# HIGH RESOLUTION SEQUENCE STRATIGRAPHIC ANALYSIS OF THE UPPER CARBONIFEROUS (VIRGILIAN, WABAUNSEE GROUP) OF THE NORTH AMERICAN MIDCONTINENT

By

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# HIGH RESOLUTION SEQUENCE STRATIGRAPHIC ANALYSIS OF THE UPPER CARBONIFEROUS (VIRGILIAN, WABAUNSEE GROUP) OF THE NORTH AMERICAN MIDCONTINENT

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# PREFACE

This research was conducted in order to construct a sequence stratigraphic framework for the Upper Carboniferous Wabaunsee Group in the Midcontinent. Previous work on within the Wabaunsee Group and adjacent strata has been interpreted as displaying a superimposed hierarchy of stratigraphic forcing. This study will determine if in fact a hierarchy of stratigraphic forcing does exist within the Wabaunsee Group.

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# I.

# Introduction

## Purpose

This is a local study of the Wabaunsee Group strata in the North American outcrop belt in central Kansas and southeastern Nebraska. The Wabaunsee Group is upper Virgilian in age and is above the Shawnee Group and below the Admire Group (Figure 1). It consists of 12 formations and 31 members (Figure 2). The outcrop area trends southwest-northeast in the states of Oklahoma, Iowa, Missouri, Nebraska, and Kansas (Figure 3). There are three goals of this study: (1) To establish a preliminary outcrop based sequence stratigraphic framework for the Upper Carboniferous (Virgilian, Wabaunsee Group) strata, (2) To characterize the hierarchy of stratigraphic forcing, (3) To produce a sea-level curve for the entire Wabaunsee Group.

## Study Area

The data was collected from two general outcrop localities (Figure 4). Three sample sites are in southern Nebraska (Pawnee County). Six sample sites are located in north central Kansas in the counties of Shawnee, Wabaunsee, Osage, and Lyon Counties.

| Series | Stage | Group |
|---|---|---|
| Upper Pennsylvanian | Virgilian | Wabaunsee |
| | | Shawnee |
| | | Douglas |
| | Missourian | Lansing-Kansas City |

Figure 1. Virgilian stratigraphic nomenclature after Kansas Geological Survey.

| | Formations | Members |
|---|---|---|
| Wabaunsee Group | Wood Siding Formation | Brownville Limestone |
| | | Pony Creek Shale |
| | | Grayhorse Limestone |
| | | Plumb Shale |
| | | Nebraska City Limestone |
| | Root Shale | French Creek Shale |
| | | Jim Creek Limestone |
| | | Friedrich Shale |
| | Stotler Limestone | Grandhaven Limestone |
| | | Dry Shale |
| | | Dover Limestone |
| | Pillsbury Shale | |
| | Zeandale Limestone | Maple Hill Limestone |
| | | Wamego Shale |
| | | Tarkio Limestone |
| | Willard Shale | |
| | Emporia Limestone | Elmont Limestone |
| | | Harveyville Shale |
| | | Reading Limestone |
| | Auburn Shale | |
| | Bern Limestone | Wakarusa Limestone |
| | | Soldier Creek Shale |
| | | Burlingame Limestone |
| | Scranton Shale | Silver Lake Shale |
| | | Rulo Limestone |
| | | Cedar Vale Shale |
| | | Happy Hollow Limestone |
| | | White Cloud Shale |
| | Howard Limestone | Utopia Limestone |
| | | Winzeler Shale |
| | | Church Limestone |
| | | Aarde Shale |
| | | Bachelor Creek |
| | Severy Shale | |

Figure 2. Wabaunsee Group formations and members.

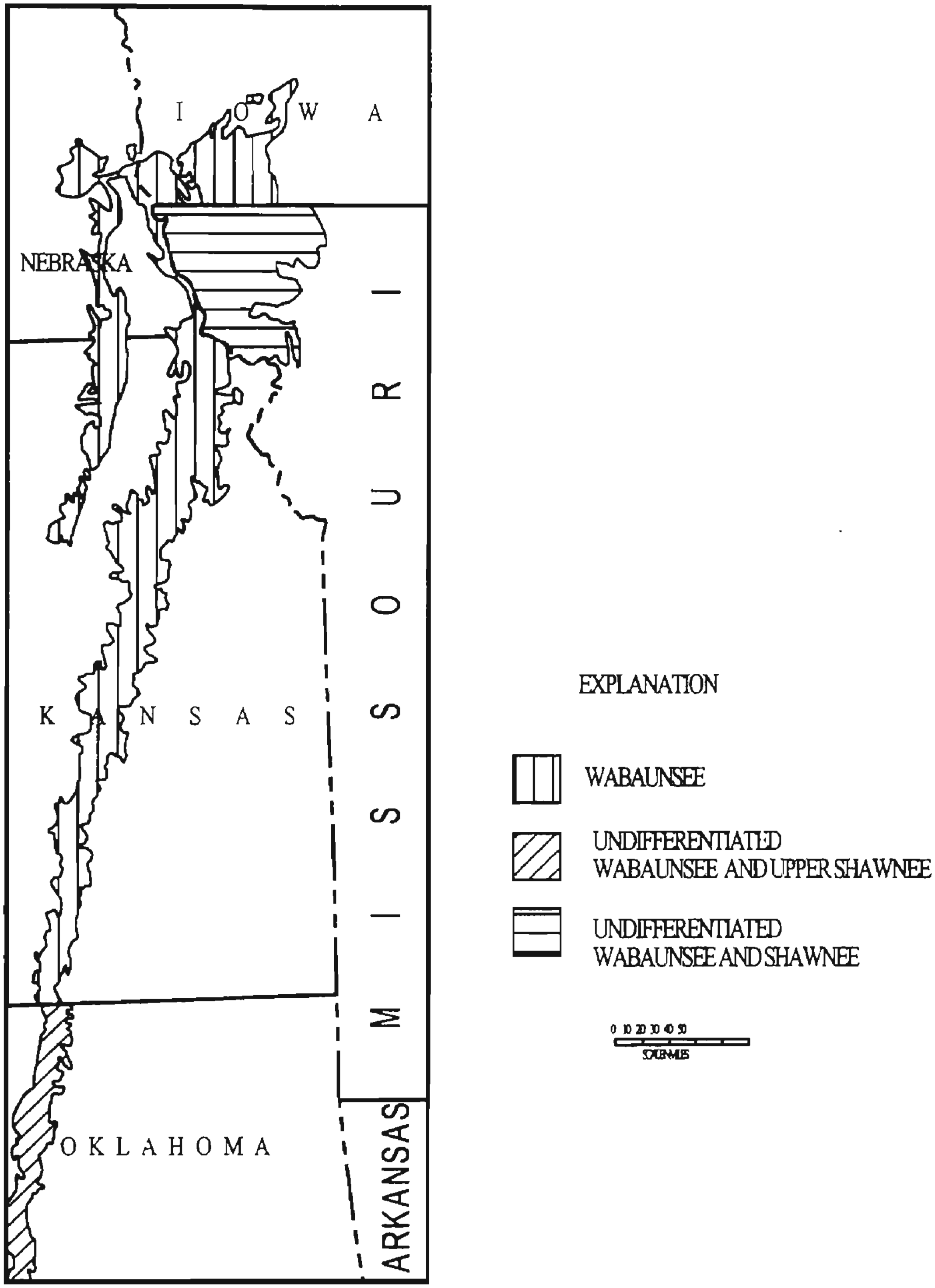


Figure 3. Outcrop belt of the Wabaunsee Group and equivalent strata.

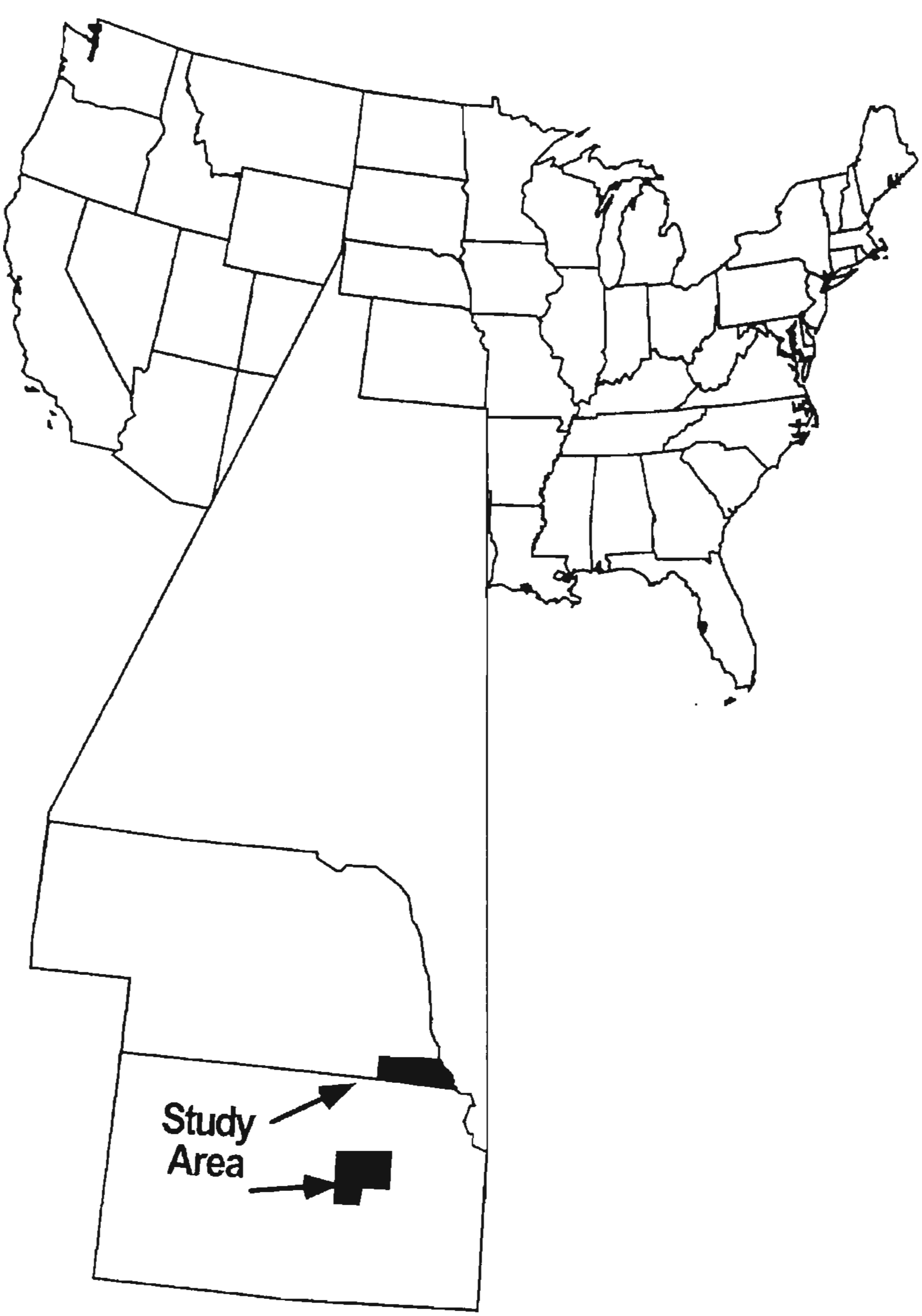


Figure 4. Area of Investigation.

These outcrop sites cover the entire stratigraphic section of the Wabaunsee Group although the Wauneta Limestone Member and Bachelor Creek Limestone Member of the Howard Limestone Formation are not present in either of these outcrop areas. They crop out only in southern Kansas. Only the top of the Severy Shale Formation is considered in this study because of poor exposures of the base.

## Methodology

The study began in the spring of 1998. The fieldwork began in May 1998 and lasted through July 1998. While working in the field, forty two outcrop locations were visited and from those outcrops the nine most complete localities (Stop 1 through Stop 9) were selected for the analysis. Most of the outcrops had incomplete contacts or were described prior to 1960 and no longer exist. To complete the above stated objectives the nine sample locations were measured and described in the field. Ninety three samples (53 shale and 40 limestone) were taken for lithologic and paleontologic analysis.

The shale samples were disassociated in hydrogen peroxide and water. The remaining insoluble residue was then extracted using a 100-mesh sieve. This residue was then analyzed for conodonts.

The limestone samples were analyzed in two different ways. First, they were dissolved in formic acid and the remaining insoluble residue was picked for conodonts. Second, the samples were cut into thin sections. The thin sections were analyzed for fossil content and lithology. Lithologic descriptions are made from the thin sections. The lithologic and faunal content was analyzed to interpret depositional environments.

## Geologic Setting

Wabaunsee Group strata were deposited on the stable continental craton of North America during the late Virgilian. During the Pennsylvanian, a tropical epicontinental sea existed in the Midcontinent with a limited open ocean connection (Heckel, 1977). Wabaunsee Group strata represent a range of marine depositional environments. The deeper water shelfal deposits are characterized by phosphatic black shales (Schenk, 1967, Heckel, 1977) and limestones with deeper water conodont fauna and/or glauconite. Thickness and lithofacies patterns of Permo-Carboniferous rock units in the Midcontinent were largely controlled by two episodes of tectonism: pre-Morrowan cratonic epiorogeny which was centered around the transcontinental arch and early Middle Pennsylvanian tectonic activity which created several important regional structural elements (Rascoe and Adler, 1983).

Rascoe and Adler (1983) constructed a paleogeographic map of the Midcontinent during the Virgilian (Figure 5). During Wabaunsee time, the Midcontinent was not experiencing any significant tectonic activity (Rascoe and Adler, 1983)(Figure 6). The most prominent structural feature in the study area is the Nemaha Uplift. A rifting event occurred sometime in the PreCambrian and was reactivated in the Pennsylvanian as an uplift due to the collision between the North American and South American plates (Rascoe and Adler, 1983).

## Previous Work

The Wabaunsee Group and equivalent strata has been recognized for over 100 years (Swallow 1855). Early geologist such as Hawn, Swallow (1855), Morcou (1864),

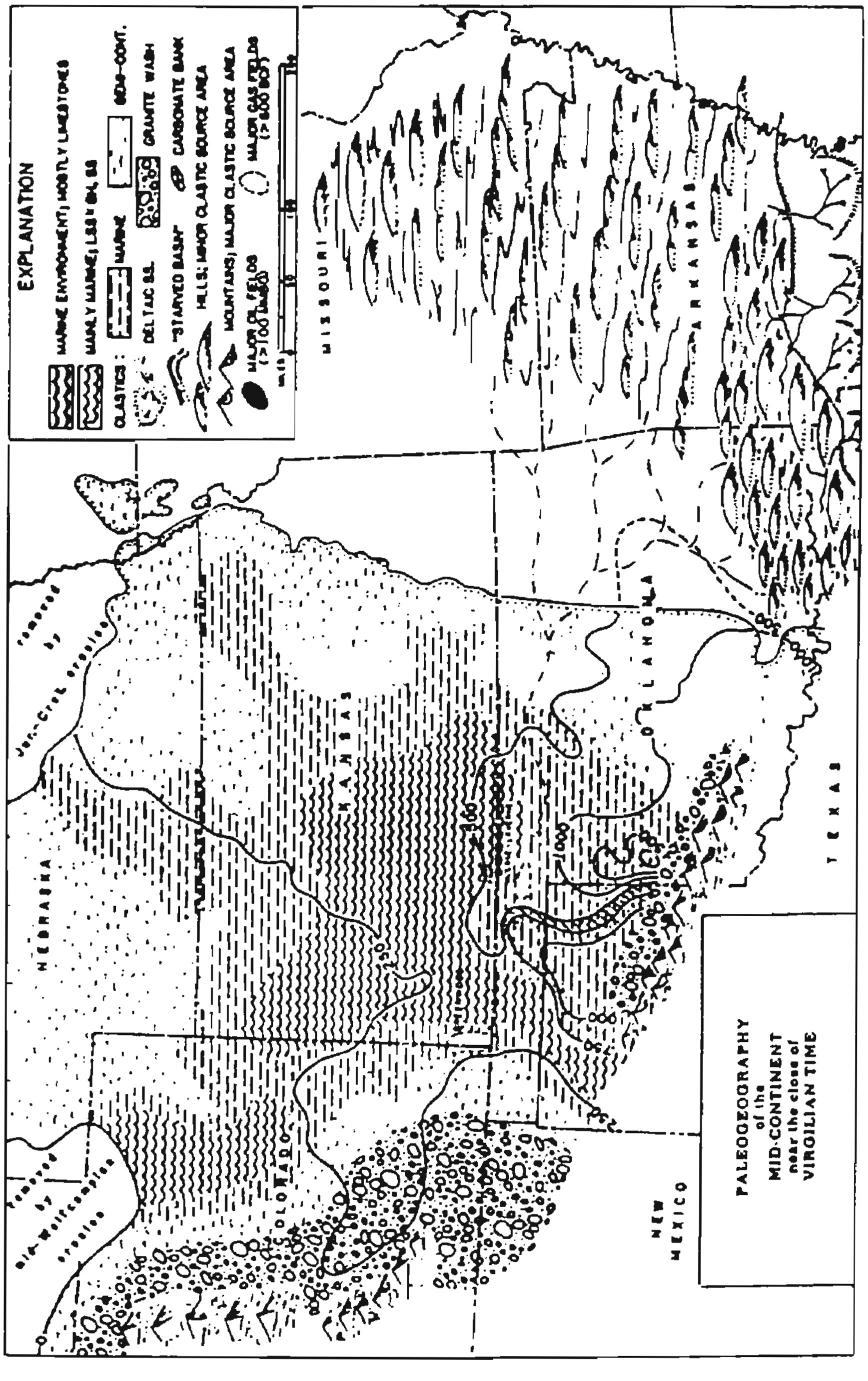


Figure 5. Paleogeography of the Midcontinent (Rascoe and Adler 1983).

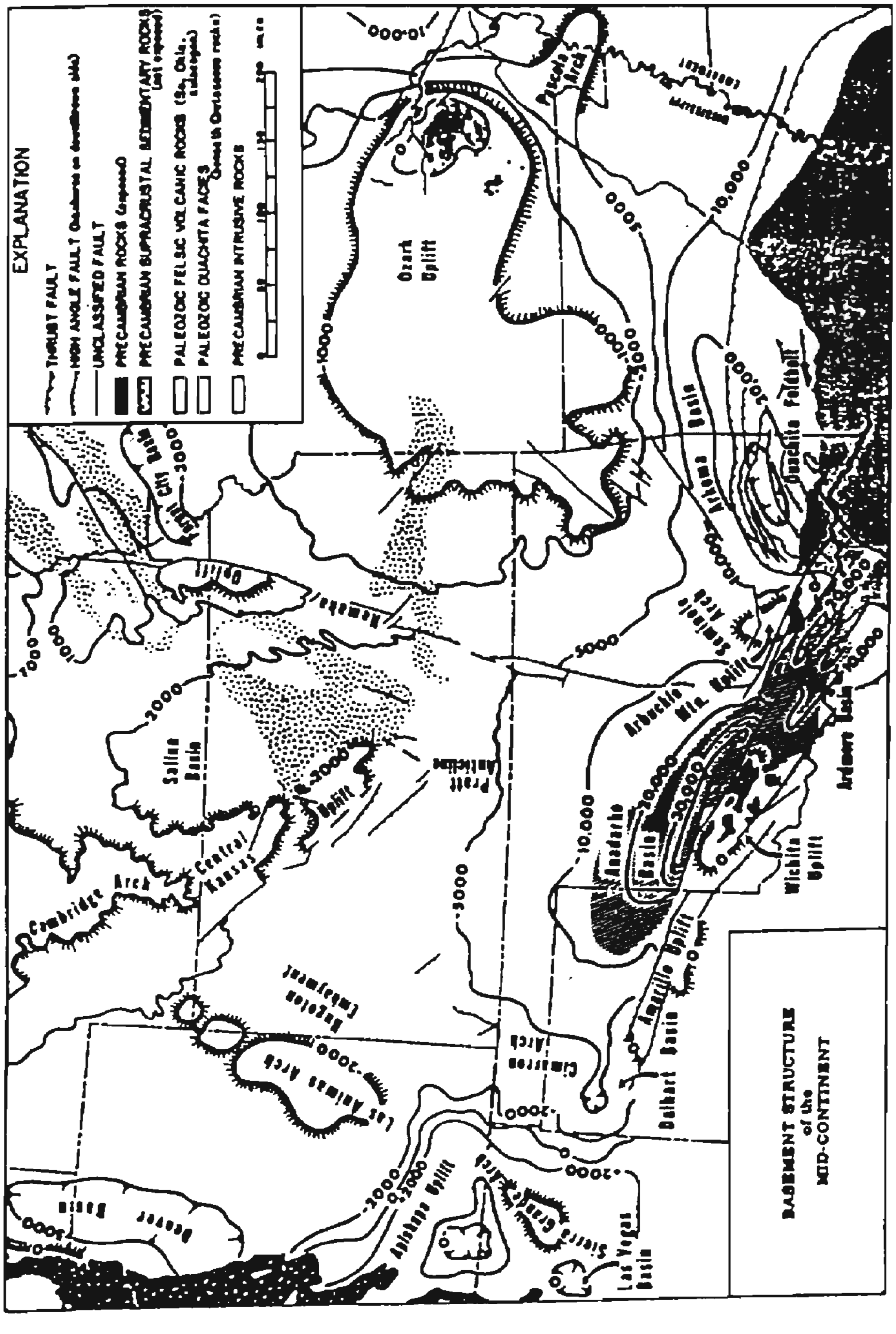


Figure 6. Basement structure of the Midcontinent during late Virgilian (Rascoe and Adler 1983).

Hayden and Meek (1872, 1873), Warren (1875) and Beede (1896); characterized the rocks present in their respective states.

Later interest in the Wabaunsee Group centered around the fact that there are at least twelve coal seams (Figure 7). Only six have been economic at one time or another (Schoewe, 1946). It was realized that most of the coal measures that occur in the Wabaunsee Group are not economic because they too thin. More recent work done on the Wabaunsee Group has been unpublished masters thesis's Mendoza (1959), Girardot (1962), Fudge (1974), Pawel (1975) and studies by Moore (1929, 1932, 1936, 1964), Mudge (1956), Mudge and Yochelson (1962), Merriam (1964, 1989). Geologist were interested if Carboniferous-Permian strata were exposed in the Midcontinent and placement of the boundary. Work done by these geologists were the first attempt at mapping and naming of these Midcontinent strata. The only debate before the turn of the century was over the age of these units. Pennsylvanian rocks of the Midcontinent have been scrutinized from the early 1900's to the present day as to the origin of the cyclic nature of the strata (Udden, 1912; Weller, 1930, 1956, 1957, 1958; Moore, 1936, 1950, 1964; Wanless and Weller, 1932; Wanless and Shepard, 1936; Laporte and Imbrie, 1964; Elias 1964; Wanless, 1967; Heckel and Baesemann, 1975; Heckel, 1977, 1980a; Crowell, 1978; Imbrie and Imbrie, 1980; Busch and Rollins, 1984; Boardman and Malinky, 1985; Boardman and Heckel, 1986; Heckel, 1986; Boardman and Nestell, 1989).

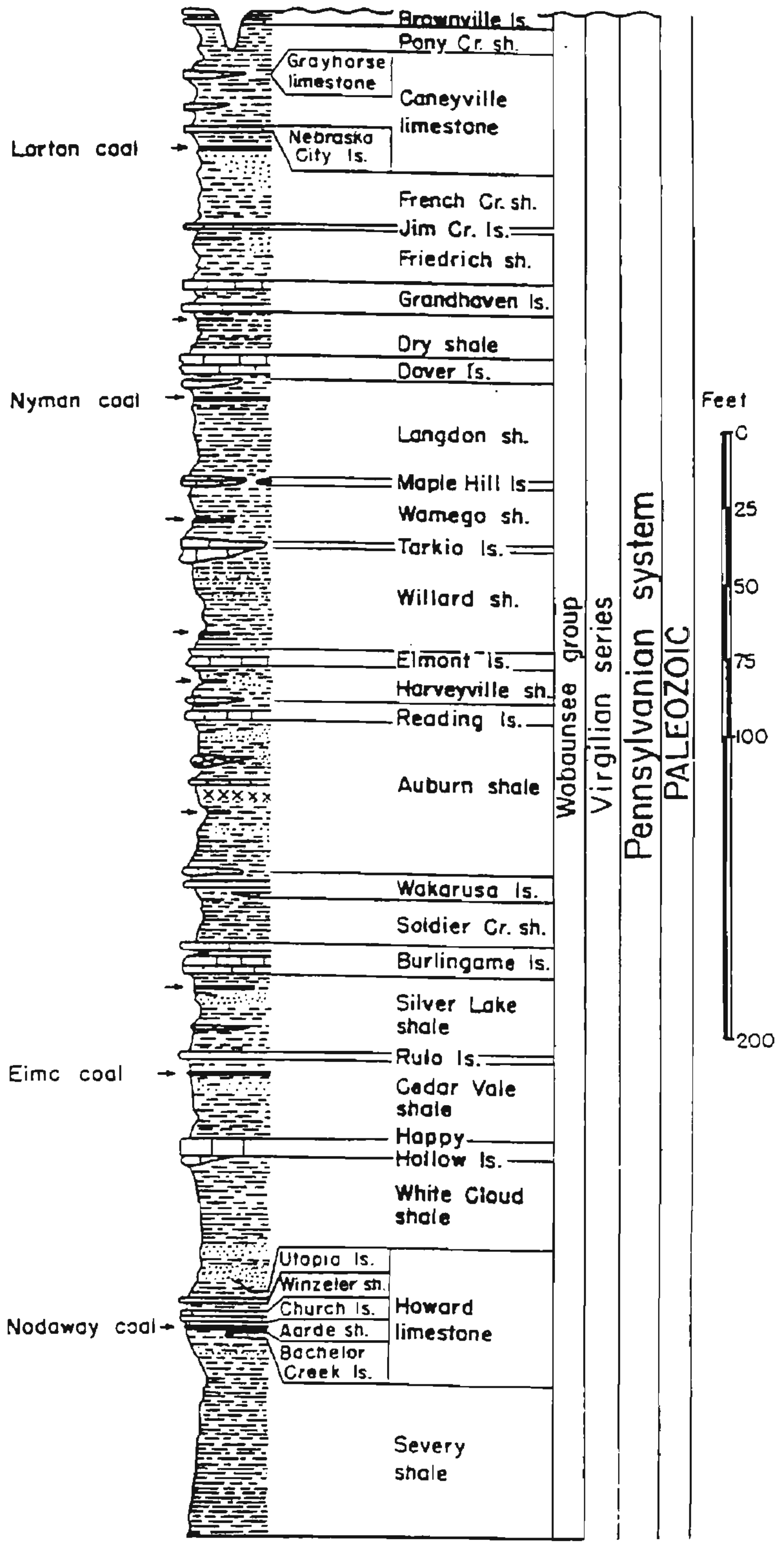


Figure 7. Coal Resources of the Wabuansee Group (Schoewe 1946).

# II.

# Stratigraphy

## Lithologic descriptions

This study covers the strata of the Wabaunsee Group (Virgilian Stage, Upper Pennsylvanian Series, Pennsylvanian Period)(Figure 1). This group varies considerably in thickness with the most section being exposed to the north and thins to the south. It generally consists of about 500 feet of strata. The Wabaunsee Group is part of the upper division of the Virgilian Series (Figure 1). The Virgilian stratotype (type section) is on the Verdigris River from Virgil, Greenwood County, Kansas (sec. 8, T. 24 S., R. 13.). The Virgilian Series contains the Douglas Group, the Shawnee Group, and the Wabaunsee Group. The Virgilian Series was named by Moore (1932) for Virgil, Kansas. He named this series for the unconformities located at the top of the Missourian Series and the unconformity marked by the local prominent channel sandstones (Indian Cave Sandstone) that cut the Brownville Limestone Member in subjacent beds in Oklahoma, Kansas and Nebraska (Moore, 1936).

The Wabaunsee Formation was named by Prosser (1895) to include rocks above the "Osage Coal" (Nodaway Coal) to the base of the Cottonwood Limestone. Haworth (1898) redefined the base of the formation as the Burlingame Limestone Member. A. E. Faith (1921) changed the rank of the Wabaunsee Formation to a group. Moore (1935) redefined the Wabaunsee Group to include the beds between the top of the Topeka Limestone to the base of the Americus Limestone. The Wabaunsee Group was restricted even further by Condra (1935) to the top of the Brownville Limestone Member. Moore (1936) defined the Wabuansee Group to its present boundary as to include strata between the top of the Topeka Limestone Member of the Shawnee Group and the base of the Towle Shale Member of the Admire Group. He defined the Wabaunsee Group because he noted a change in lithologic character, a change in the nature of the cyclothems, and faunal peculiarities. The upper boundary was not well defined but Moore (1936) did note that beds below the Cottonwood Limestone show a lithologic and faunal similarity to the succeeding Big Blue beds (Permian) and a general dissimilarity to underlying Pennsylvanian strata that the boundary between Virgil and Big Blue should be drawn not higher than this horizon.

The basal formation of the Wabaunsee Group is the Severy Shale and was named by Haworth (1898). The stratotype is located in Severy, Greenwood County, Kansas. Its generally consists of a yellowish-brown and bluish-gray clay shale with some sandstone and is commonly 75 feet (23 m) thick.

Haworth (1898) named the Howard Limestone Formation for the near Howard, Elk County, Kansas. The stratotype consists of two or more limestones and shales and the thickness ranges from 8 to 30 feet (2.4 to 10m). Named members are Bachelor Creek Limestone, Aarde Shale, Wauneta Limestone, Shanghi Creek Shale, Church Limestone, and Winzeler Shale (Figure 2). The basal unit of the Howard Limestone is the Bachelor Creek Limestone Member and it was named by Moore (1932). The stratotype is located on Bachelor Creek near Eureka, Greenwood County, Kansas. This member is commonly 1 foot (0.3 m) thick (Moore et al., 1944). This member is missing in northeast Kansas, southeast Nebraska, northwest Missouri, and southwest Iowa (Condra, 1949) where the base of the Church Limestone Member marks the boundary between the Severy Shale Formation and the Howard Limestone Formation. Moore (1932) named the Aarde Shale

Member for the Aarde farm (sec. 4, T. 26 S., R. 11E.) located in Greenwood County, Kansas. This member contains the Nodaway coal bed which was named by Gallagher (1889) for exposure in Andrew County, Missouri. Merriam (1989) named the Wauneta Limestone Member for the stratotype located along U. S. 166 in Chautauqua County, Kansas (sec. 7, T. 34 S, R. 10 E.) were its thickness is about 2 feet (0.7 m). This unit is not present in northern Kansas. Merriam (1989) also named the Shanghi Creek Shale Member. This units type section is located along U. S. 166 in Chautauqua County, Kansas (sec. 7, T. 34 S, R. 10 E.) This unit is a black phosphatic shale that overlies the Wauneta Limestone Member and is less than 1-foot (0.3 m) thick. Condra (1949) named the Church Limestone Member for rocks that crop out on the Church farm. The stratotype is along a creek about four miles southeast of Dubois, Pawnee, Nebraska. This limestone is commonly one massive bed of blue to bluish-gray limestone that weathers brown. It contains crinoid remains, brachiopods, and phylloid algae (Moore et al., 1944). It ranges from 1.5 to 6 feet (0.5 to 2 m ). Moore (1932) named the Winzeler Shale Member for the Winzeler farm in (sec. 4, T. 26 S., R. 11 E.) in Greenwood County, Kansas. This member is commonly bluish-gray to yellowish-gray clay shale that varies in thickness from 3 to 8 feet (1 to 2.4 m)(Moore et al., 1944). Moore (1932) named the Utopia Limestone Member for Utopia, Greenwood County, Kansas. It is a dark bluish-gray dense limestone that weathers light brownish-gray and it ranges from less than 1 to 4 feet (0.3 to 1.2 m). It contains algae, bryozoans, brachiopods, and mollusks (Moore et al., 1944).

Haworth and Benett (1908) named the Scranton Formation. Its members are the White Cloud Shale, the Happy Hollow Limestone, the Cedar Vale Shale, the Rulo

Limestone, and the Silver Lake Shale (Figure 2). The White Cloud Shale Member is a bluish-gray to yellowish-brown clayey and sandy shale (Moore et al. 1944) with a prominent incised valley (Fudge, 1956). Its thickness ranges from 30 to 80 feet (9 to 24 m) and is commonly 20 feet. Condra (1927) named the Happy Hollow Limestone for Happy Hollow ravine located on the Big Nemaha River southeast of near Rulo, Richardson County, Nebraska. It is generally a single persistent massive bed of pinkish-brown limestone with fusulinids (Moore et al. 1944). Condra (1930) named the Cedar Vale Shale Member for Cedar Vale, Chautaqua County, Kansas. This unit is a bluish to yellowish-brown clayey and sandy shale and sandstone with a persistent coal bed (Elmo) and averages about 25 feet (7.6 m)(Moore et al. 1944). Condra and Bengtson (1915) named the Rulo Limestone Member for the Missouri River bluffs southeast of Rulo, Richardson County, Nebraska. It outcrops from SE Nebraska to southern Kansas and with an average thickness of 2 feet (0.6 m). This is a bluish-gray limestone that locally is light brown on the weathered surface with common brachiopods, bryozoans, and less common mollusks (Moore et al. 1944). Beede (1898) named the Silver Lake Shale for the outcrops NE of Silver Lake located in Shawnee County, Kansas. It outcrops in SE Nebraska and Kansas. This is a gray and yellow clay shale that averages about 25 feet (7.6 m) of thickness with coal beds, a shaly sandstone, marine invertebrates, and plant fossils (Moore et al., 1944).

