ENVIRONMENT OF DEPOSITION OF THE GRENOLA LIMESTONE (LOWER PERMIAN) IN SOUTHERN KANSAS

By

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ABSTRACT

Study of the Grenola Limestone (Lower Permian) in the type area, Elk and Cowley Counties, Kansas, indicates that the formation was laid down under generally transgressive conditions, resulting in full development of a lower molluscan phase and an upper molluscoid-fusulinid phase. The Legion and Salem Point Shales represent pauses or slight shallowing in the generally transgressive hemicycle. During the time these members were being laid down, clay-size clastic material was the dominant sediment. Limestones in the formation resulted from deposition of fine-grained to granular calcium carbonate mud.

Except for phases "3" and "5", Elias' Permian cyclothem is well developed in the Grenola formation. The molluscan phase is inferred to be represented by pectinoid limestone, "osagite", and ostracode-bearing shales, which contain intercalated molluscan limestones. Shales containing charophytes may be equivalent to the *Lingula* phase.

The molluscan phase is characterized by a *Cavellina-Hollinella-Tetrataxis* microassemblage. The molluscoid-fusulinid phase is characterized by a *Climacammina - Glyphostomella - Bairdia* microassemblage. Thickness of chert- and fusulinid-bearing limestones in the Neva member increases southward in the area studied. It is postulated that "osagite" beds in the Sallyards and Burr Limestones are the result of wave or current sorting. *Osagia* is found to be an intergrowth of ?algae and *Ammovertella,* an arenaceous, incrusting foraminifer.

INTRODUCTION

Purpose

This investigation is an attempt to reconstruct the environment of deposition of the Grenola Limestone. A detailed study of the beds is necessary to accomplish this end; consequently, the study was restricted to the type area of the Grenola formation in Elk and Cowley Counties, Kansas (Fig. 1). The analysis required is essentially threefold, involving techniques of stratigraphy, sedimentation, and paleontology.

Stratigraphic Position of Grenola Limestone

The Grenola Limestone, consisting of five members (Fig. 2), crops out across Kansas in a south-southwest direction from eastern Nebraska into northern Oklahoma. The Grenola is a part of the Council Grove Group, Wolfcampian Series, of the Permian System. The formation is bounded below by the Roca Shale and above by the Eskridge Shale. These two shales are soft, contain only thin, nonresistant limestone strata, and are usually

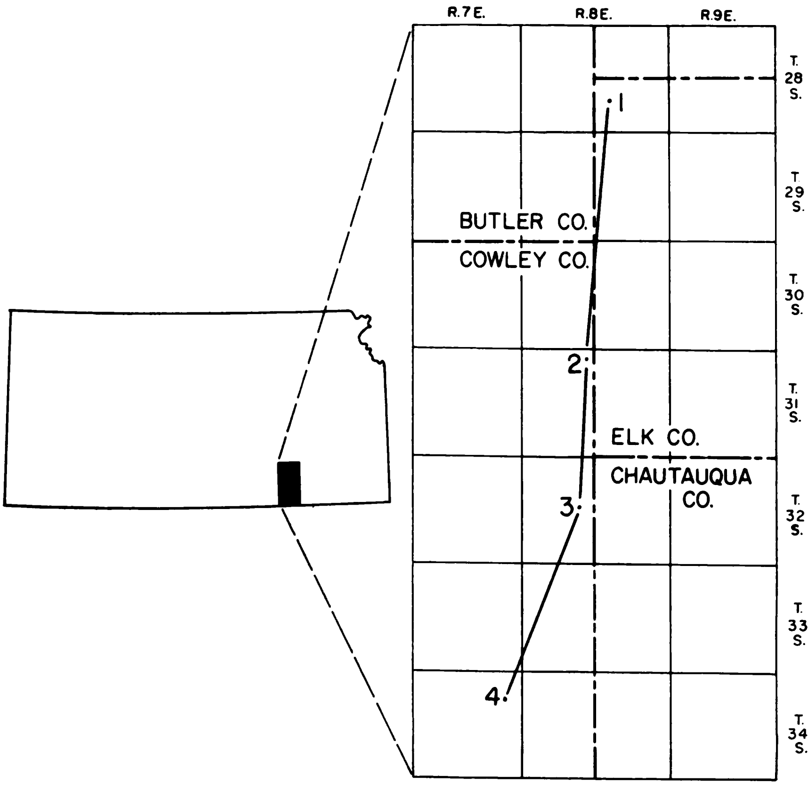

FIG. 1.—Index map showing locations of measured sections. Locality 1, cen. NE¼ sec. 27, T. 28 S., R. 8 E., on Ferrley Ranch, 100 yards east of ranch house, along banks of Elk River. Locality 2, SW¼ sec. 4, T. 31 S., R. 8 E., cuts along Santa Fe Railroad and in small stream near the railroad, just west of Murphy oil pool. Locality 3, W½ sec. 21, T. 32 S., R. 8 E., cut along Kansas Highway 38, 12 miles north and 2 miles west of Cedarvale. Locality 4, NE¼ SW¼ and SE¼ NW¼ sec. 12, T. 34 S., R. 7 E., cuts along Missouri Pacific Railroad, 300 yards south of U.S. Highway 166, 6.7 miles west of Cedarvale.

poorly exposed, but good marker beds occur above and below them. Below the Roca Shale, in southern Kansas, is the thick limestone ledge of the Red Eagle Limestone, which has been described in detail by O'Connor and Jewett (1952). Above the Eskridge Shale, the thin white fusulinid-bearing Cottonwood Limestone member of the Beattie Limestone crops out. The Cottonwood is easily recognized by the position next beneath Florena Shale, the prolific fauna of which is marked especially by abundant robust specimens of *Chonetes granulifer*. The position of the Grenola in the Council Grove Group is indicated in Table 1.

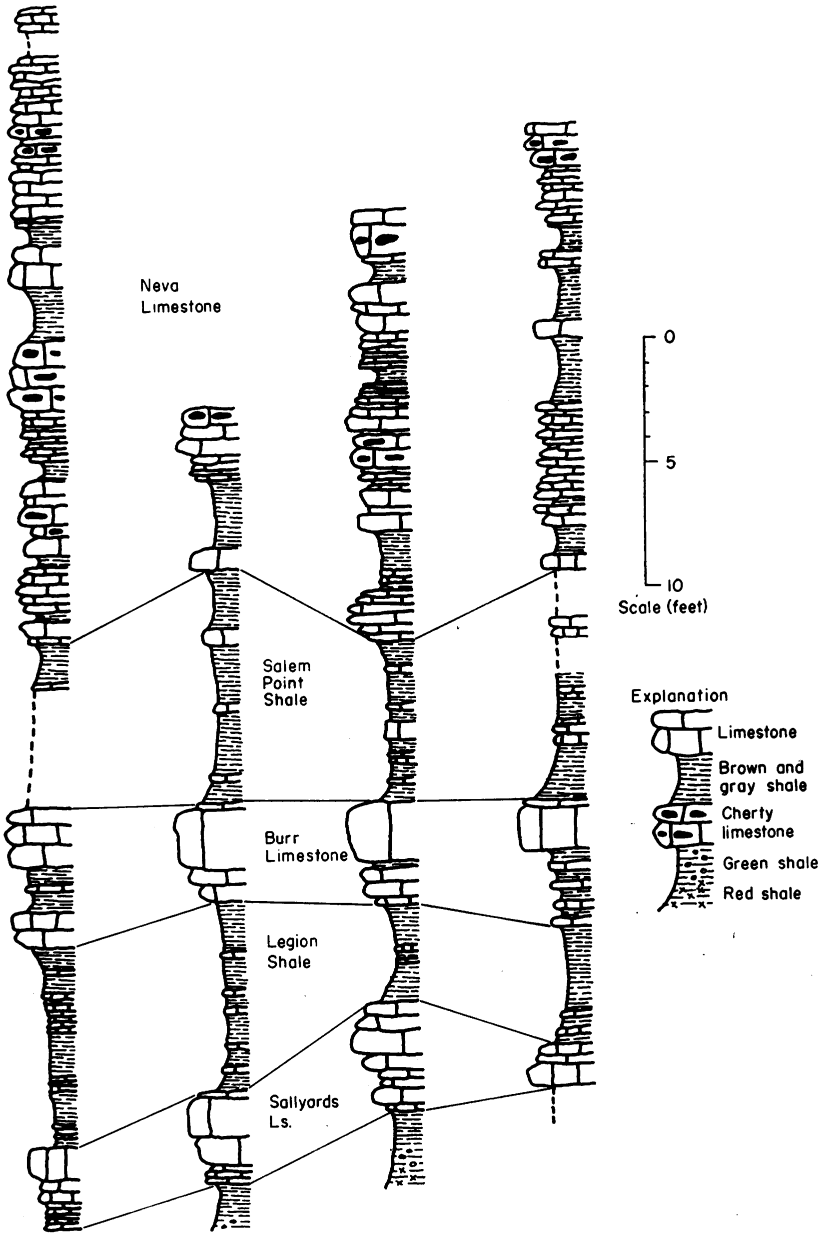

FIG. 2.—Correlation of Grenola Limestone and its members in Cowley and Elk Counties, Kansas. Localities 1 to 4, from right to left.

TABLE 1.—*Formations in the Council Grove Group, Lower Permian*

Chase Group
Council Grove Group
Speiser Shale
Funston Limestone
Blue Rapids Shale
Crouse Limestone
Easly Creek Shale
Bader Limestone
Stearns Shale
Beattie Limestone
Eskridge Shale
GRENOLA LIMESTONE
Roca Shale
Red Eagle Limestone
Johnson Shale
Foraker Limestone
Admire Group

PREVIOUS STUDY

The Grenola Limestone was not recognized as such during the early days of reconnaissance geology in Kansas. The first published reference to the Permian rocks of Kansas was by Swallow and Hawn (1858). Later, Swallow (1866), while working for the Kansas Geological Survey, published a report in which his "bed 84" was described as the "dry bone" limestone. This bed is now part of the Neva member. Swallow placed the Pennsylvanian-Permian boundary at the base of this bed. Hay (1893) included the present Grenola in what he called the Permo-Carboniferous, as he regarded the rocks from the Americus Limestone to the Fort Riley Limestone as transition beds between the Carboniferous and the Permian. The Neva member was thus involved in what has been termed the Pennsylvanian-Permian boundary dispute during the earliest days of Kansas geology.

Prosser (1895) included what is now the Grenola in his Wabaunsee Formation, which extended from what is now the Silver Lake Shale in the Sacfox Subgroup of the Waubaunsee Group to the base of the Cottonwood Limestone, in the present Beattie Limestone. This single stratigraphic unit of Prosser's classification now includes 34 recognized formations in Kansas and many more members. In the same year, Prosser (1895a) named the Neva Limestone, occurring 11 to 31 feet below the base of his Manhattan (=Cottonwood) Limestone. The placement of the present Grenola was not affected when Haworth (1896) moved the base of the Wabaunsee Formation upward to the base of the Burlingame Limestone. The reconnaissance nature of this early work may be realized by noting the statement by Haworth (1896):

"Throughout the whole of the Waubaunsee formation only one limestone is of any special interest, the heavy coarse looking system [Neva] lying about 30 feet below the Cottonwood Falls rock . . ."

In the same volume, Kirk (1896) applied the name Dunlap Limestone to the two strata occurring 20 to 25 feet below the "Cottonwood Falls rock". These limestone beds are separated by about 20 feet of blue shale. Condra and Busby (1933) did not regard this name as valid for the rocks they called the Grenola Formation, because Dunlap Limestone, as used by Kirk, seemingly included the upper part of the Red Eagle Limestone. Consequently, the name Dunlap Limestone was dropped.

In a revised classification of the upper Paleozoic of Kansas, Prosser (1902) included the present Grenola in the Missourian Series of the Upper Carboniferous and assigned it to the Wabaunsee Stage, the boundary between Wabaunsee and Council Grove deposits being placed at the base of the Cottonwood Limestone. Within this stage, he set up the Elmdale Formation, 130 feet thick, which extended from the top of the Americus Limestone to the base of the Neva Limestone. It may be seen that classification gradually became more refined as the recognition of beds became certain.

Bass (1929) included the Neva Limestone as a member of the Elmdale Formation, which by this time had been restricted in thickness to about 80 feet. Bass placed the lower boundary of the Permian at the base of the Cottonwood Limestone.

