Geology Series 5
Kansas Geological Survey

Stratigraphy, petrology, and depositional environment of sandstones in the
Rock Lake Shale Member of the Stanton Limestone (Missourian Stage, Upper Pennsylvanian)
in southeastern Kansas

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Kansas Geological Survey Geology Series 5

Stratigraphy, petrography, and depositional environment of sandstones in the Rock Lake Shale Member of the Stanton Limestone (Missourian Stage, Upper Pennsylvanian) in southeastern Kansas

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Abstract

The Pennsylvanian epicontinental sea periodically covered much of midcontinent North America during Missourian time, burying local siliciclastic source areas in Kansas with carbonate sediments. During regressive depositional phases in the Missourian, siliciclastic sediments were transported to Kansas mainly from the south. The paleoenvironmental setting within which these sediments were deposited can be delineated, despite the lack of close modern analogues, by constructing a process-response model. This is accomplished by relating the physical properties of rocks to sedimentologic processes that can be interpreted to have operated within the limits set by the stratigraphic and tectonic settings. The five members of the Stanton Limestone (in ascending order, Captain Creek Limestone Member, Eudora Shale Member, Stoner Limestone Member, Rock Lake Shale Member, and South Bend Limestone Member) form a transgressive –regressive–transgressive sequence, in which the black phosphatic shale of the Eudora Shale Member represents maximum transgression and in which the sandy Rock Lake Shale Member (where it overlies the Stoner limestone) represents maximum regression. In southernmost Kansas the Stoner limestone grades southward into a siliciclastic sequence of quartzarenite and shale, most of which is assigned to the Rock Lake Shale Member. Detailed surface and subsurface study of these siliciclastics shows that deltaic systems prograded into the sea predominantly from the southeast. Lobe complexes were sequentially abandoned as the sediment sources shifted generally northward along the eastern margin of the sea. At the same time, similar siliciclastics were transported across the carbonate platform from the northeast, filling preexisting marine channels with quartzarenites. Petrographic similarity of the sandstones from both deltaic and marine channel complexes indicates that they were derived from preexisting sedimentary rocks, possibly from the same ultimate source. Formation of the Ouachita Mountains during Pennsylvanian time uplifted early Paleozoic sedimentary rocks, from which sediments were shed northward and westward. This resulted in punctuation of the dominantly carbonate rocks of the Missourian Stage with siliciclastics in southeastern Kansas, particularly during regressive episodes. Because these sandstones were deposited in deltaic complexes on a shallow-marine shelf within a relatively stable carbonate-rich craton, they were subjected to shallow burial and mild stress fields during their postdepositional history. Diagenetic alteration of these units and associated rocks resulted in two stages of carbonate cementation, etching of siliciclastic grains, and in some units silica overgrowths.

Introduction

The rocks of the Missourian Stage of the Upper Pennsylvanian series in midcontinent North America are primarily alternating limestones and shales (fig. 1) with local lenticular sandstone bodies, particularly in southeastern Kansas. Several of the limestone formations have been studied in detail (Crowley, 1969; Mossler, 1973; Frost, 1975; Mitchell, 1981; Ravn, 1981), and some of the shale units were studied by S. R. Schutter (1983). The Stanton Limestone in particular has been the subject of detailed stratigraphic, petrologic, and paleontologic studies (Heckel, 1975a,b, 1978; Heckel et al., 1979; Senich, 1975, 1978; Wood, 1977; Malinky, 1980). The Stanton Limestone has five members, in ascending order: the Captain Creek Limestone Member, the Eudora Shale Member, the Stoner Limestone Member, the Rock Lake Shale Member, and the South Bend Limestone Member (fig. 1). The Rock Lake Shale Member is predominantly a thin shale in the north but contains several quartz sandstone units toward the south; it includes most of the sandstone known in the upper Missourian north of Oklahoma.

Geologic setting

The Stanton Limestone is the youngest unit of the Missourian Stage (Upper Pennsylvanian) in the central United States and is recognized from eastern Nebraska to southern Iowa, northwestern Missouri, eastern Kansas, and northern Oklahoma (Heckel, 1975a; Heckel, personal communication, 1981). It overlies the Vilas Shale and underlies the Weston Shale Member of the Stranger Formation (Douglas Group, Virgilian Stage). In eastern Kansas these strata dip gently toward the west and northwest (fig. 2) at approximately 5 m/km (26.5 ft/mi). The outcrop region extends from the Forest City basin across the Bourbon arch into the northern end of the Cherokee platform, all of which were relatively stable during the late Missourian (Moore, 1979).

Outcrops of the Stanton Limestone in eastern Kansas represent three different facies belts. From north to south they are the open-marine, the algal-mound, and the terrigenous-detrital (Heckel, 1968, 1975a,b, 1977; Heckel and

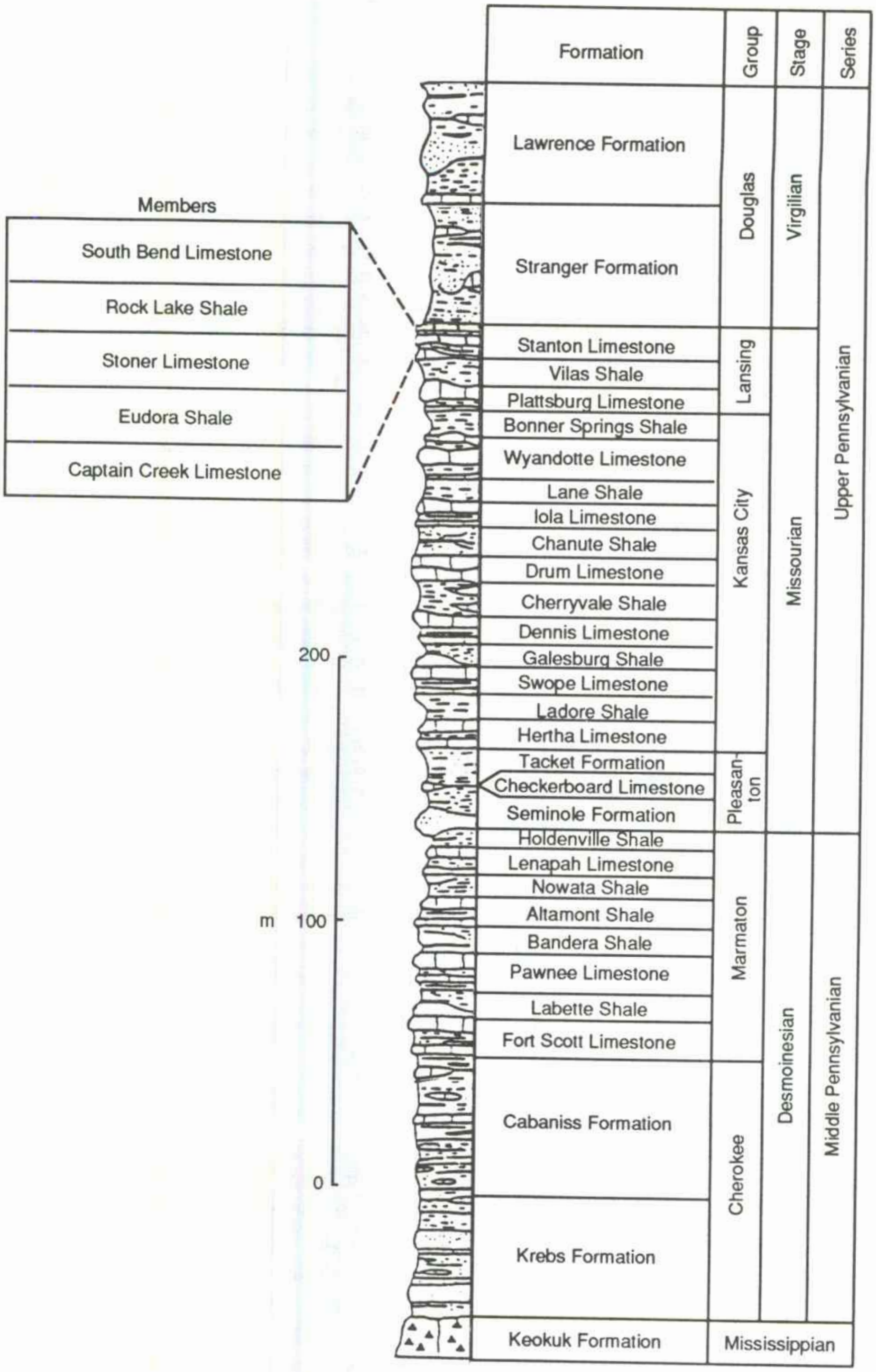


FIGURE 1—Position of Stanton Limestone and Rock Lake Shale Member in Upper Pennsylvanian sequence of Kansas [modified from Heckel (1978)].

Cocke, 1969). Most of the sandstones are in the terrigenous-detrital facies belt, but some occur in channels in the algal-mound facies belt (fig. 2). In the open-marine facies belt of northeastern Kansas, the members of the Stanton Limestone are 10.5 m (34.4 ft) thick and can be traced laterally to northern Anderson County with little change (Heckel and Cocke, 1969). Southward in the algal-mound facies belt, in northern Montgomery County, the limestone members of the Stanton Limestone thicken into algal-mound facies, reaching a thickness of 35 m (115 ft). Southward in the terrigenous-detrital facies belt the limestones thin abruptly to only a meter in thickness and the shale members thicken substantially.

Heckel (1975b, 1977, 1978) and Heckel and Baesemann (1975) described in detail the major transgressive–regressive (cyclothemic) sequence of the Stanton Limestone and other Middle and Upper Pennsylvanian formations in Kansas. The

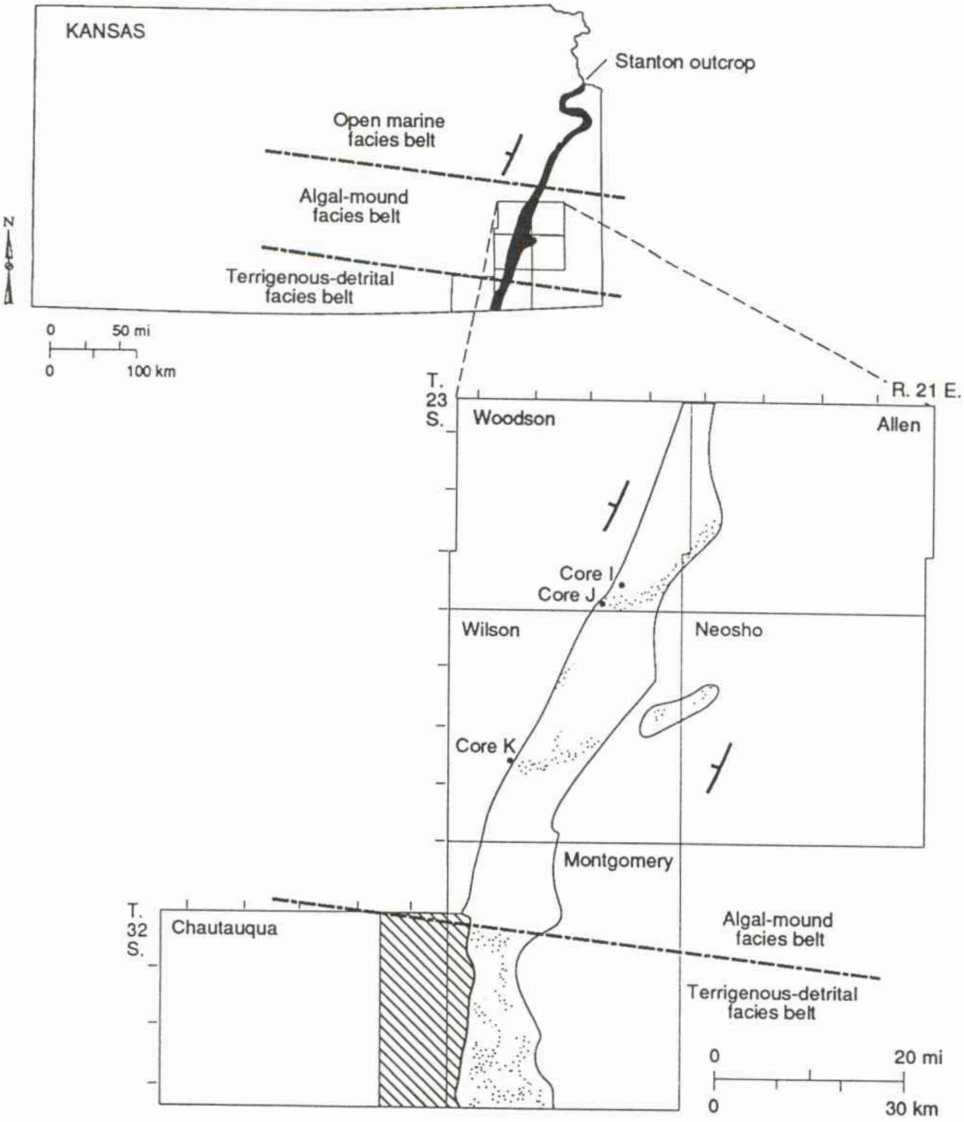


FIGURE 2—STUDY AREA showing Stanton Limestone outcrop (between dashed lines), Rock Lake sandstone outcrops (stippled), and three facies belts of Heckel (1975b). Shaded area locates subsurface extent of study.

Stanton Limestone in eastern Kansas is one complete cyclothem (Captain Creek–Eudora–Stoner) and the beginning of another cycle (South Bend). These mostly marine parts of the cycles are separated by the Rock Lake Shale Member, which was deposited mainly during the regressive phase between the two inundations.

The Rock Lake Shale Member of the Stanton Limestone [0.9–4.3 m (3–14 ft) thick] is predominantly shale in northeastern Kansas. It thins southward over most of the algal-mound facies belt (fig. 3) to 0.3–0.6 m (1–2 ft) but thickens locally to 21 m (70 ft) with a large addition of sandstone within paleochannels in this region. It thickens regionally and includes strata equivalent to the underlying Stoner Limestone Member as it grades largely into sandstone southward in the terrigenous-detrital facies belt, where it reaches 25.8 m (85 ft) in thickness in T. 33 S., R. 14 E., and 54 m (177 ft) in the subsurface of T. 34 S., R. 12 E. and R. 13 E.

Previous work

Stratigraphic work on the Stanton Limestone in the detrital facies belt has been reviewed by Heckel (1975b, p. 7). Until the work of Wilson (1957a,b), a large portion of the sandstone and shale in the detrital facies belt in western Montgomery County was misidentified as post-Stanton (Schrader, 1908; Geologic map of Kansas, 1964; Oakes, 1940). Although Winchell (1957a) assigned exposures along US–160 of what is now called the Onion Creek sandstone body (Heckel, 1975b) to the lower part of the South Bend Limestone Member of the Stanton Limestone, he nevertheless mapped most sandstones and shales of the Rock Lake Shale Member in southern Montgomery County as post-Stanton (Winchell, 1957b, plate 2B).

Heckel (1975b) mapped in detail and established a stratigraphic correlation (fig. 4) of the outcropping Stanton Lime-

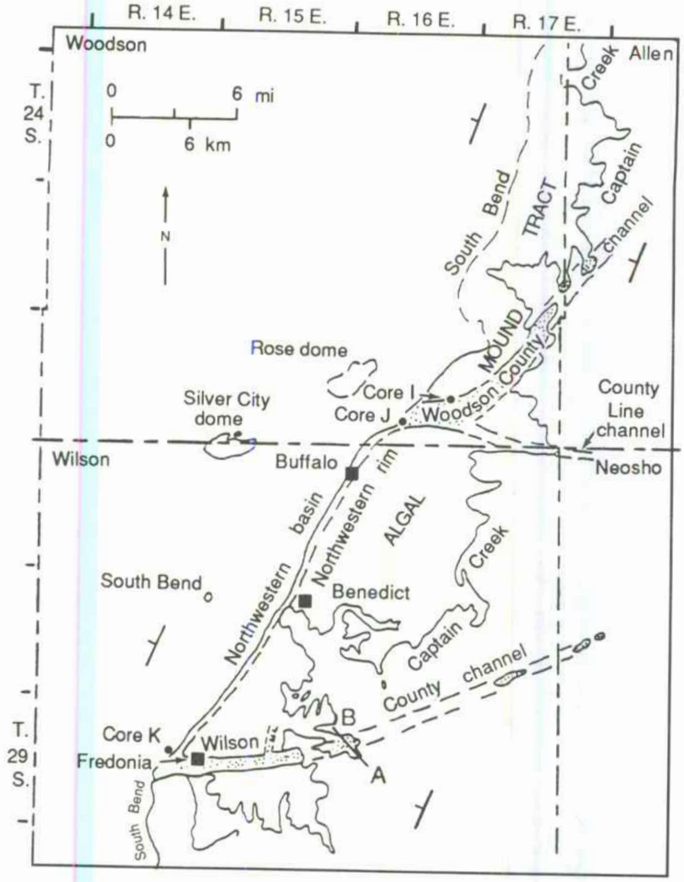


FIGURE 3—Outcrop of Stanton Limestone in algal-mound tract of Woodson and Wilson counties showing locations of cores I, J, and K. Rock Lake sandstone outcrops in channels are shown by stippled pattern [modified from Heckel (1975a, p. 45; 1978, p. 28)].

stone in the detrital facies belt, naming several discontinuous lenses of limestone and siltstone as beds (Tyro, Rutland, Bolton, Timber Hill). The Tyro bed was considered by both Wilson (1957a,b) and Heckel (1975b) to be equivalent to the Captain Creek Limestone Member. The Rutland, Bolton, and Timber Hill beds were considered the Stoner Limestone Member by Wilson (1957a,b), and Heckel (1975b) interpreted the Timber Hill and Rutland beds as equivalent to the upper Stoner limestone and the Bolton bed as equivalent to the lower Stoner limestone. These three units by definition separate the Eudora Shale Member below from the Rock Lake sandstone and shale above. In southern Montgomery County, where the Bolton bed pinches out into clastics, separation of the Eudora Shale Member from the Rock Lake Shale Member is made at the base of the lowest coarse detrital bed above the Tyro bed. On the south side of the Tyro quarry, about 1 m (3.3 ft) of conglomeratic quartz sandstone defines the base of the Rock Lake Shale Member.

In their reconnaissance studies, Wilson (1957a,b), Kenny (1968), and Heckel (1975a,b, 1977, 1978) suggested that the Rock Lake Shale Member can be attributed to a deltaic regime. On the other hand, Harbaugh (1962) suggested that the detrital sediments in the Stanton Limestone may have been deposited in a meandering stream system with a southerly source.

Purpose of investigation

The purpose of this study is to determine the nature and origin of siliciclastic sandstones in the predominantly carbonate cratonic setting of the Stanton Limestone in southeastern Kansas. Although earlier researchers suggested generalized environments for these rocks, no one has ever done a detailed study of the sandstone units. The procedures and results of this study should provide guidelines for future studies of cratonic-shelf siliciclastic paleodepositional systems by establishing and evaluating field and laboratory techniques that are useful in dealing with these systems and by developing a process-response model that can be used as a working hypothesis for the analysis of similar rock sequences elsewhere in the midcontinent.

Method of investigation

I conducted field investigations during the summers of 1978 and 1979 and the fall of 1979, measuring and describing in detail exposures of sandstones within the Stanton Limestone in southeastern Kansas. I paid particular attention to vertical textural and compositional changes and to contact relations of individual beds. Because of poor exposure of sandstones in the study area, I was not able to trace beds laterally between outcrops.

I sampled each exposure of the Stanton Limestone in detail. I used epoxy resin to impregnate samples in the laboratory before thin sectioning them because most of the sandstone samples were friable. I studied more than 150 thin sections petrographically to ascertain the composition of sandstones and to interpret diagenetic history and provenance of the grains. I analyzed textures (e.g., grain size) of sandstone and siltstone units by using the loose-grain technique of Griffiths (1967) and determined mean grain sizes from samples collected at 9 selected measured sections of the Stanton Limestone (88 samples) by measuring the maximum diameter of 50 monocrystalline quartz grains in each sample. I chose monocrystalline quartz because it is the most abundant and stable mineral component present in these rocks. Although petrographic measurements of detrital quartz grains cannot be used in statistical analyses because of diagenetic alteration of absolute grain sizes, relationships between relative grain sizes and sedimentary structures can be used to approximate energy conditions during deposition (Harms and Fahnestock, 1965).

I measured the azimuth of sedimentary structures, such as cross-stratification and ripple marks, in the field. Because these rocks have a structural dip of less than 1°, rotation corrections were not warranted. I plotted the measurements on a circular histogram and used the vector mean to interpret paleocurrent directions. Because of poor exposure, the

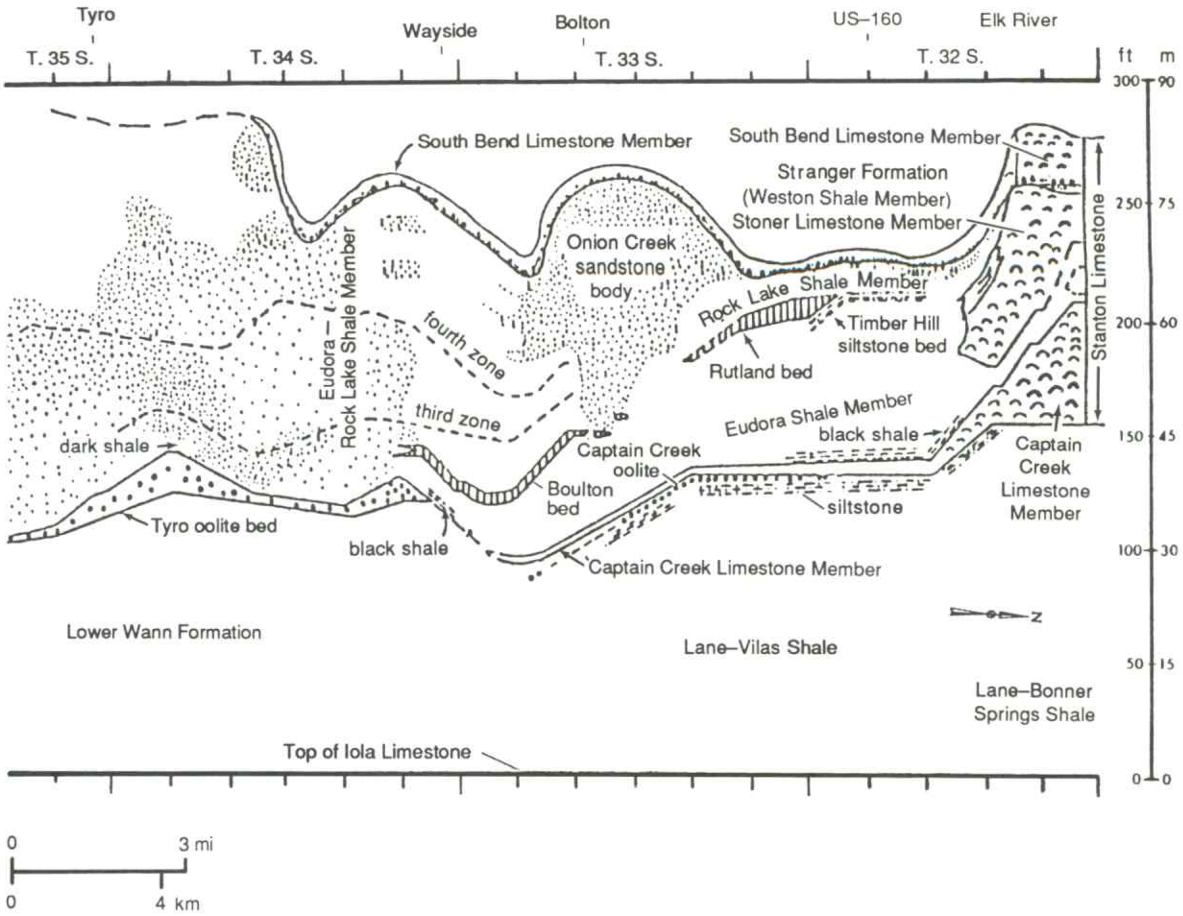


FIGURE 4—GENERALIZED CROSS SECTION showing subdivisions and facies of Stanton Limestone along outcrop across terrigenous-detrital facies belt in Montgomery County, Kansas [simplified from Heckel (1975b, p. 8)].

number of measurements taken ranged from 1 to 20 for each exposure. Although this number of measurements does not allow for statistical interpretations, these measurements in conjunction with thinning of the sandstones units in the Stanton Limestone (derived from subsurface information) can be used to make convincing interpretations of the directions of sediment transport.

One-hundred twenty-three electric logs and numerous drillers' logs from wells that either completely or partially penetrate the Stanton Formation were made available by the Kansas Geological Survey. I used all the electric logs, the outcrop descriptions, and many of the drillers' logs to generate data for construction of a structural contour map for the top of the South Bend Limestone Member of the Stanton Limestone. I constructed an isopach map from 74 electric logs that penetrate the entire formation and outcrop descriptions and a net sand isolith map from 62 electric logs in conjunction with drillers' logs and outcrop information. Some drillers' logs seemed unreliable (e.g., sandstones and limestones were not differentiated) and therefore were not used. Unfortunately, neither drillers' logs nor cutting logs were available for any of the electric logs. This necessitated the use of nearest outcrop data and generalized log signature [i.e., those suggested by Pirson (1977)] to interpret the relationships between well-log signatures and Stanton formation lithologies in the subsurface. The spontaneous potential and the resistivity curves were the only logs available for lithologic correlation purposes.