Moore and Mudge (1956) named the Bern Limestone to include the Burlingame Limestone Member, the Soldier Creek Shale Member, and the Wakarusa Limestone Member (Figure 2). Hall (1896) named the Burlingame Limestone Member for outcrops near Burlingame, Osage County, Kansas. The stratotype is west of Burlingame, Kansas and this unit outcrops from Iowa to Oklahoma and ranges in thickness from 4 to 16 feet (1.7 to 4.8 m). This is a brown, fine-grained, hard limestone with a shale commonly separating two limestone beds with few fossils (Moore et al., 1944). Beede (1898) named the Soldier Creek Shale Member for Soldier Creek about three miles northeast of Silver Lake, Shawnee County, Kansas. It outcrops from SE Nebraska to Kansas and ranges in thickness from 12 to 18 feet (3.6 to 5.5 m). This unit is a bluish-gray clayey to sandy shale commonly with a coal bed (Moore et al., 1944). It ranges from 4 to 16 ft (1.3 to 12 m). Beede (1898) named the Wakarusa Limestone Member for Wakarusa Creek south of Auburn, Shawnee County, Kansas. It outcrops from Iowa to Oklahoma and averages from 2 to 18 feet (0.6 to 5.5 m). It is composed of mostly a gray shale with minor amounts of sandstone and limestone (Moore et al., 1944).

Beede (1898) named the Auburn Shale Formation for exposures on Wakarusa Creek Auburn, Shawnee County, Kansas. It outcrops from Iowa to Oklahoma and ranges in thickness from 20 to 70 feet (6 to 21 m). This unit is composed of a dark bluish hard limestone that becomes light brown when weathered. A shale unit may separate two limestone beds.

Kirk (1886) named the Emporia Limestone for exposures near Emporia, Lyon County, Kansas. No stratotype was designated. The Emporia Limestone contains the Reading Limestone Member, Harveyville Shale Member, and the Elmont Limestone Member (Figure 2). Smith (1905) named the Reading Limestone Member. The stratotype is in the vicinity of Reading, Lyon County, Kansas and it outcrops in Kansas and Nebraska. It generally consist of a dark blue, dense, hard limestone that weathers light gray with light brown and it ranges in thickness from 1.5 to 15 feet (0.5 to 4.6 m).

Moore (1934) named the Harveyville Shale Member. The stratotype is near Harveyville, Wabaunsee County, Kansas and it occurs in Nebraska and Kansas. This unit ranges in thickness from 1 to 25 feet (0.5 to 4.6 m) and consists of a bluish and greenish-brown clay shale that is locally sandy shale with a thin sandstone (Moore et al. 1944). Beede (1898) named the Elmont Limestone Member for Elmont, Kansas. The stratotype is near Elmont, Shawnee County, Kansas and it occurs in SW Iowa, NW Missouri, SE Nebraska, Kansas and northern Oklahoma. It ranges in thickness from 1 to 15 feet (0.3 to 4.6 m) and consists of a dark bluish-gray and brown shale and sand stone.

Beede (1898) named the Willard Shale for the stratotype southwest of Willard, Shawnee County, Kansas. It occurs in SW Iowa, NW Missouri, SE Nebraska, and south into Kansas. In Kansas it ranges in thickness from 30 to 60 feet (9 to 20 m) (Moore et al., 1944).

Mudge (1956) named the Zeandale Limestone Formation. The stratotype is located near Zeandale, Riley County, Kansas. This formation contains the Tarkio Limestone Member, the Wamego Shale Member, and the Maple Hill Limestone Member. Its average thickness is about 53 feet (Pabian and Diffendal, 1991). Calvin (1900) originally named the Tarkio Limestone Member for exposures in Iowa. Condra (1935) designated a new stratotype because Calvin's Tarkio location was missing some section. The new stratotype was in the Missouri River bluff west of Tarkio Valley north of Corning, Holt County, Missouri. The Tarkio Limestone Member ranges in thickness from less than a foot to 10 feet (3 m) and consists of a gray limestone that weathers brown with large fusulinids (Moore et al. 1944). Condra (1927) named the Pierson Point Shale Member (Wamego Shale Member) for the stratotype southwest of Falls City, Richardson County, Nebraska. The name of the co-type locality west of Wamego, Pottawattamie County, Kansas. is the accepted name. The Wamego Shale Member is a bluish gray clay shale and yellowish brown micaceous sandy shale that ranges in thickness from 6 to 25 feet (1.8 to 7.6 m) (Moore et al., 1944). Condra (1927) named the Maple Hill Limestone Member for Maple Hill, Wabaunsee County, Kansas. The stratotype is south of Maple Hill and it occurs from NW Missouri and SE Nebraska southward to south central Kansas. This unit consists of hard gray limestone that weathers brown and contains crinoids, bryozoans, brachiopods, and sparse mollusks. The thickness ranges from 1 to 5 feet (0.3 to 1.5 m) (Moore et al., 1944).

Moore (1932) named the Table Creek Shale and later Moore and Mudge (1956) renamed the strata the Pillsbury Shale Formation. The Pillsbury Shale Formation occurs between the Zeandale Limestone Formation and the Stotler Limestone Formation. This unit is a bluish-gray clayey to sandy shale, the Nyman Coal, and a large channel sandstone (Fudge, 1956). It ranges in thickness from 5 to 50 feet (1.5 to 15 m) (Moore et al., 1944).

Moore and Mudge (1956) named the Stotler Limestone Formation for the abandoned Stotler Post Office, Lyon County, Kansas. It contains the Dover Limestone Member, Dry Shale Member, and the Grandhaven Limestone Member. It ranges in thickness from 10 to 30 feet (Pabian and Diffendal, 1991). Moore (1934) named the Dover Limestone Member. The stratotype is located in Dover, Shawnee County, Kansas. It occurs in Iowa, Nebraska, Missouri, and Kansas. This unit ranges in thickness from 2 to 20 feet (0.6 to 6 m) and consists of a light-gray and blue limestone which weathers white with algae and fusulinids being common (Moore et al., 1944). Moore (1934) named the Dry Shale Member for Dry Creek. The stratotype is southwest of Emporia, Lyon County, Kansas. This unit consists of a bluish-gray clayey shale containing a thin coal bed near the top and ranges in thickness from 5 to 20 feet (1.5 to 6 m) (Moore et al., 1944). Moore (1936) named the Grandhaven Limestone Member for exposures near Grandhaven, Shawnee County, Kansas. It is commonly two limestones separated by shale with a normal marine fauna of brachiopods, bryozoans, mollusks, fusulinids, and algae (Moore et al. 1934).

Moore and Mudge (1956) named the Root Shale Formation. The stratotype is at AT&SF R.R, Lyon County, Kansas (SE ¼ Sec. 23, T. 21 S., R. 11 E.). The members are the Friedrich Shale Member, the Jim Creek Limestone Member, and the French Creek Shale Member. Moore (1935) named the Friedrich Shale Member for Friedrich Creek. The stratotype is located in Greenwood County, Kansas ( Sec. 6, T. 32 S., R. 14 E.). This unit is a bluish-gray shale that weathers yellowish and brown and it contains a thin coal bed in places (Moore et al., 1944). Moore (1935) named the Jim Creek Limestone Member for Jim Creek. The stratotype is on Jim Creek in Pottawattomie, County, Kansas (Sec. 28, T. 7 S., R. 11 E.). This is a persistent bluish-gray hard limestone containing fusulinids and other marine fossils and it averages 1-foot (0.3 m)(Moore et al., 1944). Moore (1934) named the French Creek Shale Member for French Creek. The stratotype is located on French Creek, Pottawattomie County, Kansas. This unit is a bluish-gray to yellowish-brown clayey and sandy shale commonly containing a sandstone and it averages about 30 feet (9 m) thick (Moore et al., 1944).

Condra and Reed (1943) named the Wood Siding Formation. The stratotype is located at Wood Siding Station, Nemaha County, Nebraska. It is composed of the

Nebraska Limestone Member, the Plumb Shale Member, the Grayhorse Limestone Member, the Pony Creek Shale Member, and the Brownville Limestone Member. G. L. Smith (1918) named the Nebraska City Limestone Member for two distinct limestones exposed near Nebraska City, Otoe County, Nebraska. This unit is a bluish-gray to greenish-gray soft limestone that weathers brown with bryozoans, brachiopods, and sparse mollusks and ranges from 1 to 5 feet (0.3 to 1.5m) in thickness (Moore et al. 1944). Condra (1927) after later study accepted the upper subdivision as the Nebraska City with the stratotype in South Table Creek Valley, southwest of Nebraska City. Moore and Mudge (1956) named the Plumb Shale Member from Plumb Township in southeastern Wabaunsee County, Kansas. The stratotype is located in a road cut in the SW ¼, SE ¼, SE ¼ of Sec. 30, T. 14 S., R. 13 E., and at this location it is 20.3 feet. The average thickness 10 feet (3 m). Heald (1918) named the Grayhorse Limestone Member for the Little Grayhorse anticline, Osage County, Oklahoma. This member is a gray medium to course grained limestone and is absent north of Greenwood County, Kansas. It ranges from 0.5 to 6 feet (0.2 to 2 m) in thickness. In the northern Kansas and southern Nebraska, the Grayhorse Limestone Member is not present and the Plumb Shale Member and Pony Creek Shale Member are undifferentiated. Condra (1932) named the Pony Creek Shale Member. The stratotype is located 2.5 miles (4.5 km) southwest of Falls City, Richardson, Nebraska and it occurs throughout Kansas and into Oklahoma. It ranges in thickness from 5 to 20 (1.5 to 6 m). This member is a bluish-gray shale (locally sandy) with brachiopods and bryozoans common in the upper layers (Moore et al., 1944). Condra and Bengtson (1915) named the Brownville Limestone Member for outcrops near Brownsville, Nemaha County, Nebraska. The stratotype is on the Missouri River bluffs south of Brownsville, Nemaha County, Nebraska. It consists of a bluish-gray limestone that weathers yellowish or brown , typically is one or two limestone beds separated by a shale, and ranges in thickness from 2 to 8 feet (0.6 to 2.5 m).

# III.

# Cyclicity

The first recognition that coal measures are genetically related occurred in Nova Scotia (Dawson, 1854). Udden (1912) was the first person to propose a mechanism for the cyclic nature of the strata. He proposed that changing sediment influx (continental uplift and subsidence) caused the changing of lithology from sandstone to shale to limestone. This mechanism was accepted as the paradigm for more than 15 years. He characterized the cyclic nature of these strata by the type of sediment deposited. He recognized four stages of deposition: (1) accumulation of vegetation; (2) deposition of calcareous material; (3) sand importation; and (4) aggradation to sea level and soil making (Udden, 1912).

Simoens (1918) proposed that differential settling theory caused the cyclicity observed in the rocks. He believed that a constant supply of sediment was carried to the sea and that these particles settled out of seawater due to gravity and that different lithologies meant that the water depth was different. This theory emphasizes allochthonous control and the reason for different lithologies was transgression-regression of the sea.

Hudson (1924) proposed the differential uplift theory for the origin of the cyclicity, in which the source of sediment was thought to play a more important role in the sequence. Once the source area was "peneplained", sediment supply ceased. This mechanism requires many vertical changes in the source area and the time interval was not sufficient for the completion of a large number of cycles (Weller, 1930; Wanless, 1956).

Weller (1931, p. 164) stated.

> "The generally prevalent idea that Pennsylvanian sedimentation was controlled simply by periodic subsidence of the interior of North America and consisted of the silting up of a shallow sea and the development of a coal swamp along an advancing coast line, terminated by subsidence, a readvance of the epicontinental sea, and repetition of this process, does not take into account what was transpiring in the area from which the sediments were derived."

The proposed diastrophic control theory tries to integrate conditions of the source area, the area that the sediments were transported across, and the basin of deposition (1930, 1931). He believed that the exact nature of the cyclicity was not known but that they may be ultimately referred to diastrophic movements, climate changes, or some combination of both. "The series of members which makes up each cyclical formation is complex, and it seems unlikely that climatic changes entirely unrelated to any other conditions could result in such a uniform succession as is exhibited by each formation." He later says, ..."that climatic change related to or resulting from diastrophic movements which altered the topography of North America probably exerted an important influence on sedimentation but the results of climatic change are difficult to evaluate." It is closely related to Hudson's differential uplift theory but was formulated independently and it is noted that more information was gained in the six years after Hudson's original hypothesis.

Weller (1930, p. 102) divided the Pennsylvanian strata of Illinois into cycles consisting of two stages: continental and marine. His cycles described a detailed Pennsylvanian cycle composed of the following members:

Marine

8. Shale, containing "ironstone" bands in upper part and thin limestone layers in lower part.

7. Limestone
6. Calcareous shale
5. Black shale

Continental

4. Coal
3. Underclay, not uncommonly containing concretions of bedded fresh-water limestone
2. Sandy and micaceous shale
1. Sandstone

Unconformity

Wanless and Weller (1932) introduced the term cyclothem to describe rocks deposited by one cycle of the type that existed during the Pennsylvanian. These cyclothems consist of sandstone, shale, limestone, and coal. A cyclothem is an informal stratigraphic name equivalent to a formation. It represents a fourth order sequence. The reason that they identified a cyclothem is that it is a mappable rock unit independent of a change in lithology. A change in lithology is very common laterally in the Midcontinent due to the cyclic nature of the strata. The types of cyclic deposits in Kansas are different from those in Illinois. Moore (1936) coined the term megacyclothem. A megacyclothem is a combination of related cyclothems or a cycle of cyclothems. These different types of cycles resulted in different types of lithologic relationships. A Kansas megacyclothem is equivalent to three or more incompletely developed Illinois cyclothems (Heckel, 1977).

The components of a basic Midcontinent cyclothem consists upward of (1) thin, transgressive marine limestone; (2) thin, offshore non sandy, conodont rich shale with black phosphatic facies; (3) thicker shoaling upward regressive limestone; and (4) nearshore to terrestrial non carbonate strata (Heckel, 1986)(Figure 8). During times of faster rates of transgression or regression, there may be a lack of these basic characteristics (Heckel, 1986).

Wanless and Shepard (1936) proposed the glacial control theory because periodic diastrophic pulsations seem unreasonable. The authors cited well-documented evidence for late Paleozoic continental glaciation in the Southern Hemisphere, which produced sea-level fluctuations, said to be conservatively estimated at 450 feet. One objection at this time is that age and limits of Late Paleozoic glaciation are relatively unknown. Conditions and dates of Late Paleozoic glaciation have subsequently been identified (Crowell, 1978; Imbrie and Imbrie, 1980).

## Allocyclicity vs. Autocyclicity

The two types of mechanisms proposed are very different in nature. The diastrophic theory is based on an autocyclic mechanism and the glacial eustatic theory is an allocyclic mechanism. The best indicator of the type of mechanism for the cyclicity is correlation between basins. An autocyclic mechanism (diastrophism, sea floor spreading, sediment influx, or changing sedimentation patterns) should not permit the correlation of equivalent units between basins. It only operates within the specific basin of deposition. Boardman and Heckel (1989) developed a model that

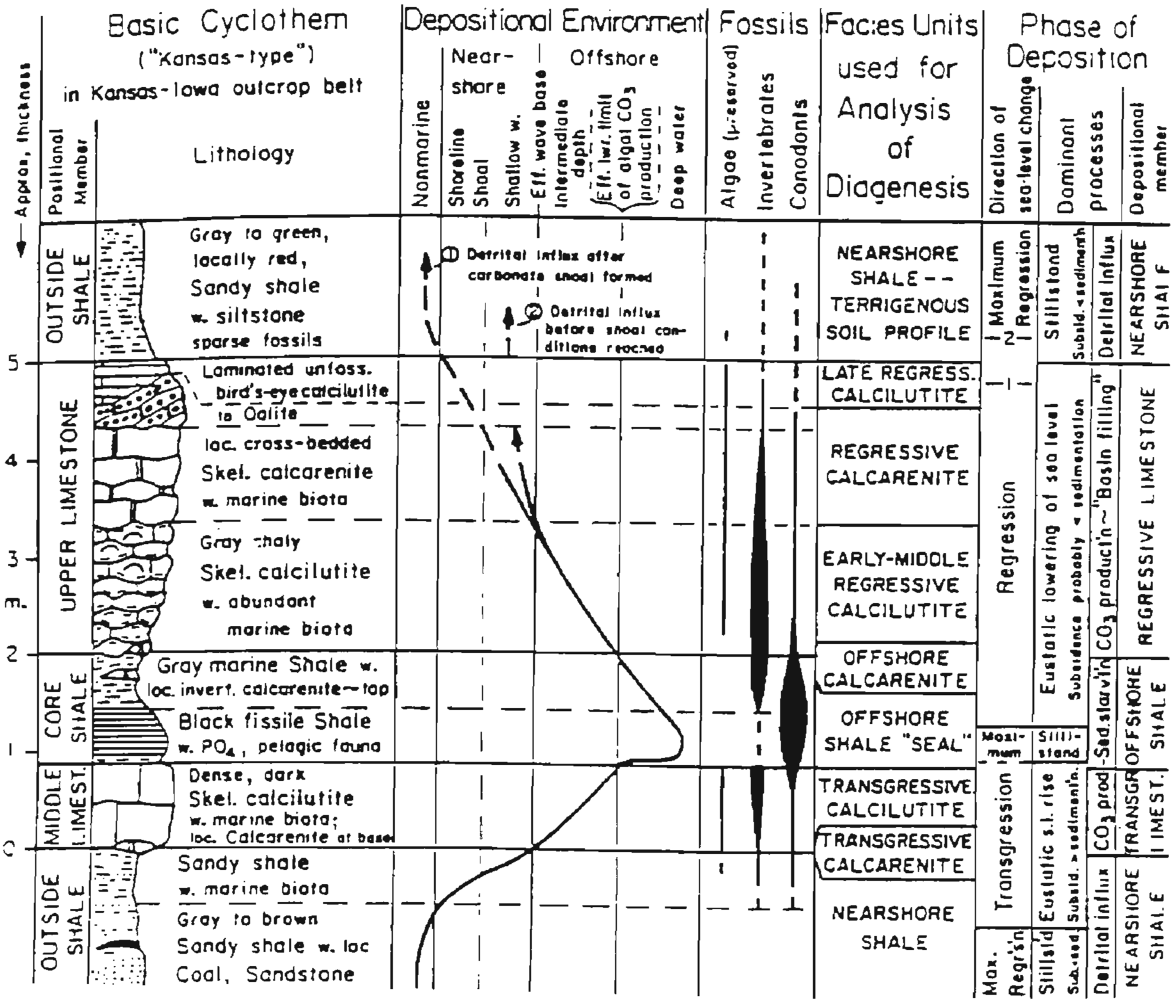


Figure 8. Basic Midcontinent cyclothem (Heckel 1986).

combines changes in sediment influx with glacial eustasy (Figure 9). They account for the role a delta can play in a system but note that during the Pennsylvanian it only secondarily affects the system that is eustaically controlled. An allocyclic mechanism (glaciation) is eustatic and should produce global changes in sea-level. Recent investigations have found that in fact Late Paleozoic strata are correlateable intracratonically (Boardman and Heckel, 1989) and globally (Ross and Ross, 1985). A correlation between Pennsylvanian units in north central Texas and the Midcontinent yield 17 cycles (Figure 10). The origin of Pennsylvanian cyclicity is currently accepted as glacial-eustaic (Miall, 1997). Miall (1997) summarized the rates and magnitude of processes affecting sea-level (Figure 11).

## Orders of Cyclicity

The magnitude of the base-level change is determined by lithology as well as paleontologic characteristics. The larger base-level change (fourth order), is associated with non-marine deposits, incised valleys, and a non-marine or restricted marine fauna. Late Paleozoic glaciation is generally thought to be attributed to orbital forcing. There are three separate components of orbital forcing: variations in eccentricity, changes in the obliquity of the elliptic, and procession of the equinoxes (Miall, 1997)(Figure12). Variations in eccentricity are changes in the shape of the earth's orbit around the sun with major periods of variation at 413 and 100 ka (Miall, 1997). Changes in the obliquity of the elliptic are changes tilt of the earth's axis (Miall, 1997). Procession of the equinoxes is the wobble of the earth's axis (Miall, 1997). A definite hierarchy of cyclicity has been identified from the rock record.

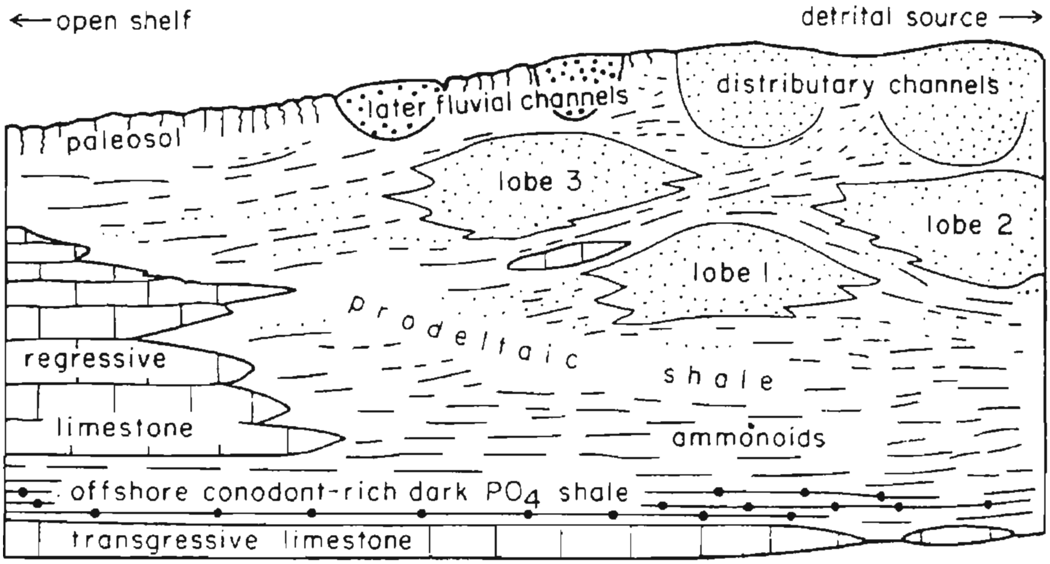


Figure 9. Sediment influx model (Boardman and Heckel, 1989).

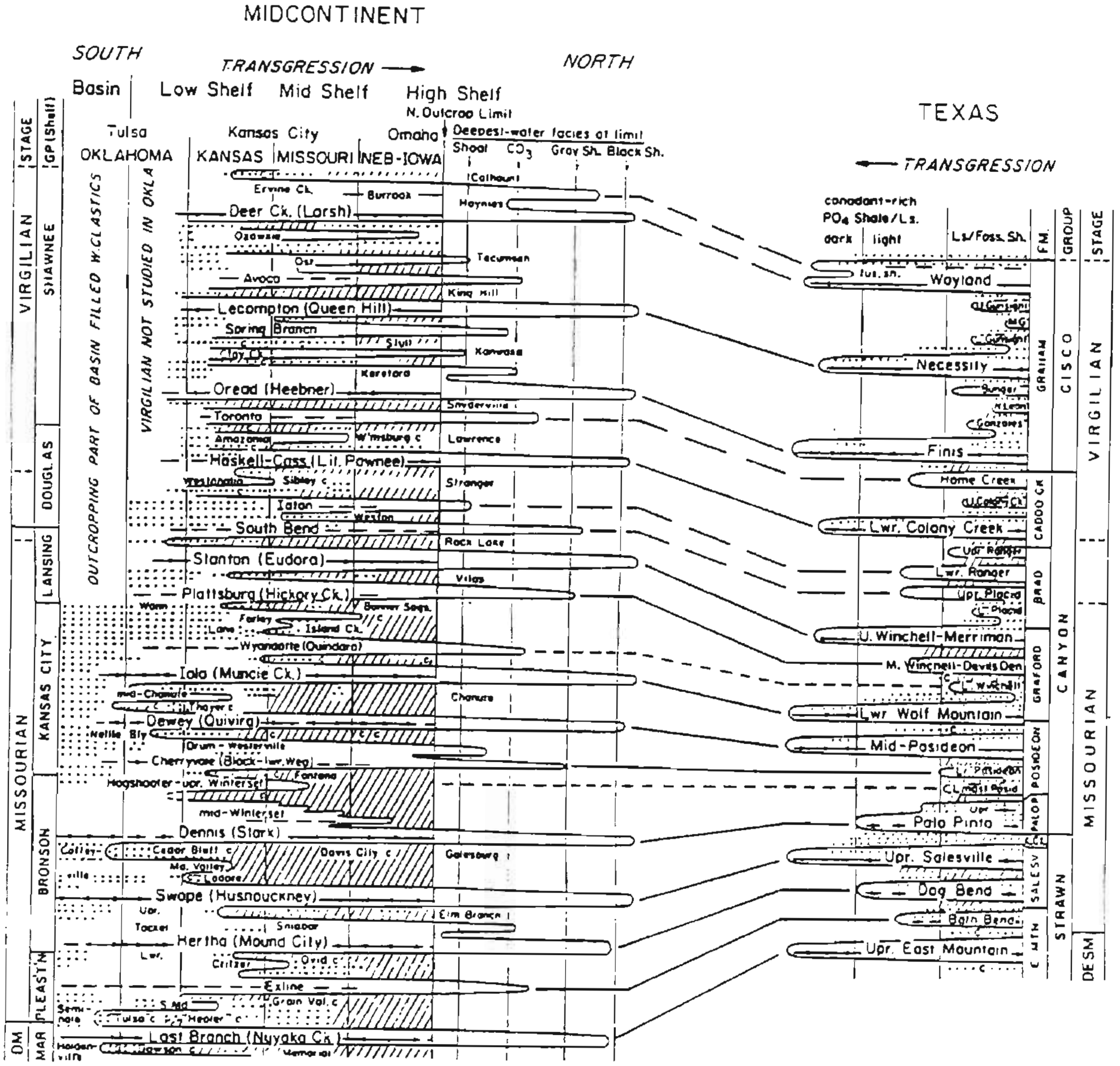
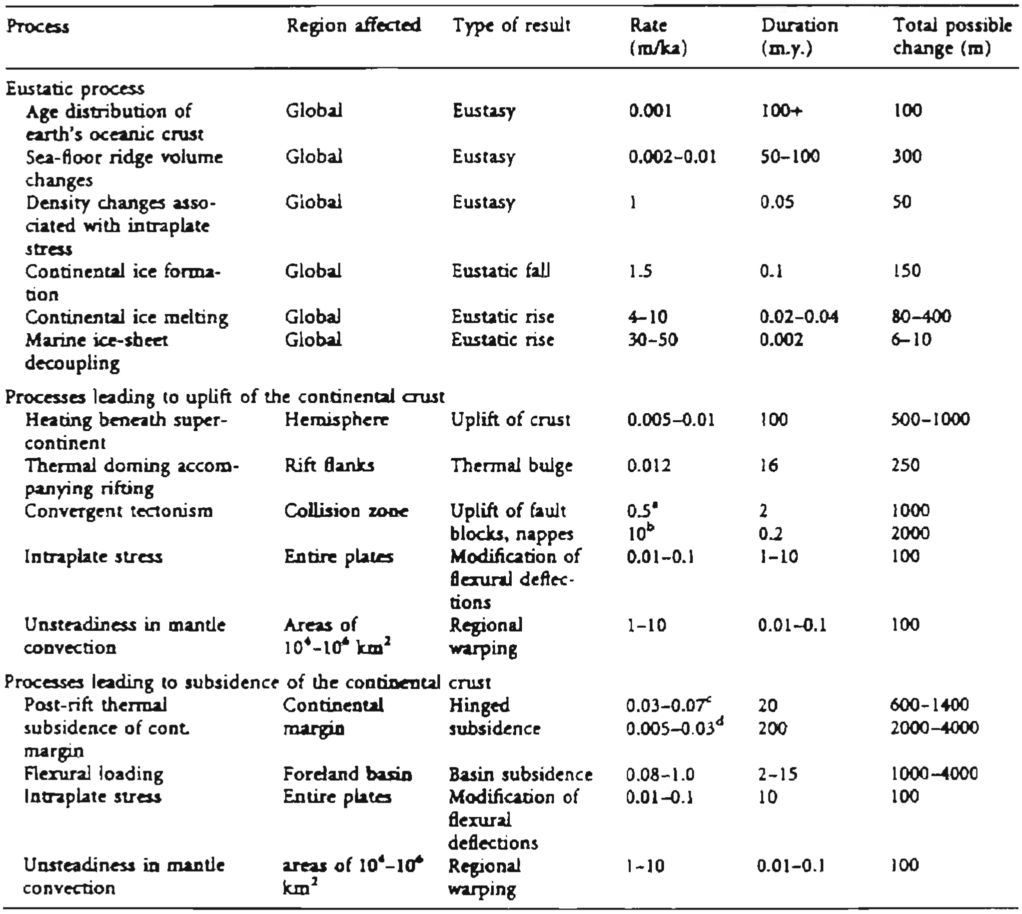


Figure 10. Correlation of north central Texas and Midcontinent cycles (Boardman and Heckel, 1989).



| Process | Region affected | Type of result | Rate (m/ka) | Duration (m.y.) | Total possible change (m) |
|---|---|---|---|---|---|
| Eustatic process | | | | | |
| Age distribution of earth's oceanic crust | Global | Eustasy | 0.001 | 100+ | 100 |
| Sea-floor ridge volume changes | Global | Eustasy | 0.002–0.01 | 50–100 | 300 |
| Density changes associated with intraplate stress | Global | Eustasy | 1 | 0.05 | 50 |
| Continental ice formation | Global | Eustatic fall | 1.5 | 0.1 | 150 |
| Continental ice melting | Global | Eustatic rise | 4–10 | 0.02–0.04 | 80–400 |
| Marine ice-sheet decoupling | Global | Eustatic rise | 30–50 | 0.002 | 6–10 |
| Processes leading to uplift of the continental crust | | | | | |
| Heating beneath supercontinent | Hemisphere | Uplift of crust | 0.005–0.01 | 100 | 500–1000 |
| Thermal doming accompanying rifting | Rift flanks | Thermal bulge | 0.012 | 16 | 250 |
| Convergent tectonism | Collision zone | Uplift of fault blocks, nappes | 0.5[a]<br>10[b] | 2<br>0.2 | 1000<br>2000 |
| Intraplate stress | Entire plates | Modification of flexural deflections | 0.01–0.1 | 1–10 | 100 |
| Unsteadiness in mantle convection | Areas of $10^4$–$10^6$ km$^2$ | Regional warping | 1–10 | 0.01–0.1 | 100 |
| Processes leading to subsidence of the continental crust | | | | | |
| Post-rift thermal subsidence of cont. margin | Continental margin | Hinged subsidence | 0.03–0.07[c]<br>0.005–0.03[d] | 20<br>200 | 600–1400<br>2000–4000 |
| Flexural loading | Foreland basin | Basin subsidence | 0.08–1.0 | 2–15 | 1000–4000 |
| Intraplate stress | Entire plates | Modification of flexural deflections | 0.01–0.1 | 10 | 100 |
| Unsteadiness in mantle convection | areas of $10^4$–$10^6$ km$^2$ | Regional warping | 1–10 | 0.01–0.1 | 100 |

Figure 11. Rates and magnitudes of processes affecting sea-level (Miall, 1997).

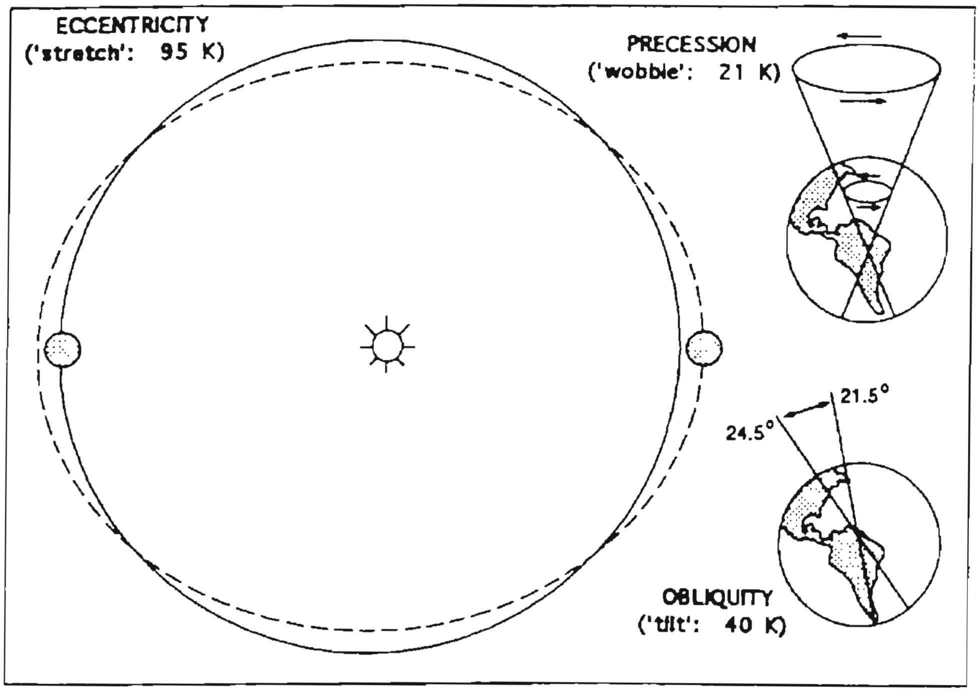


Figure 12. Origin of orbital forcing (Miall, 1997).

(Sloss, 1963)(Figure 13). Goldhammer and others (1994) summarized the order of cycles (Figure 14) and the duration of Pennsylvanian fourth-order cycles (Figure 15). Busch and Rollins (1994) give the relationship of the hierarchy of cyclicity that exists within the Pennsylvanian (Figure 16).