Condra and Busby (1933), studying Lower Permian strata in Nebraska, Kansas, and Oklahoma, gave the name Grenola Formation to the rocks previously termed Neva Limestone. The name Neva Limestone was restricted to the upper limestone member, and the names Salem Point Shale, Burr Limestone, Legion Shale, and Sallyards Limestone were given to the lower four limestone and shale members. This assignment is now in current use, although for several years after Condra and Busby's definitive paper the Kansas Geological Survey did not recognize the lower limestone and shale members (Sallyards Limestone and Legion Shale) but included them in the upper part of the Roca Shale.

Moore and Moss (1934) placed the Pennsylvanian-Permian boundary at the lower limit of the Indian Cave Sandstone member of the Towle Shale (Admire Group), thereby classifying the Grenola in the Lower Permian.

TECHNIQUES

Field Techniques

A lithologic sample of each limestone bed of the Grenola Limestone was collected at each locality where studies were made. Only one sample was taken where several 2- to 3-inch strata of limestone were indistinguishable in the field. The fauna of each bed was collected as completely as possible. The shale beds were sampled by digging a shallow trench and collecting the freshly exposed shale. Shales less than a foot thick were sampled as units, but thicker shale beds were sampled between color changes. Generally, shale partings less than 1 inch thick were not sampled. The top of each limestone sample was marked with drafting tape. Thicker strata of limestone, such as the upper massive bed of the Burr Limestone, were sampled at the top and bottom of the stratum.

All measurements of exposed rock were made with a steel tape and hand level. Covered intervals were measured with a hand level.

Laboratory Techniques

A portion of each shale sample was broken down and deflocculated; clay particles were decanted, and after the residue was dried slowly over a steam radiator it was examined for microfossils. Shales that disintegrated in water were not treated further, but indurated shales were soaked in water, boiled 15 or 20 minutes, and then the clay was decanted. A special procedure was used for the most indurated shales. They were soaked in kerosene for 10 to 20 minutes, the kerosene was poured off and water added, and the mixture allowed to stand overnight; most samples were reduced to a soft mud in that length of time. Some very calcareous shales would not break down by the kerosene method, and these were either mechanically crushed and retreated with kerosene or classed as limestones. For convenience in examination, the washed shales were sieved into three sizes.

Some shales were treated by placing several small chips of fresh shale in a watch glass, covering them with water, and then adding 2 or 3 drops of hydrochloric acid. The degree of effervescence was noted, and when all carbonate material had been dissolved, the sample was washed and decanted several times to remove the clay fraction. Then the sample was dried and the coarse fraction examined for mineralogical composition.

The top of each limestone sample was marked with a grease pencil instead of the drafting tape used in the field. A slab, approximately 1.0 cm thick and perpendicular to the bedding, was cut from each limestone sample, and then one side of the slab was ground smooth with 500-grit carborundum powder. The smooth side then was etched 1 to 2 minutes in 5 percent hydrochloric acid. It was found that etching for longer periods of time created too much relief on the surface, so that carbonate material was partly hidden by high-standing noncarbonates. The sample was then gently dipped in a pan of water to remove the acid, and dried. Etching with weak acetic acid was tested, but this acid did not provide clear differentiation between matrix and organic particles.

Care was necessary in order that the etched surface was not rubbed in any way after preparation, for rubbing crumbles the delicate argillaceous or siliceous material that stands in relief.

Cellulose-acetate peels were made from some of the limestone slabs. Comparison of peels and slabs under a binocular microscope revealed that direct observation of etched surfaces was preferable. Peels in this study had two main shortcomings: (1) they did not show color contrasts, and (2) noncarbonate material could not be distinguished clearly from carbonate material. Limestone slabs do not show the microstructure of organic particles and are difficult to photograph. Both methods must be used for a complete study.

If etched surfaces showed osagite-like structures, a portion of the sample was broken up and dissolved in hydrochloric acid. In addition, thin sections were prepared of selected beds that contained algal-like structures.

PLATE 1. **A.** Sallyards Limestone member at locality 3. **B.** Osagite limestone, upper part of Sallyards member, locality 2. Note incrustations around shell fragments and gastropods. White layers are *Ammovertella*, gray are ?algae (×10). **C.** Burr, Salem Point, and Neva members at locality 3.

STRATIGRAPHY

Sallyards Limestone Member

The Sallyards Limestone member, which is the lowest subdivision of the Grenola Limestone, was named by Condra and Busby (1933) from exposures near Sallyards, Greenwood County, Kansas (Pl. 1A, C). The description given by Condra and Busby (p. 19) for the type locality is as follows:

"Sallyards limestone, bluish-gray, top rough, weathers light gray to yellow with shale re-entrant, contains *Myalina, Aviculopecten,* gastropods, *Chonetes,* bryozoa, and crinoid joints, 2′ 6″."

The Sallyards member is underlain by the Roca Shale, which consists of red, green, and gray to light-brown shale. Directly below the Sallyards Limestone the Roca Shale is light brown and clayey to slightly silty. This brown shale is underlain by green and light-maroon clay shale that is unfossiliferous. The upper boundary of the Sallyards member is marked by a limestone stratum, 4 to 12 inches thick, above which occurs the Legion Shale member, which locally contains strata of thin impure limestone.

Physical character.—The Sallyards limestone member contains no shale breaks or partings in observed exposures (Fig. 2). The color ranges from light yellow brown to dark blue gray. Thickness of individual beds ranges from 1 inch to 2 feet. Insoluble residues from limestone in the Sallyards consist almost entirely of the tests of *Ammovertella,* an arenaceous foraminifer (Fig 3). A very few silt-size quartzose particles are present, which may be portions of *Ammovertella* tests.

Fig. 3—*Ammovertella* etched from Sallyards Limestone at Locality 2 (×25)

Organic character.—Two distinct divisions of the Sallyards limestone are distinguished on the basis of contained organic material. The lower division is characterized by a sparse distribution of long (0.1 to 3.0 cm) shell fragments, small gastropods, and ostracodes. These limestones are thin bedded, gray to yellow brown, and argillaceous, and range from 0.8 to 1.7 feet in thickness. The long shell particles may or may not be covered with an incrustation of *Osagia*-like material and *Ammovertella* tests. These coatings are found on one or both sides of a fragment and have a maximum thickness of 1.0 mm. Only part of the shell particles in any examined limestone sample shows these incrustations.

The upper limestone division of the Sallyards member contains abundant *Osagia,* high- and low-spired gastropods 2 to 3 mm high, and ostracodes (Pl. 1B). The *Osagia* consist of algae and *Ammovertella* tests surrounding small (1 to 5 mm) shell fragments. No specimens show the supposed algae surrounding recognizable *Nubecularia.* "Osagite" would surely serve for field description of the upper Sallyards limestone, for the rock is essentially composed of *Osagia.* Only part of the *Osagia* individuals shows the "rounded lozenge or bean-shaped colony" described by Johnson (1946). Those individuals that do not exhibit this shape have ?algae enclosing a fragment but no concentration of incrusting material on the ends or top of the shell particle. When a smooth etched surface of this rock is examined, 60 to 90 percent of the surface is seen to be occupied by organic material.

Megascopic fossils in the Sallyards member consist of *Composita, Aviculopecten, Pseudomonotis,* and myalinids, which usually are found in the lower strata of the member. It seems reasonable that the long shell fragments mentioned above, which show on etched surfaces, are broken individuals of the same genera. These same fossils are probably represented also in the small particles forming nuclei for ?algae and *Ammovertella* in the upper beds of the Sallyards. The organic character of the member and its relationship to organic remains in the upper part of the Roca Shale is shown in Fig. 4.

Lateral changes.—The Sallyards Limestone ranges from 1.75 to 4.6 feet in thickness in the area of this study. The increased thickness at the three southern localities is due to thickening of the osagite beds at the top (Table 2).

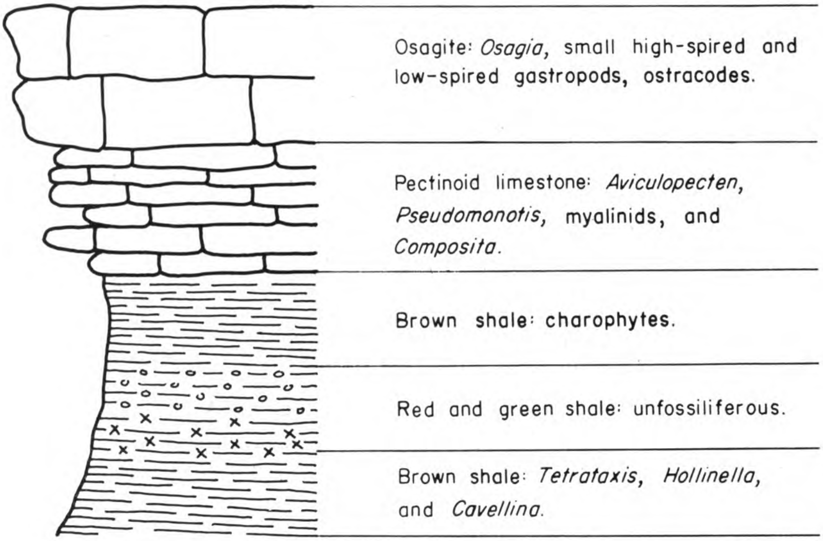

FIG. 4.—Fossil sequence in upper part of Roca Shale and in Sallyards Limestone.

TABLE 2.—*Thickness changes in the Sallyards Limestone, in feet*

Locality	4	3	2	1
Osagite limestone	2.6	3.2	2.9	......
Pectinoid limestone	0.75	0.8	1.7	1.75
Total	3.35	4.0	4.6	1.75

Legion Shale Member

The Legion Shale member, overlying the Sallyards Limestone, was named by Condra and Busby (1933) from exposures southeast of the American Legion grounds near Manhattan, Kansas. Their description of the Legion Shale at the type locality is as follows (p. 18):

Legion shale, 4′ 6″:

a. Shale, black, carbonaceous, fissile, 8″-10″.
b. Mudstone, dark gray, argillaceous, 4″.
c. Shale, dark gray, calcareous, blocky, 1′.
d. Shale, gray, calcareous, blocky, weathers yellow, 2′.

The lower boundary of the Legion Shale is marked by the lowest shale above the Sallyards member. The Sallyards Limestone contained no shale in exposures measured by the writer.

The upper boundary of the Legion at localities 2 and 3 is the base of the limestone sequence that makes up the Burr member (Fig. 2). The sequence at these localities is distinctively marked by a massive 31-inch stratum at the top. At locality 1, the boundary is placed at the base of the lowermost thin-bedded limestone in a sequence of thin limestones and shales. Above this sequence is a massive bed that is judged to be the top limestone of the Burr member.

At locality 4 the Legion Shale contains six limestone beds 2 to 18 inches thick. The top of the member is placed below a 1.5-foot bed of limestone showing characteristic Burr lithology, of a type lacking in limestone beds of the upper Legion Shale (Fig. 2).

Physical character.—The Legion member is a light-brown to gray calcareous clayey shale. Only very small amounts of silt-size noncarbonate material were noted when samples of the shale were digested in acid. Effervescence was moderate to strong. The shale is soft and regularly thin bedded, and weathers blocky.

Limestone beds in the shale range in thickness from 2 to 8 inches and average 3 inches. Most of these limestones are argillaceous, earthy or nodular, and wavy bedded, and contain few fossils. The insoluble material in them consists mainly of silt-size silica particles and clay.

Organic character.—The Legion Shale of the Elk-Cowley County area yielded no megafossils. The microfauna of the shale differs from outcrop to outcrop. At the northernmost locality (1), only very sparse, poorly preserved shells of *Cavellina* were found. At locality 2 numerous well-preserved *Cavellina* were accompanied by abundant small productid spines. The other two localities (3, 4) contained very abundant *Cavellina* and common *Hollinella, Knoxina, Tetrataxis, Glyphostomella,* crinoid stems, and productid spines. *Cavellina* seems to be a persistent and abundant constituent of the Legion microfauna (Table 3).

Those few limestones that are fossiliferous contain a molluscan fauna consisting mainly of *Aviculopecten, Septimyalina,* and the brachiopod *Juresania.* These fossils can be collected best on the upper or lower bedding plane of the limestone bed. The molluscan beds occur at the two southern localities (3, 4). At each of the two northern localities only two thin, unfossiliferous limestone strata are present.

TABLE 3.—*Percentages of identifiable microfossils in the Legion Shale at localities 3 and 4*

Fossils	Locality 3	Locality 4
Cavellina sp.	40	52
Hollinella sp.	30	21
Knoxina sp.	9	11
Tetrataxis sp.	5	1
Bythocypris sp.	3	8
Bairdia sp.	1	..
Moorites? sp.	2	..
Glyphostomella sp.	2	..
Bryozoan fragments	2	..
Crinoid stems	2	6
Holothurian remains	3	..

