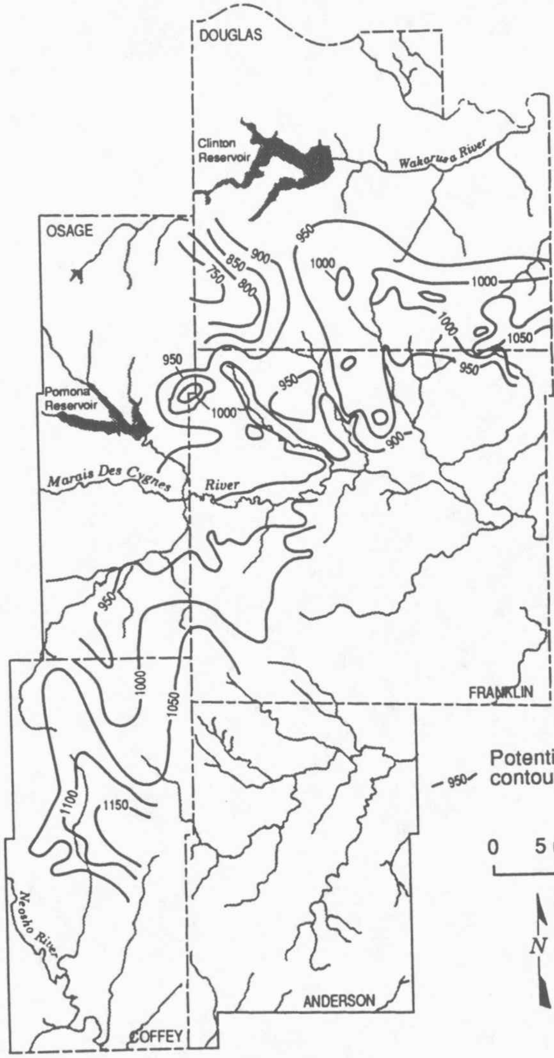

Figure 5. Potentiometric-surface map of the Douglas Group aquifers (data source: A. MacFarlane, KGS).

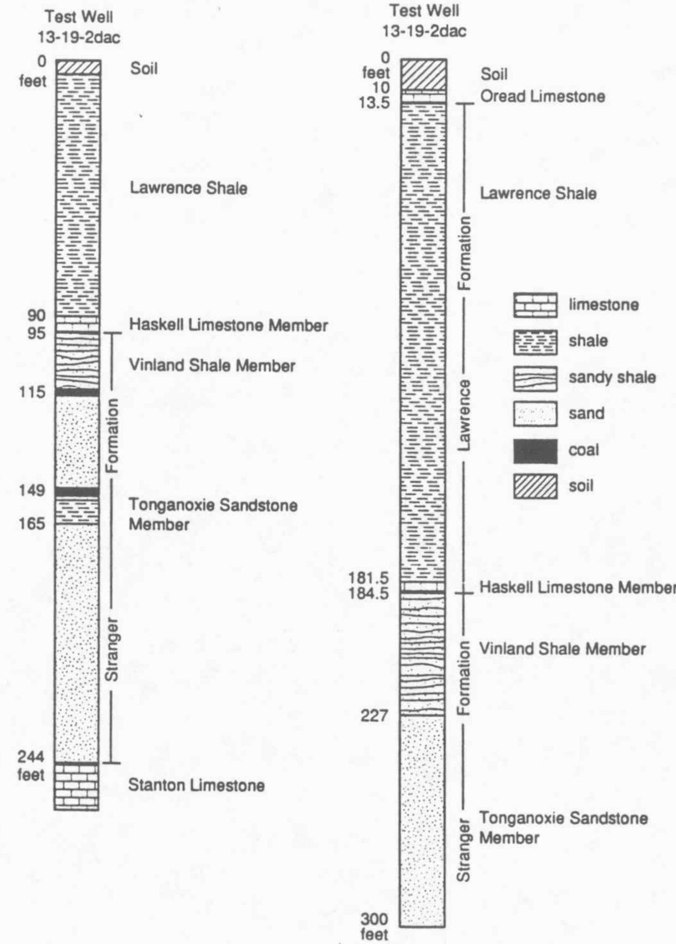

Figure 6. Record of formations encountered in two test wells located on West Campus.

Appendix A

Log for Well NWNESE sec. 2, T. 13 S., R. 19 E., close to Foley Hall

Depth in feet From	To	Lithologic Log	
0	1	Topsoil	Lawrence Shale
1	4	Weathered shale, light brown to gray	
4	104	Light to dark clayey to silty shale with harder calcareous zones scattered throughout	
104	110	Limestone, light gray to light tan	Haskell Limestone Member
110	127	Sandstone, tan, silty	Vinland Shale Member
127	135	Shale, gray, with coals at approx. 133 ft (upper Sibley)	Tonganoxie Sandstone Member
135	158	Sandstone	
158	165	Shale	
165	171	Sandstone, light-tan, silty, medium-grained	
171	172	Coal	
172	181	Shale	
181	268.5	Sandstone, light-gray, medium-grained	
268.5	279.5	Limestone (South Bend)	South Bend Limestone Member
279.5	291.5	Shale (Rock Lake)	Rock Lake Shale Member
291.5	293	Limestone (Stoner)	Stoner Limestone Member

The Garnett and Hamilton paleovalleys, and their relationship to the Douglas Group paleovalleys

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Introduction

Exposures near Garnett and Hamilton, Kansas, were initially studied because of the exquisite fossils, primarily articulated vertebrates, recovered from the sites. Further research revealed that each of the fossil localities was from the upper, fine-grained facies of paleovalley fills. The two sites contain similar sequences of facies and apparently were deposited under similar conditions, yet they are quite different in scale, facies, and fossil assemblages from the Douglas Group paleovalleys. The differences between the Garnett and Hamilton versus Douglas Group paleovalleys are attributable primarily to differences in climate and bedrock lithology. Cores from each of these sites will be available for study at the Saturday evening core workshop.

The Garnett Paleovalley

A site 6 miles northwest of Garnett, Kansas (Fig. 1) has yielded a diverse terrestrial assemblage of plants, arthropods, fishes, amphibians, and reptiles (Reisz et al., 1982). The Garnett paleovalley is within the Rock Lake Shale Member of the Stanton Limestone (upper Missourian) in the cycle immediately below the Douglas Group. The Garnett fossil site occurs in a paleovalley that is approximately 32 ft (9.8 m) deep and 984 ft (300 m) wide, and is incised into underlying members of the Stanton Limestone and Vilas Shale (Fig. 2). The axis of the paleovalley trends northwest-southeast (Woodruff, 1984). The paleovalley was eroded during sealevel lowstand when a local river cut into the underlying bedrock. Possible paleosol features in the paleovalley walls, such as carbonate crusts and iron staining (common in many carbonate paleosols), suggest subaerial erosion. The steepness of the paleovalley walls and the abundance of limestone clasts within the paleovalley fill indicate that the confining strata were lithified at the time of incisement.

The paleovalley fill can be divided into two units: a lower carbonate conglomerate, and an assortment of fine-grained facies in the upper part. The lower conglomerate is not well exposed, but is well-represented in the KGS Garnett core #1. The basal conglomeratic unit in the core is 18.5 ft (5.0 m) thick, generally fines upward, and includes conglomerate with thin siltstone and wackestone interbeds. The basal bed consists of poorly sorted, well-rounded clasts of limestone ranging from 0.5 mm to 5 cm in diameter. Clasts are composed

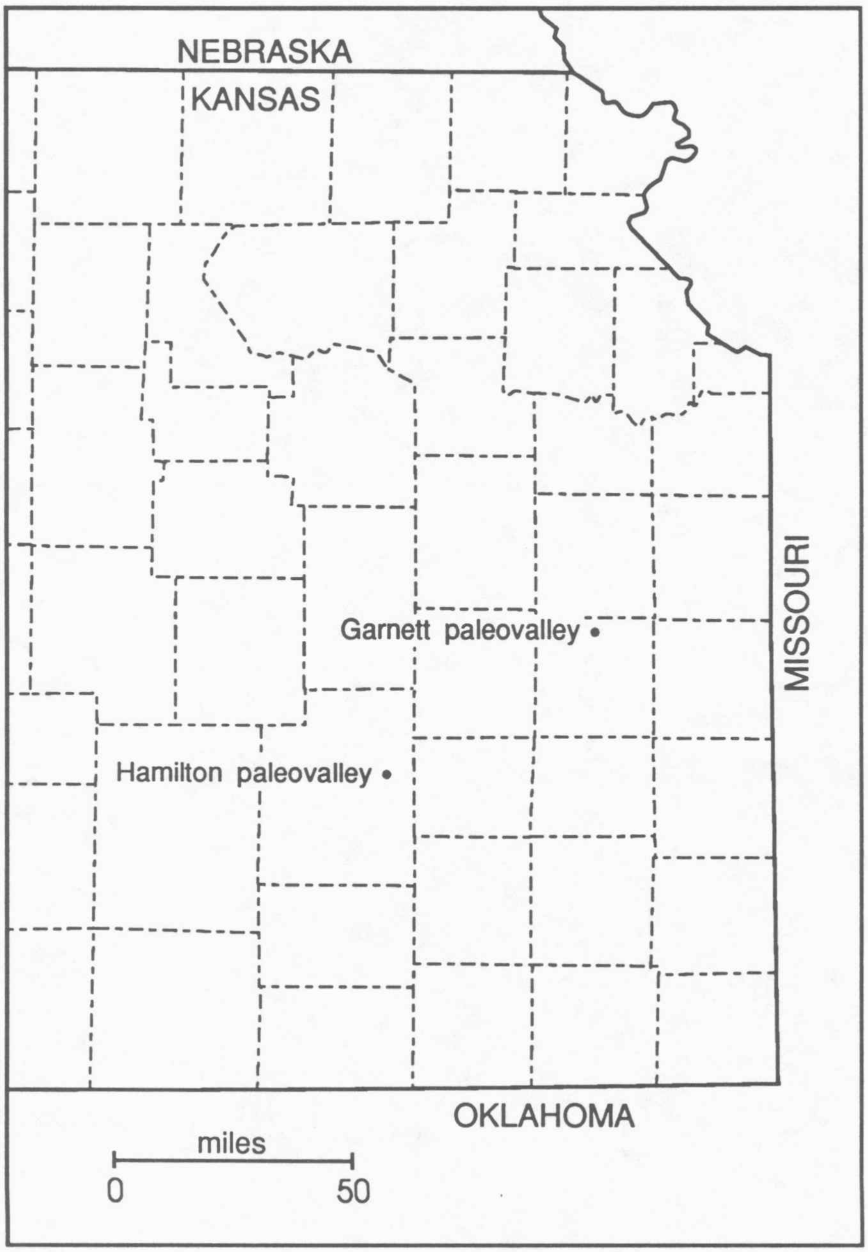

Figure 1. Map of eastern Kansas showing locations of the Hamilton and Garnett paleovalleys.

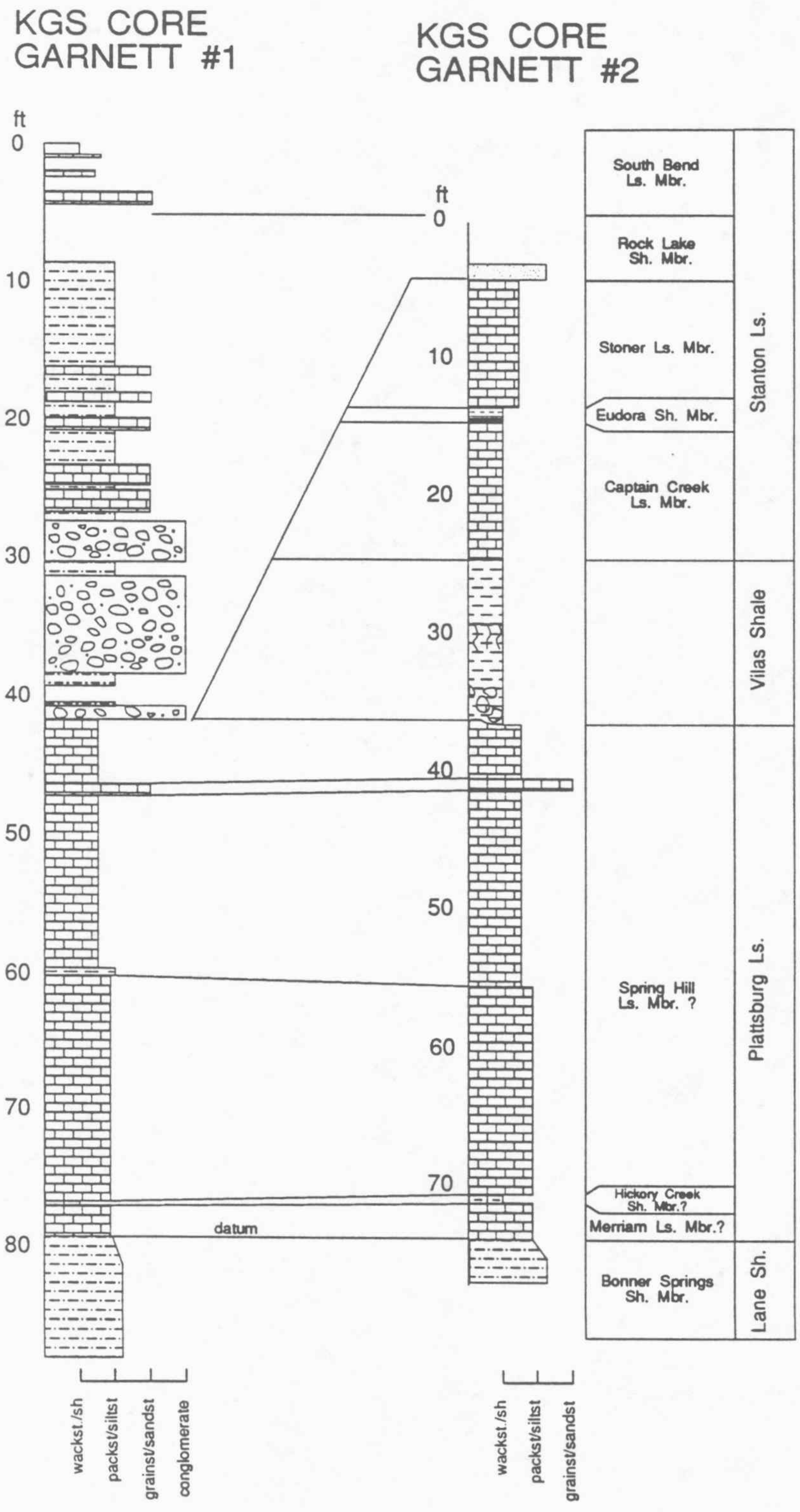

Figure 2. Cross section through part of the Garnett paleovalley based on cores.

of wackestone and packstone identical to facies within the incised limestones. Other conglomerate beds show a range of sorting and grain sizes, but most are poorly sorted with sand-sized carbonate clasts within a gravel supported conglomerate. Upper conglomerate beds have smaller average grainsizes (1 to 6 cm), but the maximum clast size remains high. Cracking of grains and pressure solution along clast contacts are common in the conglomerate, and a few clasts show features of soft-sediment deformation. Primary intergranular porosity has been nearly eliminated as a result of precipitation of coarse calcite spar cement.

There is little evidence of the depositional environment of the conglomerate. Woodruff (1984) interpreted this facies as deposits of an estuarine channel lag based on the thickness of the unit (only 1 ft is exposed) and the presence of marine fossils in the matrix. However, the marine fossils were could have weathered from the surrounding limestone and do not necessarily represent in situ shells. In addition, the thickness of the conglomerate in the core is much greater than it is in surface exposures. The coarse grain size and rounding of the clasts indicate a high-energy environment and the abundance of plant debris suggests proximity to land. Deposition as bars in a fluvial or estuarine environment is a reasonable interpretation for the conglomerate.

The overlying 14.7 ft (4 m) consists of laminated to thin bedded siliciclastic mudstone and siltstone and thin conglomerate beds. Bioturbation is lacking in these beds and they contain well preserved plants, fish, terrestrial arthropods, and large reptiles (Reisz et al., 1982; Maples and Schultze, 1988) and tetrapod trackways. Presence of at least partially articulated reptiles suggests that they were buried soon after death, which isolated them from extensive scavenging. The lack of bioturbation in the laminated fine-grained rocks is consistent with rapid deposition and oscillatory brackish- to freshwater environments. Additionally the preservation of footprints indicates they were impressed into subaerially exposed, but wet sediment. This facies was probably deposited in a intertidal flat or bar top surface in the upper reaches of an estuarine system. Modern analogs of such nonbioturbated, silt-rich laminae occur in fluvio-tidal point bars that form in the upper reaches of high-tidal range estuarine settings.

The Garnett paleovalley is capped by marine rocks of the South Bend Limestone Member. These rocks record the final flooding of the paleovalley during transgression.

The Hamilton Paleovalley

A paleovalley fill 2.5 miles east of Hamilton also has been the focus of several studies because of the diverse and abundant, well-preserved terrestrial and aquatic fossil assemblages (Mapes and Mapes, 1988; Cunningham, et al., in press). Fossil assemblage at Hamilton includes plants, terrestrial and aquatic arthropods, fishes, amphibians, reptiles, and rare marine invertebrates. The paleovalley fill has been mapped based upon outcrops and cores (Figs. 3, 4), and fine-grained facies of the fill have been excavated at two localities. Marine fossils are relatively rare and all the fossils occur within the paleovalley fill sequence. The north-south-trending paleovalley is approximately 6.0 miles (9.8 km) long, 0.17 miles (0.27 km) wide, and up to 65.6 ft (20 m) deep and is incised into the Topeka Limestone, Calhoun Shale, and Deer Creek Limestone. The depth of incision generally increases to the south.

Volumetrically the most important facies within the paleovalley is a cross-bedded limestone-pebble conglomerate that occurs at the base of most exposed and cored sections. The basal contact of the conglomerate is sharp and

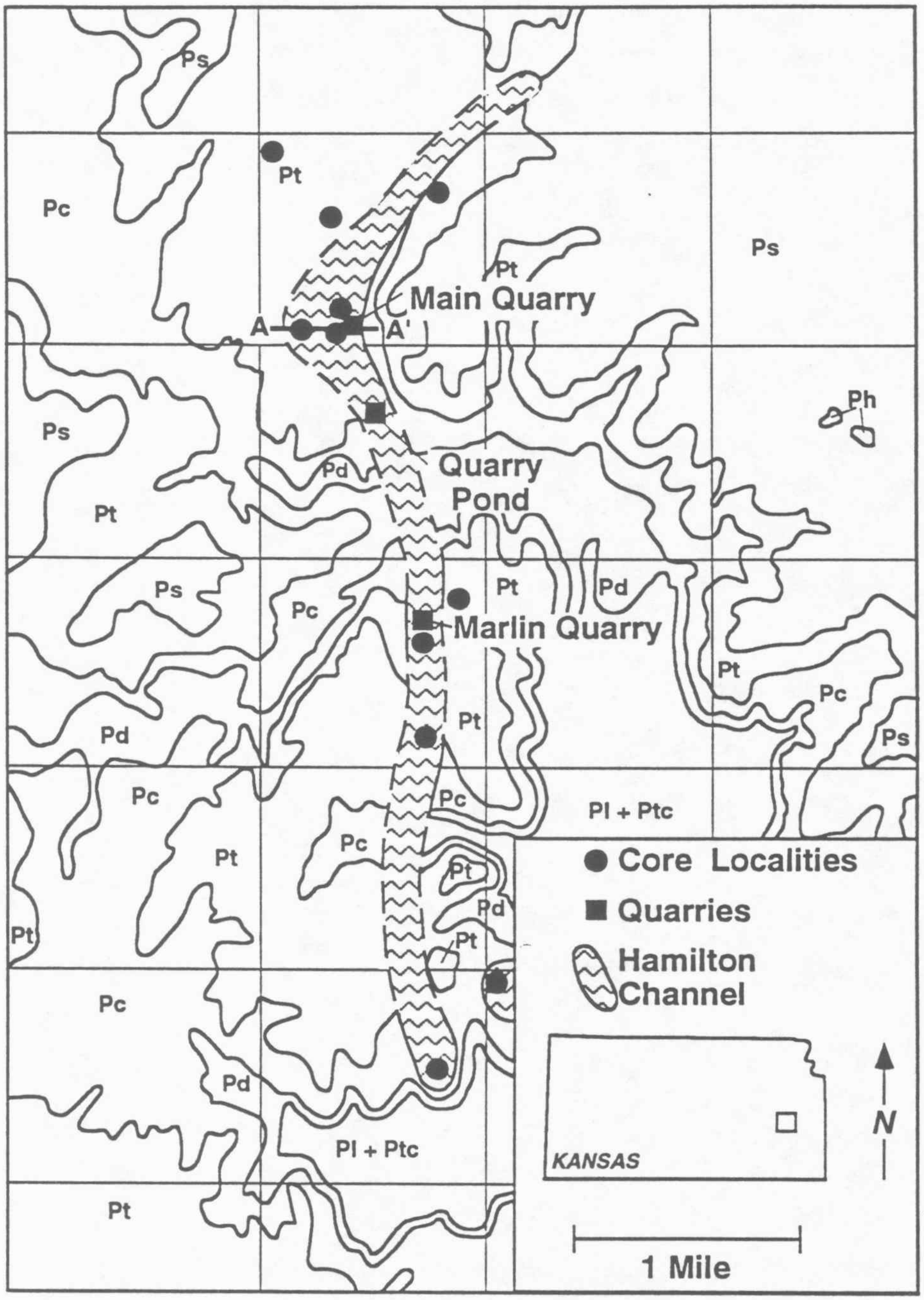

Figure 3. Map of the Hamilton paleovalley and surrounding stratigraphic units (Modified from Fahrer 1991). Pc, Calhoun Shale; Pd, Deer Creek Limestone; Ph, Howard Limestone; Pl, Lecompton Limestone; Ps, Severy Shale; Pt, Topeka Limestone; Ptc, Tecumseh Shale.

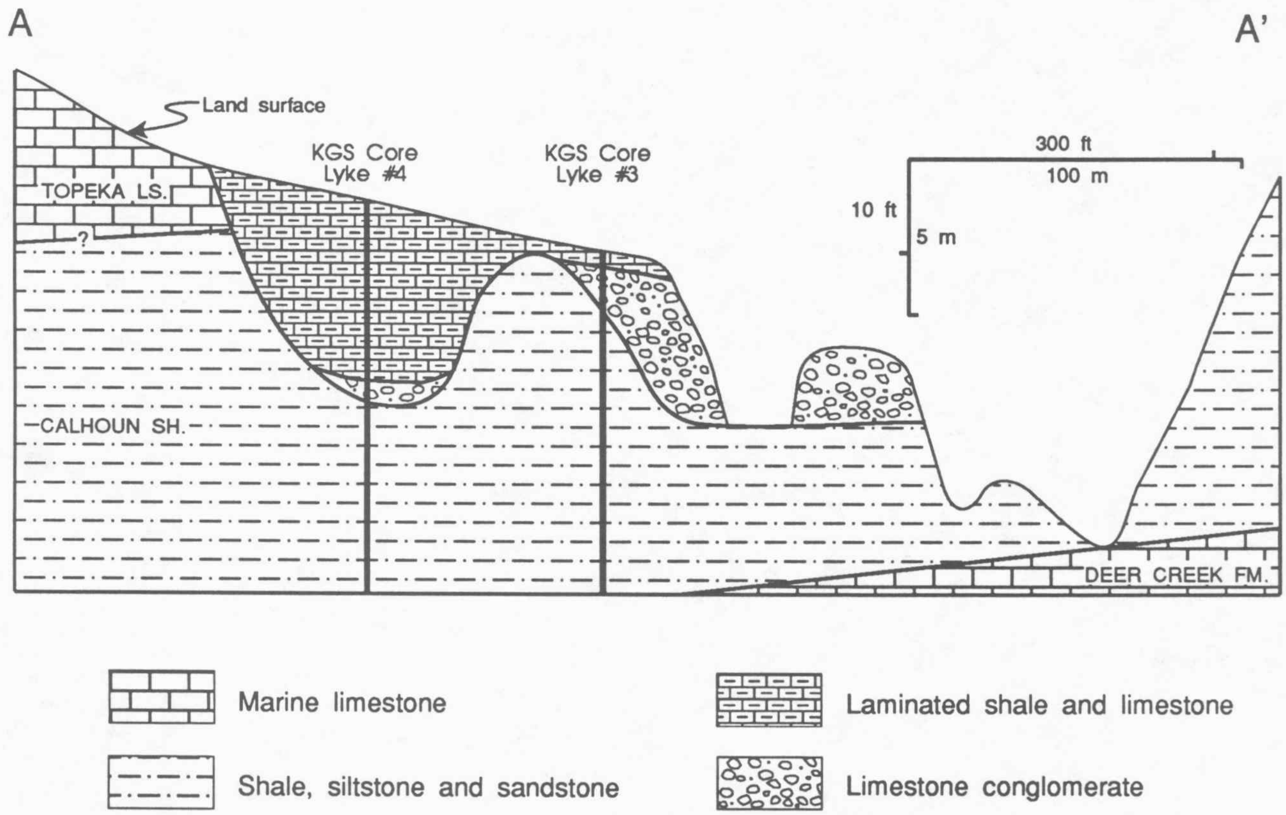

Figure. 4. Cross section A-A' showing the distribution of facies within the Hamilton paleovalley and relationship to surrounding units. See Fig. 3 for location of cross-section (modified from Cunningham et al., in press).

erosional where it has been observed. Clasts are composed primarily of limestone similar to facies of the incised Topeka Limestone. Clasts of shale and sandstone similar to the Calhoun Shale are locally common. Most clasts are sub-rounded to rounded and average 2 to 5 cm in long dimension, but range up to almost 30 cm. In addition to clasts composed of rock types exposed in paleovalley walls, there are also clasts of laminated caliche crusts, fusain, and many abraded marine fossils. Many of the marine fossils were probably eroded from older rocks, however a few may indicate possible marine conditions during deposition of the conglomerate, including productid brachiopods with long spines preserved, and bryozoans encrusting lithoclasts (West, 1988).