The spontaneous potential logs measured natural potential of rock units and potential between mud filtrate and connate fluid. The resistivity logs measured the voltage of the current passed through the formation from certain electrodes (Pirson, 1977).

P. H. Heckel obtained three cores from Wilson and Woodson counties as part of the Kansas Geological Survey drilling program (fig. 2). I examined these cores, along with samples from three cores supplied by the Trico Production Company in northeastern Chautauqua County, in detail, comparing lithic sequence, texture, and sedimentary structure in the cores to those in surface exposures. I used these comparisons, together with the geographic position of cores, to interpret subsurface stratigraphy in areas where outcrops are not available and to evaluate the diagenetic history by thin-section study of samples unaffected by present surface weathering conditions.

Stratigraphy

Outcrop belt

The Stanton Limestone is exposed along a north-south outcrop belt in eastern Kansas and increases in thickness from 10.5 m (34.4 ft) in the northeast to 35 m (115 ft) southward at the "standard section" in northern Montgomery County (Heckel, 1975b), which is the most completely exposed section of the Stanton Limestone in this area. Based on lateral continuity of the capping South Bend Limestone Member and the basal Tyro oolite bed, Cocke (1970) and Heckel (1975b) have recognized equivalent strata southward through Montgomery County into the upper Wann Formation of northeastern Oklahoma.

At the standard section in northern Montgomery County at the southern end of the algal-mound facies belt (fig. 4, right-hand side), the Stanton Limestone is composed of, from base to top: (1) the Captain Creek Limestone Member, about 15 m (49 ft) of medium-bedded skeletal calcilutite grading upward into massive phylloid algal-mound facies; (2) the Eudora Shale Member, 1.5 m (5 ft) thick and essentially covered (Heckel, 1978, p. 40); (3) the Stoner Limestone Member, 11.4 m (37.4 ft) of thin-bedded shaly skeletal calcilutite and fossiliferous shale, grading upward to massive phylloid algal limestone; (4) the Rock Lake Shale Member, 1.2 m (3.9 ft) of sparsely fossiliferous gray shale with lenses of sandstone; and (5) the South Bend Limestone Member, about 6 m (20 ft) of sparsely algal skeletal calcilutite with oolitic quartz sandstone at the base (Heckel, 1975b). All members of the Stanton Limestone undergo a radical change laterally from the south end of the algal-mound facies belt across the terrigenous-detrital facies belt (Heckel, 1975a,b, 1978).

Captain Creek Limestone Member

The Captain Creek limestone thins southward from about 15 m (49 ft) of phylloid algal calcilutite at the standard section to 1.5 m (5 ft) along US–160 (Heckel, 1975b). Between US–160 and US–75 the Captain Creek limestone is 1.5–2.1 m (5–7 ft) thick and consists of two massive limestone beds separated by fossiliferous sponge-rich calcareous shale. The upper limestone is a sponge-rich skeletal calcilutite, and the lower limestone is an oolite. Both limestones disappear south of US–75, southwest of Bolton.

The Tyro oolite (Strimple and Cocke, 1969; Heckel, 1975b) appears about 2 km (1.2 mi) farther south at the stratigraphic level of the Captain Creek limestone (fig. 5). It is a yellowish- to orange-weathering crossbedded oolitic limestone with scattered marine skeletal fragments. Heckel (1975a) and Senich (1978) reported a 1-cm-thick bed of skeletal calcilutite at the top of the Tyro oolite at the type section (south wall of the Tyro quarry), which may be equivalent to the upper skeletal calcilutite bed of the Captain Creek Limestone Member to the north. The Tyro bed is persistent throughout southern Montgomery County and as far as 3.2 km (2 mi) into Oklahoma.

Eudora Shale Member

The Eudora Shale Member thickens southward substantially from the algal-mound belt into the north end of the detrital belt, where it is separated from the Rock Lake Shale Member by the Timber Hill, Rutland, and Bolton beds (fig. 4). The Eudora shale is a 17.5–21-m (57–69-ft) thick gray shale along US–160 with a 0.3–0.6-m (1–2-ft) bed of black shale at the base (encountered in drilling; Wilson, 1957a; Heckel, 1975b). The upper 6 m (20 ft) of the Eudora shale exposed in this section contains two distinct zones of marine fauna related to turbidity (Heckel, 1975a,b, 1978; Wood, 1977; Senich, 1978). Eastward the Eudora thickens to 22.5 m (74 ft) around Walker Mound, where the exposed black shale contains phosphate nodules and a pelagic fauna. The Eudora shale thins farther southward to 5.4 m (18 ft) beneath the Bolton bed in southern T. 33 S., where it becomes a gray marine shale with black facies at the base (fig. 4). Southward, where the Bolton bed pinches out, the Eudora and Rock Lake shale members are not easily differentiated, except in the Tyro quarry where 0.3–0.6 m (1–2 ft) of dark-gray Eudora shale containing scattered phosphorite nodules and marine fauna (Malinky, 1980) is overlain by 0.9–1.2 m (3–4 ft) of conglomeratic quartz sandstone (Heckel, 1975a,b, 1978; Heckel et al., 1979; Senich, 1978), which Heckel (1983) has placed in the Rock Lake Shale Member.

Stoner Limestone Member

The Stoner Limestone Member is 11.4 m (37.4 ft) thick and consists of shaly skeletal calcilutite, shale, and phylloid algal limestone at the standard section in northern Montgomery County. It is as much as 12 m (39 ft) of more solid limestone westward along the Elk River valley (Heckel, 1978). Southward the Stoner limestone thins and pinches out as it grades into a shale sequence 1.6 km (1 mi) into the northern part of the detrital facies belt (fig. 4).

The Timber Hill bed (Heckel, 1975b) is 0.6–1.2 m (2–4 ft) of thin-bedded quartz siltstone that is well exposed along the east side of Timber Hill. Stratigraphically, it overlies shale that is equivalent to the Stoner limestone. At its southernmost exposure the Timber Hill bed (fig. 4) is overlain by the Rutland bed.

The Rutland bed (Heckel, 1975b) ranges from 0.3 m (1 ft) to 2.4 m (7.9 ft) thick. Although this calcarenitic limestone bed differs from the largely calcilutitic facies of the Stoner Limestone Member, its stratigraphic position suggests that it is equivalent to the top of the Stoner limestone (fig. 4).

The Bolton bed (Heckel, 1975b) is the southernmost limestone bed overlying the Eudora Shale Member in the

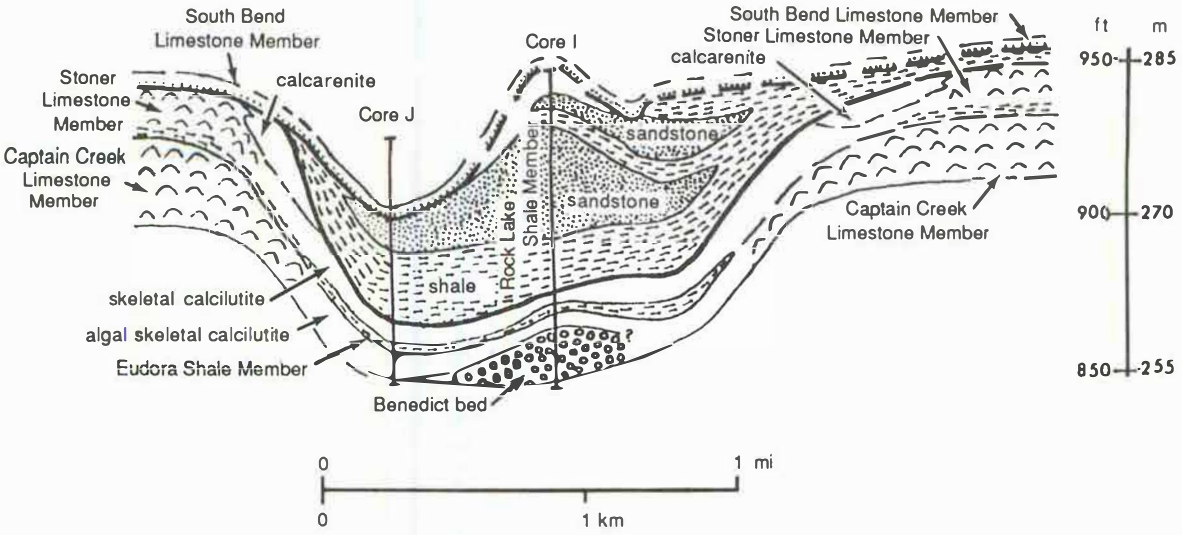


FIGURE 5—Stratigraphic and facies relationships of Stanton Limestone across Woodson County channel projected from several exposures and cores near the western end [simplified from Heckel (1975a, p. 46)]. Datum is mean sea level. Vertical exaggeration is ≈40 times.

detrital facies belt (fig. 4). It ranges in thickness from 0.3 m to 1.35 m (1–4.4 ft) and consists largely of unabraded invertebrate material. This bed is probably equivalent to the lower Stoner Limestone Member, based on its stratigraphic position and similar conodont fauna (Heckel, 1975b; Wood, 1977).

Rock Lake Shale Member

The Rock Lake Shale Member is the most lithologically variable member of the Stanton Limestone in eastern Kansas.

Algal-Mound Facies Belt—The Rock Lake shale ranges generally from 0.3 m to 0.9 m (1–3 ft) thick and is a sparsely fossiliferous shale over most of the algal-mound facies belt. In places, the Rock Lake Shale Member is absent and the overlying South Bend Limestone Member rests directly on the Stoner Limestone Member (Heckel, 1975b; Senich, 1978). In Woodson and Wilson counties contemporaneous channels (fig. 3) developed in the lower limestone members of the Stanton Limestone (Heckel, 1975b, 1978). These channels are filled with shales and sandstones of the Rock Lake Shale Member.

Across the Woodson County channel (fig. 5) the Rock Lake Shale Member ranges from 1.8 m to 22.5 m (6–74 ft) in thickness and consists mainly of light-gray to gray shale and buff to light-gray sandstone, which weathers rusty brown. The best exposures of this channel are in its northern part. Along the east side of a road cut in NWSW sec. 26, T. 25 S., R. 17 E., the Rock Lake Shale Member is a 6-m (20-ft) thick orange-brown quartz sandstone with crossbeds at the base. Wood fragments are abundant, and scattered echinoderm and mollusk molds are observed. Just to the southwest, 8.1 m (27 ft) of orange-brown crossbedded sandstone and limestone are exposed (Woodson County channel section; Moussavi–Harami, 1980, appendix C, section 22). The crossbedded skeletal calcarenite at the base, which contains fragments of echinoderms, brachiopods, and bryozoans along with interbeds of sandstone, is considered part of the Rock Lake depositional regime because quartz sandstone is unknown elsewhere in the Stoner Limestone Member (Heckel, personal communication, 1979). Along ditches in the road cut in the south line of SW sec. 3, T. 26 S., R. 17 E., 7.2 m (24 ft) of orange-brown crossbedded quartz sandstone carries many scattered plant fragments. Farther southwestward, along the creek near the south line of sec. 27, T. 26 S., R. 16 E., 2.4 m (8 ft) of the Rock Lake shale consists of dark-gray nonfossiliferous shale that grades upward into greenish-gray calcareous sandstone and siltstone.

The only good exposure of the Rock Lake Shale Member along the northwestern rim of the algal-mound track (fig. 3) is along the bank of the Verdigris River at the low-water bridge southwest of Benedict (NENE sec. 16, T. 28 S., R. 15 E.). There, 0.5 m (1.6 ft) of fossiliferous gray marine shale grades laterally into 0.9 m (3 ft) of buff to orange crossbedded sandstone with scattered clay pebbles, wood fragments, and a few marine fossil fragments. The channel-like sandstone thins toward the west and pinches out above limestone of the Stoner Limestone Member and below conglomeratic sand limestone of the South Bend Limestone Member.

Sandstone is poorly exposed all along the Wilson County channel (figs. 3 and 6). Much of the sandstone is gray to buff, fossiliferous, and conglomeratic and belongs to the South Bend Limestone Member (Heckel, 1975b). The Rock Lake Shale Member is mainly a noncalcareous reddish weathering quartz sandstone up to 2.7 m (9 ft) thick. Crossbedding is conspicuous in places (e.g., SW sec. 7, T. 29 S., R. 16 E.). One of the best exposures of sandstone is in a small tributary to the Wilson County channel along K–47 (K–47 section; Moussavi–Harami, 1980, appendix C, section 28). At this

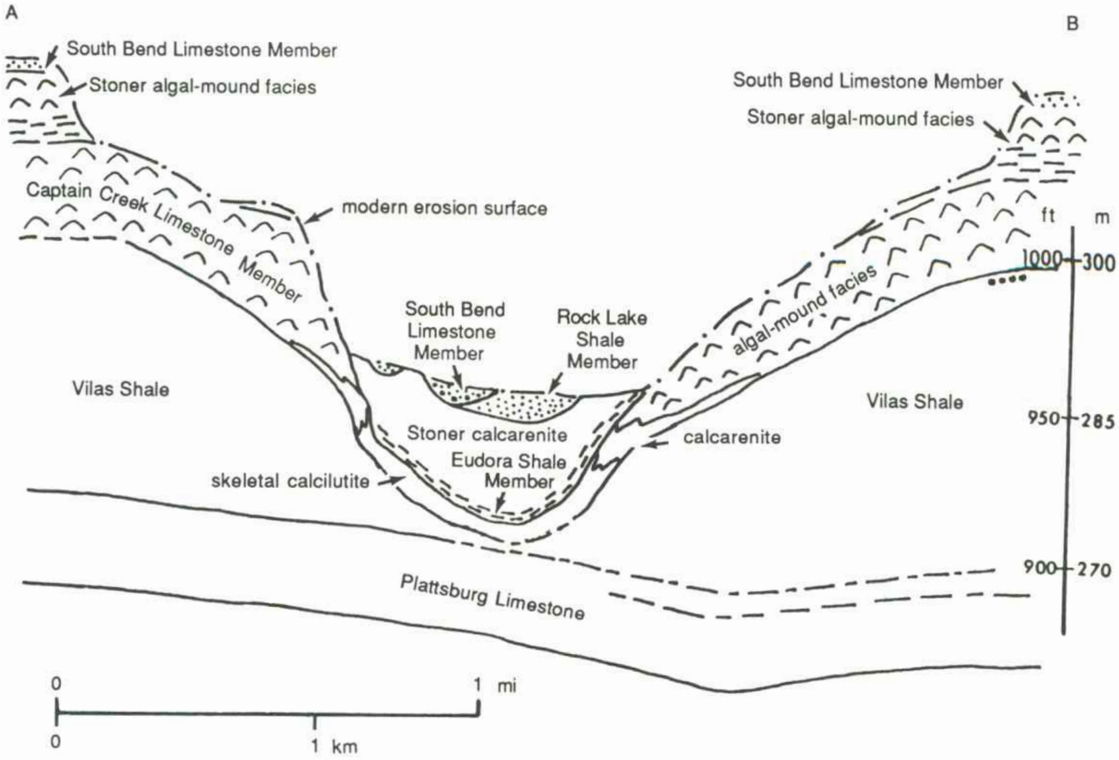


FIGURE 6—STRATIGRAPHIC AND FACIES RELATIONS within Stanton Limestone across Wilson County channel near Altoona. For locations see line AB in fig. 3 [simplified from Heckel (1975a, p. 46; 1978, p. 33)]. Datum is mean sea level. Vertical exaggeration is ≈40 times.

locality the Rock Lake Shale Member is 1.8 m (6 ft) thick and consists of 7.5 cm (3 in.) of greenish-gray shale at the base overlain by orange-brown crossbedded sandstone, which cuts beds of the Stoner Limestone Member (fig. 7).

Farther west in the subsurface, near where the Wilson County channel meets the northwestern rim of the mound tract, about 6 m (20 ft) of the Rock Lake Shale Member is present in core K (figs. 2 and 3). The lower portion of the Rock Lake shale in this core consists of interbedded buff to light-gray sandstone and dark-gray shale. The upper portion consists of buff to light-gray coarse-grained, crossbedded sandstone. Abundant but scattered plant fragments and scattered marine fossil fragments, such as echinoderms, are present.

Northeast of Elk City, 2.1 m (7 ft) of quartz sandstone is exposed in a roadbed near the north-central line of sec. 33, T. 31 S., R. 14 E. Lithologically, this sandstone is similar to that filling the channel in Wilson County, and it may fill a small low area in the Stoner mound in this region.

Near the south end of the algal-mound facies belt at the standard section of the Stanton Limestone, the Rock Lake Shale Member is 1.05 m (3.4 ft) thick. It consists of 0.6 m (2 ft) of fossiliferous gray shale overlain by 0.45 m (1.5 ft) of buff sandy shale and lenticular quartz sandstone with scattered pelmatozoan fragments (Heckel, 1975b).

DETRITAL BELT—Southward in the detrital belt, the Rock Lake Shale Member becomes much thicker and contains a greater variety of sandstones and shales. The northernmost exposure of Rock Lake sandstone in the detrital belt is in SWNW sec. 23, T. 32 S., R. 14 E., where it forms a cliff along Card Creek. At this locality, 5.1 m (17 ft) of orange-brown crossbedded sandstone is present beneath limestone of the South Bend Limestone Member. Just to the southeast, in the northeast side of Timber Hill along the road cut at the east-central line of NE sec. 26, T. 32 S., R. 14 E., the Rock Lake Shale Member is 3.3 m (11 ft) thick. The lower 2.7 m (9 ft) is nonfossiliferous gray shale that overlies the Timber Hill bed, and the upper 0.6 m (2 ft) is an orange-brown crossbedded sandstone.

Farther southwestward, the Rock Lake Shale Member thickens along US–160 to 8.4 m (28 ft) on the east side of Coon Creek and to 10.8 m (35 ft) on the west side in SE sec. 28, T. 32 S., R. 14 E. On the east side the lower 6 m (20 ft) is a tan nonfossiliferous shale that overlies the Timber Hill bed, and the upper 2.4 m (7.8 ft) is an orange-brown crossbedded sandstone. On the west side of the creek the shale thins to 5.1 m (17 ft), and the sandstone thickens to 5.7 m (19 ft) (Coon Creek section; Moussavi–Harami, 1980, appendix C, section 25). This sandstone unit thickens southward to the vicinity of Onion Creek in secs. 14, 15, 22, and 23, T. 33 S., R. 14 E., where it has been informally named the Onion Creek sandstone body by Heckel (1975b). Measurements for the present study show that the Rock Lake interval from the top of the Bolton bed (along the creek bottom in NENE sec. 24, T. 33 S., R. 14 E.) to the top of the hill (along both sides of the road cut on the east side of secs. 22 and 27, T. 33 S., R. 14 E.) is 25.8 m (85 ft) thick (Onion Creek section; Moussavi–Harami, 1980, appendix C, section 20). At this

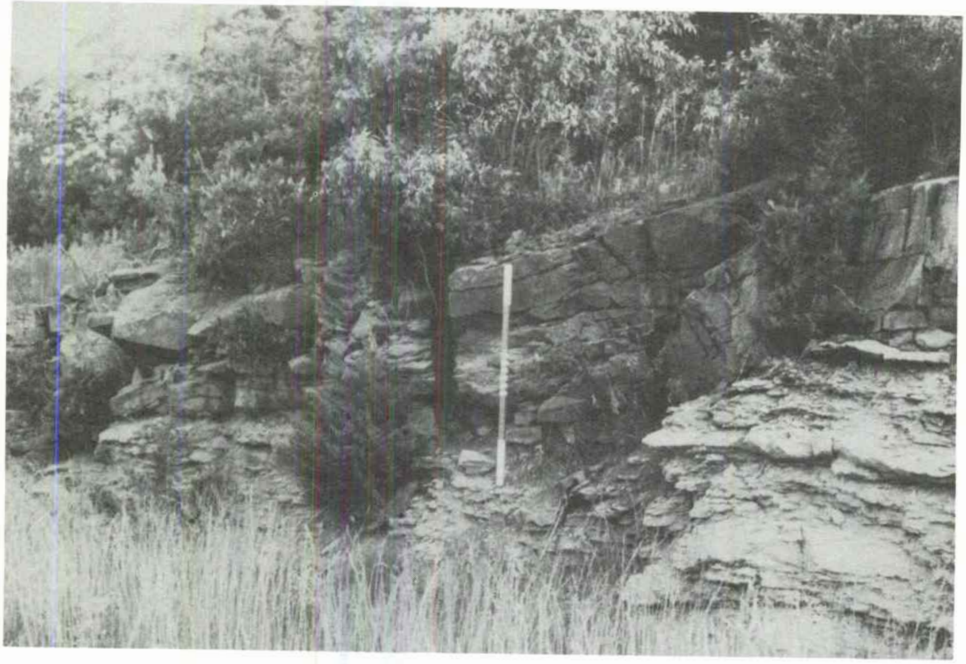


FIGURE 7—CROSSBEDDED ORANGE-BROWN SANDSTONE of small tributary to Wilson County channel east of Fredonia. Channel sandstone, marked by 5-ft rod, cuts flat-lying beds of Stoner Limestone Member (left). K–46 section (Moussavi–Harami, 1980, appendix C, section 28).

locality the lower 11.7 m (38 ft) is mainly nonfossiliferous gray shale at the base, grading upward into interbedded gray shale and light-gray shale to yellowish-brown sandstone and siltstone. The upper part is 14.1 m (46 ft) of orange-brown crossbedded sandstone.

Southward along US–75 in the vicinity of Wayside between T. 33 S. and T. 34 S., the upper part of the Onion Creek sandstone thins and grades from more massive sandstone to very thin bedded, fine-grained sandstone or siltstone and shale that resembles the lower part of the Rock Lake Shale Member in T. 33 S.

Toward the south, in T. 34 S. and T. 25 S., two major facies of sandstone, described by Heckel (1975b), appear: massive to thick-bedded sandstone and thin-bedded sandstone with intercalated shale. Poor exposures make the relationship of these two facies difficult to ascertain. Heckel (1975b) suggested that the massive sandstones northwest and southwest of Tyro are stratigraphically higher than the thin-bedded sandstone and shale. This may be true in general, but the massive sandstones appear at different levels within the Rock Lake Shale Member.

Two exposures display the two sandstone facies recognized by Heckel (1975b). The first outcrop is along a road cut on the north line of sec. 22, T. 34 S., R. 14 E., where 18.6 m (62 ft) of the Rock Lake Shale Member is exposed. The lower 15 m (49 ft) is predominantly greenish-gray shale. Within the shale a 1.5-m (5-ft) zone of thin-bedded, highly calcite-cemented sandstone occurs about 3 m (10 ft) above the base of the outcrop. Higher in this sequence the shale has been cut by 3.6 m (12 ft) of orange-brown crossbedded sandstone. The second outcrop occurs 0.8 km (0.5 mi) north of the Oklahoma border in road cuts along the west lines of NW sec. 14 and SW sec. 11, T. 35 S., R. 14 E. (Oklahoma border section), where 25.5 m (84 ft) of the Rock Lake Shale Member is exposed. At this locality, the lower 13.5 m (44 ft) are mainly gray shale with some interbeds of thin-bedded sandstone. The upper 12 m (39 ft) are orange-brown crossbedded sandstones (Moussavi–Harami, 1980, appendix C, section 3). Although Heckel (1975b) did not report fossils from these Rock Lake sandstone facies outcrops, scattered, abraded skeletal fragments of echinoderms, brachiopods, bryozoans, and pelecypods have been found in thin sections of the thin-bedded sandstone at these two localities (fig. 8).

Westward along the Oklahoma border in secs. 16 and 17, T. 35 S., R. 14 E., a massive sandstone body supports two hills. Heckel (1975b) suggested that this body is either part of the Douglas Group that cut through the South Bend Limestone Member or a local thickening of a Rock Lake sandstone. Based on subsurface data, presented later, I believe that this body represents part of a major channel-sand deposit that formed during deposition of the Rock Lake Shale Member.

Poor exposures and a wide outcrop belt prevent accurate determination of the total thickness of the Rock Lake Shale Member from surface information in southern Montgomery County. By using regional dip and total relief between exposures, Heckel (1975b) suggested that the Rock Lake shale is at least 45 m (148 ft) thick and as much as 60 m (197 ft) thick in the vicinity of Cheyenne Creek in T. 34 S. (fig. 4) northeast of Caney.

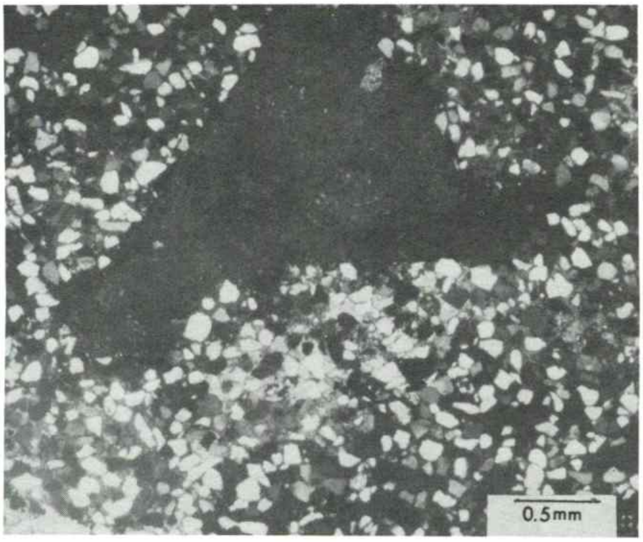


FIGURE 8—Photomicrograph of echinoderm fragment (at extinction) in fine-grained, highly calcite cemented sandstone of Rock Lake Shale Member. Cross-polarized light. Sample R.3–4, Oklahoma border section (Moussavi–Harami, 1980, appendix C, section 3).