Lateral changes.—Three distinct types of lateral change are observed in the Legion Shale. First, the total thickness of limestone beds increases from north to south (Table 4). Second, the microfauna shows an increase both in number of genera and in abundance of individuals to the south. Third, the black carbonaceous shale at the top of the Legion Shale in the type locality to the north is not present in any of the four sections measured for this study.

TABLE 4.—*Lateral changes in the limestone-shale components of the Legion Shale, in feet*

Locality	4	3	2	1
Shale	5.0	5.5	3.5	4.4
Limestone	3.4	2.6	0.4	0.3
Total	8.4	8.21	3.9	4.7
Ratio: ls/sh	0.68	0.49	0.11	0.08

BURR LIMESTONE MEMBER

The Burr Limestone, named by Condra and Busby (1933), is the third member above the base of the Grenola (Fig. 2, Pl. 2A). The member is named from a town in Otoe County, Nebraska, but no description of the Burr locality is given by Condra and Busby; instead, they refer to the section near Humboldt, Nebraska, for the "type" description of this limestone. At Humboldt, the Burr member consists of two limestones separated by 3.5 feet of brown shale, the upper bed being carbonaceous and less than a foot thick. Black carbonaceous shale in the middle of the Burr member contains abundant plant remains in Nebraska

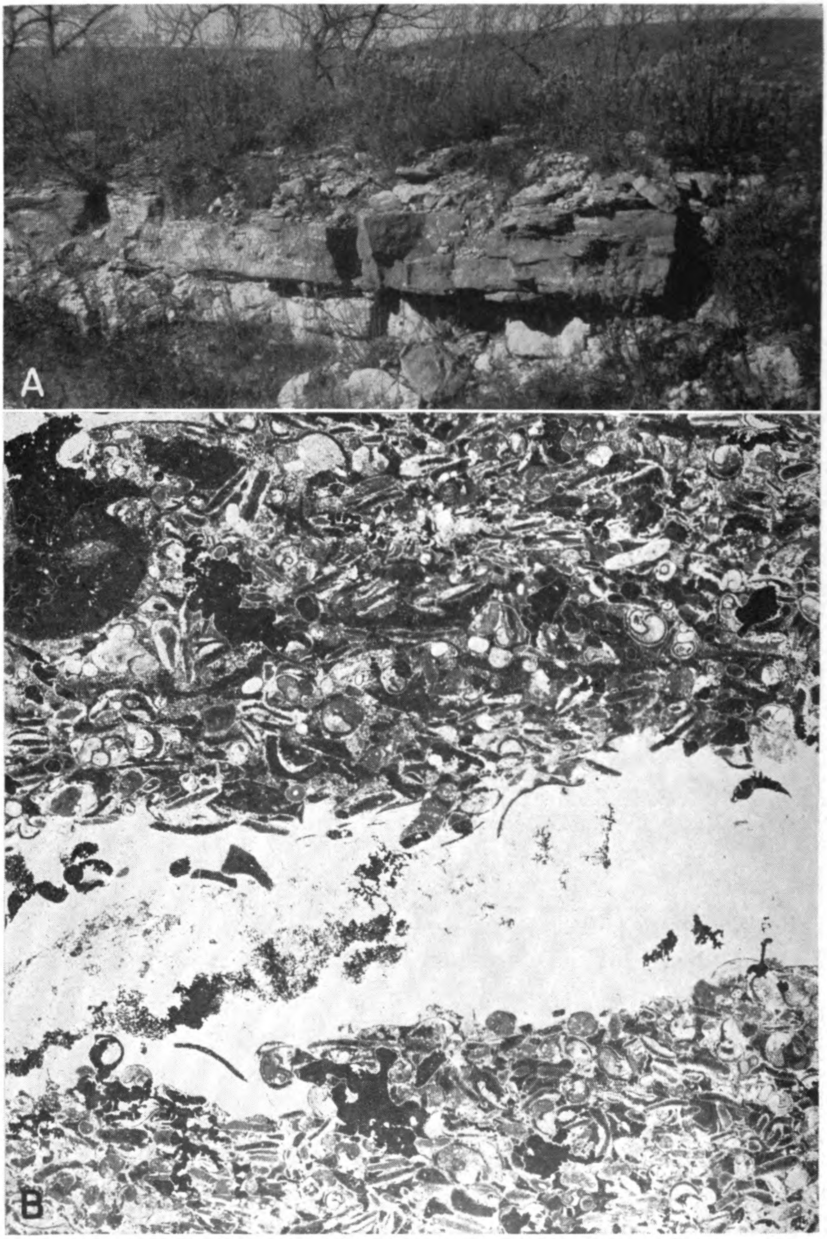

PLATE 2. **A.** Burr Limestone member at locality 2. **B.** Osagite limestone, upper part of Burr member, locality 3, showing layering of fossiliferous osagite and unfossiliferous limestone (×8).

(Condra and Busby, 1933, p. 26). Another feature is a zone of ostracodes in the upper limestone bed. This zone occurs in northern Kansas and Nebraska.

The base of the Burr Limestone in the type area of the Grenola was discussed in conjunction with the Legion Shale. The upper boundary in all sections measured is a massive to medium-bedded limestone of characteristic lithology.

Physical character.—The lower limestones of the Burr member, below the typical massive bed at the top, are argillaceous, platy or nodular, and wavy bedded (Pl. 2A). These lower limestones range from dark gray to light brown. Shale in the Burr member occurs as thin beds in the lower strata, ranging from 1 to 6 inches in thickness. This shale is everywhere calcareous, generally light brown, platy or blocky, and soft, and is composed almost entirely of clay-size particles.

The upper limestone stratum is massive at localities 2 and 3 (Fig. 2), and at other places shows three or four distinct beds ranging from 9 to 19 inches in thickness. This seeming difference in bedding may be due to effects of weathering. The upper, massive bed commonly shows a very faint, wavy, depressed line on the surface, which may be a bedding plane not sufficiently weathered to make an obvious break. The limestone is blue gray to dark gray. It contains very little argillaceous material; the matrix consists of cloudy granular calcitic material, which surrounds abundant organic debris.

Organic character.—The lower limestone beds typically contain long (maximum 3.0 cm), thin pectinoid fragments, sparse gastropods, ostracodes, crinoid stems, and echinoid spines. The shell fragments are aligned parallel to the bedding, the convex outer surface upward. This kind of organic debris occurs in thin (2- to 3-inch) beds, either at the base of the Burr member or above a limestone that is similar in organic character to the higher limestones of the member. The only megafossils observed in the lower part of the Burr member were numerous shells of *Aviculopecten* and sparse specimens of *Septimyalina.*

Like the upper beds of the Sallyards member, the upper limestones of the Burr may be termed osagite. Small shell fragments, which are surrounded with a layer of ?algae and *Ammovertella,* are very numerous, and are accompanied by numerous ostracodes and small high-spired gastropods. Organic material was estimated to occupy 80 to 95 percent of the etched surface of samples from the upper limestone stratum. A square inch of the etched surface contains 7 to 40 small gastropods, a maximum of 20 ostracodes, 2 or 3 crinoid columnals, and 75 to 125 shell fragments covered with ?algal coatings.

Shell fragments, ostracodes, and gastropods in this upper limestone average between 1.0 and 2.0 mm in length. The longest observed particle was 10.0 mm long. The uniform upper size limit of these materials seems to indicate sedimentary sorting. At locality 3 the upper part of the Burr contains parallel laminae of nonorganic, calcitic, and very fossiliferous osagite limestone, 0.5 to 1.0 cm thick, which show on both weathered and fresh surfaces (Pl. 2B). These laminae seem to be the result of current or wave action. No megafossils were found in the upper limestone beds of the Burr member.

Lateral changes.—No consistent changes in thickness or lithology were noted in the Burr member. A summary of shale, limestone, and total thicknesses is given in Table 5. No carbonaceous shale or limestone, or plant remains, were found in the Burr member.

TABLE 5.—*Lateral changes in the limestone-shale components of the Burr Limestone, in feet*

Locality	4	3	2	1
Limestone	4.3	4.0	4.0	3.5
Shale	1.4	0.1	0.2	1.5
Total	5.7	4.1	4.2	5.0
Ratio: sh/ls	0.32	0.03	0.05	0.42

SALEM POINT SHALE MEMBER

The Salem Point Shale, named by Condra and Busby (1933) from exposures near Salem, Richardson County, Nebraska, is next above the Burr Limestone. The description of the Salem Point member at the type locality is, "Salem Point shale, calcareous, 7′-8′."

In the type area of the Grenola Limestone, the Salem Point member is shale, generally unfossiliferous, interbedded with thin, earthy limestone layers. The lower boundary is marked by the upper massive osagite bed of the Burr member. The upper boundary is the base of the first fusulinid limestone, which is the lowest bed of the Neva member.

This lower fusulinid limestone of the Neva was found at all localities except locality 3, where no fusulinids were found and the Salem Point-Neva boundary was placed tentatively on the basis of other aspects of the lithology.

Physical character.—The Salem Point Shale is a calcareous to micaceous, slightly silty shale. Sand-size particles were observed very rarely. Color ranges from dark gray to light yellow brown. The shale layers are 0.2 to 2.0 feet thick and limestone strata 0.2 to 1.0 foot. The limestone beds are nodular or wavy bedded, argillaceous, and shaly. At localities 1 and 2, an argillaceous limestone crops out 2 or 3 feet below the base of the Neva member; it weathers into a limonitic boxwork. This is typical soft, earthy limestone referred to as "punky".

Organic character.—Virtually all fossils found in the Salem Point member were in the limestone beds. The only microfossils are sparse *Cavellina* and *Juresania?* spines in one bed at locality 4, and charophytes in another bed at locality 2. Both the charophytes and *Cavellina* occur about 3 feet below the Salem Point-Neva boundary.

Limestone beds contain *Aviculopecten, Septimyalina, Pleurophorus,* and *Juresania*. The pelecypods were found at localities 1, 2, and 4; *Juresania* was found only at locality 4.

Two characteristic arrangements of organic debris were observed in limestone strata of the Salem Point member. Most of the thin limestone beds contain long, curved fragments of disarticulated shells having a maximum length of 4.0 cm and an average length of 2.0 cm, associated with sparse ostracodes, small gastropods, and small crinoid columnals. Distinct algal coatings were not observed. Two limestone beds, however, showed small *Ammovertella* tests randomly arranged in the lime-mud matrix, but there was no indication that the tests were fixed to any larger organic particles.

The other arrangement of organic material in the limestone consists of approximately 90 percent organic debris of very small size (0.1 mm or less) showing a distinct lamination. The particles are so small and closely packed that they cannot be assigned to fossil groups. In one limestone, a distinct bedding surface, between fine organic particles below and fine calcareous mudstone above, can be recognized. Several small shell fragments, less than 1.0 cm long. arranged with the convex side up occur in the mud-

PLATE 3. Neva Limestone member at locality 4.

stone. These fragments are all within a millimeter of the bedding surface and surely were placed there by sedimentary transport, then covered by calcium carbonate mud, which grades upward into fine organic debris. If this debris is considered as sedimentary particles, the limestone is actually a coarse siltstone or very fine sandstone.

Lateral changes.—The only noticeable organic change in the Salem Point member is the occurrence of *Cavellina* and *Juresania* at locality 4 but not at localities farther north. The limestone-shale components do not show any consistent change (Table 6).

TABLE 6.—*Lateral changes in the limestone-shale components of the Salem Point Shale, in feet*

Locality	4	3	2	1
Limestone	1.0	1.4	1.9	2.0
Shale	2.0	8.1	4.2	7.4
Total	7.8*	9.5	6.1	9.4
Ratio: ls/sh	....	0.2	0.45	0.3

* 4.8 feet covered

NEVA LIMESTONE MEMBER

The Neva Limestone was named by Prosser (1895) from exposures near Neva, Chase County, Kansas (Pl. 3A, B), where the Neva member consists of five limestone beds ranging from 1 to 6 feet in thickness. Those are separated by thin (0.2 to 2.0 feet) shales, which are fossiliferous (Condra and Busby, 1933, p. 11). North of Elmdale, Kansas, the lower shales are black and contain *Orbiculoidea* and *Lingula,* but these black shales do not occur in the southern Kansas exposures studied.