The origin of the conglomerate remains enigmatic although it is probably of fluvial origin. Clasts of laminated crusts that have paleosol features (rootlet molds, circumgranular cracking, fenestrae, and glaebules) may represent the remains of soils that were penecontemporaneous with paleovalley formation. The conglomerate was probably deposited by rivers flowing within the valley. Alternatively, the conglomerate may have been deposited in marginal-marine environment, such as within an active tidal inlet.

Overlying the conglomerate is a range of fine-grained facies, including ostracode wackestone, laminated wackestone, and laminated siliciclastic mudstones. These facies contain abundant terrestrial (e.g. plants) and aquatic fossils, but only rare fully marine fossils such as brachiopods and fusulinids. The fine-grained beds were probably deposited in a range of shallow, marginal-marine environments. Laminated limestone beds are well-laminated to thin bedded, lack bioturbation and contain beds of well-preserved vertebrate fossils. The abundance of complete fish fossils indicates rapid deposition because slow deposition inevitably leads to decay and disarticulation of skeletons in warm, tropical environments (Zangerl and Richardson, 1963; Schäfer, 1972). In one of the fish-bearing beds the laminations form distinctive patterns of thickening and thinning strata that are similar to previously described tidal rhythmites (e.g., Archer and Kvale, 1989). This facies was probably deposited in tidal-estuarine environments, where high rates of deposition and potentially fluctuating salinity reduced scavenging and bioturbation.

The Hamilton paleovalley is only present at surface exposures, and is nowhere capped by fully marine rocks of the normal succession in Kansas. Abundance of clasts similar to the Topeka Limestone, and the presence of several exposure surfaces within the Topeka Limestone suggests that the paleovalley may occur within the Topeka Limestone. Presumably there was a marine cap to the paleovalley sequence that recorded the flooding of the area after the paleovalley had been filled with sediment.

Comparison of Garnett, Hamilton and the Douglas Group Paleovalleys

The Garnett and Hamilton paleovalleys share several characteristics that contrast with the Douglas Group paleovalleys. These are:

-Both paleovalleys are less than 1 mile wide and less than 100 ft deep.

-Thickness of fill from basal conglomerate to marine cap is not appreciably greater than the depth of incision (assuming that the Hamilton paleovalley does correlate into the Topeka Limestone).

-Carbonate facies are volumetrically subequal to or greater than siliciclastic facies.

-Plant assemblages are dominated by conifers that suggest well-drained conditions.

The morphology and fills of paleovalleys respond to many factors. Relatively simple explanations for the depth of incised stream valleys have been demonstrated to be inadequate because of the complexity of geomorphic processes involved (Schumm, 1993; Wescott, 1993). Causes of depth of incision by streams are complex, and related to numerous factors that were grouped into three categories by Schumm (1993). These are: 1) baselevel controls, which include rate of baselevel fall, amount of baselevel fall, and length of exposure time; 2) geologic controls, which include bedrock lithology and the type of valley alluvium; and 3) geomorphologic controls, which include inclination of exposed surfaces, valley morphology, and river morphology. We would add climate as a fourth major factor because changes in discharge rate can alter depositional and erosional patterns. The relative contributions of some of these factors can be estimated for these Pennsylvanian paleovalleys.

Many of the differences between the Douglas Group paleovalleys and the Hamilton and Garnett paleovalleys are consistent with their incision and filling in relatively wet and relatively dry climates respectively. The plant assemblages in Garnett and Hamilton are dominated by conifer remains, with subordinate amounts of fern foliage and other plants. Pennsylvanian conifers had xerophytic adaptations (Rothwell, 1982) and never inhabited swamps (Mapes and Gastaldo, 1986). Mapes and Rothwell (1988) interpreted the conifer-dominated plant assemblage preserved in the Hamilton paleovalley as representing a community that inhabited well-drained slopes. Similarly Reisz et al. (1982) interpreted the conifer-rich plant assemblage from the siltstones at Garnett to represent a community that lived along a river valley during the Rock Lake regression. These plant assemblages contrast with the Douglas Group assemblages that are dominated by fern foliage and sphenopsids, and even contain lycopsid remains, which are relatively rare by Late Pennsylvanian time (Cridland et al., 1963). At the Buildex quarry south of Ottawa, Kansas, (lower Tonganoxie Sandstone Member), upright Calamites and tree ferns are buried in life positions by tidal-flat deposits. Conifer remains have been collected from only one locality in the Douglas Group (Cridland et al., 1963).

Soils associated with the Rock Lake Shale Member (Stanton Limestone) and Douglas Group provide additional evidence for climatic differences. Joeckel (1988) interpreted a well-developed, laterally extensive paleosol in the Rock Lake shale in southeastern Nebraska as forming in a semiarid to arid plain. In the Douglas Group the abundance of coals argues for wet conditions, and the establishment of coal-forming swamps. The Upper Williamsburg coal ranges up to 26 inches thick, and several other coals are commonly over one ft thick (Bowsher and Jewett, 1943). In addition, the types of sediment in the paleovalley fills are consistent with climatic differences between the Douglas Group paleovalleys and Hamilton and Garnett paleovalleys. The latter paleovalleys have thin sediment fills, and are dominate by limestone conglomerates with little sandstone. Calcareous shales and carbonate mudstone occur in the estuarine deposits. In contrast, the Douglas Group sequences are thick, dominated by sandstone and shale, and lack calcareous sediments, except during maximum transgression when fully marine conditions were re-established.

Differences due to amount of sealevel fall probably had little influence on the depth of incisement of these paleovalleys. Both Schumm (1993) and Wescott (1993) maintain that the amount of baselevel fall has only a local effect and that once shoreline is far from an area, additional lowering of baselevel has little additional influence on incision. All of the paleovalleys were probably eroded when shorelines had receded at least to southern Kansas, and perhaps much further, so that the effect of the different amounts of regression is likely to be minimal. During Rock Lake Shale deposition the shoreline at maximum regression was far south of the Garnett paleovalley. Upper Rock Lake deposits in southeastern Kansas were exposed prior to South Bend deposition (Mousavi-Harami, 1990; Heckel, 1975). Douglas Group equivalents in Oklahoma record deposition of coarse alluvial deposits (e.g. Ford, 1978).

Lastly the nature of the bedrock confining the paleovalleys probably had a large influence on incisement depth and paleovalley cross-sectional shape. The Garnett paleovalley is incised into mostly limestone that was lithified at the time of erosion. Garnett paleovalley walls would have eroded slowly compared to the predominantly shale walls of the Douglas Group paleovalleys. The Tonganoxie paleovalley has a flat base, probably because of resistance of the Stanton Limestone. The Hamilton paleovalley is eroded into both limestone and shale.

Conclusions

Similarities of the Garnett, Hamilton, and Douglas Group paleovalley fills include: 1) fining-upward succession of sediments starting with a basal conglomerate; 2) presence of laminated, fine-grained estuarine deposits with well-preserved fossils in the middle to upper parts of each sequence; and 3) presence of a marine limestone cap that is widely correlated far outside the region of the paleovalleys. Differences among the paleovalleys can be primarily attributed to formation in dry (Hamilton and Garnett) versus wet (Douglas Group) conditions and secondarily to differences in bedrock types during paleovalley erosion. Dry paleovalley fills are thin, have abundant carbonates, and contain fossil floras characterized by well-drained conditions. Wet paleovalley fills are thick, have abundant coals and shale, and contain floras dominated by swamp-dwellers.

Acknowledgments

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VALLEY-FILL SANDSTONE RESERVOIR HETEROGENEITY, STATELINE TREND, COLORADO AND KANSAS

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One of the most important kinds of relatively small sandstone reservoirs being explored for and developed today is the valley-fill sandstone. Because of their relatively small size (0.5 to 4 miles wide), poorly understood origins and difficult to predict occurrences, valley-fill reservoirs have not always been attractive targets for drilling. However, in the last few years valley-fill reservoirs have become very important and some are currently undergoing secondary recovery. Because of the absence of adequate geologic descriptions, valley-fill reservoirs have, in the past, commonly not been differentiated from deltaic and river-channel sandstones. Because there are significant differences in the distribution of reservoir seals and internal heterogeneity characteristics in valley-fill reservoirs, compared to deltaic and river-channel reservoirs, different patterns of production will occur within individual fields and pools which produce from these distinctly different geologic environments.

Valley-fill heterogeneous reservoirs in the Morrowan (Pennsylvanian) age Stateline Trend along the Kansas-Colorado border produce from valley-fill reservoirs and are internally complex, contain geographically and vertically limited reservoirs and can only be effectively drained if the detailed internal architecture of the reservoirs is understood. Development of detailed geologic models utilizing core interpretations for fluvially and tidally deposited valley-fill sandstone reservoirs enhance results of reservoir simulation and improve planning for secondary recovery and possible tertiary production. Only by including the location and degree of impermeability of barriers to flow at the margins of and within the valley-fill reservoirs can historical simulation modeling and secondary recovery methods yield satisfactory economic results.

The valleys in which the reservoirs occur at Southwest Stockholm Field were cut by rivers during drops in sea level and remained as conduits (narrow open valleys trending perpendicular to the regional shoreline). At a later time, as sea level rose, the valleys were filled from the landward side by rivers or from the seaward side by shoreline processes or alternately from both the landward and seaward sides at the same time.

Detailed geologic analysis of cores from the field combined with cross sections and isopach and structure maps yielded details of reservoir heterogeneity. Reservoir production properties vary greatly between the two major valley-fill producing facies, fluvial and tidal (estuarine) sandstones. Within the approximately 150-ft thick valley-fill vertical sequence at Southwest Stockholm field, just one of the three sandstones yields significant production. Topographic highs on the valley bottom, covering an area as large as 1/2 section reduce the depositional thickness of the reservoir sandstones. Impermeable limestones and shales commonly form lateral barriers to flow at valley margins and locally within the valleys. Erosion of portions of potentially productive sandstones within the valleys was found to be important in isolating reservoirs (flow units).

Tidally deposited (estuarine) sandstones are finer grained and more clay prone than the fluvial sandstones and as a result have poorer reservoir properties. In Southwest Stockholm field fluvial deposits have average porosities of 15.4% (range from 2.8 to 21.6%) and average permeabilities of 784 md (range from 0.03 to 5500 md). Tidal-channel sandstones have average porosities of 10% (range from 3.1 to 18.4% and permeabilities of 129 md (range 0.12 to 470 md). Note the significant differences in the mean values for the two types of deposits. Where tidal sandstones interfinger with fluvial sandstones, vertical permeability is diminished and flow units are fragmented.

Valley-fill deposits in Southwest Stockholm field differ from deltaic deposits geologically, geometrically and in the characteristics and distribution of flow units. Overbank and fine-grained levee deposits, typical of deltas, are most commonly absent at the margins of valley-fill deposits and valley-fill deposits occur below the regional TSE (transgression surface of erosion) rather than above it as do many deltas.

Secondary (post burial) events affected the production characteristics of the reservoirs. The post-depositional events that affected the reservoirs were significantly different in several of the seven recognized depositional lithofacies. Up to half of the porosity in Southwest Stockholm field may be leached (secondary) porosity. Where millimeter thick shale lenses were deposited within tidally deposited sands, pressure solution of quartz in contact with the clay reduced porosity.

Reservoir characteristics are relatively similar within sandstone units interpreted to have been deposited by the same depositional processes. However, reservoir characteristics are significantly different among different depositional lithofacies. All sandstones deposited by the same processes are assigned to the same lithofacies. Although other types of sandstones were vertically or laterally "connected" to the better reservoir lithofacies, perforated intervals were commonly limited to valley-filling fluvial sandstones in Southwest Stockholm field. Understanding the differences in heterogeneity characteristics between fluvial and tidal (estuarine) valley-fills, such as those studied herein, allows proper economic evaluation and more efficient reservoir management of these kinds of reservoirs.

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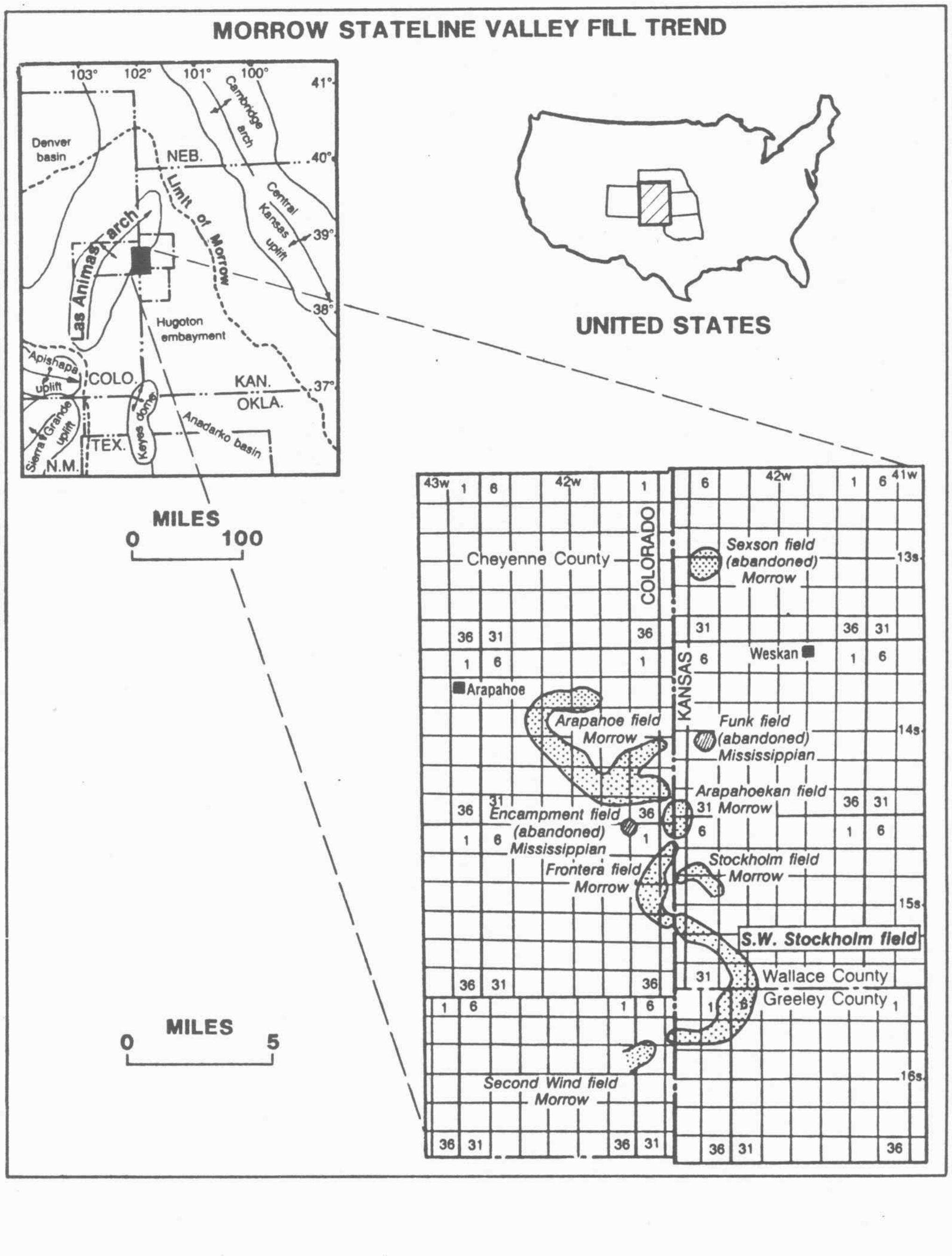


Fig. 1 - Location of 20-mile-long "Stateline Trend" Morrow Sandstone fields, which produce from valley-fill sandstone reservoirs. Southwest Stockholm field, Kansas, is located in Greeley and Wallace counties, Kansas. (Modified from Shumard and Avis, 1990).

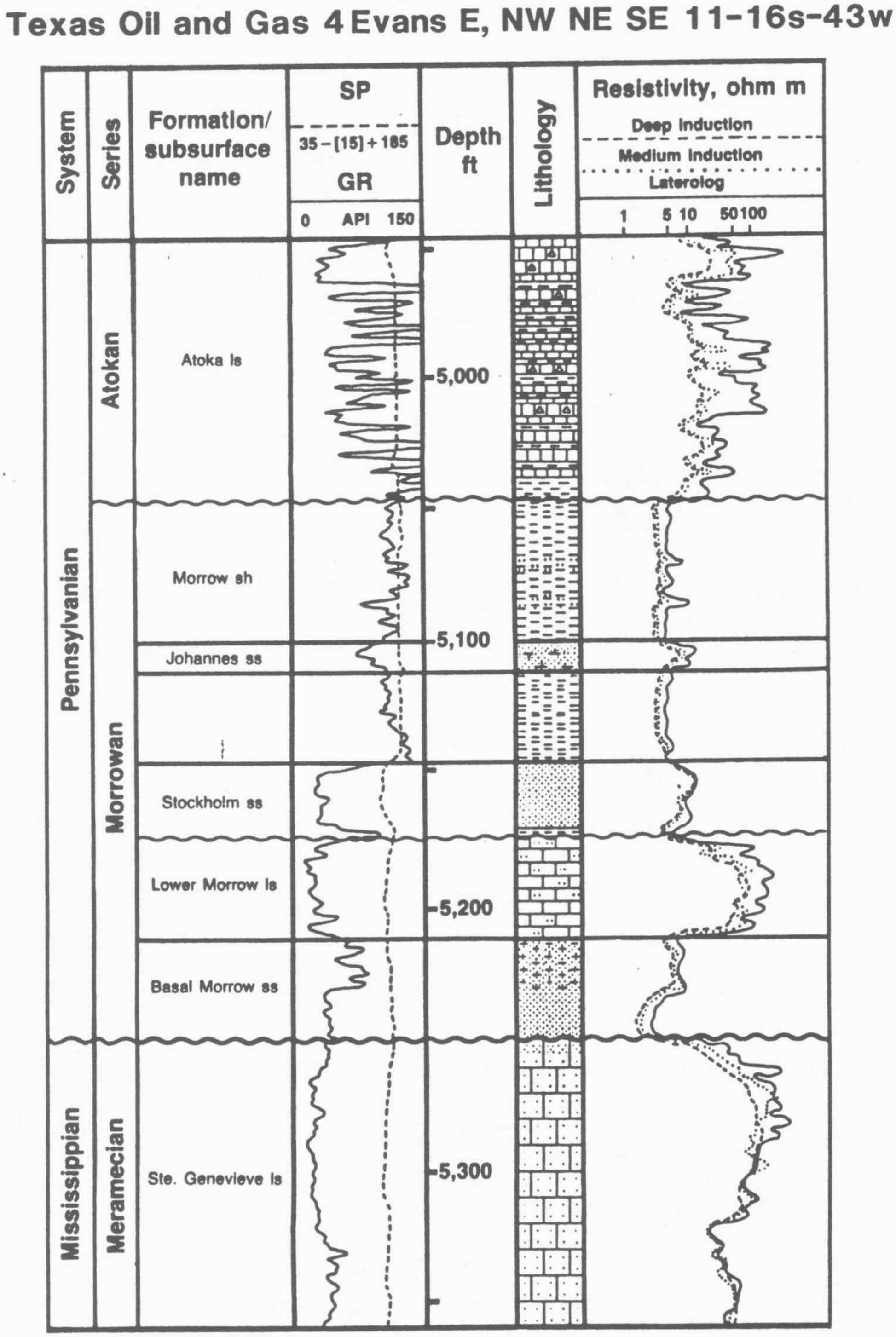


Fig. 2 - Type log for Southwest Stockholm field. Geographic location shown on Figure 4 (Well No. 124). Note that three potentially productive sandstones are present in the Morrow interval. At Southwest Stockholm field the basal Morrow Sandstone is non-productive as is the lower Morrow Limestone. The basal Morrow Sandstone is limited in distribution by limestone valley walls. The Stockholm and Johannes valley-fill sandstones are both productive in Southwest Stockholm field. The contact between the Morrow and the Mississippian limestones is a regional unconformity which in most areas forms the bottom of the valley that is filled with numerous lithologies including sandstone, limestone and shale.

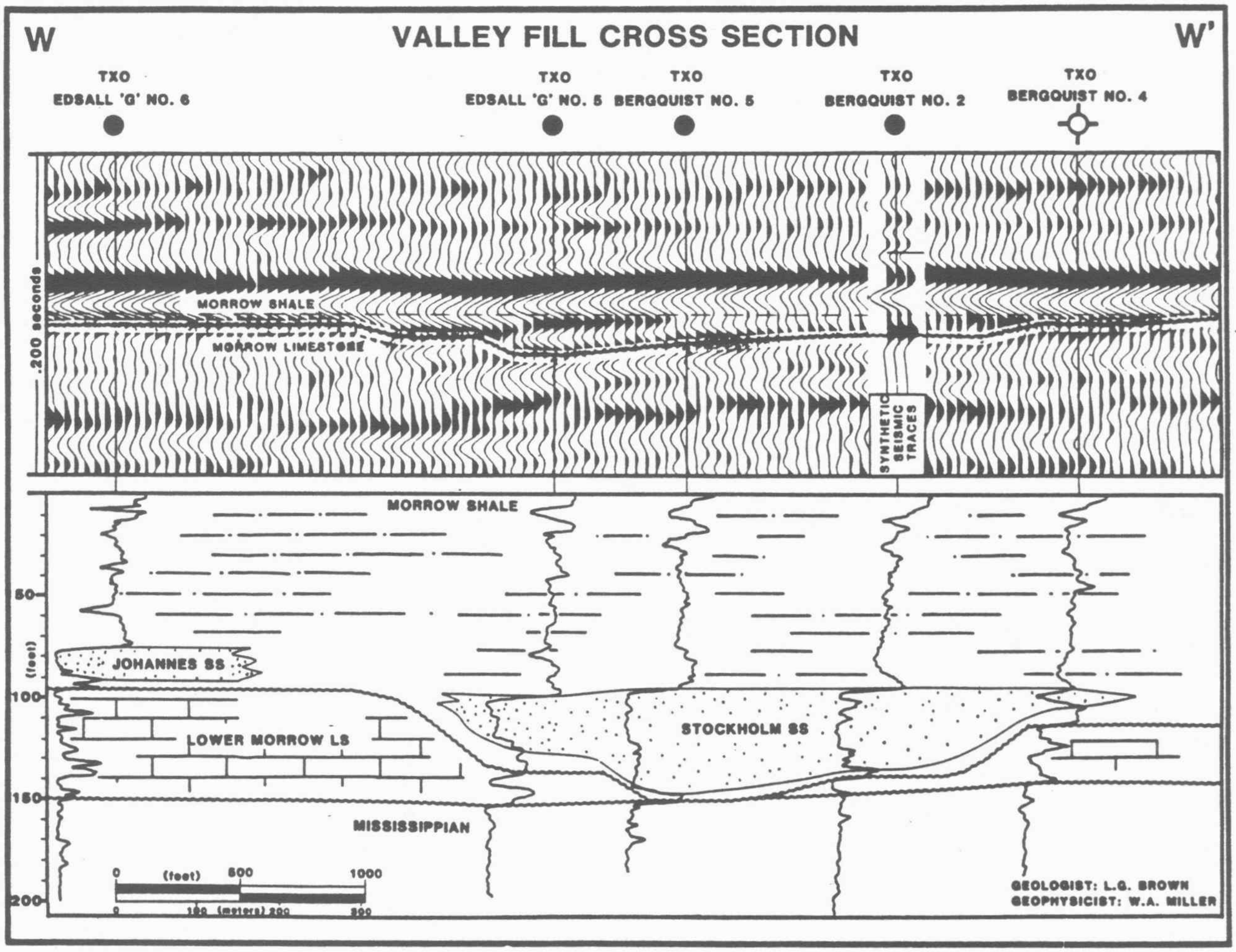


Fig. 3 - Stratigraphic and seismic cross sections through two laterally separated Morrow Sandstone valley-fill reservoirs at Southwest Stockholm field, Kansas. TXO Bergquist No. 2 is a cored well in which a synthetic seismic profile was calculated. Note that the Stockholm Sandstone fills an erosional "channel." Flow in the "channel" was out of the diagram. The Johannes Sandstone is also limited areally by valley walls but is more lenticular and is present in discontinuous lenses.