Calcareous horizons within the Rock Lake Shale Member in the detrital facies belt have been described by Heckel (1975b). He assigned the informal names third oolite zone and fourth oolite zone to two of these horizons based on their stratigraphic positions above the Tyro oolite and Bolton bed in southern T. 33 S., T. 34 S., and T. 35 S. (fig. 4). The third oolite zone consists of sparsely fossiliferous oolitic sandstones that seem traceable along the outcrop. The fourth oolite zone includes a greater variety of fossiliferous oolitic sandstone and calcarenite and seems less easily traceable along the outcrop. Heckel (1975b) also described stromatolitic layers present in NWSE sec. 4, T. 35 S., R. 14 E., and in NWSE sec. 13, T. 33 S., R. 14 E. I discovered a 0.15-m (0.5-ft) thick bed of molluskan skeletal calcarenite in shale along the road cut in SENESE sec. 29, T. 34 S., R. 14 E. This limestone has not been recognized elsewhere, and it probably pinches out laterally within the shale.

South Bend Limestone Member

The South Bend Limestone Member is the uppermost member of the Stanton Limestone in eastern Kansas, and it can be traced into northern Oklahoma. The thickness of the South Bend limestone is 1.2–1.5 m (4–5 ft) across most of the mound tract, except in the Wilson County channel, where it is as thick as 4.5 m (15 ft) (Heckel, 1975a). The lower part is mainly a conglomerate or oolitic quartz sandstone, and the upper 0.6–1.2 m (2–4 ft) is predominantly a skeletal calcilutite. In northern Montgomery County, at the standard section of the Stanton, the South Bend limestone thickens to about 6 m (20 ft) and consists of 1.5 m (5 ft) of oolitic, conglomeratic quartzose limestone at the base that grades upward into 4.5 m (15 ft) of thick-bedded marine calcilutite with invertebrate and phylloid algae fossils.

Southward into the detrital facies belt along US–160 (Coon Creek section) and around Timber Hill, the South Bend Limestone Member thins to 1.2–1.5 m (4–5 ft) of yellowish- to orange-weathering skeletal calcilutite. The lower 0.3–0.6 m (1–2 ft) is a coarse-grained sandstone that is locally oolitic and conglomeratic and grades upward into skeletal calcilutite.

The contact between the South Bend Limestone Member and the Rock Lake Shale Member is sharp and erosional where the top of the Rock Lake is shale (Heckel, 1975b) and where conglomeratic quartz sandstone overlies the top of the Onion Creek sandstone (fig. 9). The contact seems to be gradational in other outcrops, such as along the road cut along the east line of NE sec. 26, T. 32 S., R. 14 E. The upper contact of the South Bend Limestone Member with fossiliferous shale of the Weston Shale Member (Stranger Formation) is sharp in both the algal-mound and detrital facies belts.

Subsurface stratigraphy in the detrital facies belt

I used electric logs and drillers' logs furnished by the Kansas Geological Survey to construct a series of maps and cross sections of the Stanton interval in the near subsurface of western Montgomery and eastern Chautauqua counties (fig. 2). Neither drillers' logs nor lithology logs were available for any of the wells for which electric logs were available. Therefore I interpreted rock types in wells by comparing the exposed outcrop sequences with electric-log signatures in nearby wells (fig. 10). Four different types of rock can be identified on the electric logs [based on resistivity and spontaneous potential (SP) signatures]: limestone, sandstone, shale, and mixed rock. Mixed rock is interpreted as a mixture of silty shale and shaly sandstone.

Structure

I constructed a structural contour map (fig. 11) for the top of the South Bend Limestone Member, which is the most easily traced unit in the subsurface. The map indicates that strata in this part of Kansas dip generally toward the west about 5 m/km (26.5 ft/mi), as previously demonstrated on surface exposures by Heckel (1975b) and in the subsurface by Winchell (1957b, plate 2B). An anticlinal structure in the south end of the algal-mound facies belt probably is related to the topography of the South Bend mound (Heckel and Cocke, 1969, p. 1073). Three major anticlinal structures are shown west of the outcrop in the detrital facies belt. One, in the southwestern part of T. 32 S., R. 14 E., is possibly related to thickening of the Onion Creek sandstone in this area. Whether the other two structures (southeastern part of T. 32 S., R. 12 E., and west-central part of T. 33 S., R. 13 E.) are related to thickening of sandstone bodies within the Rock Lake Shale Member is not certain because of insufficient

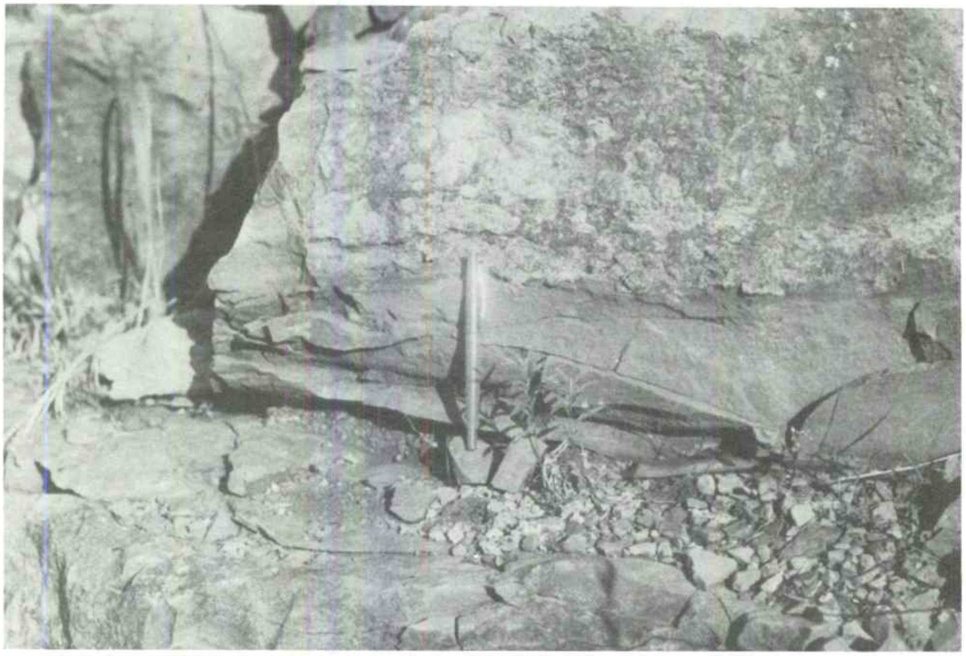


FIGURE 9—Sharp contact between conglomeratic quartz sandstone of South Bend Limestone Member (above pen) and smooth brown sandstone of Rock Lake Shale Member (behind pen) at Coon creek section along US–160 (Moussavi–Harami, 1980, appendix C, section 25).

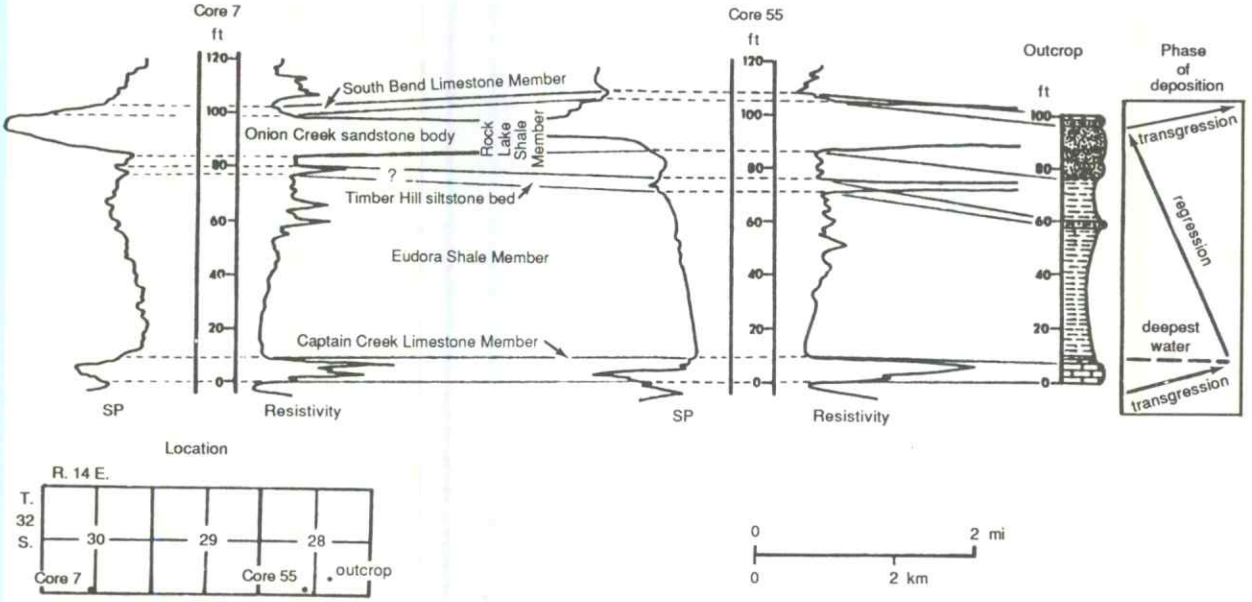


FIGURE 10—Relationship between different rock units of Stanton Limestone in outcrop (Coon Creek section) and nearby electric logs. Distance between outcrops and electric logs not to scale. Datum is base of Captain Creek Limestone Member.

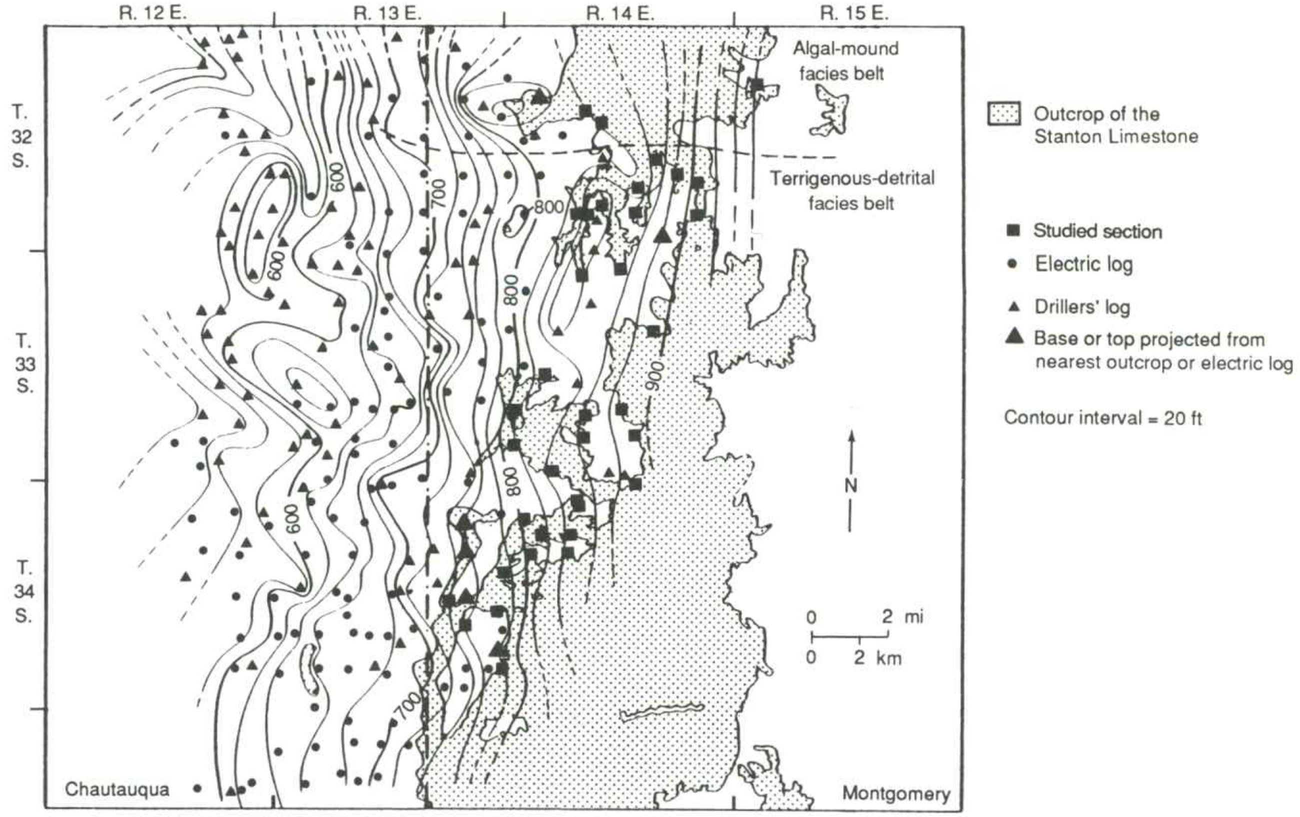


FIGURE 11—STRUCTURAL CONTOUR MAP (in feet) on top of South Bend Limestone Member of Stanton Limestone in southern Kansas. Datum is mean sea level.

data. However, no anticlinal structure is present to the south (T. 34 S., R. 13 E.), where a thick sandstone body is known in the subsurface.

Thickness

The thickness of subsurface Stanton Limestone in the detrital facies belt ranges from less than 27 m (89 ft) to as much as 54 m (177 ft) (fig. 12). It is more than 48 m (157 ft) thick at the south end of the algal-mound facies belt, where most of the unit is limestone. The Stanton Limestone thins southward to 27 m (89 ft) locally in the northern part of the detrital facies belt (southern T. 32 S. and T. 33 S.). It is locally more than 33 m (108 ft) thick in the southwestern part of T. 32 S., R. 14 E.; this may be related to thickening of the Onion Creek sandstone, as seen in outcrops to the east. The Stanton Limestone thickens southward to more than 54 m (177 ft) in T. 34 S. because of thickening of the Rock Lake sandstones, one of which cuts through the lower members of the Stanton Limestone in this area. Further southward thinning of the Stanton Limestone in T. 35 S. probably relates to thinning of the Rock Lake sandstone and southward replacement mostly by shale of the Eudora–Rock Lake interval, as exposed in new road cuts north and west of Copan, Oklahoma (Heckel, personal communication, 1980).

Sandstone distribution

A new sand isolith map of the Rock Lake Shale Member (fig. 13) indicates two major sandstone areas: one in T. 33 S., with a thickness of more than 15 m (49 ft) [the Onion Creek sandstone body of Heckel (1975b)], and the other in T. 34 S., with a thickness of more than 24 m (79 ft), as yet unnamed. Both major sandstone areas and adjacent lobes have a southeast-northwest alignment, thinning toward the northwest.

The Onion Creek sandstone thins northward and disappears at the boundary between the detrital facies belt and the algal-mound facies belt where the limestone units of the Stanton Limestone thicken abruptly northward. Both lobes of the subsurface Onion Creek sandstone in T. 32 S. and T. 33 S. reflect local thickening of the exposed Onion Creek sandstone in this area. Southward the Onion Creek sandstone thins from more than 15 m (49 ft) to 3 m (10 ft) in southern T. 33 S.

The major sandstone area in T. 34 S., which comprises upper and lower sandstone bodies in wells 134 and 138 (fig. 14), probably includes much of the exposed sandstone in southern Montgomery County. It aggregates more than 24 m (79 ft) in T. 34 S. and thins northward to less than 9 m (30 ft) toward the Onion Creek body. It thins southward to 15 m (49 ft) before thickening again to more than 18 m (59 ft) as a

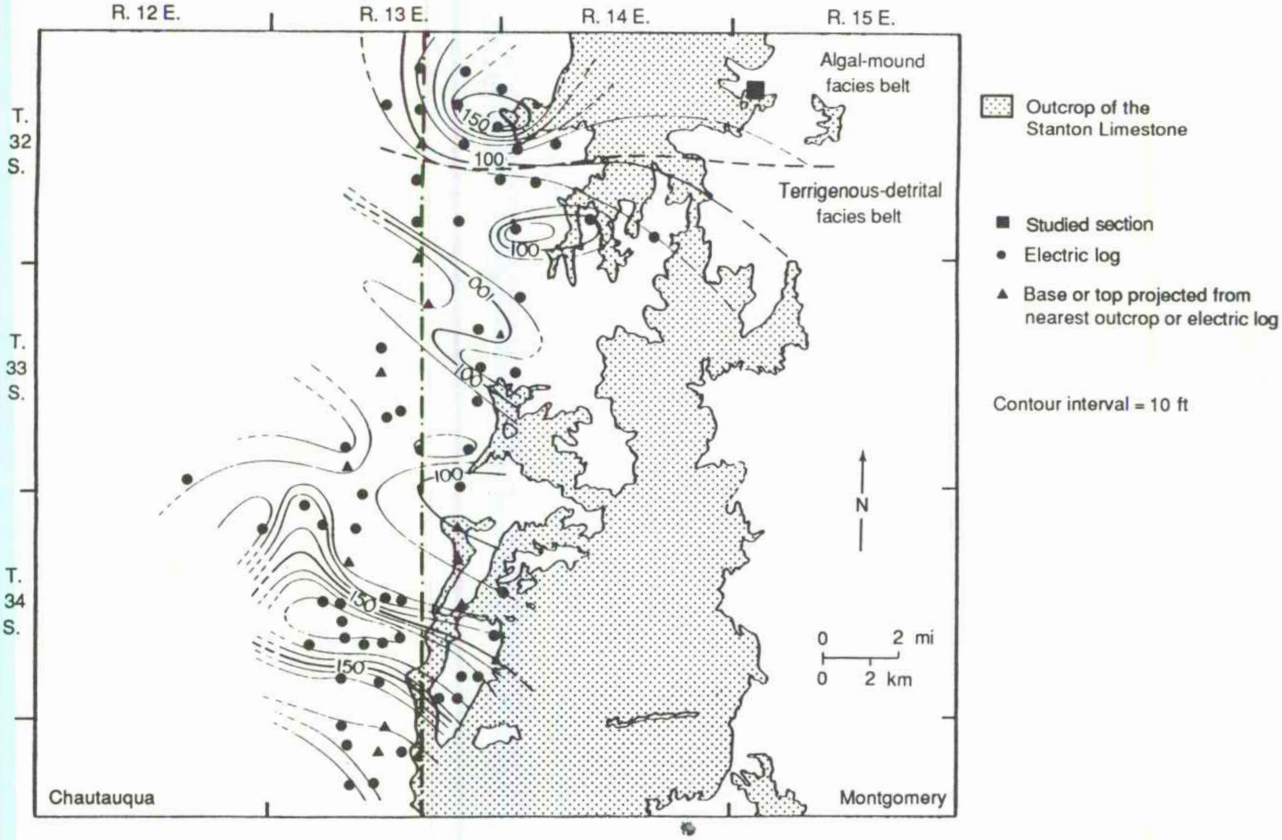


FIGURE 12—NET ISOPACH MAP (in feet) of Stanton Limestone in southern Kansas. Interval shown lies between base of Captain Creek Limestone Member, Tyro bed, or sandstone cutting through Tyro bed and top of South Bend Limestone Member.

southern lobe in T. 35 S. This southern lobe is related to thickening of only the upper sandstone in wells 134 and 138 in the southern detrital belt (fig. 14). The sandstone then thins southward into Oklahoma, and little is seen in the Stanton Limestone interval exposed around Copan.

Stratigraphy

A north-south cross section (fig. 14) was constructed along the subsurface strike of the Stanton Limestone in eastern Chautauqua County about 3–8 km (2–5 mi) west of the outcrop. Correlation is mainly lithostratigraphic, and the easily recognized base of the South Bend Limestone Member is used for the datum.

The subsurface cross section closely reflects the major facies changes observed in the outcrop. The two northernmost wells (36 and 37) penetrate a Stanton interval dominated by carbonate rock in the south end of the algal-mound facies belt. The southern 15 wells (39 to 107) penetrate a Stanton interval dominated by sandstone and mixed rock, with several individual sandstone bodies evident (units A–E, fig. 14). All outcropping members of the Stanton Limestone were recognized on the subsurface cross section.

The Captain Creek Limestone Member thins from 13.5 m (44 ft) in the algal-mound facies belt to 3.6 m (12 ft) southward into the detrital facies belt, just as it does along the outcrop. It can be traced with no difficulty southward through T. 32 S. Wells 43, 44, and 46 apparently do not penetrate far enough to identify the Captain Creek limestone in northern T. 33 S. The Captain Creek Limestone Member is recognized in southern T. 33 S. as 0.9 m (3 ft) of limestone in wells 47 and 147, but the next two wells southward (143 and 142) in northern T. 34 S. do not indicate limestone. Just to the south, however, a higher resistivity value at this horizon in well 139 may indicate the appearance of the Tyro oolite, which crops out eastward at about this latitude. (If the low resistivity and SP values in wells 142 and 143 are related less to facies change than to changes in porosity and chemical fluid within the rock unit, then the Captain Creek Limestone Member may be continuous with the Tyro oolite in this area without intervening shale or siltstone. In the absence of enough information to evaluate this subsurface data, the outcrop data is assumed to provide the best interpretation for the Captain Creek–Tyro relationship in the subsurface.) Southward the Tyro oolite can be traced in the subsurface to the Oklahoma border, as it can in the outcrop, except in the middle of T. 34 S. (wells 138 and 134), where the southern thick sandstone unit (A) of the Rock Lake Shale Member cuts both the Eudora Shale Member and the Tyro oolite.

Good resolution on electric logs allows the Eudora Shale Member to be identified with little difficulty. It ranges from 0.9 m to 1.8 m (3–6 ft) in thickness between two limestones in the south end of the algal-mound facies belt. Southward

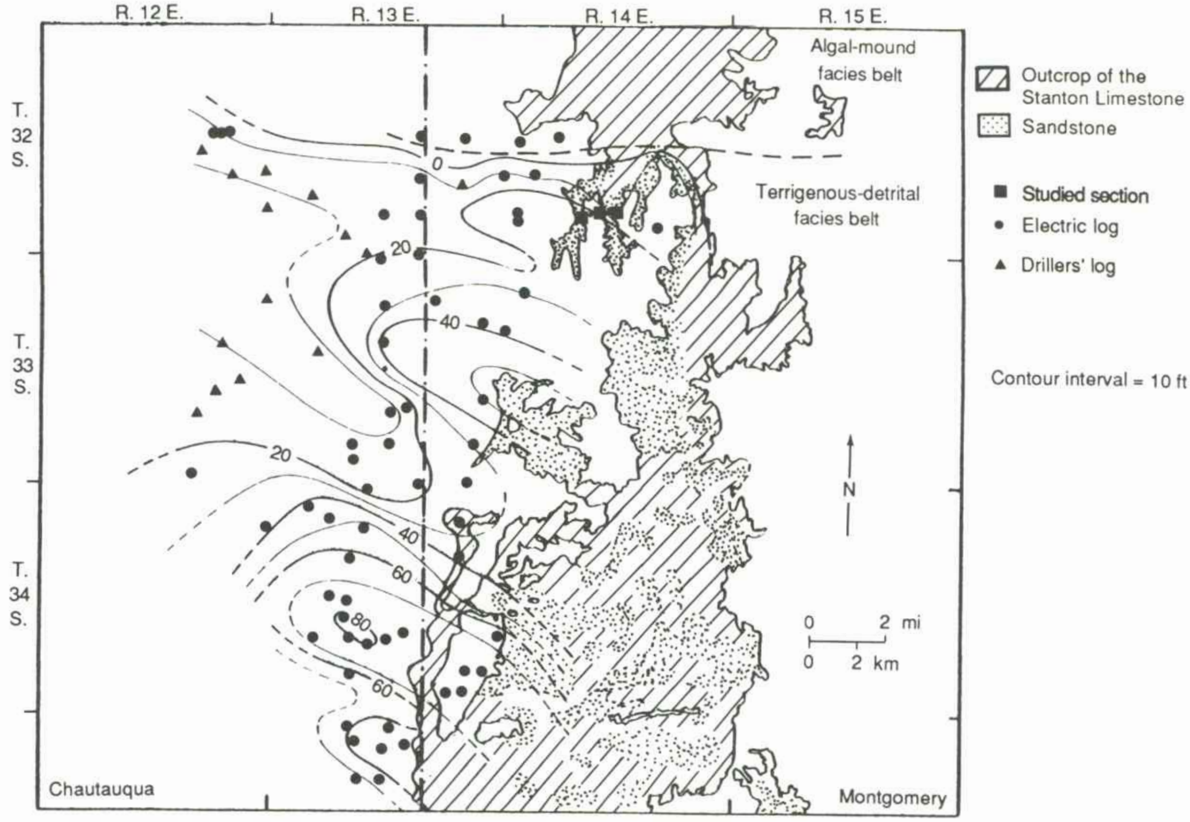


FIGURE 13—NET SAND ISOLITH MAP (in feet) of Rock Lake Shale Member of Stanton Limestone in southern Kansas. Distribution of sandstone in outcrop is modified slightly from Heckel (1975b) (see also fig. 14).

into the detrital facies belt, the Eudora Shale Member thickens to 6 m (20 ft) in well 39 and to 9 m (30 ft) in well 40. Although wells 43, 44, and 46 do not penetrate the entire Eudora shale, it is at least 2.4–6 m (8–20 ft) thick in northern T. 33 S. It thins to 1.5 m (5 ft) in well 47, where the underlying Captain Creek Limestone Member reappears, and it retains this thickness to the Oklahoma border, except where it is cut by Rock Lake sandstone in wells 134 and 138 in T. 34 S. The general pattern of southward thinning of the Eudora Shale Member is also seen in the outcrop, where thick gray shale overlies black shale in the north and thinner dark-gray shale occurs to the south.