At localities 1, 2, and 4, the base of the Neva member is defined by the lowest limestone bed in which fusulinids occur. At locality 3 the Neva-Salem Point boundary was placed on the basis of other features of the lithology. The top of the member occurs at a change in slope where the red, green, and gray shale of the Eskridge overlies the upper limestone bed of the Neva member. Upper limestone beds of the Neva Limestone commonly are badly weathered and are difficult to measure exactly.

Physical character.—One of the most noticeable gross features of the Neva member in the area studied is lack of persistence of the limestone beds. Many of these beds are dissimilar in lithology

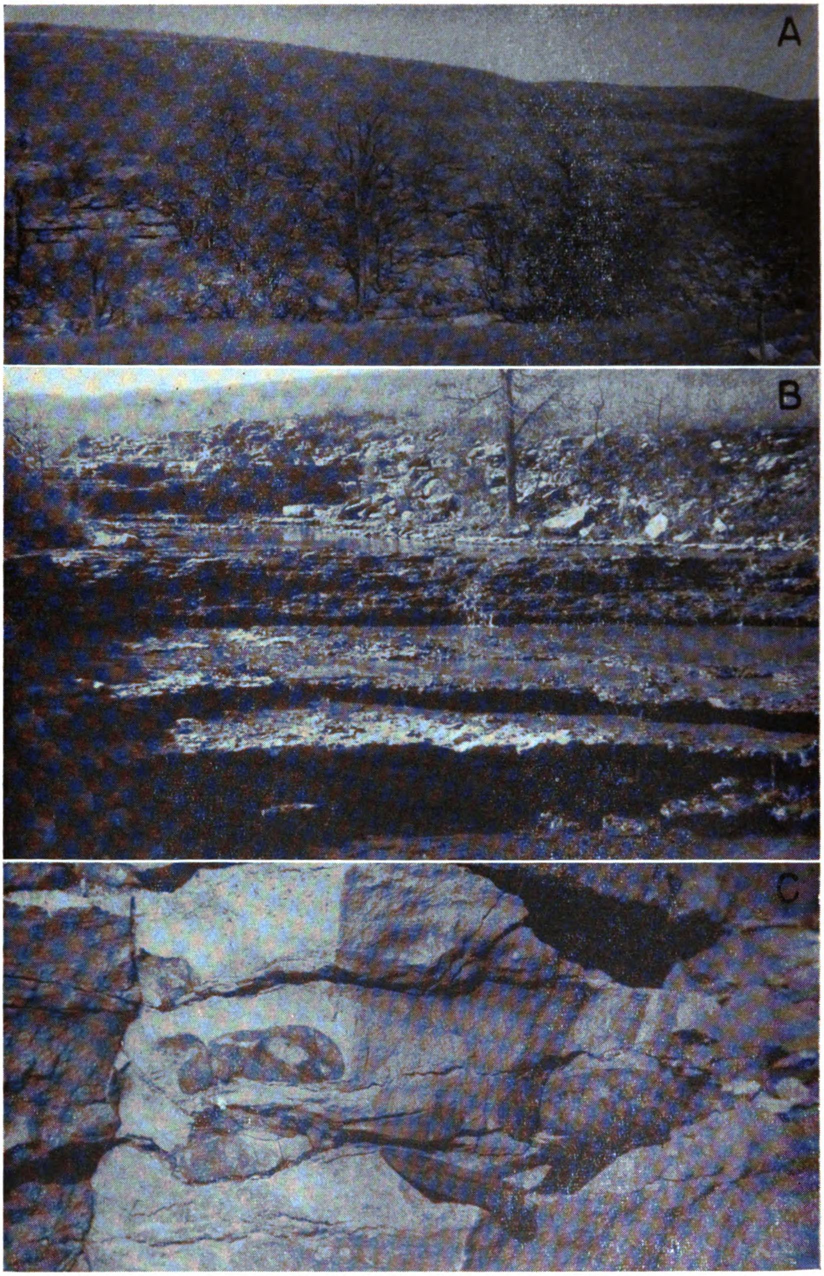

PLATE 4. A. Grenola Limestone at Grand Summit, Kansas. **B.** Neva Limestone at locality 2. **C.** Dark-gray chert nodules in Neva Limestone at locality 4.

from place to place and are difficult to correlate. Some of the limestones weather light gray to light brown and show a rough, pitted surface. Individual beds range from 0.2 to 1.7 feet in thickness. The shales are less than 3 feet thick everywhere. Limestone beds range from very light yellow brown to dark blue gray. The lower one or two limestones usually show argillaceous material on the etched surface, but higher limestone beds of the member often etch to a very smooth surface and seem to have little noncarbonate material. The shales are calcareous and contain minor amounts of silt-size noncarbonate particles.

The upper shales of the Neva member are light brown, but the lower ones are gray or dark gray and may be equivalent to black shale in the lower Neva farther north. The dark-gray shales are fossiliferous, however, and fusulinids are found in the darkest of them.

Chert is present in upper limestone beds of the Neva, individual beds or nodules of chert being as much as 0.5 foot thick (Pl. 4C, 5A). The color ranges from dark gray to whitish gray. Where the chert occurs in more than one stratum at a locality, the lowermost chert is dark gray, and higher chert is light gray to whitish gray. Fossils recognized in the chert are *Crurithyris*, fusulinids, echinoid spines, and fenestrate bryozoans. At locality 4, one bed of chert contains numerous *Crurithyris* whose shells are white silica and the interiors are filled with white and light-gray, banded, agate-like silica. The contact between chert and limestone is invariably sharp, but in many places wavy, smooth lobes of chert extend up or down into the limestone as much as 0.5 inch (Pl. 4C, 5A).

Where chert occurs in nodules, the long dimension is parallel to the bedding. Nowhere were bedding planes observed to cross or enter chert beds or nodules, and no laminations or faint bedding planes were seen in limestone near the chert. Therefore, it could not be ascertained whether laminae in the limestone would have followed the wavy chert-limestone contacts or cut across them. Some fossil fragments in the chert are aligned parallel to the chert-limestone contact, probably because the contact is approximately parallel with the limestone bedding.

A few carbonate fossil fragments are embedded in the chert. These could be observed both on etched and weathered surfaces. The limestone bordering the chert beds or nodules contains blebs

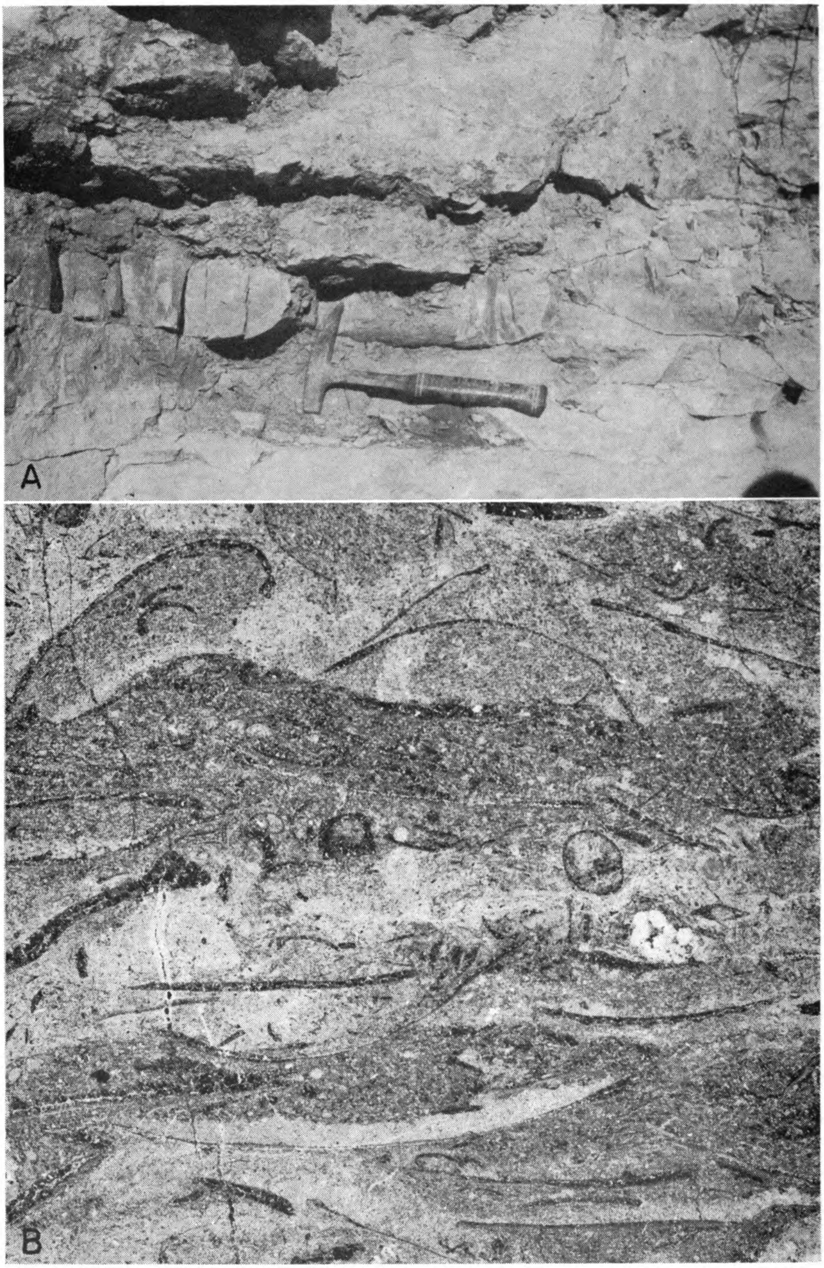

Plate 5. A. Light-gray chert nodules in Neva Limestone at locality 4. **B.** Pectinoid limestone, lower part of Sallyards member, locality 2. Organic fragments consist of long thin shell fragments (×5).

and stringers of secondary silica, and partly replaced *Crurithyris* and crinoid stems. Fusulinids are not replaced.

Organic character.—The fauna of the Neva differs noticeably from that of the other beds. Instead of an assemblage of flat-shelled pelecypods and small gastropods, the Neva member contains fusulinids, bryozoans, brachiopods, echinoderm remains, and burrowing clams. The most abundant bryzoans are fenestrate and ramose forms, fistuliporid forms being sparse. *Composita, Hustedia, Wellerella, Neospirifer,* and *Crurithyris* make up the bulk of the smooth-shelled brachiopods. More or less spinose brachiopods such as *Juresania, Dictyoclostus,* and *Linoproductus* are common. Echinoderm remains consist of crinoid stems and echinoid spines and plates. Burrowing clams include *Allorisma* and *Aviculopinna*. One trilobite pygidium, probably of a species of *Ditomopyge*, was found.

In the Neva Limestone, *Ammovertella* is not abundant, but this formaminifer does occur in the upper limestone bed at localities 1 and 2. On etched surfaces many of the limestones show sections of calcareous chambered foraminifera.

Many of the Neva Limestone strata contain large numbers of small spines, probably broken from productid brachiopods. These are so common locally that they make up 5 to 10 percent of the etched surface.

Some of the common organic associations in limestones of the Neva member are as follows:

1. Ramose and fenestrate bryozoan fragments oriented with long axes parallel to the bedding, crinoid stems, and other echinoderm fragments.
2. Fusulinids; calcareous, chambered foraminifers; and many small ?productid spines.
3. Fusulinids and echinoderm fragments.
4. Ramose bryozoans; calcareous, chambered foraminifers; and small productid spines.
5. Echinoid spines and calcareous, chambered foraminifers.

Fusulinids invariably occur with some other organic particles, nowhere alone, and are concentrated in the lower 2 to 3 cm of some limestone strata, but no preferred orientation of fusulinids was observed. Masses of fusulinids are present in shales as stringers or clusters. The fusulinids are cemented together with calcium carbonate, perhaps by secondary solution of outer parts of the test. In many of the individuals, the outer part of the theca is removed and the edges of the tunnel can be seen, presumably as a result either of rolling of the tests on the sea bottom prior to incorporation in the sediment, or of secondary solution of the test.

Both the micro- and megafauna of the Neva member show a noticeable change from the content of lower members. *Cavellina, Hollinella,* and *Tetrataxis* are dominant in the Legion and Salem Point Shales, but *Climacammina, Bairdia, Tetrataxis,* and *Glyphostomella* are leading forms in the Neva member. The absence of *Bairdia* from lower members is noteworthy, as this genus is a long-ranging, supposedly ubiquitous form.

Within the Neva member there are important differences in the microassemblages (Table 7). The shale just above the lowest limestone bed of the Neva is dark gray and contains a large amount of selacian remains and conodonts. This shale is equivalent, possibly, to black shale zones in the Neva member farther north, but in the area studied, the upper part of this shale contains fusulinids, brachiopods, and bryozoans.