## Wabaunsee Group Cyclicity

The Mediterranean basins (Aral, Black, Caspian, and Dead,) provide a modern analog of a hydrographic situation resulting from staggered advance of oceanic waters, and implication for maximum water depth (Elias, 1964). Elias (1964) reconstructed the paleoecology during Wabaunsee time (Figure 17). Heckel and Baseman (1975) developed a conodont biofacies model (Figure 18). Different species of conodont are interpreted to occupy different areas within the water column. Boardman and others (1995) further expanded the conodont biofacies model to include other fauna including ostracodes, mollusks, fusulinids, brachiopods, and ammonoids. This microfaunal biofacies model supports the earlier work of Heckel and Baesemann.

The Wabuansee Group consists of the Howard cyclothem, the Scranton cyclothem, the Bern cyclothem, the Emporia cyclothem, the Zeandale cyclothem, the Stotler cyclothem, and the Root/Wood Siding cyclothem. Moore (1936) characterized a typical Wabaunsee Group cyclothem (Figure 19) but the author did not find this generalization to be accurate within the study area. In general, the typical Wabuansee Group cyclothem consist of two limestones formations with a thin intervening marine shale formation and is bounded by thick marginal marine to non-marine shale formations. This type of cyclicity is not present in the Howard limestone. The Howard limestone is genetically related to the Shawnee Group and has similar cyclicity as the Shawnee type cyclothem (Heckel, 1986)(Figure8). The Howard Limestone represents a type-A cyclothem (Boardman and Malinky, 1985). It contains the only black phosphatic shale member of the entire Wabuansee Group. A type-A cyclothem forms in deeper water than a type-B cyclothem. The Howard cyclothem is a type-A cyclothem. The rest of the Wabaunsee Group are type-B cyclothems (Boardman and Malinky, 1985). The lithologic characteristics of the Wabaunsee Group were used to construct a lithofacies model (Figure 20).

The lithologic characteristics are a direct indicator of depositional environment. The different facies present in the Wabaunsee Group are as follows:

| | |
|---|---|
| Facies 1- | A. Incised Valley Fills<br>B. Coals and non-coal paleosols<br>C. Siltstones |
| Facies 2- | Shale to silty shale-rare ostracodes and mollusks, no conodonts. |
| Facies 3- | Mudstone to grainstone-low diversity ostracode and mollusk assemblage, rare conodonts. |
| Facies 4- | Highly fossiliferous wackestones to packstones-open marine fauna of echinoderms, bryozoans, brachiopods, fusulinids, moderately abundant conodonts. *Streptognathodus* biofacies. |
| Facies 5- | Gray clay shale-rare PO4 with diverse benthic and pelagic fauna, abundant conodonts. *Streptognathodus* biofacies. |
| Facies 6- | Black, fissile shale-PO4 nodules with pelagic fauna, abundant conodonts. Streptognathodus/Gondolella biofacies. |

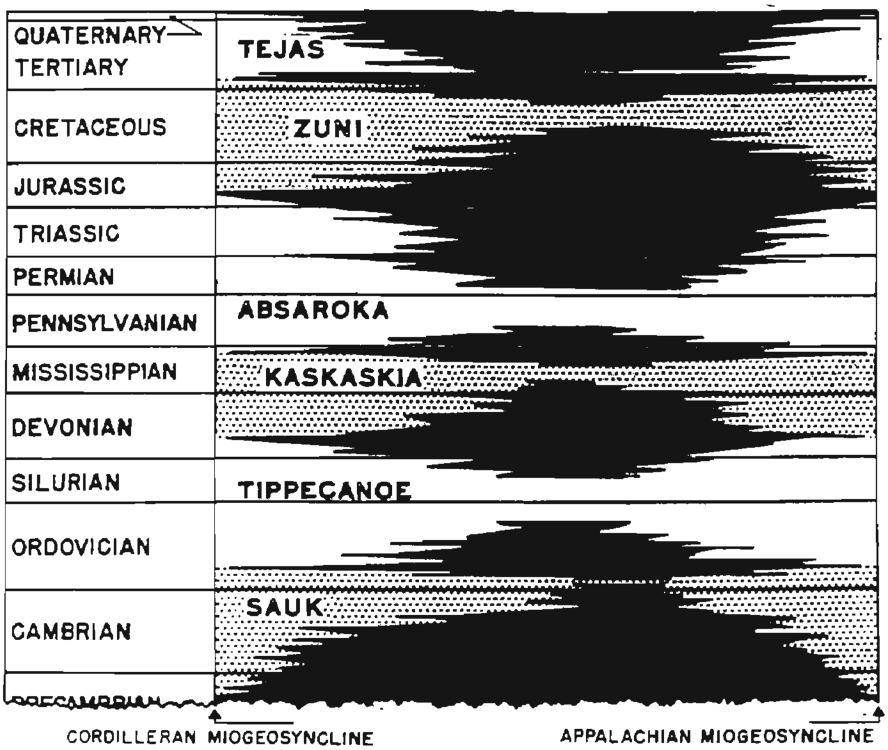


Figure 13. Sloss's supersequences

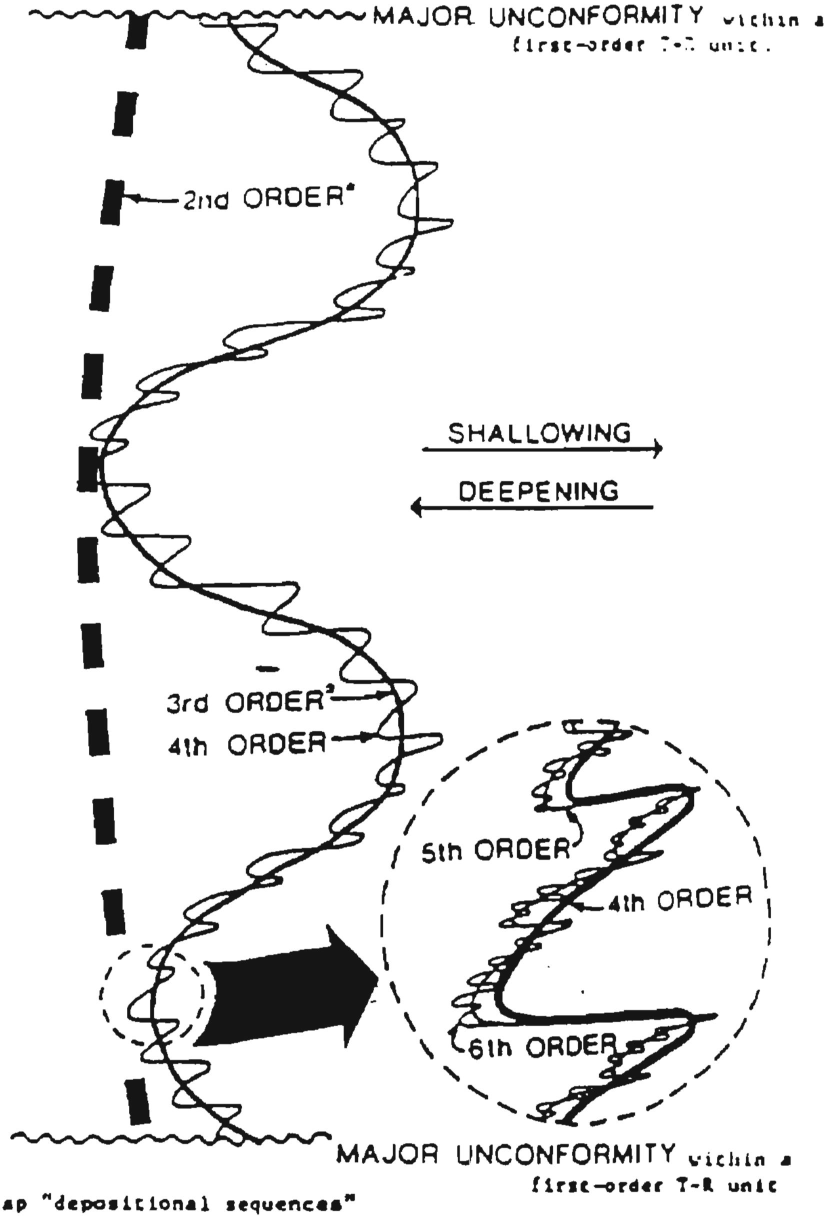
| Sequence Stratigraphic Terminology | Eustatic Cycle (Order) | Duration (m.y.) | Amplitude (m) | Rise/Fall Rate (cm/1,000 yr) |
|---|---|---|---|---|
|  | First | >100 |  | <1 |
| Supersequence | Second | 10–100 | 50–100 | 1–3 |
| Sequence | Third | 1–10 | 50–100 | 1–10 |
| Sequence, cycle | Fourth | 0.1–1 | 1–150 | 40–500 |
| Parasequence, cycle | Fifth | 0.01–0.1 | 1–150 | 60–700 |

Data summarized from Sloss (1963), Rona (1973), Pitman (1978), Donovan and Jones (1979), Schlager (1981), Kendall and Schlager (1981), Hine and Steinmetz (1984), Miall (1984), Haq et al. (1987), Goldhammer et al. (1987, 1990), Ross and Ross (1987), and Crevello et al. (1989).

Figure 14. Hierarchy of cyclicity (Goldhammer et al., 1994)

| Source | Stratigraphic Unit | Cycle Periodicity (Years) |
|---|---|---|
| This study | Desmoinesian Paradox formation: SE Utah, SW Colorado: 29 regionally correlative, basinal shale-evaporite cycles | 230,000–385,000 |
| Driese and Dott (1984) | Middle Pennsylvanian Morgan Formation: northern Utah and Colorado: 17 mixed clastic-carbonate cycles | 470,000–800,000 |
| Heckel (1986, 1989) | Middle Pennsylvanian "cyclothems" from the US midcontinent; 25 shale-based mixed clastic-carbonate cycles | 235,000–400,000 |
| Busch and Rollins (1984) | Pennsylvanian "cyclothemic PAC sequences" from northern Appalachian basin; 12 regionally extensive mixed clastic-carbonate cycles with coal horizons | 400,000–450,000 |
| Ross and Ross (1987) | Desmoinesian depositional sequences of southwestern US; 23 regionally significant sequences | 390,000 |
| Ramsbottom (1979) | Carboniferous "cyclothems" of Britain | 200,000–500,000 |
| Goldstein (1988) | Virgilian Holder formation of New Mexico: mixed clastic-carbonate cycles | 300,000 |
| Algeo and Wilkinson (1988) | Compilation of Carboniferous mesoscale cycles | 400,000 |

Figure 15. Summary of Pennsylvanian fourth-order cycle durations (Goldhammer et al., 1994)



*onlap-offlap "depositional sequences" of Vail et al. (1977).

Figure 16. Relationship between the different orders of cyclicity (Busch and Rollins, 1994).

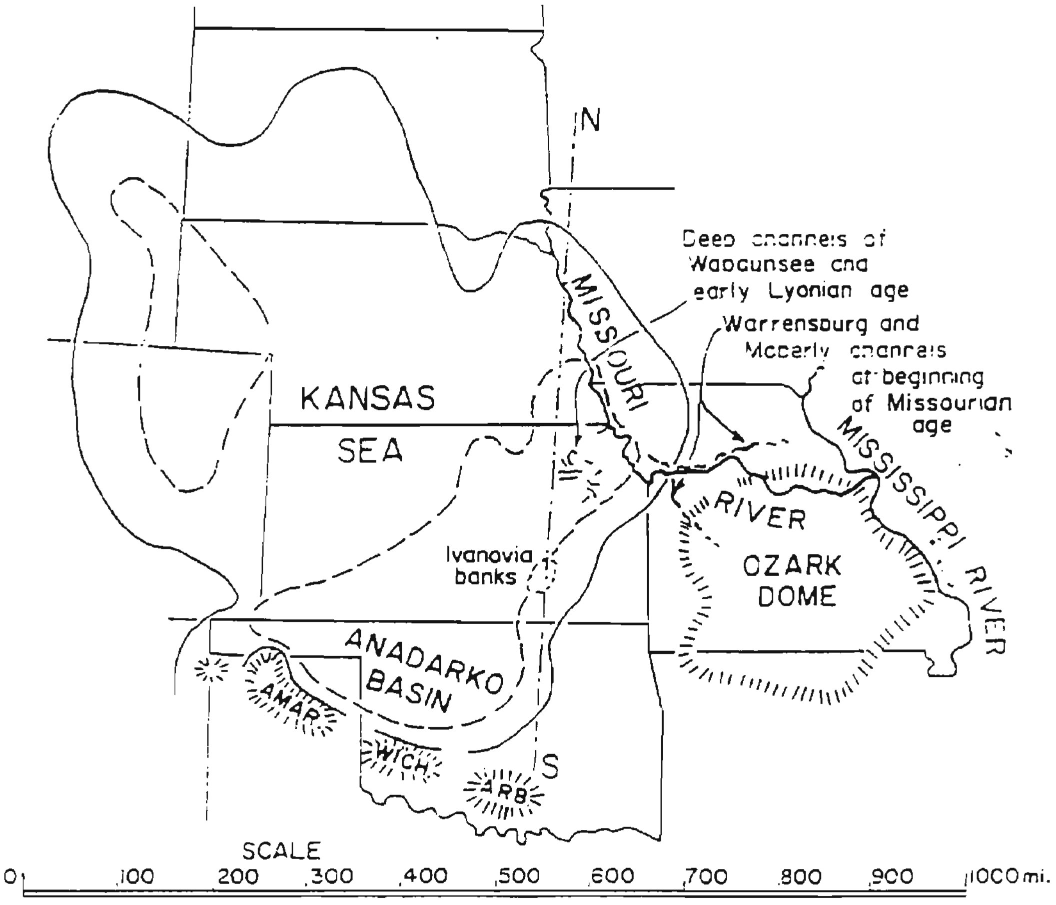


Figure 17. Relationship of Wabaunsee Group strata to the sea (Elias, 1964).

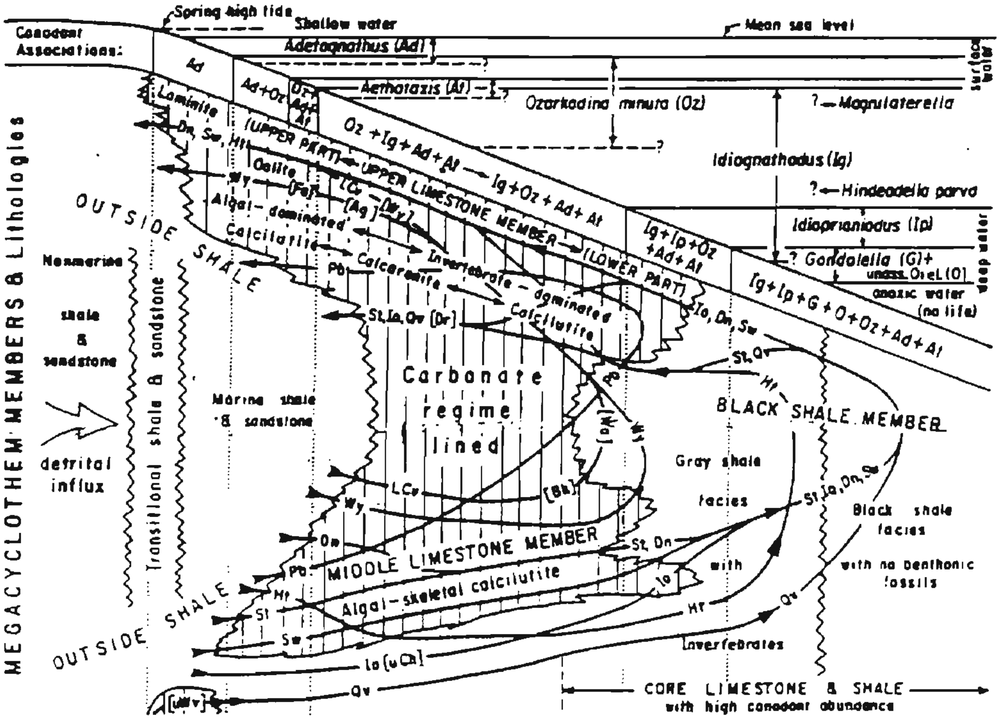


Figure 18. Conodont biofacies (Heckel and Baesemann, 1975).

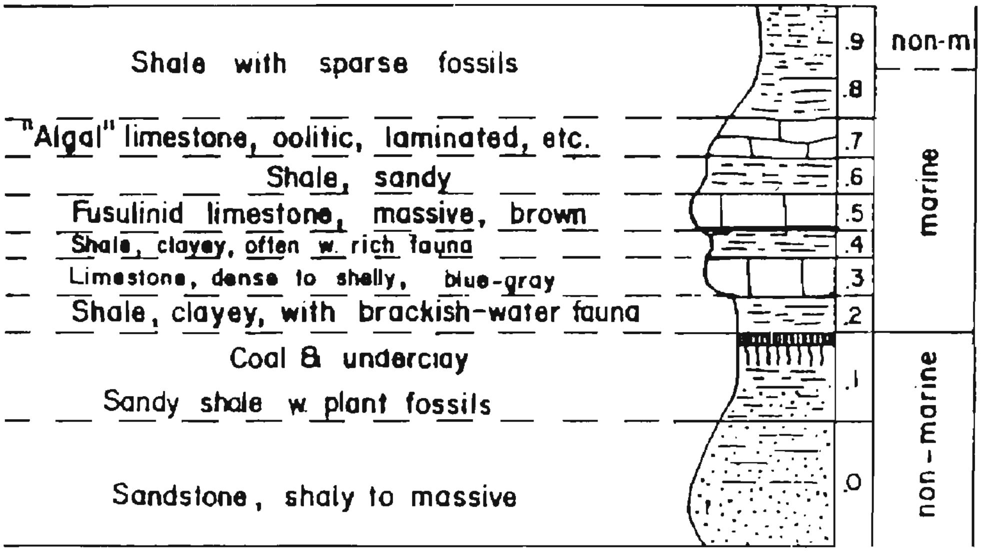


Figure 19. Wabaunsee Group cyclothem (Moore, 1936).

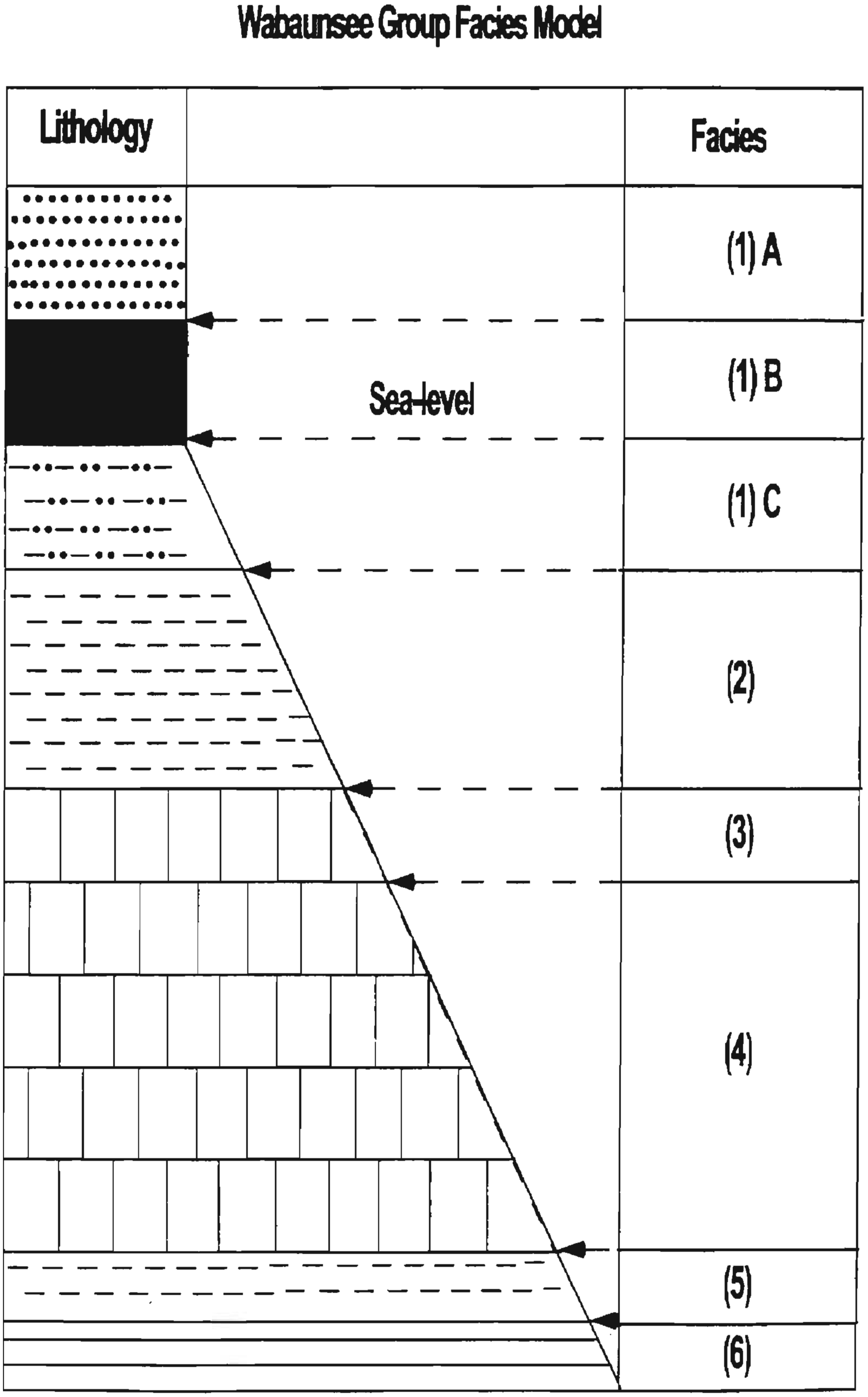


Figure 20. Wabuansee Group facies model.

# IV.

# Sequence Stratigraphy

## Overview

Isralelsky (1949) constructed a chart using species floods of relative changes in water depth at one geographic position and noticed a change in correlatable species horizons between several different wells.

Sloss and others first developed the concept of stratigraphic sequences at the 1949 Symposium of Sedimentary Facies *in* Geologic History at the Annual Meeting of the Geological Society of America. Sloss (1963) originally recognized six interregional unconformities that subdivide the stratigraphic column of the Phanerozoic Era in North America. These unconformities are the boundaries of six stratigraphic sequences and are and the result of oscillations of the sea. Each sequence represents a major transgression, beginning at the cratonic margins and in the basins of greatest subsiding tendencies, gradually spreading to the more stable areas of the cratonic interior, and ultimately lapping up on the margins of the Canadian Shield (Sloss, 1967). Sloss (1963) notes that his interregional cratonic sequences are finite and have no application to rock stratigraphy and time stratigraphy of extracratonic or extracontinental areas. These sequences are major rock-stratigraphic units of higher rank than group, megagroup, or supergroup. The unconformity bounded units that Sloss recognized are supersequences that range in age from 10 to 100 million years (Figure 8).

## Definitions

Vail and others (1977) using seismic sequence analysis based on the identification of stratigraphic units composed of a relatively conformable succession of genetically related strata termed a depositional sequence and they note that the time interval represented by strata of a given sequence may differ from place to place, but the range is confined to synchronous limits marked by ages of the sequence boundaries where they become conformities.

Van Wagoner and others (1988) developed the modern terminology and concepts of sequence stratigraphy. The resurgence was based on the fact that seismic applications were becoming more important to petroleum exploration and depositional sequences are easily identified on a seismic line with unconformity surfaces being a good reflectors.

Sequence stratigraphy is the study of rock relationships within a chronostratigraphic framework of repetitive genetically related strata bounded by surfaces of erosion, non-deposition, or their relative conformities (Van Wagoner et al., 1988). The depositional sequence is defined as a relatively conformable succession or genetically related strata bounded by unconformities or their correlative conformities (Mitchum et al, 1977). A sequence is a genetically related succession of strata with no apparent internal unconformities, composed of parasequences and parasequence sets arranged in systems tracts, and bounded by unconformities or their correlative conformities (Mitchum and Van Wagoner, 1991). A stratal package conforming to this definition is properly called a sequence and is independent of scale (Mitchum and Van Wagoner, 1991). The depositional sequence is the fundamental unit of sequence stratigraphy (Vail et al., 1991). Sequence boundaries are characterized by an abrupt basinward shift in facies or a change

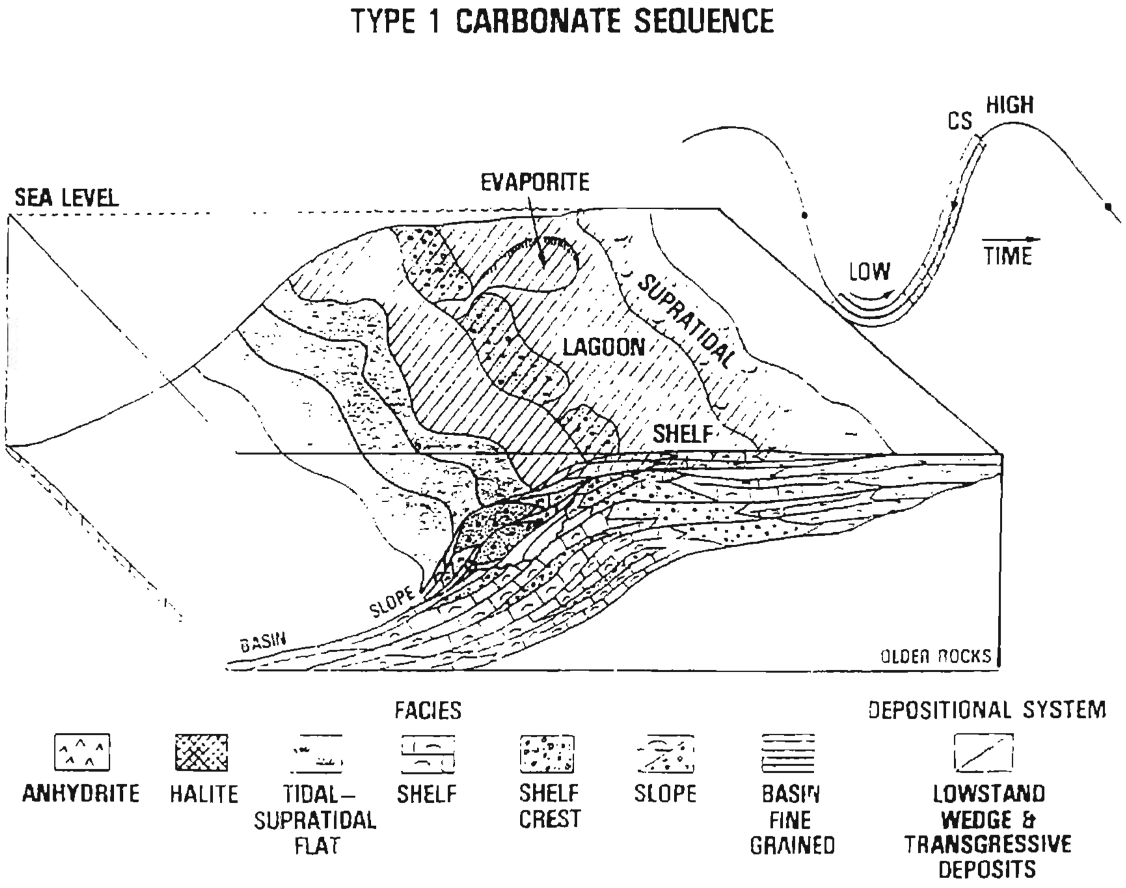


Figure 21. Type 1 sequence boundary (Sarg, 1988).

in parasequence stacking patterns (Van Wagoner et al., 1990). As mentioned earlier, these sequences are bounded by unconformity surfaces. There are two types of unconformity surfaces. A type 1 sequence boundary is characterized by subaerial exposure and concurrent subaerial erosion associated with stream rejuvenation and a basinward shift in facies (Van Wagoner et al., 1988)(Figure 21). A type 2 sequence boundary forms by subaerial exposure and a downward shift in coastal onlap landward of the depositional-shoreline break without concurrent but lacks a basinward shift in facies erosion (Van Wagoner et al., 1988)(Figure 22). A depositional sequence is composed of several system tracts, which are a body of rock that groups several intergradational, and part, contemporaneous depositional systems (Brown and Fisher, 1977). Van Wagoner and others (1988) recognize four types of system tracts and they are lowstand, shelf margin, transgressive, and highstand. These system tracts are the result of deposition and erosion during changes of sea-level and are comprised of parasequences or parasequence sets (Van Wagoner et al., 1988). Parasequences are bounded by flooding surfaces (Van Wagoner et al., 1988). A lowstand systems tract is bounded below by a sequence boundary and above by a transgressive surface (Van Wagoner, 1987). A transgressive systems tract is bounded below by the transgressive surface and above by the maximum flooding surface (Van Wagoner, 1987). A highstand system tract is bounded below by the downlap surface and above by the next sequence boundary (Van Wagoner, 1987). Sarg (1988) further expanded on the original Exxon model in an effort to characterize a carbonate ramp (Figure 23).

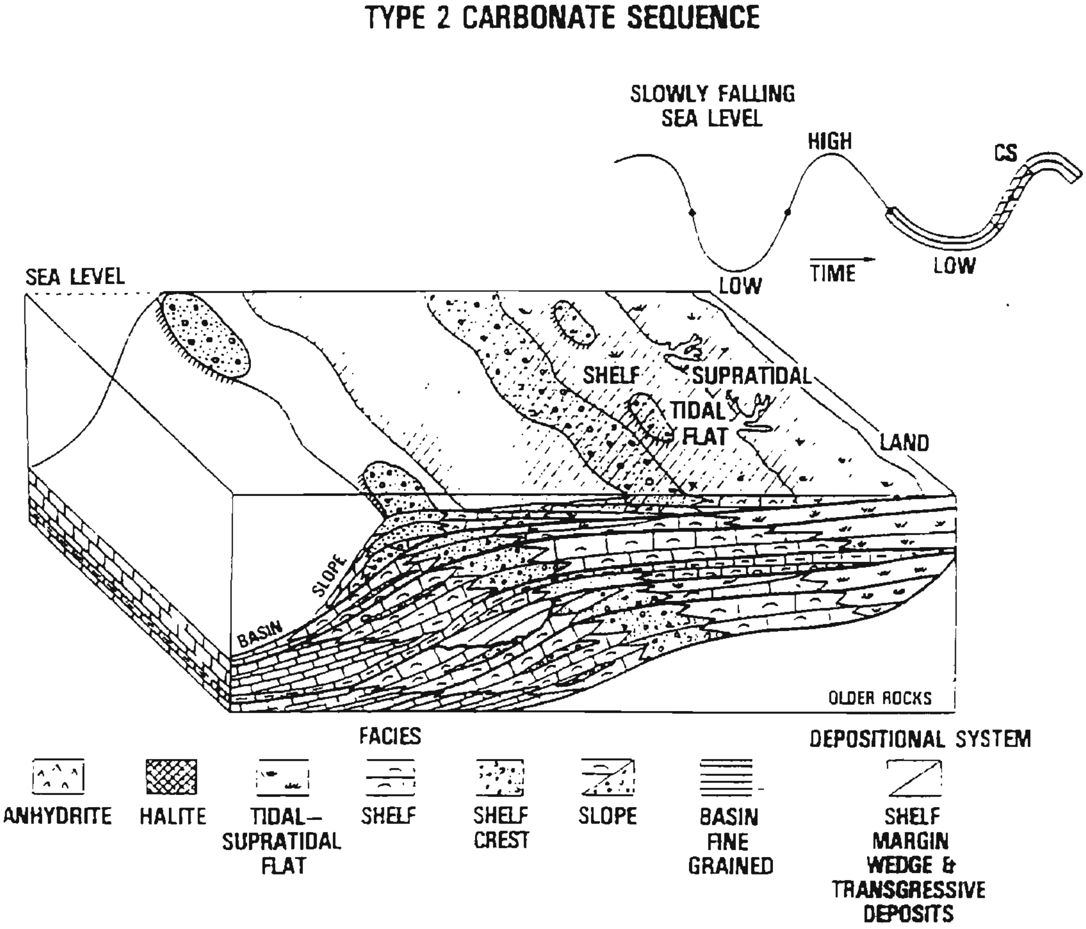


Figure 22. Type 2 sequence boundary.

SEQUENCE STRATIGRAPHY DEPOSITIONAL MODEL
SHOWING CARBONATE AND
EVAPORITE LITHOFACIES

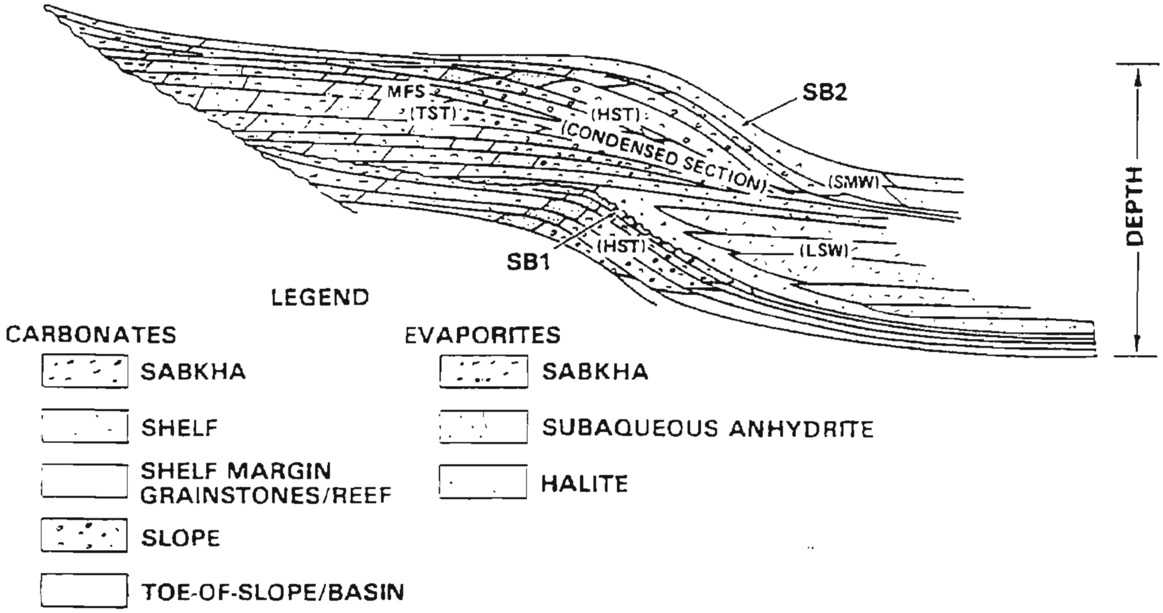


Figure 23. Carbonate sequence stratigraphic model (Sarg, 1988).

