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Upper Pennsylvanian Shoreline Deposits form Iowa and Nebraska: Their Recognition, Variation, and Significance

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Upper Pennsylvanian Shoreline Deposits from Iowa and Nebraska: Their Recognition, Variation, and Significance

ABSTRACT

Evidence from stratigraphy, carbonate mineralogy, and primary sedimentary structures indicates that the Rakes Creek Shale, Ozawkie Limestone, and Oskaloosa Shale Members in eastern Nebraska and western Iowa were deposited along the shore of a fluctuating sea. Adjacent positive land areas were located to the west (Nehawka Arch) and locally to the south (Redfield Anticline); the subsiding Forest City basin was located to the southeast.

Stratigraphic evidence supporting these conclusions includes the progressively decreased thickness, increased insoluble content, and increased amount of red shale in these members toward the west. There is also a general increase in the dolomite content of these rocks from the ancient intertidal to the supratidal zone. Primary sedimentary structures suggestive of supratidal and intertidal origin such as birdseyes, desiccation structures, "worm" trails, and thin, wavy laminations are also more abundant toward the west. However, the most diagnostic shoreline features are the well-developed and varied cryptalgal structures of the lower Ozawkie Member which are arranged in subparallel belts analogous to those in the modern intertidal and supratidal zones of Shark Bay, Western Australia. The cryptalgal structures further indicate that the tidal range was at least 8 in., and the paleoslope of the intertidal-supratidal zone was only about 2 in./mi.

The interval from the Rakes Creek to the Oskaloosa Shale is part of a typical midcontinent Pennsylvanian megacyclic sequence, the Deer Creek Megacyclothem (Moore, 1936). The sequence began with the subaerial accumulation of clastic sediments of the Rakes Creek Shale Member followed by marine invasion and deposition of the Ozawkie Limestone Member. The overlying Oskaloosa Shale Member represents a minor regressive phase which ended with a second marine transgression during deposition of the Rock Bluff Limestone Member. Another minor regression with restricted circulation is represented by the lower Larsh Shale Member, which in turn was succeeded by a third transgression during deposition of the upper Larsh and lower Ervine Creek Members. The megacyclic sequence ended with a final major regression at the end of Ervine Creek time.

INTRODUCTION

Because of its extreme variation and complexity, the transition zone between marine and terrestrial environments has attracted the attention of ecologists and sedimentologists for many years. However, during the decade of the 1960s, the pace of research on modern shoreline processes, organisms, and sediments greatly accelerated, especially in areas of carbonate deposition, and this research has provided a firm foundation for the study of such aspects of ancient shoreline deposits as thickness, texture, mineralogy, and sedimentary structures of both physical and biologic origin.

The purpose of this report is to describe in detail a succession of Upper Pennsylvanian rocks deposited in the shallow subtidal, intertidal, and supratidal zones in a restricted area of western Iowa and eastern Nebraska (Fig. 1) and to interpret their paleoecologic and paleogeographic significance.

The authors examined the rocks in twelve stratigraphic sections, including cores from two drill holes. Data from one core drilled near Bedford, Iowa, 51 mi southeast of location 1, were used only incidentally. The data from the

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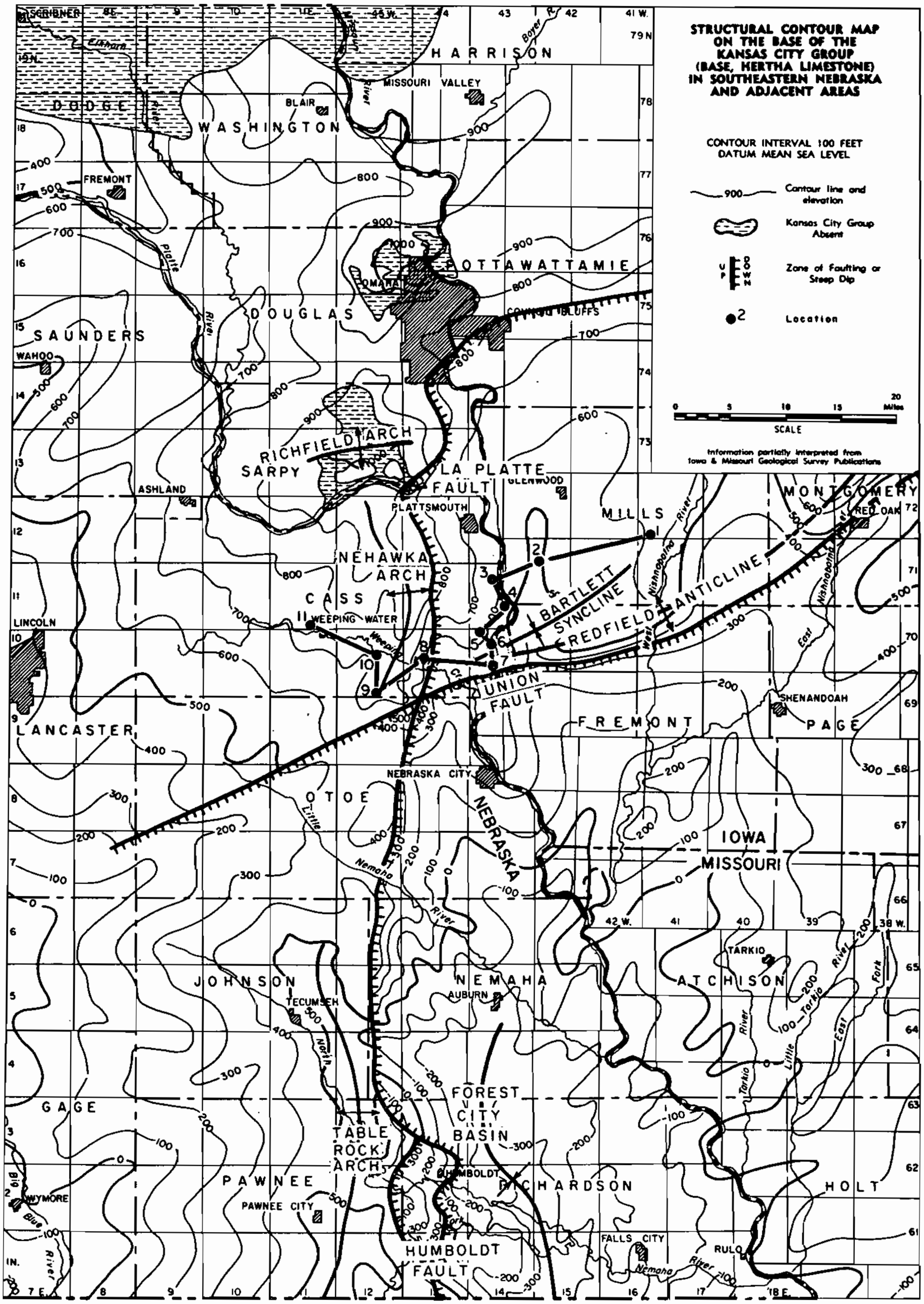
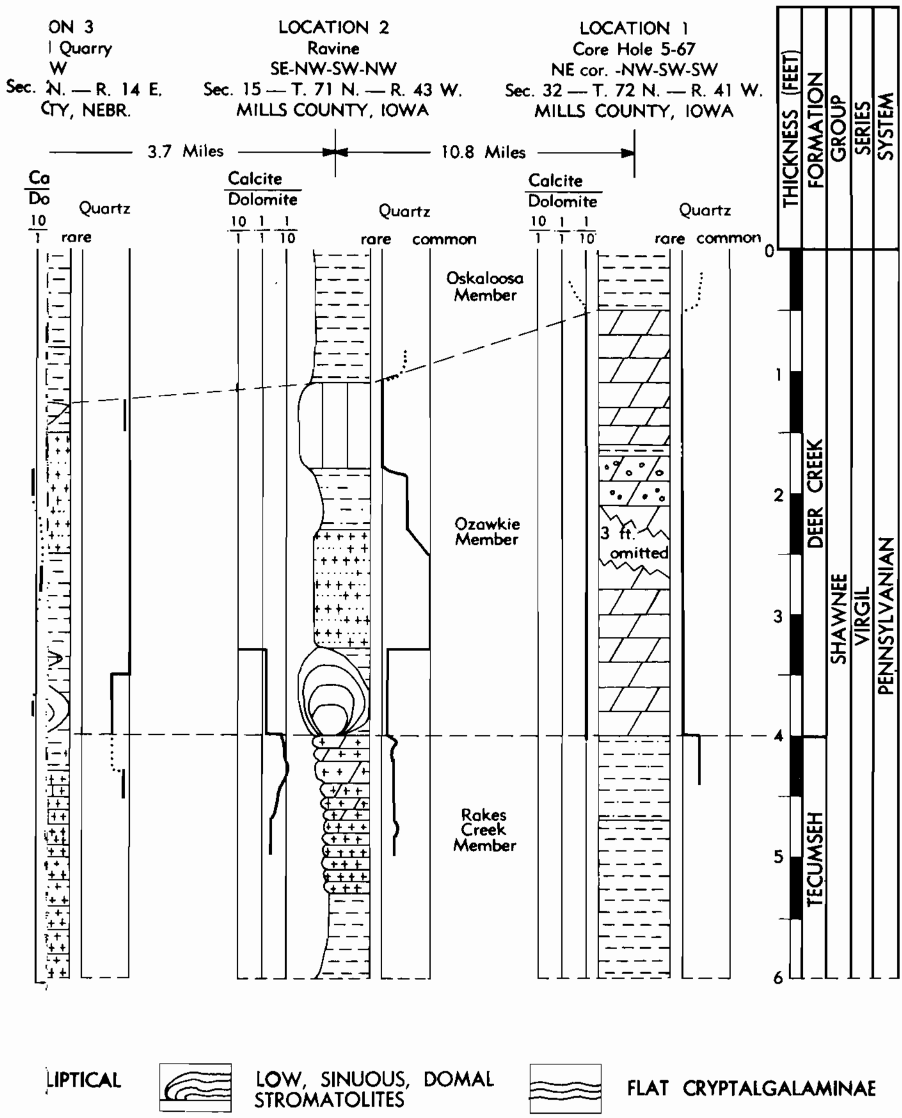


Figure 1. Structural contour map on the base of the Kansas City Group, southeastern Nebraska.