TABLE 7.—*Percentages of identifiable microfossils in shales of the Neva member*

Locality 1		**Locality 2 Beds 24-25**		**Locality 2 Bed 21**	
Climacammina	31	*Climacammina*	23	Selacian remains	39
Bairdia	19	*Tetrataxis*	16	Conodonts	20
Glyphostomella	19	Echinoid spines	14	Gastropods	20
Tetrataxis	18	*Glyphostomella*	11	Bryozoan fragments	7
Bythocypris	5	Bryozoan fragments	11	Brachiopod spines	7
Fusulinids	4	*Bairdia*	10	Vertebrae?	3
Moorites	3	Fusulinids?	7	*Hollinella*	2
(128 individuals)		Crinoid stems	6	Crinoid stems	2
		Fusulinids	1	(55 individuals)	
		Bythocypris	1		
		(100 individuals)			

Lateral changes.—The total thickness of shale in the Neva member decreases from north to south in the area studied (Table 8). The shale-limestone ratio of the Neva north and south from the area studied was computed from the published sections of Condra and Busby (1933). At Sallyards, Greenwood County, the shale-limestone ratio is 0.79 and at Americus, Lyon County, this ratio decreases to 0.26. There is a steady increase in the ratio from Americus northward, the ratio reaching a maximum value of 0.59 at Sabetha, Kansas. At Burbank, Oklahoma, south of the type area, the ratio is 0.53, and at Ralston, Oklahoma, it is 0.28.

TABLE 8.—*Thickness of the Neva member and limestone-shale components in feet*

Locality	4	2	1
Limestone	20.2	14.2	10.8
Shale	4.9	3.1	6.7
Total	25.1	17.3	17.5
Ratio: sh/ls	0.24	0.21	0.62

As has been pointed out, black shale is not found in the Neva Limestone in the type area of the Grenola. It is possible, however, that the dark-gray shales recognized in this region are equivalent to the black shale zones farther north.

Two distinct lateral changes in the Neva member take place with respect to the chert and fusulinids. At the northernmost locality (1), a single bed of chert 0.3 foot thick was recognized, which occurs near the top of the member. At locality 2 (Pl. 4B), two layers of chert were found; a light-gray layer is in the uppermost bed of the member, and a dark-gray one near the center of the member. Five limestone beds contain chert at locality 4. Within the lowermost, black and light-gray chert nodules occur; the upper chert layers are light gray.

Thickness of limestone contining fusulinids likewise increases southward. At locality 1, three shales and one limestone contain fusulinids, but the upper 4.3 feet of the Neva member contains no fusulinids. Four limestones and two shales contain fusulinids at locality 2, and sparse fusulinids are found in the top bed of the member. At locality 4, two shales and four limestones contain this foraminifer, and one of these beds, almost 8 feet thick, contains fusulinids throughout. Fusulinids were also found in the chert nodules in this bed. The total thickness of strata containing fusulinids is 5.3 feet at locality 1, 9.8 feet at locality 2, and 14.6 feet at locality 4, a southward increase in thickness of beds containing fusulinids.

LIMESTONES OF THE GRENOLA

General characteristics.—The limestones of the Grenola exhibit the following general characteristics:

1. The bedding planes between strata are all somewhat wavy. No very smooth bedding surface was observed.

2. Colors range from dark blue gray to light yellow brown.

3. Matrices are composed of clay and fine silt-size argillaceous material, mixed with clear or cloudy granular or subcrystalline calcite. The matrix is a consolidated calcium carbonate mud.

4. With very few exceptions, all limestones contain discrete organic particles. These are the most distinctive features of the rock and will be described separately.

Organic components.—Several characteristic associations and arrangements of whole fossils and fragmentary fossils were observed, which, taken together, make up what may be termed the organic texture of the limestone. Using particle length as a criterion, most limestones studied can be divided into two groups: those containing fragments predominantly 1 to 3 mm in length, and those containing longer particles.

Ammovertella and ?algae form common shell coatings in many limestones containing abundant small fossil fragments, which generally make up 70 to 90 percent of etched limestone surfaces. Rocks containing abundant, incrusted organic debris 1 to 3 mm long have an osagite organic texture.

In rocks containing longer fragmentary shells (Pl. 5B) such particles invariably make up less than 25 percent of etched limestone surfaces. Pelecypod valves are found on the surfaces of these limestones; therefore, contained shell fragments are probably those of mollusks, and the limestones are referred to as molluscan limestones. In a few molluscan limestones, algal coatings are found on one or both sides of long shell particles. If both sides of a particle are coated, it is probable that both surfaces were, at one time or another, exposed to light rays. If the incrusting material is the same in width on all sides, then all surfaces must have been exposed to light for approximately the same length of time.

In limestones containing long, fragmentary organic particles, three kinds of orientation with respect to the bedding were observed: (1) broken shells parallel to the bedding, all arranged with the convex side up; (2) organic particles lying at all angles to the bedding; and (3) fragments parallel to the bedding with either convex or concave side up.

Associated with large and small broken shells are minute high- and low-spired gastropods, ostracodes, sparse crinoid stems, and small spines. Gastropods and ostracodes are most numerous in limestones that contain organic debris less than 3 mm in length. The associated small spines are identified as brachipod rather than echinoid spines, for cross sections of them show a concentric laminar structure, and not the minute honeycomb structure characteristic of echinoderms.

An important associate of shell fragments is the supposed algal incrustations. These have been given the generic name *Osagia* (Twenhofel, 1929). Because designation is based solely on shape, *Osagia* is a form genus. Working exclusively with thin sections, Johnson (1946) found that *Osagia* in the Grenola rocks consists of two groups of filaments or tubes, about 0.0018 and 0.4 mm in width, which he identified as *Girvanella,* an alga, and *Nubecularia,* a calcareous foraminifer, respectively. In thin sections prepared for the present study, no fine algal filaments were seen, but coarse tubes parallel to the surface of the shell nucleus were observed. The larger tubes could be seen standing out in relief on etched surfaces of the limestone, and coarse filaments freed from the limestone were found in insoluble residues from *Osagia*-bearing rocks. The freed tubes have been identified as *Ammovertella,* a common arenaceous Pennsylvanian-Permian foraminifer.

In regard to *Osagia,* Elias (1946) says "These fossil lumps and incrustations do not correspond to actual somata of living algae, but are merely accumulations of successive calcareous precipitations, presumably by the countless filmlike aggregates of microscopic simple colonial algae, and are mixed with calcium carbonate precipitated by organisms other than algae, or (and) precipitated inorganically." This may well explain why the small algal filaments described by Johnson were not observed.

Associations of brachiopods, bryozoans, and fusulinids in limestone constitute another type of organic texture. Brachiopod shell fragments and whole brachiopods occur in the limestones, usually in association with ramose or fenestrate bryozoans, or both. Most fragmentary brachiopods and bryozoans lie flat, parallel to the bedding of the rock. Associated with these two dominant groups are calcareous foraminifers, crinoid stems, echinoid spines, and sparse gastropods and ostracodes.

In general, organic debris in brachiopod-bryozoan limestones occupies less than 50 percent of etched surfaces, which percentage is less than for beds having osagite organic texture. The brachiopod-bryozoan limestones contain a very small amount of argillaceous material, for commonly the only insoluble residue from several grams of limestone consists of a few small *Ammovertella* tests. In contrast with molluscan limestones, such tests and algal material are rare on the etched surfaces of brachiopod-bryozoan, or more conveniently, molluscoid, limestones.

Another dissimilarity between molluscan and molluscoid limestones is the nature of preservation of the shell fragments. The substance of mollusk shells usually is recrystallized into brown or white calcite crystals, whereas fine original internal structure of brachiopod and bryozoan fragments commonly is preserved. The organic particles show on etched surfaces as white, microcrystalline calcite, generally with laminar structure. This difference is explained by the dissimilarity in crystal structure of the shell material in mollusks and molluscoids.

Limestone groups.—The gross lithologic features of the Grenola limestones in the type area are not diagnostic. In order to distinguish one limestone sample from another, stratigraphic sequence being ignored, it is necessary to rely on organic textures. On this basis, the groups of limestone indicated below are diffenentiated. Because only Grenola limestones were studied, the limestone groups suggested may be useful in the examination of other marine limestone formations, but an exhaustive stratigraphic study of organic textures of limestone would undoubtedly reveal characteristic groups of fossil debris not found in the Grenola rocks. In regard to classification of sedimentary rocks, Pettijohn (1949) says "The only test of significance is whether the characteristics are or are not basic to understanding of origin." The organic particles are the only characteristics of the Grenola limestones that are useful for cyclic interpretation and therefore the only ones that are "basic to understanding of origin."

These groups have been distinguished by laboratory examination of etched surfaces of the limestones, but probably they may be identified also in the field with the aid of a hand lens. The limestone groups are as follows:

1. Molluscan limestones. The organic content of these consists chiefly of complete or fragmentary pelecypod valves and small

high- and low-spired gastropods. The molluscan limestones may be divided further into osagite limestones, which contain many small *Osagia*-incrusted pelecypod shell fragments and gastropods; and pectinoid limestones, which contain long pelecypod shell particles, generally free of algal incrustations.

a. Osagite limestones. These are composed of very abundant small (1 to 3 mm) molluscan shell particles, and common small gastropods and ostracodes, many of which are surrounded by a thin algal crust containing *Ammovertella* tests (Pl. 1B, 2B). Organic debris in osagite limestones ranges from 1 to 5 mm in length, the average being 2 mm. A maximum of 150 shell particles was counted on one square inch of etched limestone surface. Total organic debris occupies 70 to 90 percent of etched surfaces. The narrow range in size of all the small fossil particles (gastropods, ostracodes, and shell fragments) is the result of wave or current sorting.

b. Pectinoid limestones. These contain common long thin convex valves of pelecypods (Pl. 6A), which are predominantly, if not exclusively, *Pecten*-like forms and hence appropriately called pectinoid. It is impossible to identify the fragments definitely as belonging to genera of the Pectinacea. Associated with pelecypod particles are small gastropods and ostracodes, but algal incrustations, so abundant in osagite limestones, are generally lacking. Where nearly all fragments in a limestone are oriented with their convex side up, it is likely that such orientation was effected by current or wave action. Where particles exhibit random orientation, or several have their concave side up, it is probable that little or no current action influenced sedimentation.

2. Molluscoid limestones. These contain a predominance of particles derived from brachiopods and bryozoans.

a. Brachiopod limestones. Fossils in these consist mostly of entire valves or fragments of brachiopods. Included also are limestones that contain very few brachiopod fragments other than spines.

b. Bryozoan limestones. Ramose or fenestrate bryozoans, or both, predominate over other fossils in this kind of limestone, commonly associated with small multichambered calcareous foraminifers (Pl. 6B). The bryozoan remains may be broken particles or whole colonies. A rock containing both brachiopods and bryozoans may be classed simply as a molluscoid limestone.