## Third-Order Sequence

Vail and others (1977) at Exxon Production Research Company constructed a model of a depositional sequence using seismic data which was more practical than the work that Sloss had done. Vail and others (1977) were interested in global changes in sea-level to be used for correlation and the identification of unconformities. Vail and others (1991) refer to the depositional sequence as a third-order cycle that ranges from 0.5 to 3 m.y. in duration.

## Third-Order Composite Sequence

In contrast to Sloss, the new Exxon definition of a depositional sequence is much smaller in scale and duration. As previously mentioned, a sequence is a genetically related succession of strata with no apparent internal unconformities, composed of parasequences and parasequence sets arranged in systems tracts, and bounded by unconformities or their correlative conformities (Mitchum and Van Wagoner, 1991). Early applications workers at Exxon of sequence stratigraphic concepts involved studies in basins of Tertiary and Cretaceous age in which the mechanisms of sea-level change were different than in the Paleozoic.

A stratal package conforming to this definition is properly called a sequence and is independent of scale (Mitchum and Van Wagoner, 1991). A stratal package bounded by unconformities but internally composed of high-frequency sequences, cannot itself be properly called a sequence, and Mitchum and Van Wagoner (1991) call this type of stratal unit is called a composite sequence. These third order sequences range in age from 1 to 10 million years. These third-order relative sea-level cycles are interpreted to represent a composite sequence (Mitchum and Van Wagoner, 1991), subdivided into three sequence sets.

The three sequence sets are: transgressive sequence sets, highstand sequence sets, and late-highstand sequence sets. The transgressive sequence sets are deposited during maximum rates of a third-order relative sea-level rise (Mitchum and Van Wagoner, 1991). Incised-valley fill estuarine sandstones are best preserved within the sequences that comprise the transgressive sequence set (Youle, 1992). The highstand sequence set is deposited when the rate of sea-level rise slows, stops, and falls slowly (Mitchum and Van Wagoner, 1991). Because the rate of change is slow, higher-frequency relative sea-level fluctuations may have a better preservation potential. The late-highstand sequence set is deposited on the falling limb of the third-order sea-level curve (Mitchum and Van Wagoner, 1991). When third-order fall in sea-level occurs at high rates, higher frequency changes may not be preserved.

Posamentier and others (1992) originate the concept of forces regression. A regression forms when sea-level falls due to either an actual decrease in sea-level or when rate of basin subsidence is faster than a sea-level rise, producing a relative fall in sea-level. He introduces criteria for recognizing forced regressions, and they are:

1. Relatively coarse-grained lowstand deposits occur seaward of, and are detached and separated by, a zone of bypass from the immediately preceding depositional system.

2. Lowstand shorelines are characterized by sharp-based shoreface sediments proximally and gradational shoreface sediments distally.

3. Lowstand shoreface deposits typically are relatively narrow (e.g., less than 12 km wide) in the examples studied.

4. Transgressive systems tract deposits typically onlap the distal limits of, as well as overlie, lowstand shoreface deposits.

5. Incised-valley feeder systems for lowstand shoreface deposits are not always preserved.

6. Landward of the lowstand shoreline pinch-out, the sequence-bounding unconformity commonly is merged with a transgressive surface of erosion forming an erosion/transgression surface (after Plint et al., 1986)

7. Seaward of the lowstand shoreline pinch-out, the sequence-bounding unconformity occurs below the lowstand shoreline, and the transgressive surface of erosion occurs above the lowstand shoreline.

## Pennsylvanian Sequence Stratigraphy

The fundamental building blocks of ancient shallow marine platform carbonates are high-frequency (meter-scale), shallowing upward depositional cycles (Goldhammer et al., 1994). These high-frequency cycles consist of a relatively conformable succession of genetically related subtidal facies bounded by peritidal facies, subaerial exposure surfaces, and/or marine flooding surfaces (Goldhammer et al., 1994).

There are some problems associated with sequence stratigraphy in the Midcontinent (Watney et al., 1989). The application of sequence stratigraphy to cratonic Paleozoic strata presents challenges due to: 1) Limited accommodation potential on platform areas, 2) slow, episodic sedimentation rates and limitations in sediment preservation, and 3) difficulty in establishing independent methods of correlating parasequences (Watney et al., 1989). Depositional sequences in a shelf setting thus are characterized by numerous local and regional truncations and facies changes involving thin, but commonly mappable, beds (Watney et al., 1989).

The shelf preserves a better record of sea-level high-stand events than does the sediment starved setting in the basin and the basin and shelf margin preserve a better record of sea-level low-stand events while contemporaneous subaerial exposure or nondeposition dominates the shelf (Watney et al., 1989).

Watney and others (1989) describe how to construct a sequence stratigraphic framework for the Midcontinent without seismic profiles. Sequence-stratigraphic analysis can be accomplished without seismic profiles, if adequate rock and wireline-log data are available. The general approach is given as follows:

1. Vertical-sequence analysis:

   a) Describe strata in terms of depositional environment and relative water depth (relative sea-level change) and evidence for shallowing or deepening trends; identify potential marker beds (thin distinctive units to aid in correlation)

   b) Describe surfaces: bedding planes (frequency and nature; distinguish diagenetic from depositional); association of surfaces with facies dislocation; ranking of facies dislocation according to water depth change; establish evidence of subaerial exposure or prolonged nondeposition, e.g. hardground developed in marine environment

   c) Draw profiles of sections providing interpretation of genetic units and water depth; genetic units consisting of *flooding or transgression units (usually associated with base of depositional sequence; usually thin limestone or coal on shelf areas in Pennsylvanian depositional sequences) of

*condensed sections (may be associated with accumulation of organic matter, e. g. , black shale or hardgrounds);

*shallowing upward unit (shadowing carbonate or siliciclastic succession or combination; thickest and most complex component of a sequence; frequently associated with multiple parasequences

*paleosol development (may represent sequence or possibly parasequence boundary if it forms a surface).

2. Correlation between localities

a) Establish correlations of marker beds and surfaces, utilizing lithostratigraphic, paleontologic, geophysical, or geochemical data (preferably through continuous or detailed systematic sampling).

b) Identify the depositional sequence(s). Correlate major genetic units and bounding surfaces associated with a depositional sequence using all information available.

c) If possible, extend control to the 3rd-dimension and over more extensive areas of shelf, shelf margin, and into basin to address stratal geometries in more comprehensive manner and evaluate allogenic and autogenic causal mechanisms(eustatic, subsidence). Youle and others (1994) use scale-independent methods because Pennsylvanian cyclothems posses all components of a depositional sequence.

## Sequence Stratigraphic Debate

A debate has arisen over the past several years as to the definition of the systems tracts. Hunt and Tucker (1992) have identified discrepancies in how the system tracts are defined. The error in "Exxon" thinking is that by definition the lowstand deposits are above the sequence boundary and the shelfal parasequences are below the sequence boundary (Figure 24). These pelagic sediments are deposited at the same time and a sequence boundary is not time transgressive. Two new system tracts are defined to alleviate the problem and now has a genetic relationship between the "stranded" parasequences and the lowstand deposits. The new system tract is the forces regressive system tract (Figure 25)(Hunt and Tucker, 1992).

## Wabaunsee Group Sequence Stratigraphy

A sequence stratigraphic analysis of the Wabaunsee Group involves not only defining the sequence boundaries but also bed by bed analysis of base-level change. The Virgilian stage is composed of one third order sequence . There are the two orders of cyclicity observed in the Wabaunsee Group. A third order sequence is composed of multiple fourth order sequences. A fourth order sequence is composed of multiple fifth order cycles (Figure 16). This study uses scale dependent methods because the data is interpreted to indicate a relative scale of sea-level change.

Sequence stratigraphic concepts suggest that stratal geometries develop and are largely controlled by changes in base-level (Posamentier et al., 1992). A change in base-

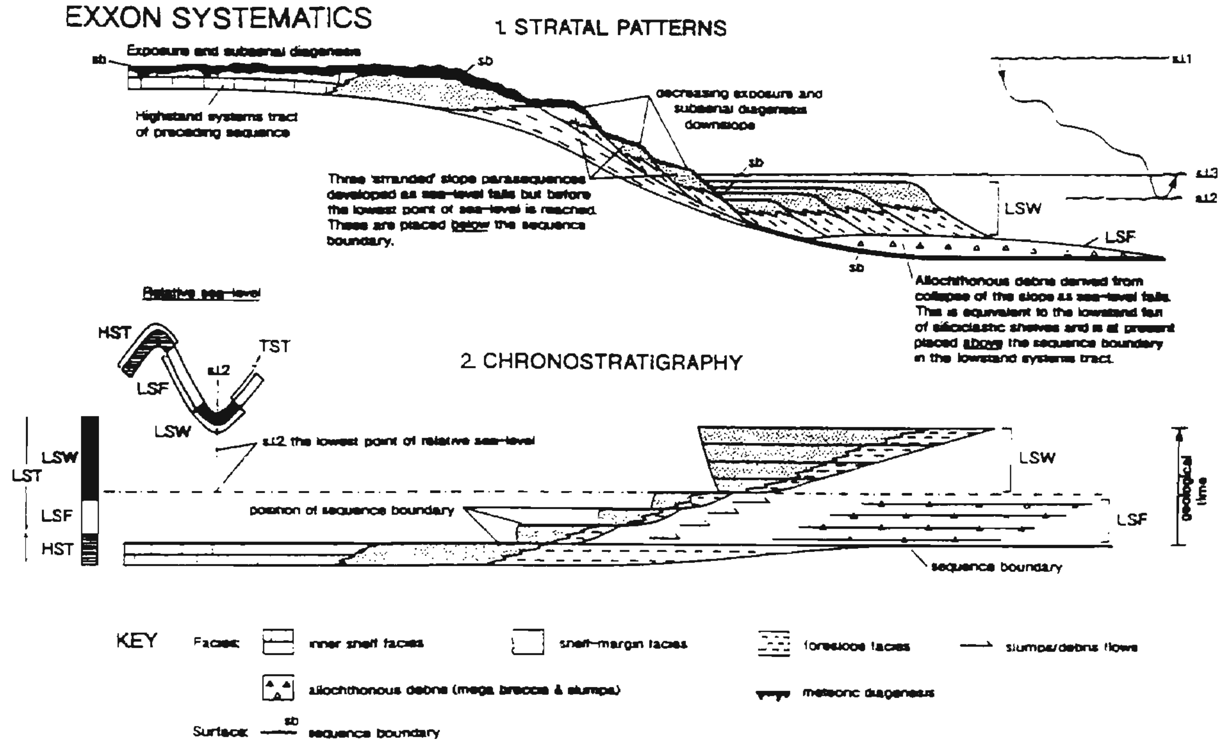


Figure 24. Exxon depositional sequence (Hunt and Tucker, 1992).

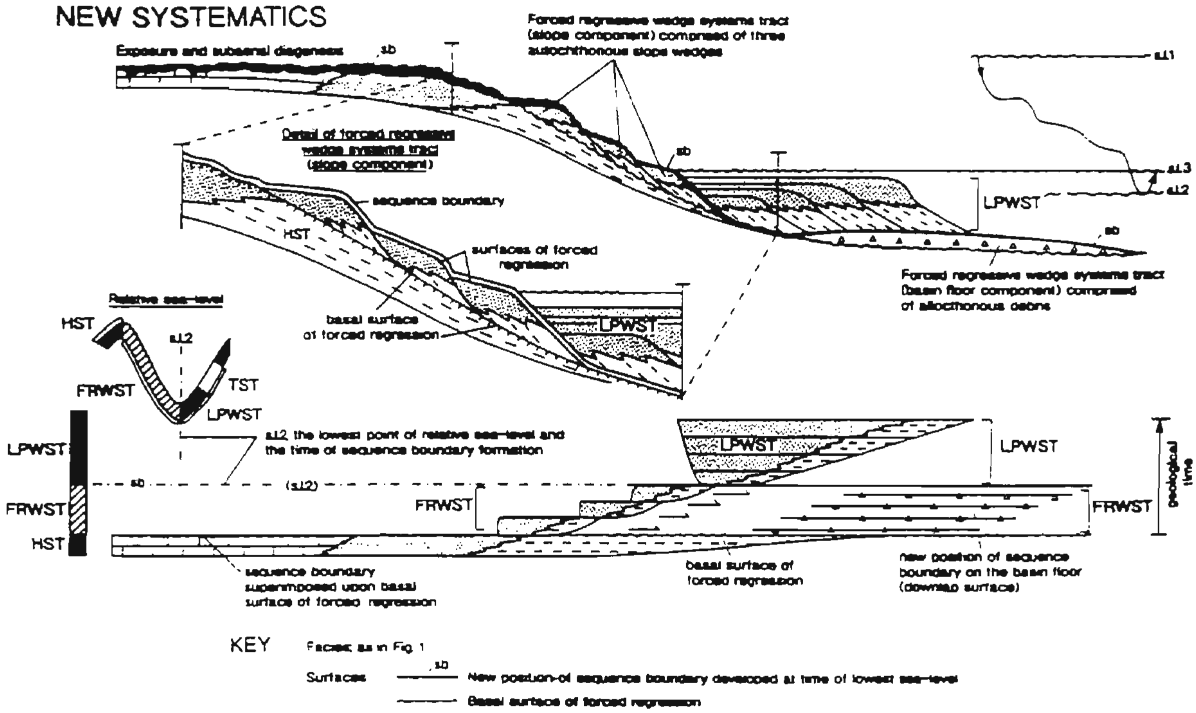


Figure 25. New depositional model (Hunt and Tucker, 1992).

level because of a fall in sea-level is termed a forced regression (Posamentier et al., 1992)(Figure 26). This means that falling base-level during Wabuansee time was a forced regression. Although this study does not incorporate any subsurface data for three dimentional analysis, that Watney and others (1991) and Posamentier and others (1992) feel is necessary for sequence stratigraphic analysis, the author feels that the sequence stratigraphic analysis of the Wabaunsee Group has been fully characterized.

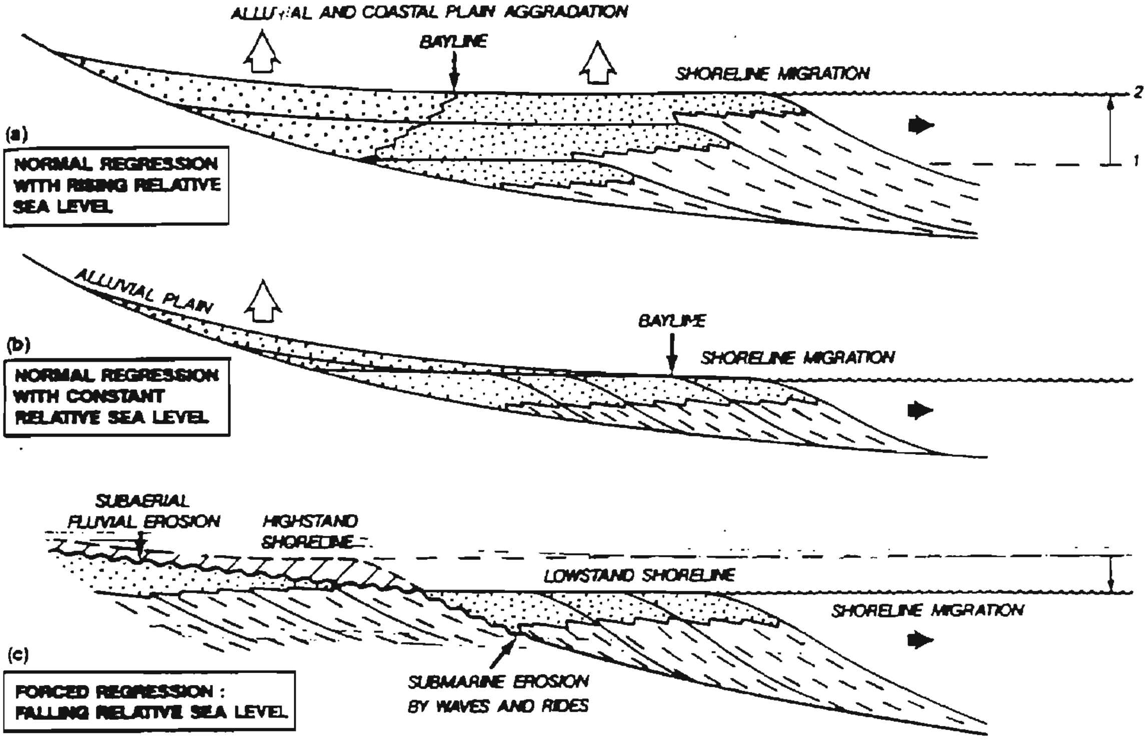


Figure 26. Forced regressive model (Posamentier et al., 1992).

# V.

# Surface Study

A proper evaluation of outcropping Wabaunsee Group strata must include placement of strata into a sequence stratigraphic framework. Constructing a sequence stratigraphic framework requires estimating relative base level of each lithologic unit and how base level changes above and below that unit. Both macroscopic and microscopic paleontological associations and facies associations were used to determine relative change of base level.

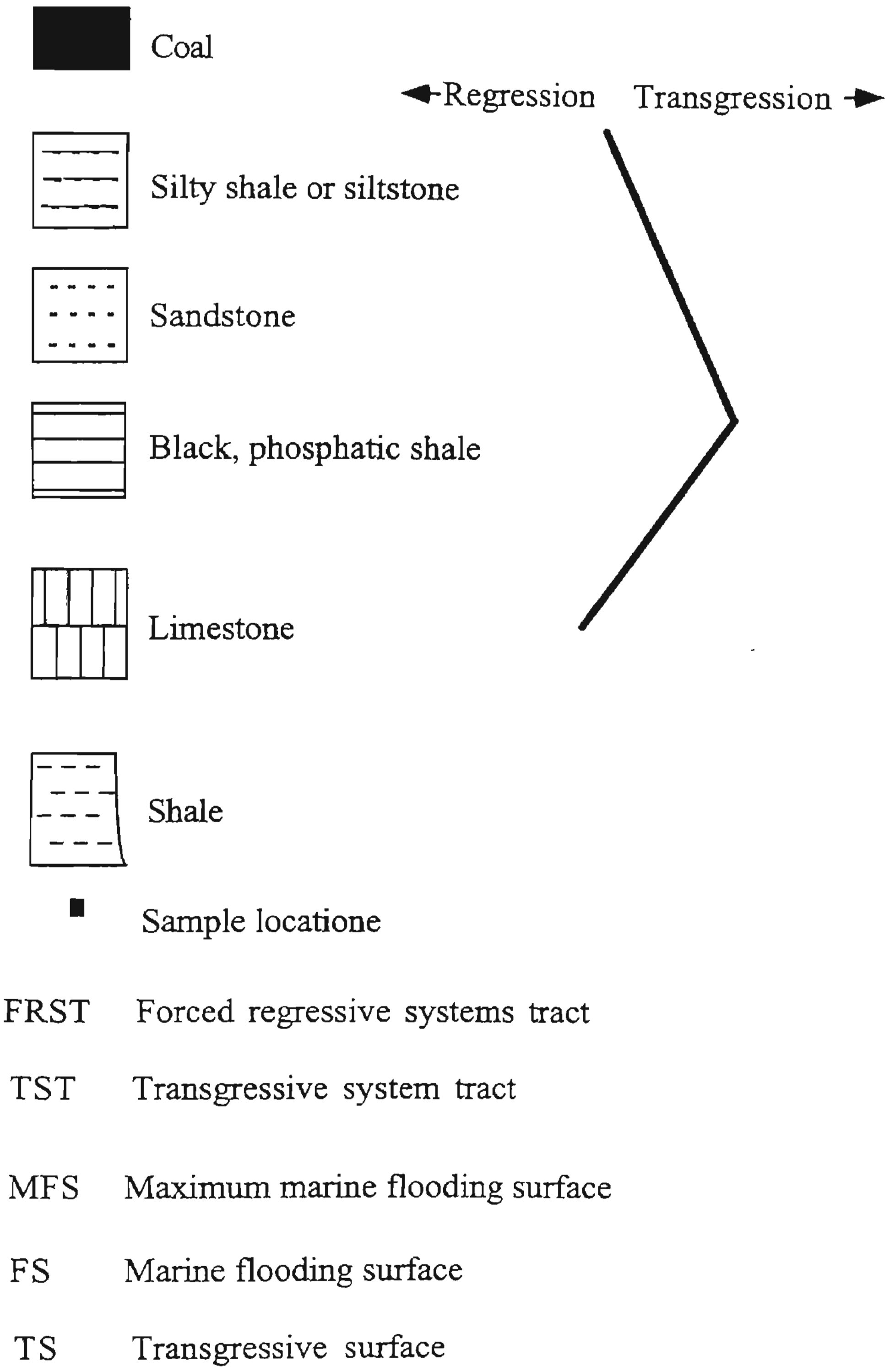


Figure 27. Key to measured sections.

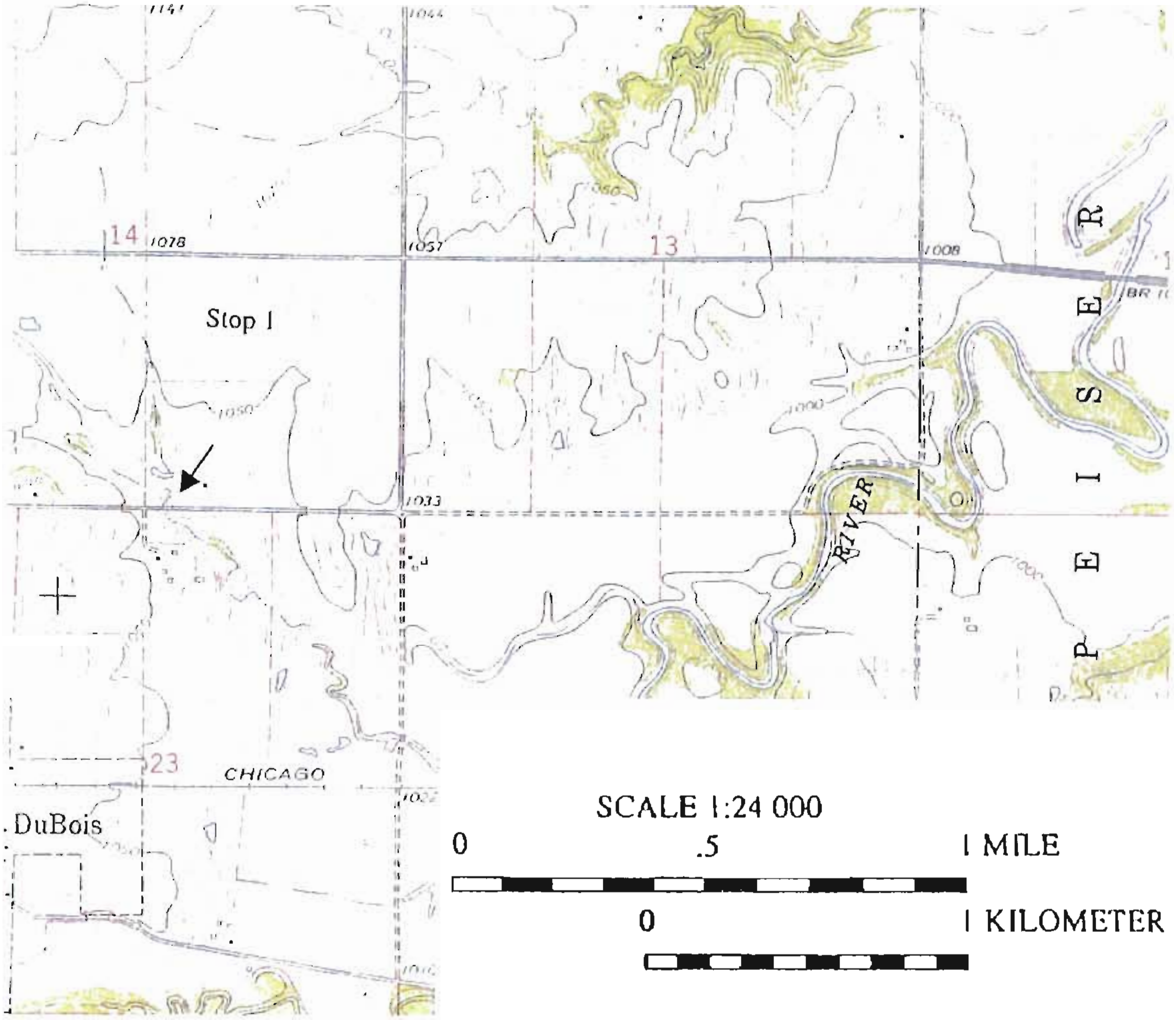


Figure 28. Location of stop 1.

Photograph 1. Stop 1-Northeast of Dubois, Nebraska.

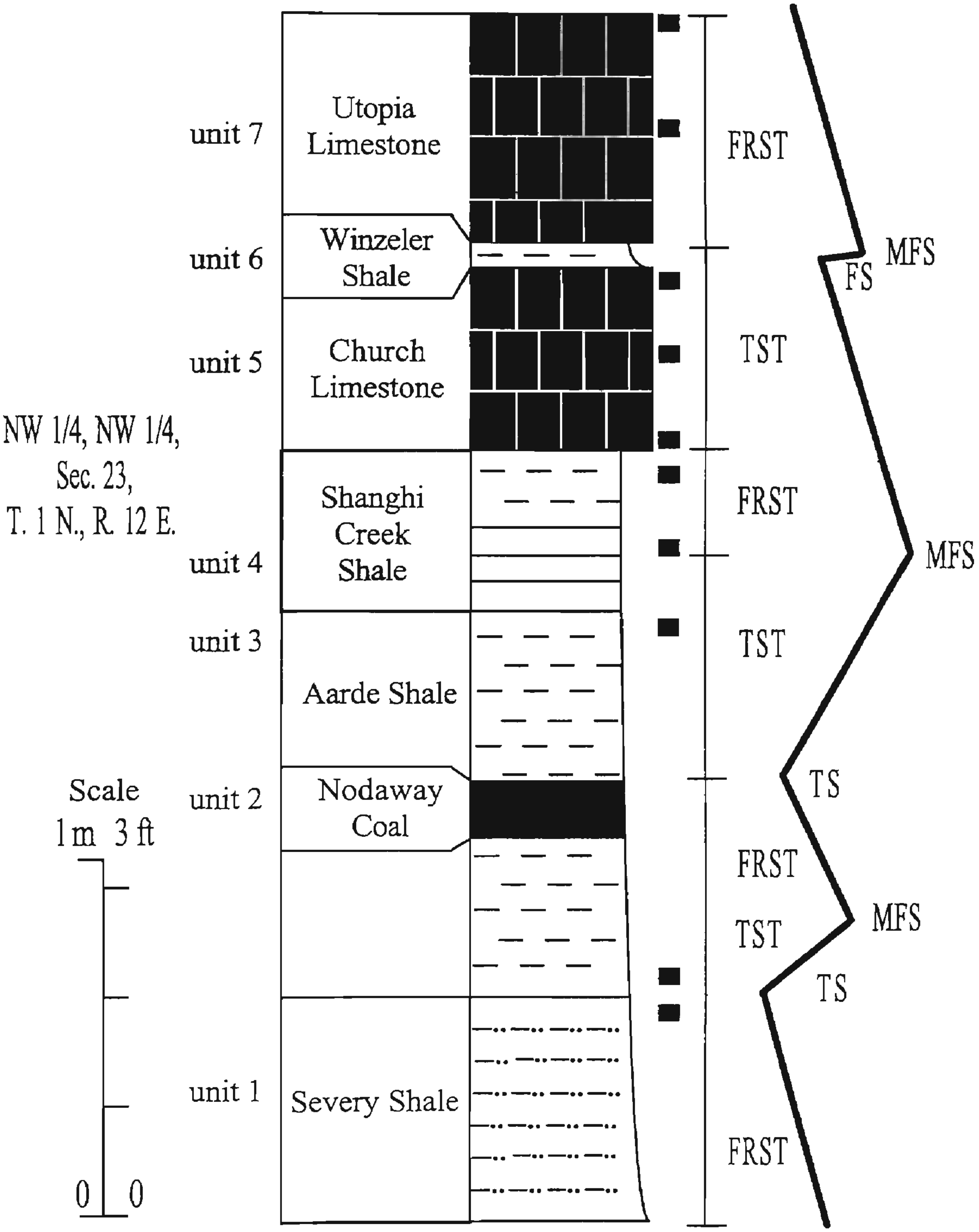


Figure 29. Measured section of stop 1.

Stop 1.

State: Nebraska County: Pawnee

Stream cut on south side of road (modified after Pabian and Boardman)

Howard limestone Formation

Unit 1. Severy Shale Formation Facies 1C

1m (3 ft)- Micaceous sandstone with ripple marks and cross beds

Unit 2. Aarde Shale Member Facies 2

0.6 m (2 ft)- Grey siltstone, unfossiliferous

Unit 3. Nodaway Coal Bed Facies 1B

0.3 m (1 ft)- Coal with calcareous concretions at the top and pyritized fossils (brachiopods, bivalves, gastropods, cephalopods)

Unit 2. Aarde Shale Member Facies 2

0.15 m ( 0.5 ft)- Grey shale, no macrofossils with abundant *Streptognathodus*

Unit 4. Shanghi Creek Shale Member Facies 6

1m (3 ft)- Grey mudstone containing an black phosphatic shale

Unit 5. Friedrich Shale Member Facies 2

5.6 m (19 ft)- Gray shale, no macrofossils

Unit 6. Church limestone Member Facies 4

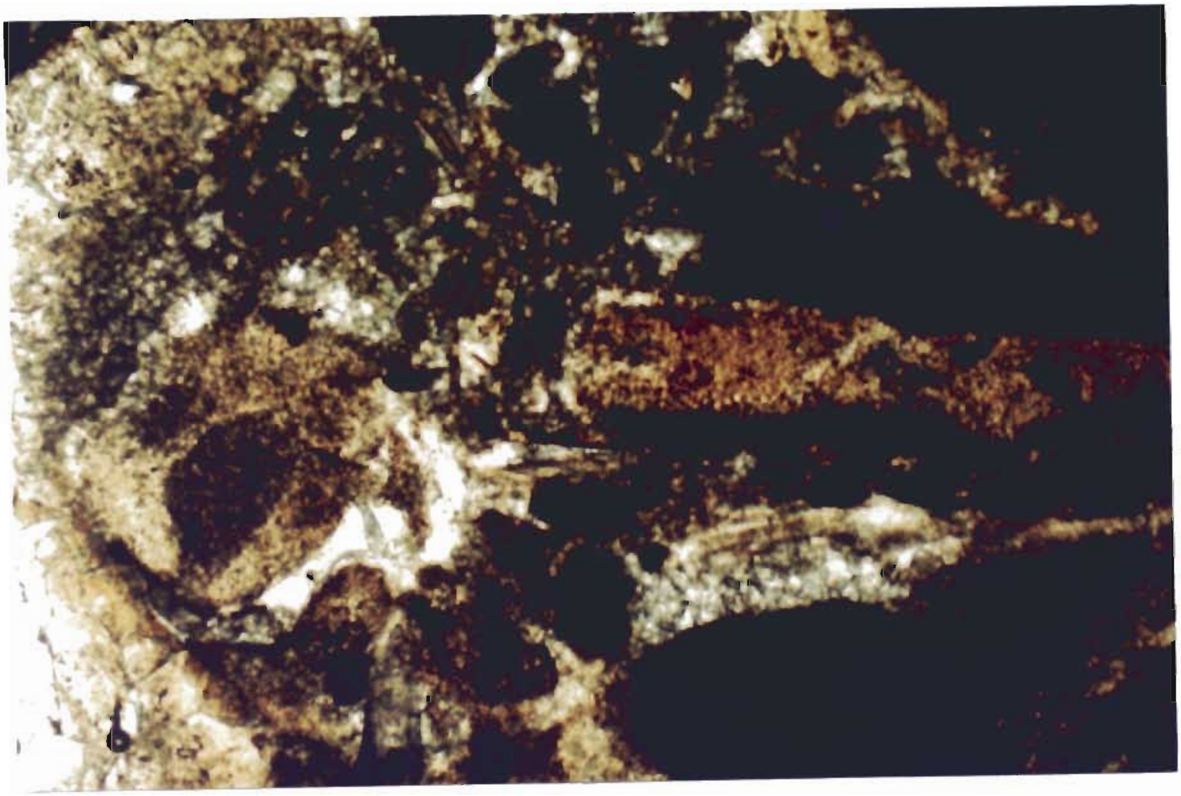
1.1 m (3.5 ft)- Grey wackestone to packstone and contains gastropods, bivalves, crinoids, bryozoans, fusulinids

Unit 7. Winzeler Shale Member Facies 5

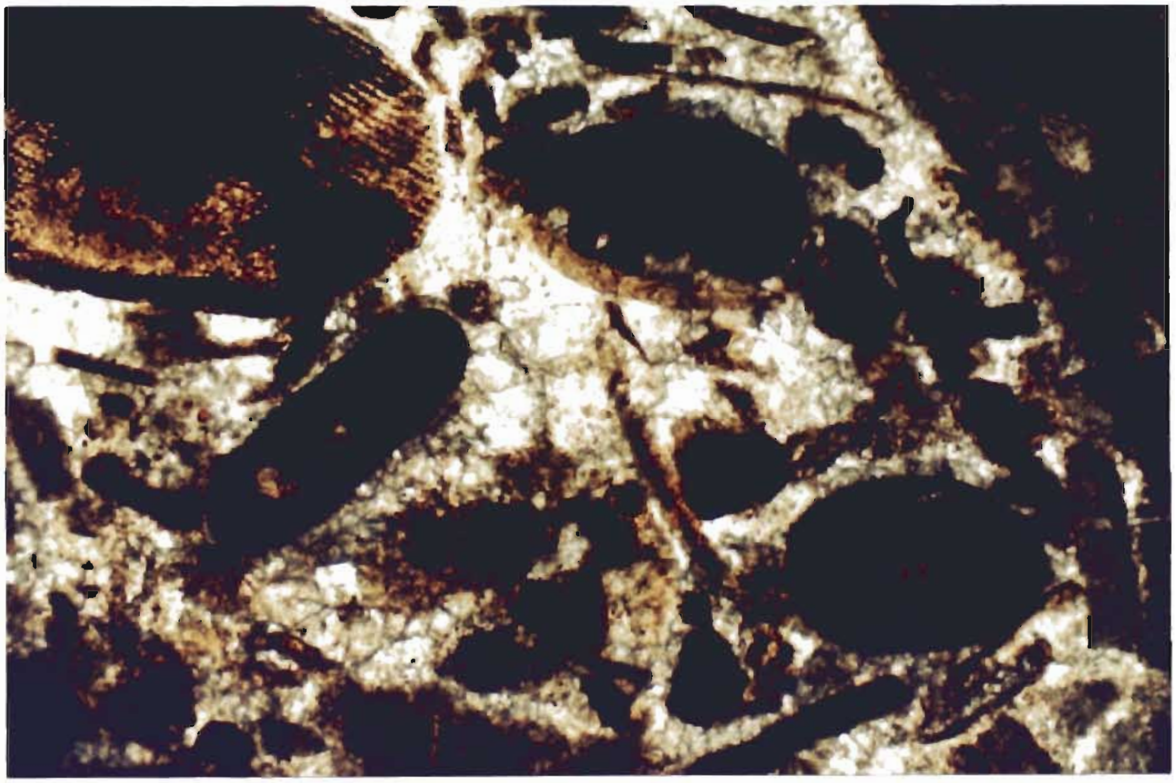
0.2 m (>.5 ft) – Grey mudstone containing bryozoans and brachiopods

Unit 8. Utopia Limestone Member Facies 4

0.6 m (2 ft) – Grey wackestone with brachiopods, crinoids, bryozoans, gastropods, and algae



Photograph 2. Church Limestone Member (40x) which consists of a bioclastic wackestone/packstone with echinoderm fragments and other fossils.