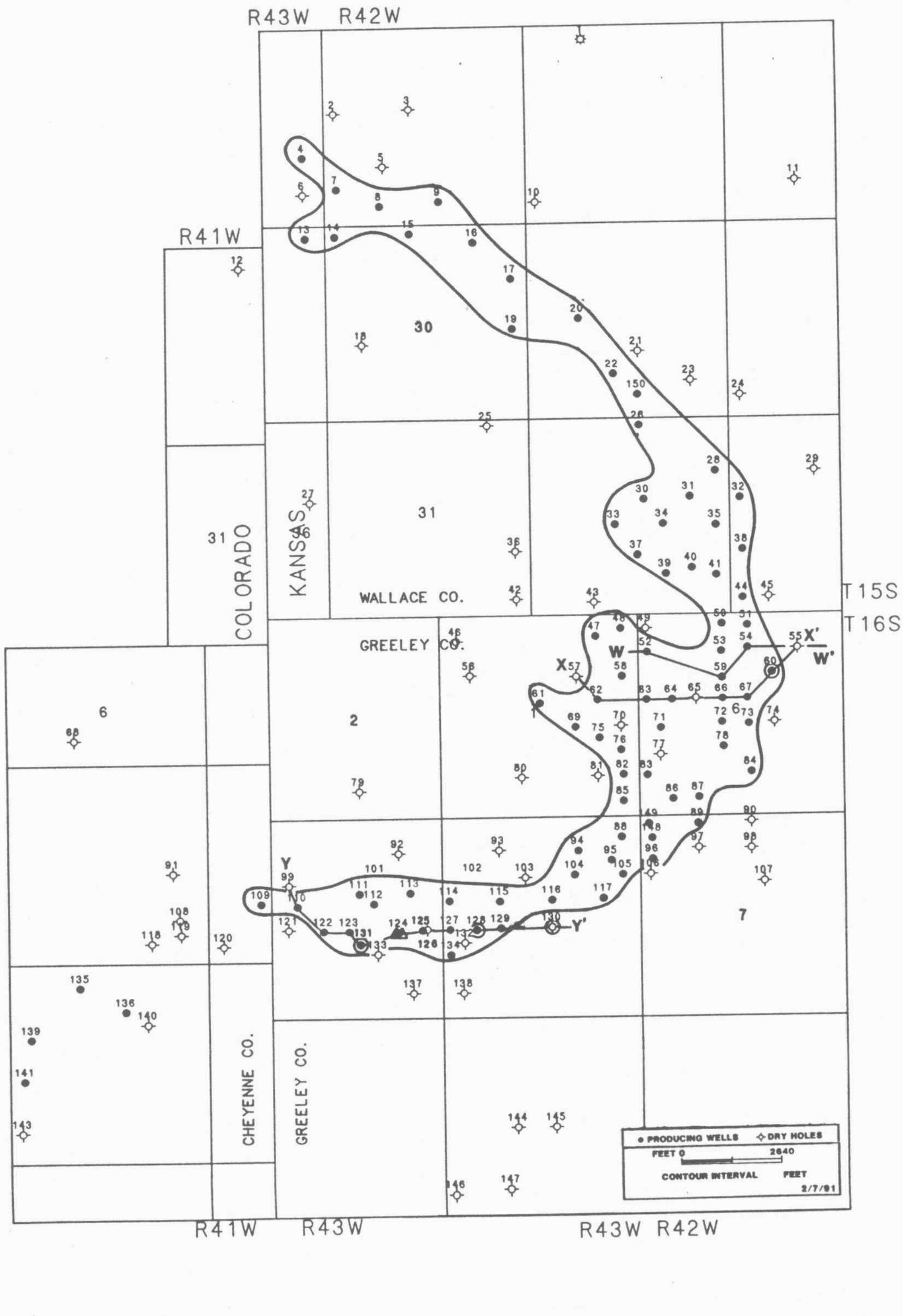
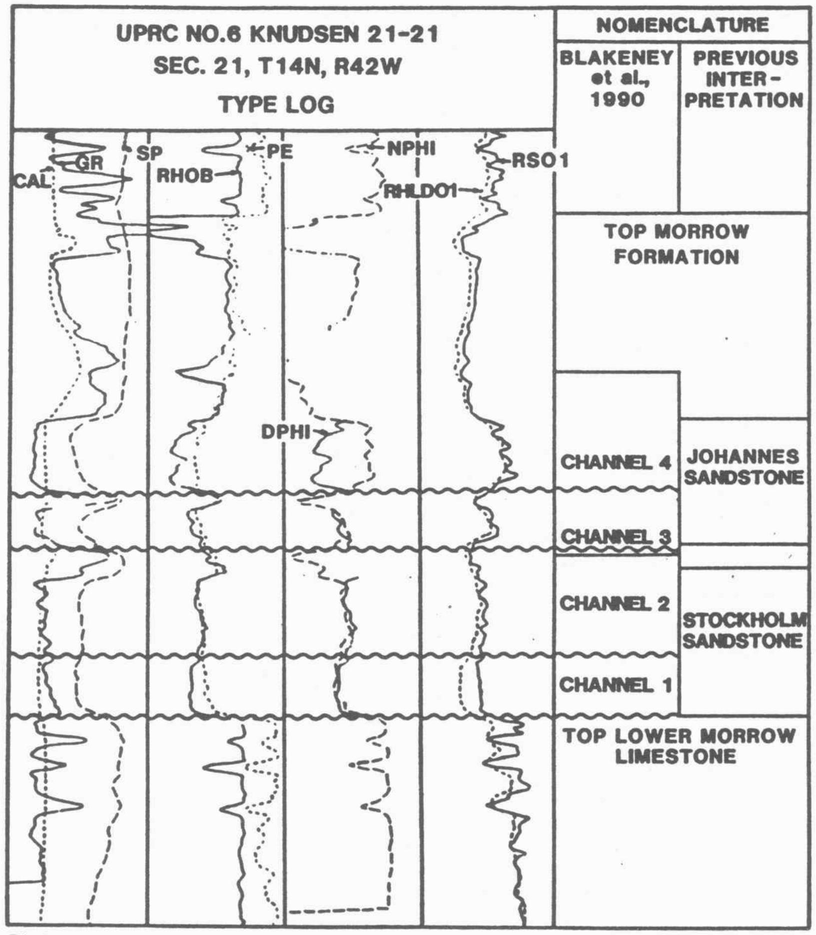
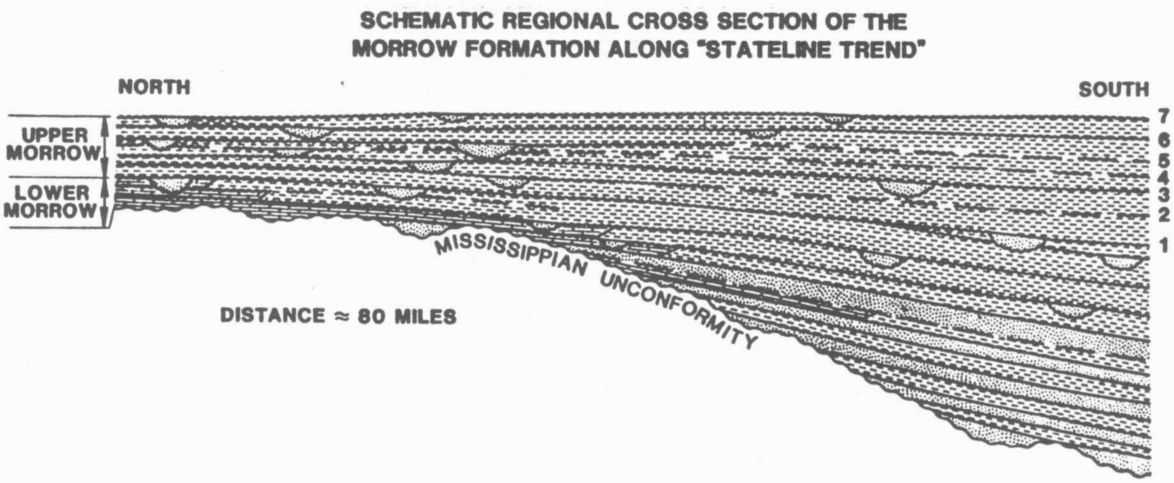


Fig. 4 - Base map, outlining borders of Southwest Stockholm field, Kansas. Cored wells described for this study are circled. Location of the type-log well (#124, Fig. 2) is indicated by a triangle. A list of all numbered wells on this map is available from the senior author.



Blakeney et al., 1990

Fig. 5 - Morrowan stratigraphic section in Arapahoe field of "Stateline Trend". Includes four valley-fill units; three are valley-fill sandstones (Basal Morrow, Stockholm and Johannes) and a valley-fill carbonate (Lower Morrow Limestone). Unconformity at base of Morrowan is a regional unconformity with significant relief.



Wheeler et al., 1990

Fig. 6 - Schematic regional cross section of the Morrow Formation along the "Stateline Trend" of the Kansas-Colorado border. A subareal unconformity separates each of the valley-fills from the underlying marine shales and/or carbonates. The unconformities are numbered (1 to 7) from the base to the top. A map of the valley for the unconformity labeled number 1 is shown in Figure 7. (Wheeler, 1990)

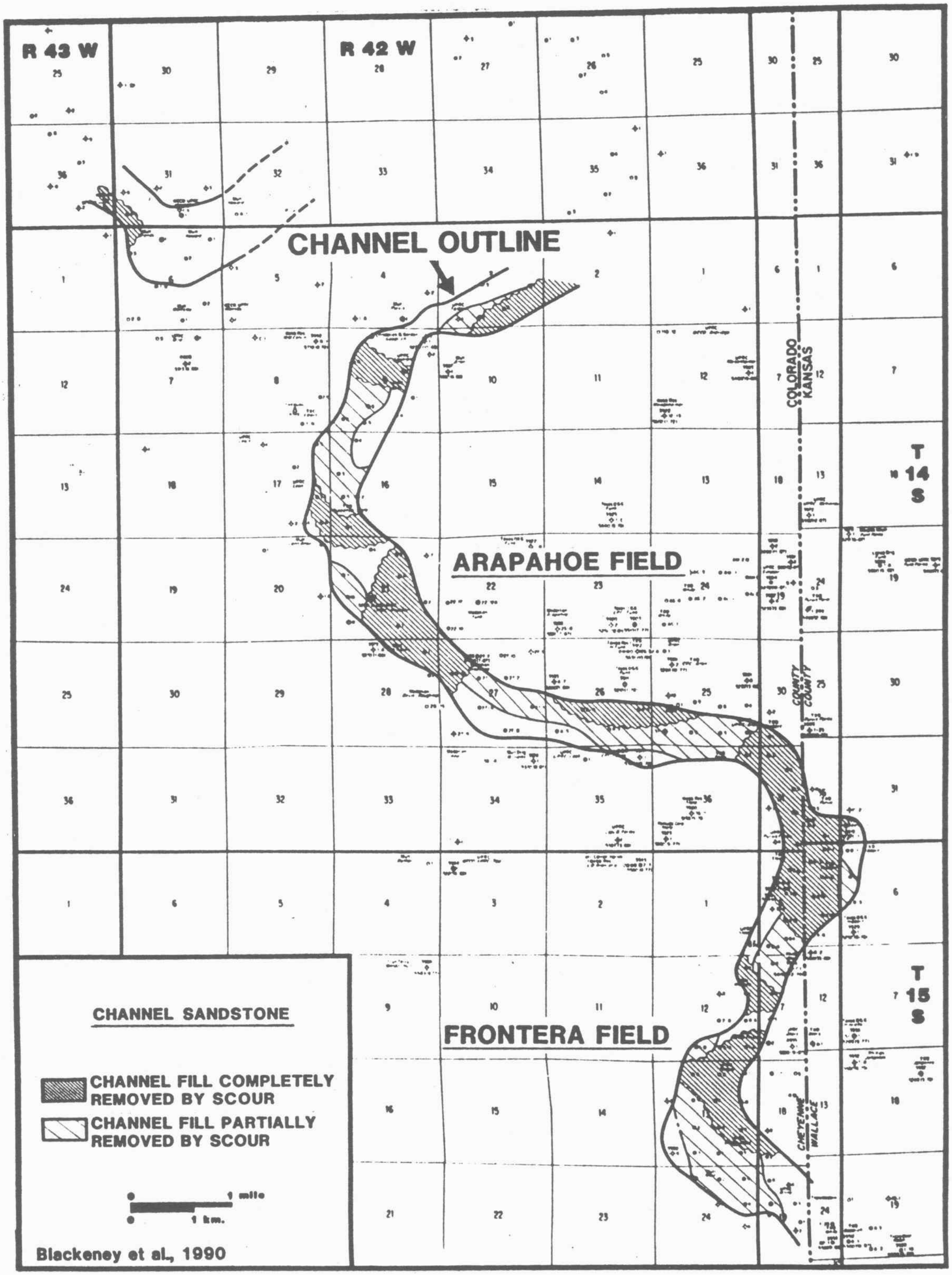


Fig. 7 - Valley in Morrow Sandstone, "Stateline Trend", Colorado and Kansas.

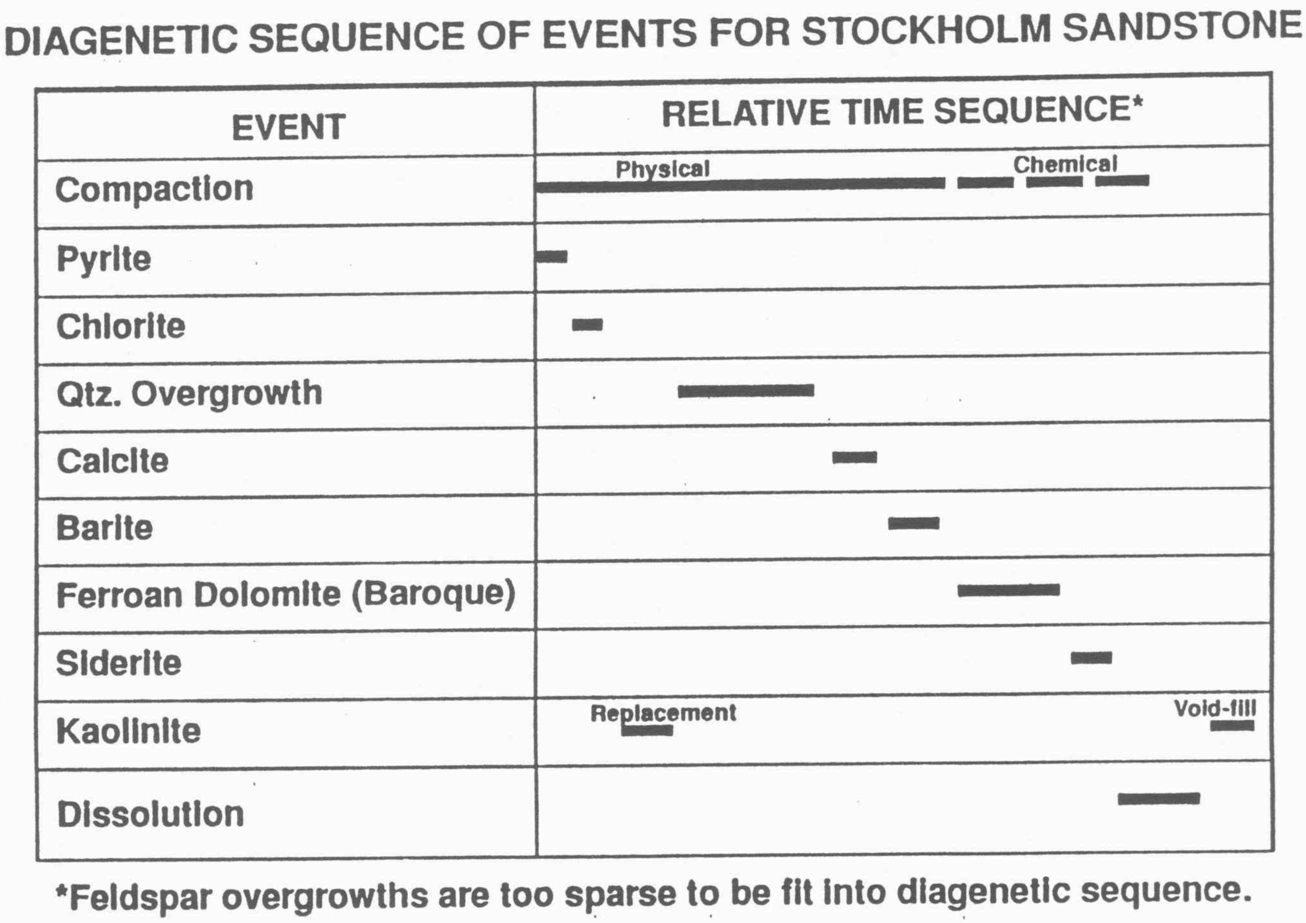


Fig. 8 - Diagenetic sequence of events for the Stockholm Sandstone, Southwest Stockholm field. One of the most important events in some facies after burial of sediments is dissolution of carbonate cement giving significant "secondary porosity". All events listed on figure, other than dissolution, tend to decrease porosity in Morrow valley-fill sandstones.

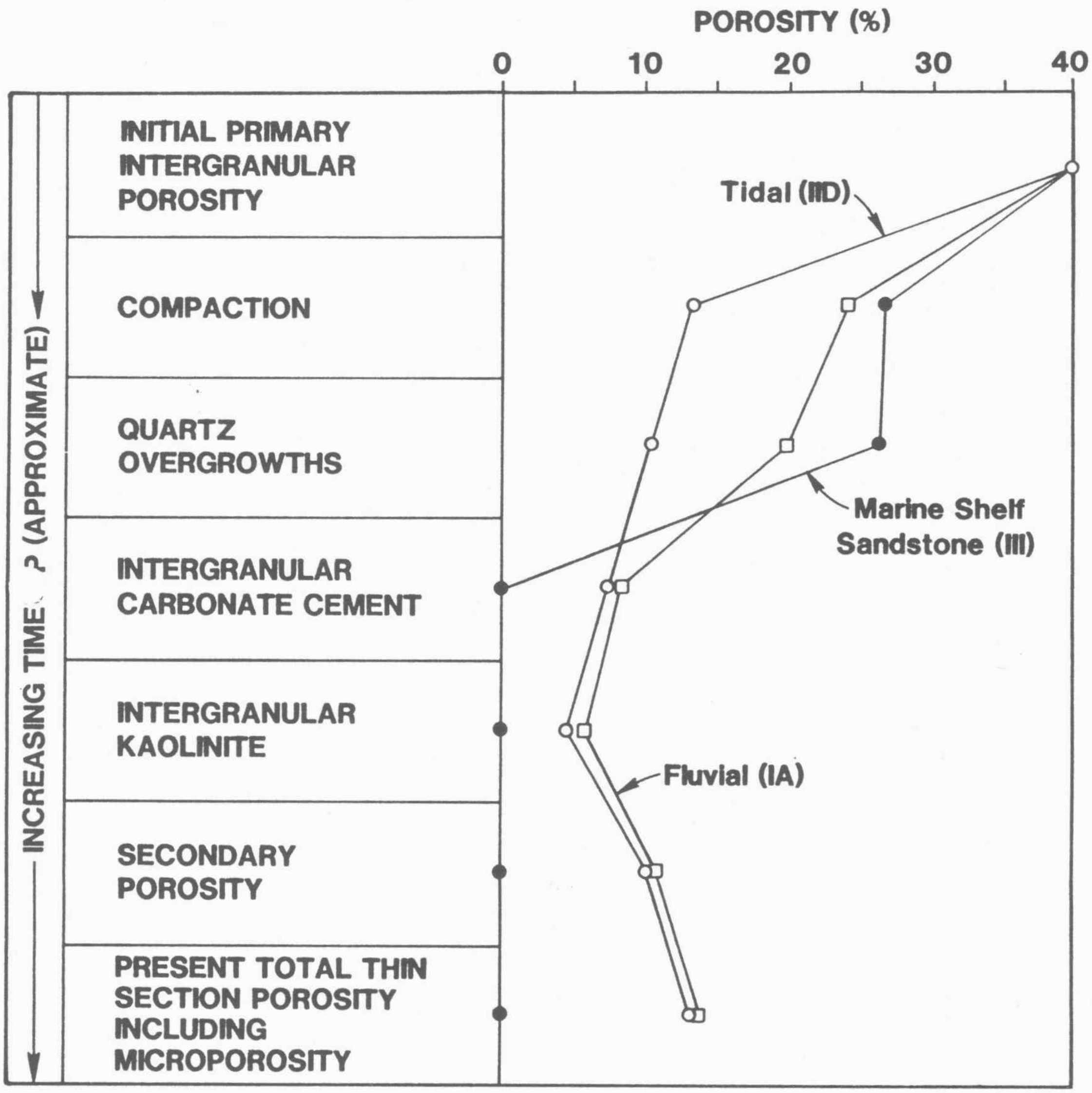


Fig. 9 - Diagram expressing the effect of the major diagenetic events on porosity for selected facies in SW Stockholm field. Interpreted sequence of porosity destroying events resulting from secondary processes in three Morrow reservoir sandstone facies: fluvial, tidal and marine shelf. Note that because rock properties differ among lithofacies, the method and amount of porosity diminution vary among the facies. Note especially the increase in porosity for fluvial and tidal sandstones due to formation of secondary porosity. Because diagenetic events commonly overlap through time with increasing depth of burial, this is not a time or depth diagram. For this diagram, however, except for compaction, depth and time generally increase downward. Comparison of the history of the Stockholm Tidal Facies (based on only two samples) and Stockholm Fluvial Facies indicates that compaction is more important in the Tidal Facies and that quartz overgrowths and carbonate cement are more important in the Fluvial Facies. However, the two facies, despite the differences in their history, have about the same total thin-section porosity. The Stockholm Marine Shelf Sandstone, Facies, developed pervasive carbonate cement that destroyed porosity. The later dissolution event did not dissolve the carbonate, probably because the low permeability did not permit entry of the leaching solutions.

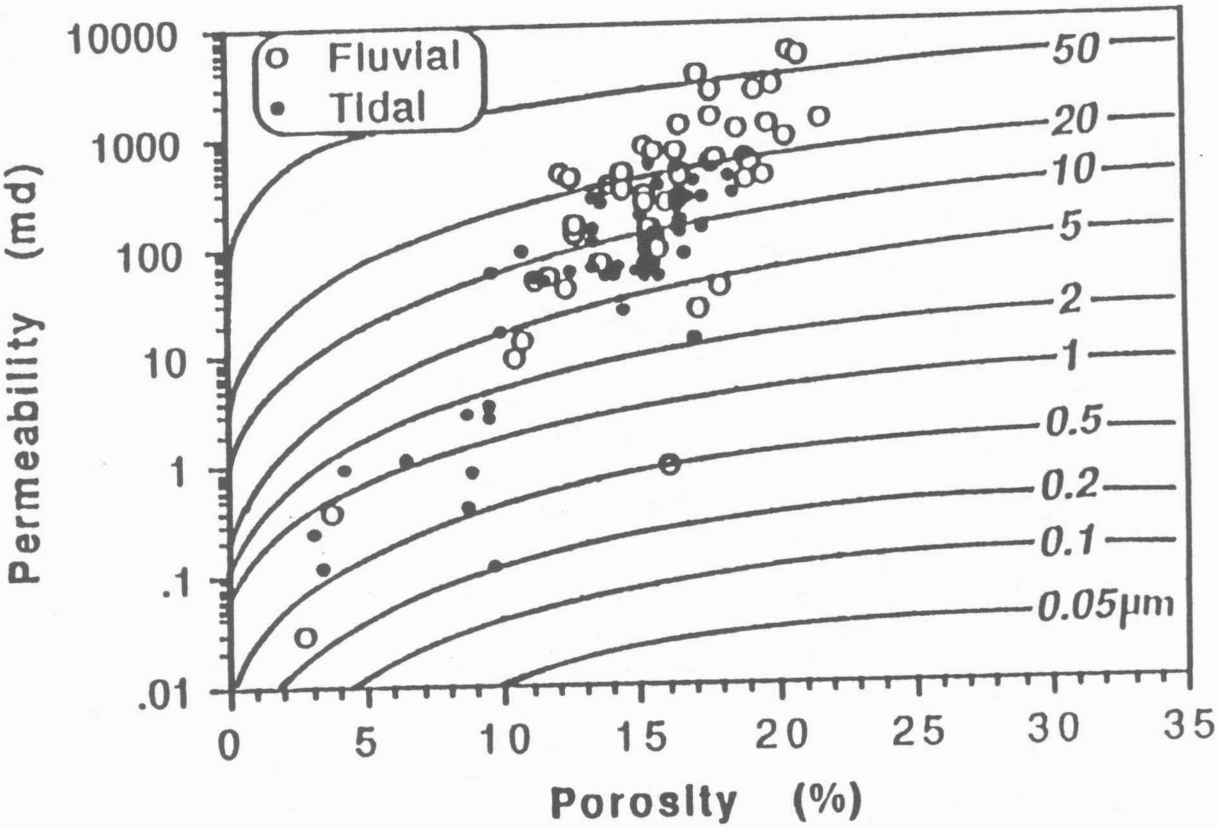


Fig. 10 - Plot of K vs. Ø graphical solution to Winland's equation (from Hartmann and Coalson, 1990) showing Stockholm Sandstone samples from Southwest Stockholm Field. The Morrow Sandstones that produce from Southwest Stockholm field are primarily fluvial valley-fill sandstones.