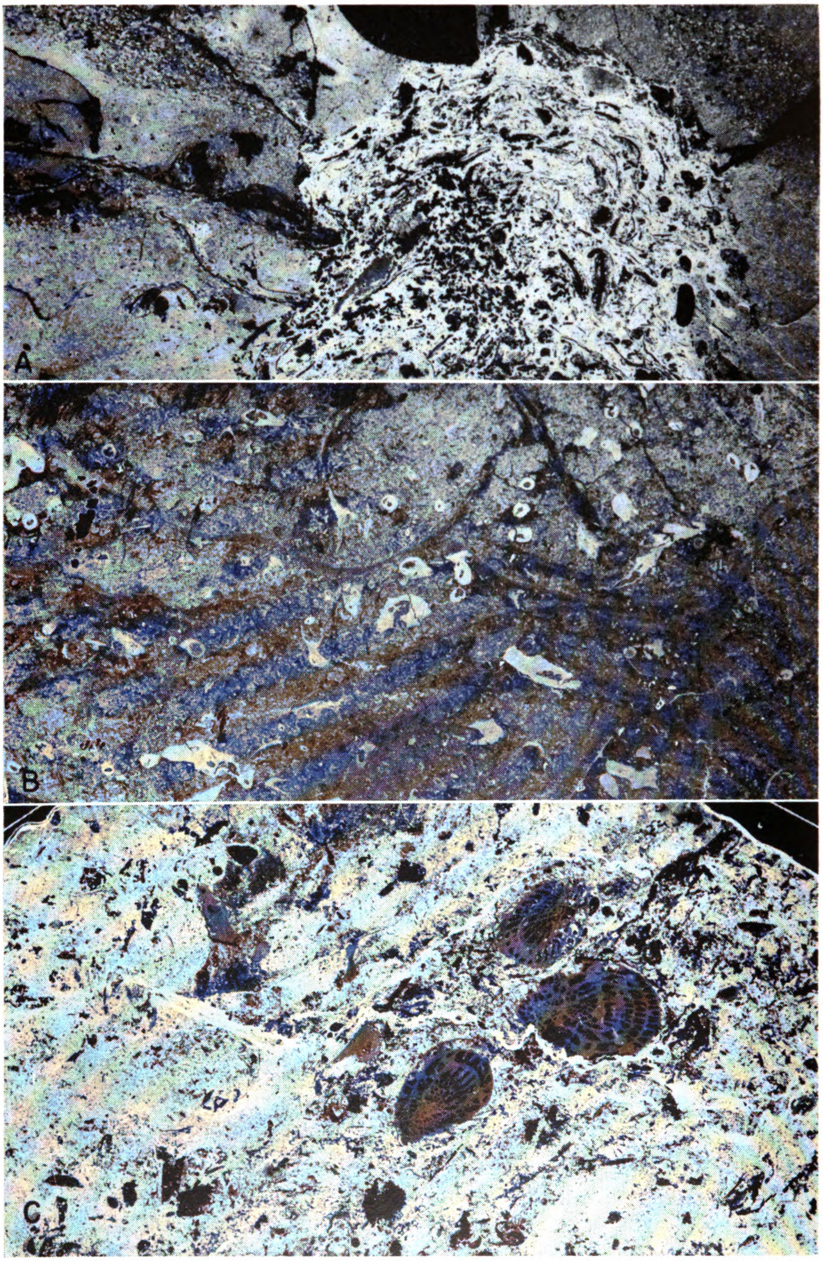

PLATE 6. A. Small algal mass in pectinoid limestone, lower part of Sallyards member, locality 3. *Composita* and pectinoid shells attached to top and side of algal mass (×2.4) **B.** Bryozoan limestone, Neva member, locality 4 (×2.4). **C.** Fusulinid limestone, Neva member, locality 4 (×4).

3. Echinoderm limestones. Limestones that contain organic remains composed mostly of echinoderm particles are less common than type 2a or 2b, and only a few of them were observed in the Grenola. Echinoid spines and plate fragments associated with crinoid stems and plate fragments are common in these limestones. The minute honeycomb internal structure is preserved in most of the echinoderm remains.

4. Fusulinid limestones. Any limestone containing sparse to very abundant fusulinids is here classed as a fusulinid limestone, although molluscoid debris is present in all limestones containing fusulinids (Pl. 6C). The reason for this procedure is that fusulinids constitute the only indication of the culminating transgressive phase of the cyclothem, making this arbitrary division necessary. Robust *"Triticites"* is the common fusulinid, and may constitute 50 percent of an etched surface.

CYCLIC SIGNIFICANCE OF GRENOLA LIMESTONE

Definition of the Cycle

Jewett (1933) published the first paper indicating the cyclic nature of Lower Permian rocks in Kansas. He called attention to the repetition of regular sorts of limestone and shale successions but made very little mention of the cyclic significance of faunal assemblages in the deposits.

After field work in the early 30's, Elias (1937) published a much more detailed analysis of the Lower Permian rocks (called "Big Blue Series" by Elias). The cycles were divided into parts termed phases, which he distinguished mainly by the kinds of fossils in the beds. Table 9 illustrates Elias' conception of the phases and depth distribution of various groups of fossils in the Lower Permian rocks.

Table 9.—*Idealized Big Blue transgressive hemicycle in north-central Kansas. The regressive hemicycle is the same succession, in reverse order.* (Modified from Elias, 1937.)

No.	Phase	Corresponding typical lithology	Depth
7.	Fusulinid phase	Limestone, flint, calcareous shale.	160-180′
6p.	Brachiopod phase		110-160′
5p.	Mixed phase	Massive mudstone, shaly limestone.	90-110′
4p.	Molluscan phase	Clayey shale, mudstone to bedded limestone.	60-90′
3p.	Lingula phase	Sandy, varved (?), rarely clayey shale.	30-60′
2p.	Green shale	Clayey to fine sandy shale, rarely consolidated.	0-30′
1.	Red shale		0

Although these Lower Permian cycles may be regarded as a continuation of the Pennsylvanian cyclothems, they differ in several respects. Sandstone and coal are absent from most of the Lower Permian cycles, but red shale and green shale commonly are present.

Grenola Cyclothem

The Grenola cyclothem may arbitrarily be defined as beginning at the base of unfossiliferous red and green shale in the Roca formation, next below the Grenola. Elias regarded the red shale as subaereal in origin and the green shale as deposited in shallowest marine water (depths ranging to 30 feet). Krynine (1949), on information provided by Swineford, stated that red beds of the Kansas Permian are primary detrital marine deposits. The fine-grained even texture of these shales and their relatively constant thickness and lateral persistence point to marine origin. Whether these shales were deposited in a submarine or subaereal environment, field evidence proves that known marine nonred sediments in Kansas interfinger southward with coarser red deposits in Oklahoma.

Green shale in the Roca formation, which is next above the red shale, may owe its color to reduction of ferric to ferrous iron, or the color may be due to large quantities of the green chlorite group of minerals (Swineford, Ada, personal communication).

Next below red shale in the Roca is brown shale containing a microfauna represented by *Cavellina, Tetrataxis, Hollinella,* and ?productids (spines). This assemblage is found also in the Legion Shale member, associated with a molluscan (phase 4) fauna, and it probably indicates that nearshore marine conditions prevailed during deposition of both the Legion member and this shale of the Roca.

An upper brown shale, next above red and green shale, contains very sparse charophytes and a few pistachio-green glauconite pellets, which indicate that marine conditions obtained. Charophytes live today in fresh or brackish water, but during the Permian they may have been washed into shallow marine waters and preserved thus, or they may have been true marine forms. The charophytes may be diagnostic of Elias' *Lingula* (3) phase, because the brown shale in which they occur is in the correct stratigraphic position for phase 3. No inarticulate brachiopods were found in the charophyte-bearing shale, however.

The Sallyards Limestone contains a predominantly molluscan fauna, consisting mostly of pectinoid pelecypods, which denote the molluscan (4) phase. The Sallyards member may be divided into two distince parts, based on the contained organic fragments. In the lower, shaly limestones of the member, whole pelecypod valves may be found, especially on bedding surfaces, whereas the upper strata consist of osagite limestone containing no megafossils. In the upper beds, small shell particles, which are nuclei for ?algae and *Ammovertella,* could be derived from pelecypods, gastropods, brachiopods, or ostracodes, and are evidence for a megafauna. Because pectinoid pelecypods are the fossils most commonly found in beds next above and below the upper Sallyards, these shell particles probably are pelecypod fragments. Further evidence that the osagite limestone should represent the molluscan phase (4) is the fact that several fragmentary shells observed have a ribbed surface, resembling a pectinoid fragment, and the fact that small gastropods are common. Therefore, the upper Sallyards is regarded as denoting the molluscan phase of the cyclothem.

As mentioned above, the narrow range in size of the fine organic debris in the osagite limestones seems to indicate sorting by currents or waves. Above the red shale in the Roca, green shale (phase 2), the *Lingula* (3), and molluscan (4) phases have been noted in that order, and denote part of a transgressive hemicycle. Because there is no apparent break between the lower pectinoid and upper osagite limestones of the Sallyards, it seems logical to assume that the osagite is a continuation of this transgressive condition and was deposited in an environment slightly farther offshore, or in deeper water, than were the lower pectinoid limestones.

Certain requirements must be fulfilled by any explanation of the origin of an osagite limestone, such as the upper Sallyards; (1) a mechanism must be available to produce small shell fragments 1 to 3 mm in length, (2) this or some other mechanism must sort these small particles from larger material and deposit them separately, (3) environmental conditions must be such that algae will flourish and precipitate calcium carbonate around these small shell fragments, and (4) the algae must be able to grow on all sides of the particles. Assuming that wave or current action, or both, is the mechanism that fulfills requirements 1 and 2, it is necessary to distinguish the significant elements of present wave and current action.

Powers and Kinsman (1954), working with cores from the Atlantic continental shelf, have distinguished two zones in the sediments of their cores. An upper (traction) zone is characterized by abundant small organic particles, more than 95 percent of which are 2.0 mm or less in size. This traction zone, providing that algal incrustations developed around the shell particles, could closely resemble an osagite upon lithification. A lower (accumulation) zone contains ". . . a coarser, more abundant, and larger macrofauna, and scarcer microfauna. . . ." Although size ranges of the Recent organic remains closely resemble the size ranges of fossils in the upper and lower Sallyards, Powers and Kinsman's core sediments were gravel and coarse to fine sand, rather than a fine calcium carbonate mud. They postulate that "swell can easily account for the vertical sorting of the sediments. . . ." If vertical sorting is postulated as the mode of occurrence of the osagite limestone, then shell material forming an osagite is broken up, sorted, and then incrusted with algae without appreciable transportation of the shell fragments. If vertical sorting did not take place, the shells must have been broken up in one area, and the small particles suspended or rolled along the botton, accumulating on another part of the sea floor.

In present oceans, maximum breakage of large shells into small fragments takes place where maximum agitation of bottom sediments occurs. According to Garrels (1951), maximum quantities of sediment are stirred up at the plunge point (point where the wave crests begin to break over), as shown in Figure 5.

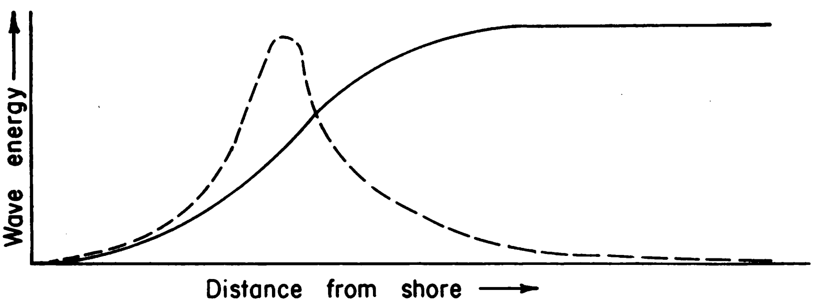

FIG. 5.—Relationship between wave energy and amount of bottom material stirred up. Dashed line, amount of stirred up material; solid line, wave energy. (Garrels, 1951).

Assuming that shell material is broken up at or near the plunge point, then small shell particles would be transported and gradually carried out to slightly deeper water where the fragments could accumulate under quieter conditions. Algae probably grew on the small shell fragments after sorting, and their presence indicates that conditions were favorable for plant growth. This means that the osagite probably formed at a depth to which light rays could penetrate and that carbon dioxide concentration, pH, salinity, temperature, and amounts of dissolved phosphates and nitrates must have been favorable for plant life (Rankama and Sahama, 1950).

Illing (1954) has shown that calcareous incrusting algae in the Bahamas are most abundant at depths of about 60 feet, for on the Banks, which are less than 60 feet deep, incrusting algae average only 1 percent of the contents of bottom samples, but at the outer edges of the Banks, approximately 60 feet deep, calcareous algae make up 39 and 27 percent of bottom samples in two different areas. If the same order of depth can be assumed for the growth of algal incrustations in osagite, the small shell particles that serve as nuclei may have accumulated at depths approximating 60 feet. Gentle wave or current action, easily developed at a depth of 60 feet, is necessary in that the shell particles must have been turned over from time to time to allow algal growth on all sides.

The depth of disturbance of sand on present sea beaches is rarely more than 20 cm (King, 1951). King says:

> Assuming a maximum wave height of 20 feet, which is rare close inshore, the corresponding depth of disturbance would be about 20 centimeters or about 8 inches. A more likely depth of disturbance is probably of the order of 6 inches and the average under normal calm conditions is very much less, being about 1 or 2 inches or less. In deep water the depth of disturbance is probably very much reduced, because of the decrease in turbulence of the water as the depth increases.

Heavy wave currents produced by storms would agitate particles down to a depth of 6 inches or less, according to King. Osagite limestone is 2 to 3 feet thick in the Sallyards member, and because algal incrustations are evenly distributed throughout the osagite from top to bootom, the shell fragments must have accumulated slowly, for once an incrusted particle was buried under 6 inches of material, it probably could not be brought back to the surface by wave agitation, and the algae would die. Therefore, the entire 2 to 3 feet of small shell fragments could not have been deposited at or nearly at the same time, but must have accumulated slowly.