Photograph 3. Utopia Limestone Member (40x) which consists of a bioclastic wackestone with echinoderm fragments and other fossils.

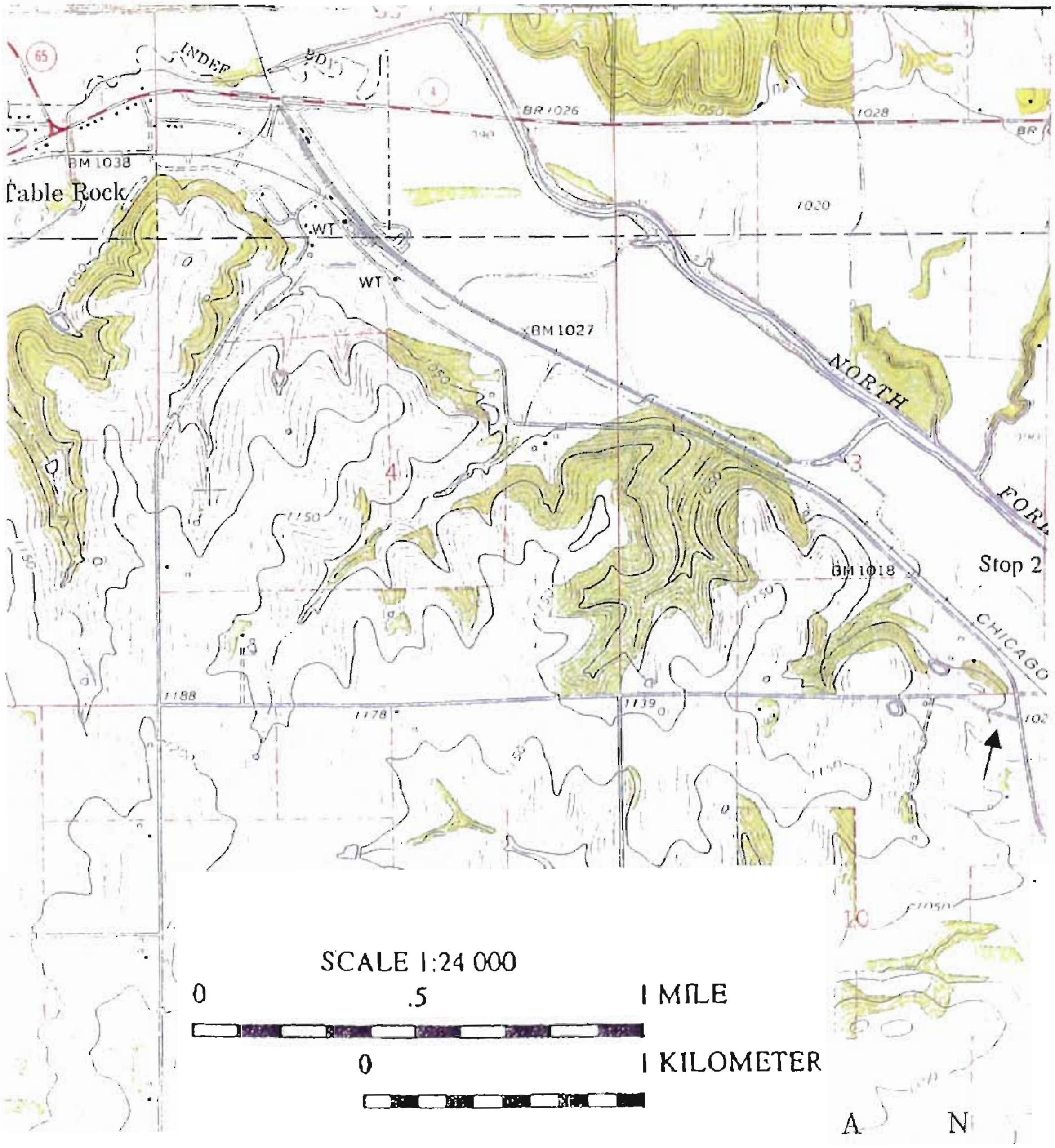


Figure 30. Location of stop 2.

Photograph 4. Stop 2-Southeast of Table Rock, Nebraska.

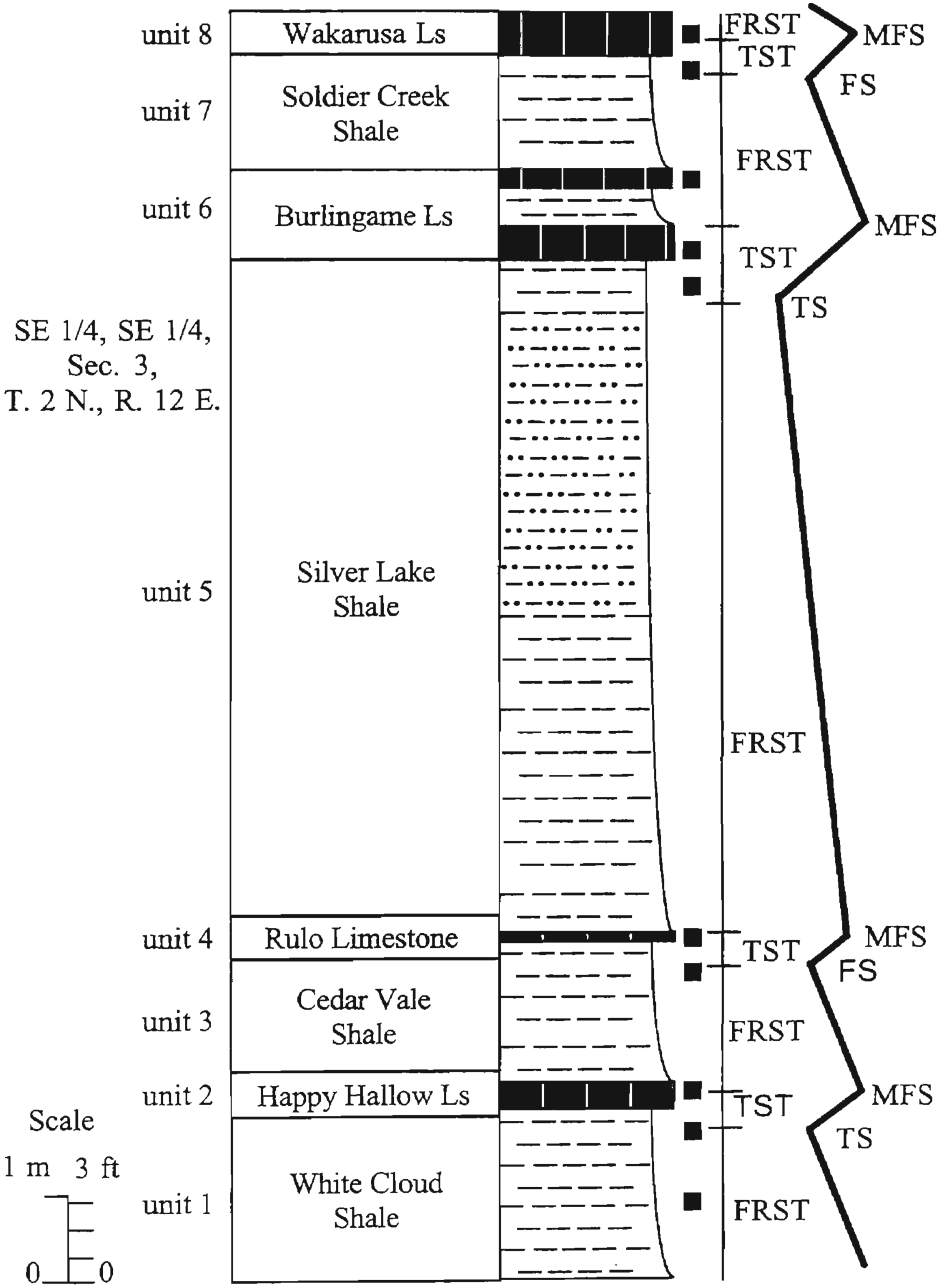


Figure 31: Measured section of stop 2.

Stop 2

State: Nebraska County: Pawnee

East of Table Rock, Nebraska (after Pabian and Boardman, 1995)

Unit 1. White Cloud Shale Member Facies 1C-2

2.4 m(8 ft)- Grey shale with iron oxide in lower part

0.6 m (2 ft)- Gray mudstone to wackestone with fusulinids, brachiopods, crinoids, and algae.

0.9 m (3 ft)- Gray-green shale at base and orange at top, unfossiliferous

2.3 m (7.5 ft)- Brown shale with calcareous iron oxide concretions

Unit 2. Happy Hollow Limestone Member Facies 4

0.5 m (1.5 ft)- Gray packstone with bivalves, crinoids, bryozoans, trilobite fragments, foraminifera, gastropods and algae.

0.3 m (1 ft)- Orange mudstone, unfossiliferous

Unit 3. Cedar Vale Shale Member Facies 2

2.1 m (7 ft)- Gray to black shale with ostracodes and bivalves

Unit 4. Rulo Limestone Member Facies 4

0.1 m (0.3 ft)-Gray packstone that weathers yellowish-brown and contains crinoids, bivalves, bryozoans, algae, and phosphate

Unit 5. Silver Lake Shale Member Facies 1C-2

3 m (15 ft)- Gray clayey shale with pyrite and marcasite

(5 ft)- Gray siltstone with plant remains

(2 ft)- Gray clayey shale

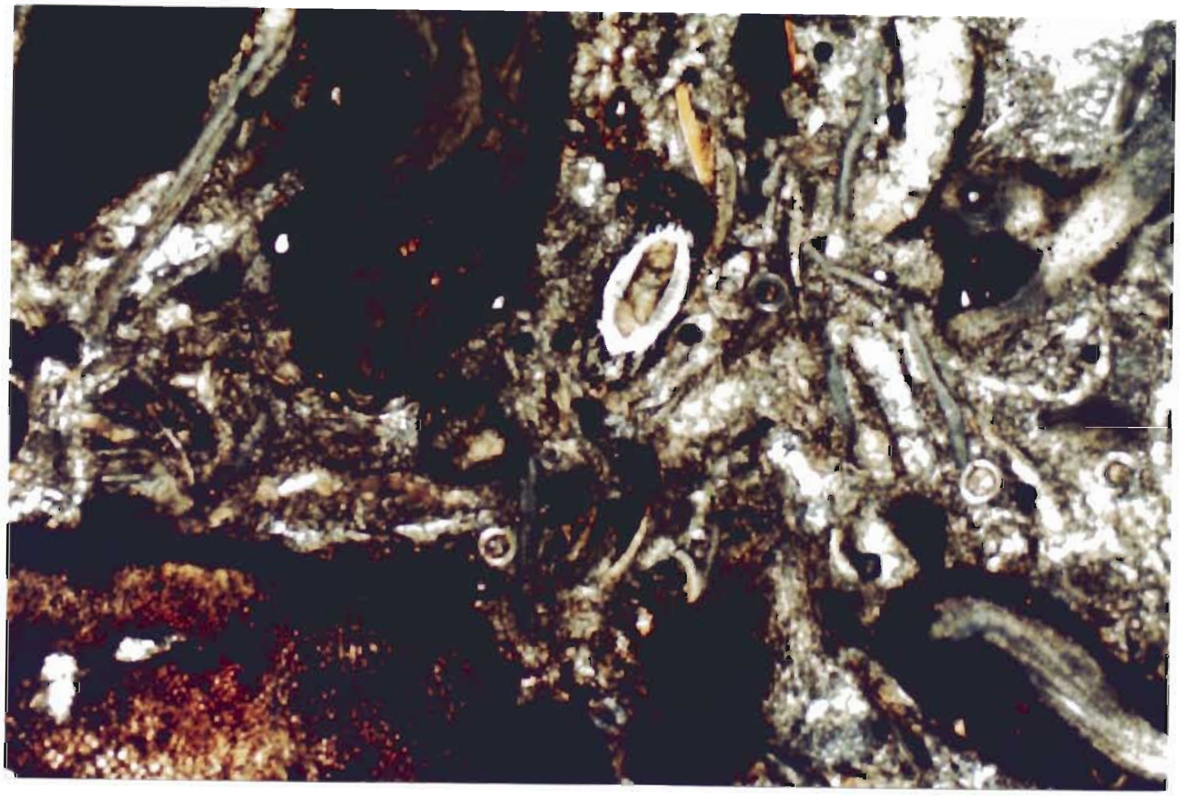
(1 ft)- Coal

0.3 m (1 ft)- Gray shale

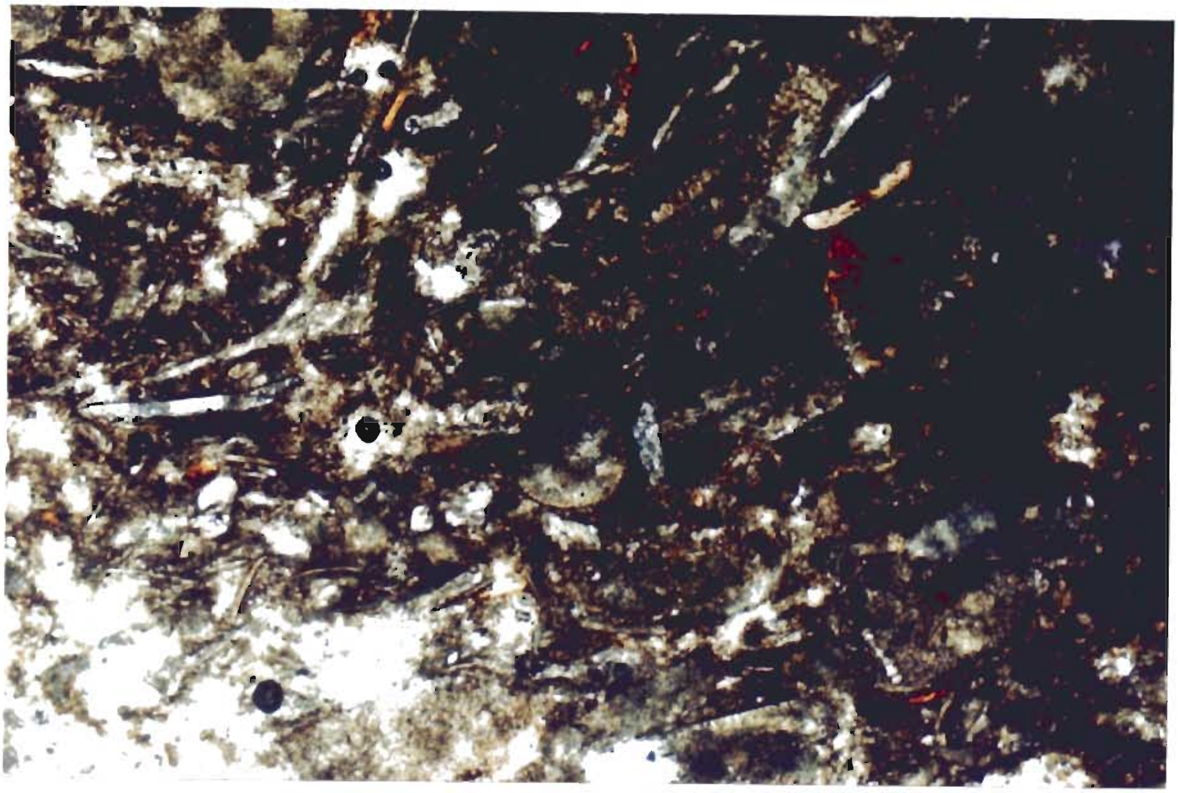
Unit 5. Burlingame Limestone Member      Facies 3

0.1 m (0.3 ft)- Gray mudstone to wackestone that weathers yellow-orange and contains some brachiopods.

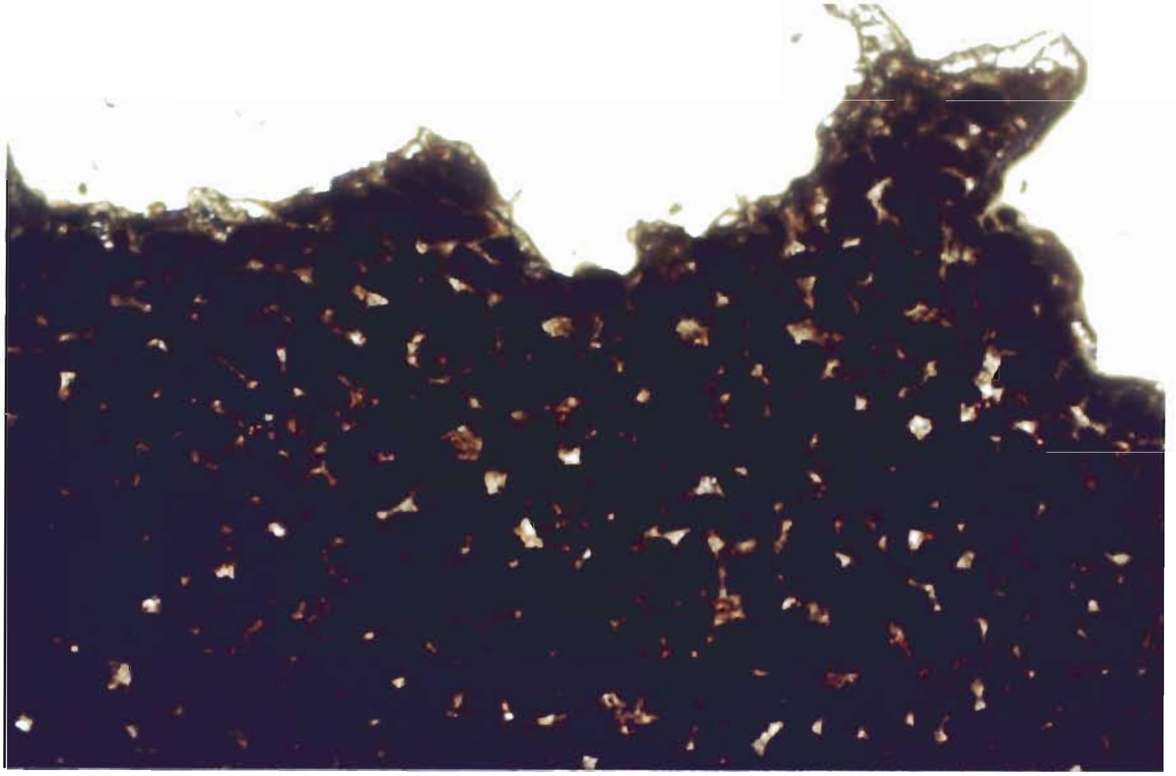
0.1 m (0.3 ft)- Gray dense wackestone to pelloidal packstone that weathers yellow-orange and contains brachiopods, bivalves, and gastropods



Photograph 5. Happy Hollow Limestone (40x) which consists of a bioclastic wackestone/packstone with echinoderm fragments, brachiopod fragments, and other fossils.



Photograph 6. Rulo Limestone Member (40x) consisting of a bioclastic wackestone/packstone with micrite, echinoderm fragments, and phosphate (collophane).



Photograph 7. Burlingame Limestone Member (40x) consisting of a bioclastic grainstone with peloids.

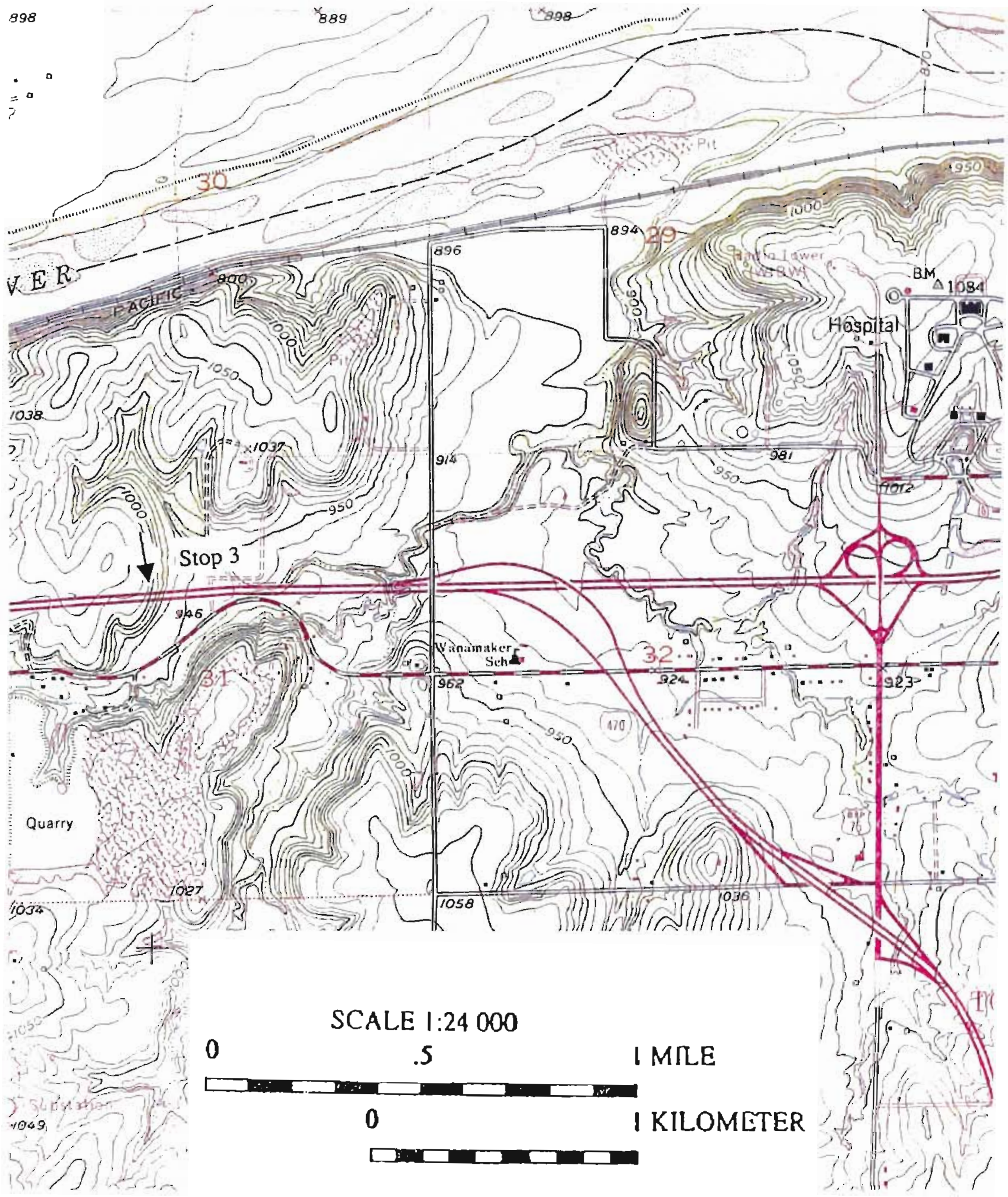


Figure 32. Location of stop 3.

Photograph 8. Stop 3-West of Topeka.

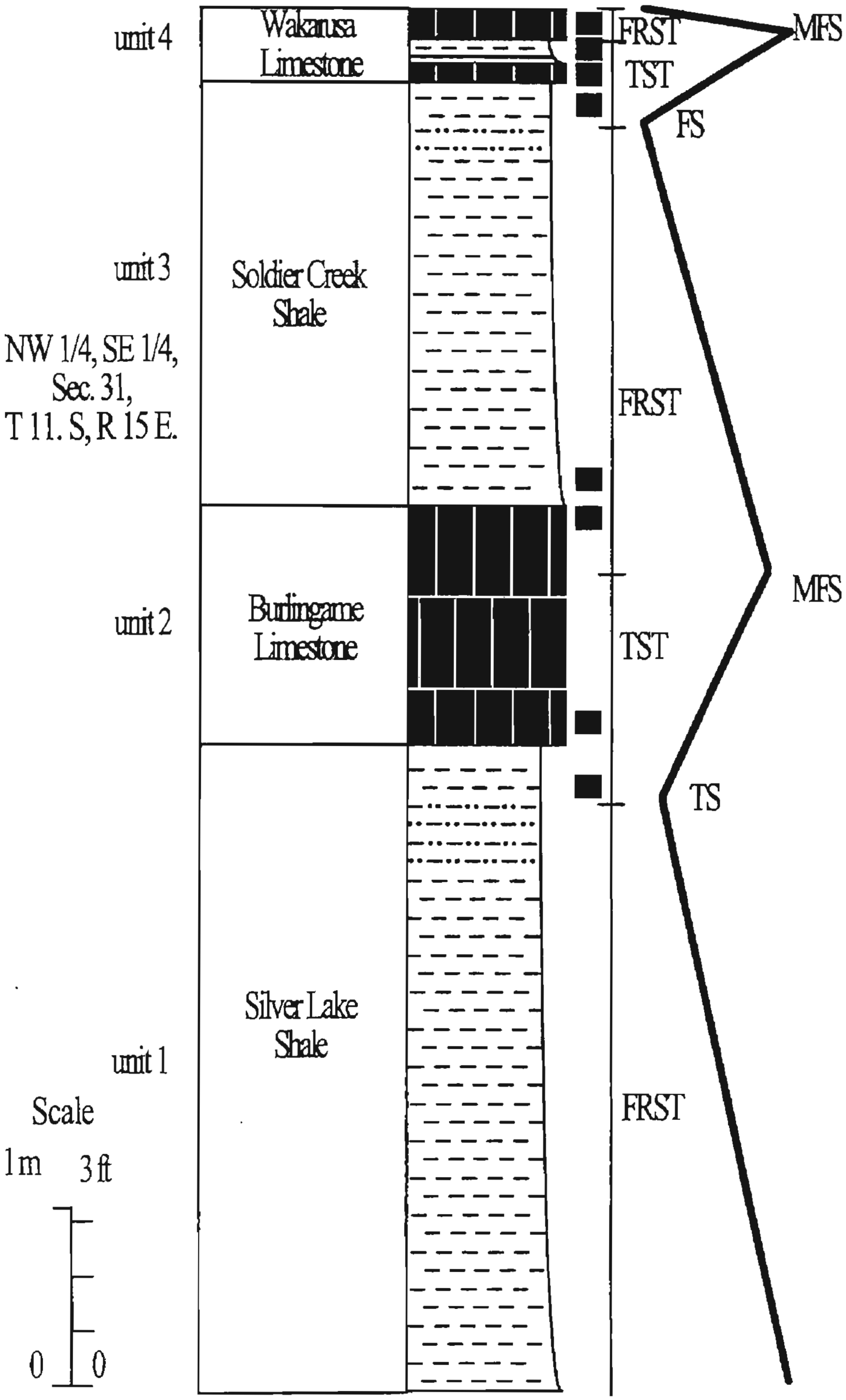


Figure 33. Measured section of stop 3.

Stop 3

State: Kansas County: Shawnee

Along westbound I-70, 2 miles west of I-470 (Modified after Heckel

Unit 1. Silver Lake Shale Member Facies 1C

0.3 m (1 ft)- Gray shale, unfossiliferous

1.5 m (5 ft)- Gray shaly sandstone to sandy shale with ripple marks, tracks, and trails

Unit 2. Burlingame Limestone Member Facies 3

1.5 m (5 ft)- Gray to tan wackestone with algal fragments

Unit 3. Soldier Creek Shale Member Facies 2

3 m (10 ft)- Gray shale, unfossiliferous

Unit 4. Wakarusa Limestone Member Facies 4-5

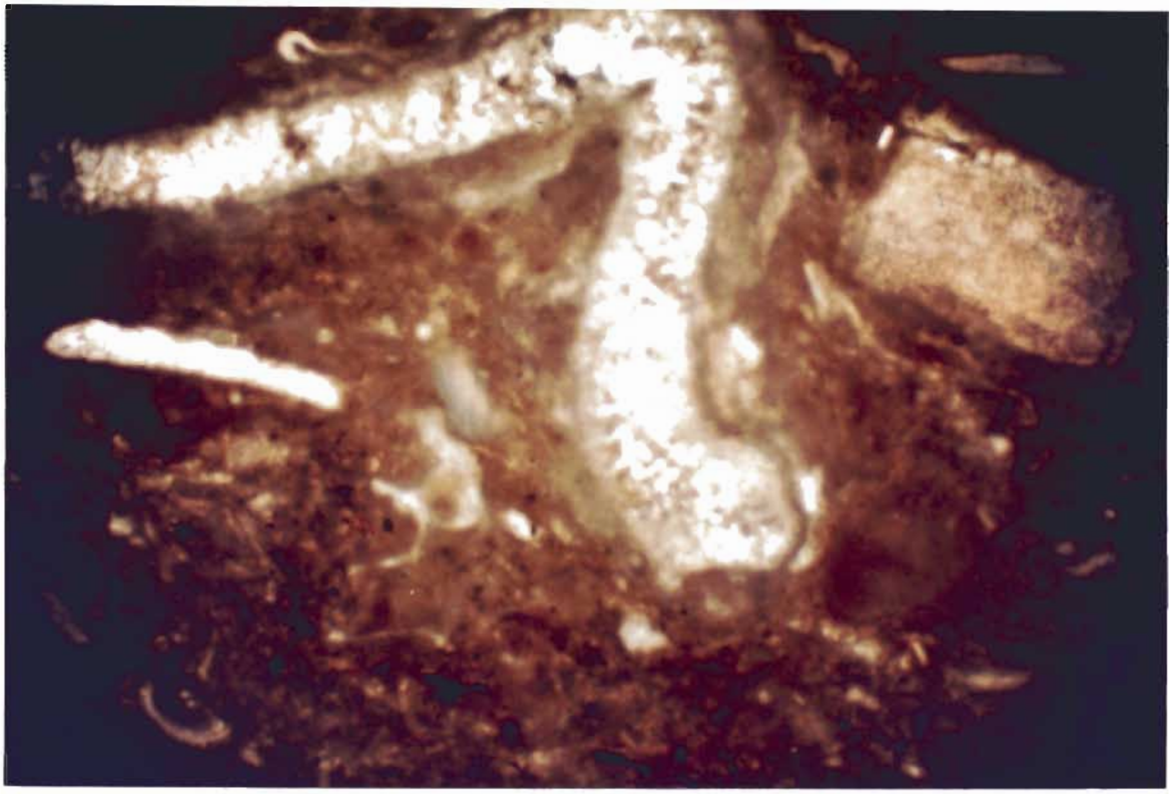
0.1 m (0.3 ft)- Brown to tan wackestone to packstone with bryozoans, ostracodes, trilobite fragments, crinoids, and brachiopods

0.15m (0.5 ft)- Gray limey shale, with a diverse biota

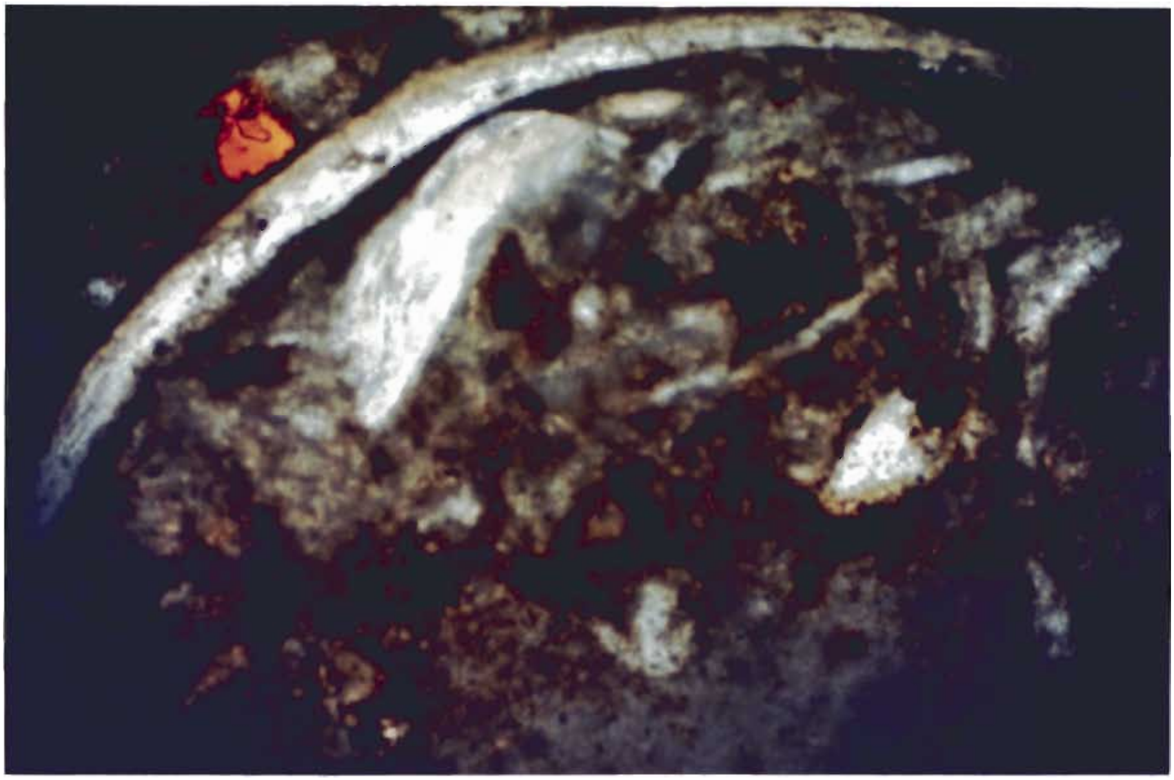
0.15 m (0.5 ft)- Brown to tan wackestone to packstone with crinoids, bryozoans, ostracodes, bivalves, algae, and phosphate

Unit 5. Auburn Shale Formation Facies 1C

0.9 m (3 ft)- Gray shale, unfossiliferous



Photograph 9. Lower Wakarusa Limestone bed (40x) consisting of a bioclastic wackestone with micrite, echinoderm fragments and phylloid algae.