FAGERSTROM, FIGURE 2
Geological Society of America Bulletin, v. 83

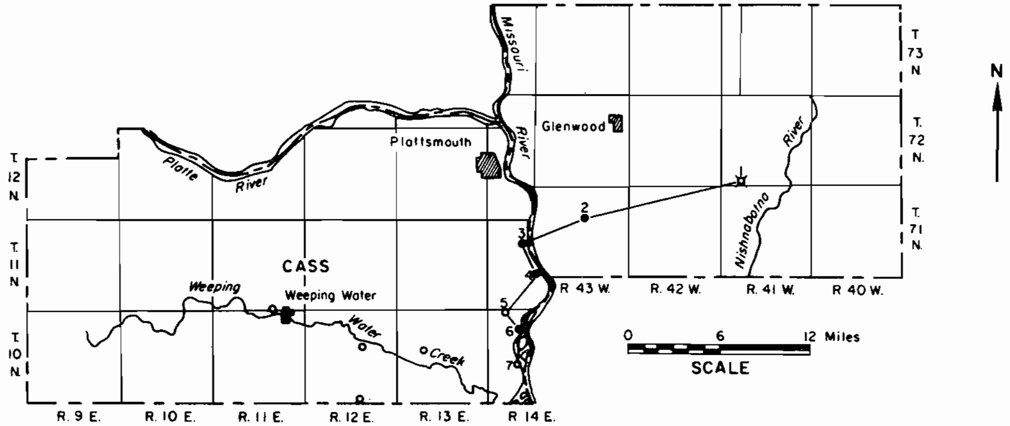


Figure 2b. Index map of Cass County, Nebraska, and Mills County, Iowa, showing location of cross section. ☓ core, Ozawkie present, • outcrop, Ozawkie present, ○ outcrop, Ozawkie absent.

other core (Fig. 1, location 1) and outcrop sections at locations 2 to 7 provided the chief basis for the conclusions reached; these data are summarized in Figure 2 and Appendix.[1] Outcrop data from locations 8 to 11 were used in the preparation of Figure 8, but have been omitted from Figure 2 and Appendix.

STRATIGRAPHIC AND TECTONIC SETTING

The classification of the Upper Pennsylvanian (Virgil Series) in the northern midcontinent region is given in Table 1 (*see* Condra and Reed, 1959, p. 47, 48). The present study concerns the interval from the base of the Ost Limestone to the top of the Ervine Creek Limestone with particular emphasis on the upper Rakes Creek, Ozawkie, and lower Oskaloosa Members.

TECUMSEH SHALE FORMATION

In the area of study, the Ost Limestone is locally absent or indeterminable. In such cases, the shale below the basal member of the Deer Creek Limestone is here considered to be undifferentiated Tecumseh Shale and ranges in thickness from 16.5 ft at location 1 (Appendix 1) to 25.0 ft at location 7. Another stratigraphic problem occurs in determining the boundary between the Deer Creek and Tecumseh Formations when the Ozawkie Limestone is also missing. In such cases the term "Tecumseh Shale-Lower Deer Creek Limestone" is used by the authors to include the rocks between the top of the Lecompton Limestone and the base of the Rock Bluff Limestone. The thickness of this interval ranges from 33 ft (location 8) to 47 ft (location 7).

Rakes Creek Shale Member

The original designation of the type section of the Rakes Creek Shale Member (Condra, 1930) on Rakes Creek (location 5) appears to have included shale and siltstone of the overlying Oskaloosa Member. It is here proposed to restrict the use of the term Rakes Creek to the interval between the top of the Ost Limestone and the base of the Ozawkie Limestone where

TABLE 1. AN ABBREVIATED STRATIGRAPHIC CLASSIFICATION OF THE UPPER PENNSYLVANIAN (VIRGIL SERIES) IN THE NORTHERN MIDCONTINENT REGION

- Wabaunsee Group
- Shawnee Group
  - Topeka Limestone Formation
  - Calhoun Shale Formation
  - Deer Creek Limestone Formation
    - Ervine Creek Limestone Member
    - Larsh Shale Member
    - Rock Bluff Limestone Member
    - *Oskaloosa Shale Member*
    - *Ozawkie Limestone Member*
  - Tecumseh Shale Formation
    - *Rakes Creek Shale Member*
    - Ost Limestone Member
    - Kenosha Shale Member
  - Lecompton Limestone Formation
  - Kanwaka Shale Formation
  - Oread Limestone Formation
- Douglas Group

Units emphasized in the present report are indicated in italic type.

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[1] For Appendix order NAPS Document 01620 from ASIS National Auxiliary Publications Service, % CCM Information Corporation, 909 Third Avenue, New York, New York 10022; remitting $2 for microfiche or $5 for photocopies. Checks may be made payable to CCMIC-NAPS.

these units can be recognized. Although the lithology of the Rakes Creek is highly variable, this member is persistent over the area of study (Fig. 2), and ranges in thickness from 5.8 ft at location 2 to 10 ft at location 7.

At locations 5, 7, 8, 9, 10, and 11, there are no carbonate units identifiable as part of the Ozawkie. Thus, parts of the upper Rakes Creek and lower Oskaloosa at these locations may have been deposited concurrently with the Ozawkie at locations 1, 2, 3, 4, and 6. It is necessary in these cases, where the Ozawkie is missing and the exact boundaries of members are uncertain, to combine units (for example, Rakes Creek Shale Member–Oskaloosa Shale Member). The lower contact of the Rakes Creek Shale is irregular and wavy due to thinning and thickening of the underlying units. Where the Ost Limestone is missing, it is preferable to combine the Rakes Creek Shale–Kenosha Shale as one unit, such as occurs at location 1, or to refer to the unit as the Tecumseh Shale Formation without distinguishing individual members.

DEER CREEK LIMESTONE FORMATION

Ozawkie Limestone Member

The Ozawkie Limestone Member is widely distributed in western Iowa but was not recognized in Nebraska outcrops until Schrott (1966) discovered a thin stromatolite bed at location 3 which proved to be equivalent to the lower bed of the Ozawkie Limestone at location 2 (Fig. 2). Since then, detailed study in Nebraska has resulted in the recognition of the Ozawkie also at locations 4 and 6.

Although the Ozawkie appears to be persistent in the Forest City basin, it pinches out against the Nehawka–Table Rock arches (Fig. 1). Lithologically, the Ozawkie is highly variable (Fig. 2). A core obtained from a drill hole at location 1 penetrated 6.2 ft of dolomite containing thin interbedded shale seams. At location 2, the Ozawkie is 2.7 ft thick and consists of a 0.6-ft stromatolite layer separated from an upper limestone by 1.3 ft of siltstone and shale. The upper limestone bed described at location 2 is absent or reduced to thin lenses of flat-pebble breccia at locations 3 and 4, but the underlying siltstone, shale, and stromatolite beds are present. The Ozawkie Limestone is also present at location 6 where it consists of 1.8 ft of shale with interbedded thin, sandy limestone and dolomite seams.

Oskaloosa Shale Member

The Oskaloosa Shale Member, like the underlying Ozawkie, was not recognized in Nebraska outcrops until 1966. Although the Oskaloosa appears to be persistent over the area of study, the lithologies of this interval are also highly variable.

At location 1, it is 12.8 ft thick and consists mainly of siltstone. This member thins to the west and at location 2 consists of 4.8 ft of pale-olive shale; however, just across the Missouri River at location 3, the Oskaloosa interval thickens to 8.4 ft and a thick siltstone is present in the upper part. At locations 4 and 5, the Oskaloosa is chiefly shale with thicknesses of 5.7 ft and 3.7 ft, respectively. The Oskaloosa thickens agains to 12.0 ft at location 7 where it consists mainly of alternating layers of soft and hard siltstone with some shale at the top.

The contact between the Oskaloosa and the underlying Rakes Creek is indefinite at locations 8 to 11 because the Ozawkie is absent.

This sequence of Upper Pennsylvanian rocks was deposited in the area of the Forest City basin (Lee, 1943), a major tectonic feature of southeastern Nebraska and adjoining parts of Iowa, Missouri, and Kansas located east of the Nemaha arch, a combination of the Table Rock–Nehawka-Richfield arches as shown in Figure 1. Initial structures were formed during the Early Pennsylvanian (post-Morrow pre–Des Moines); subsequent minor uplift along the Nemaha arch area produced various anticlines along this trend. These anticlinal areas have been described and named from surface exposures such as the Richfield arch in Sarpy County, the Nehawka arch in Cass County, and the Table Rock arch in Johnson and Pawnee Counties, Nebraska. Other structural features (Redfield anticline and the Bartlett syncline), extending southwest to northeast from Nebraska into Iowa, were also formed during the Early Pennsylvanian (Condra, 1938).