ORIGIN OF GRAY-SHALE LITHOFACIES ("CLASTIC WEDGES") IN U.S. MIDCONTINENTAL COAL MEASURES (PENNSYLVANIAN): AN ALTERNATIVE EXPLANATION

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ABSTRACT

Cyclic laminations in gray shales are noted above many major coal seams in the Illinois Basin. These features, which are termed "tidal rhythmites", indicate significant tidal influence during deposition of the roof strata. Many existing models, however, suggest fluvial dominance and crevasse splay deposition for such gray shales.

Based on sedimentological and paleogeographical considerations, appropriate deposition models require micro- to mesotidal environments, limited wave reworking, and a mud-dominated, tropical setting. Following these requirements, tidally influenced estuarine/deltaic models can be generated for roof strata of many Illinois Basin coals. This model is based upon modern mud- rich tidally influenced estuaries and deltas in near equatorial settings and can be used to explain occurrence of shales that lack obvious marine influence (based upon paleontology) above low-sulfur coals in the Illinois Basin.

INTRODUCTION

Gray-shale lithofacies -- The "gray-shale sequence" as defined herein is predominantly clay- and silt-rich shales interbedded with siltstones and generally fine-grained sandstones. In fresh exposures the shale ranges from medium light gray (N6) to dark gray (N3) and weathers to pale yellowish orange (10 YR 8/6) to medium brown (5 YR 4/4). These shales commonly contain well-preserved plant fossils, including upright trees (Shabica, 1970; DiMichele and DeMaris, 1987; Kvale et al, 1989), are generally lacking in marine fossils, and commonly contain sideritic concretions containing a variety of terrestrial and marginal marine fossils (Richardson and Johnson, 1969; Baird et al., 1985a, 1985b; Kuecher et al., 1990).

Our use of the term "gray shales" include interbedded mudstones and sandstones that exhibit a variety of primary structures ranging from lenticular to flaser bedding. Well-sorted siltstones that range from massive to laminated also occur in this sequence. Although these deposits are generally nonbioturbated, diverse trace-fossil assemblages do occur locally (see Archer and Maples, 1984). Lenticular sandstones up to 25 m thick and mudstone are common within the gray shale sequence. Primary structures associated with thinner sandstones (1 to 10 m) include massive, relatively structureless sandstones to ripple-laminated sandstones. These sandstones can contain abundant clay partings and flaser- and wavy-bedding. Thicker sandstone bodies (> 10 m) may exhibit a variety of large-scale structures including stacked sets of planar and trough cross-stratified sandstones.

Stratigraphic relations.--Gray shales and associated coal beds in the Illinois Basin can be divided into the Lower Pennsylvanian

(Atokan and older) and the Middle Pennsylvanian (DesMoinesian) coals. Stratigraphic correlations (Fig. 1) of the shales and coal beds used in the following discussion are based on Phillips and others (1985) and Shaver and others (1986). Lower Pennsylvanian coal beds are exemplified by the Block Coals of the Brazil Formation in Indiana. The Block Coals are latest Atokan (upper Westphalian C) in age (Eggert and Phillips, 1982). These coals have some of the lowest sulfur and ash values in Indiana. Coals are dull to moderately dull banded coals. They range from 0.2 to 2 m in thickness and tend to be podlike, discontinuous and of only local economic importance. The gray-shale lithofacies both overlies and (below the underclay) underlies these coals (Fishbaugh et al., 1989; Kvale and Archer, 1990).

Conversely, Middle Pennsylvanian coal beds are correlated over widespread areas and serve as stratigraphic markers in subsurface studies. Examples are the Colchester, Springfield, and Herrin coals. Overlying gray shales are the Francis Creek, Dykersburg, and Energy shales respectively. The coal beds are upper DesMoinesian (upper Westphalian D) in age and consist generally of bright-banded coals. They may be as much as 4 m thick. In areas of thick Springfield Coal, the generally bright banded coal may dull upward (Neavel, 1961; Hower and Wild, 1982). The gray-shale lithofacies overlying these coals is only locally developed and have been referred to as "clastic wedges" (Wanless, 1964). Thus instead of gray shales, the most common and areally extensive roof strata includes black, organic-rich shales and limestones. Sulfur and ash values for the coals can be low where thick gray shales are present, but average sulfur and ash values for these coals are considerably higher than those of the lower Pennsylvanian coals.

Past interpretations.--Previously, many of the gray-shale sequences have been interpreted as totally nonmarine and indicative primarily of fluvial and lacustrine environments (Franklin, 1939; Gray, 1962; Johnson, 1972; Edwards et al., 1979; Eggert, 1982, 1987; Eggert and Phillips, 1982; Burk et al., 1987). These interpretation is commonly based upon the proximity of the gray-shale lithofacies to coals (which need fresh porewater to form), abundance of upright lycopod trunks, well preserved plant fossils, presence of insect-wing fossils (Smith, 1871), and the absense of marine macrofossils.

The association of gray shales and low-sulfur coals has been repeatedly documented (Hopkins, 1968; Gluskoter and Hopkins, 1970; Hopkins and Nance, 1970; Edwards et al., 1979; Eggert and Adams, 1979; Eggert, 1982; 1987; Baird et al., 1985a,b, 1986; Burk et al., 1987). Gluskoter and Hopkins (1970) stated low sulfur values (2% or less) were related to relatively rapid deposition of more than 6 m (20 ft) of muds over the peats prior to deposition of sediments containing marine fossils. Although they did not state that the shales were freshwater, they suggested that such shales "lack distinct marine affinities (Gluskoter and Hopkins, 1970, p. 91). Many subsequent workers assumed that such shale must be freshwater and therefore fluvial/lacustrine in origin (Edwards et al., 1979; Eggert and Adams, 1979; Eggert, 1982, 1987; Burk et al., 1987).

Sandstones that interfinger with the gray-shale lithofacies have been interpreted as fluvial channels formed, at least in part, contemporaneously with coals (Johnson, 1972). For the Springfield and Herrin coals, these channels have been named the Galatia and Walshville channels, respectively (Johnson, 1972; Nelson, 1983). Similar gray-shale sequences (Dykersburg Shale and Galatia Channel) overlying the Springfield Coal were considered to be predominently fresh-water and related to crevasse splays (e.g., Eggert, 1982). In addition, gray shales within the Energy Shale of Illinois, which overlies the widespread Herrin Coal, have been interpreted as freshwater crevasse-splay and lacustrine deposits (Edwards et al., 1979; Burk et al., 1987).

CHARACTER OF GRAY-SHALE LITHOFACIES

Geometry.--Lower Pennsylvanian gray shales are areally extensive although underlying coals are not widely tracable. Field-based studies have indicated the lateral relations of gray shales and channel-form sandstones for this interval (Fishbaugh et al., 1989). Numerous large-scale strip and underground mines in Middle Pennsylvanian coals allows for more precise delineation of geometries for gray-shale lithofacies across large areas.

One of the more complete delineations of the gray-shale facies was presented by Hopkins (1968). A generalized model depicting the geometry of a clastic wedge, referred to as a "lenticular gray shale", and the relationship of gray shale roof strata to underlying low-sulfur coal was subsequently presented by Gluskoter and Hopkins (1970). These Middle Pennsylvanian gray shale sequences are commonly depicted as having wedge-shaped geometries when viewed in cross section (Fig. 2). In the idealized model, the wedges fine and thin away from this core facies. The wedges can locally punctuate the common repetition of thin, widespread beds of underclays, coals, black shales, and limestones that constitute normal Illinois Basin cyclothems (Wanless, 1964). At the outer margin of a wedge, the gray shale sequence thins and become discontinuous. Lenses or pods of gray shale are overlain by black shale and limestone (Fig. 3). Organic-rich black shales are the dominant roof type for the widespread Middle Pennsylvanian coals and areally comprise about 90% of the roof strata above Middle Pennsylvanian coals in the Illinois Basin (see distribution maps in Hopkins, 1968 and Gluskoter and Hopkins, 1970).

The Middle Pennsylvanian Energy Shale of Illinois is a typical gray-shale wedge. The wedge is up to 26 m thick along the sandstone-dominated Walshville channel (Fig. 3). Away from the channel the overall grainsize decreases and marine fossil content increases eastward over an approximate distance of 35 km. In addition to a lateral fining, there is also a pronounced coarsening upward of more proximal (coarser) facies over more distal (finer) facies (Burk et al., 1987).

ENVIRONMENTAL SETTING

Considerations for modern analogs.--Earlier Illinois Basin gray-shale models are based upon reconstructions that invoke single active fluvial channels or channels associated with birds-foot type deltas. We suggest such models are inaccurate. A more complete model should: 1) be tidally influenced with a limited tidal range (microtidal to mesotidal), 2) have limited marine wave reworking, 3) be mud dominated, 4) occur within a tropical setting, and 5) be laterally associated with extensive peat accumulations. These features are more commonly associated with estuarine models and tidally influenced muddy deltas in peat-producing coastal areas.

The Orinoco Delta in northeastern South America and the Mahakam Delta on the east-central coast of Kalimantan (Borneo) are examples of deltas that meet these criteria. Based upon the works of van Andel (1967) and Pfefferkorn and others (1988) for the Orinoco and by Allen and others (1979) for the Mahakam, important generalities can be summarized. Both systems have significant tidal influence, with tidal ranges of 1 to 3 m at the head of distributaries. Microtidal condistions exist as much as 150 km inland from the delta front. Both areas experience low wave energies and exhibit broad, mud-rich tidal flats that form much of the lower delta plain. Such flats have abundant plant debris and minimal marine fauna. Both occur in low latitude tropical climates and are laterally associated with peat-forming environments; however, high quality peats are not forming on active deltaic lobes.

Tidally influenced, mud-rich estuaries also potentially meet the criteria described above. There has been less study of tropical, tidally influenced estuaries than of temperate varieties. Many estuaries exhibit a tripartite subdivision whereas there is an upper, fluvial-dominated sand-rich part, a middle mud-rich part, and a lower, marine-dominated sand-rich part (Dalrymple et al., 1990). Even within the upper fluvial part of an estuary, tidal influence may extend inland for hundreds of kilometers (Schubel, 1984). A turbidity maximum occurs in the middle part of the estuary and this zone can experience very high rates of mud deposition (Allen, 1971). Clay particles are commonly aggregated by a variety of processes, including floculation along the saline-freshwater boundary and various types of biogenic processes. Rates of mud accumulation as high as 10 cm/week have been reported (Dalrymple and Makino, 1989). Many of the tidal rhythmites described from the Illinois Basin may have been deposited in such estuarine settings. Similar estuarine settings have been proposed for coal-bearing strata of the Cretaceous of Alberta (Rahmani, 1988) and Paleocene of Texas (Breyer, 1987; Breyer and McCabe, 1986).

Problems with existing models.--Several problems exist with the prevailing Pennsylvanian coal-measures models that relie heavily on nonmarine, fluvially dominated processes. Interbedded sandstones, siltstones, and shales in the gray-shale facies are commonly interpreted as crevasse splays (Burk et al., 1987). Crevasse-splay deposition is contingent upon the development of a significant natural levee system, such as that which characterizes the Mississippi River Delta or the Brahmaputra River. However, levee deposits have never been unequivocally documented from the Pennsylvanian of the Illinois Basin. Interpretations invoking crevasse-splay deposition, which date back to Johnson (1972) and Allgaier and Hopkins (1975), are problematic because "[n]o natural levees of the Walshville channel have been conclusively demonstrated" (Nelson, 1987, p. 12).

On-going studies of modern domed and planar peats present along the coast of Malaysia (eg. Cecil et al., 1988; Cecil and Englund, 1989) have proposed similarities between these peats and the coal-producing peats that were present during the Pennsylvanian in the eastern U. S. (including the Illinois Basin). Such studies have suggested similar climates and depositional environments for these modern and ancient peats. Currently in Malaysia, the rivers that are present between the peat deposits exhibit very low frequencies of flooding, even during the monsoonal season. Because the amounts of rainfall are constantly high throughout the year (and seasonal flooding is generally absent), channels are capable of confining discharge on a yearly basis. As a result, splays are very rare (James Staub, Southern Illinois University, pers. comm., 1989). In fact, splaying is so rare that peat deposits can form right up to the edges of the rivers.

Figure 4a illustrates a transgressive sequence and associated muddy, tidally influenced delta interpreted for the strata above the Springfield Coal in Illinois that can be compared to the clastic wedge model of figure 2. Rather than the fluvial model for gray-shale deposition the gray shales may have been deposited in a small, mixed fluvio-delta tidal. Alternatively, the shales could easily have been formed flanking a major active estuarine channel. Some of the thick "sandstone" channels of the fluvial models actually consist entirely of ripple-bedded sandstones and interbedded mudstones that can be explained in terms of mixed tidal-fluvial processes within an estuary rather than riverine processes. Much of the gray-shale component flanking the sandstone cores of the shale wedges may be related to the development and lateral shifting of subtidal to intertidal channels and flats flanking an active distributary channel complex or estuary margin (e.g., Dalrymple and Makino, 1989; Dalrymple et al., 1990) (Fig. 4b) rather than splays and floodplains. The pervasive occurrence of laminated mudstones and lenticular-, wavy-, and flaser-bedding, some containing well-defined tidal cycles, supports this interpretation.

CONCLUSIONS

The occurrence of tidally generated sedimentary structures within gray- shale lithofacies indicates that tidally influenced environments produced a significant portion of the gray shales above Illinois Basin coals. Many of the major coals may have been formed within coastal settings rather than the commonly depicted upper-delta plain setting. The gray-shale lithofacies was dominant during the Lower Pennsylvanian. Conversely, during the Middle Pennsylvanian, the relationship of the laterally restricted, volumetrically unimportant gray-shale wedges to the widespread black shale facies indicates only limited siliciclastic input to the coast after major peat-forming episodes. The lack of siliciclastics available to mantle the coals during ensuing transgressive phases resulted in high-sulfur coals in areas removed from the areas of gray-shale deposition.

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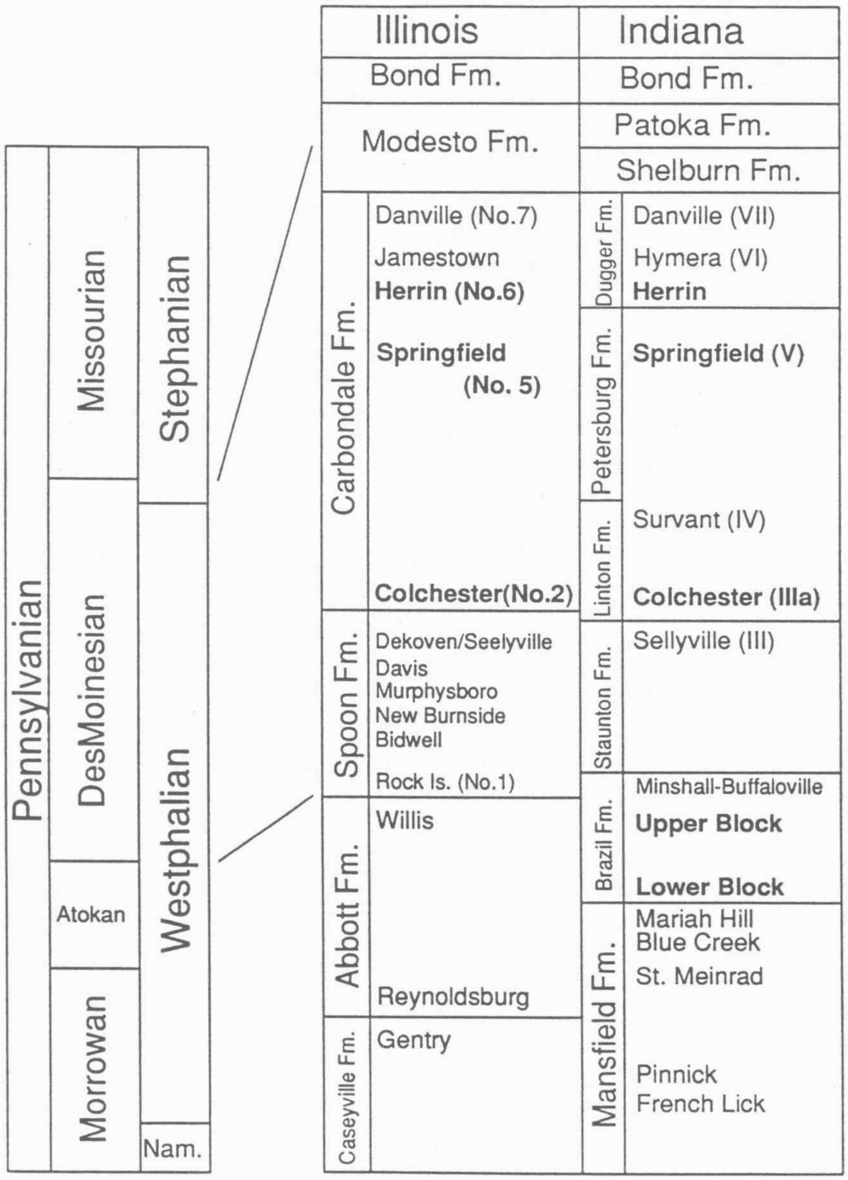

Figure 1. Generalized stratigraphy of the major coals in Indiana and Kentucky.

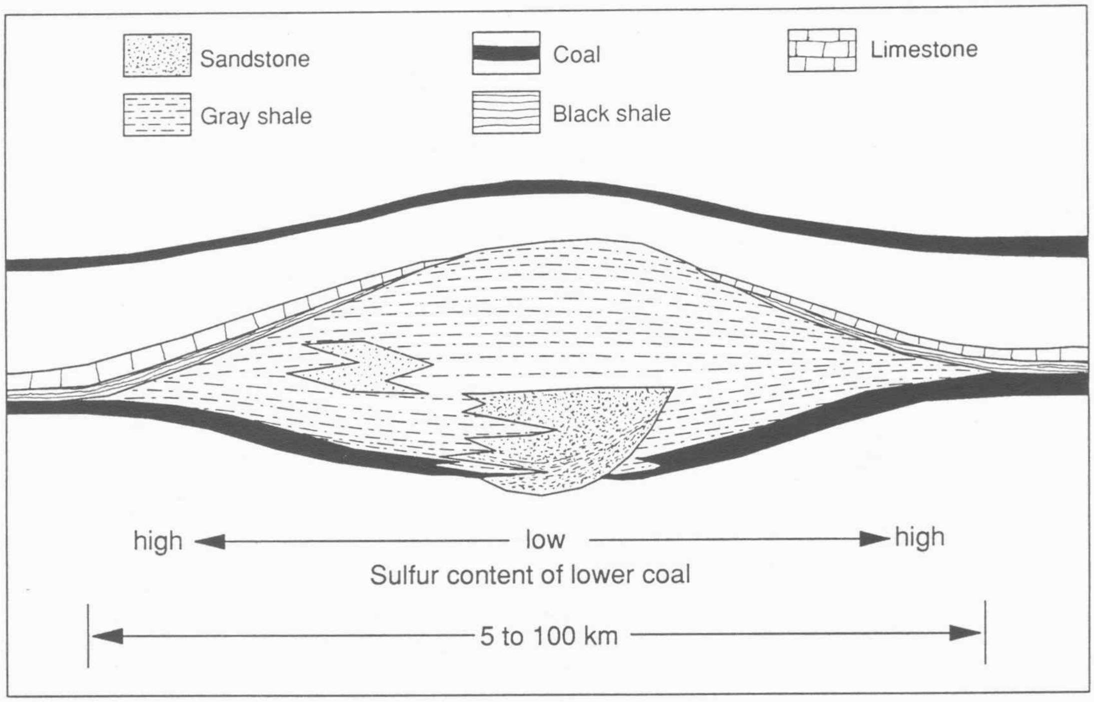

Figure 2. Diagrammatic section transverse through a gray shale clastic wedge. Modified from Gluskoter and Hopkins (1970, p. 94).

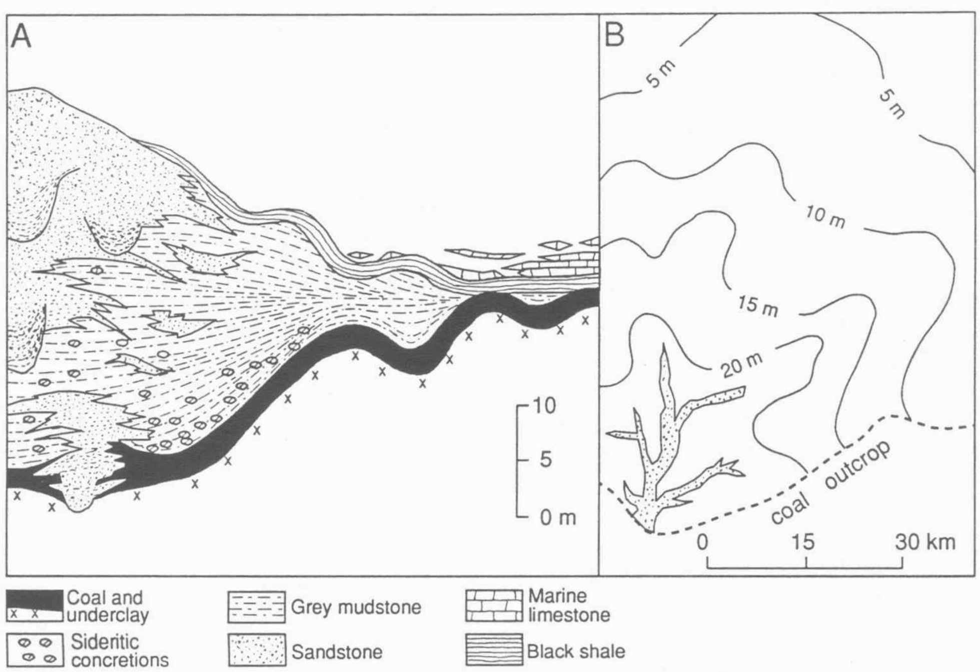

Figure 3. Schematic cross-section of the Francis Creek Shale above the Colchester Coal. Modified from Baird and others (1985a).

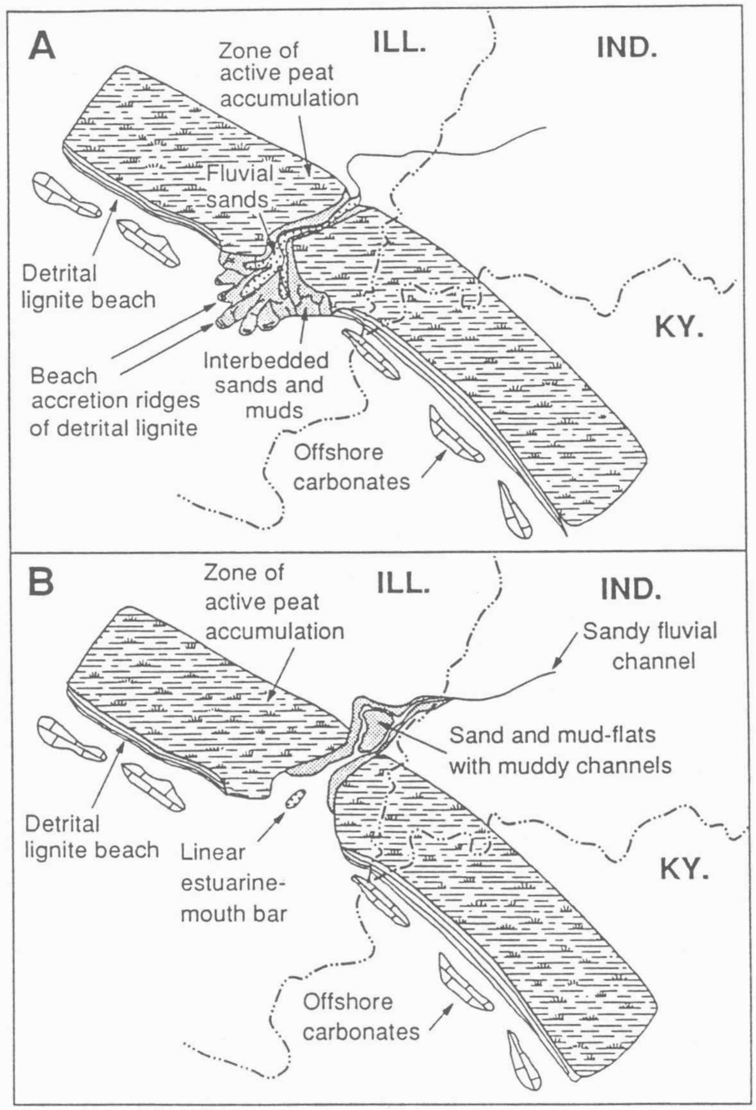

Figure 4. Gray-shale lithofacies depositional models based upon (A) muddy, tidally influenced delta and (B) estuarine system. In the deltaic system, potential lithofacies variaions formed by transgression of a mixed fluvial and tidal delta formed immediately following deposition of the peats that were to form the Springfield Coal. In the estuarine model, these same lithofacies are produced within a localized estuarine sequence developed during transgression of a preexisting fluvial system.