Photograph 10. Upper Wakarusa Limestone bed (40x) consisting of a bioclastic wackestone/packstone with micrite, brachiopod fragments, and phosphate (collophane).

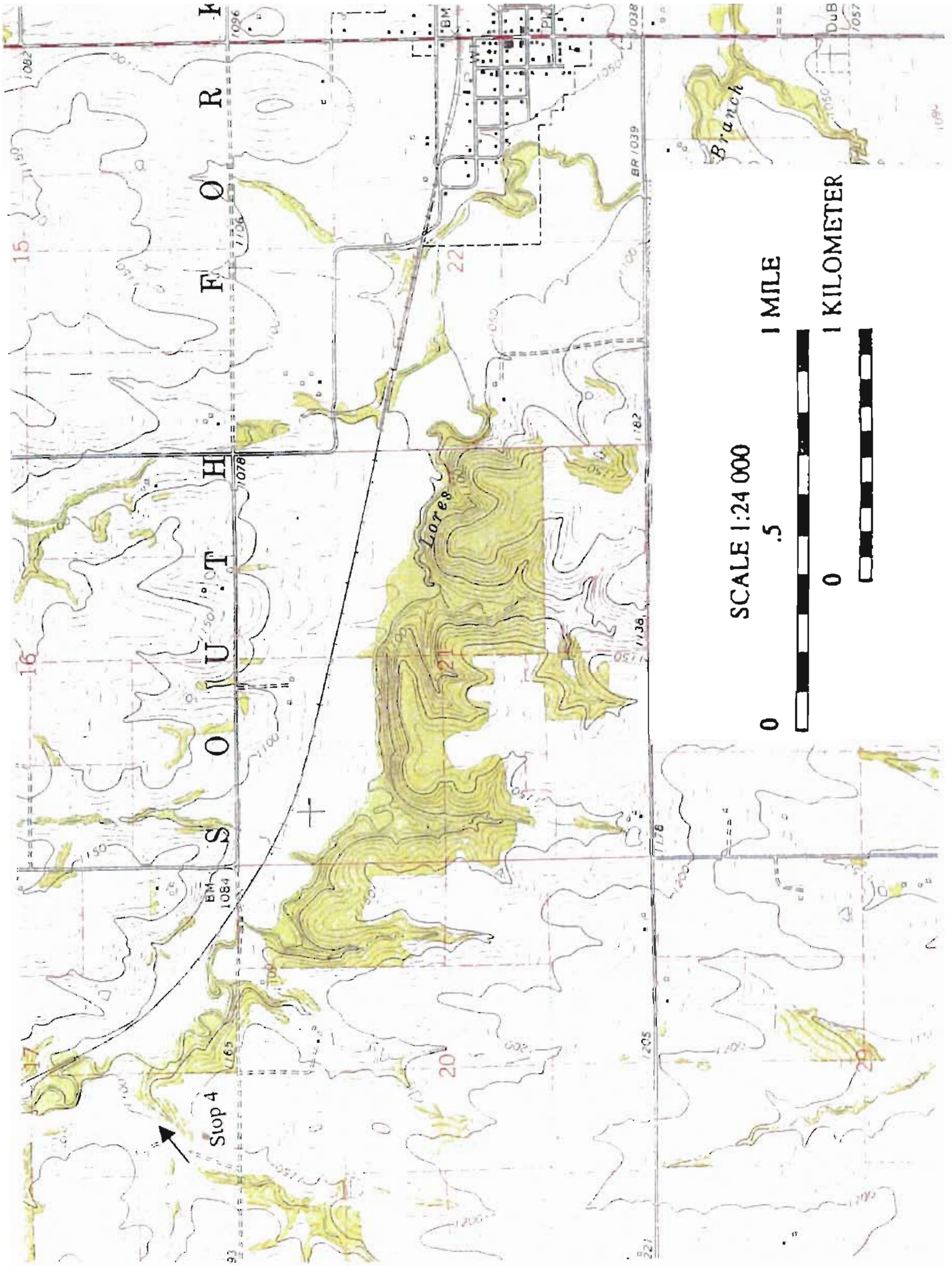


Figure 34. Location of stop 4.

Photograph 11. West end of outcrop, Stop 4.

Photograph 12. Middle of outcrop, Stop 4.

Photograph 13. East end of outcrop, Stop 4.

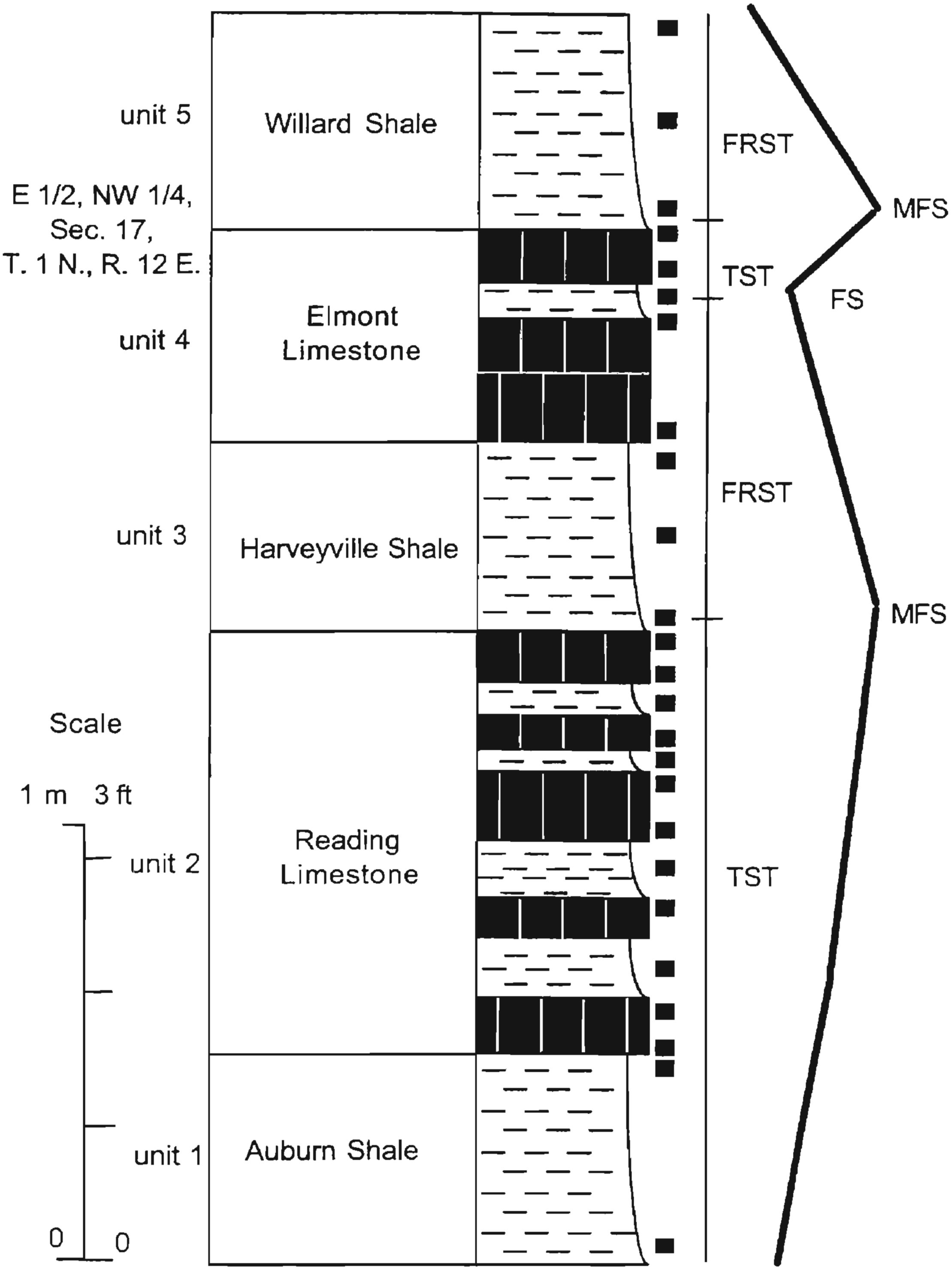


Figure 35. Measured section of stop 4.

Stop 4

State: Nebraska County: Pawnee

Iron Horse Lake emergency spillway

Unit 1. Auburn Shale Formation Facies 1C

1.5 m (5 ft)- Gray shale, unfossiliferous

Unit 2. Reading Limestone Member Facies 3-4

0.3 m (1 ft)- Gray wackestone with algae and ostracodes

0.4 m (1.2 ft)- Brown to gray shale with brachiopods and bivalves

0.2 m (0.7 ft)- Gray wackestone to packstone with ostracodes, foraminifera, bivalves, bryozoans, and gastropods

0.9 m (3 ft)- Brown-gray shale with brachiopods and limestone stringers at the top

0.6 m (2 ft)- Gray wackestone with crinoids, gastropods, algae, and ostracodes

0.15 m (0.5 ft)- Gray shale, unfossiliferous

0.15 m (0.5 ft)- Gray wackestone with algae, bivalves, and ostracodes

0.1 m (0.3 ft)- Brown-gray shale with brachiopods

0.8 m (2.5 ft)- Gray wackestone with crinoids, foraminifera, brachiopods, algae, bivalves, bryozoans, trilobite fragments, and minor phosphate

Unit 3. Harveyville Shale Member Facies 5

1.5 m (5 ft)- Gray shale with bivalves, gastropods, and ammonoids

Unit 4. Elmont Limestone Member Facies 4

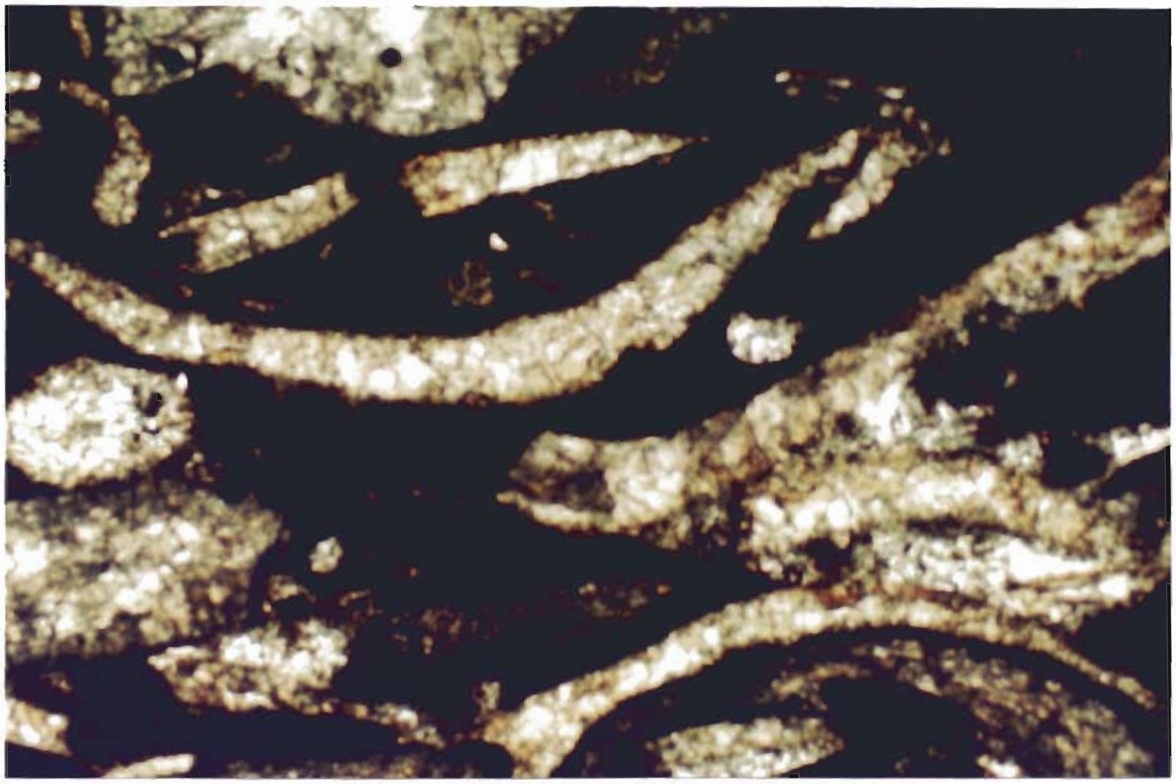
0.8 m (2.5 ft)- Gray wackestone to packstone with bryozoans, fusulinids, ostracodes, gastropods, and trilobites

0.3 m (1 ft)- Gray-tan shaly sandstone, unfossiliferous

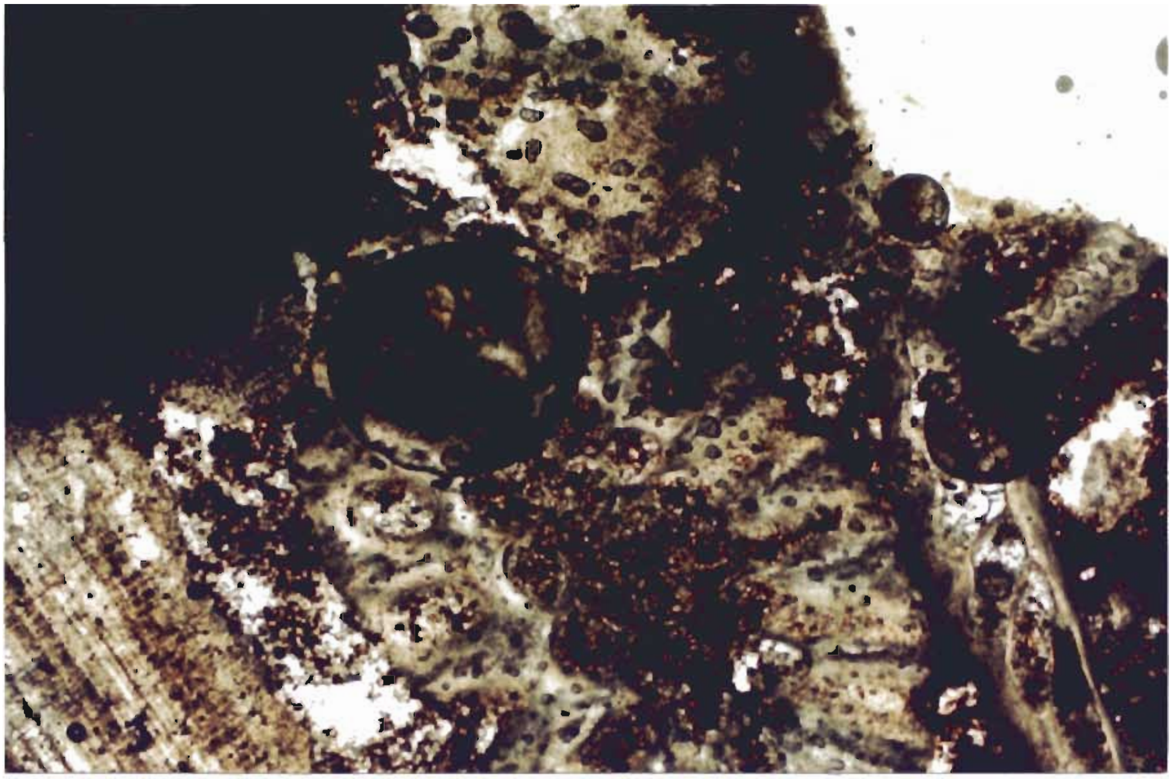
0.5 m (1.5 ft)- Gray packstone with crinoids, ostracodes, fusulinids, trilobites, and algae

Unit 5. Willard Shale Formation Facies 1C-5

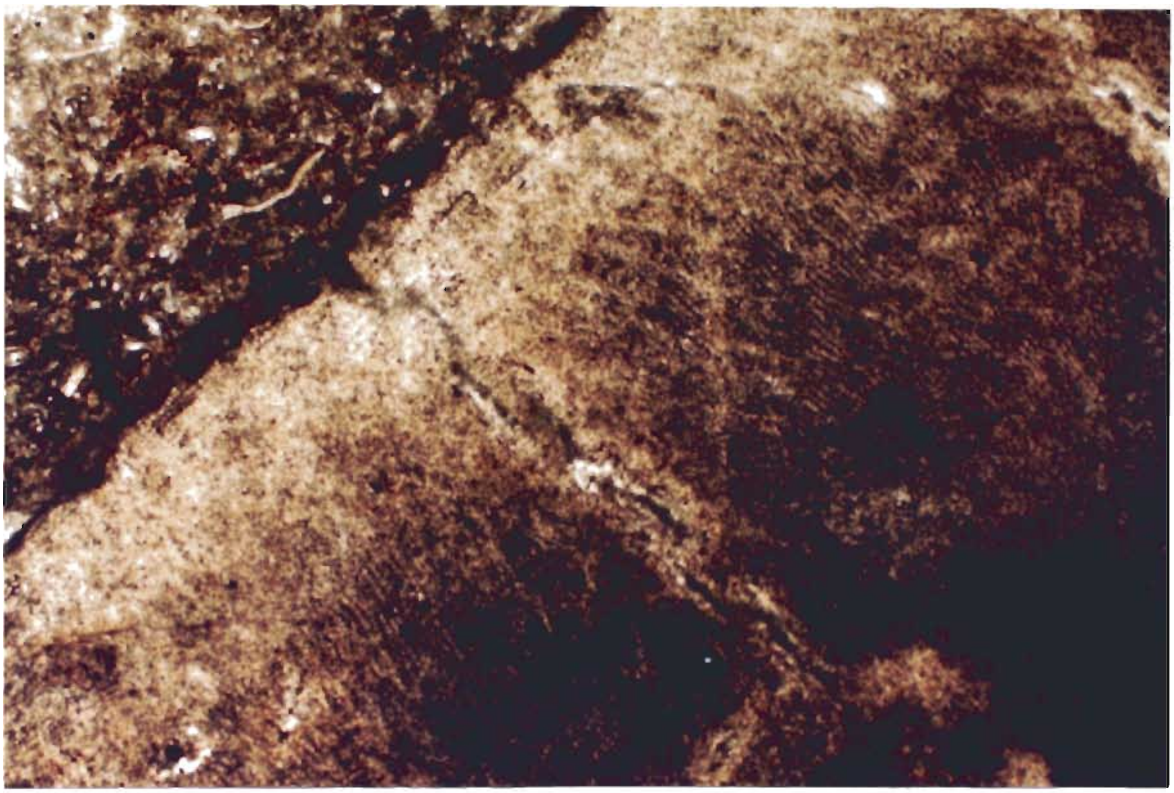
1.8 m (6 ft)- Brown shale with bivalves, gastropods, and ammonoids at the base. It contains more sand toward the top



Photograph 14. Lower Reading Limestone Member (40x) consisting of a bioclastic wackestone/packstone with phylloid algae and micrite.



Photograph 15. Upper Reading Limestone Member(40x) consisting of a bioclastic wackestone/packstone with micrite, echinoderm fragments, and bryozoan fragments.



Photograph 16. Elmont Limestone Member (40x) consisting of a bioclastic wackestone/packstone with a large echinoderm fragment.

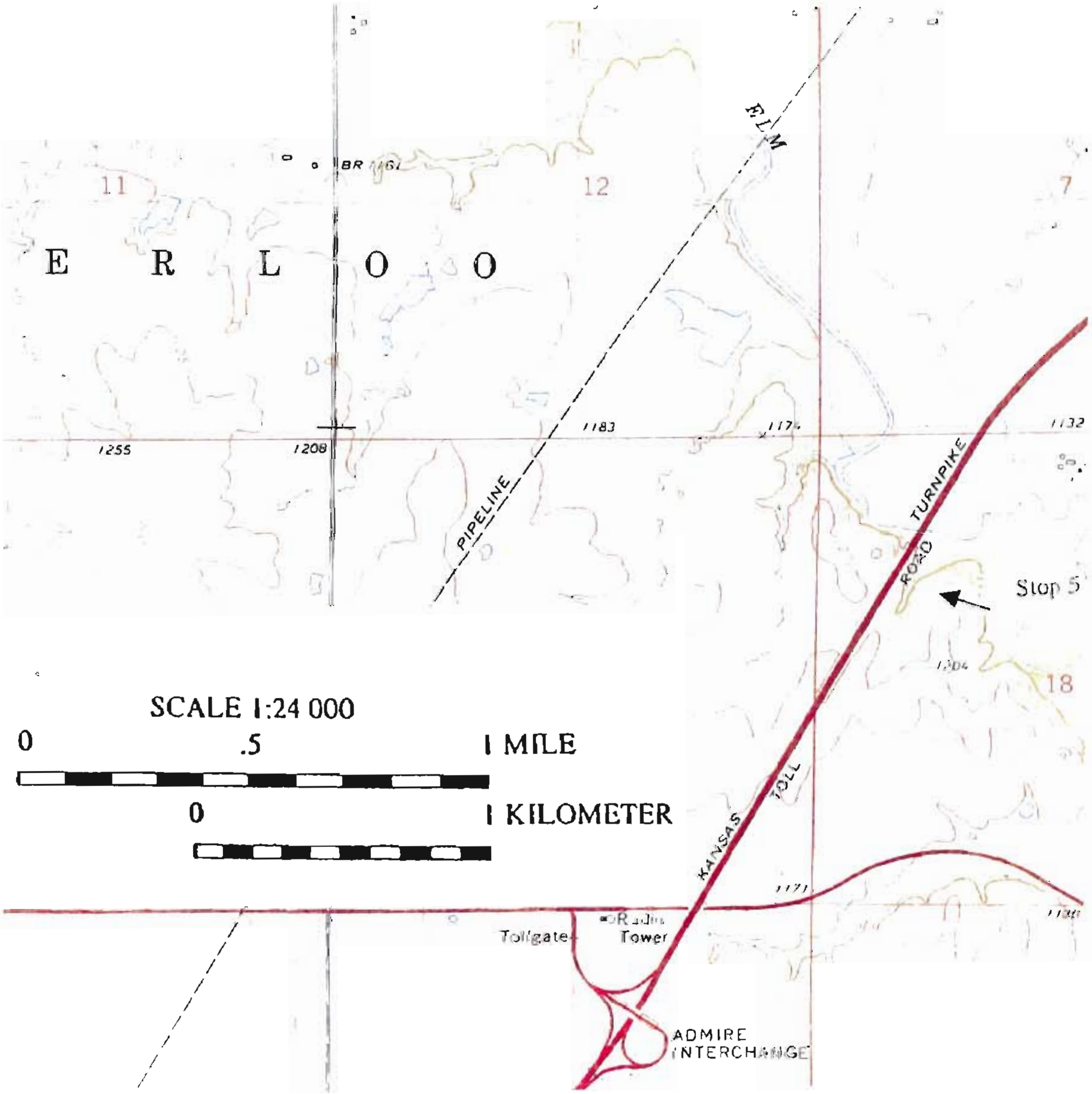


Figure 36. Location of stop 5.

Photograph 17. Southbound Kansas Turnpike, Stop 5.

Photograph 18. Northbound Kansas Turnpike, Stop 5.

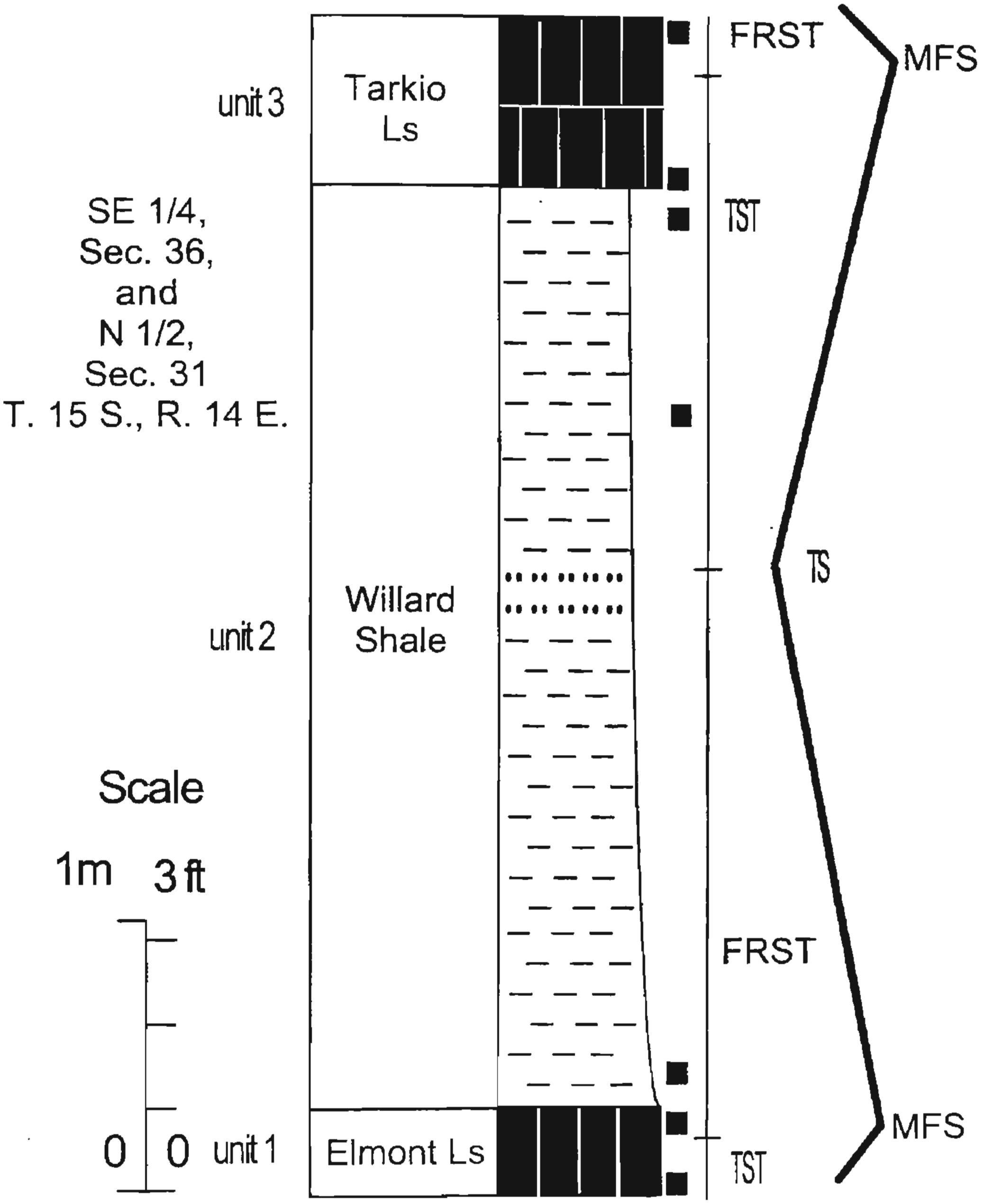


Figure 37. Measured section of Stop 5.

Stop 5

State: Kansas County: Osage

Along southbound Kansas Turnpike, about 11 miles south of Topeka

Unit 1. Elmont Limestone Member Facies 4

0.4 m (1.25 ft)- Tan gray wackestone with ostracodes, fusulinids, gastropods, algae, and foraminifera.

Unit 2. Willard Shale Formation Facies 1C-2

3.2 m (10.6 ft)- Covered interval

0.9 m (3 ft)- Gray shale that weathers brown, unfossiliferous

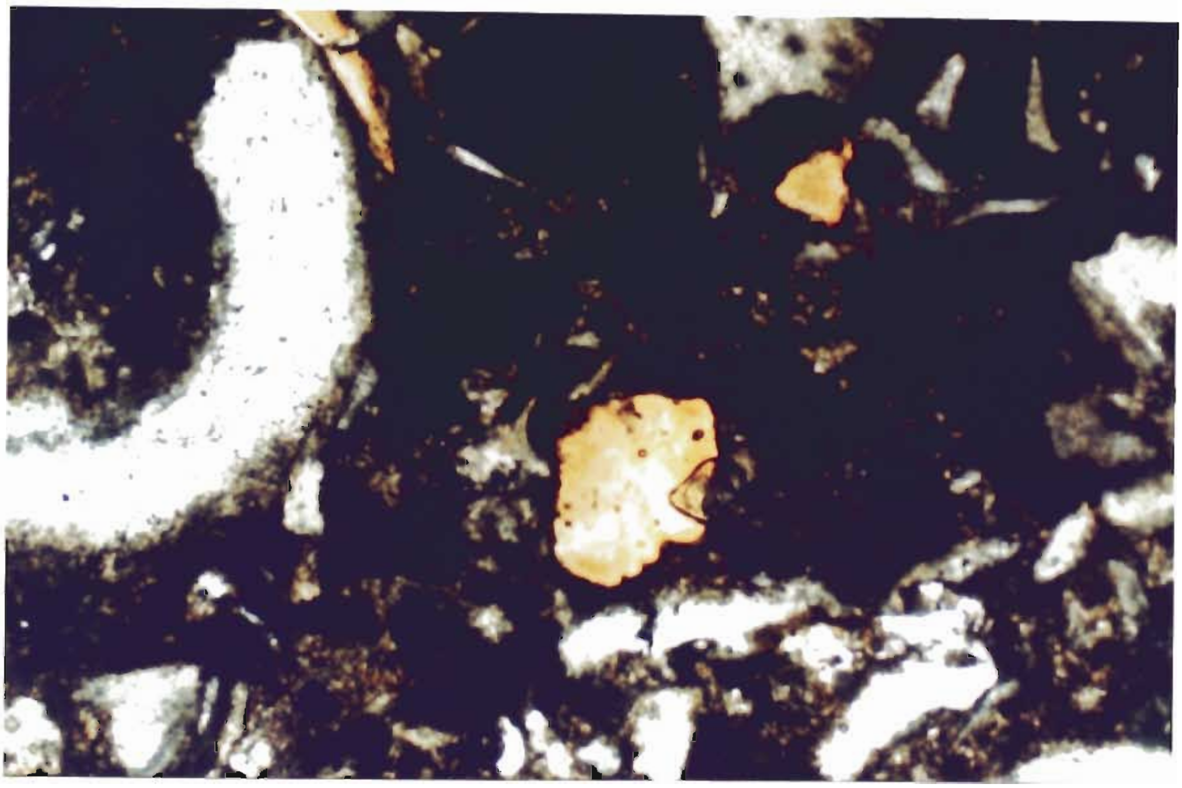
0.2 m (.5 ft)- Gray sandstone

3 m (10 ft)- Gray to brown clay shale with that weathers tan, unfossiliferous

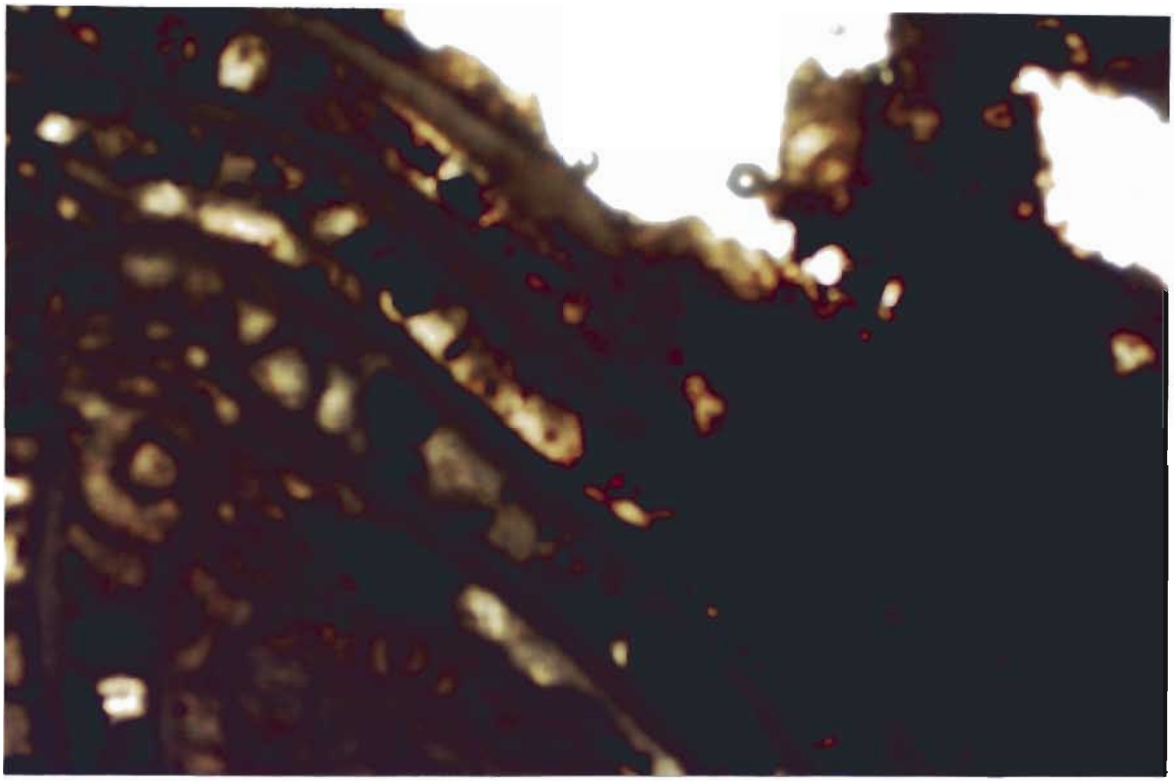
Unit 3. Tarkio Limestone Member Facies 3-4

0.5 m (1.6 ft)- Brown packstone to grainstone with ostracodes, crinoids, fusulinids, phylloid algae, bivalves, and grapestone grains

0.1 m (0.3 ft)- Shaly, brown wackestone to packstone with ostracodes, crinoids, fusulinids, phylloid algae, and bivalves



Photograph 19. Elmont Limestone Member (40x) consisting of a bioclastic wackestone/packstone with micrite, phylloid algae, and phosphate (collophane).