The base (Hertha Limestone) of the Kansas City Group is one of the stratigraphic units present below the rocks described in this report. This unit originally approached the horizontal and thus is useful as a datum. A structural contour map (Fig. 1) on this datum shows central Cass County, Nebraska, associated with the Nehawka arch and eastern Cass County and Mills County, Iowa, lying within the Forest City basin (Burchett, 1970, p. 8; Burchett and Carlson, 1966).

CRYPTALGAL STRUCTURES OF THE OZAWKIE LIMESTONE MEMBER

Cryptalgal structures (*defined by* Aitken, 1967, p. 1163 as structures "believed to originate through the sediment-binding and/or carbonate-precipitating activities of nonskeletal algae") are the predominant constituents of the lower Ozawkie in outcrops along the Missouri River, where they occur above dolomitic or calcitic siltstones at the top of the Rakes Creek. The base of the cryptalgal unit is typically smooth (*compare* Fig. 3–2), so that neither the form nor the presence of these structures appears to be related to pre-existing substrate relief.

Morphologic Types

In his discussion and classification of cryptalgal structures, Aitken (1967, p. 1163–1164) made a clear distinction between stromatolites and cryptalgalaminate carbonate rocks that is particularly applicable to the Ozawkie Member. According to Aitken, stromatolites are "fixed bodies of cryptalgal origin, characterized by non-planar lamination and possessing definable boundaries or contacts with other stromatolites," whereas cryptalgalaminate rocks are characterized by "discontinuous, more or less planar lamination." This distinction has considerable merit for the interpretation of ancient carbonate depositional environments (Aitken, 1967, p. 1175–1176) and will be used later in the present report for reconstructing the environment of the Ozawkie Limestone in western Iowa and eastern Nebraska.

The Ozawkie cryptalgal structures occur in three distinctly different forms: (1) spherical to elliptical stromatolites; (2) low, sinuous domal stromatolites; and (3) flat cryptalgalaminae. Nomenclature used in the following descriptions has been slightly modified from the method suggested by Logan and others (1964).

Spherical to Elliptical Stromatolites. At location 2, the lower Ozawkie consists of numerous, closely spaced (Fig. 4–1), spherical to elliptical *Cryptozoon*-type stromatolites about 8 in. high and with diameters as much as 24 in. (Logan, 1961, Pl. 2, Fig. 4; Raup and Stanley, 1971, Figs. 9–15, A, B). The individual stromatolites are overlain by shale (Fig. 5–1) and are laterally separated by less than 1 in. of shale; their upper surfaces are rough and irregular (Fig. 5–3) due to numerous, closely spaced, low "wartlike" (Zenger, 1965, p. 115) nodules (Logan, 1961, p. 526). Maximum diameters of these nodules range from 1 to 3 in.

Study of internal stromatolite morphology based on polished sections indicates the presence of an interesting sequence of developmental stages of the "colony" (Figs. 4–2, 4–3) culminating in the final, large compound structures. Initially, the algal laminae were flat to slightly undulatory. Later, the height of the undulations gradually increased until a stage of space-linked hemispheroids (LLH-S) was reached. Continued expansion of the individual spheroids caused them to join laterally, producing close lateral linkage (LLH-C). Continued development resulted in the coalescence of two or more close-linked structures; then began a series of three stacked hemispheroidal stages (SH_{1-3}) that conform essentially to the outer surface of the mature stromatolite. The stacking of hemispheroids during later developmental stages followed neither the mode C nor mode V patterns of Logan and others (1964), because of a rapid expansion in basal radius during development and a tendency of the upper laminae to laterally envelop the preceding ones to form a "fan-shaped" (Rezak, 1957, p. 132) or nearly spheroidal structure. Throughout this entire developmental sequence, the stromatolites remained attached to the substrate and thus cannot be described as oncolites (SS).

The laminae in all stages of development are broken by nearly vertical to radial cracks (Fig. 4–3). The abundance and size of these cracks increases peripherally so that they are so numerous and closely spaced near the stacked hemispheroidal stages (SH_2 and SH_3) that many individual laminae or packets of laminae appear scalloped or wrinkled and resemble small, close-linked hemispheroids. The basal diameter of these scallops or wrinkles varies from about ¼ in. to 2 in., and undulations of their outer laminae are responsible for the nodular external surface of the complete stromatolites (SH_3).

In summary, this sequence of developmental stages is remarkably similar to the sequence noted by Logan (1961, p. 524). The succession of forms can be expressed, using the conventions of Logan and others (1964) for compound forms as:

$$\frac{SH_3}{\text{flat laminar} \rightarrow \text{LLH-S} \rightarrow \text{LLH-C} \rightarrow SH_1 \rightarrow SH_2.}$$

The chief difference between this example and those given by Logan and others (1964) is that


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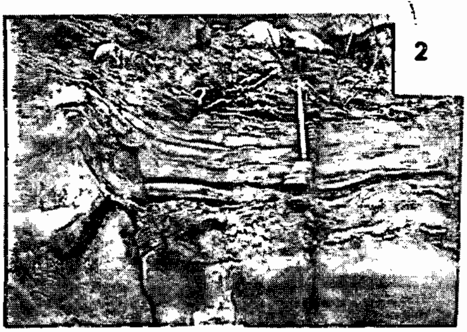
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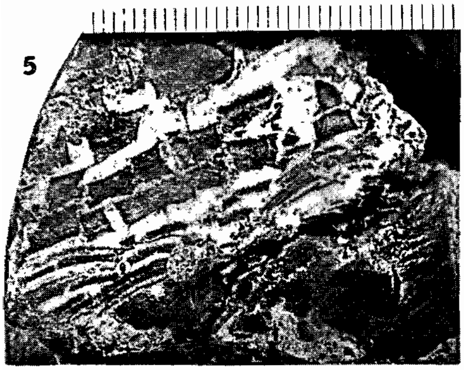
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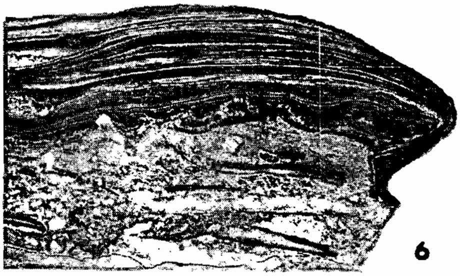
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the Ozawkie developmental sequence is on a microscale (the denominator in the formula), whereas their examples of developmental sequences are on a macroscale.

Study of thin sections from late developmental stages at location 2 (Fig. 5–4) indicate that individual laminae are very thin (0.1 to 0.25 mm), closely spaced, and composed of aligned, rather round, densely to loosely packed, flocculent carbonate particles, averaging about 0.075 mm in diameter. Light-gray laminae predominate in the sections, but the general banding is accentuated by occasional darker gray laminae.

The stromatolites at location 3 are generally similar to those described above except for the following features:

(1) They are not as well developed. They are smaller (up to about 12 inches in diameter and 5 in. thick) and not so abundant or so continuous along the outcrop.

(2) There is no apparent initial flat laminar developmental stage, and the hemispheroids in the space-linked stage (LLH-S) are much more closely positioned. There are fewer vertical and radial cracks, but there is considerable microscale wrinkling of laminae in the later-stacked hemispheroidal (SH) stages.

(3) In thin sections, the lamination is not as well developed; the laminae are brown rather than gray, thicker (0.20 to 1 mm), and less closely spaced. The spaces between laminae contain numerous irregularly arranged, round to angular, open pores 0.20 to 0.8 mm in diameter. In addition, there are also numerous aggregates of dark-brown, opaque minerals that tend to be aligned between the laminae.

Low, Sinuous Domal Stromatolites. At location 4A, the stromatolite unit is only 2 to 3 in. thick (Figs. 3–2) and consists of a series of laterally confluent, low, sinuous *Collenia*-type domes (Fig. 3–1) similar to those described and illustrated by Logan (1961, p. 525–526, Pl. I, Fig. 3), Hoffman (1967, Fig. 2), and Raup and Stanley (1971, Figs. 9–15C). The size and shape of individual domes vary extremely; the largest have maximum diameters of about 8 in. and vary in shape from flattened, low hemispherical structures to distinctly elongate, sinuous "rolls." The surface depressions between adjacent domes and "rolls" are generally shallow so that many adjacent domes appear to be somewhat confluent in plan view (Fig. 3–4). Contrasted with the very rough exterior surfaces of the stromatolites from locations 2 and 3, the upper surfaces of those at location 4A are smooth or gently undulose.