The Stoner Limestone Member is found only in wells 36 and 37 at the south end of the algal-mound facies belt. It thins and disappears southward into mixed rock of the Rock Lake Shale Member and shale of the Eudora Shale Member as it does in the outcrop.

The Rock Lake Shale Member in well 36 in the algal-mound facies belt is about 3 m (10 ft) of mixed rock. It begins thickening southward to 7.2 m (24 ft) in well 37 at the south end of the algal-mound facies belt and reaches 15–51 m (49–167 ft) thick in the detrital facies belt, where it consists predominantly of sandstones and mixed rock. Five different sandstone units can be recognized in the subsurface Rock Lake Shale Member (fig. 14) in the detrital facies belt. They are described, partly in ascending stratigraphic order, in what follows.

Unit A, a thick sandstone, occupies the lower part of the Stanton Limestone in T. 34 S. where its central part cuts the Eudora Shale Member and Tyro oolite in wells 134 and 138. It grades upward into alternating sandstone and mixed rock. Abrupt changes of resistivity and SP values within the sandstone unit suggest occasional lenses of shale within the sandstone, as seen in outcrops. Unit A thins southward from 34 m (112 ft) in well 134 to 17.4 m (57 ft) in well 90 and is replaced by mixed rock in well 107 near the Oklahoma border. It also thins northward (well 139) and may correlate with the lower part of sandstone unit D in well 142. Unit A is possibly an extension of the thick sandstones low in the Stanton Limestone exposed along Cheyenne Creek in T. 34 S., R. 14 E., and the massive crossbedded sandstone exposed in the top of the Tyro quarry (Moussavi-Harami, 1980, appendix C, sections 8 and 9). Stratigraphically, this thick sandstone unit is the oldest major sandstone within the Stanton Limestone.

Unit B (fig. 14) is best developed in wells 107 and 90 in T. 35 S., where it is 10.5–15 m (34–49 ft) thick. It overlies mixed rock, which in well 90 lies above unit A. It is overlain by a thin sequence of mixed rock below the South Bend Limestone Member. Unit B thins northward and is replaced by mixed rock and thin sandstone of unit C. Unit B is possibly an extension of the exposed thick sandstone body that forms the two hills north of the Oklahoma border in secs. 16 and 17, T. 35 S., R. 14 E. This unit is definitely younger than unit A and is probably older than most of unit C in wells to the north.

Unit C is a rather thin sandstone [7 m (23 ft)] that formed at the top of the Rock Lake Shale Member above unit A in T. 34 S. It is directly overlain by the South Bend limestone and thus is stratigraphically the highest and probably the youngest sandstone unit formed in this part of the detrital facies belt. It is likely that unit C formed from northward shifting of the sand sources responsible for unit B and perhaps from southward shifting of the sand sources responsible for unit D (well 142).

Unit D is a thick sandstone (fig. 14) and is apparent only in well 142. It thins from 21 m (69 ft) both southward and northward, into alternating sandstone and mixed rock. The presence of a thin sequence of mixed rock at the top of unit D indicates that this unit probably formed at roughly the same time as unit B to the south but before unit C. Although unit D is stratigraphically higher and mostly younger than unit A, the lower part of unit D may be equivalent to the upper part of unit A. This suggests that unit D may have formed by northward shifting of the major sand source responsible for unit A. Although unit D is not definitely recognized in outcrops, it is replaced northward in the subsurface by alternating thin lenses of sandstones and mixed rock, possibly the thin interbedded shale and sandstone seen in outcrops along US–75 east of Wayside at about this latitude.

Unit E, up to 13.5 m (44 ft) thick, is present at the top of the Rock Lake Shale Member beneath the South Bend Limestone Member farther north in northern T. 33 S. and southern T. 32 S. This is probably the eastern subsurface extension of the Onion Creek sandstone. The absence of mixed rock between this sandstone and the overlying South Bend Limestone Member suggests that unit E and unit C are the youngest sandstones in the Rock Lake Shale Member and that they formed at roughly the same time. (Although some drillers' logs indicate that unit E is replaced by a thick sequence of limestone between T. 32 S. and T. 33 S., it is likely that these particular drillers mistook Stanton chips for limestone because some drillers' logs show limestone next to outcropping sandstone.) The lower part of the Rock Lake Shale Member in T. 32 S. and T. 33 S. is primarily mixed rock, possibly silty shale, as seen in outcrop along US–160.

The South Bend limestone is easily recognized in all wells in the cross section (fig. 14), marking the top of the Stanton–Rock Lake interval throughout the detrital facies belt in Kansas. It thins from 7.5 m (25 ft) in well 36 (probably algal-mound facies as in outcrops) southward in T. 32 S. to 1.2–1.5 m (4–5 ft), just as it does at this latitude along the outcrop. It rests directly on Rock Lake unit E (Onion Creek sandstone) in southern T. 32 S. and northern T. 33 S., on unit C in central T. 32 S., and on mixed rock of the Rock Lake Shale Member elsewhere. The South Bend Limestone Member is overlain conformably by the Weston Shale Member of the Stranger Formation. Although Winchell (1957a,b) reported an erosional unconformity between the Tonganoxie Sandstone Member of the Stranger Formation and the Lansing Group (Stanton Limestone) in south-central Kansas, Ball (1964) noted that the erosional unconformity at the base of the Tonganoxie member in northeastern Kansas is not continuous and that the Weston shale rests conformably on the South Bend limestone in southern Kansas. Present subsurface tracing of the South Bend Limestone Member across the detrital belt supports Ball's (1964) interpretation.

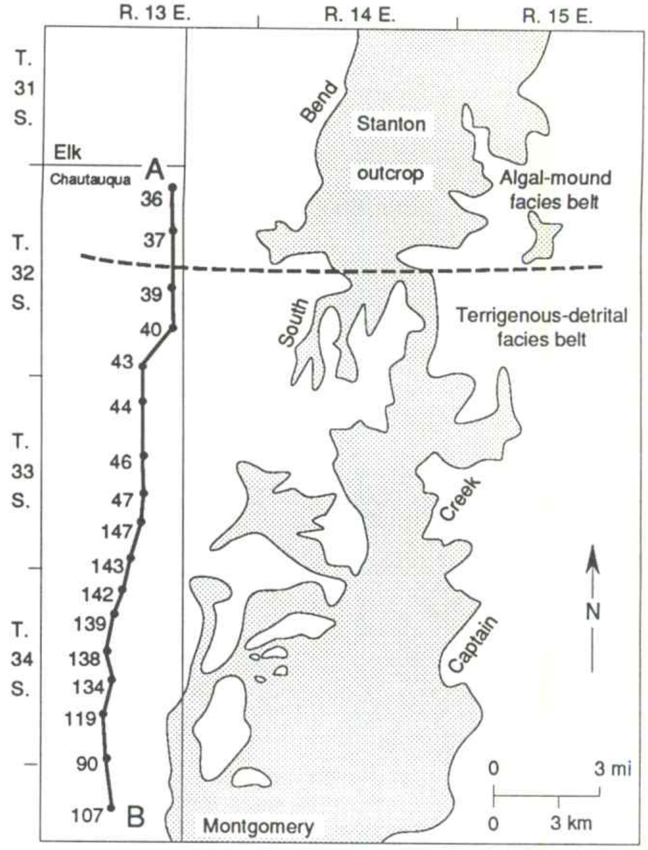
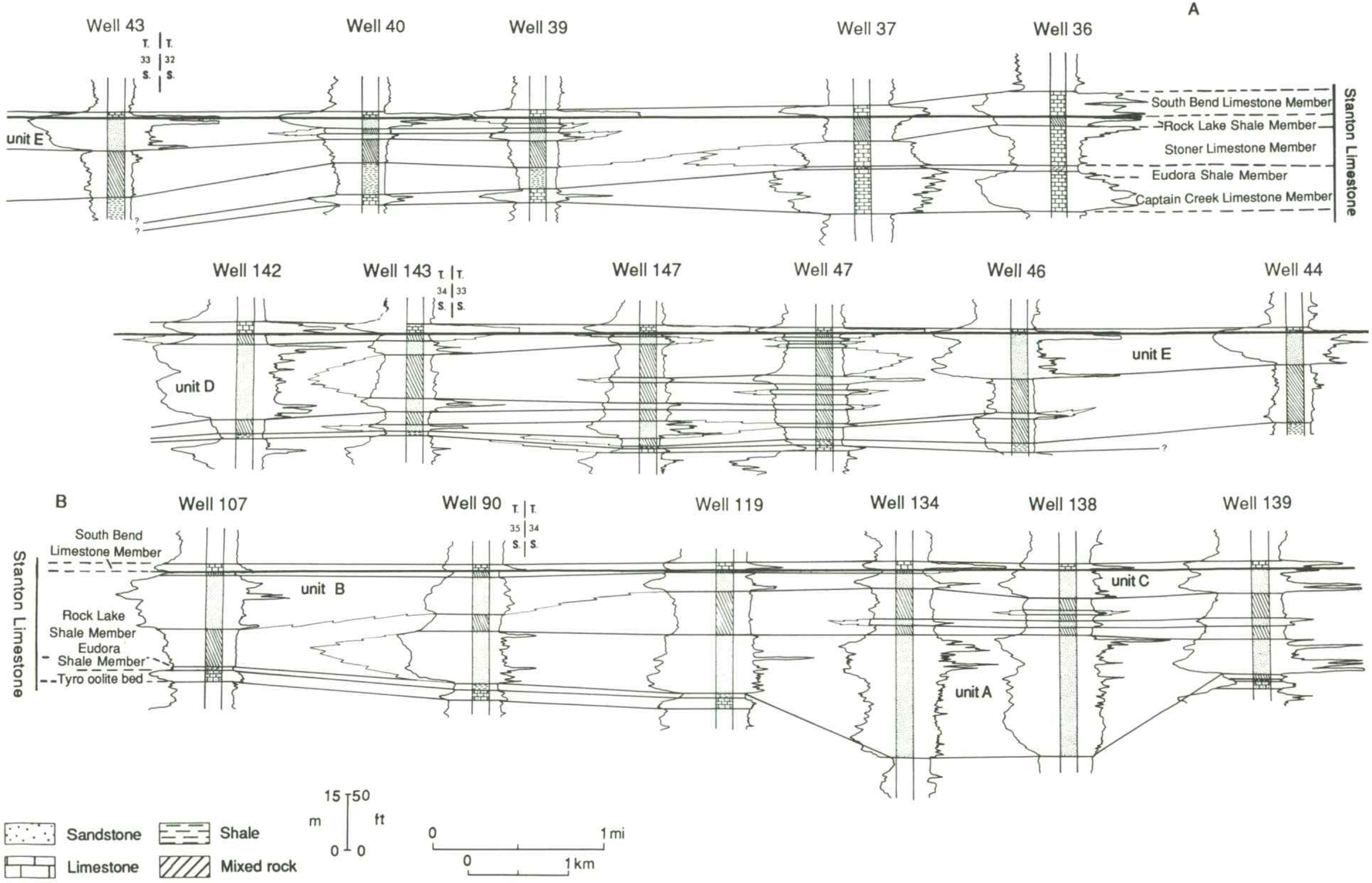


FIGURE 14 (above and opposite)—SUBSURFACE CORRELATION OF THE STANTON LIMESTONE in the detrital facies belt. Datum is the base of the South Bend Limestone Member. Lettered units refer to described sandstone units in the Rock Lake Shale Member.

The Timber Hill, Rutland, and Bolton beds are difficult to recognize in the subsurface (fig. 14). These thin siltstone and limestone beds either pinch out westward into Rock Lake sandstone and shale or become too thin to be resolved by logging tools. Figure 10, however, indicates that the Timber Hill bed can be detected up to 3.2 km (2 mi) west of its outcrop in the electric logs of wells 55 and 7. Where these beds are not recognized in the subsurface in the detrital facies belt, the Eudora Shale Member is differentiated from the Rock Lake Shale Member as a basal shale in a sequence that grades upward into mixed rock and sandstone.

Calcareous zones, such as the third and fourth oolites, exposed along the outcrop in southern Montgomery County,


A
Well 43
T. 33 S. | T. 32 S.
Well 40
Well 39
Well 37
Well 36
unit E
Stanton Limestone
South Bend Limestone Member
Rock Lake Shale Member
Stoner Limestone Member
Eudora Shale Member
Captain Creek Limestone Member
?
?
Well 142
Well 143
T. 34 S. | T. 33 S.
Well 147
Well 47
Well 46
Well 44
unit D
unit E
?
B
Well 107
Well 90
T. 35 S. | T. 34 S.
Well 119
Well 134
Well 138
Well 139
Stanton Limestone
South Bend Limestone Member
Rock Lake Shale Member
Eudora Shale Member
Tyro oolite bed
unit B
unit C
unit A
Sandstone
Shale
Limestone
Mixed rock
m 15 0
ft 50 0
0 1 mi
0 1 km

also were not recognized in the subsurface. Although some high resistivities on logs in the southern part of the detrital facies belt might be interpreted as calcareous, they lack sufficient continuity to be interpreted as marker horizons. Thus they probably represent low-porosity calcite-cemented sandstones similar to those observed at various stratigraphic levels in the outcrops.

Petrographic analysis

For this study I examined 152 thin sections of sandstone and siltstone samples from the Rock Lake Shale Member of the Stanton Limestone. The siliciclastic components of these rocks consist mainly of monocrystalline and polycrystalline quartz, with minor amounts of orthoclase, plagioclase, microcline, muscovite, zircon, and tourmaline. Petrographically, sandstones of the Rock Lake Shale Member are all quartzarenites [classification of Folk (1974)], with quartz grains averaging more than 97% of all detrital grains (table 1).

Components

Grains

Monocrystalline quartz is the dominant component, averaging more than 78%. These grains vary in average size among samples from very fine grained to medium-grained sand. Most grains are clear, with less than 10% containing inclusions or fractures. About two-thirds of the quartz grains show unit extinction, and the remainder show undulatory extinction. Silt-size quartz grains are the dominant component of the siltstone beds.

The polycrystalline quartz grains are well rounded and vary from very fine grained to fine-grained sand, making up 2% of the sandstones (table 1). Most of the polycrystalline grains are smaller crystals of uniform size, but some contain several crystals of different sizes that are stretched (foliated) and contain strongly sutured intercrystalline boundaries. These foliated textures suggest a metamorphic origin.

The only other significant detrital rock fragment type in Rock Lake sandstones are well-rounded, fine-grained sand-size chert grains, which constitute about 1% of the grains in the sandstones.

Feldspar is the second most abundant mineral in the sandstones but constitutes only up to 3% of the grains in any one sample (table 1). Untwinned orthoclase, twinned plagioclase, and microcline are all present in small amounts. Most of the feldspar grains show various stages of alteration to clay minerals.

Muscovite commonly occurs as an accessory mineral in Rock Lake sandstones but never exceeds 0.5% of any one sample (table 1). Elongated rectangular flakes of muscovite, ranging from 0.05 mm to 0.2 mm, are usually found oriented parallel to bedding planes. However, some of the flakes are bent around more compact siliciclastic grains, indicating that they were deformed during compaction (fig. 15a).

Zircon and tourmaline are the only heavy minerals found in the sandstones. Zircon occurs in trace amounts in most samples; tourmaline (in trace amounts) was found in only 7 of 25 samples analyzed (table 1).

Carbonate grains, such as oolites, coated grains, and skeletal fragments of marine organisms (mostly echinoderm, brachiopod, bryozoan, and mollusk), are present in a few samples of fine-grained sandstones (fig. 15b) in the lower part of the Rock Lake Shale Member in southern Montgomery County (table 1). Pyrite has replaced calcite in some of the skeletal fragments (fig. 15b). Carbonate grains were not found in the upper massive sandstones of southern Montgomery County nor in the Onion Creek sandstone. Thin sections of core samples from the northern channels of Wilson and Woodson counties show a few scattered skeletal fragments. These were observed in outcrop samples only in SE sec. 26, T. 26 S., R. 16 E., in the Woodson County channel and in the basal channel lag from a small side channel to the Wilson County channel in section K–47 (Moussavi–Harami, 1980, appendix C, section 28).

In terms of grain components, the Rock Lake sandstones are quite mature compared with other sandstones recently studied in the midcontinent. Missourian sandstones from lower cycles (Wyandotte, Iola) in the Kansas City region (Verhulst, 1970) and Desmoinesian sandstones from much older cycles in southeastern Kansas (Reinholtz, 1982; Worthington, 1982) contain significantly greater amounts of rock fragments, feldspar, and mica relative to quartz.

Cements

Four different types of cement are present in Rock Lake sandstone units: calcite, iron oxide (limonite), sericite, and silica (table 1). Calcite is the dominant cement in many of these rocks, accounting for up to 41% of some samples. It is more abundant in surface samples of the lower sandstones than in the upper massive sandstones there and the Onion Creek sandstone in Montgomery County. Thin sections from cores I, J, and K (in the northern channels in Wilson and Woodson counties) and from the Trico Production Company (Onion Creek sandstone), however, show that calcite cementation is also important in the upper rocks in the subsurface. Much of the calcite cement shows a poikiloblastic fabric, in which single cement crystals encompass numerous sand grains (fig. 15c). In some samples detrital grains seem to "float" within the calcite cement, indicating that early cementation preceded compaction.

Iron oxide (limonite) is the second most abundant cement, occurring in most samples in amounts up to 4.5%. It forms coatings around grains and fills pore spaces. Limonite is relatively abundant in thin sections from surface exposures but is quite rare in subsurface samples. This indicates that iron oxide may be primarily a modern weathering product.

Sericite is present in most of the thin sections studied, occurring mainly as coatings around quartz grains. It also fills some of the pore spaces between detrital grains and is associated with altered feldspar (fig. 15d). Silica is present as quartz overgrowths on detrital grains (fig. 16a) and as chert replacing calcite.

TABLE 1—MODAL ANALYSIS DATA from 25 selected thin sections (200 points per thin section) representing different sandstone facies in the Rock Lake Shale Member.

	Quartz			Feldspar				
Sample	**Monocrystalline unit extinction**	**Monocrystalline undulatory extinction**	**Polycrystalline**	**Orthoclase**	**Plagioclase**	**Microcline**	**Chert**	**Muscovite**
Southern Montgomery Co.								
R.3–4	43.0	14.0	2.0	T	0.5	–	1.0	T
R.3–7	59.0	32.0	1.5	T	T	–	1.0	T
R.3–11	58.5	27.5	1.5	1.5	1.0	T	1.0	T
R.5–1	63.5	31.5	1.0	0.5	T	–	T	T
R.5–2	65.0	29.5	1.5	0.5	T	–	0.5	T
R.5–3	62.5	32.5	1.5	T	0.5	–	0.5	T
R.8–4	51.5	34.5	4.0	2.0	0.5	–	1.0	0.5
R.15–2	30.0	18.5	4.0	1.0	0.5	–	1.0	–
R.15–4	61.5	22.5	1.0	2.5	0.5	–	0.5	T
Average	54.88	26.94	2.0	0.88	0.38	T	0.72	0.05
Onion Creek								
R.27–1	47.5	34.0	3.0	0.5	T	–	0.5	T
R.27–2	46.5	22.5	2.5	T	T	–	1.0	–
R.20–1	43.0	16.0	4.0	T	T	–	1.0	T
R.20–6	62.0	24.0	2.0	0.5	T	–	2.0	T
R.20–7	63.0	26.5	2.0	0.5	T	–	2.0	T
R.20–8	59.5	29.0	1.5	1.0	T	–	1.5	T
R.2A–430	73.0	14.0	3.0	T	T	–	1.0	T
Average	56.35	23.71	2.57	0.35	T	–	1.28	T
Wilson Co. channel								
R.28–1	53.5	16.0	2.5	T	0.5	–	1.5	T
R.28–2	60.0	26.0	2.5	0.5	T	–	2.0	T
R.28–3	58.5	33.5	0.5	T	T	–	0.5	T
K–39	42.0	29.5	3.0	0.5	T	–	0.5	T
K–40.5	49.0	37.5	1.5	1.0	1.0	–	0.5	0.5
Average	52.6	28.5	2.0	0.4	0.3	–	1.0	0.1
Woodson Co. channel								
I–37.4	40.5	20.0	1.0	T	T	–	0.5	T
I–44.4	36.5	21.0	0.5	0.5	T	–	T	T
J–28.7	37.5	22.5	1.0	T	0.5	–	1.0	T
J–31	41.0	22.5	3.0	1.0	0.5	–	0.5	T
Average	38.87	24.0	1.37	0.37	0.25	–	0.5	T
Total Average	52.28	25.88	2.06	0.56	0.24	–	0.9	0.04

Sample	Heavy minerals		Skeletal fragments	Oolite	Coated grains	Cement				Clay	Percentage of quartz within total detrital grains in each thin section
	Zircon	Tourmaline				Calcite	Limonite	Sericite	Silica		
Southern Montgomery Co.											
R.3–4	T	–	0.5	–	–	39.0	–	–	–	–	97.5
R.3–7	T	T	–	–	–	–	3.5	1.0	0.5	1.5	98.9
R.3–11	0.5	T	–	–	–	0.5	3.0	2.5	0.5	2.0	95.6
R.5–1	T	–	–	–	–	–	1.0	2.0	–	0.5	99.48
R.5–2	T	T	–	–	–	–	T	1.5	1.0	0.5	98.96
R.5–3	T	T	–	–	–	–	T	1.5	–	1.0	98.97
R.8–4	T	–	–	–	–	–	1.5	2.5	1.0	1.0	95.7
R.15–2	T	–	1.5	2.5	5.0	37.0	–	–	–	–	95.4
R.15–4	T	–	–	–	–	–	6.0	3.0	1.0	2.0	96.0
Average	0.05	T	0.22	0.27	0.55	8.5	1.66	1.55	0.44	0.94	97.39
Onion Creek											
R.27–1	T	–	–	–	–	7.5	4.5	2.0	–	0.5	98.83
R.27–2	T	T	–	–	–	24.5	2.5	0.5	–	–	98.62
R.20–1	T	–	T	–	–	36.0	T	–	–	–	98.4
R.20–6	T	–	–	–	–	–	5.5	2.5	1.5	–	97.2
R.20–7	T	–	–	–	–	–	2.0	3.0	–	1.0	97.3
R.20–8	T	T	–	–	–	–	3.5	2.0	0.5	1.5	97.3
R.2A–430	T	–	–	–	–	9.0	T	T	–	–	98.9
Average	T	T	–	–	–	11.0	2.57	1.35	0.35	0.42	98.07
Wilson Co. channel											
R.28–1	T	T	T	–	–	21.0	4.5	0.5	–	–	97.2
R.28–2	T	–	–	–	–	–	4.0	4.5	0.5	–	97.25
R.28–3	T	–	–	–	–	–	4.0	1.5	0.5	1.0	99.4
K–39	–	–	T	–	–	22.0	–	1.0	1.5	–	98.93
K–40.5	–	–	–	–	–	1.5	–	3.0	3.5	1.0	96.7
Average	T	T	T	–	–	8.9	2.5	2.1	1.2	0.4	97.87
Woodson Co. channel											
I–37.4	T	–	–	–	–	38.0	–	–	–	–	99.19
I–44.4	–	–	–	–	–	41.0	–	–	0.5	–	99.14
J–28.7	T	–	–	–	–	37.5	–	T	–	–	97.6
J–31	T	–	–	–	–	16.0	–	1.5	2.5	1.5	97.45
Average	T	–	–	–	–	33.12	–	0.37	0.75	0.37	98.34
Total Average	0.02	T	0.08	0.1	0.2	13.22	1.82	1.44	0.62	0.6	97.83

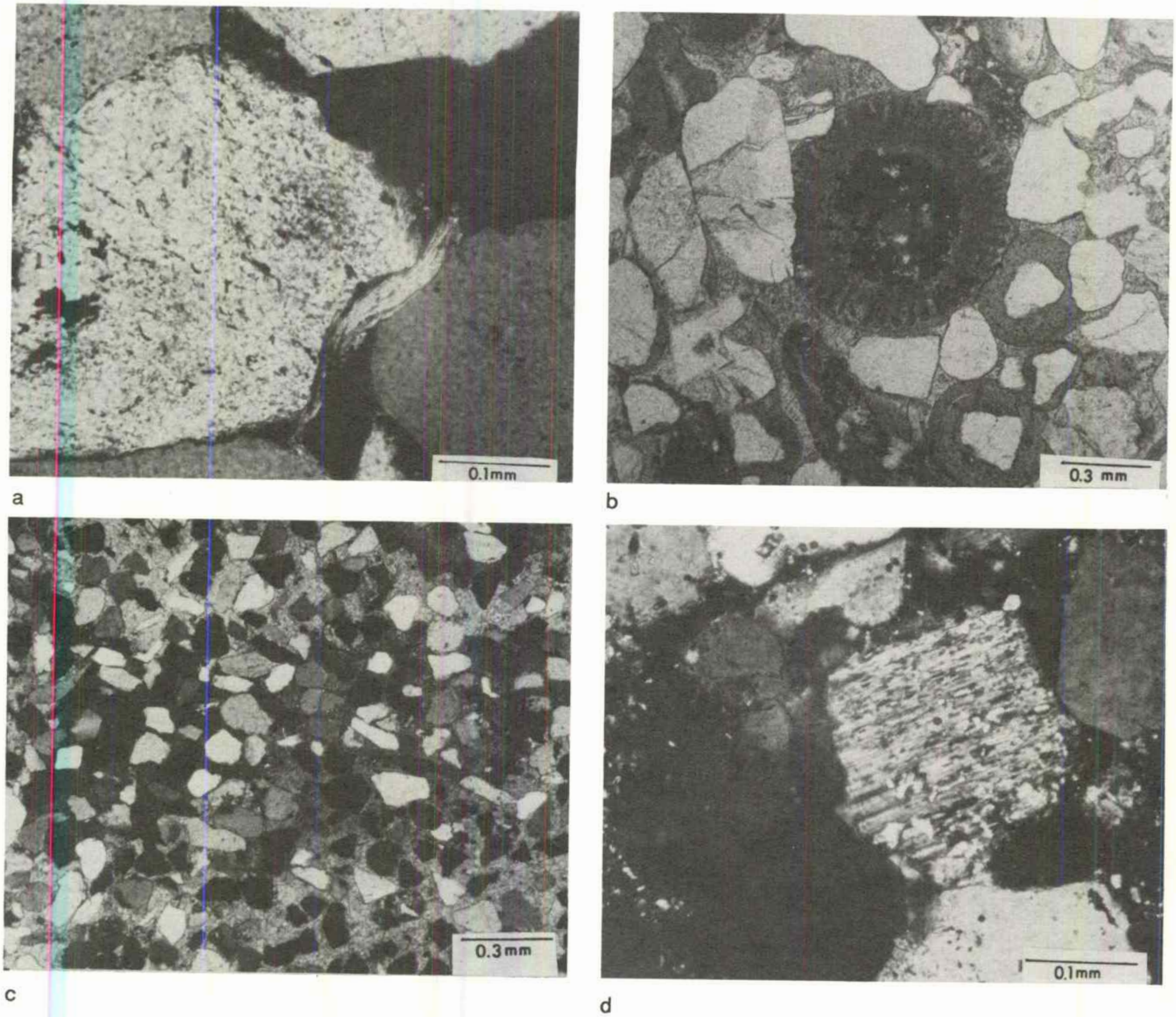


FIGURE 15—Photomicrographs showing petrographic characteristics of Rock Lake sandstone units. (a) Deformed muscovite flake bent around quartz grains; sample K–39; cross-polarized light. (b) Pervasive calcite-cemented quartzarenite with echinoderm fragments and coated grains; note replacement of calcite by pyrite in middle of echinoderm fragment and filling of fractures in quartz grain with calcite cement; sample R.9–2; plane-polarized light. (c) Poikiloblastic cementation texture; many detrital grains appear to be "floating" in single crystal of coarse calcite cement; sample R.3–4; cross-polarized light. (d) Very fine sand-sized plagioclase feldspar grain partially altered to sericite; sample J–31; cross-polarized light.