From these considerations the following tentative conclusions can be drawn with relation to the origin of osagite beds:

1. Fragments constituting osagite beds were broken by wave or current action, possibly at the plunge point, and either vertically or laterally sorted.

2. Light penetration and other environmental conditions must have been favorable for plant growth at the depth of accumulation of the osagite material.

3. By comparison with the Bahama Banks, the osagite beds probably formed at depths approximating 60 feet.

4. Algal incrustations throughout the osagite denote slow accumulation of the fragmental shell nuclei.

The Legion Shale member is next above the Sallyards Limestone. Shale beds in the Legion have no megafossils but contain an abundant ostracode assemblage of *Cavellina, Hollinella,* and *Knoxina,* and interbedded thin limestone strata contain *Aviculopecten, Septimyalina,* and *Juresania,* which denote a molluscan (4) phase. Hence, microfossils in the shale probably represent a micro-equivalent of the molluscan phase indicated by the limestones.

The Burr Limestone member, next above the Legion Shale, contains almost a duplication of limestone groups and fossil assemblages found in the Sallyards. The lower Burr is a pectinoid limestone, like the lower part of the Sallyards member, and the upper Burr strata are osagite limestone, generally thicker than the osagite portion of the Sallyards.

Because shale occurs next below the Sallyards and Burr members, and the limestone groups in both members are similar and in the same relative stratigraphic position, the Burr limestones probably denote a return to environmental conditions like those that affected deposition of the Sallyards. The Legion Shale between these limestones indicates an influx of fine argillaceous material into the area, perhaps due to slight shallowing of the sea. Several thin pectinoid limestones interbedded with the shale indicate that environmental conditions surely were not much modified.

The Salem Point Shale member contains a microassemblage of sparse *Cavellina* and charophytes and a megafauna of pectinoid mollusks, in thin intercalated limestones, which represent phase 4 of the cycle. In the Legion Shale, *Cavellina, Hollinella,* and *Knoxina* were deduced to be a microequivalent of the molluscan phase, and charophytes in the upper part of the Roca Shale were regarded as a microequivalent of the *Lingula* phase; therefore, the Salem Point member should represent both phases 3 and 4. Charophytes present in the Salem Point perhaps indicate a slight regression or shallowing.

Fusulinid limestone is next above the Salem Point member, hence, the first beds of the Neva member denote Elias' fusulinid (7) phase; phases 5 and 6 seem to be missing. The lowermost limestone of the Neva also contains ramose bryozoans, echinoid spines, and small brachiopod fragments, however, indicating an apparent mixing of fossils diagnostic of phase 6 and phase 7.

The Neva member contains numerous brachiopods, bryozoans, and fusulinids, but pelecypods, common in lower members, are rare or absent. Neva limestone and shale beds are not constant in thickness or lithology from exposure to exposure, denoting that at times deposition of limestone and of shale proceeded simultaneously in different parts of the area. Seemingly some rapid alternation of phases 6 and 7 took place, because thin molluscoid- and fusulinid-bearing rocks are intercalated with molluscoid-bearing beds, and all fusulinid limestones contain other fossil remains.

Total thickness of Neva limestone beds increases southward, possibly indicating that more calcium carbonate sediments were being deposited there, but an increase in amount of argillaceous material northward might mask disseminated carbonate deposition that could be uniform over the area studied.

Every chert-bearing limestone in the Neva also contains fusulinids, and the thickness of chert- and fusulinid-bearing limestone increases southward, which seems to indicate that chert is characteristic of phase 7. The validity of this statement depends on proof that the chert is primary. A similar lateral increase in thickness of chert is found in the Foraker Limestone, two limestone formations below the Grenola (Moore and others, 1951), where both the Hughes Creek Shale member and the Americus Limestone member become cherty in the southern part of Kansas, and contain abundant robust fusulinids both in chert nodules and in limestone. This close stratigraphic recurrence of the same lateral change is an argument for primary, or perhaps penecontemporaneous, deposition of the chert. No evidence for primary or secondary deposition of the chert could be deduced from study of bedding planes in and around chert nodules, nor from examination of arrangement and composition of siliceous and carbonate fossils in the chert.

The upper limestone bed of the Neva member at locality 1 exhibits the mixed (5) phase of the cycle; the bed contains *Allorisma, Aviculopinna,* and calcareous brachiopods. Recurrence of small *Osagia*-like forms and gastropods at locality 2 in the upper Neva also indicates a slightly regressive phase, just before the beginning of Eskridge Shale deposition.

Microfossils in the Neva differ from those in lower members; the predominant forms are *Climacammina, Bairdia, Tetrataxis,* and *Glyphostomella,* rather than an ostracodal assemblage of *Cavellina, Hollinella,* and *Knoxina.* The Neva foraminifers are found in shales characterized by a molluscoid-fusulinid fauna, and this microassemblage is peculiar to phases 6 and 7 in the Grenola in the area studied. Lateral and stratigraphic studies of wider extent are necessary to determine whether this group of fossils is generally associated with deeper water phases of the cycle.

In summary, the Grenola Limestone in the type area exhibits a generally transgressive trend, dominated by a lower molluscan phase and an upper molluscoid-fusulinid phase. The molluscan (4) phase is represented by osagite and pectinoid limestone in the Sallyards and Burr members, and by pectinoid limestone and shale containing *Cavellina, Hollinella,* and *Knoxina* in the Legion member. The Neva Limestone contains predominantly molluscoid and fusulinid limestones, phase 6 or phases 6 and 7 being represented in most of the limestone and shale beds. A microassemblage of *Climacammina, Bairdia,* and *Glyphostomella* is also judged to represent phases 6 and 7.

ENVIRONMENTAL HISTORY OF GRENOLA LIMESTONE

Synthesis of the foregoing facts into an organized and continuous picture seems necessary. Southwestern Elk County during the time when the Grenola Limestone was laid down could be visualized from the following statement.

At first we may picture a low-level mud flat, composed of red clay and silt, crossed by slow-flowing rivers carrying fine sediment into a nearby marine basin. Then as saline waters flooded inland over the mud flat, iron-reducing bacteria and decaying organic debris changed the upper part of the red mud to green mud. As the water became progressively deeper, clams, small snails, *Juresania,* and ostracodes migrated slowly into the area, living on the bottom and feeding on minute organisms in the water. The water probably was brackish or perhaps freshened from time to time, keeping less tolerant animals away from these shallow waters. Deposition of new material formed a bottom of fine mud, composed of argillaceous material and disseminated calcium carbonate.

Breaking and sorting of shells was effected by waves and currents, and small shell fragments and debris were transported by waves, coming to rest in areas where such action was less intense or less frequent. In this slightly deeper and perhaps clearer water, small organic particles, gastropods, and ostracodes became nuclei for attachment of lime-secreting algae and small arenaceous foraminifers.

Gradually, as the water deepened, clams and snails moved into the shallower water and were replaced by delicate fronds and stalks of bryozoans and by brachiopods that attached themselves to the bottom with their muscular pedicle or by stout spines. Spiny echinoids moved or burrowed among the stems of crinoids. Ostracodes, which thrived in more argillaceous sediments, were supplanted by small arenaceous and calcareous foraminifers.

From time to time the water became slightly deeper, and many robust fusulinids populated the bottom, living either on top of or in soft carbonate ooze, which later lithified to limestone. Seemingly the foraminifers had little competition for this ecologic niche, as their tests are extremely abundant. Brachiopods and bryozoans either lived on fusulinid-populated bottoms or their tests were moved to slightly shallower molluscoid bottoms by gentle currents, because today both kinds of fossil are found in the same rock.

In this deeper water, colloidal and dissolved silica carried in by rivers may have gelatinized or precipitated and settled to the bottom, where agitation resulted in coalescence into nodules, which gradually hardened, incorporating organic particles. Finally, a slight shallowing took place, accompanied by a re-entrance of clams, gastropods, and algae, which was followed by more rapid shoaling and covering of the deeper-water carbonate sediments by argillaceous material. This was the beginning of deposition of the Eskridge Shale formation.

CONCLUSIONS

1. The Grenola in the type area is a well-defined traceable lithologic unit.

2. Black shale and plant fragments such as those found in the Neva, Burr, and Salem Point members farther north are not present in the type area.

3. The Sallyards, Legion, Burr, and Salem Point members are characterized by a molluscan fauna, accompanied in the Legion by a microfauna containing numerous specimens of *Cavellina, Hollinella,* and *Knoxina.*

4. Charophytes found below the Sallyards Limestone and in the Salem Point Shale probably indicate nearshore conditions intermediate between the environments of deposition for green shale and molluscan limestone. Charophytes may be a microrepresentative of the *Lingula* phase.

5. *Osagia* found in the rocks is an intimate intergrowth of ?algae and *Ammovertella.*

6. Limestones of the Grenola Limestone may be divided on the basis of their organic textures into types as follows:

   1. Molluscan limestones
      a. Osagite limestones
      b. Pectinoid limestones
   2. Molluscoid limestones
      a. Brachiopod limestones
      b. Bryozoan limestones
   3. Echinoderm limestones
   4. Fusulinid limestones

7. Osagite beds at the top of the Burr and Sallyards members probably were formed: (a) in water approximately 60 feet deep, (b) under generally quiet conditions with slow accumulation of shell fragments, and (c) under conditions favorable for the growth of algae. The shell particles probably were derived from a shallow water zone characterized by roiling and approximating the plunge point in depth.

8. The Neva member contains a molluscoid and fusulinid fauna, and an equivalent microassemblage of *Climacammina, Glyphostomella,* and *Bairdia.*

9. Thickness of fusulinid- and chert-bearing limestones increases southward, indicating that deeper water prevailed to the south for a longer period of time than in the north.

10. The chert nodules in the Neva member seem to be primary.

11. The members of the Grenola Limestone may be classified in terms of Elias' cyclic phases as follows:

a. Sallyards member, molluscan (4) phase, pectinoid and osagite limestone.

b. Legion member, molluscan (4) phase, *Cavellina-Hollinella-Knoxina* shale, and thin pectinoid limestones.

c. Burr member, molluscan (4) phase, pectinoid and osagite limestone.

d. Salem Point member, *Lingula* (3) and molluscan (4) phases; charophytes, *Cavellina,* and pectinoid limestones.

e. Neva member, brachiopod (6) and fusulinid (7) phases; molluscoid and fusulinid limestones; *Climacammina-Glyphostomella-Bairdia* shales.

APPENDIX

Locality 1

Center NE¼ sec. 27, T. 28 S., R. 8 E., on Ferrley Ranch 100 yards east of ranch house, along banks of Elk River

	Thickness, feet
Grenola Limestone (38.6 feet)	
Neva Limestone member (17.5 feet)	
22. Limestone, cherty, whitish gray, deeply weathered; sparse *Osagia,* ramose bryozoans, gastropods	2.0
21. Limestone, nodular, thin bedded, light brownish gray; *Allorisma,* large ramose bryozoans, abundant echinoid spines and plates	2.3
20. Shale, platy, calcareous, light brown; *Tetrataxis, Bairdia, Glyphostomella,* fusulinids	0.9
19. Limestone, thin bedded, laminated weathered surface, gray to brownish gray; ramose bryozoans	0.8
18. Shale, blocky, light yellow brown; *Hollinella, Tetrataxis, Bairdia, Glyphostomella*	2.0
17. Limestone, argillaceous, dark brown, weathers to rough, pitted surface; large fusulinids, crinoid stems	0.6
16. Shale, blocky, very calcareous, grayish brown; fusulinids, *Climacammina, Hollinella, Bairdia, Orthovertella,* echinoid spines	2.7
15. Limestone, shaly, wavy bedded, blue gray; echinoid spines, crinoid stems	3.8
14. Limestone, argillaceous, laminated, brownish gray, pitted weathered surface; numerous small shell fragments; a 0.2-foot shale parting above	0.8