Polished sections of specimens from location 4A (Fig. 6) indicate that the initial algal laminae were flat to gently undulatory, becoming close-linked hemispheroidal domes (LLH-C) with later development. Sediment-filled U-shaped depressions or cracks of variable depth mark the margins of individual domes and never penetrate the entire stromatolite thickness. Some cracks are traversed by occasional subhorizontal to sharply depressed laminae joining adjacent domes (Logan, 1961, p. 523). The elongate particles of the crack-filling sediment include limestone fragments of heterogeneous sizes, shapes, and arrangements (*see also* Zenger, 1965, p. 115) which are suggestive of rapid deposition from currents sweeping the stromatolite surface. Marginal laminae of nonconfluent domes are sharply bent down and may partially envelop the edges

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Figure 3. Stromatolites and associated sedimentary structures at location 4A. 3-1. Oblique vertical view of low, sinuous domal stromatolites, Ozawkie Member. Length of pen is 6 in. 3-2. View transverse to laminations and bedding of low, domal stromatolites, Ozawkie Member, overlying extraordinarily uneven upper surface of Rakes Creek Member. Length of pencil is 6 in. 3-3. Photomicrograph of thin section (×10) of stromatolite, Ozawkie Member, showing well-developed, persistent laminae of varying thickness. Note that the thinner laminae are composed of finer-textured material and have more clearly defined upper and lower surfaces. The thicker laminae may be poorly graded (Shinn and others, 1969, Fig. 20). 3-4. Vertical view of low, domal stromatolite (×¼), Ozawkie Member, divided into two semiconfluent lobes by U-shaped depression partially filled by sediment. 3-5. Polished, stained vertical section from lens of nearly *in situ* flat-pebble breccia 6 in. above stromatolite bed. Scale in millimeters. Note the fine internal lamination in some of the mud chips. 3-6. Polished, unstained vertical section (×⅔) of low, domal stromatolite, Ozawkie Member. Note: (a) overhanging and partial envelopment of early laminations by later laminations and (b) fragments of cryptalgalaminate structure "floating" in the subjacent dolomite matrix; the fragments probably represent pieces of original algal mats that were torn loose by currents from a nearby intertidal location. 3-7. Polished, stained, vertical section of finely laminated dolomite 4 to 5 in. below top of Rakes Creek Member. Dark layers are finer textured than lighter layers. Note the thin layer of *in situ* flat-pebble breccia at top of section. Scale in millimeters.

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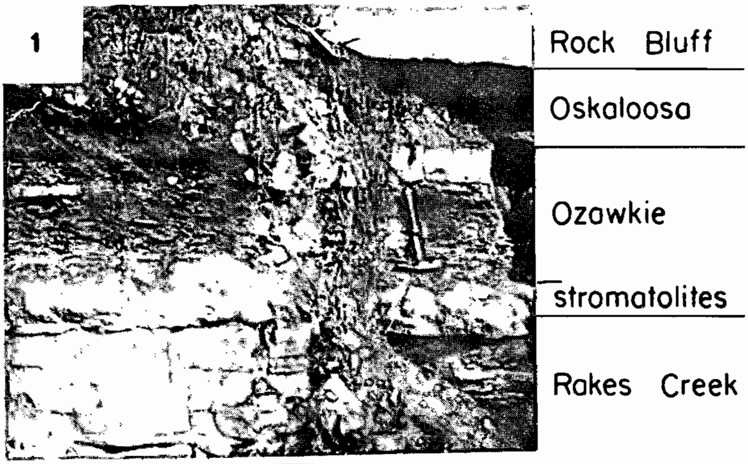
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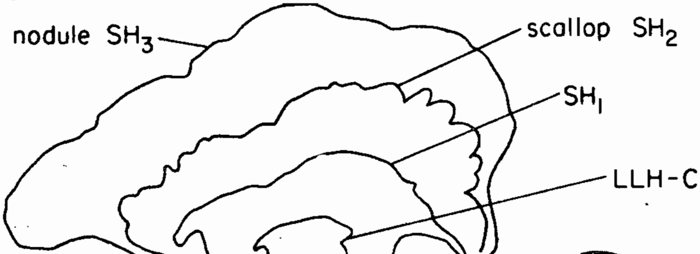
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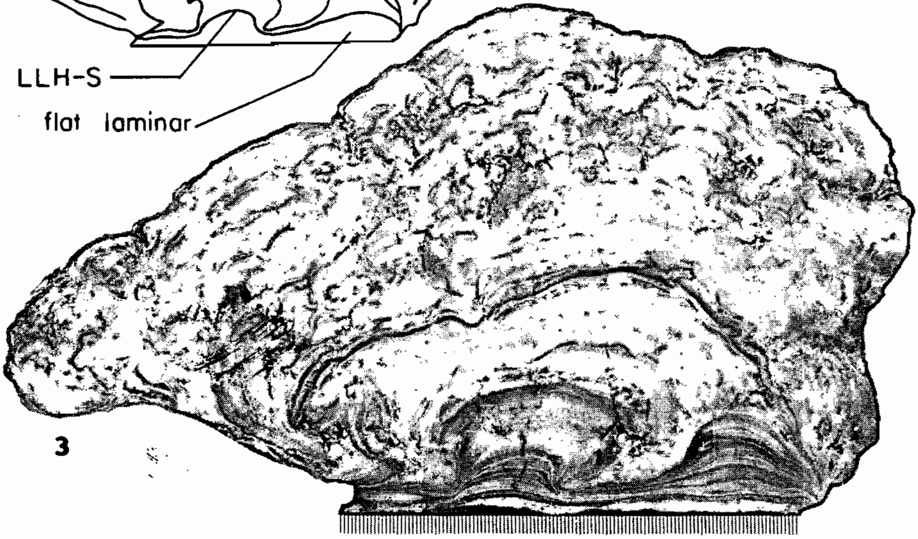

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of pre-existing laminae (Fig. 3–6) to form what may have originally been an overhanging lip above the surrounding depositional surface similar to the discoid structures described by Logan (1961, p. 524–525).

The laminae in thin sections of stromatolites from location 4A (Fig. 3–3) are very prominent, laterally persistent, and vary considerably in thickness (0.1 to 0.6 mm) in a non-uniform manner vertically through the structures. The carbonate particles comprising individual laminae vary in size from micrite to distinct, angular to rounded, tightly packed grains up to about 0.1 mm in greatest dimension. There is a distinct size segregation of particles so that individual laminae are composed of uniformly sized material. The laminae composed largely of coarser textured grains are typically gray, thicker, moderately lenticular, irregularly distributed in vertical sections, may be poorly graded, and probably were deposited under conditions of nonbiotic influence. In contrast, laminae composed of finer textured material are darker colored (generally tan to brown), thinner, more laterally persistent, and with prominent upper and lower surfaces due to a concentration of dark material (? bitumen) that is possibly of organic origin.

Flat Cryptalgalaminae. At location 4C, the Ozawkie is only 1 to 2 in. thick and consists of a cryptalgalaminate limestone bed that lacks the stromatolitic structures described above. The cryptalgalaminae are poorly defined in both polished and thin sections but appear to be thin (0.05 to 0.1 mm) and closely spaced (Fig. 5–5). The laminae are composed of densely packed, gray, lime mud; in some cases, they are separated by irregularly arranged lenses of coarser, lighter colored, angular carbonate and quartz grains up to about 0.1 mm in diameter.

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Figure 4. Stromatolites and associated sedimentary structures at location 2. 4-1. Outcrop of the upper Rakes Creek to lower Rock Bluff stratigraphic section. Note the three units of the Ozawkie Member: lower stromatolite, middle shale, and upper limestone. Figure 4-2 is a "map" of Figure 4-3. 4-2, 4-3. Polished, unstained vertical section of subelliptical stromatolite, lower Ozawkie Member, showing a sequence of "astogenetic" stages from flat laminar cryptalgalaminae to the final nodular stacked hemispheroidal stage (SH_3). Note the presence of numerous, dark, relatively short, vertical to radially arranged, spar-filled desiccation cracks. Scale in millimeters. 4-4. Polished, unstained vertical section of mud-cracked upper dolomite bed of Rakes Creek Member. Scale in millimeters.

ASSOCIATED SEDIMENTARY STRUCTURES

Birdseye Structures

Spar-filled birdseye structures are intimately related to the Ozawkie stromatolites. They occur between the laminations of both the spherical to ellipitical and the low, sinuous domal forms (Fig. 6), but are absent from the flat, cryptalgalaminate forms. The birdseyes vary in size (1 to 10 mm) and shape (round to elongate) and are concentrated in subhorizontal bands, especially in the portions of the colonies near the exterior surface. The presence of the birdseyes has resulted in disruption of the lamination, expansion of the spacing of adjacent laminae, and accentuation of the hemispherical structure of the colony. At location 2, they have produced an irregular upper surface on what probably began as evenly laminated, smooth hemispheroids.

Desiccation Structures

Spar-filled desiccation cracks, approximately normal to the laminae, are present in the spherical to elliptical stromatolites of the Ozawkie at locations 2 (Fig. 4–3) and 3.

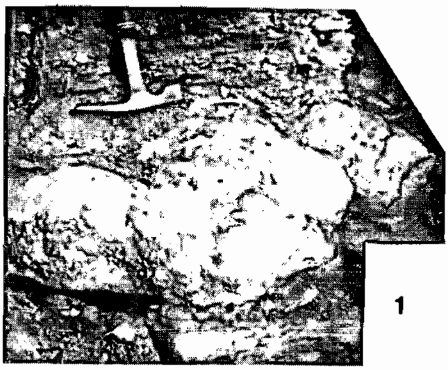
Large, irregular, open cavities and vertical cracks as well as subhorizontal open cracks separating calcareous bands of differing texture and insoluble residue content characterize the flat, cryptalgalaminate bed of the Ozawkie Member at location 4C (Fig. 7). These structures are remarkably similar to those illustrated by Shinn and others (1965, Fig. 6) from Holocene Bahamian supratidal carbonate muds.