Matrix

Clay is present as a matrix. It makes up as much as 2.0% of some thin sections but averages less than 1% of the rock (table 1). It is possible that most of the clay in these rocks is authigenic and formed during the alteration of feldspar. Most of the apparently authigenic clay in these rocks occurs as pore fillings, pore linings, and pseudomorphic replacements of feldspar grains similar to those illustrated by Wilson and Pittman (1977). Schroeder (1967) reported that some clay minerals in algal-mound facies and associated limestones of Woodson and Wilson counties are dickite and kaolinite. X-ray diffraction analyses indicate that the white powdery clay in the sandstones of cores I, J, and K is dickite.

Thin sections from two core samples from a well in the northern end of the detrital facies belt (SE sec. 14, T. 32 S., R. 12 E.) supplied by the Trico Production Company show the presence of intergranular oil.

Textures

I measured the average grain size petrographically in 88 samples of Rock Lake sandstone using the loose-grain analysis method of Griffiths (1967). Measurement of 50 monocrystalline quartz grains in each sample indicates that the average grain size in these rocks varies between 0.0625 mm (very fine grained sand) and 0.5 mm (medium-grained sand).

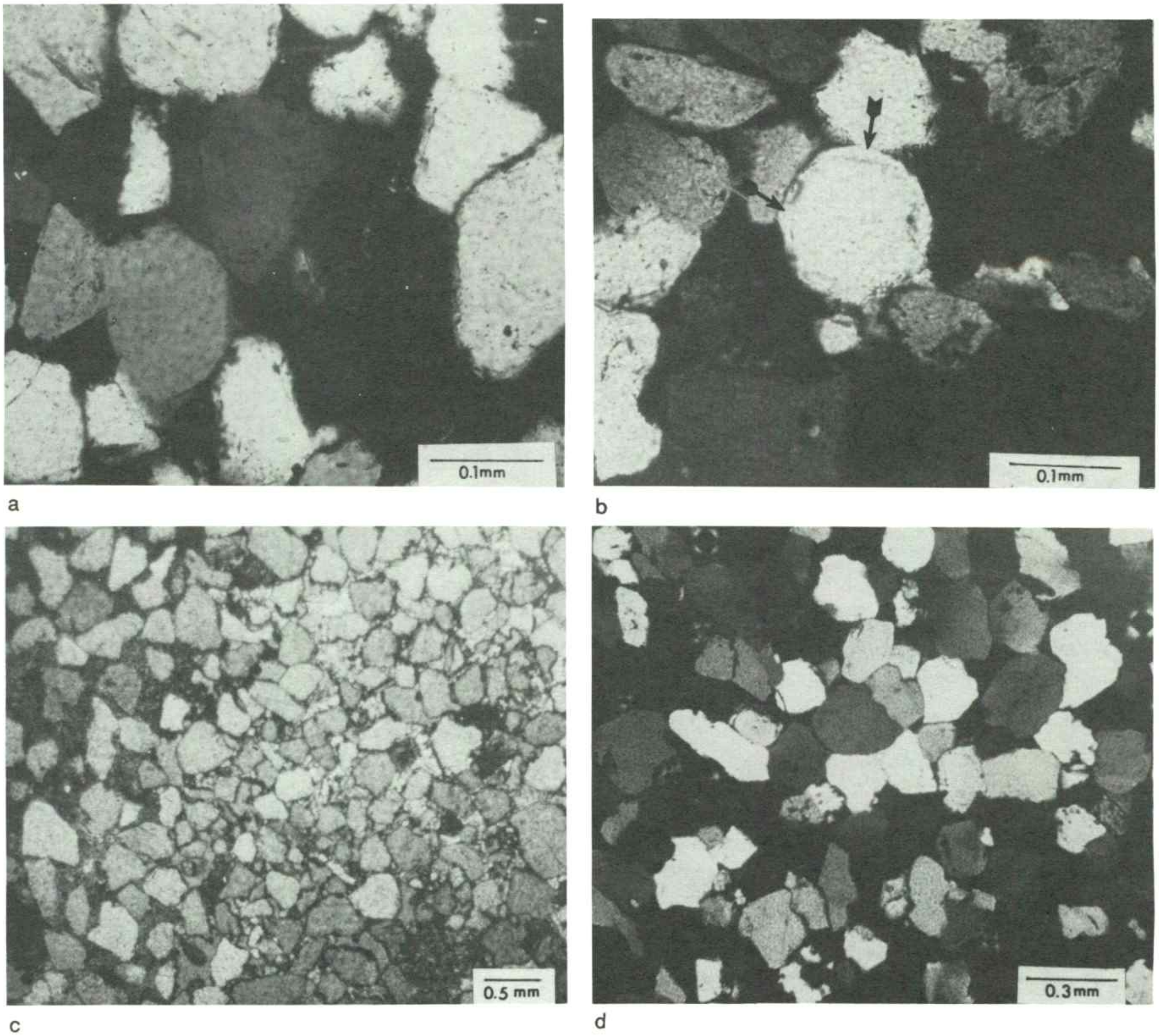


FIGURE 16—PHOTOMICROGRAPHS SHOWING CHARACTERISTICS OF SILICA AND CARBONATE CEMENTS in Rock Lake sandstone units. (a) Subrounded to rounded detrital quartz grains with authigenic silica cement forming overgrowths; most of the dark areas are pore spaces filled with epoxy; sample R.3–7; cross-polarized light. (b) Well-rounded quartz grains with recycled (rounded) overgrowths, shown by "ghost" rims (arrows); sample R.20–4; cross-polarized light. (c) Pervasive calcite (lower relief, lighter color) and iron-rich dolomite (higher relief, darker color) cements in sample TPC–2A, 422.1; plane-polarized light. (d) Syntactic overgrowths of quartz forming a mosaic of interlocking crystals; sample R.26–4; cross-polarized light.

These analyses indicate that the lower sandstone unit exposed in southern Montgomery County, the lower sandstone beds in the Onion Creek area, and some of the sandstone beds in the northern channels are predominantly fine to very fine grained. In contrast, the upper massive sandstones of southern Montgomery County, the upper Onion Creek body, and most of the northern channel fillings are fine to medium grained.

Mineralogically and texturally, these sandstones are submature to mature (Folk, 1951, 1974). The siliciclastic grains probably have been subjected to several cycles of erosion and sedimentation. Grains in these units are predominantly moderately to well sorted, except in conglomeratic lenses at the base of channel deposits. Grain shape varies from subangular to rounded, and, less commonly, angular. Where observable in thin section, contacts between grains are mainly tangential and longitudinal.

In many sandstones detrital grains float within coarser crystals of calcite cement in a poikilotopic fabric (Fuhrmann, 1968; Pettijohn et al., 1973; Scholle 1979, p. 119). Authigenic silica overgrowths are present as rims around quartz grains. On some of these grains the silica overgrowths are well rounded, indicating that overgrowth occurred during a previous cycle of deposition (fig. 16b). Because authigenic overgrowths may have modified original grain shape and size, care must be used when interpreting textural features (Jacka, 1970).

Diagenesis

In what follows I discuss a variety of postdepositional events that affected the petrographic characteristics of these rocks.

Compaction

Friability of exposed and core-sample sandstones of the Rock Lake Shale Member renders them unamenable to packing calculations. Compaction in these sandstones is related to lithostatic pressure (overburden) and to concomitant mechanical rearrangement of grains during the early stages of diagenesis. Because these rocks were probably not buried deeply in the nonorogenic cratonic setting, high temperatures and pressures would not have been controlling factors in their diagenesis. The presence of concave-convex grain-to-grain contacts indicates that some compaction did take place. However, detrital grains "floating" in calcite cement indicates that cementation was a major factor in lithification of some sandstones before any significant compaction.

Cementation

Calcite, the most common cement, averages more than 13% of these rocks (table 1). Calcite-cement crystals are predominantly large, ranging from 1 mm to 3 mm in diameter. Boundaries between adjacent cement crystals are straight.

It is likely that calcite cement in Rock Lake sandstones formed in two different generations, similar to the situation in the Lower Cretaceous Muddy Sandstone of Wyoming described by Almon and Davies (1979). Early generation of calcite cement occurred before much compaction. The cement exhibits poikilotopic texture (grains "floating" among large calcite-cement crystals). Early cementation is probably related to solution of unstable carbonate fossil fragments in percolating meteoric water during regression and the emergence of the sand bodies, as outlined by Heckel (1983) for regressive carbonates. This resulted in supersaturation of the percolating water with respect to calcium carbonate. Crystallization of poikilitic calcite crystals probably resulted from slow precipitation from a dilute solution with few nuclei rather than from rapid crystallization around many nuclei, such as what occurs when many carbonate grains are present. Poikilitic cement is observed mostly in the lower sandstone facies in southern Montgomery County. This level is low enough in the sand sequence for percolating meteoric water to have become saturated with dissolved carbonate from higher levels.

The poikilotopic cementation texture is also observed in some outcrop and core samples from the Trico Production Company well at the northern end of the detrital facies belt. Here it is probably related to dissolution of unstable carbonate grains from the southern end of the algal-mound facies belt. Poikilitic cementation has also been observed in some thin sections of outcrop and core samples from the northern channels (in Wilson and Woodson counties), where it is probably related to solution of adjacent emergent carbonate buildups and reprecipitation as sparry calcium carbonate in the channel sandstones.

The later generation of calcite cement, which partially replaces silica overgrowths, occurs in more compacted sediments and was probably precipitated in response to supersaturation of deeper connate waters with calcium carbonate. A sample from the Trico core at the northern end of the detrital facies belt displays two different cement types (fig. 16c): ferroan dolomite, which fills most of the pore space in one thin section, and patches of nonferroan calcite in small areas. Al–Shaieb and Shelton (1978) state that the ferroan dolomite in the shallow-burial sediments of the Chadra Sands (Oligocene of Libya) formed in a meteoric-connate mixing environment similar to the situation described by Folk and Siedlecka (1974) and Folk and Land (1975) and that the source of iron was probably alteration of glauconite. Because the Rock Lake sandstones were buried only to shallow depth, it is possible that the ferroan dolomite formed from the mixing of meteoric and connate waters, probably during cementation of calcite, similar to the situation described by Al–Shaieb and Shelton (1978). The source of iron was possibly dissolved iron in the low-oxygen connate water, or the iron may have come from adjacent shales during diagenetic alteration of clay minerals, for example, chlorite.

The second most abundant cement in Rock Lake sandstones, iron oxide (limonite), constitutes an average of less than 2% of the total rock (table 1). It fills some of the pore space between grains and is also seen as coatings around some detrital grains in outcrop samples. Because iron oxide occurs as a cement in surface exposures compared to only traces of iron oxide present in shallow core samples and because there is no evidence of iron-bearing minerals (e.g., hornblende, chlorite, or magnetite) in subsurface rocks, the major source of iron oxide is probably modern soil-forming processes, such as hydration of brown amorphous ferric oxide to limonite. The presence of iron oxide in shallow core samples suggests that another source of iron may be dissolution of ferroan dolomite. It is also possible that a small amount of iron was dissolved in the connate water and precipitated as iron oxide in the subsurface.

Sericite, the third most abundant cement in these rocks, occurs most commonly as a pore filling but also occasionally as a grain coating. Sericite cement may form as a result of recrystallization of clay minerals or hydrolysis of feldspar during compaction. It is more likely that most of the sericite cement formed from alteration of feldspar because most feldspar grains show some form of incipient alteration, especially along cleavage traces.

Silica cement, the least abundant type of cement in Rock Lake sandstones, averages less than 1% of the total rock (table 1). The most common form of silica cementation is syntactic overgrowths that form euhedral crystals or a mosaic of interlocking overgrowths (fig. 16d). The well-rounded silica overgrowths in these rocks are related to previous cycles of sedimentation and therefore are not counted as diagenetic components in the present study.

Chert is another form of silica cement that has been observed as a void filling in some sandstone units. Chert cement is found in a few subsurface samples of the northern channels (Wilson and Woodson counties) but has not been observed in either surface or subsurface samples from the Onion Creek sandstone or southern Montgomery County sandstones. The presence of scattered calcareous fossil fragments and the size of chert-filled areas in sandstone suggest that chert may have replaced some fossil fragments.

The sources of silica cement in sandstone have been reviewed by Waldschmidt (1941), Heald (1955, 1956), Siever (1959, 1962), Siever et al. (1965), Dapples (1971), Thompson (1959), Weyl (1959), Towe (1962), Phillip et al. (1963), and Füchtbauer (1967). Blatt (1979) suggested several possible sources of silica overgrowths: (1) dissolved silica in pore spaces from pressure solution along grain boundaries, (2) precipitation of silica produced from hydrolysis of feldspar grains by a weak carbonic acid solution, (3) release of silica from conversion of clay minerals (e.g., smectite and interlayered smectite-illite to pure illite), (4) diagenetic alteration of volcanic rock fragments within sandstone, and (5) dissolution of opaline siliceous skeletal fragments, such as diatoms and radiolarians. All possibilities except item 4 are likely sources of silica in the Rock Lake sandstones.

Replacement

Quartz-calcite cement contact relationships indicate that replacement of quartz by calcite has taken place in sandstones of the Rock Lake Shale Member. One of the most conspicuous contact features is the etching of quartz grains with embayments filled with calcite cement. Such replacement cementation is related mainly to chemical instability of quartz grains relative to calcite. Dapples (1971) suggested that replacement of quartz by calcite in certain sandstones is related to pH changes, which is controlled by carbon dioxide changes near the outcrop. Silica solution takes place contemporaneously with calcite cementation if the rate of dissolution is slow (Dapples, 1971). Blatt et al. (1980) suggested that both pH and temperature are important controlling parameters in the replacement of quartz by calcite. As both pH and temperature increase, the solubility of silica tends to increase and the solubility of calcite decreases. Nevertheless, it is likely that pH rather than temperature was the major controlling factor of replacement in the Rock Lake sandstone because these rocks are located in a tectonically inactive area and were not buried deeply and thus were not subjected to high temperatures.

Replacement of calcite by chert is suggested in a few core-sample thin sections from the northern channels. The evidence for this is a few small crystals of calcite that occur in patches of chert. It is possible that a decrease in pH caused calcite to dissolve and silica to precipitate.

Pyrite occurs as a partial replacement of calcite is some shell fragments. Berner (1971) reported that stable pyrite can form under conditions of low Eh and moderate to low sulfur content. Such an environment is found where organic matter is abundant, that is, where sulfur is reduced by bacteria. The presence of scattered fossils in the Rock Lake sandstones provides a source of sulfur in the organic compounds of decaying organisms. The iron may have been brought into the system by low-oxygen meteoric waters that leached soils or may have been derived later from dissolution of ferroan dolomite.

Alteration

The most common diagenetic alteration in the Rock Lake sandstones is decomposition of feldspar to clay. Both plagioclase and alkali feldspar grains are partially altered to sericite. The localization of sericite in areas of feldspar decay suggests recrystallization of the alumina and silica components. Sericite and other clay minerals were probably a product of partial hydrolysis of feldspar grains along surfaces of exposure, such as grain surfaces and cleavage traces. Füchtbauer (1967) suggested that, during the early stages of coalification, water with dissolved humic acid and CO_2 migrated from coal beds into Upper Carboniferous sandstones of northern Germany, forming an acidic environment in which feldspars were hydrolyzed and replaced by kaolinite. The presence of organic matter, such as plant fragments, in the Rock Lake sandstones supports formation of an acidic environment in this way, creating the proper conditions for hydrolysis of feldspar grains.

Paragenesis

Definitive paragenetic relations among all the diagenetic events in the Rock Lake sandstones are complicated by present-day weathering of the outcrop and the relatively small number and local distribution of subsurface samples. A hypothetical sequence of diagenetic events can be proposed based on the criteria and relations discussed previously (fig. 17).

STAGE 1—The first stage took place during shallow burial with only minimal compaction, indicated by a loosely packed grain fabric. Early calcite cementation produced a poikiloblastic texture with grains "floating" in calcite cement. It probably occurred during a regression, when meteoric water replaced marine connate water in the sediment, dissolved carbonate fossil fragments in the sandstones, and began to dissolve emergent carbonate buildups along the northern channels until the water became supersaturated with calcium carbonate, which then precipitated as cement (Longman, 1980; Heckel, 1983). Replacement of quartz by calcite, indicated by corroded quartz grains with embayments filled with calcite cement, may have occurred during early calcite cementation, as both pH and temperature increased (fig. 17, substage B). This caused silica to be dissolved and calcite to be deposited.

Alteration [hydrolysis of feldspar to sericite (sericitiza-

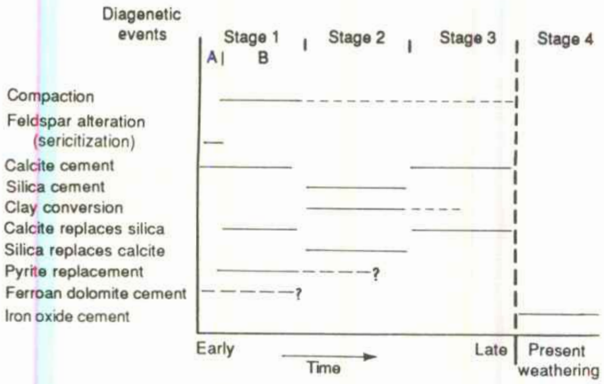


FIGURE 17—Probable sequence of diagenetic events (paragenesis) occurring since deposition of Rock Lake sandstones.

tion) and other clay minerals] along the surface of grains is also probably a precompaction phenomenon (fig. 17, substage A) that released some silica into the connate water. Both processes may have aided later silica cementation. In one core ferroan dolomite in a poikiloblastic cementation texture possibly formed during early cementation in a meteoric-connate mixing environment before the South Bend Limestone Member was deposited. Replacement of calcite by pyrite in carbonate shell fragments may have been contemporaneous with compaction and cementation in low Eh microenvironments created by the decay of organic matter within the skeletal fragments.

Stage 2—Conversion of clay minerals, such as smectite to illite, is considered to correspond in time with compaction and would have provided some silica for formation of silica cement. Silica cement (quartz overgrowths) formed after silica was released into the connate water by the processes discussed earlier. Replacement of calcite by silica, as shown by a few crystals of calcite left within the chert cement, probably is related to a decrease in pH that caused calcite to dissolve and silica to precipitate.

Stage 3—Second-generation or late calcite cement formed in overcompacted pore space in more deeply buried sediments and is probably related to the supersaturation of later connate water. Replacement of silica by calcite occurred along the margins of quartz grains in sediments with tighter packing modes than those discussed in stage 1.

Stage 4—Iron oxide cements, which surround most of the detrital grains in outcropping rocks, probably formed from the migration of modern oxygenating meteoric ground water through the rocks as they were exhumed. This process dissolved ferroan carbonate cements and oxidized the released ferrous ions, which then precipitated as ferric oxide coatings on grains. The formation of iron oxide cements probably is continuing at present.

Sedimentologic analysis

Outcrop analysis

I present detailed sedimentologic analyses of selected outcrops for the following geographic areas: southern Montgomery County, the Onion Creek area of west-central Montgomery County, a tributary to the Wilson County channel, and the Woodson County channel. I determined hydraulic flow regimes from the nature of bed forms, as suggested by Simons and Richardson (1961). Because stratification is the product of bed forms, flow regimes can be determined from the characteristics of stratification, as outlined by Harms and Fahnestock (1965).

Southern Montgomery County

OKLAHOMA BORDER SECTION—In the Oklahoma–Kansas border area the Rock Lake Shale Member consists of several distinct lithologic units. I describe these units in ascending order (fig. 18). The data were obtained from a well-exposed section.

Unit 1 is a calcareous clayey shale at the base that coarsens upward to silty shale at the top. Scattered wood fragments are present. These parallel-bedded clayey and silty shales were probably deposited in a quiet water environment from suspended sediments.

Unit 2 is an interbedded silty shale and well-sorted, very fine grained to fine-grained sandstone with scattered marine fossil fragments (echinoderms, brachiopods, bryozoans, and mollusks) and a few wood fragments. The sandstones are highly calcite cemented, very thin bedded, and locally laminated. These thin-bedded sandstones probably formed intermittently in the lower part of the upper flow regime from coarser sediments that were supplied from the source area in greater amounts.

Unit 3 is a poorly fossiliferous silty shale with scattered wood fragments. This unit was deposited in quiet water from suspensions that contained coarser material than those from which unit 1 clayey shale was deposited.

Unit 4 consists of two horizons of massive, well-sorted, medium-grained sandstone with conglomerates at the base. There is an erosional basal contact with grooves and burrows. The orientation of the basal grooves suggests unidirectional transport, primarily to the northwest. There is no internal stratification in either the massive sandstone or the conglomerate. Pebbles in the conglomerate consist mainly of clay chips derived from the shale unit below and vary in diameter from 1 cm to 2 cm. The presence of an erosional contact with conglomerate at the base and the absence of internal stratification suggest that the massive sandstones in the Rock Lake Shale Member formed by rapid deposition of sediments carried in channels.

Unit 5 consists of planar crossbedded, moderately to well-sorted, fine- to medium-grained sandstones. Because of poor exposure in southern Montgomery County, it was not possible to determine unequivocally the presence or absence of trough crossbedding in this unit. However, it is possible that some of the planar crossbeds are actually oblique to longitudinal views of trough crossbed sets. The planar crossbeds in this unit formed within the upper part of the lower flow regime, as suggested for similar beds in the Rio Grande River by Harms and Fahnestock (1965). The mean azimuth of dip direction of planar crossbeds indicates that the direction of sediment transport was toward the northwest (fig. 19).

Unit 6 consists of thin-bedded to very thin bedded and laminated, well-sorted, fine-grained sandstone that grades upward into very fine grained sandstones. Horizontal stratification in channel sandstones is probably a product of plane bed transport in the transition between the lower and upper flow regimes (Harms and Fahnestock, 1965). Some thin beds of silty shale (less than 1 cm thick) are intercalated with the thin-bedded sandstone toward the top of this sequence. Parallel stratification in the silty shale at the top is probably a product of slow deposition of suspension materials under quiet water conditions. These silty shales are overlain by thin-bedded sandstone with scattered clay chips at the base, which were probably rapidly deposited.