PEAT ACCUMULATION AND SEDIMENTATION IN THE LIVINGSTON PALEOVALLEY (MORROWAN), EASTERN KENTUCKY

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ABSTRACT

The Livingston Conglomerate Member of the Lee Formation partially fills a paleovalley 2 to 6 km wide and 34 km long. The dominant facies of the valley fill is a pebbly, crossbedded sandstone that represents the aggradation of fluvial bedload streams within the valley. The fluvial facies is capped by a thin coal or paleosol, inferred to represent peat accumulation on exposed interfluves within the paleovalley. The coal is capped by bioturbated, heterolithic facies of the Breathitt Formation, inferred to represent renewed transgression and the development of estuarine circulation during the final phase of valley filling. A second coal caps the valley fill and extends onto the paleoupland surface and is interpreted to represent exposure and progradation of a tidal coastline beyond the limits of the valley. Peat accumulation was controlled by topographic relief on the paleoupland surface and by subsidence of the estuarine fill within the paleovalley.

INTRODUCTION

The Livingston Conglomerate Member of the Lee Formation was delineated as part of a paleovalley fill during the joint U.S. Geologic Survey-Kentucky Geologic Survey mapping project (see references in Rice, 1984). The paleovalley is as much as 62 m (200 ft.) deep, 6.3 km (4 miles) wide, and can be traced for 34 km along the margin of the central Appalachian Basin (Fig. 1). The paleovalley is mostly filled by the Livingston Conglomerate Member (Fig. 2), which is texturely similar to other pebbly Lee sandstones of the central Appalachian basin, but differs from other members in that it occupies a very narrow paleovalley. Other Lee members occur in broad belts 64 to 91 kilometers wide, parallel to the strike of the basin, and onlapping the Early Pennsylvanian unconformity toward the west and north along the Cincinnati Arch (Rice, 1984; Chesnut, 1992). The Livingston Conglomerate, with its deep, narrow valley is much more similar to lower Pennsylvanian paleovalleys of the Illinois Basin than it is to other Morrowan-age sandstones of the central Appalachian Basin (Fig. 2).

UNIT DESCRIPTIONS

Livingston Conglomerate Member

The Livingston Conglomerate Member occurs in a belt 6.3 km wide and 34 km long (Fig. 1) and may be as much as 37 meters thick (Brown and Osolnik (1974). The member is dominated by pebbly, crossbedded, fine- to coarse-grained sandstones that interdigitate with true quartz-pebble conglomerates. Conglomerates may also contain chert and limestone cobbles (Brown and Osolnik, 1974; Wixted, 1977). Crossbeds consists of broad, stacked cosets of planar and trough crossbeds. Individual crossbeds range from 0.4 to 1.2 m tall. Trough crossbeds rarely truncate through more then two underlying bed sets, and distinct channel-form bodies are rare. Crossbed dip azimuths throughout the member are unimodal to the south and southeast (Fig. 1).

Livingston Coal

The upper part of the Livingston Conglomerate consists of a thin (0.5 to 3 m) fining-up sequence of sandstone and shale, which is capped by a paleosol or the Livingston coal (Fig. 3). The Livingston coal is a 0 to 25 cm thick (mean overlying strata are assigned to the Breathitt Formation.

Heterolithic strata and shales

The Livingston coal is sharply overlain by a 3 to 5 m thick sequence of bioturbated sandstones, siltstones and shales, overlain by 3 to 8 m of dark, carbonaceous shale (Figs. 3, 4). As much as 13 m of heterolithic strata and shale may occur between the Livingston and New Livingston coals within the paleovalley, although only 0 to 5 m occur between the New Livingston coal and the early Pennsylvanian unconformity surface along the valley margins.

In the lower part of the heterolitihic strata, 0.5 to 1.5 cm thick, sandstone laminae are separated by 0.1 to 0.5 cm of clay-draped siltstone laminae (Fig. 4). Between 1 and 4 clay-draped siltstone laminae may separate sandstone laminae. Sandstone laminae contain abundant Bergauria and Conostichus traces, while shalier intervals contain common Conostichus and rare Planolites, and Teichichnus trace fossils.

The bioturbated heterolithic strata is overlain by, and may grade laterally into dark, carbonaceous shales that contains disseminated fossil plant material, Planolites, and rare lingulid brachiopods (Fig. 4). Similar shales were reported to interdigitate with thin, quartz-pebble sandstones along the margin of the paleovalley (Brown and Osolnik, 1974; Wixted, 1977).

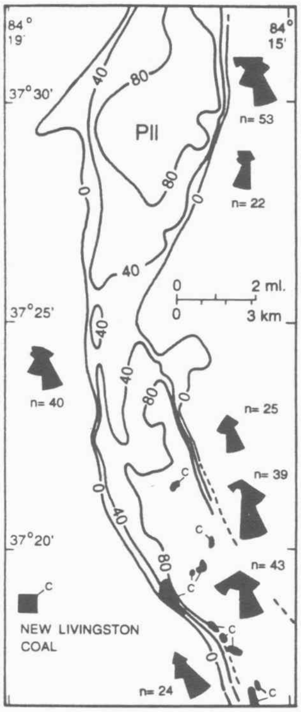
New Livingston Coal

West of the limits of the paleovalley, the New Livingston coal is stratigraphically the lowest Pennsylvanian coal exposed (Fig. 3). The coal is usually less than 50 cm thick, although it reaches thicknesses of a meter locally. Outside of the valley, the coal tends to drape irregular surfaces on the early Pennsylvanian unconformity (Fig. 3). Analysis of a thick coal pod, which drapes a small channel west of the paleovalley, shows that the coal has a low ash yield (12.6 to 17.9%), and low sulfur content (0.5 to 1.2 %) even though it fills channels and tends to be overlain by bioturbated strata (Eble and others, 1992).

Above the valley fill, the coal may drop in elevation, split into thinner coals and coaly shales, or pinchout (Fig. 3). Where split, the coals interdigitate with sediments similar to the bioturbated heterolithic strata of the Breathitt Formation within the paleovalley proper. Rare Planolites, Rosselia, and Teichichnus burrows were found in shaly intervals between two coal splits, while Bergauria were noted in a sandstone channel between coal splits.

INTERPRETATION

The scour at the base of the paleovalley can be thought of as a Type 1 unconformity surface and represents lowstand truncation of Mississippian carbonates along the Cincinnati Arch. Deposition



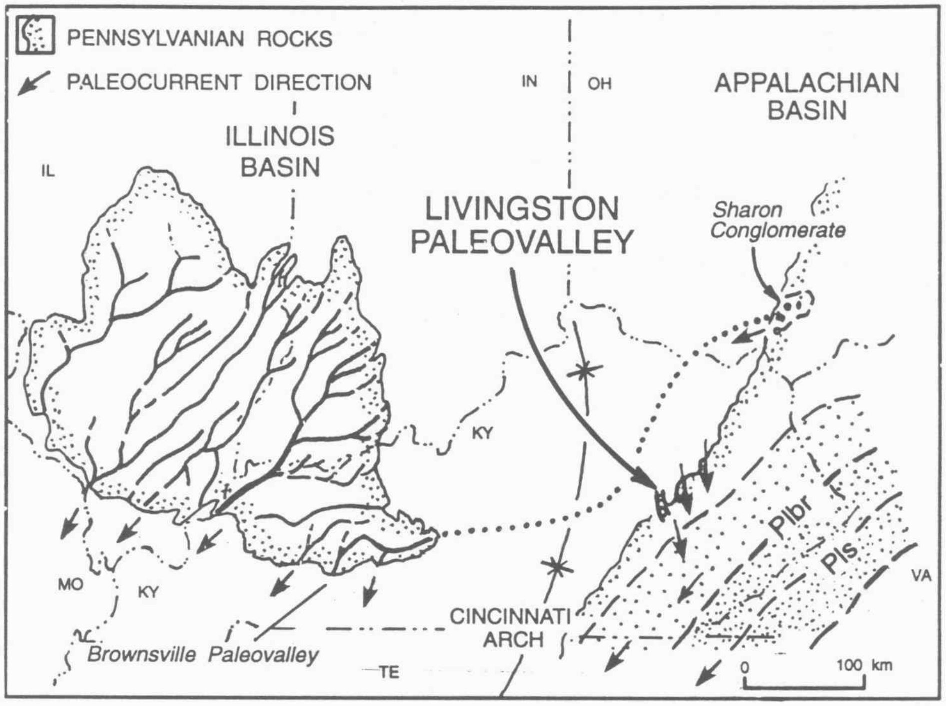


Figure 1. (LEFT) Isopach map of a part of the Livingston Conglomerate Member. Paleocurrent roses reflect crossbed measurements within the member (after Brown and Osolnik, 1974; Wixted, 1977; Rice, 1984).

Figure 2. (RIGHT) Regional paleogeology of Kentucky and surrounding areas during the Morrowan. Plbr=Bee Rock Sandstone, Pls=Sewanne Sandstone (after Bristol and Howard, 1971; Rice, 1984; Droste and Keller, 1989; Greb, 1989; Chesnut, 1992).

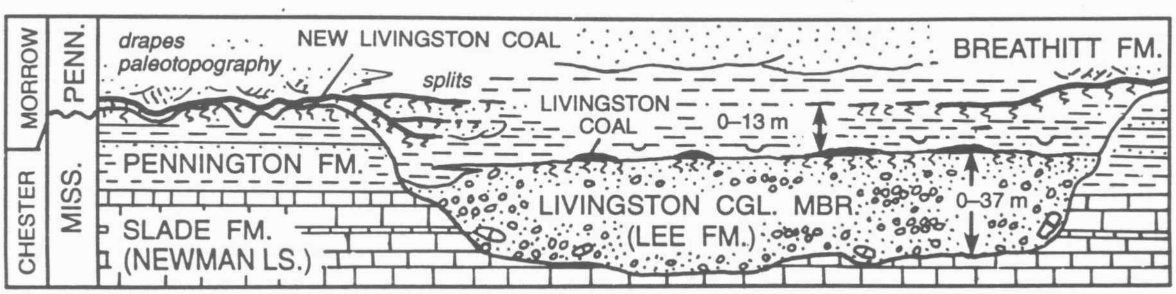


Figure 3. Schematic section of the Livingston Paleovalley showing inferred facies relations discussed in this report.

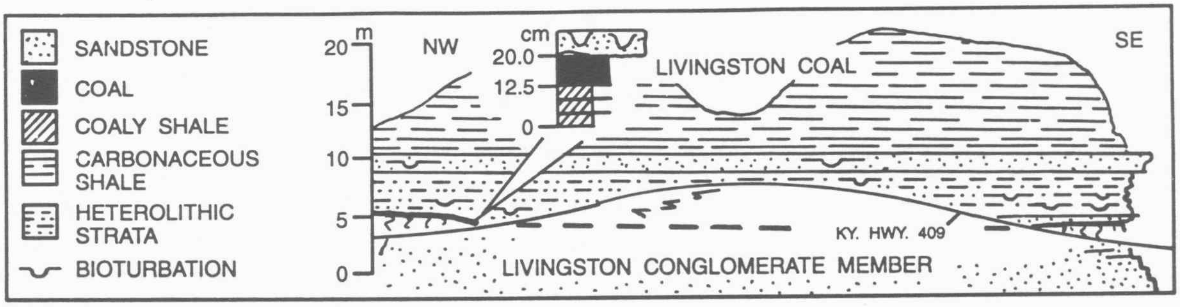


Figure 4. Outcrop of the Livingston coal and overlying strata. The New Livingston coal occurs 10 to 13 m above the Livingston coal here, and caps the paleoupland surface beyond the valley.

within the valley was dominated by bedload, fluvial streams that deposited the Livingston Conglomerate Member (Wixted, 1977; Rice and Weir, 1984). Chert and limestone cobbles at the base of the unit were derived locally from exposed Mississippian carbonates along the valley walls. Erosional contacts between cosets are mostly even-parallel indicating broad, rapidly aggrading rivers that did not greatly disect preexisting deposits within the valley. Quartz pebbles were derived from extrabasinal sources in the northern Appalachians similar to sources for the basal Morrowan paleovalleys of the Illinois Basin (Greb, 1989).

Sediment flux from the source area ceased or bypassed the valley when the valley was nearly filled. Peats of the Livingston coal accumulated on top of abandoned fluvial deposits and exposed interfluves within the valley. The lateral restriction of the coal to the paleovalley represents topographic control on accumulation, and a period of stillstand in which fluvial aggradation ceased.

The peats were buried by bioturbated, heterolithic strata of the Breathitt Formation inferred to represent subtidal to lower tidal flat sedimentation similar to sedimentation in modern estuaries (Terwindt, 1981; Allen, 1991, Nio and Yang, 1991). Bergauria and Conostichus indicate subtidal to lower tidal flat conditions (Miller and Knox, 1985; Greb and Chesnut, in press), and the rhythmic-appearing laminae above the coal may record amalgamated tidal rhythmites. Each sandstone laminae is separated by clay-draped siltstone laminae. The rhythmic appearance of the strata is suggestive of partial preservation of tidal cycles, but complete cycles were probably precluded by periodic biotic reworking of the sediment substrate. Bioturbated sandstone laminae contain numerous dwelling burrows of Bergauria, which probably indicates some period of time, on a scale of days to seasons, between sedimentation.

Dark, carbonaceous shales with rare Planolites, Rosselia, and Teichichnus cap the heterolithic strata within the paleovalley and may indicate continued bayhead advance and the development of muddy, middle estuarine circulation similar to modern tripartate estuaries (Allen, 1991). Similar dark shales have been interpreted as lagoonal and estuarine sediments in other parts of the basin (Knox and Miller, 1985; Greb and Chesnut, 1992, in press). Where the Livingston coal is absent, estuarine sedimentation is inferred to have reworked underlying fluvial deposits leading to the interbedded shales and thin, quartz-pebble sandstones reported by previous workers. The abundant channeling and sand-dominance of Breathitt facies on the paleoupland surface relative to the muddier facies within the paleovalley is probably reflective of the accomodation space within the valley as compared to the paleovalley margins.

The New Livingston coal records a period of shoreline progradation over the underlying estuarine deposits when the valley filled. Eble and other (1992) inferred that the coal represents a planar swamp that may have become slightly domed toward the top in thicker pods. The splitting of the coal into the valley, and drop in elevation undoubtably reflect subsidence of the thick, muddy, estuarine sediments in the top of the valley fill, and possibly concurrent tidal sedimentation marginal to the New Livingston mire. Interestingly, the coal often has a low sulfur content even though it is overlain by strata deposited in brackish-marine waters.

DISCUSSION

The Livingston Paleovalley is the deepest of several incised channel systems along the western margin of the central Appalachian Basin. Rice (1984) inferred that the Livingston Paleovalley began as a small channel system which breached the Sharon-Brownsville Paleovalley headward, and then deepened and widened its valley. The connection of the Sharon Conglomerate of Ohio and the Brownsville (Drakesboro) Paleovalley of the Illinois Basin (Fig. 2) was inferred by connecting outlyers of quartz-pebble conglomerates on the Cincinnati Arch.

It is also possible that the Livingston Paleovalley represents the incisement of a channel system on the flanks of the structurally high Cincinnati Arch when base-level was lowered during formation of the Rockcastle (part of the Bee Rock) or Sewanee Sandstones to the east in the basin (Fig. 2). Tectonic controls are interpreted to have influenced other Lee sandstones of the Appalachian Basin (Chesnut, 1992), and the paleovalleys of the Illinois Basin (Greb, 1989).

Significantly, each of the Lee sand belts exhibits a similar vertical section to the Livingston Paleovalley with fluvial conglomeratic sandstones capped by coals and estuarine facies. In some cases, estuarine facies may both underly and overly valley-capping coals. These facies are significant because they provide evidence for transgressive tracts during valley backfilling, and a basis for combining the diverse marine to deltaic models that have been applied to the Lee sandstones.

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VALLEY FILL DEPOSITS OF THE CRETACEOUS DAKOTA SEQUENCES COMPRISING A MAJOR AQUIFER SYSTEM IN KANSAS

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BACKGROUND

This contribution is intended to supplement the Dakota Formation core (KGS Jones # 1) that will be available for inspection during the Saturday evening core workshop. The core extends from the uppermost Permian to the Cretaceous marine shales and limestone of the Graneros Shale and Greenhorn Limestone. This contribution is part of an ongoing multi-disciplinary project by the Kansas Geological Survey to map the Dakota Aquifer, and determine the availability of potable water in this system. The Dakota Aquifer includes the Cheyenne, Kiowa, and Dakota formations. Stratigraphic analysis of these units was undertaken in order to understand the distribution of the sandstone, which is the major aquifer lithology. The formations comprising the Dakota aquifer of Kansas were subdivided into unconformity-bounded sequences and, within that framework, were related to their environment of deposition, such as deltaic, coastal plain, fluvial, etc. (Fig. 1).

Sequence stratigraphy is the study of rock relationships within a framework of repetitive, related sedimentary deposits, known as sequences. Sequences are bounded by sub-aerial unconformities (and their correlative conformities) that formed in response to a change of relative sea level. Using the log data base compiled by the Kansas Geological Survey, the intervals comprising the Dakota aquifer were investigated using sequence stratigraphic concepts, and the major sandstones of the system were identified as valley fill deposits.

Major falls of sea level cause incision of fluvial valleys, and the formation of major, regional, subaerial erosional surfaces, or unconformities, in exposed areas (Fig. 2). The Dakota aquifer system is bounded at its base by a Lower Cretaceous erosional surface that cuts across both Jurassic and Permian units in Kansas. Deposition during sea level lowstand and the early part of a subsequent transgression infilled the incised river valleys in Kansas, while to the north and west coastal and marine sediments accumulated in the Cretaceous Seaway. The Cheyenne Formation, which overlies the basal Cretaceous unconformity in Kansas is the basal Cretaceous incised valley fill. Transgression following Cheyenne deposition resulted in deposition of coastal deltaic and marine sediments of the Kiowa - Longford succession above the Cheyenne (Franks, 1979).

Another major drop in sea level formed an unconformity or sequence boundary that separates the Kiowa Formation from the overlying Dakota Formation. Following the stratigraphic nomenclature of the Dakota Formation along the Front Range of Colorado (see Weimer and Land, 1972) two major sandstones are recognized in the Dakota Formation in Kansas, the D and J sandstones (Fig 3, 4). The basal J sandstone of the Dakota Formation was deposited as an incised valley fill during the lowstand to early transgressive periods following this fall in sea level. In extreme northwestern Kansas, the remnants of the subsequent transgressive marine deposits are preserved as a thin section of the Huntsman Shale. A minor fall of sea level followed the incursion of the Huntsman Sea and developed a less prominent erosional boundary. Such minor falls in sea level tend to rejuvenate river systems, and basal fluvial deposits in the lowermost Dakota D sequence are coarser grained than the sediments underlying the unconformity. The Rocktown Channel Sandstone Member of the Dakota is an outcrop expression of the D sandstone in Russell County. This valley fill consists of fine to coarse, cross-bedded fluvial sandstone that occurs in discontinuous, narrow (a few miles wide or less) sinuous belts (Rubey and Bass, 1925). Interbedded with the fluvial D and J sandstones are alluvial plain clay deposits of the Terra Cotta Member of the Dakota Formation.

After the minor drop of relative sea level that formed the D/J unconformity, sea level gradually rose and deposition of marine deposits progressed from west to east over the basal fluvial D sediments. The uppermost Dakota D section contains estuarine to deltaic deposits as shown in the Jones #1 core. The overlying marine Graneros Shale was deposited during the transgressive event that drowned the deltaic/estuarine Dakota D sands and the coastal plain clays of the Jansen Member. The Greenhorn Formation, which was deposited at a time of maximum flooding with little sediment influx, is a widespread marine limestone.

KGS Jones #1 Core

The KGS Jones #1 core was drilled in northcentral Lincoln Co., Kansas (NE NE NE s. 2, T. 10 S., R. 8 W.) and extends from the lower Greenhorn Limestone to the uppermost Permian (Fig. 5). On display is the upper part of the core from near the base of the D sandstone to the lower Graneros. In this core the D and J sandstones are not distinct, and may be amalgamated, or perhaps only one of the two sequences is present. Also, Dakota sandstones are not well cemented, and are commonly lost during coring. In the Jones, core the base of the fluvial sandstone was not recovered. The section on display comprises a single transgressive unit recording fluvial through marine deposition.

12-15 ft — **Description:** Fossiliferous limestone.
Interpretation: Clear water, marine.

15-59 ft — **Description:** Dark grey shale with a few interbeds of sandstone. Fossils are most common in upper half and include fish teeth, bivalves, and unidentifiable shell debris. Fossiliferous limestone (packstone) at 33 ft. Sandstones contain ripple-scale cross bedding, burrows, low-angle cross bedding.
Interpretation: This is the marine Graneros Shale. The sandstone beds are likely storm deposits. The bed at 46 ft may contain hummocky cross stratification.

59-120 ft — **Description:** Interbedded sandstone, and mudstone to siltstone. Sandstone medium to fine grained, well to poorly sorted. Finer grained facies laminated to bioturbated. Sedimentary structures include individual burrows to bioturbation, clay drapes, starved ripples, horizontal to low angle cross bedding. Plant debris is abundant. Rooted zone at 78-80 ft. Molds of small bivalves at 60 ft. Sequence consists of several cycles with sharp bases, some with lags of rip-up clasts. Cycles commonly coarsen upwards, and are darkest at base.
Interpretation: This interval represents a range of nearshore to coastal environments. The rooted zone at 78-80 ft was probably subaerially exposed. Low angle cross-beds in a very well sorted fine-grained sandstone at

95 ft are similar to beach deposits. The amount of bioturbation and the presence of fossils suggests a strong marine influence. The cycles appear to be shallowing upwards from an erosive base, into dark, marine, bioturbated sediment, up to shallow water to exposed facies at their tops. These may represent small oscillations in relative sea-level.

120-154 ft **Description:** Interbedded sandstone and mudstone to siltstone. Finer grained units bioturbated or with faint horizontal bedding. Sandstone bioturbated or with faint horizontal bedding, rare clay drapes. Locally abundant plant debris. Sequence organized in cycles with sharp bases, commonly fining upwards. Wood-chip lag at 140 ft.
Interpretation: Increased bioturbation, and rare clay drapes indicate estuarine to marine environments. Cycles may result from channel migration, or sea-level changes.

154-170 ft **Description:** Interbedded mudstone and sandstone at top to mudstone at base. Faint horizontal bedding in mudstone, abundant pyrite and siderite(?) Interlaminated sandstone and clay with horizontal laminations, starved ripples, rare burrows, and possible rhythmic bedding. Sharp contact at base.
Interpretation: Alternating sand laminae and clay drapes indicate alternating energy conditions, as can occur in tidal settings. Presence of burrows may indicate a marine influence. This facies is very similar to many Pennsylvanian and modern estuarine deposits.

171-228 ft **Description:** Quartz arenite, fine to medium sandstone, mostly well sorted. Poorly sorted muddy sandstone at 207 ft. Sedimentary structures include ripple-scale cross bedding, horizontal bedding (possibly upper flow regime), low angle possibly large-scale cross-bedding at 177-171 ft. Lower contact not preserved.
Interpretation: Deposition in high energy, shallow water conditions with little mud and constant flow. Probably fluvial channels.