Mud cracks, polygons, and associated flat-pebble breccias of varying sizes and shapes are present in the upper Rakes Creek Member at locations 2 (Fig. 4–4), 4C, and 6, in carbonate lenses in the upper Ozawkie at locations 4A (Fig. 3–5) and 6, and in the lower Oskaloosa at location 7.

Miscellaneous Structures

Thin, wavy laminations of varying thickness and texture are common in the upper Rakes Creek at locations 4A (Fig. 3–7), 5, and 7; they are also present immediately above the Ozawkie stromatolites at location 3 and in the lower Oskaloosa at location 7.

"Worm" trails are found on the bedding surfaces of the upper Rakes Creek at location 6, the Ozawkie at locations 4C (Fig. 5–2) and 6, and the lower Oskaloosa at location 7.



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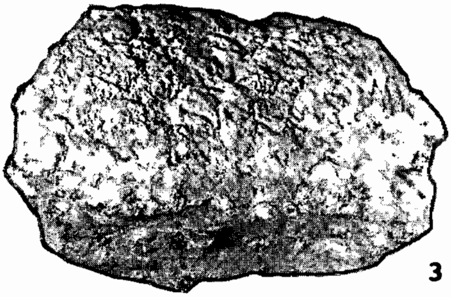

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MINERALOGY

Forty-nine samples from the upper Rakes Creek, Ozawkie, and lower Oskaloosa Members at locations 1 to 7 were prepared and analyzed by x-ray diffraction methods. These samples were selected from lithologic units that appeared to consist of at least moderate amounts of carbonate minerals. X-ray analysis indicated that calcite or dolomite, or both, is present in all but five of the samples. These five samples were collected immediately adjacent to the Rakes Creek–Oskaloosa contact at location 7 and the top of the Rakes Creek at location 1.

Quartz and clay minerals are also present in all of the samples, except for the uppermost limestone bed of the Ozawkie at location 2. The abundance of quartz in the other samples was estimated by the intensity of the 26.6° (2θ) peak. No attempt was made to identify the clays or determine their abundance by x-ray diffraction. The results of these x-ray analyses are expressed in Figure 2 as vertical profiles of the calcite:dolomite ratio and relative abundance of quartz.

X-Ray Techniques

The percentage dolomite was determined by a method modified slightly from the one described by Tennant and Berger (1957) using a Ni-filtered, Cu-radiation General Electric XRD-5 x-ray diffractometer.

The instrument and the method were checked on samples of "pure" dolomite and sparry calcite as well as weighed mixtures of these two end members. Each sample was mechanically pulverized for 2 min; the weighed mixtures were then blended by additional pulverization by hand in a mortar and pestle. Each sample was run twice on the x-ray from 25° to 33° at a rate of 4°/min to determine the location and relative intensities of the quartz ($2\theta = 26.6°$), calcite ($2\theta = 29.40°$), and dolomite ($2\theta = 30.96°$) peaks and the approximate location and relative intensities of the troughs just ahead of the calcite peak ($\sim 2\theta = 28.90°$) and just after the dolomite peak ($\sim 2\theta = 31.9°$). Then the maximum (peaks) and minimum (troughs) intensities were more precisely determined by holding and counting x-ray intensities in 0.1° increments above and below the angles suggested by the chart peaks and troughs.

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Figure 5. Stromatolites and associated sedimentary structures. 5-1. Close-up view of spherical to elliptical elongate stromatolites, lower Ozawkie Member, location 2. Note draping of shale over convex upward stromatolite surface. 5-2. Vertical view of casts of trails associated with cryptalgalaminae, Ozawkie Member, location 4C. Scale in millimeters. 5-3. Oblique vertical view (×1/10) of nodular surface of elongate elliptical stromatolite, lower Ozawkie Member, location 2. 5-4. Photomicrograph of thin section (×10) of stromatolite, lower Ozawkie Member, location 2, showing thin, closely spaced laminae composed of dark, rounded carbonate particles. 5-5. Photomicrograph of thin-section (×10) of cryptalgalaminae, Ozawkie Member, location 4C showing poorly developed, thin, closely spaced laminae.

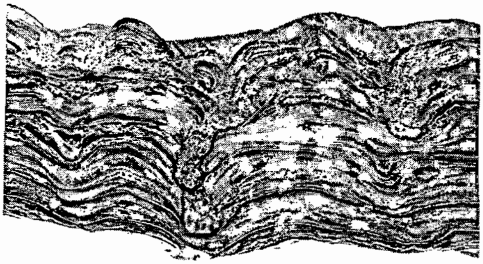

Figure 6. Polished, unstained, vertical section (×1) of low, domal stromatolites, Ozawkie Member, location 4A. Note the following features: (a) continuous layer of gently undulating cryptalgalaminae at base, (b) a deep, U-shaped, sediment-filled desiccation crack to left of center which was repaired by a continuous, depressed cryptalgalaminate layer below center, (c) variation in size, shape, and structure of crack-filling carbonate grains, and (d) bands of dark, clearly defined round to laterally elongate spar-filled birdseye structures. The concentration of birdseyes in bands suggests origin as oxygen bubbles produced by photosynthetic activities of algae and subsequent entrapment below impervious mats (Fagerstrom, 1967).

Results of these standardized procedures were within 5 percent of the weighed percentage of dolomite in the mixed samples which is within the limits of accuracy of the method. Discrepancies between the percentage dolomite in the weighed mixtures and the percentage dolomite by the Tennant and Berger method were partly caused by minor amounts of quartz and clay minerals in both the dolomite and calcite standards, possible feldspar in the dolomite standard, and difficulty in precise interpretation of Figure 1 in Tennant and Berger's paper.

The same procedure was used for each of the unknown samples from the Ozawkie and associated rocks.

The relative amount of quartz in each of the Ozawkie and associated rock samples was esti-

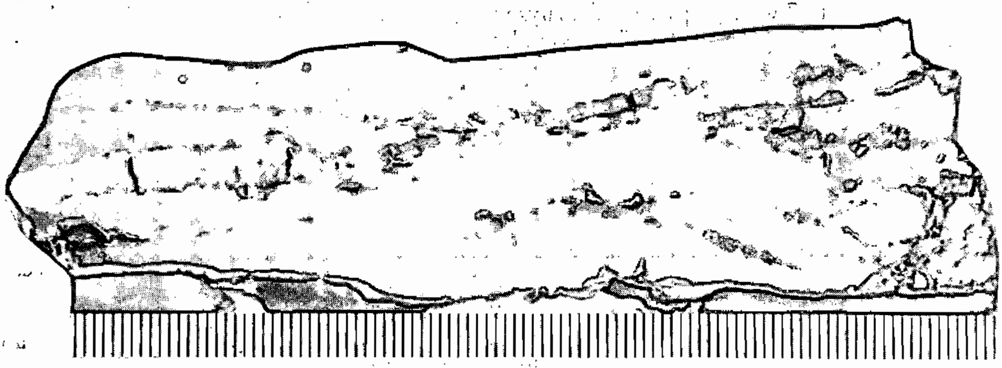

Figure 7. Polished, stained, vertical section of cryptalgalaminate limestone, Ozawkie Member, location 4C. The lenticular, lighter bands are coarser textured than the enclosing darker matrix. Note the presence of vertical desiccation cracks and larger, laterally elongate open cavities (Shinn and others, 1969, Figs. 21 and 22). Scale in millimeters.

mated by comparing the intensity of the 26.6° (2θ) peaks on the charts. The height of this peak was measured above the trough (~26.4°) located just ahead of the peak. The mean height of the peak was then calculated for the 49 samples, and relative abundance of quartz estimated by comparison of each sample with the mean.

The determination of the presence of fine-grained pyrite, rather than marcasite, in the Ozawkie stromatolites was also done by x-ray diffraction.

Carbonate

The abundance of calcite or dolomite (or both) is extremely variable both laterally among approximately correlative rock units and vertically among samples from the same locality. Furthermore, there is no over-all pattern apparent in this variation.

The Ozawkie at location 1 is composed of nearly pure dolomite, whereas this same member at location 6 is dominantly calcite. There is a lateral gradation within the cryptalgal bed from approximately equal amounts of calcite and dolomite at locations 2 and 3, to nearly pure dolomite at locations 4A and 4B, to nearly pure calcite at location 4C. Conversely, the carbonate at the top of the Ozawkie is dominantly calcite at locations 2 and 3 and dominantly dolomite at locations 4A and 4B. The present relative concentration of dolomite in the cryptalgal bed at location 2 is probably somewhat less than the original concentration due to the abundance of spar-filled birdseyes and desiccation cracks which could not be separated from the surrounding matrix during sample preparation.

Lateral variation in calcite and dolomite in the upper Rakes Creek appears to be just as great as in the Ozawkie, although there are fewer data to support this suggestion. At its type section (location 5) there is minor calcite in the Rakes Creek; at location 3, the stratigraphically equivalent beds have very little dolomite. At location 2, just 3.7 mi east of location 3, the carbonate is again largely dolomite.

Carbonate in the Oskaloosa was sampled only at locations 5 and 7, and yet these very limited data are suggestive of extensive lateral variation in the distribution of calcite and dolomite. At location 5, the lower Oskaloosa contains virtually no calcite; at location 7, just 3.4 mi to the south, calcite is the dominant carbonate mineral.