	Thickness, feet
13. Shale, platy, light grayish brown; fusulinids, crinoid stems, fenestrate bryozoans, echinoid spines, *Tetrataxis*	1.1
12. Limestone, nodular, earthy, dark gray, unfossiliferous	0.5
Salem Point Shale member (9.4 feet)	
11. Shale, covered	2.0
10. Limestone, argillaceous, yellow brown, weathers with a boxwork appearance	0.8
9. Shale, covered	1.4
8. Shale, platy, calcareous, dark gray at top, light bluish gray at bottom, 2-inch limestone in center, unfossiliferous	1.8
7. Limestone, medium bedded (0.3 to 0.6 foot), slabby, light gray; abundant *Aviculopecten*	1.2
6. Shale, platy, calcareous, blue gray, unfossiliferous	2.2
Burr Limestone member (5.1 feet)	
5. Limestone, thin bedded, argillaceous; abundant *Ammovertella*	0.3
4. Limestone, massive, gray to dark brown; abundant *Osagia*, small gastropods, sparse ostracodes, bellerophontids	1.8
3. Shale, platy, brown, and thin (0.1 to 0.3 foot) nodular limestones; common pectinoid fragments	3.0
Legion Shale member (4.8 feet)	
2. Shale, blocky, brown, two 2-inch gray, earthy limestone beds at base; sparse *Cavellina* in shale	4.8
Sallyards Limestone member (1.8 feet)	
1. Limestone, thin bedded, wavy bedded, gray; sparse small pectinoid fragments, gastropods	1.8

Locality 2

SE¼ sec. 4, T. 31 S., R. 8 E., railroad cuts along Santa Fe Railroad, and in small stream adjoining the railroad, between Murphy oil lease and Grand Summit

Grenola Limestone (35.9 feet)	
Neva Limestone member (17.3 feet)	
28. Limestone, massive, wavy bedded, gray chert layer in center, top of limestone contains small *Osagia*, sparse fusulinids throughout	2.2
27. Shale, calcareous, light brown; echinoid spines, fenestrate bryozoans	0.7
26. Limestone, medium bedded, gray, weathers light yellow gray; robust fusulinids, fenestrate bryozoans	2.1
25. Limestone, thin bedded, flaggy, light gray; echinoid spines, calcareous foraminifers, fenestrate bryozoans	1.4
24. Shale, blocky, very calcareous, light yellow brown; fusulinids, crinoid stems, calcareous foraminifers	0.5
23. Limestone, thin bedded, shaly to platy, light gray to whitish brown; abundant fusulinids near base	1.0
22. Limestone, thin bedded to medium bedded, gray to light brown, gray chert nodules 1.3 feet below top; fusulinids, ramose bryozoans, large shell fragments, sparse ostracodes	5.1
21. Shale, platy, dark gray, two thin, nodular limestones at base. Shale contains *Composita, Meekella, Dictyoclostus, Hustedia, Chonetina*, fusulinids echinoid spines, ramose and fenestrate bryozoans, echinoid spines and plates, sparse conodonts, selacian remains, and *Ditomopyge?*	2.2
20. Limestone, thin bedded, nodular, blue gray; small fusulinids, ramose bryozoans, sparse ostracodes	2.1
Salem Point Shale member (6.1 feet)	
19. Shale, platy, calcareous, dark gray, a thin, nodular, blue-gray limestone in center containing abundant small high-spired gastropods	2.4

	Thickness, feet
18. Limestone, argillaceous, blue gray to dark gray, irregular tube-like nodules on lower bedding plane; contains sparse small, well-rounded, light-gray limestone fragments, small gastropods, sparse crinoid stems	0.2
17. Shale, platy, dark gray; charophytes, very sparse selacian remains	0.3
16. Limestone, nodular, argillaceous, dark gray brown to light yellow brown; numerous small *Ammovertella*	0.8
15. Shale, platy, gray, unfossiliferous; includes two thin, earthy limestone beds containing *Aviculopecten, Septimyalina, Pleurophorus,* and small gastropods	1.5
14. Limestone, wavy bedded, light brownish gray; numerous pectinoid fragments, small high-spired gastropods	0.2
13. Shale, blocky, dark gray brown, unfossiliferous	0.7
Burr Limestone member (4.1 feet)	
12. Limestone, dense, limonitic, blue gray; abundant *Osagia* and small high-spired gastropods; separated from bed 11 by 0.1-foot brown shale parting	2.6
11. Limestone, dense, blue gray; abundant *Osagia,* crinoid stems, small gastropods, ostracodes	1.3
10. Limestone, shaly, flaggy, limonitic, brownish gray; large pectinoid fragments, sparse crinoid stems, echinoid spines	0.2
Legion Shale member (3.8 feet, upper 2.7 feet exposed)	
9. Shale, blocky, slightly silty, hard, light brown to yellow brown; productid spines, abundant *Cavellina;* two 2-inch limestone beds, dense, earthy, unfossiliferous, in center	3.8
Sallyards Limestone member (4.6 feet)	
8. Limestone, medium bedded, limonitic, light gray; very abundant *Osagia*, small high- and low-spired gastropods	2.9
7. Limestone, thin bedded, wavy bedded, argillaceous, grayish brown; sparse large pectinoid fragments	0.9
6. Limestone, medium bedded, light gray; small gastropods, ostracodes, small shell fragments	0.5
5. Limestone, wavy bedded, yellowish gray to gray, weathers light brown; long pectinoid fragments, sparse small gastropods	0.3
Roca Shale (8.6 feet exposed)	
4. Shale, clayey, blocky, light yellow gray to brown, green mottling at base, unfossiliferous	2.1
3. Shale, clayey, blocky, light maroon	2.7
2. Shale, light green, deeply weathered	0.8
1. Shale, silty, calcareous, red to light maroon	3.0

Locality 3

W½ sec. 21, T. 32 S., R. 8 E., Cowley County, Kansas; road cut on Kansas Highway 38, 12 miles north and 2 miles west of Cedarvale, Kansas

Grenola Limestone (31.7 feet exposed)	
Neva Limestone member (6.1 feet exposed)	
28. Limestone, medium bedded, dark brownish gray, chert nodules at top; ramose and fenestrate bryozoans, crinoid stems	2.0
27. Limestone, shaly, thin bedded, dark blue gray	0.6
26. Shale, calcareous, light brown; 3-inch limestone near base; *Linoproductus, Composita, Septimyalina, Juresania*	2.8
25. Limestone, granular, thin bedded, light gray; fenestrate bryozoans	0.7
Salem Point Shale member (9.5 feet)	
24. Shale, platy, dark gray at top; blocky, brown at top; *Hollinella,* crinoid stems	2.2

	Thickness, feet
23. Limestone, massive, earthy, argillaceous, brownish gray, unfossiliferous	0.9
22. Shale, platy, very calcareous, light gray brown	2.3
21. Limestone, light gray; *Aviculopecten*, small pyrite crystals	0.5
20. Shale, very calcareous, platy, blue gray; *Aviculopecten, Ammovertella*	1.8
19. Shale, platy, gray, 2-inch limestone in center, unfossiliferous	1.8
Burr Limestone member (4.0 feet)	
18. Limestone, platy, argillaceous, like no. 17 but contains numerous ostracodes	0.2
17. Limestone, massive, yellow gray, separated trom bed below by distinct wavy bedding plane; abundant *Osagia*, small gastropods, ostracodes	2.6
16. Limestone, massive, brownish gray; *Osagia*, small gastropods, crinoid stems	1.2
Legion Shale member (8.1 feet)	
15. Shale, blocky, yellow brown, unfossiliferous	1.3
14. Shale, platy, blue gray, and thin-bedded nodular limestone containing *Aviculopecten, Septimyalina, Juresania*, fenestrate bryozoans, *Euomphalus?*	2.2
13. Shale and nodular limestone, gray; *Aviculopecten*, gastropods, myalinids	0.4
12. Limestone, earthy, nodular, gray, unfossiliferous	0.2
11. Shale, platy, dark gray	0.6
10. Limestone, nodular, earthy	0.2
9. Shale, platy, calcareous, dark gray, and thin, argillaceous, unfossiliferous limestone	2.1
8. Limestone, argillaceous, gray; few small pectinoid fragments	0.4
7. Shale, blocky, brown; *Hollinella, Tetrataxis, Knoxina, Cavellina*	0.7
Sallyards Limestone member (4.0 feet)	
6. Limestone, granular, earthy, bluish gray, unfossiliferous	0.3
5. Limestone, massive, wavy bedded, blue gray; abundant *Osagia*, gastropods, ostracodes	2.9
4. Limestone, thin (0.2 foot) beds, wavy bedded, argillaceous, brownish gray; sparse shell fragments at bottom and common long (1 to 2 cm) shell fragments and *Composita* at top	0.8
Roca Shale (8.0 feet exposed)	
3. Shale, silty, blocky, brown; charophytes	5.0
2. Shale, silty, red, unfossiliferous, red and green mottled shale at top	2.0
1. Shale, blocky, brown; *Cavellina, Tetrataxis*	1.0

Locality 4

NE¼ SW¼ and SE¼ NW¼ sec. 12, T. 34 S., R. 7 E., cuts along Missouri-Pacific Railroad, 300 yards south of U. S. Highway 166, 6.7 miles west of Cedarvale, Kansas

Grenola Limestone (50.4 feet)	
Neva Limestone member (25.1 feet)	
33. Limestone, light gray, deeply weathered; numerous long (1 to 2 cm) shell fragments	1.0
32. Covered	1.0
31. Limestone, thin bedded, cherty, light gray; robust fusulinids, crinoid stems, fenestrate bryozoans	7.8
30. Shale, blocky, calcareous, dark brown; *Climacammina, Tetrataxis, Bairdia*	0.6

	Thickness, feet
29. Limestone, massive, light gray, gray chert nodules in center	1.7
28. Shale, platy, brown to dark gray, 0.9-foot earthy limestone in center. Shale contains robust fusulinids, *Crurithyris, Neospirifer, Hustedia, Wellerella, Composita,* fistuliporid, ramose, and fenestrate bryozoans	2.2
27. Limestone, massive, light gray, containing grayish-brown chert nodules; robust fusulinids, abundant *Crurithyris,* echinoid spines, ramose bryozoans	2.8
26. Limestone, thin bedded, wavy bedded, earthy, light brown to gray; common fusulinids, echinoid spines, crinoid stems, bryozoan fragments	2.0
25. Shale, calcareous, gray; fusulinids, ostracodes, ramose bryozoans	0.6
24. Limestone, massive to medium bedded, gray, containing 4-inch zone of black chert nodules; crinoid stems, echinoid spines, fenestrate bryozoans	3.1
23. Shale, very calcareous, platy, dark gray	0.5
22. Limestone, medium bedded to thin bedded, upper bed massive, brownish gray, containing small fusulinids, echinoid spines, fenestrate bryozoans	1.8
Salem Point Shale member (7.8 feet)	
21. Shale, platy, bluish gray, unfossiliferous	0.3
20. Limestone, medium bedded, light gray; common bryozoan fragments, sparse small echinoid spines	1.0
19. Shale, gray, containing three 0.2-foot limestone beds; *Juresania, Septimyalina,* sparse *Cavellina,* productid spines	1.7
18. Shale, covered	4.8
Burr Limestone member (5.7 feet)	
17. Limestone, argillaceous, light gray; abundant *Osagia,* small gastropods	2.4
16. Shale, deeply weathered; *Derbyia, Chonetes, Marginifera, Composita, Juresania, Septimyalina*	0.7
15. Limestone, gray; long pectinoid fragments	0.3
14. Shale, blocky, light yellow brown	0.8
13. Limestone, massive, wavy bedded, light gray; *Osagia,* ostracodes, small gastropods	1.5
Legion Shale member (8.4 feet)	
12. Shale, blocky, light brown; includes 0.2-foot limestone bed containing *Aviculopecten*	1.7
11. Limestone, argillaceous, limonitic, dark gray to blue gray; bryozoan fragments, productid spines	1.5
10. Shale, platy, calcareous, hard, gray brown, unfossiliferous; nodular dark-blue-gray unfossiliferous limestone in center	1.5
9. Limestone, argillaceous, light grayish brown; *Aviculopecten, Juresania, Septimyalina,* sparse fenestrate bryozoans, crinoid stems	1.2
8. Shale, platy, calcareous, unfossiliferous	1.1
7. Limestone, earthy, wavy bedded, gray with brown splotches; sparse pectinoid fragments	0.3
6. Shale, like bed 4	0.4
5. Limestone, earthy, nodular, brownish gray; small shell fragments	0.2
4. Shale, blocky, brown; abundant *Cavellina,* sparse *Hollinella, Glyphostomella*	0.5
Sallyards Limestone member (3.4 feet)	
3. Limestone, massive, slightly argillaceous, dark gray brown; abundant *Osagia*	1.4

	Thickness, feet
2. Limestone, medium bedded, gray to light brown; abundant *Osagia*, small gastropods, ostracodes	1.2
1. Limestone, flaggy, argillaceous, gray, unfossiliferous at base, large ribbed pectinoid fragments and *Ammovertella* at top	0.8

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