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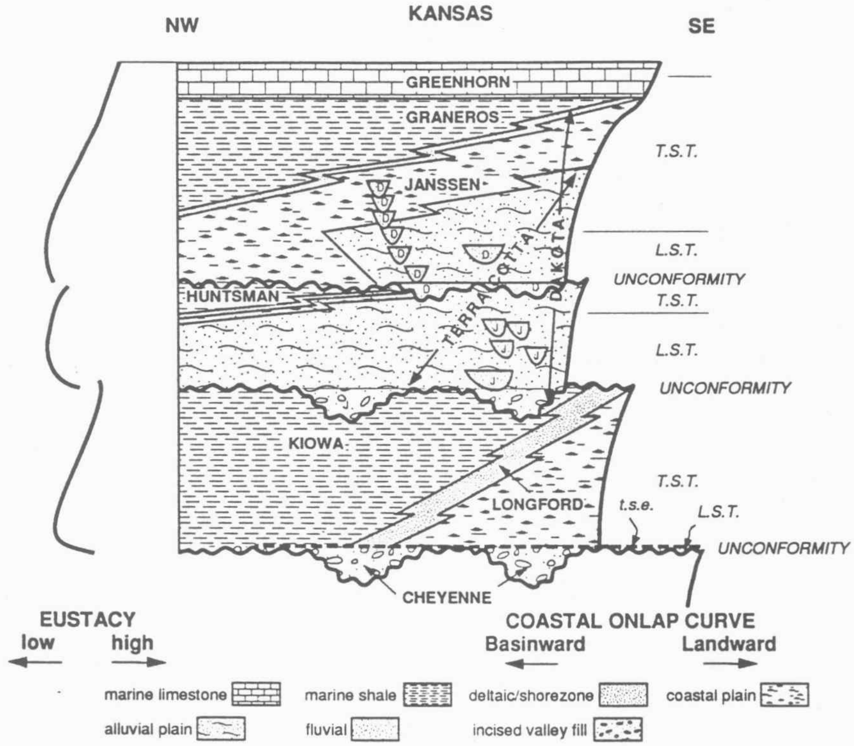

Figure 1. Stratigraphic relationships of the Dakota Aquifer in Kansas.

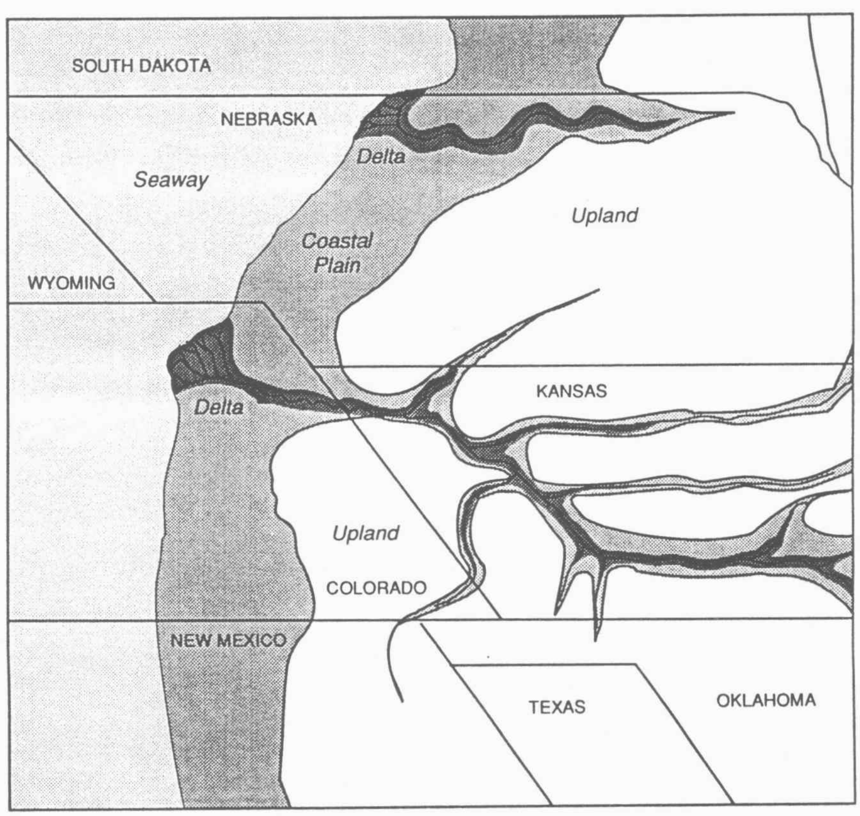

Figure 2. Midcontinent geography during deposition of the middle portion of the Dakota aquifer. From Macfarlane et al. (1991).

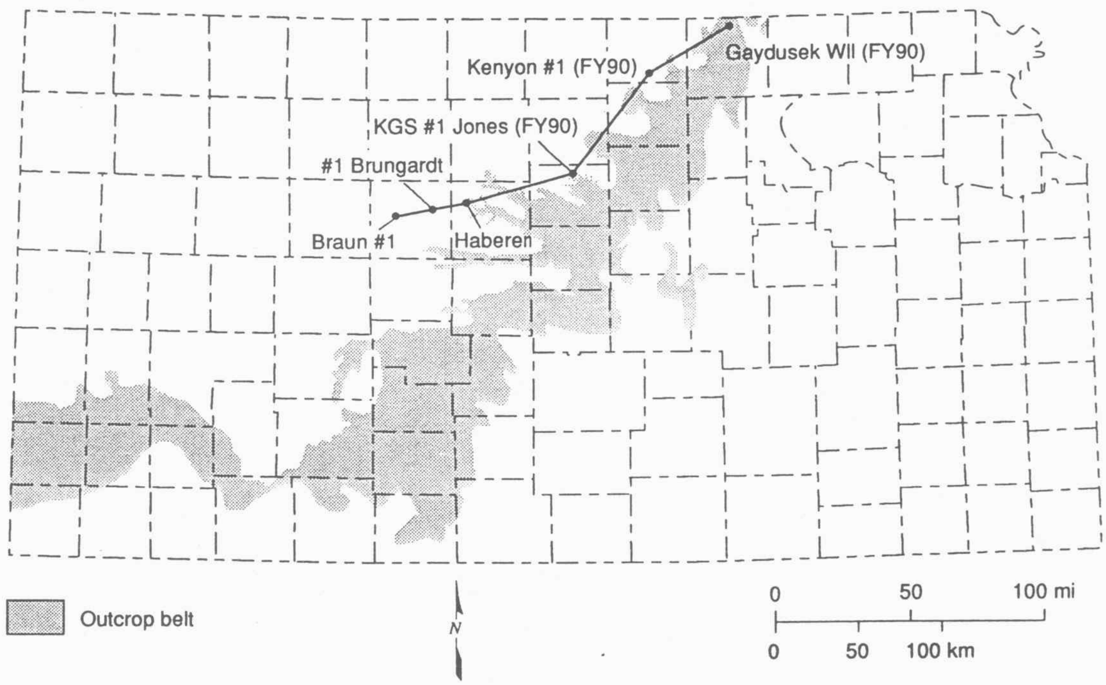

Figure 3. Outcrop belt of Dakota Aquifer, and location of cores and cross section in Fig. 4. From Macfarlane et al. (1991).

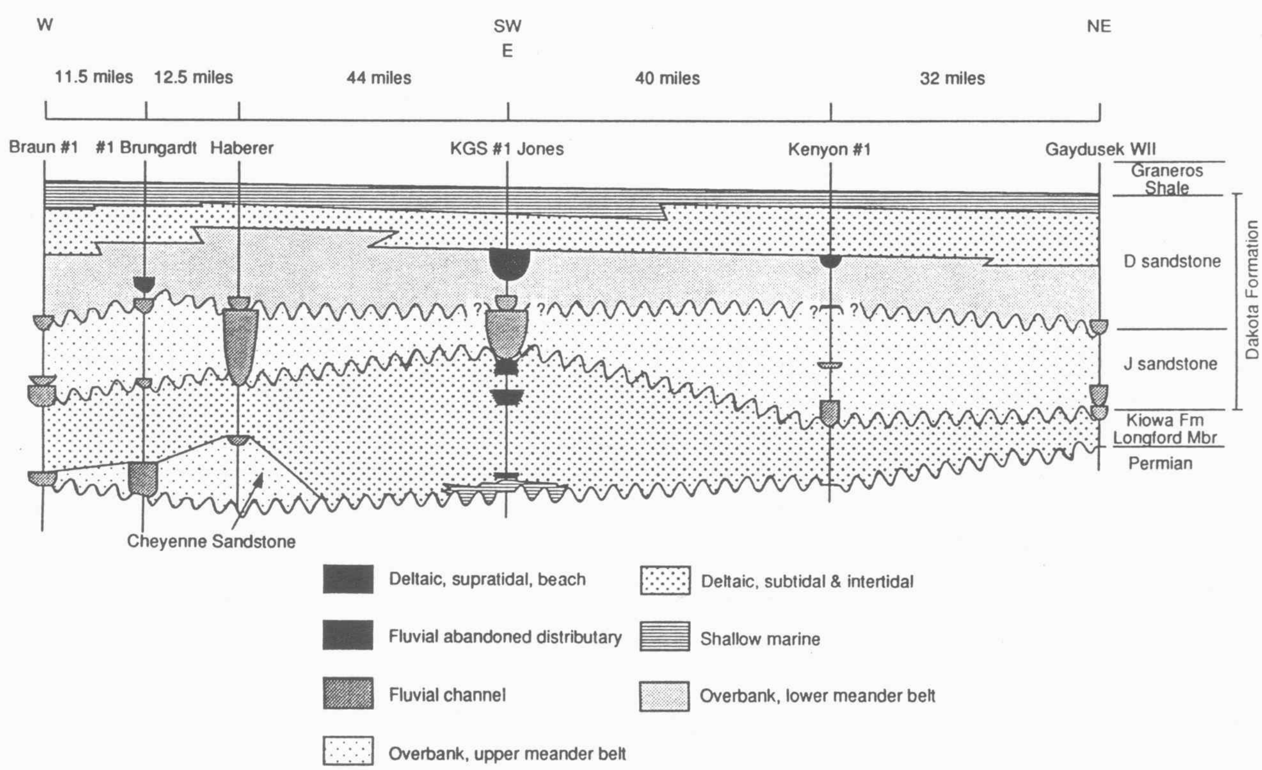

Figure 4. Cross section along coring transect. From Macfarlane et al. (1991).

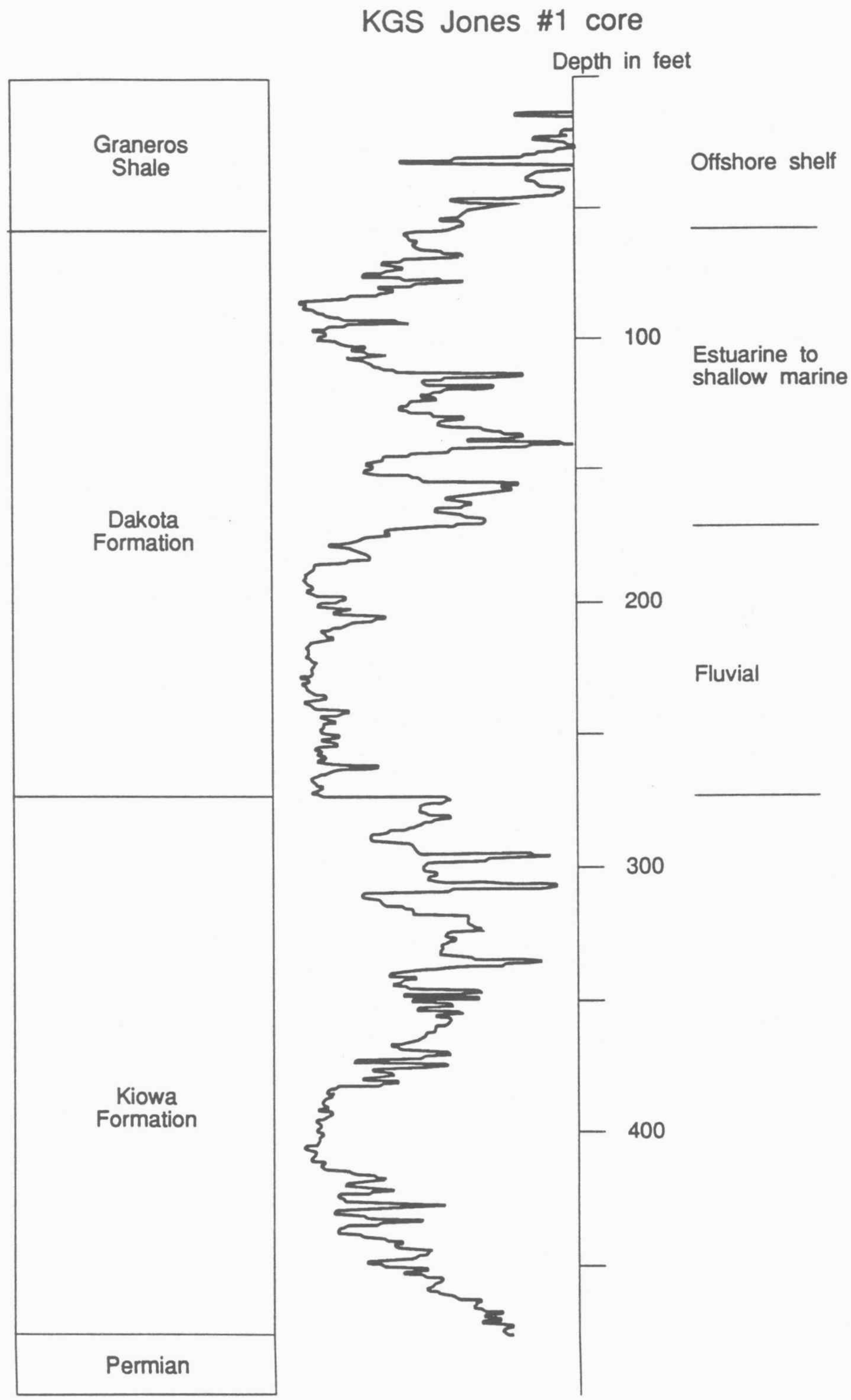

Figure 5. Gamma ray profile of the KGS Jones #1 core.

OCCURRENCE AND ENVIRONMENTAL SETTING OF ESTUARINE TIDAL RHYTHMITES: EXAMPLES FROM THE BAY OF FUNDY (CANADA), BAY OF MONT SAINT MICHEL (FRANCE), AND CARBONIFEROUS COAL BASINS (U.S.A.)

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Tidal rhythmites are a unique type of sand-mud alternation in which a vertically accreted record of tidal cyclicities has been preserved in the form of rhythmic variations in the thickness of the sand-mud couplets. Tidal rhythmites in which neap-spring periodicities are clearly displayed require the following general conditions. 1) A "sheltered" setting is necessary to allow the regularity of the tidal signal to be preserved without random "noise" introduced by non-tidal processes. This places constraints on the geographic setting where rhythmites can be formed: the area must be protected from variations in wave energy, and cannot be exposed to significant, aperiodic variations in current speed such as those associated with fluctuating river flow. Thus, rhythmites are unlikely to form either on an open coast, or in the inner, fluvially dominated but tidally influenced portion of a fluvial system. 2) High rates of sediment supply are needed to allow deposition of a faithful record of the tidal periodicities. As most of the deposition occurs from suspension (see more below), this necessitates that suspended-sediment concentrations were high, perhaps due to high tidal-current speeds in nearby tidal channels. 3) Finally, because tidal rhythmites commonly contain mud drapes, rhythmites are best developed in the intertidal zone (exposure favours consolidation and preservation of the mud drape), on bar tops and channel margins, and in abandoned channels, rather than within active channels.

Although these three conditions could be met in a number of different coastal settings, including estuaries and deltas, the following discussion will concentrate on rhythmites in modern and ancient, estuarine facies because such occurrences have been studied in more detail to date. Detailed studies have been completed on the sedimentology of tidal rhythmites in two, modern estuarine settings: the Bay of Mont Saint Michel in northwestern France, and the Cobequid Bay-Salmon River area (Bay of Fundy) in eastern Canada. These localities are both macrotidal and exhibit some of the highest tidal ranges in the world, but differ in several significant ways. Firstly, the geometry of the two bays is significantly different: the Cobequid Bay-Salmon River area (CB-SR) lies within an elongate, fault-controlled basin, and exhibits a gradually flaring, funnel shape, whereas the Bay of Mont Saint Michel (MSM) is a more open, coastal embayment with a shorter, less elongated estuarine portion. Because of these geometric differences, wave action is much less throughout CB-SR than it is in the outer part of MSM. The composition of the sediment comprising the rhythmites also differs markedly; in MSM the sediment is primarily carbonate of marine origin, whereas the CB-SR sediments are siliciclastics that are dominantly of marine origin but with a minor fluvial contribution. The details of the tidal regime also differ between the two areas, with the Bay of Fundy tidal system exhibiting a well-developed diurnal inequality which is not present in MSM.

Despite these differences, the rhythmites in both settings share many similarities. The smaller wave sizes in the CB-SR estuary mean that tidal rhythmites are more widespread than in MSM, but it appears (on the basis of limited data in the case of MSM) that rhythmites are best developed in the inner portions of the two estuaries where wave action is minimal. The rhythmites in both areas display a similar range of facies and sedimentary structures, including both planar- and ripple-bedded types. Sand to mud ratios also span a similar range, with ripple-bedded types ranging from flaser-, through wavy- to lenticular-bedded varieties. The common occurrence of climbing ripples, and the lack of significant erosion of the mud drapes, indicates that most of the sand in the rhythmites is carried to the site of deposition in suspension, with limited, tractional reworking to form ripples. Bioturbation by infaunal organisms is absent, due to the high sedimentation rates (several millimetres to centimetres per tidal cycle), periodic exposure and fluctuating salinities, but superficial biogenic structures (trails and trackways) formed by vagrant, marine and terrestrial organisms are common on the surfaces of the mud drapes.

In the CB-SR and MSM estuaries, the rhythmites with the most spectacular cyclicity form in higher portions of the intertidal zone. This may be because the weak currents and subaerial exposure (which promotes dewatering and consolidation of the mud layer) which characterize the upper intertidal zone favour preservation of the mud drapes. Within active channels, higher-speed currents tend to erode mud drapes and produce amalgamated sand layers in which the rhythmicity is difficult to detect. Rhythmite deposition in the subtidal zone is not precluded, but the extent to which they form there in estuaries remains to be determined.

Ancient examples of tidal rhythmites occur in all of the major Carboniferous coal basins in the eastern United States. These deposits have been studied most extensively in the Eastern (Illinois Basin) and Western Interior Basins (Forest City and Cherokee). Reconnaissance work in the Appalachian Basin also indicates the occurrence of tidal rhythmites in some coal-bearing sections. Some Carboniferous rhythmites occur within incised-valley fills which exhibit a vertical succession from fluvially dominated, to estuarine, to more marine-influenced depositional environments. Other examples, which are less laterally extensive, were formed as channel fills. The rhythmites are interpreted to have formed in an estuarine setting. Both siliciclastic and carbonate tidal rhythmites, that may be counterparts of those in CB-SR and MSM respectively, have been documented. Indeed, many similarities exist between the modern and ancient examples in terms of bedding types and physical and biogenic structures. In all cases, the stratification is flat to gently inclined. The thicknesses of individual neap-spring cycles in all areas is generally in the centimeter to decimetre range. The sand layers are flat bedded or rippled, and climbing ripples are as common as in the modern examples. Likewise, biogenic structures are limited to surficial tracks and trails. The lateral extent of individual sand-mud couplets observed in open-pit mines reaches 200 m; this is similar to values recorded in CB-SR, but exceeds the extent of laminae in MSM where occurrences are apparently restricted to smaller, abandoned and secondary channels. A principal difference of the Carboniferous examples is that the overall thickness of rhythmite-bearing sections, which can reach 7 m, is greater than in the modern examples where thicknesses are typically 2-3 m. The explanation for this may lie in the underlying paleogeographic and paleoclimatic differences between the Carboniferous (tropical coastal plain) and modern (temperate, rocky coasts) examples. The particularly thick, Carboniferous rhythmite sections commonly lie directly above coals and encase upright tree trunks; thus, the accommodation space required for rapid deposition of the thick rhythmites may have been produced (and accentuated) by the compaction of the underlying peat. Thick peat accumulations are not present in the modern analogues.

The study of tidal rhythmites is particularly useful because the inherent cyclicities are a unequivocal indicator of deposition in a tidally influenced setting. The recognition of rhythmites in the Carboniferous coal basins has been particularly useful because such facies were formerly interpreted as terrestrial, including lacustrine and floodplain, deposits. The widespread occurrence of rhythmites in both modern estuaries and ancient inferred estuarine settings clearly shows that this environment is conducive to rhythmite formation and preservation. In this setting, rhythmites may be particularly useful in distinguishing subenvironments along the fluvial to marine transition, because of their sensitivity to variations in physical and biological processes. Thus, the longitudinal variations in the degree of fluvial overprinting, the amount and type of bioturbation, and the extent of wave reworking which characterize estuaries should influence the types of rhythmites present, and the perfection of preservation of tidal cyclicities. Additional comparisons of modern examples and ancient counterparts is needed to test such hypotheses.

Several additional, unresolved questions remain regarding the origin and distribution of tidal rhythmites. The available modern analogs are restricted to areas with large macrotidal ranges, and a complete search for rhythmites in meso- to microtidal settings has not been undertaken. Thus, the lower limit of tidal range at which cyclical rhythmite production occurs is not known. In addition, the best-documented rhythmites in both the modern and ancient occur in estuarine depositional systems. Whether or not rhythmites are common in other settings, such as tidally influenced deltas, remains to be documented.

TIDAL INFLUENCES IN MARINE CARBONATES, UPPER PENNSYLVANIAN, MID-CONTINENT, U.S.A.

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INTRODUCTION

Older ideas of epicontinental seas (Shaw, 1964, p.7; Irwin, 1965) envisioned them as shallow puddles of marine water reaching far onto the craton across extremely broad, "pool table" flat shelves. Tides were influential in only a relatively narrow (tens of miles wide) zone of high energy where they impinged the bottom and were damped out before reaching the shoreline, which was hundreds of miles further inland. More recent work on modern tidal deposits, however, has led to the recognition of tidal influence in many ancient epeiric sequences. Although most of these examples are from coastal or shelf margin deposits, tides can also influence the open marine portion of shelves. Both theoretical models and field studies suggest that tidal deposition may have been more influential in the highstand seas of the Pennsylvanian Mid-Continent than previously recognized.

THE NORTH SEA--A MODERN PROCESS ANALOG

Although offshore tidal deposits have been described from all over the world, the most systematically studied tidal basin is the North Sea (Stride, 1982). It lies between latitudes 50°N and 60°N and is open to Arctic oceanographic influences along its northern margin. At its southern end is the English Channel, a narrow passage to the Atlantic Ocean which concentrates tidal energy and magnifies tidal amplitude and current velocities in its immediate area. The North Sea's tides have three amphidromic points fed by energy input from the northern opening; their positions are determined by the wavelength of oceanic tides, the shape and size of the basin margins, and the range and distribution of water depth (Pethick, 1984, p.60-63). This resonant system helps to maintain relatively high tidal energy far from the shelf margin to the north, producing a seven meter tidal range at Skegness on the English coast and up to three meters at Cuxhaven in Germany (both approximately 1000 km from the northern margin). Although the sediment type and geographic position of the North Sea are very different from the Mid-Continent, Pennsylvanian sea, it can serve as a partial analog for tidal processes which may have been acting offshore at the same time that tides were influencing nearshore deposition like that of the Douglas Group (Archer, 1991; Section 4, this volume).

Tidal bedforms on the floor of the North Sea are controlled by the velocity and direction of local tidal currents. Depositional bedforms range in size across three orders of magnitude from ripples (wavelength<60 cm, height<5 cm) to sand banks (wavelength≈5-20 km, height≈40 m), and are made of sand-sized or coarser material. Erosional features, cut by daily tidal currents ranging from less than 50 cm/sec to more than 150 cm/sec, can be cut into any type of sediment from mud to gravel. A very important point illustrated by North Sea deposits concerning tidal sedimentary structures is that bedforms may appear to be the result of unidirectional flow if any asymmetry exists between ebb and flood current velocities (i.e. herringbone crossbedding is not the only feature characteristic of tidal regimes; see Section 2, this volume). This can lead to a mosaic of sediment types, sediment structures, and current indicators varying on the scale of the resonant amphidromies which control local flow. In addition, the orientation of a bed-form's long axis and avalanche surfaces can be perpendicular or parallel to the tidal currents. Reconstructing detailed paleoflow on the basis of sedimentological indicators in such a complex system is virtually impossible, but using them to estimate the contribution of tidal influence is a very profitable exercise.

NUMERICAL SIMULATIONS

Any paleoceanographical model concerning tides will depend on the complex interaction of a large number of factors like aerial and bathymetric geometry of the basin, source of tidal energy (independent or co-oscillating), and a number of astronomical factors. Numerical models for two times when there was an epicontinental sea covering parts of North America have been published; they concern the Cretaceous Western Interior Seaway (Slater, 1985) and the late Devonian Catskill Sea (Slingerland, 1986; Ericksen et al., 1989).

Slater's (1985) study, although it makes a number of simplifying assumptions like uniform depth and simplified basin margin geometry, makes a number of interesting points. One, theoretically, epeiric seas can have tides. Two, tides largely reflect the independent component rather than any external, co-oscillating driver. Three, although tidal amplitude is highest when basin depth allows fully developed resonance, amphidromies develop at all depths tested. Just to provide an idea of the order of magnitude of tidal range and current velocities produced, the most "realistic" run (parameters most like those known for the Cretaceous) achieved maximum tidal amplitude of 86 cm and current speeds of 10 cm/sec. As Slater points out, however, these could easily be increased locally by shoreline geometry or bathymetric features.