Photograph 20. Tarkio Limestone Member (40x) consisting of a bioclastic wackestone with a large fusulinid and micrite.

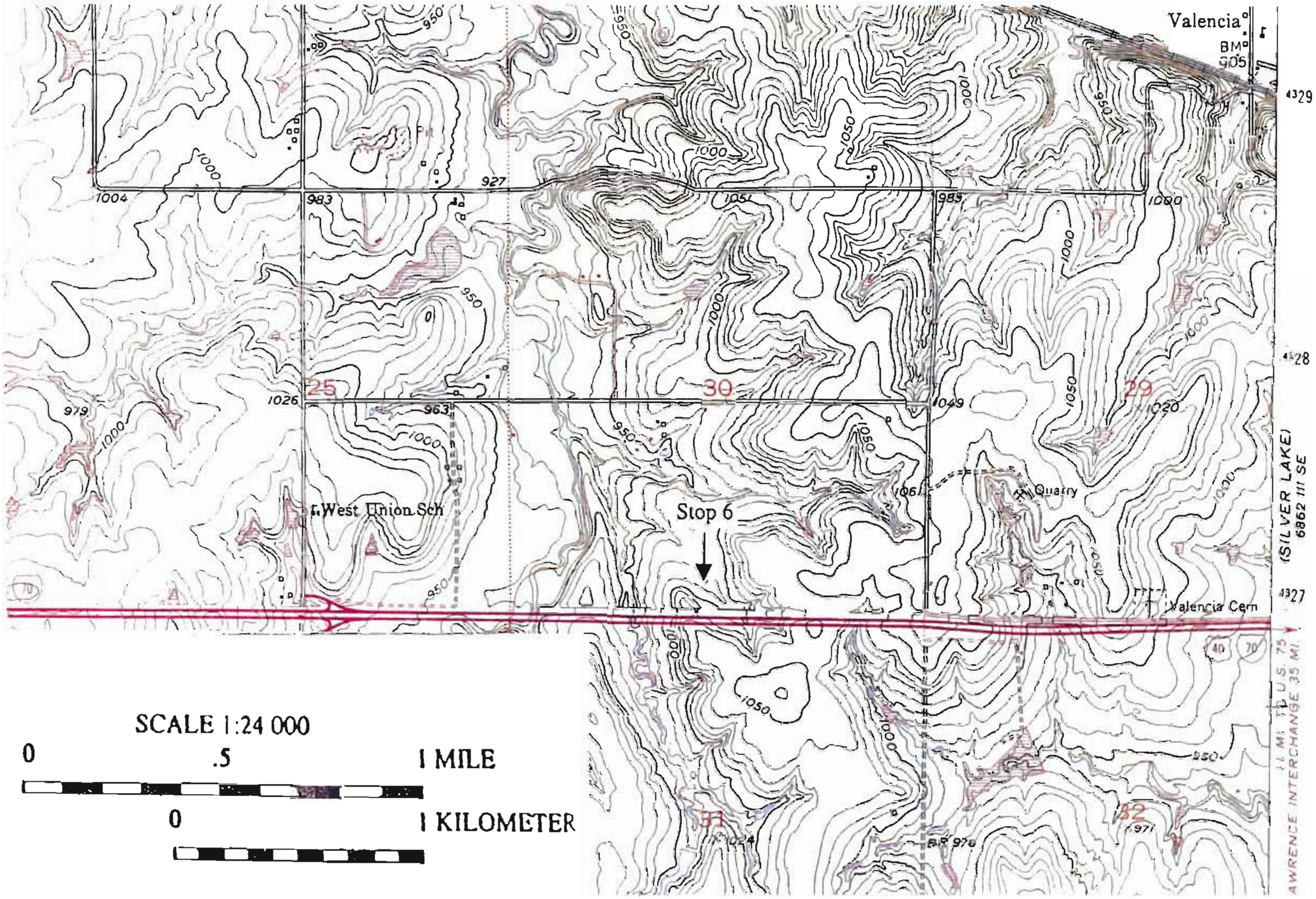


Figure 38. Location of stop 6.

Photograph 21. Stop 6.

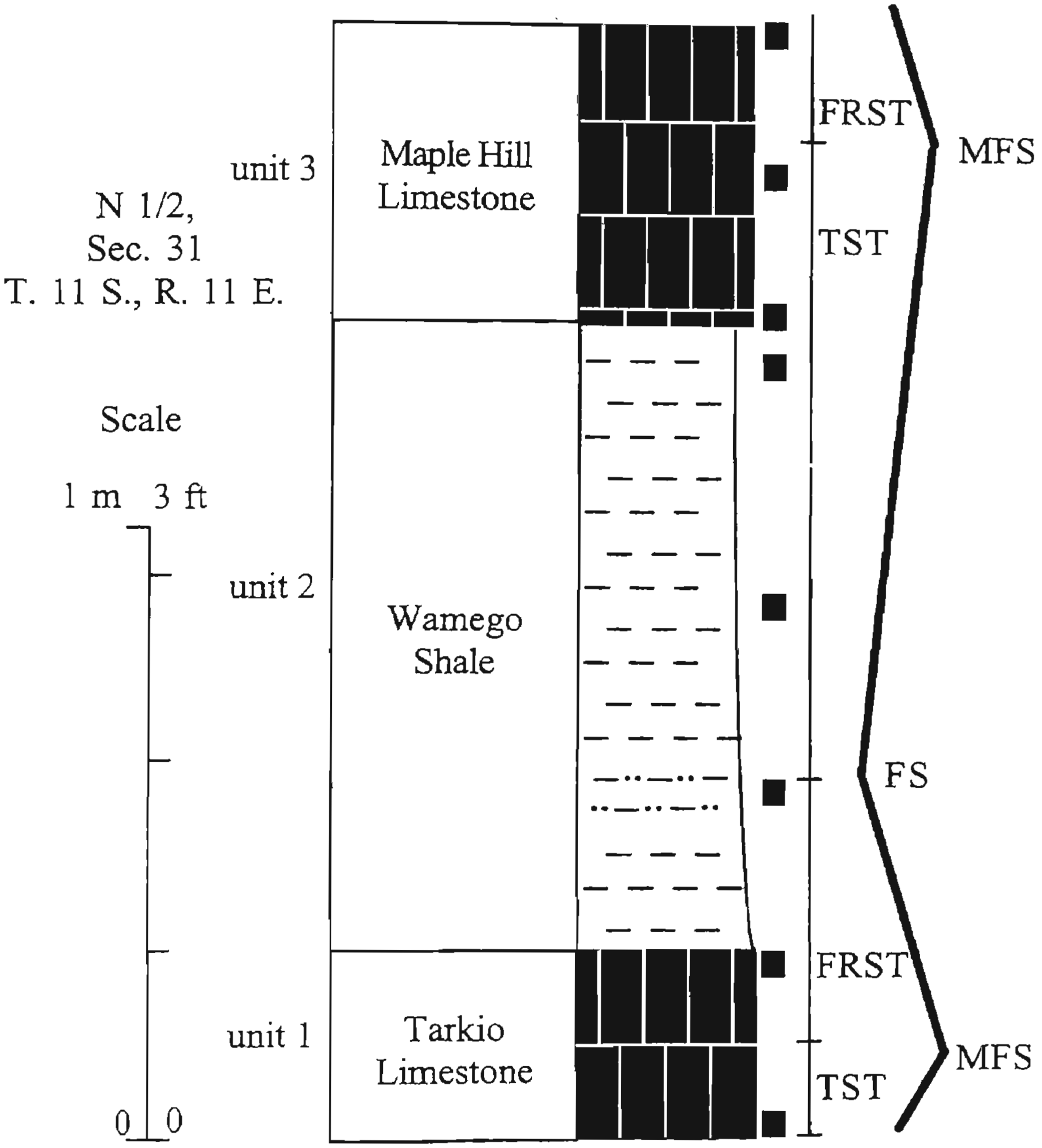


Figure 39. Measured section of stop 6.

Stop 6.

State: Kansas County: Wabaunsee

Along U. S. 70, 8 miles west of Topeka

Unit 1. Tarkio Limestone Member Facies 3-4

0.9 m (3 ft)- Brown, dense, massive wackestone to grainstone with ostracodes, crinoids, fusulinids, phylloid algae, and bivalves

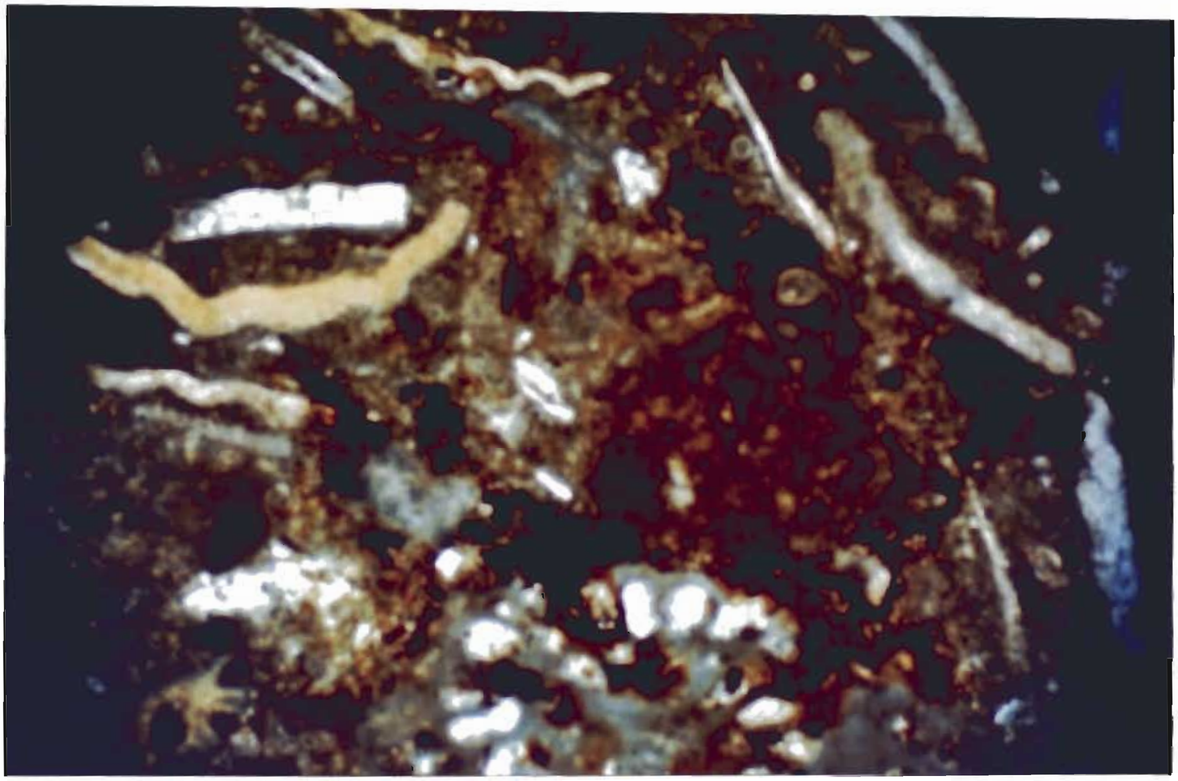
0.3 m (1 ft)- Brown rubbly mudstone to wackestone with fusulinids and ostracodes.

Unit 2. Wamego Shale Member Facies 2

1.5 m (5 ft)- Gray clayey shale, unfossiliferous

Unit 3. Maple Hill Limestone Member Facies 4

0.5 m (1.5 ft)- Gray wackestone to packstone with crinoids, trilobites, bryozoans, and bivalves



Photograph 22. Maple Hill Member (40x) consisting of a bioclastic wackestone/packstone with micrite, phylloid algae, and a foraminifer fragment.

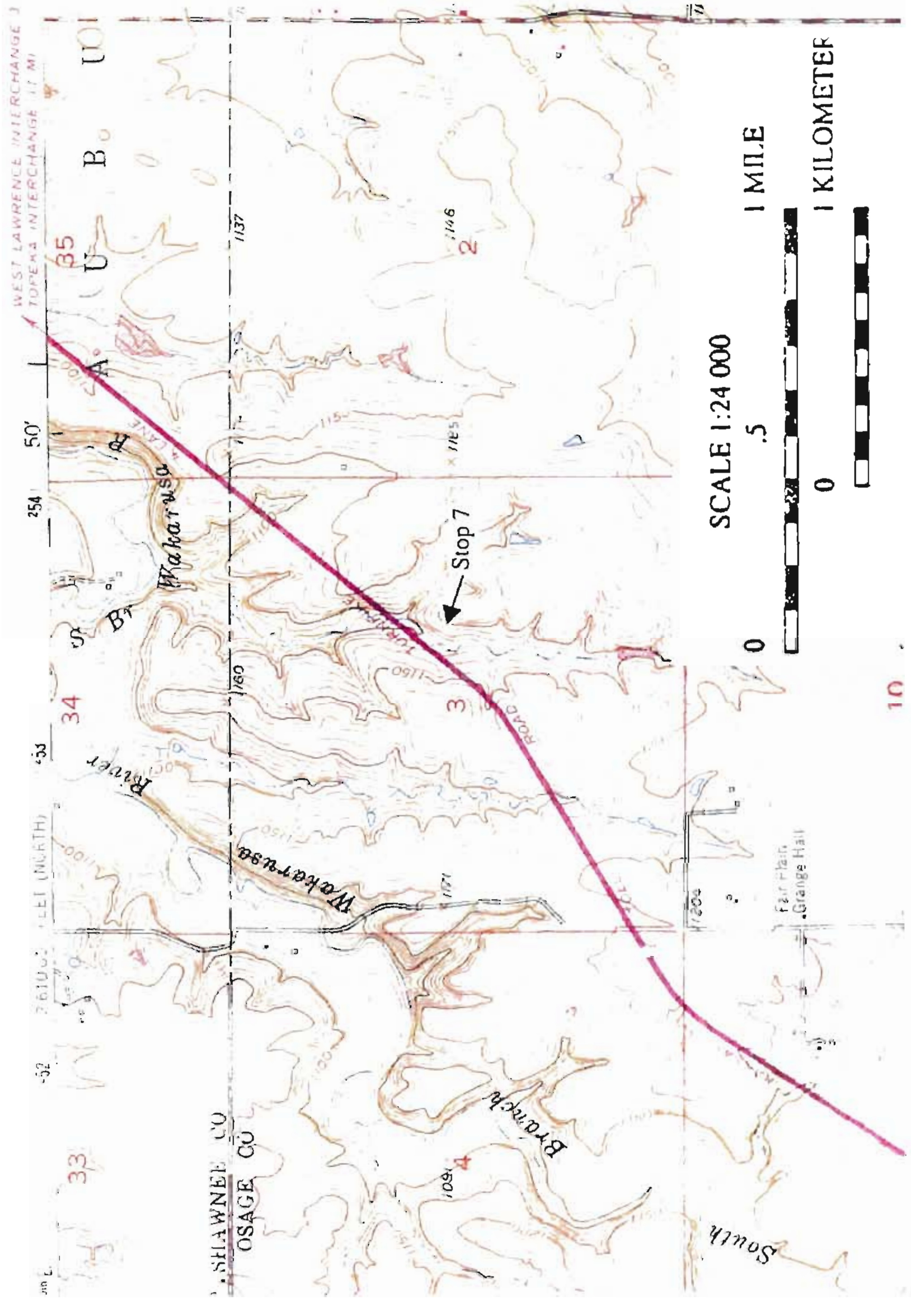


Figure 40. Location of stop 7.

Photograph 23. Southbound on Kansas Turnpike, Stop 7.

Photograph 24. Northbound on Kansas Turnpike Stop 7.

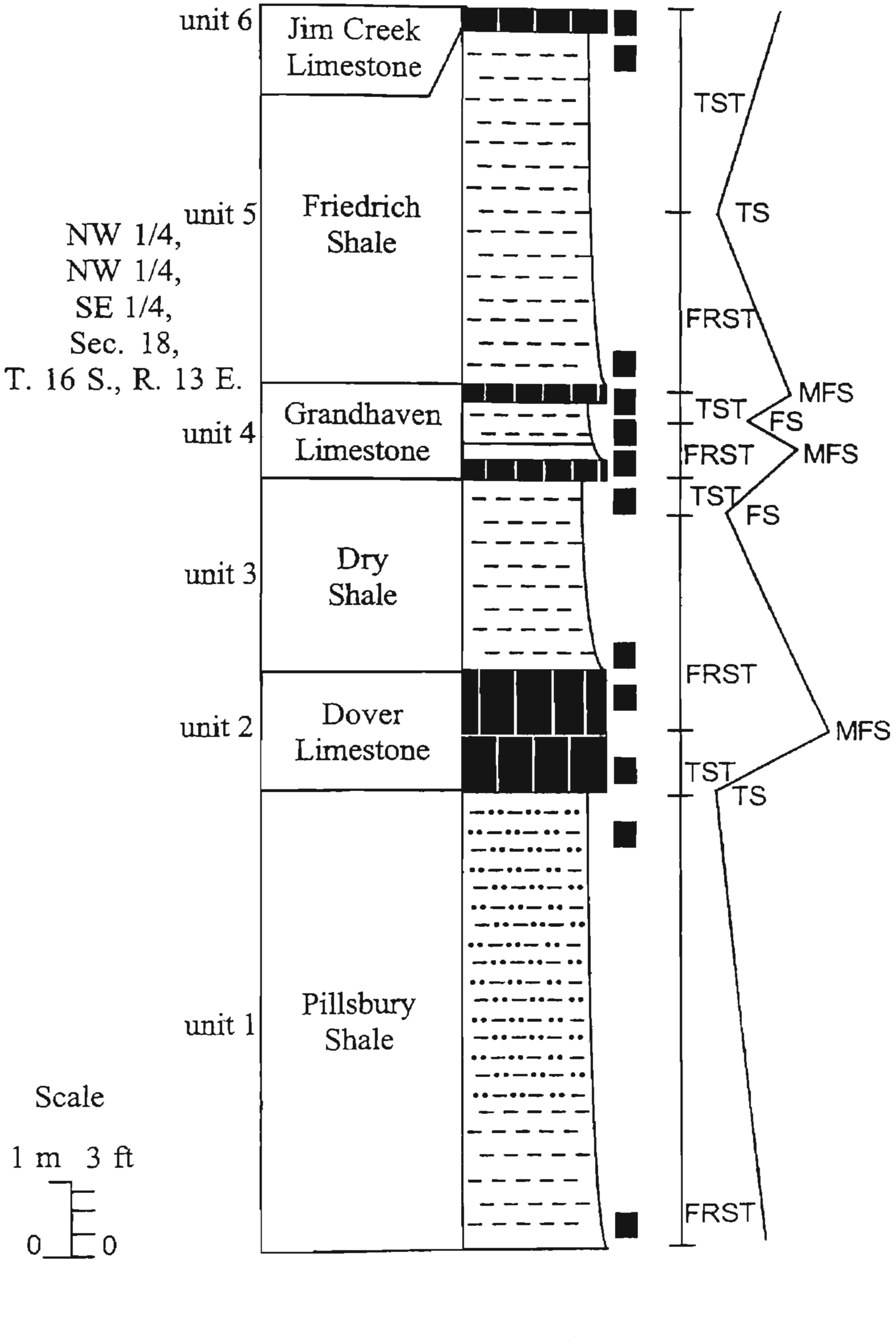


Figure 41. Measured section of stop 7.

Stop 7.

State: Kansas County: Lyon

Along southbound of Kansas Turnpike

(modified after Jewett and Merriam, 1956)

Unit 1. Pillsbury Shale Formation Facies 1C

4.3 m (14 ft)- Gray, sandy shale, unfossiliferous

Unit 2. Dover Limestone Member Facies 4

1.2 m (4 ft)- Light gray to gray mudstone to wackestone that weathers reddish brown and contains fusulinids, bryozoans, crinoids, algae, and some brachiopods near the top

Unit 3. Dry Shale Member Facies 1C-2

0.3 m (1 ft)- Gray shale with limey rubble, unfossiliferous

0.15 m (5 ft)- Gray to greenish clay shale, unfossiliferous

1.2 m (4 ft)- Gray shale that weathers yellow, unfossiliferous

Unit 4. Grandhaven Limestone Member Facies 3-4

0.5 m (1.5 ft)- Bluish gray wackestone to packstone containing fusulinids, ostracodes, crinoids, and bryozoans

0.9 m (3 ft)- Gray clayey calcareous shale

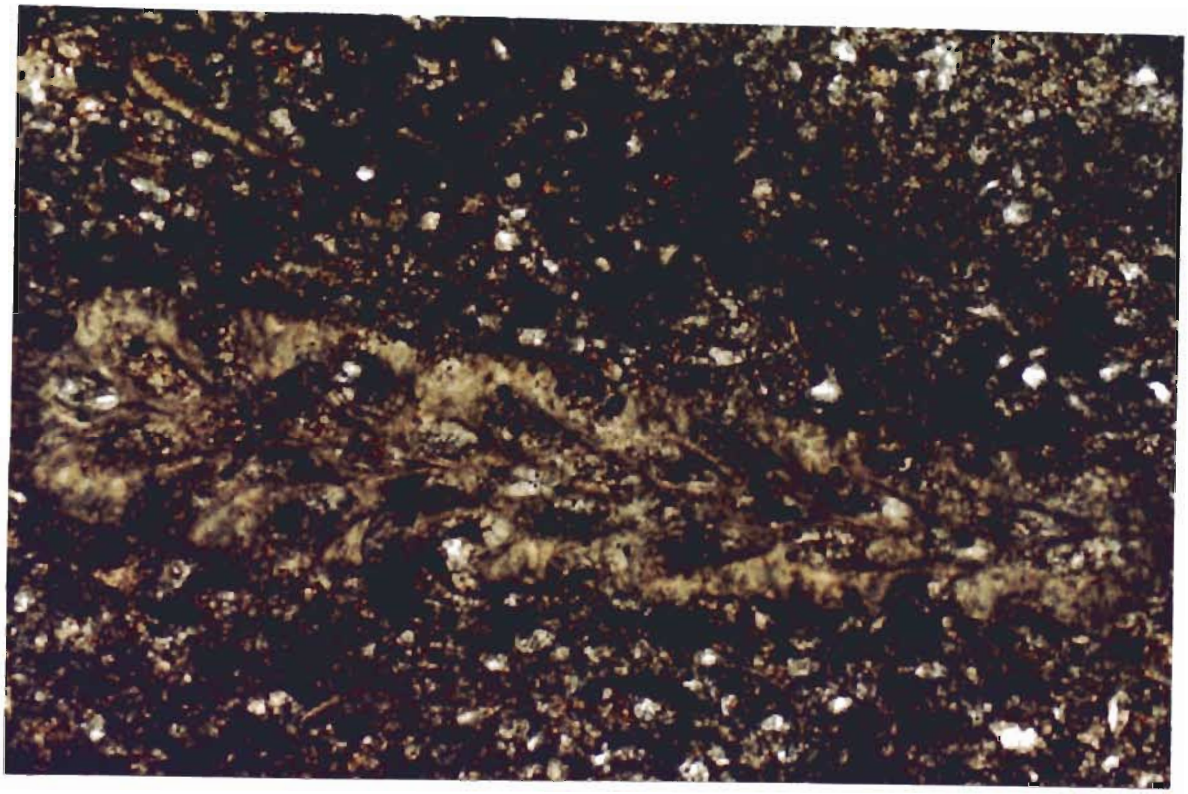
0.3 m (1 ft)- Bluish gray wackestone that weathers tan containing algae, fusulinids, bryozoans, and crinoids

Unit 5. Friedrich Shale Member Facies 2

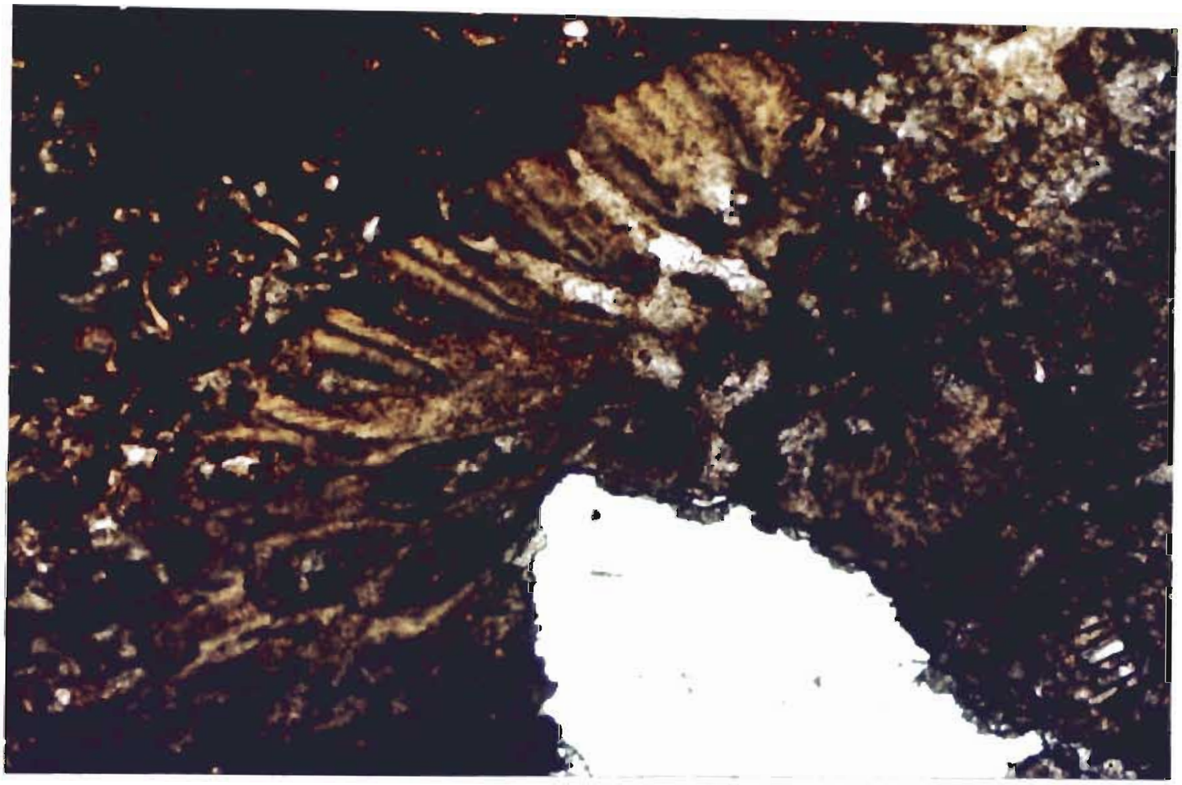
5.8 m (19 ft)- Gray shale, unfossiliferous

Unit 6. Jim Creek Limestone Member Facies 4

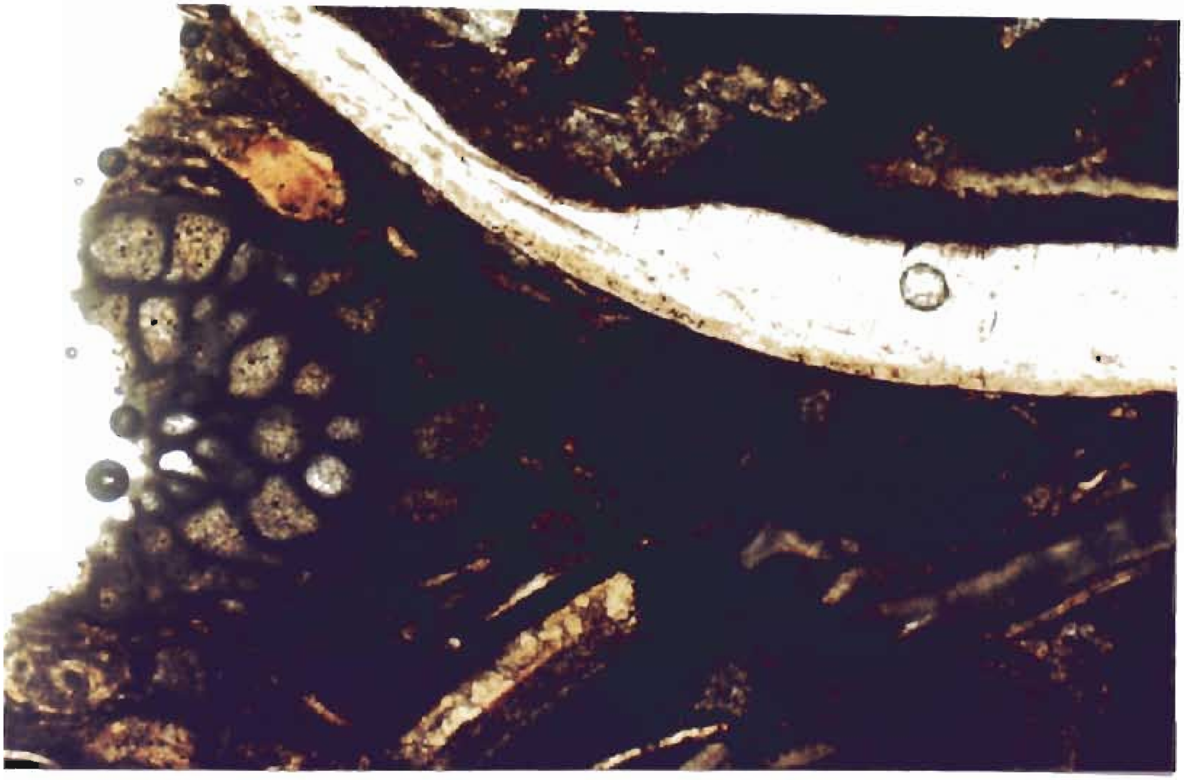
0.3 m (1 ft)- Tan to brown wackestone containing gastropods, fusulinids, and bryozoans



Photograph 25. Dover Limestone Member (40x) consisting of a bioclastic wackestone/packstone with a bryozoan fragment.



Photograph 26. Grandhaven Limestone Member (40x) consisting of a bioclastic wackestone/packstone with a bryozoan fragment.



Photograph 27. Jim Creek Limestone Member (40x) consisting of a bioclastic wackestone/packstone micrite, pelecypod, and fusulinid.