Locally, small-scale cut and fill structures are present (fig. 20). These cut and fill deposits consist of conglomeratic quartz sandstone with shale pebbles at the base overlain by small-scale, thinly planar crossbedded, horizontally laminated sandstone, and parallel stratified silty and clayey shale that is cut by the next sandstone unit above. Grooves and burrows are present at the base of the sandstone unit above the cut and fill structure (fig. 20). The processes that formed these minor channel cuttings are the same as for the major channels already discussed and are probably related to local changes in velocity of the major channel. Within each minor channel the vertical sequence from basal conglomerate upward to medium- and fine-grained sandstone indicates a general decrease in energy during the deposition of sandstone as the channel filled and shifted position. Nevertheless, the overall increase in grain size from base to top reflects a change in deposition from offshore shale to channel sand, which is characteristic of a regressive phase of deposition.

TYRO QUARRY—Northeastward in the Tyro quarry (Moussavi–Harami, 1980, appendix C, sections 8 and 9), the base of the Rock Lake Shale Member is a conglomeratic quartz sandstone about 1 m (3 ft) thick. It lies above the dark-gray offshore marine Eudora Shale Member studied by Malinky (1980). The basal conglomeratic sandstone grades upward into thin-bedded sandstone with scattered marine fossil fragments and small-scale cross-laminations that dip alternately east and west in different horizons. Pebbles in the conglomerate are composed of shale, fossils, and fragments of oolitic and other types of limestone. Pebbles range in diameter from 0.5 cm to 6 cm and decrease in size toward the top and to the west. There is no internal stratification in the basal conglomerate. This unit is exposed only in the south wall of the quarry and thins toward the west.

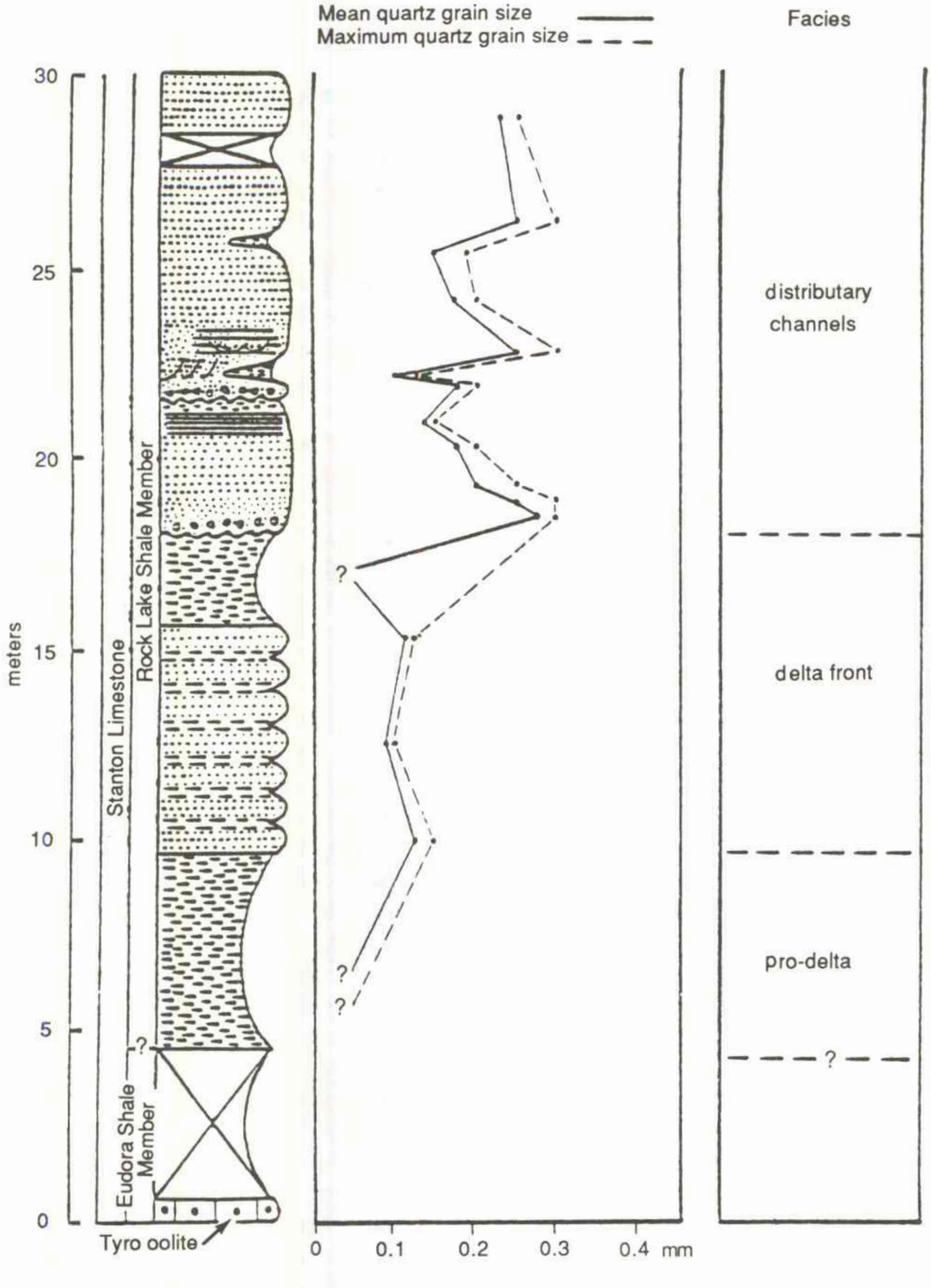


FIGURE 18—LITHOLOGIC UNITS AND GRAIN SIZE DISTRIBUTION IN ROCK LAKE SHALE MEMBER at Oklahoma border section. Located on west line of NW sec. 14 and west line of SW sec. 11, T. 35 S., R. 14 E. See also Moussavi–Harami (1980, appendix C, section 3).

The thinning of this unit and the decrease in pebble size toward the west in conjunction with the absence of this unit in the west and north walls of the quarry indicate that the source must have been to the east or southeast. The pebble composition and the sharp basal contact of this unit indicate that the channel cut into both the underlying offshore shale and perhaps into the Tyro oolite 0.6 m (2 ft) below the outcrop.

Fahnestock and Haushild (1962) stated that pebbles larger than 2.5 cm in diameter with a specific gravity of 2.0 or more cannot be transported downstream in the lower flow regime but will roll into scour pockets formed upstream of the pebbles. Thus such pebbles can be moved downstream only in the upper flow regime. The velocity and turbulence of the depositional environment in the Tyro quarry area decreased to a lower flow regime at the top, as indicated by the thin-bedded sandstone that contains small-scale dune cross-laminations. Small-scale asymmetric ripples (amplitude 0.5 cm) present at the top of this unit indicate that the current velocity decreased even further to the lower part of the lower flow regime and that the direction of transport shifted toward the south (fig. 21). The thin bed of silty shale (about 1 cm) that separates the layered sandstones probably records normal deposition of finer silt-size sediments between pulses of coarser sediment. The overall fining-upward sequence of conglomerate and sandstone containing marine fossil frag-

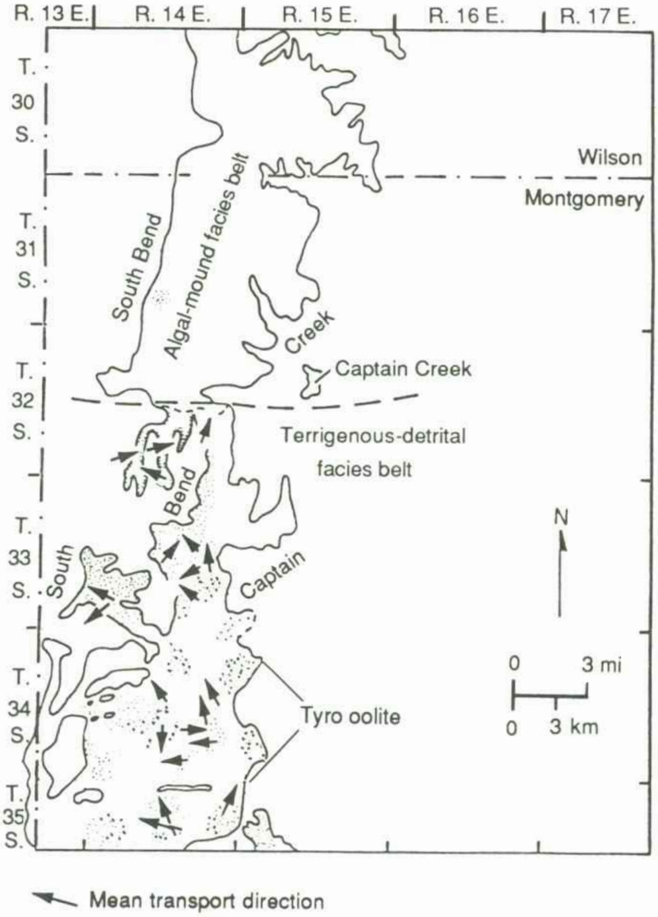


FIGURE 19—Mean transport directions of planar cross-beds in detrital facies belt.

ments indicates rapid pulses of deposition in marine water with an overall decrease in energy toward the top. It is possible that this marine channel was formed by a spillover of sand down a prodelta slope, scouring into the offshore shale and locally into the underlying carbonate sediment nearby.

The silty shale [about 2 m (6.7 ft) thick] that overlies the marine channel sandstone contains widely scattered marine fossils, indicating deposition from suspension under normal low-energy conditions of the encroaching prodelta. At the top this shale is cut by a channel sandstone that is conglomeratic in two levels at the base. Pebbles in the conglomerate are mainly shale chips, which range in diameter from 1 cm to 2 cm. Grooves and load structures at the base of the conglomerate indicate rapid deposition in the upper flow regime. The conglomerate grades upward into a well-sorted, medium-grained, massive sandstone with no internal stratification. This is overlain by a moderately to well-sorted, fine- to medium-grained sandstone with small-scale trough cross-beds that grades upward into a well-sorted, fine-grained, thin-bedded sandstone with ripple marks at the top. Trough crossbeds probably formed in the lower flow regime and represent migrating dunes (Harms and Fahnestock, 1965). The mean azimuth of axes of the trough crossbeds indicates that the direction of transport within the channel was toward the northwest (fig. 22).

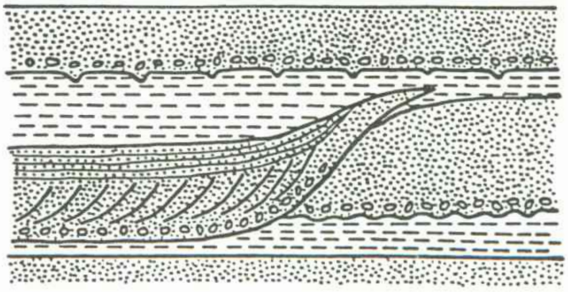


FIGURE 20—Small-scale cut and fill structure in unit 6 at Oklahoma border section (see fig. 18).

In the top of this unit thin-bedded to very thin bedded sandstones with ripples along the surface of the beds formed in the lower part of the lower flow regime. The ripple marks usually have a continuous crest, but some multiripples with crests joined to other ripples are present. This is probably related to changes in direction of wave movement in shallow water. The mean azimuth of these ripple marks indicates that the waves moved toward the south at this locality, perhaps under prevailing winds (fig. 21). There are some very thin beds of silty shale between most of the thin-bedded sandstones. Many scattered shale pebbles occur at the base of the thin-bedded sandstone overlying a shale unit. This indicates that the quiet conditions during the deposition of silty shale were suddenly interrupted by turbulent currents that eroded the upper part of the shale and transported coarser sediments that eventually were deposited over the top. The fining-upward sequence with conglomerate at the base, an erosional basal contact, and the other sedimentary features discussed suggest that these rocks were deposited in a channel system (Allen, 1964; Visher, 1965, 1972; Visher et al., 1975; Siemers, 1976).

Cheyenne Creek—One of the best exposures of Rock Lake sandstone is in a road cut near Cheyenne Creek (NENENE sec. 32, T. 34 S., R. 14 E.; Moussavi–Harami, 1980, appendix C, section 6). It consists of three lithologic units. Unit 1, the lowermost unit, consists of interbedded thin-bedded, fine-grained sandstone and silty shale. The sandstone beds are well sorted and contain scattered marine fossils (echinoderms, brachiopods, bryozoans, and mollusks) and a few scattered oolites. Unit 2 consists of interbedded thin-bedded, moderately to well-sorted, fine- to medium-grained sandstone and silty shale. These sandstone beds do not contain marine fossils or oolites. The lower sandstone beds of unit 1 formed under low-energy conditions at a relatively slow rate of detrital influx with perhaps reworked oolites; the upper coarser-grained sandstone beds of unit 2 were deposited under more turbulent conditions with more detrital influx. Unit 3 consists of a thin-bedded, well-sorted, medium-grained sandstone with a conglomeratic base and an erosional basal contact. Pebbles in the conglomerate are primarily shale and range in diameter from 1 cm to 3 cm. This sandstone unit is overlain by trough crossbedded, ripple-

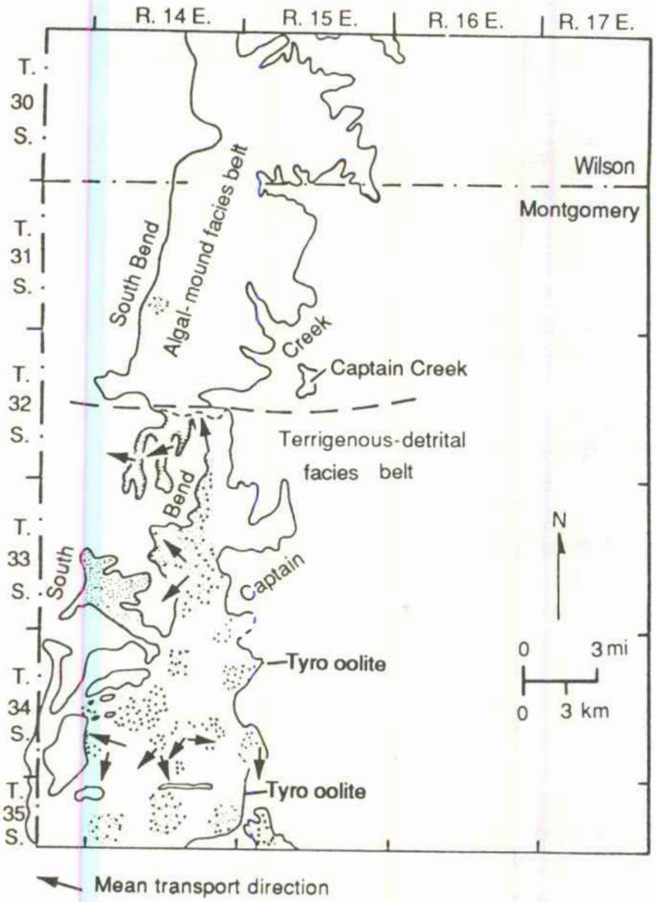


FIGURE 21—MEAN TRANSPORT DIRECTIONS OF RIPPLE MARKS in detrital facies belt.

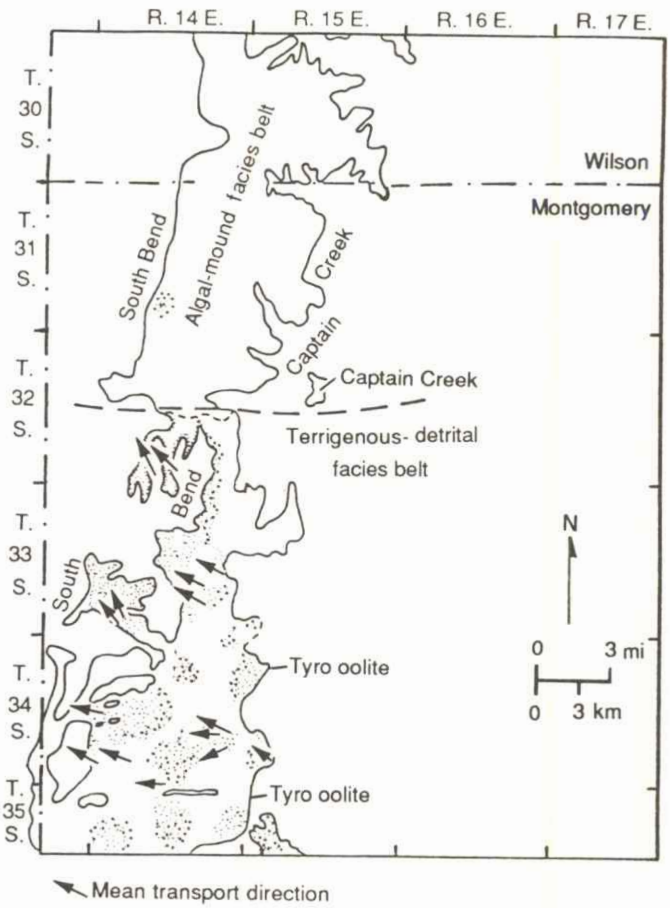


FIGURE 22—MEAN TRANSPORT DIRECTIONS OF TROUGH CROSSBEDS in detrital facies belt. Note unidirectional orientation toward northwest.

laminated sandstone. The mean azimuth of the axes of the trough crossbeds indicates a direction of transport toward the northwest (fig. 22). This sequence along Cheyenne Creek represents a coarsening-upward sequence of shallow marine deposition that was subsequently cut by a channel at the top.

OTHER FACIES—The slightly oolitic quartz sandstone with scattered marine fossils in the third oolite zone in the lower part of the Rock Lake Shale Member was deposited in an agitated shallow-water environment, as suggested by Heckel (1975b). The skeletal oolitic quartz sandstone of the fourth oolite zone, which is crossbedded in some areas, probably records deposition in an even more highly agitated shallow-water environment at a time of low detrital influx. The presence of generally stenohaline organisms (e.g., echinoderms) indicates that nearly normal marine salinities were established during deposition of the lower and middle Rock Lake Shale Member.

Northward, in the vicinity of Wayside between T. 33 S. and T. 34 S., the Rock Lake Shale Member consists predominantly of interbedded clayey to silty shale and very thin bedded, very fine grained, hard, calcite-cemented sandstones. These were deposited under generally quiet conditions with periodically more agitated detrital influx, perhaps between the channels.

West-central Montgomery County

ONION CREEK SECTION—Nearly the entire Rock Lake Shale Member is exposed along road cuts near Onion Creek (fig. 23) in west-central Montgomery County. The nonfossiliferous shale at the base of the member is clayey at the base and silty toward the top, indicating suspension deposition in a quiet environment under the influence of a distant but encroaching detrital source. This shale is overlain by a very thin bedded, very fine grained sandstone with burrows on the bottoms of the beds. The presence of ripple marks indicates that this unit was deposited in the lower part of the lower flow regime in shallower water than the shale below. Upward in this sequence there are interbedded thin-bedded to very thin bedded, fine-grained to very fine grained sandstone and covered intervals. If most of the covered intervals represent more easily eroded shale, then these interbeds were deposited under two alternating energy conditions as the detrital source spasmodically approached this area.

The topmost shale unit has been cut by a massive sandstone with a conglomeratic base, which is probably a channel-lag deposit. Unidirectional grooves, which trend northwestward, are present at the base of the conglomerate. Pebbles in the conglomerate are predominantly shale and vary in

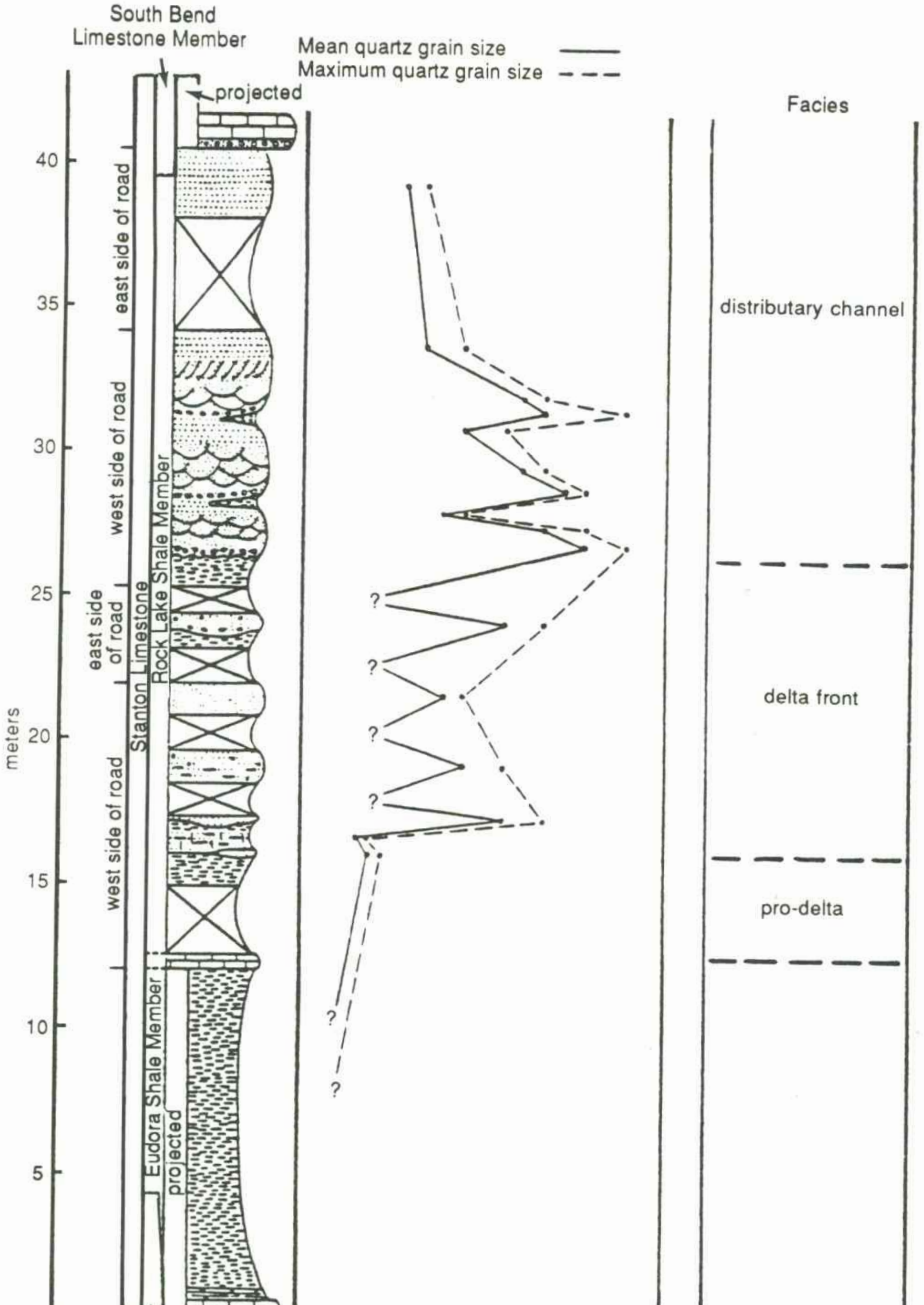


FIGURE 23—LITHOLOGY AND GRAIN SIZE DISTRIBUTION IN ROCK LAKE SANDSTONE at Onion Creek section. Located along east lines of secs. 22 and 27, T. 33 S., R. 14 E. See also Moussavi-Harami (1980, appendix C, section 20).

diameter from 1 cm to 3 cm. Upward in this sequence the conglomerate grades into a well-sorted, medium-grained, massive sandstone with medium-scale trough crossbeds and planar crossbeds and finally into thin-bedded sandstones, illustrating a fining-upward sequence at the top of the section (fig. 23). The channel processes that controlled the deposition of these sandstones were similar to those suggested for the southern Montgomery County sandstones. Very thin beds of silty shale are present between the thin-bedded sandstones, suggesting periodic suspension deposition in a quiet environment. The few scattered shale pebbles in the base of these sandstone units indicate a rapid influx of sand above partially coherent shale.

All the evidence indicates that the lower sandstone and shale units were deposited in a generally quiet environment under increasing detrital influx, such as a prodelta or a delta front. The upper sandstone was deposited in a more turbulent environment with periodic pulses of sediment influx followed by decreasing energy conditions, such as would be found in a channel system. A sequence of three sand-filled channels cutting into shales suggests fluctuating supplies of sediment from source areas, perhaps a result of channel abandonment and reoccupation or perhaps channel meandering. The mean azimuth of the axes of the trough crossbeds indicates that the direction of transport in the channels was toward the northwest (fig. 22).

Coon Creek Section—Northward along US–160 at Coon Creek (Moussavi–Harami, 1980, appendix C, section 25), a medium-grained, crossbedded sandstone unit with a conglomeratic base overlies silty shale, and except for the 0.9-m (3-ft) thick Timber Hill siltstone bed, the lower interbedded sandstone and shale facies is absent. In this area the basal offshore shale with marine fossils (Eudora Shale Member) below the Timber Hill bed is thicker than to the south (fig. 4). The Timber Hill siltstone bed contains a few scattered marine fossils and may represent the marine reworked distal end of a sandstone in the Onion Creek area. The grain size within the Timber Hill siltstone decreases toward the top and to the west. This indicates that the source area was probably to the east or southeast and supports the idea that the Timber Hill bed resulted from marine reworking of a greater than normal sand influx from the usual Rock Lake source.

The lower part of the Rock Lake Shale Member above the Timber Hill bed is a nonfossiliferous silty shale that is cut by sandstone at the top. The shale was deposited in a quiet environment but probably more rapidly and from a closer source than the underlying less silty, fossiliferous Eudora Shale Member. The conglomeratic base of the overlying sandstone contains shale pebbles that have the same composition as the shale unit below.