Vertical variation in carbonate distribution at individual locations appears to be just as great as lateral variation and involves changes within the same member as well as changes between adjacent members. Examples of sharp variation within the same member include the Ozawkie at locations 2, 3, and 6 and the Rakes Creek at locations 4A and 6. The changes in the calcite:dolomite ratios near the Rakes Creek–Ozawkie contact at locations 3 and 6 are examples of variation between adjacent members. It should be further emphasized that at location 3, the only dolomite encountered is in the cryptalgal bed, and at location 4A, the highest concentration of dolomite occurs in this same unit.

In an effort to determine the distribution of calcite and dolomite within particular beds, polished and etched vertical sections were prepared for 14 selected samples and stained with alizarin red S as described by Warne (1962, p. 35). In each sample, the dolomite was stained dark blue to purple, indicating the presence of iron. Variations in the intensity of the stained color resulted largely from textural and structural variation in the polished surfaces and were particularly helpful in recognizing fine laminations, birdseye, and desiccation structures, and tabular fragments in the lenses of flat-pebble breccia above the cryptalgal beds. Staining failed to indicate higher concentrations of dolomite in the carbonate material filling the cracks between the mud-crack polygons in the upper Rakes Creek at locations 4 and 2 (*compare* Shinn and others, 1965; Shinn, 1968b).

Differential thermal analysis of one purple-stained sample from about 10 in. below the stromatolite bed at location 2 failed to indicate the presence of ankerite by the method described by Deer and others (1962, p. 297–298), but wet chemical analysis of this same sample indicated the iron content to be 1 to 1.5 percent. Thus, the dominant carbonate mineral in this sample, and in all other samples that were stained purple, probably is a ferroandolomite.

Insoluble Residues

Insoluble residues were obtained from selected carbonate samples of the upper Rakes Creek and Ozawkie Members using the method described by McQueen (1931). The residues consist of rounded quartz grains about 0.1 to 0.15 mm in diameter, clay minerals, small irregular grains of pyrite, and (at location 4) some black material in the Ozawkie Member. The percentage of insoluble residues varies considerably among the lithologic units at each locality and among samples from approximately correlative stratigraphic horizons at different localities.

The insoluble content of the Ozawkie cryptalgal bed is generally less than in the adjacent strata and varies from 11 percent at location 4A to 13 percent at location 2, 21 percent at location 4C, and 37 percent at location 3. The highest percentage of insoluble residues ($\cong$80 percent) is in the upper Rakes Creek at location 3.

Quartz is the dominant insoluble mineral (up to 90 percent) in all samples analyzed. Estimates of relative abundance were made by comparison of the 26.6° (2θ) quartz x-ray diffraction peaks of the same 49 samples used for the carbonate analysis and, similar to the calcite:dolomite ratios, there is extensive lateral and vertical variation in the amount of quartz. (*See* vertical profiles of relative quartz abundance in Figure 2.)

The carbonate units of the Ozawkie Member at locations 1 and 2 contain less quartz than at locations 3, 4A, 4C, and 6. The percentage of quartz in the Ozawkie increases up the stratigraphic column at locations 2 to 4B. The quartz content of the upper Rakes Creek Member is also variable, but no over-all pattern of variation is apparent from the data in Figure 2. In this regard, it is interesting to contrast the upward decrease in quartz content across the Rakes Creek–Ozawkie contact at locations 1, 2, and 4B with the increase in quartz across the same contact at locations 4A and 6. There is also a general increase in quartz content in the Ozawkie above the cryptalgal bed at locations 2 to 4B which may have been partly responsible for killing the original mat-forming algal community.

PALEOECOLOGIC AND PALEOGEOGRAPHIC SIGNIFICANCE

Depth

Cryptalgal Structures. The morphology, distribution, and mode of formation of Holocene carbonate cryptalgal structures have been described by numerous authors from a variety of tropical to subtropical shallow-water environments, including the Bahamas (Black, 1933; Monty, 1965, 1967; Neumann and others, 1970), Bermuda (Gebelein, 1969), Florida (Ginsburg, 1960; Gebelein and Hoffman, 1968), and Shark Bay, Western Australia (Logan, 1961). The environmental significance of some of these observations was summarized by Rezak (1957, p. 141–147) and Logan and others (1964).

The very close resemblance between the cryptalgal structures of the Ozawkie Member and those of Holocene age in Shark Bay is indeed remarkable and of considerable importance in the comparison and interpretation of analogous depositional environments. Each major cryptalgal form in Shark Bay, except for the confluent heads and possibly the discoid structures, has its counterpart in the Ozawkie. Furthermore, the same form zonation described by Logan (1961, p. 528–529) from the intertidal and supratidal zones of Shark Bay is present in the Ozawkie.

At headland areas in Shark Bay, the intertidal and supratidal zones contain stromatolites arranged in elongate belts subparallel to the shore (Logan, 1961, p. 528–530). The outer, reeflike belt extends from approximately the low tideline up the shore nearly to the high tideline; that is, it almost coincides with the limits of the intertidal zone. In this belt, the Shark Bay stromatolites are mostly large, discrete, club-shaped heads analogous to the spherical to elliptical stromatolites in the Ozawkie at locations 2 and 3. The chief difference is that the most well-developed Ozawkie stromatolites are not as thick as the tallest Shark Bay specimens; but, since height is related to tidal range and position within the intertidal zone, this difference does not diminish the paleoecologic significance of this remarkable analogy. The inner stromatolite belt of the supratidal zone at Shark Bay is characterized by low sinuous domes similar to those in the Ozawkie at locations 4A and 4B interspersed with flat, algal-laminated sediments similar to those at location 4C. The relatively poor development of algal lamination in the Ozawkie at location 4C and the absence of such lamination at location 6 may be the result of poor development of the original algal mats, destruction of lamination during decay of the mats, or removal of the mats and laminations by grazing and bioturbation activities of the "worms" that produced the trails in these rocks.

Despite the fact that cryptalgal structures are nearly worldwide in distribution in Precambrian to Holocene rocks, the similarity between the Shark Bay (Holocene) and the Ozawkie (Pennsylvanian) form zonations is the most complete of any known to the present authors. Goldring (1937, 1938) described a somewhat similar occurrence from Upper Cambrian–Lower Ordovician rocks along the border of the Adirondack Dome in New York, and Donaldson (1963, p. 17) alluded to a similar zonation in the Precambrian of eastern Canada, but in neither case is the form zonation analogy so perfect as that in the Ozawkie.

Thus, on the basis of the cryptalgal form zonation, it is highly probable that deposition of the lower Ozawkie at locations 2 and 3 took place in the intertidal zone and that location 4 was supratidal. The occurrence of similar cryptalgal structures (Black, 1933, types A and B; Monty, 1965, 1967) in intertidal and supratidal situations on Andros Island, Bahamas, further supports this suggestion. However, stromatolite formation in Holocene environments is not restricted to intertidal and supratidal zones; Ginsburg (1964, p. 22) reported the presence of algal mats in water as much as 50 ft deep, and Gebelein (1969, p. 55), in water as deep as 35 ft. Playford and Cockbain (1969) have also reported stromatolites from Australian Devonian rocks that are presumed to have been deposited in water depths up to 150 ft.

Birdseye Structures. Shinn (1968a) described the origin of Holocene birdseye structures as voids resulting from the entrapment of gas in carbonate sediments and noted that these structures are found only in intertidal and supratidal environments. He was uncertain (Shinn, 1968a, p. 218–219) of the nature and origin of the void-producing gas, but suggested that in many cases it was trapped air or gas released during the decay of organic materials. However, Fagerstrom (1967) described the occurrence of oxygen bubbles produced in shallow water by the photosynthetic activities of mat-forming algae and their subsequent entrapment beneath thin, submerged, and floating mud crusts. This latter mode of formation of gas-filled voids is theoretically possible in depths to the base of the photic zone, and if the bubbles become trapped beneath coherent algal mats, it appears quite possible that birdseyes originate in subtidal environments (Shinn, 1968a, p. 220–223). The concentration of birdseyes in clearly defined layers beneath continuous algal laminations (Wolf, 1965, p. 200–202) in the Ozawkie stromatolites (Fig. 6) is highly suggestive of origin by entrapment of photosynthetically produced oxygen. Furthermore, the birdseyes under the stromatolite domes tend to be larger and more numerous than those under the intervening troughs, suggesting that the entrapment of gas was also an important cause of domal development (*compare* Logan, 1961, p. 521–522).

At locations 2 and 4A, the birdseyes are closely associated with desiccation cracks in the stromatolites and at the latter location are also present in the crack-filling carbonate mud (Fig. 6). This joint occurrence of low, domal stromatolites, desiccation cracks, and birdseyes rather clearly indicates that the original gas-filled voids developed in either the intertidal or supratidal zone. Furthermore, the stromatolites, desiccation cracks, crack-filling mud, and birdseyes must have formed in that order prior to lithification and the entire episode of deposition, drying, and formation of the gas-filled voids must have taken place over a relatively short period of time.

Desiccation Structures. The environmental significance of desiccation cracks, mud polygons, and flat-pebble breccias has been noted by Barrell (1906), Kindle (1917), Shrock (1948), Roehl (1967, p. 2006–2009), and Fagerstrom (1967, 1972). These authors concluded that, except for the relatively uncommon case of syneresis cracks (for which there is no evidence in the Ozawkie and related rocks), these structures result from subaerial drying of unlithified sediments deposited along the shores of fluctuating or ephemeral aquatic environments. Furthermore, since the incidence of these structures in the upper Rakes Creek, Ozawkie, and lower Oskaloosa generally increases from locations 2 to 7, they support the hypothesis of progressively increased subaerial exposure from an intertidal environment at locations 2 and 3, to supratidal at locations 4 to 7.