Two models simulating circulation in the late Devonian Catskill Sea are in the literature (Ericksen et al., 1989; Slingerland, 1986). The more recent one incorporates not only tidal effects but also paleoclimatic and paleogeographic factors to develop an integrated model of sediment transport. This sea is much more similar to the Pennsylvanian than the Cretaceous seaway in its general orientation and shape; it is a near equatorial embayment open to the west. A major difference is the well defined shelf break within the Devonian sea that is not clearly defined in the Pennsylvanian. Using an external co-oscillating tide of 60 cm Ericksen et al. (1989) found the development of amphidromic nodes and tidal amplification up to 200 cm on some parts of the shelf (not including further magnification due to local effects). With the addition of wind driven currents, a complex patchwork distribution of deposition and erosion was probably present across the Devonian embayment.

TIDES IN EPEIRIC SEAS

Klein and Ryer (1978) present literature evidence for tidal influence in clastic, shoreline deposits of eleven ancient seas. They point out that broad shelves in the Holocene do not result in damped tides but are correlated with higher tidal amplitudes and current velocities; extrapolation of this pattern implies well developed tides in broader epeiric systems. Some offshore sand bodies in the Late Jurassic and Cretaceous Western Seaway have been interpreted as the result, at least in part, of tidal currents (Brenner, 1980). These studies suggest that tides in broad epeiric seas were present and influenced both coastal and offshore deposits.

Concerning the Pennsylvanian, there is gradually accumulating evidence of tidal influence in numerous environments throughout the epeiric embayment. In the Appalachians of eastern Kentucky, Martino and Sanderson (1993) report tidally influenced deposits in an estuarine sequence. Study of Illinois Basin deposits also reveals sedimentary features characteristic of the middle to upper portion of an estuary (Kvale and Archer, 1991). Both of these examples are from paleocoasts where tidal waveforms are amplified as they enter shallow water or a confining estuary mouth and do not prove strong tidal influence in the open marine portion of the basin. Their significance is in the fact that there were tides in the basin under at least some conditions. The Appalachian example, however, despite being coastal, represents deposits laid down near the time of maximum transgression: presumably during carbonate deposition in the Mid-Continent. Tidal energy must have been largely conserved as it traveled along the east-west axis of the basin to be able to influence deposits in the far eastern and most interior coastline.

In Kansas, previous studies and recent work both strongly suggest some role for tides in the open marine part of the Pennsylvanian embayment. Hamblin (1969) studied crossbedding in marine limestone of the Kansas City Group focusing mainly on oolitic and bioclastic calcarenites. In every limestone unit investigated he found a bimodal distribution in the direction of crossbedding with paleocurrent directions running northeast-southwest. Bimodality strongly supports a tidal interpretation for these depositional structures because of the bidirestional nature of tidal flow. Storm or wind generated currents would have resulted in either less consistent or, at best, unimodal paleoflow directions. Besides the cross-bedded calcarenites, which are generally found only near the top of limestone units, Hamblin also suggested that "hummocks" lower down in the Winterset and Iola Limestone Formations are megaripples. Personal observation (Olszewski, 1993) and fortuitous weathering of a roadcut exposure of the Iola near Osawatomie in Miami County reveals that these "hummocks" really are megaripples with a coarse, crossbedded internal structure. These features make up the major part of the thickness of the Raytown Member of the Iola Formation from Miami to Allen Counties. The lithology of these fossil dunes is primarily made up of phylloid algal blades and intraclasts in a sparry, relatively mud-free matrix suggesting that they are the product of persistent, strong currents over a large area and therefore are probably not the result of intermittent storm action. The final hint that tides were influencing deposition comes from the phylloid algal thickenings found in virtually all the Missourian cycles (Heckel and Cocke, 1969). Heckel (1972) described calcarenite filled channels through a phylloid algal buildup in the Stanton Limestone Formation in southeastern Kansas. As analogs to these bodies he proposed the tidal channels which separate reefs along the Trucial Coast. Subsurface delineation of a similar algal body in the Raytown Limestone indicates a number of lobes on top (Fig. 1). These lobes can be interpreted as flood and ebb tidal deltas on either side of the algal barrier. And finally, personal observation (Olszewski, 1993) of the Raytown Member in a core from northwestern Missouri confirms the existence of supratidal carbonate mud deposits similar to those reported by Mitchell (1981) in a different core from Nebraska. Although tidal influence is expressed differently in different parts a given limestone body--carbonate mudflats near the coastline, dunes on the open shelf, channels and deltas associated with the phylloid algal ridges, and bimodal crossbed orientations in the shoaling cap--there is consistent indication of well developed tides in the open marine, carbonate deposits of the Pennsylvanian Mid-Continent.

FIRST ORDER APPROXIMATION OF MID-CONTINENT TIDES

Pethick (1984) described a means of approximating the position of the nodal lines of North Sea tides by making a series of simplifying assumptions about the basin.

Viewing the basin as a rectangle open on its northwestern side with average uniform depth of 50 m and being pumped by the oceanic tides of the North Atlantic (tidal period equals 12.4 hours), the tides can be treated as shallow water waves described by the following two equations:

$C=\sqrt{gD}$ (1)
$L=CT$ (2),

where C = tidal wave speed
g = gravitational acceleration
D = average depth
L = tidal wave length
T = tidal wave period.

If average depth is presumed, it becomes a simple matter to find tidal wave length. This value will determine the position of the nodal lines. In Pethick's (1984) example the amphidromic points of the North Sea do, in fact, lie on these lines.

Using Witzke's (1990) paleogeographic reconstruction of the Pennsylvanian and presuming a series of possible average depths, it is possible to solve these equations and plot the approximate position of the nodal lines for each depth. In figure 2, two depths, 50 m and 100 m, and a tidal period of 12.4 hours were used. This last parameter is the same value used by Pethick (1984) and has certainly undergone change since the late Paleozoic due to evolution of the Earth-Moon system (Slater, 1985); the influence of these changes has not been considered. Other factors potentially influencing nodal positions are the non-rectangular shape of and the presence of land masses within the basin. The embayment gets progressively narrower to the southeast; this would help to conserve or possibly amplify tidal energy. The land masses and islands would focus tidal energy much like the English Channel does today, so there would probably be strong tidal currents around these features. Finally, because tidal energy increases toward the equator, the external oceanic tides driving the Pennsylvanian embayment would probably have been stronger than the driver for the North Sea, so they could most likely be maintained further inland than in the modern example. No attempt was made to incorporate independent tides despite their importance in other studies (Slater, 1985).

Any amphidromic nodes like those depicted in the models of Slater (1981), Ericksen et al. (1989), and Pethick (1984) would lie somewhere on or near these lines. In addition, these are where tidal amplitude would be smallest and tidal current velocities greatest. Highest tides and slowest currents, on the other hand, would occur at the midpoints between nodes. The nodal line positions can be tested by tracing the lateral changes in deposits along the margin of the basin to see if tidal influence in the sediments varies as predicted. One problem with this approach would be distinguishing local amplification or attenuation from overall basin pattern; another is overcoming the effect of changing basin depth and margin shape as sea level rises and falls. These changes would influence both the position and number of nodal lines through a transgressive-regressive cycle.

CONCLUSIONS

The realization that tides can play an influential role in modern marine basins and recognition of tidally derived sedimentary features in the stratigraphic record refutes older models of tideless epeiric seas. This raises the distinct possibility that tides were present during the open marine highstands of the Pennsylvanian embayment. Physical evidence in the form of bimodal cress-bed distributions in shoaling calcarenites, flood/ebb tidal lobes across phylloid algal mounds, tidal mud flat deposits, and high energy dune deposits in the carbonate portion of Missourian cycles and for tidal estuarine deposits in the correlative siliciclastic rocks of the

Appalachians strongly supports the notion that tides were present.

Numerical models based on the principles of physical oceanography can be constructed to predict the nature and importance of tides in ancient basins. A first order approximation based on presumed tidal wave length and basin depth makes predictions about the positions of high tidal amplitudes and fast tidal currents. To refine predictions of nodal point positions, current velocities, and tidal amplitude more elaborate modeling needs to be conducted.

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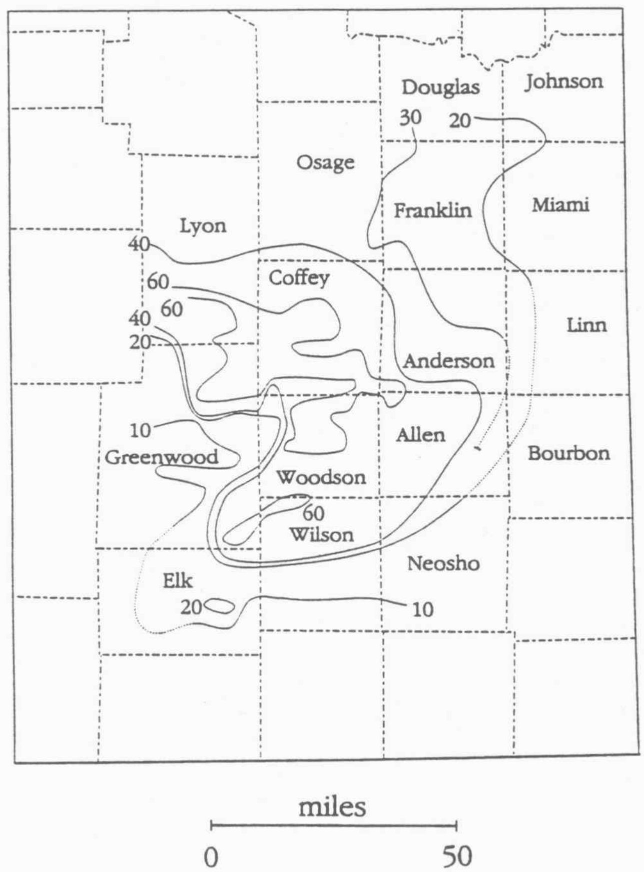

Figure 1. Isopach Map of the Iola Limestone Formation in Southeastern Kansas. Thicknesses are in feet and dashed lines are inferred. Note the symmetrical lobes on the 60 foot isopach which trend perpendicular to the northwest-southeast axis of the phylloid algal thickening. These are interpreted as flood and ebb tidal deltas consistent with current directions found in Hamblin's (1969) study.

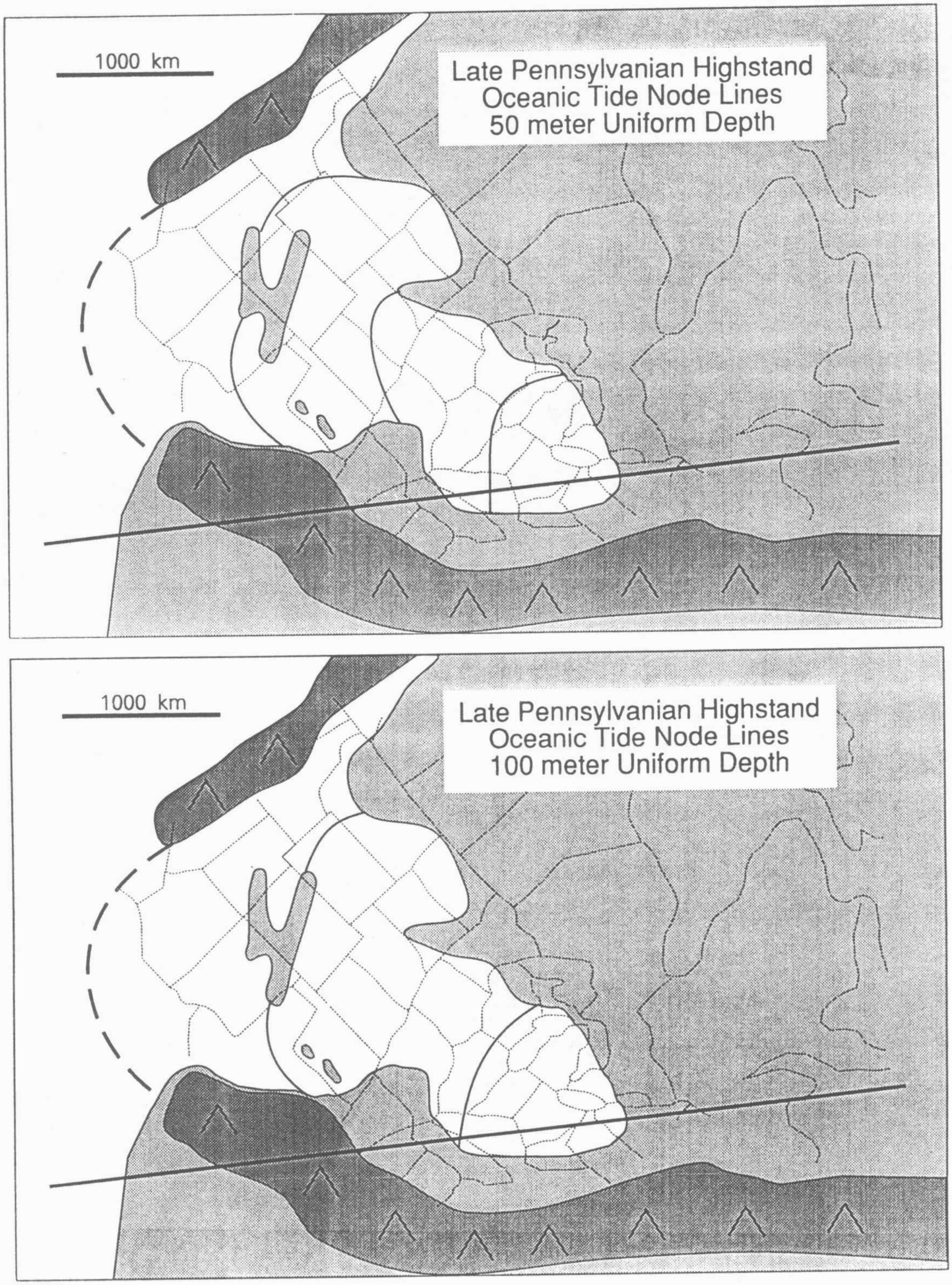

Figure 2. Tidal Nodal Lines for the Pennsylvanian Embayment. Nodal lines were placed at the tidal wave length found by the method described in the text. [a, TOP] Given 50 m uniform water depth and 12.4 hour tidal period, wavelength is 986 km. [b, BOTTOM] Given 100 m uniform water depth and 12.4 hour oceanic period, wavelength equals 1397 km. Paleogeographic reconstruction adapted from Witzke (1990).

GENERALIZED CLIMATO-STRATIGRAPHIC ANALYSES OF THE EXPOSED PERMO-PENNSYLVANIAN SECTION OF KANSAS

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ABSTRACT

Based on the compilation of Zeller (1968) for outcropping Permo-Pennsylvanian rocks of Kansas, we have subdivided the stratigraphic section into nine major lithofacies. Based upon their most common occurrence in the stratigraphic section, these lithofacies dominate the section in the following order (from oldest to youngest): 1) coals, 2) gray mudrocks and sandstones, 3) black mudrocks, 4) carbonates, 5) cherty carbonates, 6) fossiliferous mudrocks, 7) variegated mudrocks, 8) evaporites, and 9) variegated dolostones, siltstones, and sandstones. These nine lithofacies have a climatic significance; the order described above goes from generally wetter to generally drier conditions.

When the composite section is reduced to these major lithofacies, large-scale lithostratigraphic variations are evident. The Desmoinesian exhibits a gradual upward shift from siliciclastic coal-bearing "Illinois Basin type" cyclothems to a more carbonate-rich system. Carbonates continue to increase in relative abundance through the Missourian; it is within this part of the section that "Kansas-type" cyclothems dominate. The lower Virgilian exhibits a shift back toward Desmoinesian-type cyclicity; however, the mid- to upper Virgilian shows a dramatic shift in lithofacies. This shift, which is toward drier climate lithofacies, continues throughout the Permian, although the rate of change diminishes in the upper Leonardian and more-or-less stable conditions persist through the upper Leonardian, Guadalupian, and lower and middle Ochoan.

We attribute the overall shift of dominant lithofacies from Desmoinesian through Guadalupian paleogeographical shift from a humid tropical equatorial climate through dry seasonal to arid paleolatitudes. However, the smaller-scale changes (i.e., greater similarities of the Desmoinesian to parts of the Virgilian than to the intervening Missourian) indicates linear paleolatitudinal shifts cannot explain all the stratigraphic variability; shorter-term climatic and eustatic cyclicity must have also been operative.

INTRODUCTION

Despite decades of debate it can still be argued that understanding of late Paleozoic "cyclothems" has not progressed significantly since the application of the concept by Wanless and Weller (1932). A recurring problem in the use of cyclothem models and cause of much misunderstanding is that specific models, which are perhaps suitable for specific stratigraphic ranges, have instead been used to characterize large parts of the Pennsylvanian-Permian stratigraphic interval (see Klein, 1992). These misunderstandings are compounded because not only is the stratigraphic nomenclature of the U.S. and Europe considerably different, but also because considerable nomenclatorial differences exist between eastern and midcontinental U.S. stratigraphy (Fig. 1).

The cyclothem concept, invoked to explain vertical lithologic variation in the Illinois Basin of the midcontinental U.S., was employed by Moore (1936, 1949, 1950) to describe cycles in Pennsylvanian strata of Kansas. Moore described and defined a variety of cyclothems, as well as cycles of cyclothems (megacyclothems) and others (Jewett, 1933; Elias, 1937) described similar cycles in the Permian. Subsequent to these earlier descriptive works, the concept has been applied to a variety of scales of cyclicity. For example, one type of cycle, termed a "Kansas cyclothem," (Heckel, 1984) only occurs in its complete development within specific parts of the Permo-Pennsylvanian section of Kansas and is best developed within part of the Missourian and middle Virgilian. However, this type is not a pervasive cycle that occurs throughout the entire Permo-Pennsylvanian section. Conversely, the original type of cycle described from the Illinois Basin, or "Illinois-type cyclothem", also occurs in the Kansas section and is particularly well developed in the Desmoinesian and at the Missourian-Virgilian boundary.

Stratigraphic occurrences of specific models: Pennsylvanian cycles have been discussed previously at great length (see Heckel, 1984, for summary). In general, the Desmoinesian-age Cherokee-type cycle is analogous to an Illinois Basin cycle except that the clastic wedges (see Wanless, 1964) are not as well developed in Kansas. Not only are these cycles lithologically similar, but the Cherokee cycles are chronostratigraphic equivalents of Illinois Basin type cyclothems (see Wanless and Wright, 1978). The next stratigraphically higher cycle is the Kansas-type cyclothem, a conceptual model discussed widely by Heckel (1977, 1984). There is some similarity between these Kansas-type cyclothems and the overlying Shawnee-type cycles originally described by Moore (1931) and referred to as "megacyclothems." Moore (1936) also defined Wabaunsee-type cycles, these can be considered as either a Kansas-type cycle that lacks a black shale or as a more carbonate-rich version of an Illinois-type cycle. Cycles in the Permian of Kansas were originally recognized by Jewett (1933) who defined these cycles as consisting of four units in ascending order: (1) varicolored, nonfossiliferous shale, (2) thin limestone or calcareous shale, (3) gray, fossiliferous shale, and (4) massive, light colored limestone. Combining lithologic and paleontologic data, Elias (1937) documented cyclicity for the entire sequence that is now referred to as the Chase and Council Grove groups. Permian cycles are highly variable and contain little or no coal beds. Typical lithologies are distinctive fine-grained carbonates, commonly cherty limestones, calcareous mudrocks, and evaporites.

METHODS

In this study, we have adapted the stratigraphic database described by Zeller (1968) for the exposed Permo-Pennsylvanian rocks of Kansas . It should be noted this is based largely upon outcropping strata along the Kansas River Valley and as such is characteristic only of the outcrop belts of the Permo-Pennsylvanian strata in eastern Kansas. Zeller's data was used because it is the most comprehensive compilation available that makes use of a consistent set of lithologic descriptions for the entire Permo-Pennsylvanian interval. From this stratigraphic database, we have delineated nine broadly defined lithofacies. The composition of our nine lithofacies was determined by subjective assessment of Zeller's lithofacies descriptions together with the desire to reduce the overall stratigraphic section into major lithofacies. After much discussion, we decided on the following subdivisions. (1) "Coal," which includes not only coals but siliciclastics with abundant coaly partings. (2) "Gray mudrocks and sandstones," which includes nonfossiliferous (nonmarine) laminated gray shales and mudrocks, siltstones, ripple- and crossbedded sandstones. (3) "Black mudrocks," which included any organic-rich, dark-colored shales and mudrocks. This subdivision includes both above coal, bituminous shales as well as phosphatic black shales that occur within some carbonate-rich parts of the section. (4) "Carbonates," which include a variety of limestones, but exclude those that are chert bearing. (5) "Cherty carbonates," which include any chert-bearing carbonate. (6) "Fossiliferous mudrocks," which include mostly marine, fossil-bearing shales and mudrocks. (7) "Variegated mudrocks," which include a great variety of fine-grained siliciclastics. Especially in the uppermost Pennsylvanian and Permian, this subdivision includes a variety of types of paleosols. (8) "Evaporites," which include intervals with evaporites or collapse-breccias interpreted to be related to near-surface evaporite dissolution. (9) "Variegated dolomitic siliciclastics," which include a heterogeneous suite of thin, dolomitic carbonates interbedded with red and green mottled, fine-grained siliciclastics. We would be the first to admit that our coding of the data is extremely simplistic; nonetheless, such a simplification provides a useful framework in which the entire section can be evaluated and analyzed.

We then subdividing Zeller's section into 10-ft (3-m) increments and determined which of our nine lithofacies best characterized that interval. Vertical distribution of the nine lithofacies was then used to assign a numeric ranking to our nine major lithofacies. This ranking orders the lithofacies into a sequence where the first lithofacies is that which occurs most commonly in the lowest part of the section and the last lithofacies is that which occurs most commonly in the upper part of the section. Thus, because coal dominates the lower part of the stratigraphic section, it is assigned a numeric code of "1." Similarly, because "variegated dolomitic siliciclastics" characterize the upper part of the stratigraphic sections, this major lithofacies was assigned a numeric code of "9." Remaining lithofacies are ordered into intermediate positions based upon where they dominantly occurred within the stratigraphic section (Fig. 2).

RESULTS

"Coals" (Lithofacies 1; Fig. 2) occur most frequently in the lower part (Cherokee) of the Middle Pennsylvanian sequence in Kansas. The southeastern corner of the state, where these rocks are exposed at or near the surface, has produced economic quantities of coal. Coal beds are rare in the uppermost Desmoinesian, through most of the Missourian, but increase again at the Missourian-Virgilian boundary. Coal beds are also known from rocks of Lower Permian age, but because of their thinness, they are not a significant lithology of any 10-ft (3-m) interval. Occurrences of these thin coal beds declines and none are known from rocks younger than the lower Permian.

The "gray mudrock and sandstone" lithofacies (Lithofacies 2; Fig. 2) is typical of the siliciclastic-rich parts of the Pennsylvanian section in Kansas. Underclays and gray mudrocks that characterize "outside shales" (see Heckel, 1984) are included in this lithofacies, as are incised, channel-form sandstones. These different facies are lumped together because they comprise an associated suite of lithofacies, originally termed a "clastic wedge" by Wanless (1964). Similar to the coal beds, this facies occurs most commonly in the lower part of the Pennsylvanian interval studied, and although the frequency of occurrence is lower in the Missourian interval, it increases slightly in the Virgilian. Although underclays and paleosols occur in association with coal beds, high chroma, variegated paleosols are rare to absent. Variegated paleosols, however, are characteristic of "variegated mudrocks" (Lithofacies 7) that occur in the upper Virgilian into and through the Permian.

"Black mudrocks" (Lithofacies 3; Fig. 2) include several types of organic-rich shales that were formed at a variety of depths and positions relative to paleoshorelines (Coveney et al., 1991). These include carbonaceous shales that overlie coals and phosphate-bearing shales that occur within carbonate-rich intervals. The frequency of black mudrocks following intervals in which coal is a conspicuous component, namely the upper Desmoinesian and upper Virgilian, appear to reflect clastic swamps or "failed" coal-producing environments. Conversely, the Missourian and lower Virgilian occurrences of black mudstones include more offshore, phosphate-bearing "core" shales (Heckel, 1977).

"Carbonates" (Lithofacies 4; Fig. 2) are a dominant lithofacies in the entire sequence. Their frequency of occurrence is, however, more-or-less inversely associated with occurrences of siliciclastic strata. No attempt was made to differentiate between the different types of non-cherty carbonates, but our experience indicates these carbonates include those that contain conspicuous amounts of siliciclastics as well as those that are quite pure. In addition, most contain fossils of typical marine invertebrates. Carbonates with the least amounts of siliciclastics occur in the upper Desmoinesian and Missourian. The high frequencies of carbonates in the upper Virgilian and lower Permian (Wolfcampian) are often associated with cherty carbonates (Lithofacies 5); these carbonates commonly contain significant amounts of siliciclastics.

Few of the carbonate units are "cherty carbonates" (Lithofacies 5; Fig. 2) until the Wolfcampian and evidence exists that some, if not most, of these Permian cherty carbonates were originally evaporitic carbonate muds (West et al., 1987). This association agrees with a more arid climate during the latter part of the Paleozoic in Kansas. Original evaporite textures and fabric are easily observed in the chert layers and nodules in some of these carbonate beds (West et al., 1987).