The sandstone is composed of an ascending sequence of (1) a moderately to well-sorted, medium-grained, massive sandstone; (2) a well-sorted, fine- to medium-grained, thin-bedded sandstone with medium-scale trough crossbeds; (3) a well-sorted to medium-grained, thin-bedded sandstone with small-scale planar crossbeds; and (4) a well-sorted, fine-grained, thin-bedded to very thin bedded sandstone with ripple marks.

Below the top of the Rock Lake Shale Member by 1.2 m (4 ft) is a thin-bedded to laminated convolute deformational structure. Petrographic measurements of quartz grains from convolute structures and thin-bedded sandstones above and below indicate no significant differences in grain size. It is likely that the laminations in the convolute structures formed during periods of slow sedimentation. However, rapid deposition of thin-bedded sandstone under high velocity and turbulence conditions may have caused the laminated units to be deformed into the convolute structure by means of a loading phenomenon. The mean azimuth of the dip of the trough crossbed axes indicates a direction of transport toward the northwest (fig. 22). The mean of directions of planar crossbeds indicates a transport direction toward both the north and northeast (fig. 19), whereas the mean azimuth of the ripple mark crests and the sense of asymmetry indicate a direction of transport to the west (fig. 21). The lack of shale interbeds at this locality suggests continual higher-energy conditions, possibly in shallower water than stratigraphically lower sandstones.

All the evidence suggests that this sand was deposited in channel systems. The two sand-filled channels visible in the Rock Lake Shale Member at Coon Creek are probably related to migration of a channel toward the north. The medium-grained massive sandstone of the upper channel cuts into the fine-grained, thin-bedded, ripple-laminated sandstone of the lower channel. The lack of conglomerate at the base of the massive sandstone of the upper channel indicates that deposition took place in the presence of coarser incoherent sediments.

Summary of Rock Lake deposition in the detrital facies belt

The general vertical sequence of Rock Lake lithology in western Montgomery County consists of (1) clayey shale at the base becoming silty upward; (2) interstratified thin-bedded, very fine grained to fine-grained sandstone and silty shale; (3) massive medium-grained sandstone with conglomerate at the base; (4) medium-scale trough crossbedded, fine- to medium-grained sandstone; (5) fine-grained, planar crossbedded sandstone; and (6) thin-bedded, fine-grained to very fine grained sandstone. This records progressive encroachment of prodelta (items 1 and 2), distributary channel (items 3–5), and overbank deposits (item 6) of a delta lobe.

Tributary to Wilson County channel

In Wilson County the only good vertical exposure of Rock Lake sandstone is along K–47 east of Fredonia in a small channel that is cut into the Stoner Limestone Member. This channel is a tributary to the larger Wilson County channel. At this locality the base of the Rock Lake Shale Member consists of a thin (7 cm) clayey and silty shale that was deposited under quiet water conditions. This shale unit is cut by sandstone at the top (fig. 24). The base of the sandstone is

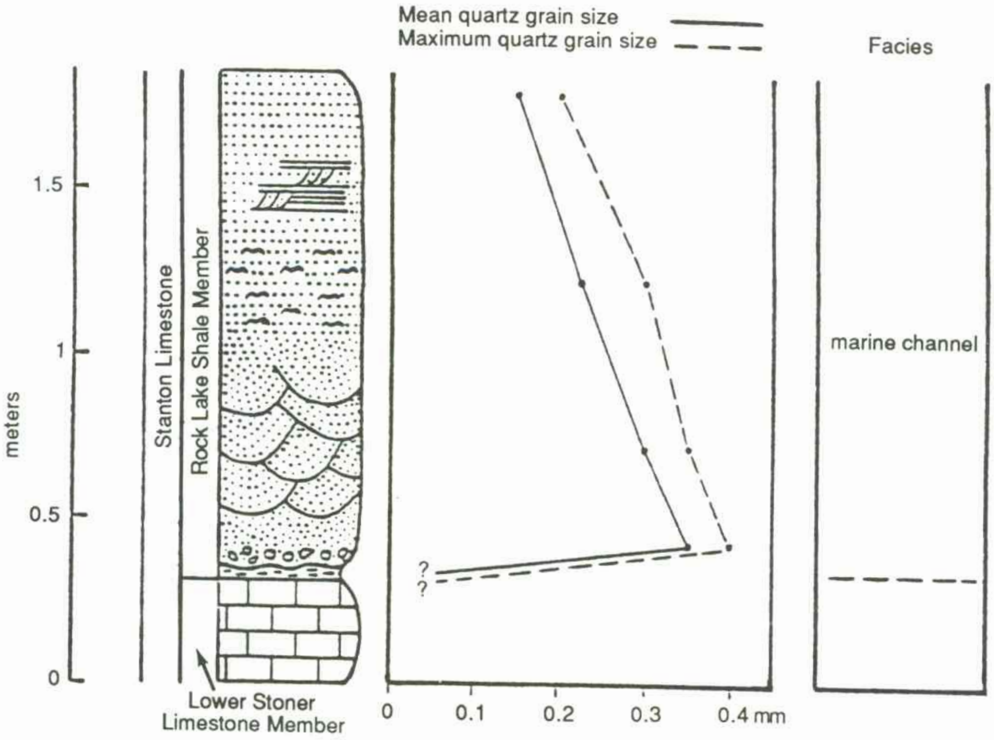


FIGURE 24—Lithology and grain-size distribution in small tributary to Wilson County channel at K–47 section. Located in north side of road cut along K–47 in north-central sec. 16, T. 29 S., R. 15 E. See also Moussavi–Harami (1980, appendix C, section 28).

conglomeratic, with shale pebbles and a few scattered fossil fragments forming a channel-lag deposit. The pebbles vary in diameter from 1 cm to 3 cm. Upward in this sequence the sandstone is well sorted and thin bedded with medium-scale trough crossbeds; it grades upward into a well-sorted, horizontal thin-bedded, ripple-laminated sandstone. A few small-scale cut and fill structures are present. The mean azimuth of the axis of trough crossbeds indicates that the direction of transport was southwesterly, toward the main channel (fig. 25). This coincides with the apparent alignment of the tributary channels. The medium-grained sandstone at the base fines upward to fine-grained at the top (fig. 24). The conglomerate at the base formed under upper flow regime conditions. As the velocity and turbulence decreased, trough crossbeds formed in the upper part of the lower flow regime. Flow energy probably increased again to form the horizontal beds in a transition between the lower and upper flow regimes (Harms and Fahnestock, 1965). Higher in this sequence ripple marks formed as the velocity decreased again to the lower part of the lower flow regime.

Westward in the subsurface, core K shows a series of channel cut and fill structures, each with a channel lag of conglomeratic quartz sandstone at the base and massive to crossbedded sandstone grading to silty shale at the top.

Woodson County channel

One of the best exposures of the Woodson County channel in the Rock Lake Shale Member is in the hill west of Humboldt (fig. 26). At this locality the lower part of the outcrop (unit A) is skeletal to lithoclastic calcirudite with small-scale planar crossbeds and lenses of very fine grained, laminated sandstone. This unit probably represents erosional debris derived from semiconsolidated Stoner limestone and incorporated into the base of the Rock Lake Shale Member. Small-scale dunes and ripples are present in the interbedded sandstone, indicating deposition in the lower flow regime. It is possible that these lenses formed at the edge of the channel during high siliciclastic sediment supply. The overlying very fine grained, thin-bedded sandstone (unit B, fig. 26) with laminated ripples and dunes was also deposited in the lower flow regime. This unit is cut at the top by a well-sorted, medium-grained sandstone (unit C) that has grooves and burrows at the base. The grooves indicate unidirectional transport toward the south and southwest. The entire sandstone unit (C–E on fig. 26) is massive at the base and thin-bedded to very thin bedded to laminated toward the top, fining upward in grain size. Small-scale channel cut and fill structures may be related to local shifting of the channel in the upper flow regime. Fining-upward crossbeds and ripple laminations also are present down-channel in the subsurface. The evidence supports the idea that these rocks were deposited in the large channel mapped by Heckel (1975a).

Well-log interpretation

Four different lithofacies were identified in the subsurface by using resistivity and SP logs in conjunction with outcrop

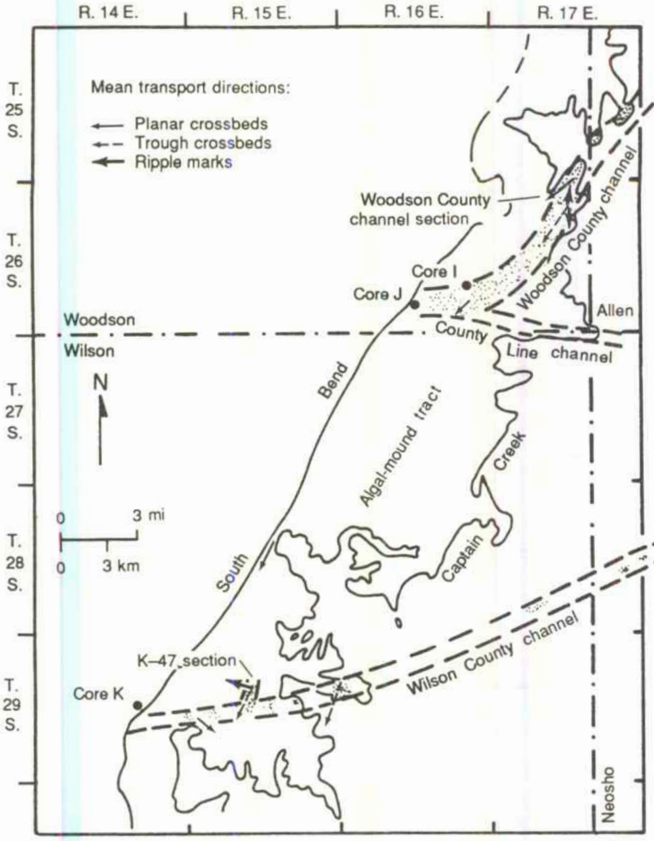


FIGURE 25—Direction of sediment transport in channels transecting algal-mound tract. Note unidirectional orientation of trough crossbeds.

data (fig. 27), as described in the previous section. These lithofacies are (1) limestone, (2) sandstone, (3) shale (mainly clayey), and (4) mixed rock (mixture of clayey or silty shale and shaly sandstone). The thickness of the Rock Lake Shale Member, predominantly sandstones and mixed rock, increases from north to south. The net sand isolith map (fig. 13) and cross section AB (fig. 14) indicate that the amount of sandstone increases southward toward the Oklahoma border. These facts, in conjunction with sandstone geometries, indicate that the source area for the Rock Lake siliciclastics was toward the south and southeast.

Higher resistivity and SP values at the base of the Stanton Limestone indicate the presence of limestone, interpreted to be the Captain Creek Limestone Member (fig. 14) in the northern part of the detrital belt (T. 32 S. and T. 33 S.). This interval is overlain by units characterized by low resistivity and low SP values, indicating fine-grained, clay-rich sedimentary rocks, interpreted to be the Eudora Shale Member, deposited under widespread quiet water, offshore conditions at maximum transgression. Upward in the sequence the fluctuation of resistivity and SP values indicates the presence of fine- and coarse-grained sediments that are interpreted as mixed rock. The low values probably represent finer-grained sediments (clay and silt) deposited under quiet water conditions from suspension; the higher values represent coarse-grained sediments (sand) deposited under conditions of greater sediment influx and perhaps higher energy. A similar sequence is seen in the exposed rocks in the vicinity of Onion Creek (fig. 27), but the mixed rock overlies silty shale in the lower part of the Rock Lake Shale Member. This mixed-rock subsurface interval is overlain by a unit with high resistivity and SP values that indicates coarser-grained sediments. These probably represent a medium-grained sandstone, possibly channel-fill sediments deposited under high to low flow regime, if this unit is analogous to the outcropping rocks of the upper part of the Onion Creek sandstone body that cuts into finer-grained sediments 6.4 km (4 mi) to the east. At the top of this sequence the widespread horizon of high resistivity and SP values is interpreted to represent the South Bend Limestone Member, which overlies the sandstone and represents the next transgressive phase of deposition.

Southward between T. 33 S. and T. 34 S., most resistivity and SP values decrease, although some thin intervals with high values persist (fig. 14, wells 47, 147, and 143). The lower resistivity and SP values are interpreted as mixed rock, representing a unit of finer-grained sediments, for example, very fine grained sandstones interbedded with silty shale such as those seen cropping out in the vicinity of Wayside along US–65. These units were probably deposited under relatively low-energy conditions. The thin intervals of high resistivity and SP values probably represent lenses of fine- to medium-grained sands that were probably deposited under higher-energy conditions. Some of the thicker sand lenses can be correlated with channel sands both northward and southward (fig. 14). This suggests shifting of channels during periods of increased detrital influx.

In the southern part of the detrital belt (T. 34 S.) in wells 134 and 138, the high to low resistivity sequence of the Tyro oolite–Eudora shale sequence disappears and is replaced by high resistivity and SP values (fig. 14), which are interpreted as representing coarser-grained sand-size sediments that fill a channel. This indicates an increase in coarse detrital influx from the south at a much earlier stage of Rock Lake deposition than is seen to the north and an influx that resulted in the erosional removal of the lower units of the Stanton Limestone followed by deposition of channel sands. Some abrupt vertical changes in resistivity and SP curves above these sediments are interpreted as a sequence of interbedded sandstone and very thin bedded shale within the channel deposits, as seen in some outcrops. These represent periods of quiescence interrupting normally high-energy conditions in the channels. In wells 134 and 138 the thick sequence of channel-sand deposits (higher resistivity and SP) are overlain by alternating intervals of low and high resistivity and SPs (fig. 14), indicating interbedding of finer-grained mixed rock and coarser-grained sandstone, which record deposition under two different energy conditions. This interbedding might represent encroachment of floodplain deposits, but because these have not been observed in outcrops, it might merely

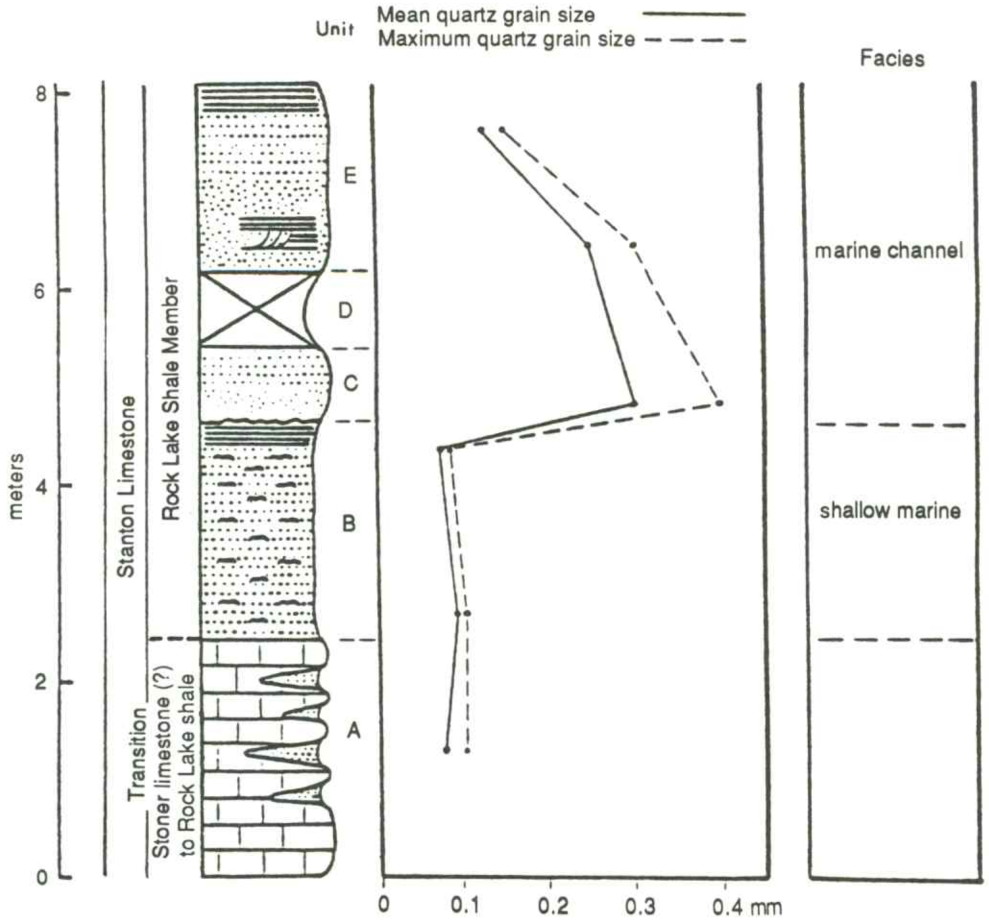


FIGURE 26—LITHOLOGY AND GRAIN-SIZE DISTRIBUTION IN WOODSON COUNTY CHANNEL in cut on hill west of Humboldt. Located on north side of road cut in SWSW sec. 34, T. 25 S., R. 17 E. See also Moussavi-Harami (1980, appendix C, section 33).

reflect alternation between suspension deposition during low channel flow stages and higher flow regime sand transport during floods or possibly shifting of channels across quiet interdistributary-bay suspension deposits.

These alternating sequences of high and low resistivity and SP values are next overlain by an interval characterized by high resistivity and SP values that represent a thick sequence of coarse-grained sandstone (fig. 14), which was probably deposited in a new major channel that shifted into the area. In well 138 this interval of high resistivity and SP deflection is directly overlain by the widespread high-resistivity values that are interpreted to be the next transgressive limestone unit (South Bend Limestone Member) capping the Stanton Limestone. However, in well 134 the high values of the sandstone intervals are overlain by a low-value interval of finer-grained mixed rock, indicating shifting of the major channel away from this area some time before the South Bend transgresssion.

Southward in well 107, 1.6 km (1 mi) north of the Oklahoma border (fig. 14), the Rock Lake Shale Member consists of three different units. Unit 1, the lowermost unit, has low resistivity and subdued SP curves that indicate finer-grained mixed rock deposited under relatively quiet conditions. Unit 2 exhibits high-valued curves that are interpreted as coarser sediments, probably a medium-grained sandstone similar to that observed in correlative outcrops, deposited under higher flow regimes in channel systems. Unit 3 has low resistivity and subdued SP curves at the top of the sequence, which represents finer-grained mixed rock. This sequence shows an upward decrease in grain size and an upward decrease in current energy conditions and is probably related to the shifting of a channel complex away from this area some time before deposition of the overlying transgressive limestone.

The general trend of increasing resistivity and SP deflections upward through most of the subsurface Rock Lake Shale Member indicates gradual coarsening (i.e., a decrease in clay content) and an increase in siliciclastic influx through time. This sequence of rocks, which appears to represent a regressive or progradational phase of deposition, grades upward from offshore clayey and silty shales to nearshore mixed sandstones and shales to channel sandstones. Southward thinning of offshore clayey and silty shales as they are replaced from the top of mixed rock and channel sandstones (fig. 14) seems related to a progressive increase in supply of coarse siliciclastic sediments from the southern source area.

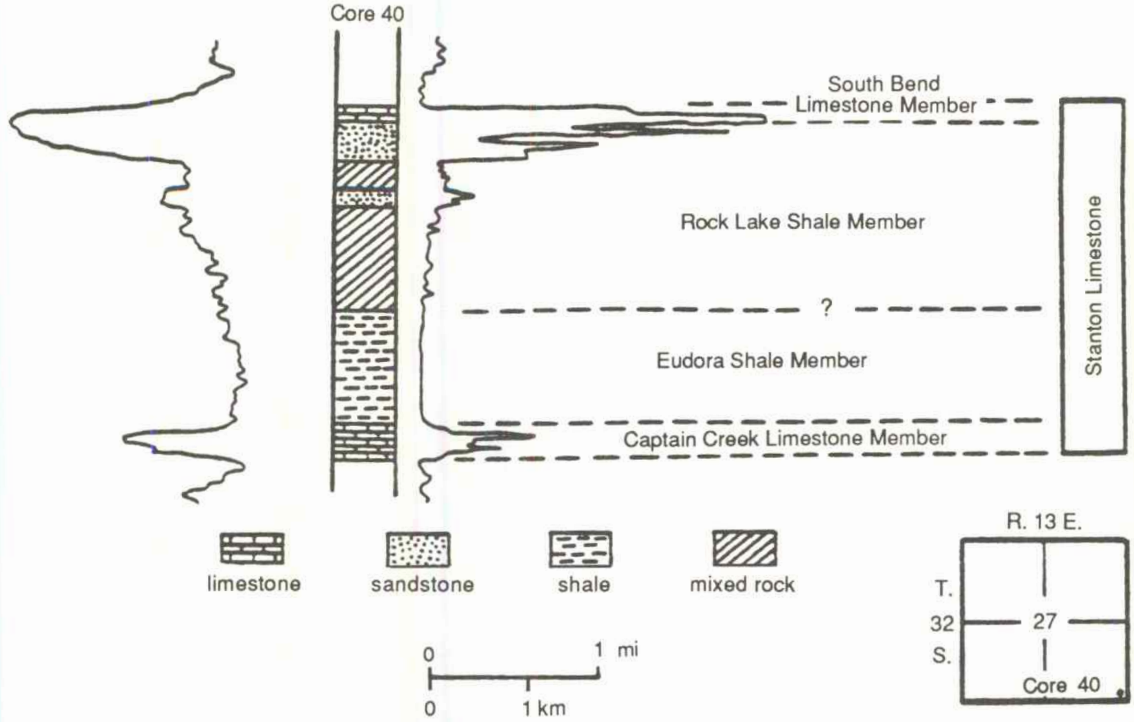


FIGURE 27—Lithologic interpretation of well-log signatures of Stanton Limestone 4 mi (6.4 km) west of outcrop in detrital facies belt.

Process-response depositional model for the Rock Lake Shale Member of the Stanton Limestone in the detrital facies belt

By combining data from regional stratigraphic studies, outcrop observations, and well-log interpretations, I have developed a depositional model for sandstones and shales of the Stanton Limestone in the detrital facies belt of southeastern Kansas. This model is a process-response model developed by asking the following question: Given the regional geologic setting of the Pennsylvanian sea, what reasonable processes based on modern analogues could have formed the physical characteristics of the rocks observed today (Brenner, 1980)? Reconnaissance study by earlier workers suggested that siliciclastic sediments of the Stanton Limestone may have been deposited in deltaic environments (Wilson, 1957a,b; Harbaugh, 1962; Kenny, 1968; Heckel, 1975a, 1975b, 1977, 1978). The older Chanute Shale of the Kansas City Group (fig. 1) has been interpreted as a deltaic deposit with a southerly source (Haggiagi, 1970). S. L. Brown (1967) stated that the younger Elgin Sandstone Member of the Virgilian Stage exposed in Chautauqua County, Kansas, had a source from the south and was deposited in deltaic distributary channels. The older Warner, Little Cabin, and Hartshorne sandstones (Desmoinesian Stage, Middle Pennsylvanian) in northern Oklahoma were deposited in deltaic environments with an easterly source from the Ozark dome area (Scruton, 1950). L. R. Brown (1969, 1973, 1979) interpreted the Upper Pennsylvanian sandstones and shales in north-central Texas as deltaic deposits. The Coffeyville Formation (Lower Missourian) of northern Oklahoma was interpreted as a deltaic deposit with a southerly source by Visher et al. (1975).

The Rock Lake Shale Member was deposited during a regressive phase of cyclic deposition characteristic of the Pennsylvanian epicontinental sea in midcontinent North America (Heckel, 1977, 1980). In the present study sedimentologic analysis and facies relationships between different units of the Rock Lake siliciclastics in both surface exposures and subsurface well logs in the detrital facies belt strongly suggest that these rocks were deposited in a fluvial-dominated deltaic environment. Thinning of offshore shales and concomitant thickening of sand units toward the south (figs. 13 and 14), in conjunction with unidirectional trough cross-beds to the northwest (fig. 22) in sandstone outcrops, suggest that the Rock Lake sediments entered the basin from the south and southeast of the study area. The presence of well-rounded quartz overgrowths and the dominance of rounded, well-sorted quartz grains in the quartzarenitic sandstones of the Rock Lake Shale Member suggest that the source was preexisting sedimentary rocks, probably in the tectonically active Ouachita Mountain belt.