Laminations and Trace Fossils. Thin, wavy laminations may form in a variety of environments (McKee, 1964, p. 277–280) so that by themselves they are seldom conclusive paleoecologic indicators. However, when they occur in association with other sedimentary structures suggestive of particular environmental settings, they may be useful supporting evidence; this is the case with those in the upper Rakes Creek, Ozawkie, and lower Oskaloosa at locations 4A, 5, and 7. Studies of Holocene carbonate mud flats (*see* Shinn and others, 1969, p. 1209–1213) and noncarbonate mud flats (van Straaten, 1959; Conybeare and Crook, 1968, p. 47, 146) indicate that thin, wavy laminations are much more prevalent in supratidal than intertidal or subtidal positions, because in submerged areas, the original lamination is commonly destroyed by the abundant burrowing organisms (Moore and Scruton, 1957, p. 2741–2743). Thus the evidence again suggests supratidal conditions during deposition of these rocks at locations 4 to 7.

Seilacher (1967) has demonstrated the value of some trace fossils in determining water depth; however, the value of the "worm" trails in the upper Rakes Creek, Ozawkie, and lower Oskaloosa at locations 4C, 6, and 7 for this purpose is limited for two reasons: (1) poor preservation and the difficulty of exposing large bedding plane surfaces make it uncertain whether the trails are pascichnia or repichnia (Seilacher, 1964), and (2) both pascichnia and repichnia are being formed in Holocene sediments in terrestrial and aquatic environments from the supratidal zone to the deep seas (Seilacher, 1967, p. 425–426). Although pascichnia are most characteristic of the deep-water *Nereites*-facies (Seilacher, 1964, p. 307–313), they are not restricted to this environment. Furthermore, the weight of the other lines of evidence from the upper Rakes Creek, Ozawkie, and lower Oskaloosa indicates conclusively that these rocks are not of deep-water origin.

Dolomite. Interpretation of the environmental significance of dolomite in the Ozawkie and associated rocks is difficult because of the relative scarcity of data on the mode of formation, distribution, and diversity of environments of Holocene dolomitic sediments, and because of problems concerning the diagenetic history of ancient dolomitic rocks (Fairbridge, 1957). The relatively small and widely distributed areas of Holocene dolomite occurrences (Shinn and others, 1965; Illing and others, 1965; Deffeyes and others, 1965; Shinn, 1968b) provide excellent analogs for the interpretation of some ancient dolomites (for example, Laporte, 1967; Matter, 1967; Schenk, 1967; Textoris, 1968), but are not entirely satisfactory to explain the origin of all dolomitic rocks (Zenger, 1970).

In some dolomites, diagenesis has so completely destroyed the original depositional features that the paleo-environment of the carbonate deposits cannot be determined. Such does not appear to be the case for the dolomitic portions of the Ozawkie and associated rocks. In thin section, this dolomite generally consists of very fine-textured, anhedral grains which evidently have undergone some early diagenetic alteration by penecontemporaneous dolomitization and recrystallization. In addition, the presence of sharp vertical and lateral gradients in dolomite concentration suggest that dolomitization by later migration of magnesium-rich ground water was fairly localized. Thus, the present distribution of dolomite in these rocks must approximate the early diagenetic distribution.

The majority of examples of Holocene dolomite formation are from sediments deposited in supratidal locations in areas of high evaporation where magnesium has been concentrated by periodic recharge from hypersaline water. However, the mere presence of dolomite in ancient rocks is not proof of deposition in a supratidal environment. Instead, it is the association of dolomite with cryptalgal, desiccation, and birdseye structures, thin laminations, and "worm" trails that supports the supratidal to intertidal origin for most of the dolomite in the Ozawkie and associated rocks. Therefore, the presence of dolomite in the cryptalgal bed at locations 4A and 4B is supporting evidence rather than proof of supratidal deposition of these rocks and those in the upper Rakes Creek–lower Oskaloosa succession at location 5.

Dolomite is not ubiquitous in Holocene supratidal environments and does not appear to have been so during deposition of the lower Ozawkie as exemplified by its virtual absence at locations 4C and 7 and at location 6 (except for one bed). Stratigraphic and tectonic evidence and the nature and distribution of primary sedimentary structures suggest that these rocks are also of supratidal origin.

Furthermore, dolomitization of the upper Rakes Creek–lower Oskaloosa succession apparently was not confined to rocks deposited in the supratidal and intertidal zones. Thus, although the Ozawkie is chiefly dolomite at location 1 and in an 8-ft section from a core obtained near Bedford, Iowa, (approximately 51 mi southeast of location 1), there is no additional evidence that any of these rocks are of supratidal origin. In fact, the presence of pseudo-oölites at location 1 and the progressive basin-ward (southeastward) increase in thickness of the Ozawkie suggest that these rocks were deposited subtidally. Subaqueous precipitation of dolomitic sediments has been described by Skinner (1963) from several shallow, warm, brackish to hypersaline lakes and lagoons of high *p*H in southeastern Australia. Use of this analogy to explain the origin of the presumably subtidal dolomite in the Ozawkie at location 1 and near Bedford is not entirely satisfactory. Despite the fact that the data on these rocks are limited to cores, there is no evidence for the presence of either evaporite minerals or plants in association with the dolomite. Furthermore, the apparent wide distribution of dolomite in southwestern Iowa contrasts sharply with its apparent limited distribution in the Australian analog.

Thin sections from the calcareous layers in the Ozawkie at location 6 contain relatively large, subhedral calcite crystals which may be the result of the recrystallization of an original aragonite. If this interpretation is correct, these repetitive carbonate layers may simply represent the periodic recurrence of an environment exposed to the spray of breaking waves and subsequent cementation by percolating lime-rich sea water, that is, an ancient beachrock. The anomalous thick section of Ozawkie at location 6 results from the coincidence of this outcrop with the axis of a minor actively subsiding trough, the Bartlett syncline (Fig. 1; Condra, 1933).

Acceptance of the general concept of supratidal to intertidal origin for dolomitic rocks containing thin wavy laminations and desiccation structures in the upper Rakes Creek–lower Oskaloosa interval leads to the recognition of an orderly southwestward shift in the shoreline. This transgression from the Forest City basin onto the eastern limb of the Nemaha arch and the northern limb of the Redfield anticline (Fig. 1) can be inferred from changes in the lateral and vertical distribution of dolomite concentration in these rocks (Fig. 2). Thus, the relatively widespread occurrence of abundant dolomite, thin, wavy laminations (locations 4A, 5, 7), and desiccation structures (locations 2, 4A, 4C, 6) in the upper Rakes Creek suggests that deposition at locations 2 to 6 was supratidal. In addition, the absence of carbonates in correlative rocks at locations 1 and 7 may be the result of subaerial leaching prior to the accumulation of the overlying beds. The upward decrease in dolomite concentration at locations 2 to 4B is probably the result of reduced circulation of hypersaline water which, in turn, is related to a change in the environment. Thus, during Ozawkie deposition, locations 2 and 3 changed from intertidal, when the cryptalgal bed formed, to subtidal during accumulation of the upper limestone bed and lenses. At this same time, the general upward decrease in dolomite at locations 4A and 4B suggests that here the environment changed from supratidal to intertidal. During this entire transgressive episode locations 4C to 11 probably remained supratidal.

In summary, if this interpretation is correct, the cryptalgal bed represents the initial deposit of a transgressive cycle. This transgression resulted in a southwestward shift of the intertidal zone from somewhere east of location 1 (during late Rakes Creek time) to locations 2 and 3 (during early Ozawkie deposition) to locations 4A and 4B (during the late Ozawkie), a distance of about 6 mi. The very limited data on the occurrence of dolomite in the lower Oskaloosa Member suggest that location 5 continued to be supratidal during this transgression; the presence of desiccation structures and "worm" trails in correlative rocks at location 7 suggest that this area also remained supratidal.

Currents and Tides

Logan (1961, p. 527), Roehl (1967, p. 2002–2003), and Gebelein (1969, p. 65) have described the occurrence of elongate stromatolites from Holocene shallow-water carbonate environments and noted the relation between the direction of elongation and the direction of the currents. Goldring (1937; 1938, p. 12, 17, 18), Zenger (1965, p. 115, 142), and Hoffman (1967) have described similar elongate stromatolites from ancient rocks. The conclusion reached by these authors is that the direction of elongation parallels the direction of the dominant currents which in the intertidal zone are approximately perpendicular to the shoreline.

Pronounced elongation of the Ozawkie stromatolites at location 2 is readily apparent, and at location 4A there is some evidence of elongation. The mean azimuth of the maximum dimension of four stromatolites at location 2 is N. 55° E., and for 13 stromatolites at location 4A the mean azimuth is N. 38° E. These directions generally parallel a line joining locations 2 and 4A which, in turn, is generally parallel to the form zonation trend present in the intertidal-supratidal zones previously described for the Ozawkie at these locations. Furthermore, if these directions generally coincide with the dominant current direction in these zones, it is safe to infer that they are approximately perpendicular to the shoreline. Thus, the direction of elongation of the Ozawkie stromatolites provides additional evidence to support the conclusion of a general north-south–trending shoreline with location 2 near the base of the intertidal zone and location 4A near the base of the supratidal zone.