The lithofacies coded as "fossiliferous mudrocks" (Lithofacies 6; Fig. 2) included only those mudrocks that contain fossils of marine invertebrates. Thus, gray mudrocks with only plant fossils are excluded from this facies (but were included in Lithofacies 2) to retain only those mudrocks that exhibit a significant marine influence. This serves to explain why there are no "fossiliferous mudrocks" recorded for the Desmoinesian, lower Missourian, and parts of the Virgilian. Thin fossiliferous mudrocks occur in these intervals, but because the coding is based on 10 ft (3 m) intervals, they were not recorded as the dominant lithofacies. Most of the fossiliferous mudrocks occur in the siliciclastic sequences between the "Kansas-type cyclothems" and record a conspicuous marine influence in addition to the marine influence recorded by the fossiliferous carbonates. The frequency of this lithofacies fluctuates widely in the Wolfcampian and is interbedded with variegated mudrocks (Lithofacies 7).

"Variegated mudrocks" (Lithofacies 7; Fig. 2) become a conspicuous part of the lithologic sequence in the upper Virgilian, Wolfcampian, and Leonardian. Distinctive layers of silty mudrocks of red, green, purple, and yellow gray are complexly interbedded. The association of these different colored layers with characteristic pedogenic textures and fabrics indicates that subaerial exposure and soil development were common occurrences during this time interval (Miller, 1991; Miller and McCahon, 1992). Rocks of this lithofacies are associated with cherty carbonates (Lithofacies 5) and evaporites (Lithofacies 8).

"Evaporites" (Lithofacies 8; Fig. 2) together with "cherty carbonates" (Lithofacies 5) and variegated mudrocks (Lithofacies 7) characterize the Permian section of Kansas. In addition to the thick occurrences of halite and anhydrite in the Leonardian and

Guadalupian, layers and nodules of gypsum and anhydrite occur in beds of mudrocks and carbonates of the Wolfcampian in the subsurface. Because of the effects of groundwater and surficial weathering, equivalent surface sections exhibit brecciation and large-scale vugs apparently related to evaporite dissolution.

The uppermost lower Permian is characterized by a mixed lithofacies that we termed "variegated dolomitic siliciclastics" (Lithofacies 9; Fig. 2). These evaporite-bearing sections are not well exposed. Therefore, they have not been extensively studied lithologically or paleontologically. A notable exception is the detailed studies by Tasch (1963, 1964) of the conchostracan-bearing beds and associated insect beds in the Wellington Formation. More such detailed studies of this interval are needed. Thus, the degree of stratigraphic detail available is limited, and resolution particularly of upper Permian strata is diminished.

PERMO-PENNSYLVANIAN CYCLOTHEMS

Because Permo-Pennsylvanian cyclothem concepts traditionally and conceptually rely heavily on the stratigraphic record in Kansas, herein we describe some of the stratigraphic variability in cycle types and relate specific parts of the stratigraphic column to previously described cyclothem models. Furthermore, we suggest that shifts in paleoclimate, related to shifts in paleolatitudinal positions, controlled the generalized lithologic variability among the different types of cyclothems. Lithologic variability within an individual cyclothem has been related to glacio-eustatically induced changes in sealevel (see Heckel, 1986; Crowley and Baum, 1991). Thus, because our intent is to describe the changes that occurred over the entire Permo-Pennsylvanian time interval, the shorter-term intracyclothem lithofacies variability, such as that related to changes in depositional depths related to glacio-eustacy, is not the focus of our analyses.

Based upon paleogeographic reconstructions (Schutter and Heckel, 1985; Witzke, 1990), Kansas underwent a paleolatitudinal shift from an equatorial position in the Middle Pennsylvanian (Desmoinesian) to more arid latitudes in the late Permian. Thus the distribution of lithofacies reflects large-scale variations in climate (Archer et al., 1990) related to changing paleolatitudinal position of the paleocontinent and the vertical distribution of the lithofacies illustrates this dramatic shift (Fig. 2)

Because of the shorter-term variability of the lithofacies (i.e., the "cyclothems"), a significant degree of processing must be performed on the data before it can be depicted in any reasonable graphical format. For this study we converted the major lithofacies to a numeric code, ranging from 1 to 9, based upon their order of occurrence in the stratigraphic section (Fig. 2). This conversion allows for simple mathematical and graphical analyses of the entire section. In particular, it is of interest to examine the range of lithofacies within the different stratigraphic intervals and the longer-term trends that can be extracted by smoothing the lithologic data (Fig. 3). Such a graphical depiction clearly delineates the major changes in lithofacies composition of the cyclothems within the Permo-Pennsylvanian sequence of eastern Kansas. This type of depiction indicates the general trend from coal-bearing strata in the Desmoinesian and Missourian/Virgilian boundary sections, through limestone- bearing facies in the Missourian and middle parts of the Virgilian, to progressively more variegated mudrock, evaporite, and dolomitic facies in the upper parts of the Permian. The Permian rocks, especially the upper Permian, are potentially as cyclic (Miller et al., 1991) as Pennsylvanian rocks but are poorly exposed and have not been studied as extensively.

In addition, the different stratigraphic positions of the defined cyclothem models, discussed previously, can also be compared to this large-scale lithologic variability (Fig. 4). Such a comparison indicates the range of lithologies that occurs in intervals delineating specific cyclothems is quite different. For example, the Cherokee, or Illinois Basin-type, cyclothem occurs stratigraphically lower than the Kansas-type cyclothem. Contrary to the suggestions of some workers, these two types of cyclothems should not be conceptually related in time, because they are not chronostratigraphically related to each other. For example, Illinois Basin-type cycles were formed during the Desmoinesian in both in the Illinois Basin as well as in eastern Kansas. Thus, these Illinois Basin-type cyclothems are not geographically restricted to the Illinois Basin, but are characteristic of the Illinois Basin and eastern Kansas during the Desmoinesian. Similarly, Kansas-type cyclothems do not characterize the entire Kansas stratigraphic section, but are only characteristic of specific parts of the Missourian section. The use of geographic identifiers for such cycles has been misleading because such usage confuses temporal versus spatial relationships.

DISCUSSION

A model of climate-related lithofacies has been proposed by Cecil (1990) for the Appalachians and can be applied to the Kansas section (Archer et al., 1990); our ordered lithofacies can be placed along a spectrum of wetter to drier climates (Fig. 5). This entire range of lithofacies is not developed within any individual "cyclothem"; instead individual cycles are essentially constrained to specific limits depending on their potential lithofacies variability. Conceptually, the cycles in the lowest part of the Permo-Pennsylvanian section exhibit variability within the wetter end of the spectrum and the Permian cycles exhibit a variability that is limited to the drier end of the spectrum (Fig. 6).

Cherokee-type cyclothems, which characterize the Desmoinesian, contain coals, gray mudrocks and sandstones, black shales, and limestones and thus exhibit a range from Lithofacies 1 to Lithofacies 4 (Fig. 6a). The Kansas-type cyclothem (Heckel, 1984), contains the same lithofacies, but contains only very thin, localized coal. In addition, this type of cyclothem has a wider range of lithofacies including cherty carbonates, or Lithofacies 5, and fossiliferous mudrocks, or Lithofacies 6 (Fig. 6b). Shawnee cyclothems (Moore, 1931) are not significantly different from the Kansas cyclothem (Heckel, 1984) in terms of the range of lithofacies (Fig. 6c). Wabaunsee cyclothems (Moore, 1936) contain lithofacies that suggest significantly dryer climates; these include variegated mudrocks, evaporates, and variegated dolomitic siliciclastics, or Lithofacies 7, 8, and 9, respectively (Fig. 6d). Lithofacies from the climatically wetter end of the spectrum (Fig. 5), such as coals, gray mudrocks and sandstones, and black shales, are only expressed as thin units in this part of the stratigraphic section. Finally, the Permian cyclothems (Jewett, 1933; Elias, 1937) range from carbonates and cherty carbonate to evaporates and variegated dolomitic siliciclastics (Lithofacies 5 through 9) and are notable for lacking organic-rich units (Lithofacies 1, 3).

When viewed in a stratigraphic context, the range of major lithofacies within any given cyclothem is limited. Thus, cycles do not occur that contain both a well-developed coal bed and thick evaporite or variegated dolomitic facies.

CONCLUSIONS

The Permo-Pennsylvanian section of Kansas exhibits a high degree of lithologic variability and no single "cyclothem" model can characterize the entire section. Nonetheless, specific ranges of lithofacies, potentially related to both glacio-eustatic and climatic factors, characterize different types of lithologic cycles (the "cyclothem"). The range of lithofacies expressed in individual cycles shifts from the Pennsylvanian through Permian sequences is a consequence of shifts from relatively wet equatorial to drier, northerly latitudes in the paleolatitudinal position of Kansas. Thus, although Permian cycles exhibit roughly similar amounts of lithologic change when compared to Pennsylvanian cycles, the Permian lithofacies indicate significantly drier paleoclimates. Similar smaller-scale shifts occur throughout the Pennsylvanian and there is no simple linear shift in dominant lithofacies throughout the section. Variations in Pennsylvanian cyclothem content appear to be related more to degree of variability, which in turn was probably related to shorter-term oscillations in climate and climatogenically induced glacio-eustatic facies oscillations.

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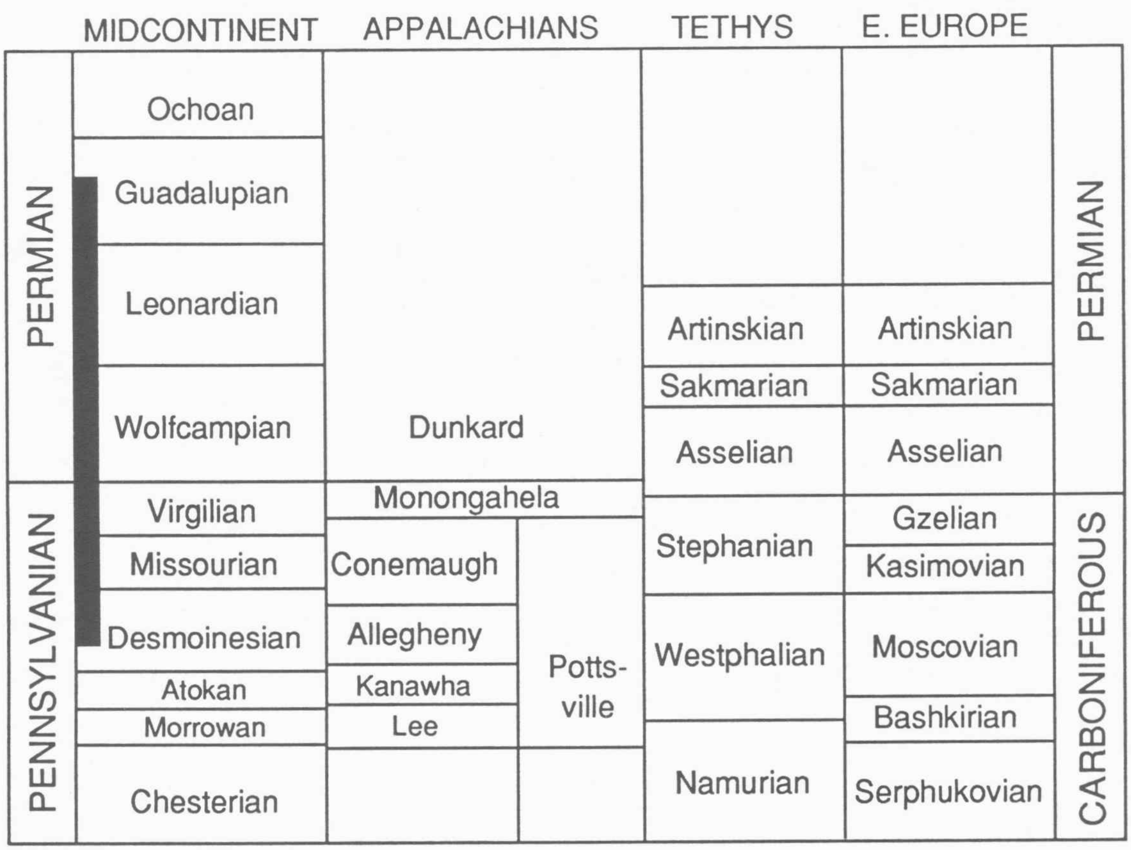

Figure 1. Comparative stratigraphic nomenclature of the Kansas stratigraphic section in the U.S. midcontinent, Appalachian area of the eastern U.S., Tethys area, and eastern Europe. Stratigraphic interval analyzed herein delineated by solid black bar.

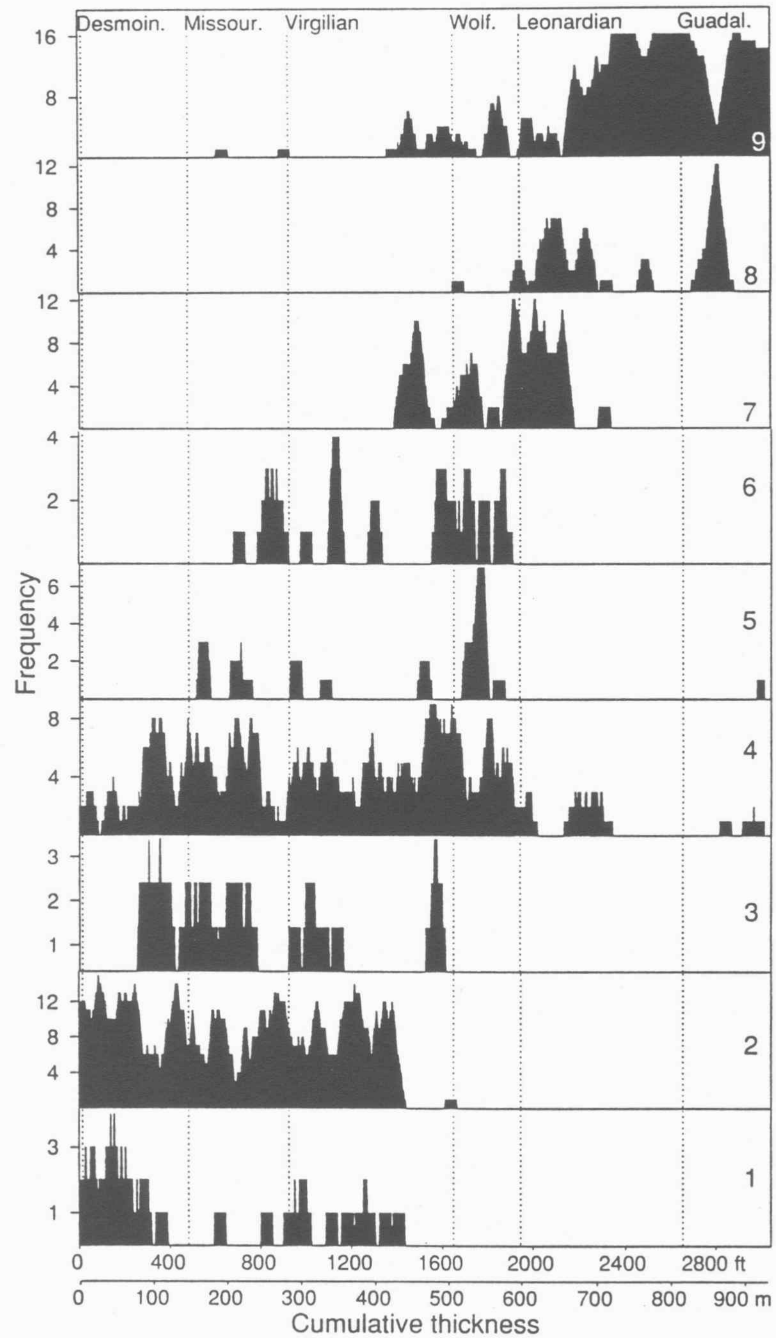

Figure 2. Distribution of lithofacies, coded from Zeller (1968) for the exposed section of the Kansas rock column. Coding involved assignment of dominant lithofacies occurring within 10-ft (3-m) increments of Zeller's composite section. The lithofacies are: (1) coals, (2) gray mudrocks and sandstones, (3) black mudrocks, (4) carbonates, (5) cherty carbonates, (6) fossiliferous mudrocks, (7) variegated mudrocks, (8) evaporites, and (9) variegated dolomitic siliciclastics. The lithofacies are ordered based upon their mode of dominant occurrence in the vertical stratigraphic sequence. Frequency is based upon number of occurrences of given lithofacies in 160 ft (49 m) vertical section.

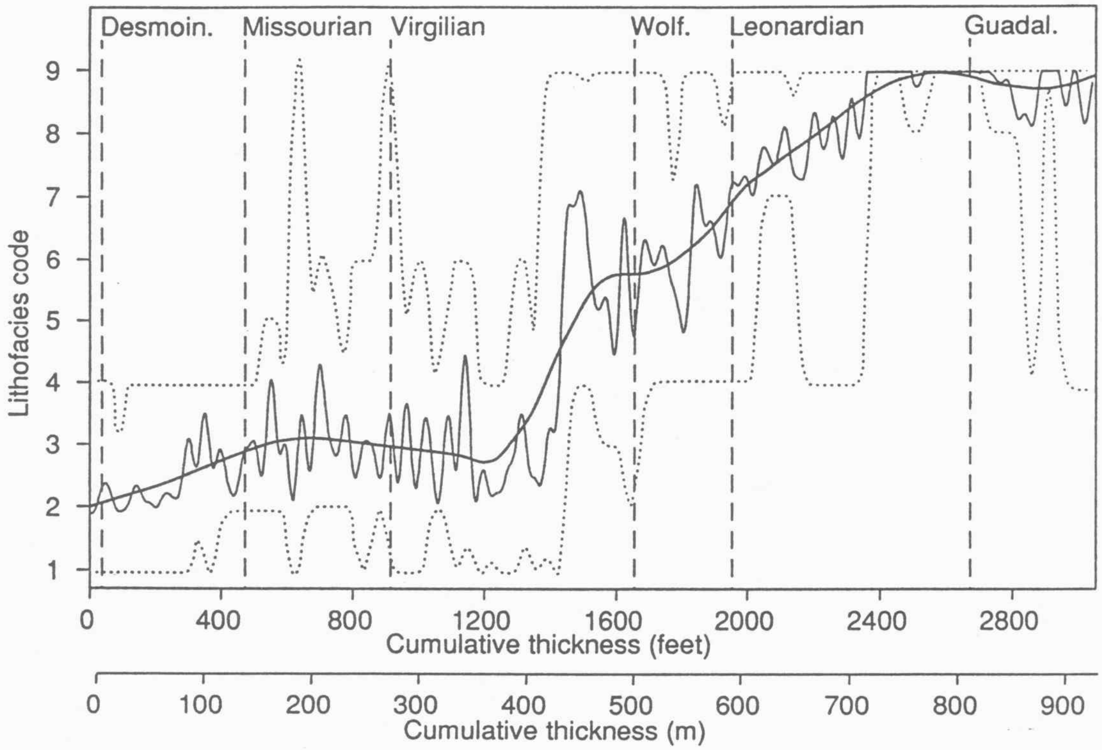

Figure 3. Averaged lithofacies distributions for exposed Permo-Pennsylvanian rocks of Kansas. Lithofacies along vertical axes as in Figure 1. Heavy solid line is 1000 ft (305 m) smoothing of coded lithofacies; light solid line is 150 ft (46 m) smoothing; dashed lines encompass the range of variability occurring in 150 ft (46 m) intervals.

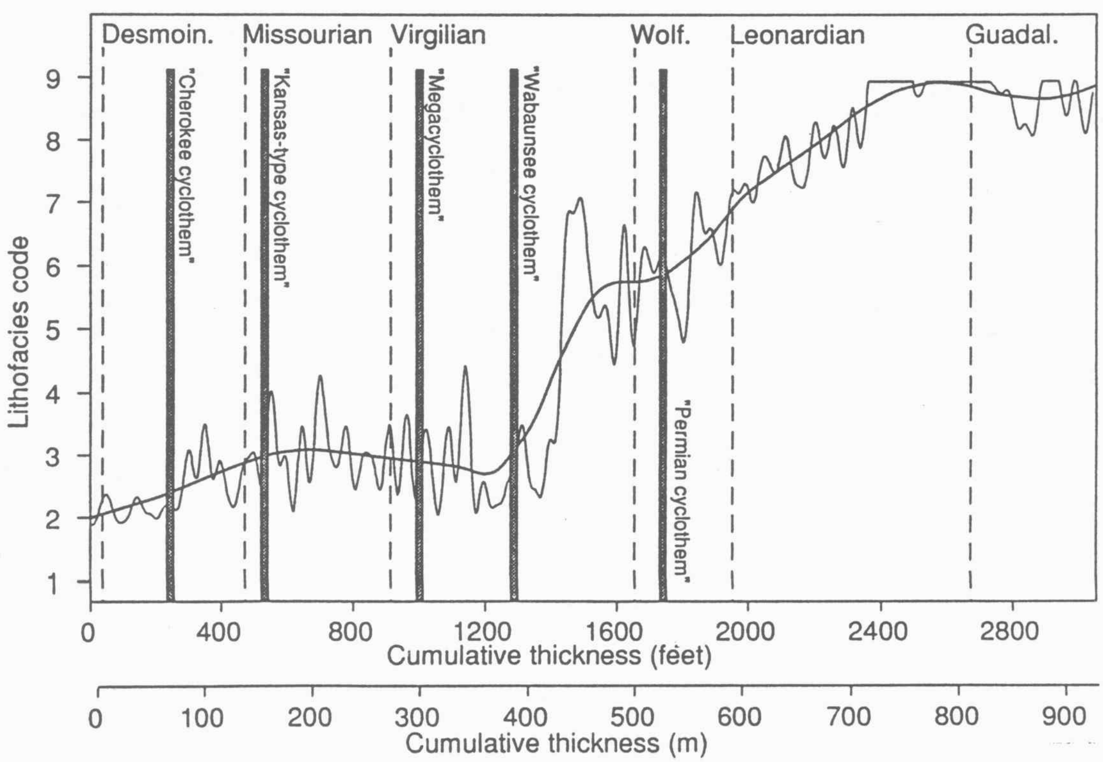

Figure 4. Relative positions of cyclothem models proposed for different parts of the vertical stratigraphic section of Kansas. Lithofacies curves described in Figure 2.

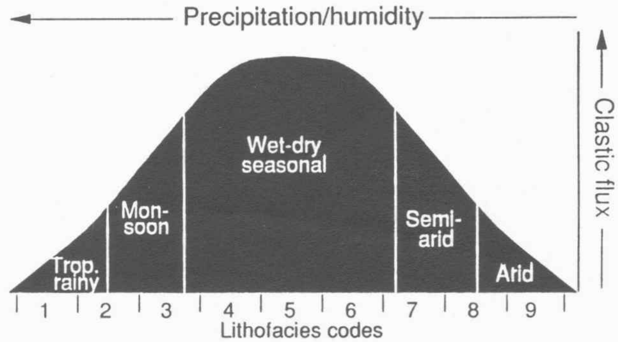

Figure 5. Climatogenic lithofacies spectrum based upon Cecil (1990). Lithofacies codes along horizontal axes refer to Figure 2. In a general sense, coals (Lithofacies 1) were produced in wetter climates than were evaporites (Lithofacies 8) and dolomitic facies (Lithofacies 9). Carbonates (Lithofacies 4 and 5) occupy intermediate positions.

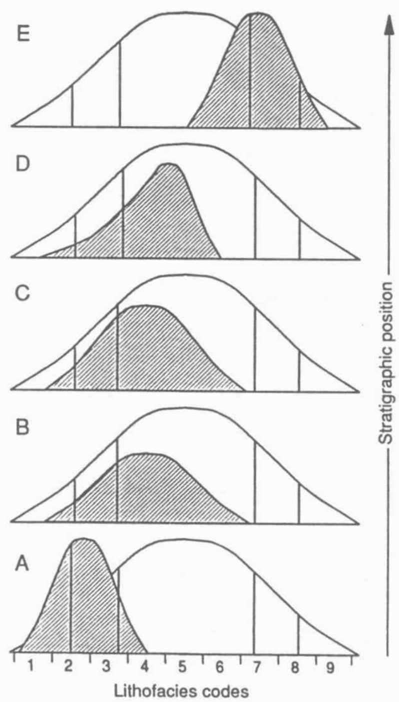

Figure 6. Relative range of lithofacies developed within specific "cyclothem" models (shaded area) superimposed on climatogenic lithofacies spectrum of Figure 5. Cyclothem models include: (A) Cherokee or Illinois cycle (Moore, 1949; Wanless and Weller, 1932); (B) Kansas-type cycle (Heckel, 1984); (C) Shawnee cycle (Moore, 1931), (D) Wabaunsee cycle (Moore, 1936); and (E) Permian cycle (Jewett, 1933; Elias, 1937). The vertical distribution of cycles indicates shifts from wetter to drier lithofacies that were formed under potentially similar eustatic oscillations.