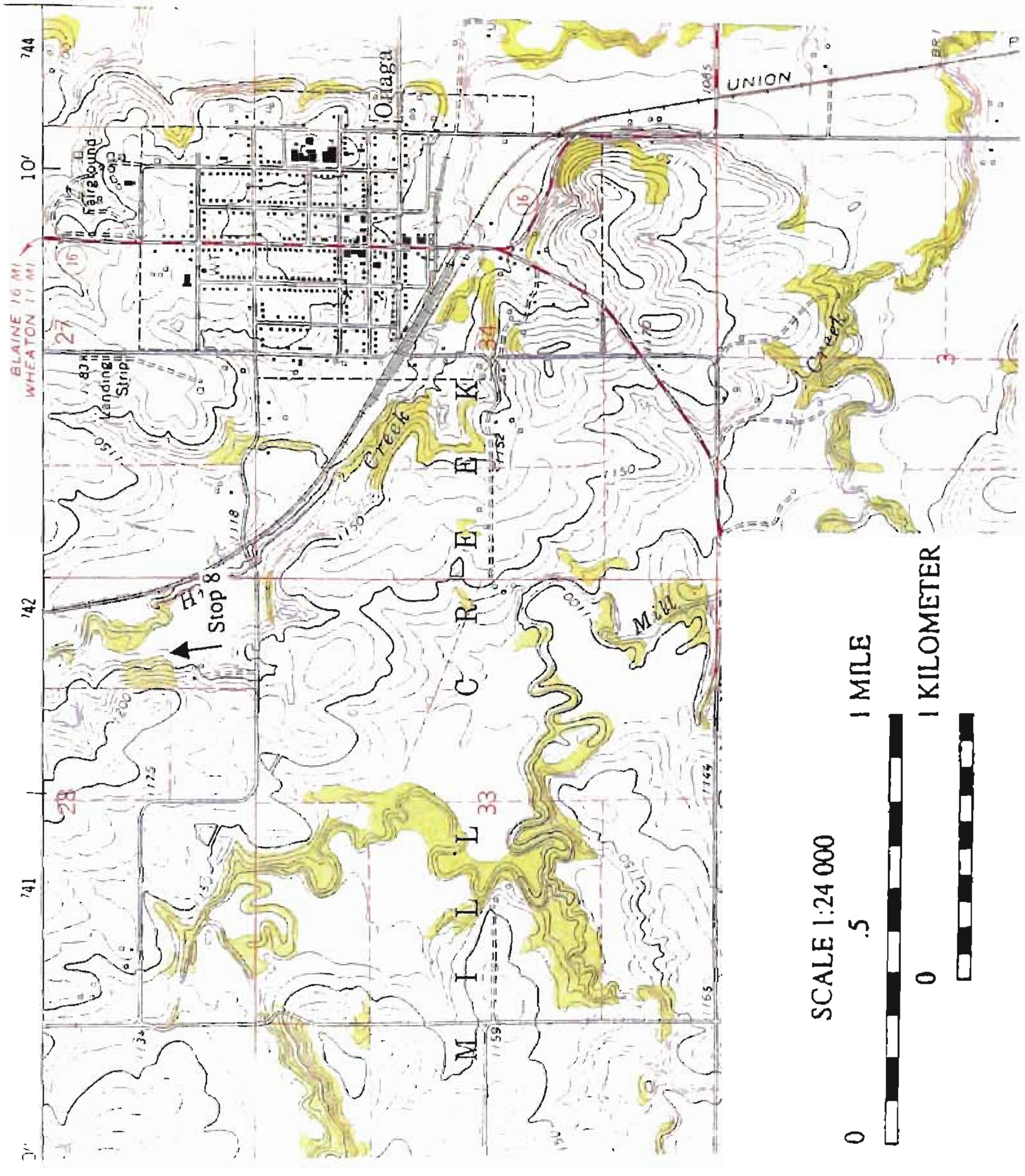


Figure 42. Location of stop 8.

Photograph 28. Stop 8.

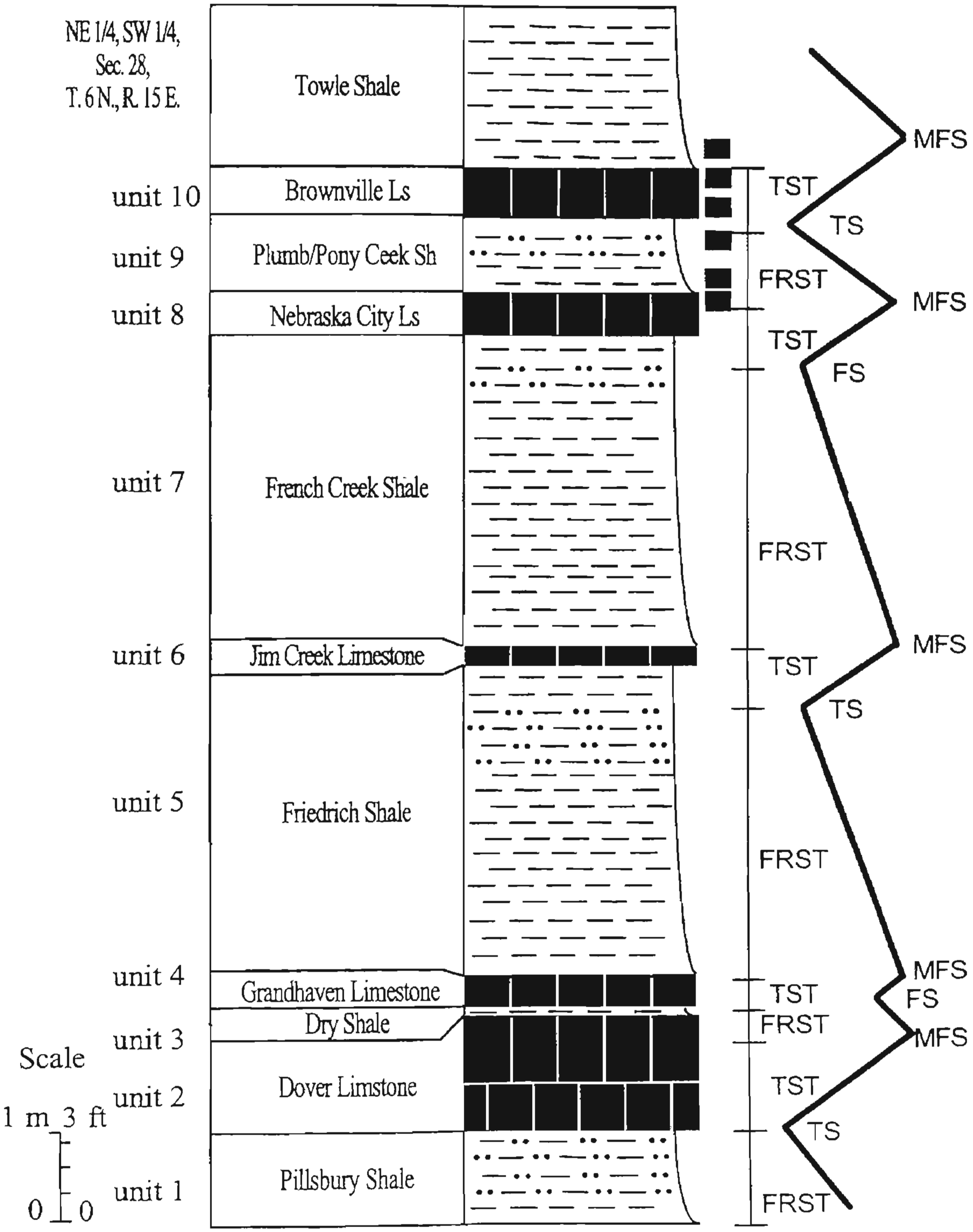


Figure 43. Measured section of stop 8.

Stop 8

State: Kansas County: Pottawatomie

Northwest of Onaga, Kansas (modified after Mudge and Yochelson 1962)

Covered section

Unit 8. Nebraska City Limestone Member Facies 3

0.5 m (1.5 ft)- Tan to gray wackestone with abundant brachiopods

Unit 9. Plumb/Pony Creek Shale Member Facies 1C-2

4.1 m (13.5 ft)- Tan to gray to green, sandy, silty, clay shale that is conglomeratic in places with iron stains and nodules

Unit 10. Brownville Limestone Member Facies 3-4

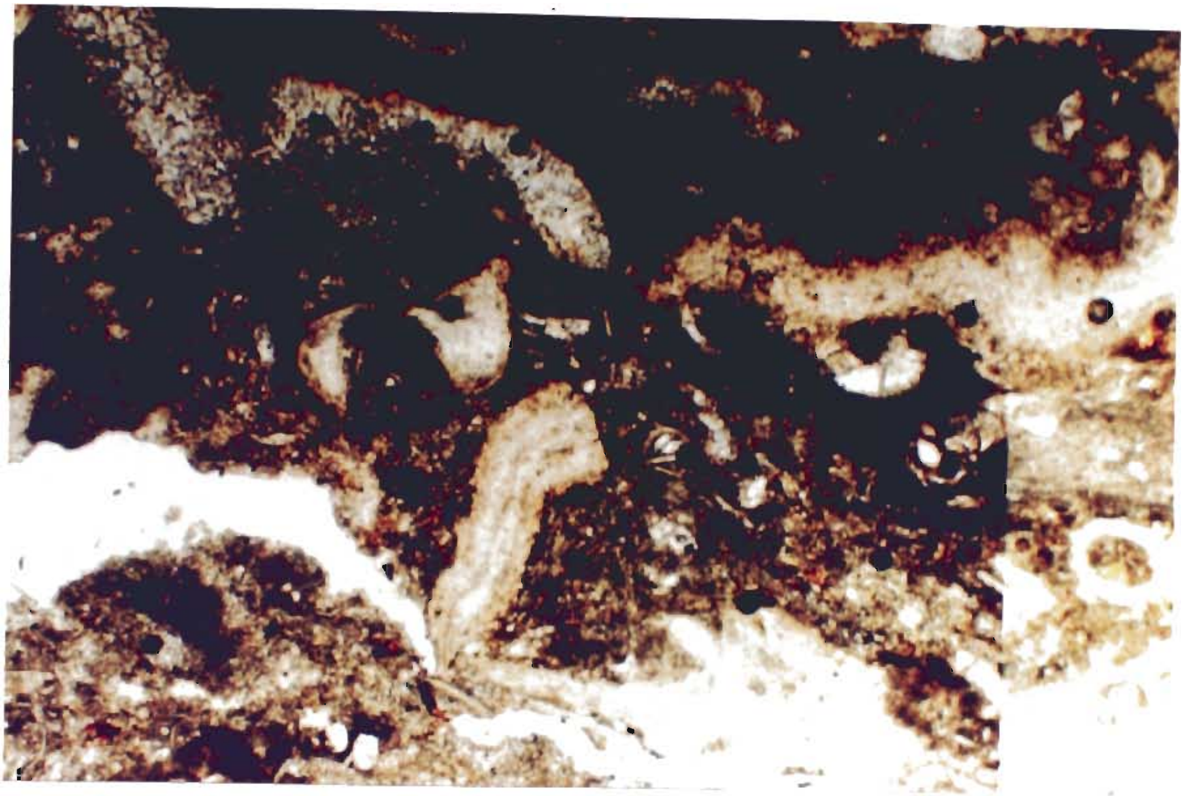
0.6 m (2 ft)- Light brown wackestone that weathers blocky with abundant brachiopods

Unit 11. Towel Shale Member of the Onaga Shale Formation

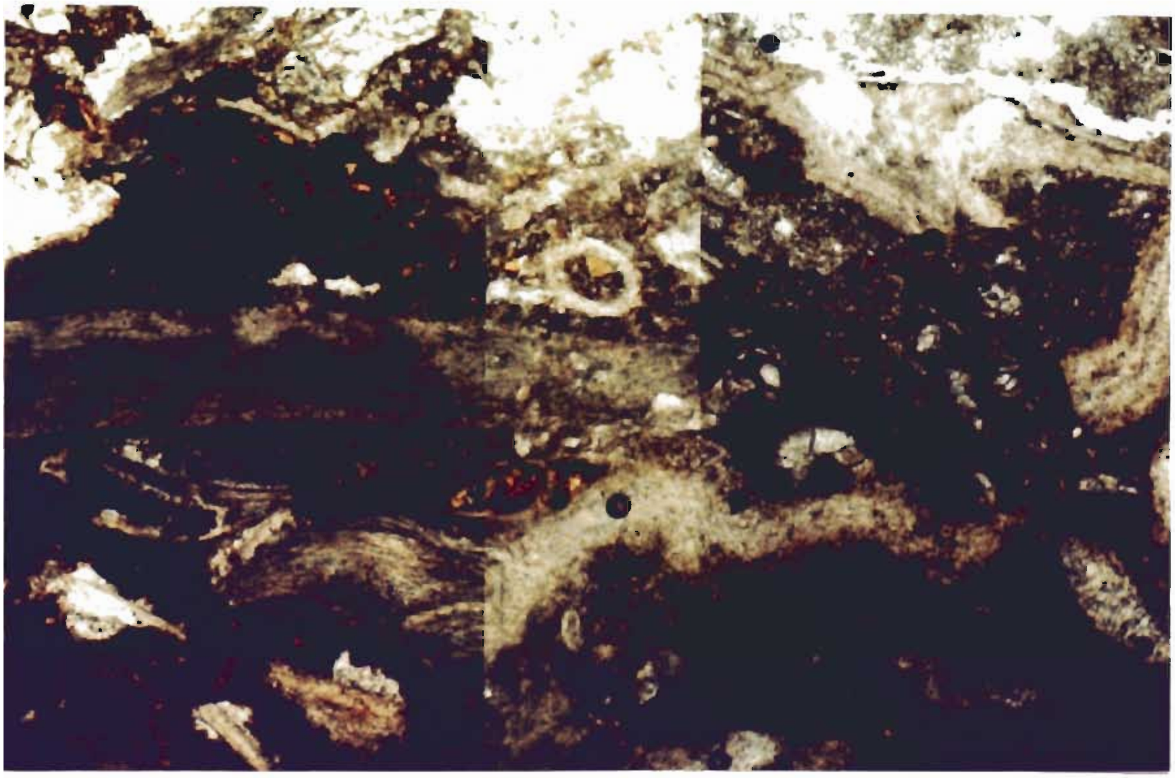
3 m (10 ft)- Gray clayey to silty to sandy shale with nodules and iron stains

Aspinwall Limestone member of the Onaga Shale Formation

0.3 m (1ft)- Gray limestone



Photograph 29. Nebraska City Limestone Member (40x) consisting of a bioclastic wackestone/packstone with micrite and brachiopod fragments.



Photograph 30. Brownville Limestone Member (40x) consisting of a bioclastic wackestone/packstone with micrite and brachiopod fragments.

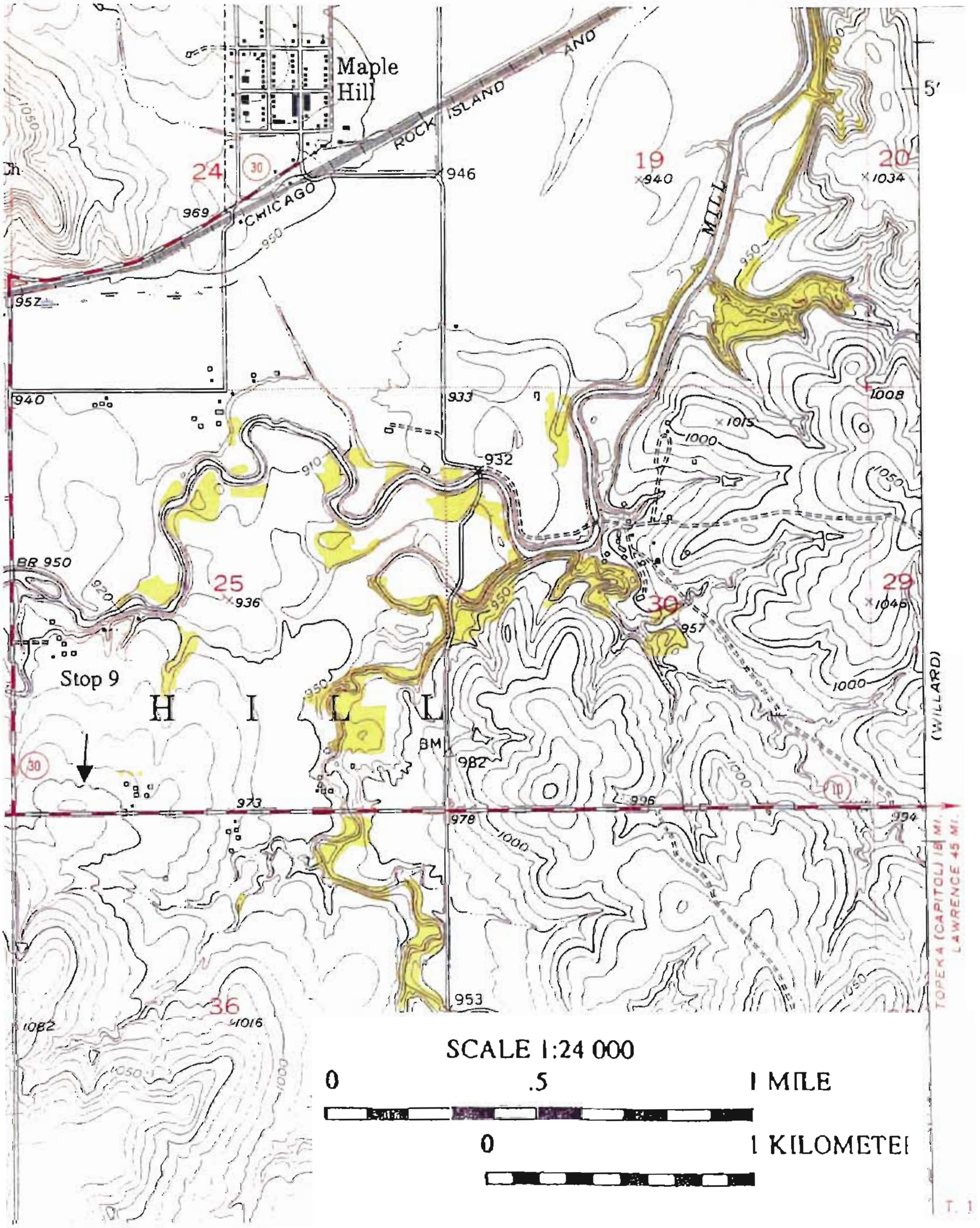


Figure 44. Location of stop 9.

Photograph 31. Westbound I-70, South of Maple Hill, KS, Stop 9.

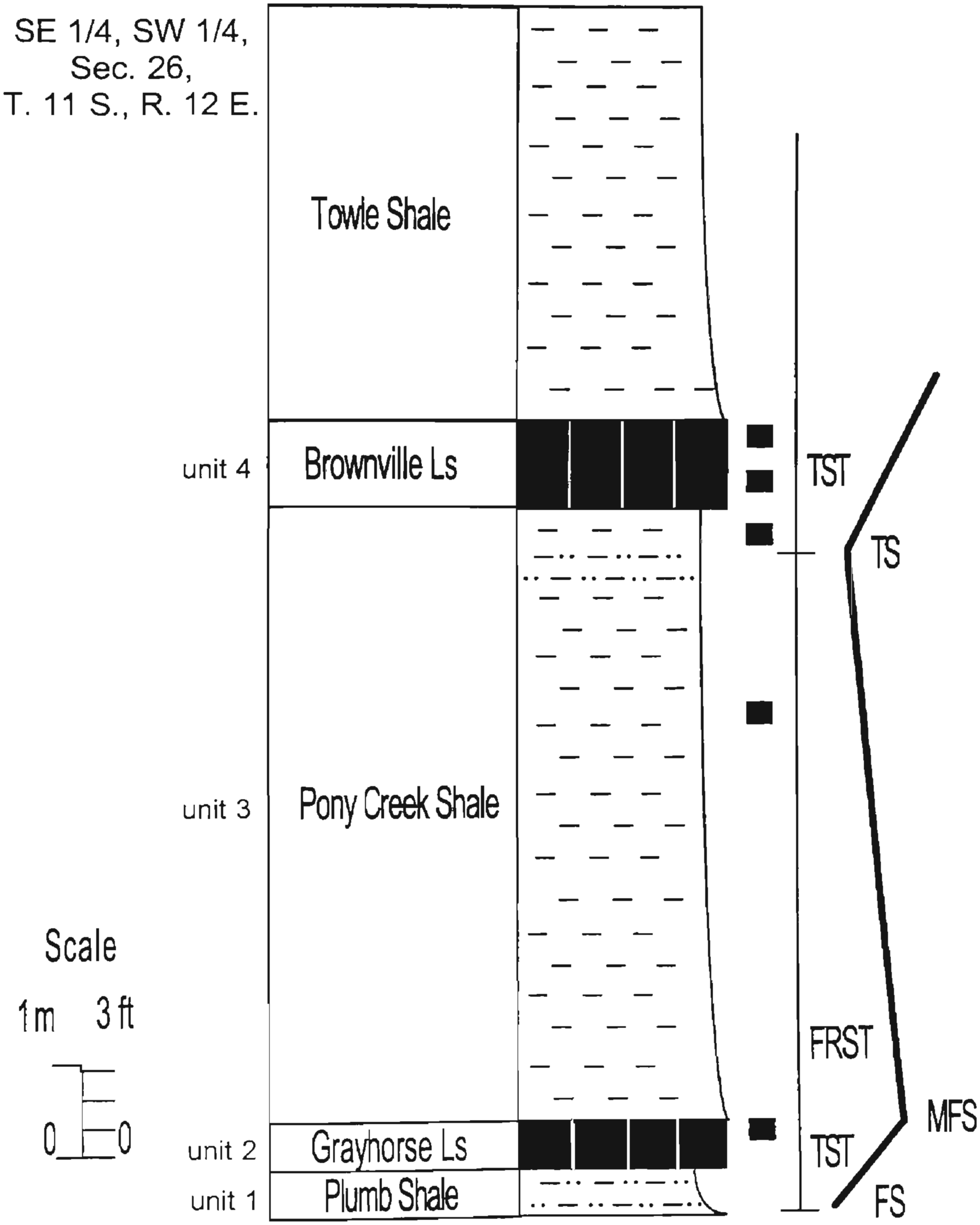


Figure 45. Measured section of stop 9.

Stop 9

State: Kansas County: Wabaunsee

Along I-70, ½ a mile west of overpass to Maple Hill

(modified after Ball and Ball, unpublished data at Kansas Geological Survey)

Unit 1. Plumb Shale Member Facies 1C

(0.6 ft)- Gray silty shale, unfossiliferous

Unit 2. Grayhorse Limestone Member Facies 3

0.9 m (3.0 ft)- Tan to yellow wackestone that weathers gray and is conglomeratic in places

Unit 3. Brownville Limestone Member Facies 4

0.9 m (3.0 ft)- Gray-green wackestone with bivalves, algae, fusulinids, and little phosphate

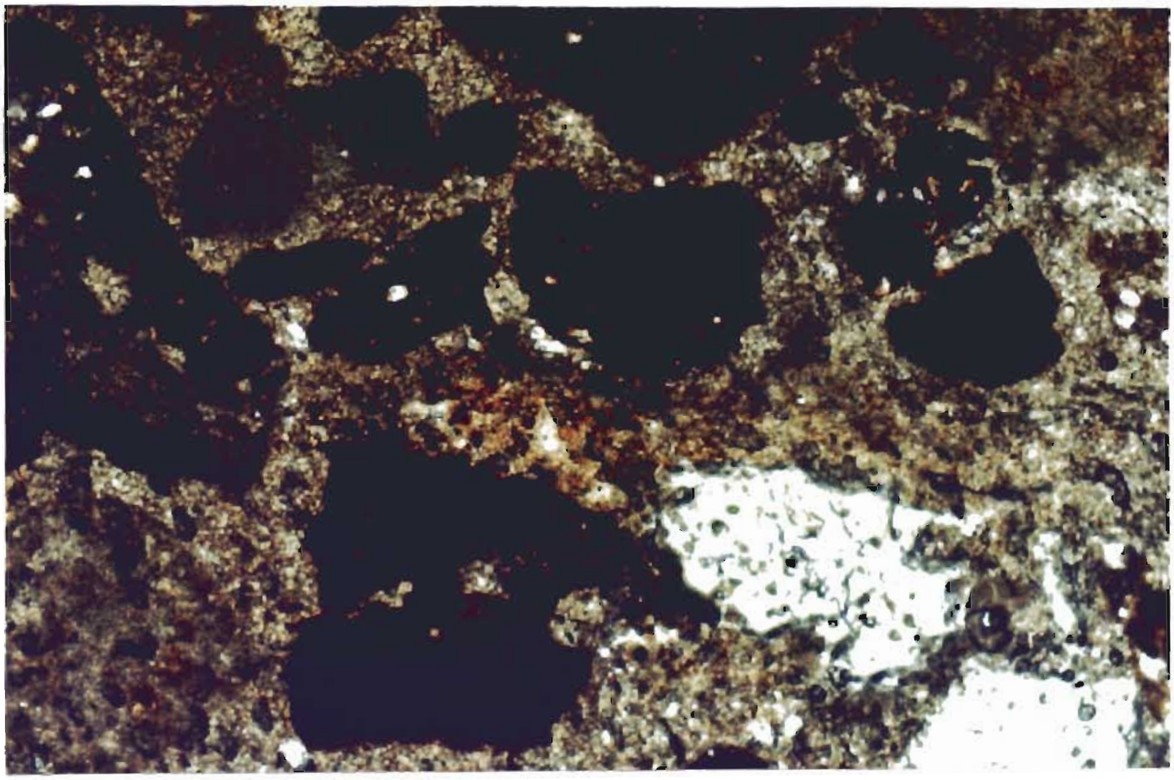
Unit 4. Towel Shale Member of the Onaga Shale Formation

6.0 m (20 ft)- Gray to tan clayey to silty shale, red-green at top, that weathers brown to tan, containing bivalves, brachiopods, and bryozoans at top

4.3 m (14 ft)- Red to tan siltstone, unfossiliferous

Aspinwall Limestone

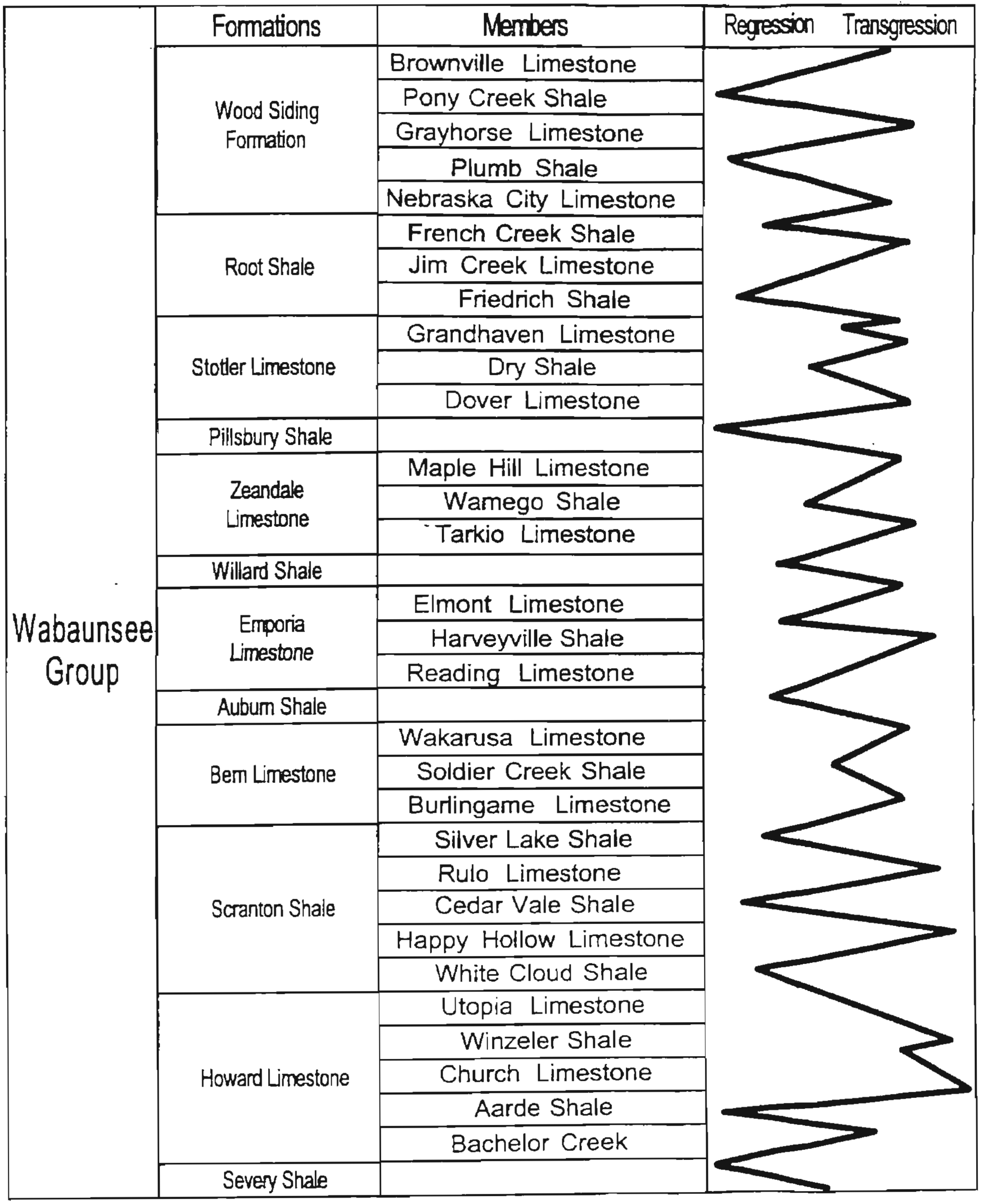
0.9m (3 ft)- Gray to tan limestone that weathers tan to yellow , conglomeratic in places



Photograph 32. Grayhorse Limestone Member (40x) consisting of a bioclastic wackestone with large intraclasts.

|  | Formations | Members | 5 th | 4 th |
|---|---|---|---|---|
| Wabaunsee Group | Wood Siding Formation | Brownville Ls |  |  |
|  |  | Pony Creek Shale |  | ■ |
|  |  | Grayhorse Limestone |  |  |
|  |  | Plumb Shale | ■ |  |
|  |  | Nebraska City Ls |  |  |
|  | Root Shale | French Creek Shale | ■ |  |
|  |  | Jim Creek Limestone |  |  |
|  |  | Friedrich Shale |  | ■ |
|  | Stotler Limestone | Grandhaven Ls | ■ |  |
|  |  | Dry Shale | ■ |  |
|  |  | Dover Limestone |  |  |
|  | Pillsbury Shale |  |  | ■ |
|  | Zeandale Limestone | Maple Hill Ls |  |  |
|  |  | Wamego Shale | ■ |  |
|  |  | Tarkio Limestone |  |  |
|  | Willard Shale |  |  | ■ |
|  | Emporia Limestone | Elmont Limestone |  |  |
|  |  | Harveyville Shale | ■ |  |
|  |  | Reading Limestone |  |  |
|  | Auburn Shale |  |  | ■ |
|  | Bern Limestone | Wakarusa Limestone |  |  |
|  |  | Soldier Creek Shale | ■ |  |
|  |  | Burlingame Ls |  |  |
|  | Scranton Shale | Silver Lake Shale |  | ■ |
|  |  | Rulo Limestone |  |  |
|  |  | Cedar Vale Shale | ■ |  |
|  |  | Happy Hollow Ls |  |  |
|  |  | White Cloud Shale |  | ■ |
|  | Howard Ls | Utopia Limestone |  |  |
|  |  | Winzeler Shale |  |  |
|  |  | Church Limestone | ■ |  |
|  |  | Aarde Shale |  | ■ |
|  |  | Bachelor Creek |  |  |
|  | Severy Shale |  |  | ■ |

Figure 46. Wabaunsee Group Cyclicity.



| | Formations | Members |
|---|---|---|
| Wabaunsee Group | Wood Siding Formation | Brownville Limestone |
| | | Pony Creek Shale |
| | | Grayhorse Limestone |
| | | Plumb Shale |
| | | Nebraska City Limestone |
| | Root Shale | French Creek Shale |
| | | Jim Creek Limestone |
| | | Friedrich Shale |
| | Stotler Limestone | Grandhaven Limestone |
| | | Dry Shale |
| | | Dover Limestone |
| | Pillsbury Shale | |
| | Zeandale Limestone | Maple Hill Limestone |
| | | Wamego Shale |
| | | Tarkio Limestone |
| | Willard Shale | |
| | Emporia Limestone | Elmont Limestone |
| | | Harveyville Shale |
| | | Reading Limestone |
| | Auburn Shale | |
| | Bern Limestone | Wakarusa Limestone |
| | | Soldier Creek Shale |
| | | Burlingame Limestone |
| | Scranton Shale | Silver Lake Shale |
| | | Rulo Limestone |
| | | Cedar Vale Shale |
| | | Happy Hollow Limestone |
| | | White Cloud Shale |
| | Howard Limestone | Utopia Limestone |
| | | Winzeler Shale |
| | | Church Limestone |
| | | Aarde Shale |
| | | Bachelor Creek |
| | Severy Shale | |

Figure 47. Wabaunsee Group sea-level curve.

# VI.

# Conclusion

The Wabaunsee Group has a different cyclicity pattern than the megacyclothems of the underlying Shawnee Group. The northern Wabaunsee Group outcrop belt consists of 16 fifth-order cycles and seven complete fourth-order sequences. There is one partial fourth-order sequence that begins in the Pony Creek shale member of the Wood Siding formation and continues into the Admire Group, and there is a partial fourth-order sequence that ends in the Severy Shale. The partial cycles associated at the boundaries of the group are also not taken into consideration.

The Howard cyclothem, the Scranton cyclothem, the Bern cyclothem, the Emporia cyclothem, and the Zeandale cyclothem are composed of two fifth order cycles. The Stotler cyclothem and the Root/Wood Siding cyclothem both are composed of three fifth order cycles. In the outcrop area studied, the Howard Limestone is missing some of the units so in some areas it may contain another cycle. The mechanism of cyclicity within the Wabaunsee Group is influenced by sediment influx and accommodation space but mostly controlled by eustatic changes.

Additional studies may include but are not limited to correlation of strata into the subsurface, correlation of strata in adjacent basins, and determining what effect other earth processes may have had on Wabaunsee sedimentation.

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