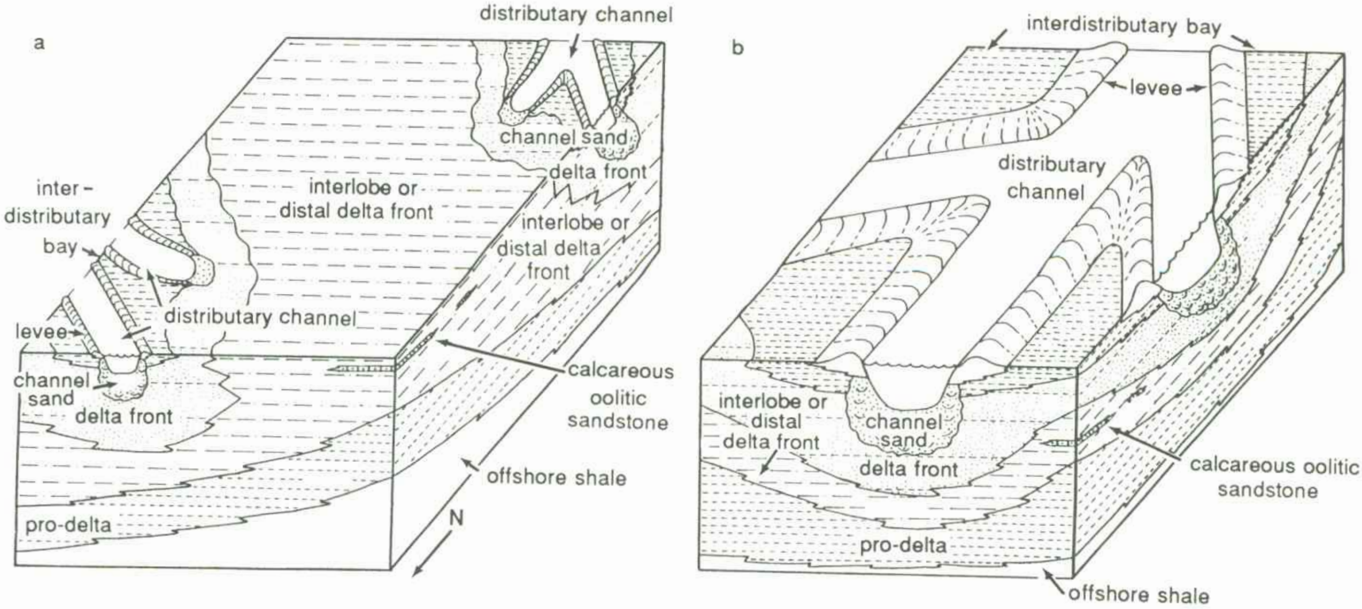


FIGURE 28—PROCESS-RESPONSE DEPOSITIONAL MODEL for Rock Lake Shale Member of Stanton Limestone in detrital facies belt. (a) Early regression. (b) Late regression.

Based on the information presented here, I propose a two-phase process-response model for the siliciclastic sediments of the Rock Lake Shale Member of the Stanton Limestone in the detrital facies belt.

Phase 1

During early regression (fig. 28a), the delta complex was located to the south and southeast of the study area. Because of the low rate of detrital influx, a thin sequence of offshore mud with marine fossils (clayey shale of the Eudora Shale Member) formed in the detrital belt. Progradation of the delta to the north caused the thick sequence of clayey and silty mud of the prodelta to be deposited from suspended sediments under quiet, relatively offshore marine conditions, forming the lower Rock Lake Shale Member (and the upper Eudora Shale Member, where thick). The boundary between these two shale units is gradational and ascends northward in the study area. As the delta prograded to the north, interbedded very thin bedded, very fine grained to fine-grained sands, silts, and muds were deposited in distal delta-front environments and interlobe areas (fig. 28a) under variable water depths and low-energy conditions. These beds contain a few scattered marine fossils, such as echinoderms and brachiopods, in the lower part of the Rock Lake Shale Member in the southern portion of the detrital facies belt.

The presence of lenses of calcareous oolitic sandstone with crossbeds and scattered marine fossils (third and fourth oolites) in southern Montgomery County (T. 34 S. and T. 35 S.) indicates that the water was locally shallow and agitated. This allowed the oolitic sands to be formed and deposited in areas away from active detrital influx (fig. 28a). Gradational contacts between these oolitic sandstones and sandstone units below suggest that the constituent grains of oolite formed nearby or in place. The presence of stenohaline echinoderms indicates that nearly normal marine salinity was established during deposition of these calcareous horizons. Lateral discontinuity of the beds within each possibly correlative horizon suggests two possible factors in the deposition of these units: (1) They formed only in the most shallow and thus warmest and most agitated water on local highs in the broad interlobe areas, or (2) they formed in local areas only during times of generally reduced detrital influx, perhaps when dry climates prevailed.

Phase 2

Both eustatic lowering of sea level during later regression and slow subsidence of the prodelta deposits allowed the delta front to prograde northward in the study area. As the delta prograded, coarse-grained sand was transported into southern Kansas and deposited as interbedded thin-bedded delta-front sands and muds (fig. 28b). The presence of a few scattered marine fossils in these units indicates that deposition was still slow enough to allow these organisms to live under slightly turbid conditions.

Northward, progradation of the delta caused distributary channels to cut into previously deposited delta-front sandstones and shales. This was a time of more rapid detrital influx from the source area. In later Rock Lake time conglomeratic channel-lag deposits with unidirectional grooves and erosional bases were deposited under high flow regime conditions to the upper part of the lower flow regime conditions in the distributary channels. These rocks are overlain by massive to thin-bedded, medium-grained sands with unidirectional trough crossbeds (fig. 22). Grading laterally from the channel-fill deposits, interbedded silts and silty or clayey muds were deposited in interdistributary bays from suspen-

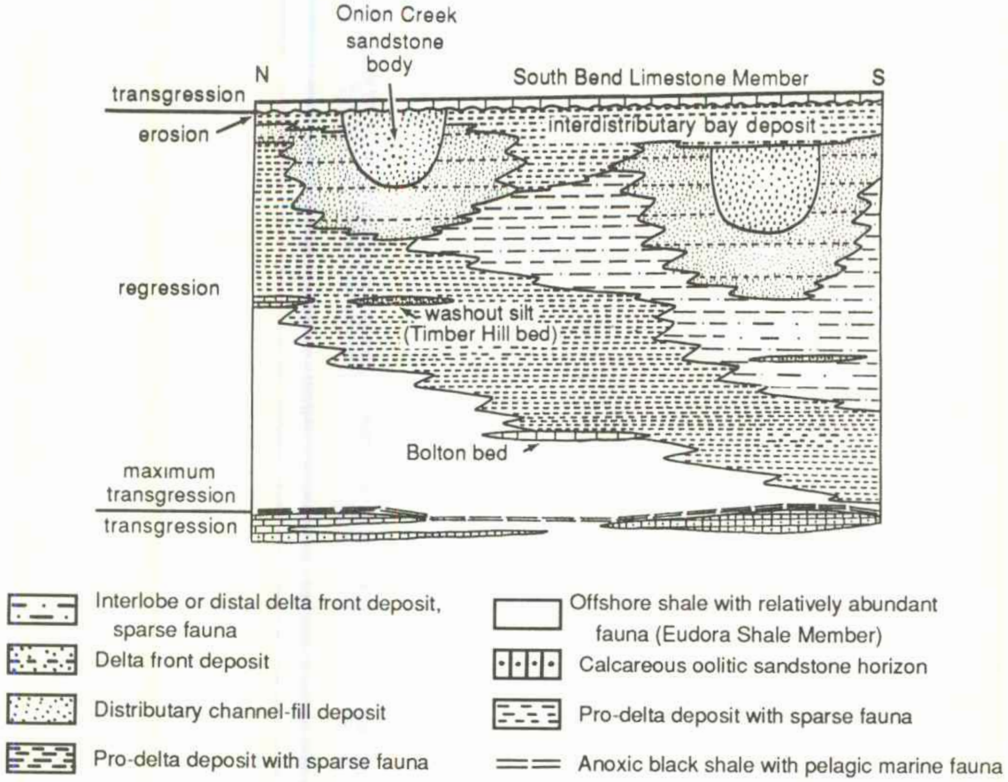


FIGURE 29—IDEALIZED NORTH-SOUTH CROSS SECTION OF STANTON LIMESTONE in detrital facies belt showing probable relationships among different facies. All dash-dot patterned areas between top of Eudora Shale Member (white) and base of South Bend Limestone Member (wavy line) constitute the Rock Lake Shale Member in this area. For location, see figs. 2 and 4.

sion under low-energy (current and turbulence) conditions.

An idealized north-south cross section across the detrital facies belt (fig. 29), based on surface and subsurface data, shows the relationships among the different facies of Stanton siliciclastics. Maximum transgression is indicated by the offshore phosphatic black and dark-gray fissile shale with mostly pelagic marine fossils. This shale was deposited slowly under low-oxygen bottom conditions (Heckel, 1977, 1980) during early Eudora time. The black shale grades upward into gray clayey shale with a diverse benthic and pelagic marine fauna deposited under higher-oxygen bottom conditions. As the delta prograded into the southern part of the study area, siltier mud of the prodelta was deposited more rapidly on top of the offshore shale in the south. At the same time, this increasing rate of detrital influx to the north caused deposition of a thicker sequence of marine mud, forming the upper part of the thicker Eudora Shale Member to the north.

At the top of the offshore shale between T. 33 S. and T. 34 S. is a skeletal calcarenite (Bolton bed) that contains a normal marine fauna of unabraded fossil material and scattered oolites. All evidence derived from this study supports the interpretation of Heckel (1975b) that this limestone lens was deposited in a quiet-water, offshore environment under low sediment influx, into which ooids were periodically transported from a more strongly agitated shoal.

As the delta prograded to the north, very thin bedded sands, silts, and muds of the interlobe or distal delta front were deposited progressively northward over the prodeltaic mud in the southern portion of the detrital facies belt (fig. 29). At the same time, the prodelta moved northward into the northern portion of this belt. Lenses of calcareous oolitic sands (third and fourth oolites) formed in the southern area, perhaps during times of generally lessened detrital influx within this sequence (figs. 28a and 29). During a period of rapid detrital influx, a pulse of silt-size sediment was washed, perhaps by storm-generated floods, from interlobe or distal delta-front deposits and deposited and then reworked as a fairly clean silt lens (Timber Hill bed) within the muddy prodelta deposits in the northern end of the detrital facies belt (fig. 29).

Continued sediment influx with little delta subsidence eventually allowed the distributary channel to move into the southern part of the study area and to cut through the delta-front silt and sand (figs. 28b and 29). The erosional contact beneath the conglomerate at the base of the channel records high flow regime conditions, which left channel-lag deposits. A subsequent decrease to the higher part of the lower flow regime left massive to thin-bedded sandstones with unidirectional trough crossbeds within the distributary channel. Small-scale channel cut and fill structures in these segments probably represent periods of rapid increase in detrital influx in the lower flow regime in the channel. As the distributary channel was abandoned and shifted northward along the eastern margin of the sea, it became filled with finer sediments, leaving interbedded very fine grained to fine-grained sands and silty mud at the top of the channel fill, which grades upward into interdistributary muds deposited from suspension.

Deltaic distributary channel deposits are similar to alluvial channel deposits. Fining-upward sequences in fluvial distributary channels are related to slow lateral migration of channels or, more abrupt, channel abandonment. Finer-grained sediment toward the top grades into overbank flood sediment of an adjacent active channel (Reading, 1978). The presence of marine organisms in the lower sandstones and shales and partly equivalent third and fourth oolite horizons in conjunction with lateral relationships between the different units of the Rock Lake and upper Eudora shale members indicates that these channels are deltaic distributary channels rather than alluvial systems. Interbedded very thin bedded (locally laminated), very fine grained sandstone or siltstone and clayey to silty shales (between T. 33 S. and T. 34 S. in the vicinity of Wayside along US–75) were probably deposited in an interdistributary bay. It is possible that delta-front sands may have formed as bar-finger sands similar to those of the Mississippi delta complex described by Fisk (1961). However, poor exposures and insufficient subsurface control make this a conjectural interpretation.

As distributary channel systems shifted to the north (T. 33 S.), delta-front sands and muds were deposited. These are represented by the lower part of the Onion Creek sandstone body (fig. 29). Subsequently, the Onion Creek distributary channel system cut through these delta-front deposits as sediment influx increased without much subsidence of the delta, producing the massive upper part of the Onion Creek sandstone.

This was probably the last major deltaic system established before the time of maximum regression in the exposed portion of the detrital facies belt, because the Onion Creek sandstone is overlain by the basal conglomeratic quartz sandstone of the South Bend Limestone Member, which records early marine transgression on the erosional surface (Heckel, 1975b) that records maximum regression. Further transgression to below wave base is recorded by the widespread calcilutite at the top of the South Bend Limestone Member (Heckel, 1975b).

The Rock Lake deltaic system is different from most well-known modern deltaic systems because of the association of the deltaic facies with extensive carbonate deposition on the Pennsylvanian stable cratonic shelf of North America.

Paleogeographic summary

During the Middle Pennsylvanian thick sequences of deltaic sediments with a northerly source were deposited in northern Oklahoma (Visher et al., 1971). The major sources for clastics during this time were the Appalachian Mountains far to the east, the Ouachita Mountains and the Amarillo–Wichita uplift to the south, the Canadian Shield to the north, the Nemaha Ridge to the west, and the ancestral Rocky Mountains far to the west (fig. 30). The Ouachita, Canadian, and Nemaha sources were most accessible to the area of study. Periodically the sea transgressed to the north, establishing a broad carbonate shelf over much of the midcontinent and resulting in cyclic sedimentation (Wanless, 1967; Moore, 1979).

During the early Missourian (early Late Pennsylvanian) the Nemaha uplift became thinly covered by marine carbonate sediment (Moore, 1979) and was no longer a significant source of clastic sediments in the southern midcontinent. By late Missourian time the northern midcontinent was characterized by a shallow carbonate shelf, resulting in a relatively thick sequence of predominantly carbonate sediments in this region.

The series of major transgressions and regressions that caused widespread units of cyclic sedimentation in the midcontinent throughout the Middle and Late Pennsylvanian reflect eustatic sea-level changes related to glaciation in Gondwanaland (Wanless and Shepard, 1936; Crowell, 1978; Heckel, 1980). In the units studied, initiation of a major transgressive sequence is represented by the upper part of the Vilas Shale. Further transgression is marked by the widespread Captain Creek Limestone Member and equivalent Tyro oolite. Maximum transgression is represented by the thin black phosphatic facies of the Eudora Shale Member (fig. 29).

The Rock Lake Shale Member of the Stanton Limestone in the detrital facies belt of southern Kansas was deposited during the entire regressive phase of deposition, whereas the Stoner Limestone Member formed to the north (figs. 4 and 14). Thickening of siliciclastic sediments toward the southeast (figs. 12 and 13) in conjunction with dipping of unidirectional trough crossbeds to the northwest (fig. 22) in this area indicate that the source area for the detrital belt was the Ouachita Mountains, which were uplifted earlier in the Pennsylvanian (fig. 30). Deposition of the lower part of the Rock Lake Shale Member occurred as deltas encroached on the detrital belt of southeastern Kansas (fig. 28a). At the same time, Stoner carbonates were forming to the north. The general mean azimuths of ripple marks in the upper Rock Lake Shale Member toward the south and west (fig. 21) suggest that currents generated by the prevailing winds were moving from northeast to the southwest, which coincides with the trade winds direction (fig. 30) postulated by Heckel (1980).

As the sea started to withdraw from the detrital facies belt toward the west, the upper part of the delta complex prograded into the study area from the south and southeast (fig. 28b). Distributary channel-filling sands and finer-grained interdistributary bay sediments were deposited in the study area, where they are represented by sandstones, siltstones,

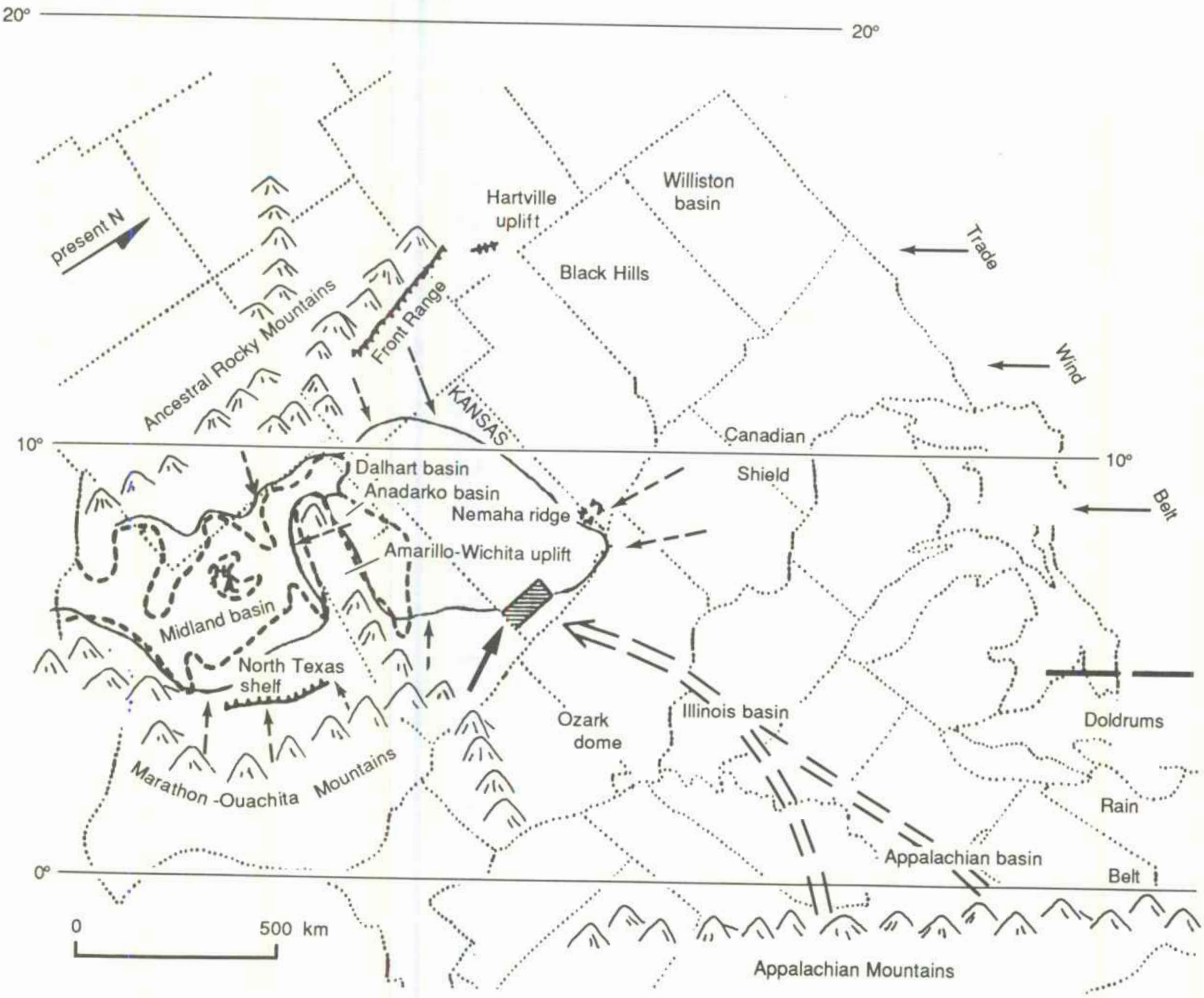


FIGURE 30—Paleogeography and source of siliciclastic sediments during deposition of Rock Lake Shale Member (Missourian Stage, Upper Pennsylvanian) in central United States [modified from Heckel (1980)]. The Nemaha Ridge is covered by upper Missourian deposits. Shaded area is area of study. Solid line indicates probable extent of epicontinental sea during early Rock Lake deposition. Dashed line represents approximate boundary of basins in West Texas–Oklahoma area. Solid arrow shows definite source of Rock Lake siliciclastics. Dashed arrows show less likely sources of Rock Lake siliciclastics.

and shales of the upper Rock Lake Shale Member. Further withdrawal of the sea to maximum regression is represented by the erosion surface at the top of the Rock Lake Shale Member below the conglomeratic basal South Bend Limestone Member in southeastern Kansas, in which clasts of diverse origin represent a variety of lithic materials available on the erosion surface (Heckel, 1975b).

The two marine channel-filling sandstones of the Rock Lake Shale Member in the northern part of southeastern Kansas had their immediate source to the east, with sediment from a more eastern deltaic environment washed into preexisting depressions in the Stoner carbonate shelf of Wilson and Woodson counties (fig. 25). This indicates that deposition of the Rock Lake Shale Member in the algal-mound facies belt took place mainly during the late regressive phase of deposition, when the sea was withdrawing from the Stoner carbonate shelf in the northern part of the study area.

Summary and conclusions

A holistic approach to studying a stratigraphic unit requires using all data available. For this study I used surface outcrops, subsurface cores, geophysical well logs, drillers' logs, and thin sections of rock samples to decipher stratigraphic, petrographic, and sedimentologic characteristics of sandstones in the Rock Lake Shale Member of the Stanton Limestone.

Subsurface isopach and sandstone-isolith trends of the Rock Lake Shale Member in southern Kansas thin toward the northwest, strongly suggesting a southeasterly source of siliciclastics. The Rock Lake Shale Member contains five distinct sandstone units, informally labeled A–E, in the near subsurface of the detrital facies belt of eastern Chautauqua County, Kansas (fig. 14). Unit A cuts through the underlying Eudora Shale Member and Tyro oolite in T. 34 S. just north of the Oklahoma border and is the oldest sandstone in the Rock Lake Shale Member. Unit B developed later, south of unit A. Unit C is a thin sandstone that lies above unit A and slightly higher than unit B; it appears to be the youngest sandstone in the southern part of the detrital facies belt. Unit D is found only in the middle of the detrital facies belt and may have been deposited penecontemporaneously with units A and B. Unit E is the youngest sandstone in the northern part of the detrital facies belt and appears to be the subsurface extension of the Onion Creek sandstone. These sandstones are separated from each other mostly by mudrocks, and the whole interval is capped by the marine transgressive South Bend Limestone Member, which can be traced from the algal-mound facies belt southward across the detrital facies belt into Oklahoma.

Petrographic analyses indicate that the sandstones of the Rock Lake Shale Member were derived from older sedimentary rocks. Monocrystalline quartz is by far the predominant grain type, averaging 95–96% of the grain components. The relatively rare lithic fragments in the quartzarenites are mainly chert and polycrystalline metamorphic quartz. High degrees of textural and mineralogic maturity indicate a long, repeated transportation history, which in some cases included marine reworking. Low grain-to-grain contact densities indicate that these sandstones underwent only shallow burial and minimal compaction before early cementation.

In order of decreasing abundance, cement types consist of calcite (including ferroan calcite), iron oxides, sericite, and silica. An early stage of calcite cementation probably resulted from meteoric solution of carbonate fossil fragments and adjacent emergent carbonate buildups, when the deposits were emergent during later regression before the South Bend transgression. Pore fluids changed during subsequent transgression and again became supersaturated with carbonate, probably because of warming concomitant with deeper burial. Hydrolysis of feldspars, conversion of expandable clay minerals to mixed-layer varieties in adjacent compacting shales, and dissolution of siliceous fossil fragments resulted in quartz overgrowths on partially compacted quartz grains. Sericite cement also resulted from hydrolysis of feldspars. Iron oxide cements, which are common in outcrop samples but relatively rare in subsurface samples, appear to have resulted from oxidation of ferroan carbonate cements and iron-bearing ground waters related to the modern weathering regime. Replacement of silica by calcite and vice versa were probably related to postdepositional changes in pH and temperature of the pore waters within Rock Lake sandstones. Replacement of calcite by pyrite in carbonate shell fragments probably occurred in low Eh environments created by decay of the organic matter of the shell-forming organism.

Sandstone units in the lower part of the Rock Lake Shale Member are for the most part very fine grained to fine-grained and commonly exhibit ripple marks and cross-laminations and carry sparse marine fossils. In contrast, the sandstones in the upper portion of this member are generally nonfossiliferous and fine- to medium-grained and contain both planar and trough crossbedding. They often form fining-upward sequences with erosional bases. These observations suggest that this member was deposited as a regressive sequence. The lower sands formed under relatively low-energy conditions at the margin of a sea, whereas the higher sands formed under higher-energy conditions in channels, which show the characteristic waning-upward energy sequence of point-bar deposits. Transport directions measured from trough crossbedded sets are to the north and northwest, which supports the isopach–sand isolith indications of a southeastern siliciclastic source.

Using the stratigraphic, petrographic, and sedimentologic data and interpretations and relating these to the regional setting in which the sediments represented by the Rock Lake Shale Member were deposited, I developed a process-response model. This model depicts a fluvially dominated deltaic system that was active during the regressive depositional phase of the Stanton cycle within the Upper Pennsylvanian epicontinental sea. The Rock Lake deltaic system consisted of several lobes, which developed initially in the southern part of the detrital facies belt. After deposition of sediments associated with the initial lobes ceased, new lobes formed to the north along the eastern margin of the Missourian seaway in response to the northward shifting of the sediment-laden fluvial systems. The Timber Hill siltstone may represent the marine reworking of a washout from one of the lobes, and the Onion Creek sandstone represents one of the later delta lobes that formed in the detrital belt. The third and fourth oolite quartz sandstone horizons may represent shoal-water deposits on local highs in interlobe positions that received reduced amounts of siliciclastics, possibly during dry periods. The channel sandstones in Wilson and Woodson counties may represent sands from a now-eroded eastern lobe that were washed westward across the carbonate shelf and into preexisting low areas on the carbonate surface. The mechanism for the seaward movement of sediment is unclear, but it probably was related to unusually high discharges from storms and floods.

The most probable source of siliciclastic sediments of the Rock Lake Shale Member of the Stanton Limestone is eroded quartzose sedimentary rock from the uplifted Ouachita Mountains (fig. 30). This stands in contrast to both older Missourian sandstones in the Kansas City area and to much older Desmoinesian channel sands in southeastern Kansas, which have much higher percentages of unstable minerals and reflect immature, nearby sediment sources. Thus Appalachian and Canadian Shield sources contributed little if any siliciclastic sediment to late Missourian deposits in southeastern Kansas.

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