Logan (1961, p. 531) noted that the maximum height of the *Cryptozoon*-type stromatolites in Shark Bay is approximately the same as the tidal range. If this was also true during formation of the Ozawkie *Cryptozoon*-type stromatolites, the tidal range must have been at least 8 in., which is the maximum height of the stromatolites observed at location 2. In addition, it is possible to estimate the paleoslope of the Ozawkie intertidal-supratidal zones by use of the Shark Bay analogy. The decrease in height of the Ozawkie cryptalgal structures from 8 in. at location 2, to 3 in. at location 4A, and 1 in. at location 4C occurs along a traverse that is approximately perpendicular to the ancient shoreline. Thus, the reduction in height of the cryptalgal structures from 8 in. to 1 in. across this 4-mi-wide intertidal-supratidal zone indicates a paleoslope of less than 2 in. per mile. This figure contrasts with a value of 5 in. per mile suggested by Brown (1969) as typical of clastic deltaic rocks from the Upper Pennsylvanian of north-central Texas and a paleoslope of approximately 250 in. per mile in the tectonically active area of the Middle Pennsylvanian Ancestral Rockies of central Colorado (Stevens, 1969).

If the paleoslope data based on the Ozawkie stromatolites is typical of midcontinent late Paleozoic topography, then each tidal change must have resulted in relatively great lateral shifting of the shoreline. Furthermore, if the tidal range was greater and the days shorter during the Pennsylvanian as suggested by Wells (1963) and Lamar and Merifield (1967), the volume of water moving across midcontinent intertidal zones during each tidal change must have been considerably greater than has been recognized previously from uniformitarian principles. The resulting intertidal, subtidal, and estuarine currents may also have been so strong as to make the environmental stress prohibitive to occupation by most of the common marine invertebrates; this theory could partly explain the absence of shell-bearing invertebrates in the upper Rakes Creek–lower Oskaloosa interval at all locations examined in this study.

Sources for Insoluble Clastic Materials

Because quartz and clay minerals in carbonate rocks are generally of terrigenous origin, numerous previous authors have used trends of increasing amounts and coarser textures of quartz and clay to suggest directions toward ancient source areas. Thus, the relatively greater abundance of insolubles at locations 3, 4A, 6, and 7 in the upper Rakes Creek and Ozawkie Members is probably indicative of greater proximity to a terrestrial source (Nehawka arch) than were locations 1 and 2. Similarly, the increase in the insoluble content of the lower Oskaloosa from location 5 to location 7 suggests that the latter was closer to a very local source (Redfield anticline).

GEOLOGIC HISTORY

The general late Paleozoic tectonic history in the northern mid-continent region consists of

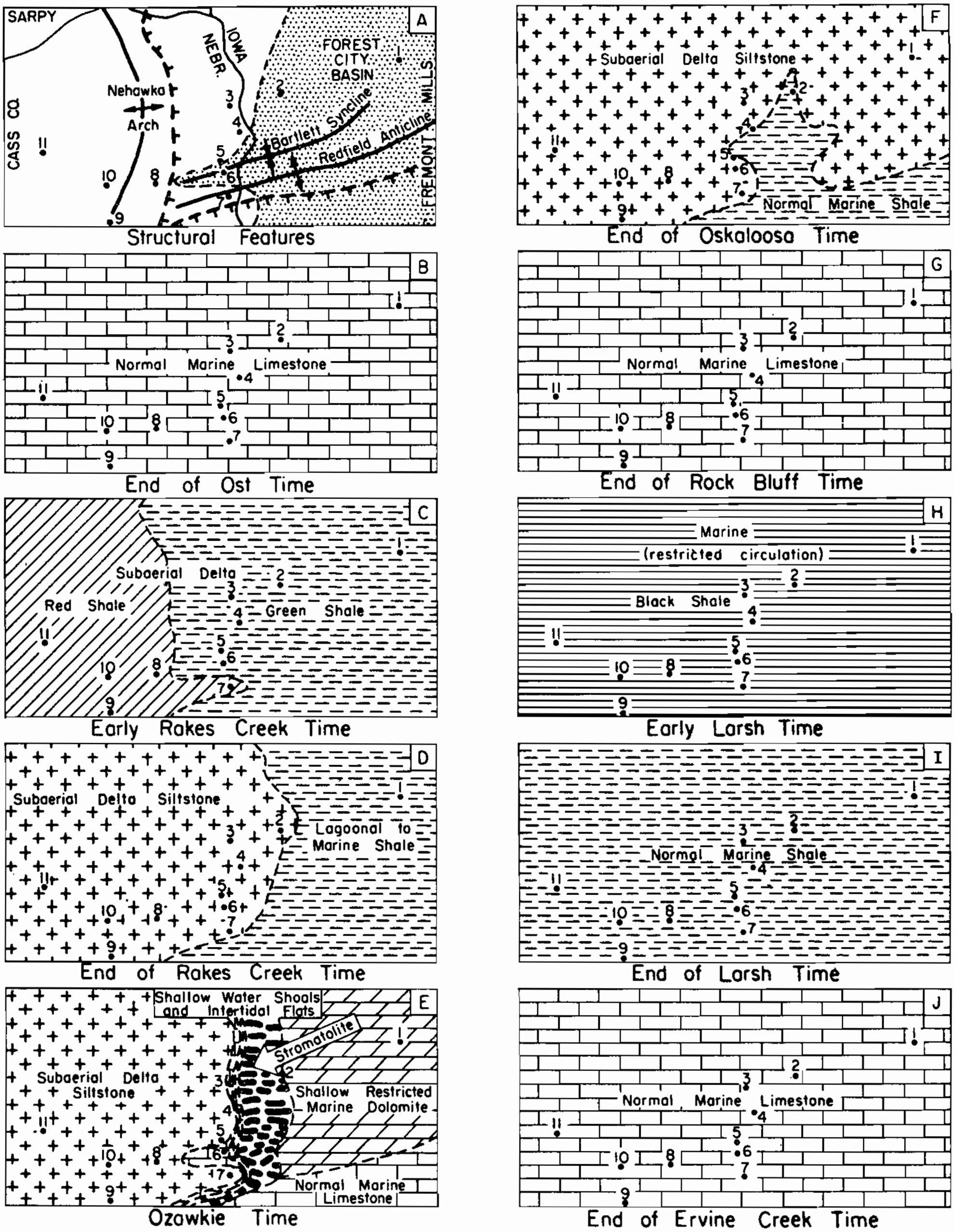

Figure 8. Summary of the geologic history of western Iowa and eastern Nebraska during deposition of the Deer Creek Megacyclothem. Figure 8A indicates the location of the described outcrops and core in relation to the major structural features. The data for Figures 8B to 8J are described in Appendix 1 (*see* footnote 1) with supplemental data for Figures 8D and 8E described in the text and in Figure 2.

periodic slow and gentle epeirogenic warping: relative uplift of the positive structural features and subsidence of the negative features. The times and rates of these movements are highly variable as evidenced by great lateral variation in the distribution, thickness, and lithology of some rock units in contrast to the remarkable uniformity in these same aspects of other rock units. The rocks described in this report include examples of both the highly varied and the remarkably uniform types.

Contemporaneous uplift of the Nehawka arch and Redfield anticline (Fig. 8A) resulted in regression, restriction of the sea, and erosion, so that these structural features became local sources of terrigenous clastic materials (*see* Reed and Burchett, 1964). Subsidence produced transgression, widespread uniform depositional environments, and filling of the Forest City basin and Bartlett syncline (Fig. 8B).

A major eastward regression of the shore followed Ost time (Fig. 8B). The relatively thick sequence of nonmarine gray, green, and red shales of the lower Rakes Creek mark the initial phase of a major unit of cyclic deposition recognized and named the Deer Creek Megacyclothem by Moore (1936). During most of Rakes Creek time, these clastic sediments accumulated subaerially; red shale predominates to the west and gray to green shale to the east (Fig. 8C). At the end of Rakes Creek time, however, marine transgression brought the shoreline westward to a position between locations 1 and 2 (Fig. 8D).

Continued transgression during Ozawkie time brought the shoreline to the eastern flank of the Nehawka arch and into a western embayment coincident with the axis of the Bartlett syncline (Fig. 8E); in Moore's terminology for midcontinent late Paleozoic megacyclic deposits, the Ozawkie is a "lower" limestone.

During early Oskaloosa time, there was a brief regression followed by a transgression from the Forest City basin in the late Oskaloosa. This transgression extended northward at least to location 2 (Fig. 8F) where the upper Oskaloosa contains marine fossils. The Rock Bluff (a "middle" limestone of Moore, 1936) represents the culmination of this transgressive cycle (Fig. 8G) which uniformly inundated both the positive and negative structures.

Subsequent uplift and shallower-water ended the deposition of carbonate materials and led to an environment of restricted circulation and stagnant substrates represented by black, fissile shales of the lower Larsh (Fig. 8H). Another minor transgressive cycle began with the accumulation of gray marine mud during late Larsh time (Fig. 8I) and continued with progressive deepening, reduced turbidity, and return of a carbonate substrate in the Ervine Creek (Fig. 8J), an "upper" limestone of Moore (1936). The beginning of another major regression is recorded by shallow-water oölitic limestone of the upper Ervine Creek. This regression continues to the upper boundary of the Ervine Creek which also marks the end of the Deer Creek Megacyclothem in this area.

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