CARBONATE DIAGENETIC FACIES IN THE UPPER PENNSYLVANIAN DENNIS FORMATION IN IOWA, MISSOURI, AND KANSAS[1]

L. BRUCE RAILSBACK[2]
Department of Geology
University of Iowa
Iowa City, Iowa 52242

ABSTRACT: The carbonate members of the Dennis Formation can be divided into five regional diagenetic facies that are defined by differing preservation of originally unstable carbonate grains. Such grains contain no relict internal structure in the uppermost facies (A); they are better preserved in middle facies (B and C); and they are well preserved in the lowest facies (D). A fifth facies (E) contains no originally unstable grains and is characterized by a microcrystalline dolomite fabric. The five facies exhibit differing patterns of compaction and dolomitic void filling.

The textures and interpreted diagenetic environments of the diagenetic facies were caused by progressive interaction of initially unsaturated meteoric water with the marine sediments during a general regression. Transfer of $CaCO_3$ in that interaction and the resulting distribution of cements governed later patterns of pressure solution and void filling by ferroan dolomite. Paleohydrologic controls caused irregularities in the distribution of diagenetic facies. Paleotopographic and depositional trends derived from diagenetic evidence agree with previous interpretations based on depositional evidence.

INTRODUCTION

Diagenetic Facies

Diagenetic facies are rock bodies defined by distinctive diagenetic textures. They are therefore objectively defined units, are not based on interpretations of diagenetic history, and are generally independent of depositional facies. The characteristics of different diagenetic facies presumably result from passage through differing sequences of diagenetic environments (Longman 1980). Diagenetic facies thus differ from depositional facies in allowing interpretation of several environments, rather than only one.

Five carbonate diagenetic facies can be recognized in the Missourian Dennis Formation. These facies are distinguished by differing preservation of original structures within carbonate grains that are interpreted as having originally unstable mineralogies (i.e., aragonite and very high Mg calcite). For simplicity, these facies are named Diagenetic Facies A, B, C, D, and E (Fig. 1 and Table 1). The nature and distribution of these facies allows interpretation of both diagenetic environments (Longman 1980) and the resultant transfer of $CaCO_3$ in the Dennis Formation.

Dennis Formation

The Dennis Formation is a cyclothemic limestone and shale unit in the Missourian (Upper Pennsylvanian) Kansas City Group. It crops out in Iowa, Missouri, and Kansas and extends westward into the subsurface (Watney 1980) (Fig. 2). The Dennis consists, in ascending order, of the thin and laterally restricted Canville Limestone Member, the Stark Black Shale Member, and the Winterset Limestone Member, which is up to 30 m thick (Fig. 3).

The Canville Member consists of skeletal calcilutites and calcarenites. In southeastern Kansas, the Winterset Member consists of algal mounds with oolite beds in their upper reaches, and in Missouri and Iowa it consists largely of skeletal calcilutites with skeletal calcarenites near its top, below relatively barren laminated calcilutites (Fig. 3).

Faunal and stratigraphic studies indicate that deposition of the Dennis Formation was entirely marine (Horne 1965; Payton 1966;

---

[1] Manuscript received 25 April 1983; revised 10 April 1984.

[2] Presently with Shell Oil Company, New Orleans, Louisiana.

JOURNAL OF SEDIMENTARY PETROLOGY, VOL. 54, NO. 3, SEPTEMBER, 1984, P. 0986–0999

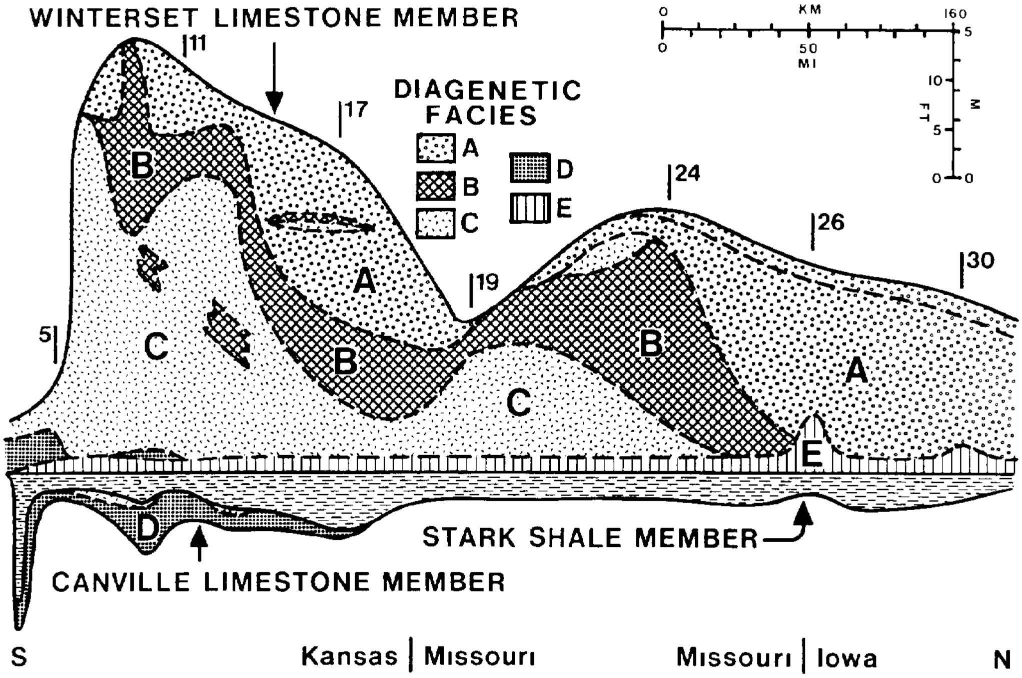

FIG. 1.—Stratigraphic cross-section of Dennis Formation showing diagenetic facies. Characteristics of facies are listed in Table 1. Area above dashed line within Facies A is rubbly, nodular zone. Datum is top of Stark Shale Member. Numbers by vertical lines match locality numbers in Figure 2.

Frost 1975; Schutter 1983). Heckel's (1977, 1980) model for deposition of Midcontinent Pennsylvanian cyclothems suggests that the Canville Member was deposited during transgression, the Stark Shale Member during maximum transgression, and the Winterset Member during regression.

Recent studies of the Dennis include Payton (1966), Frost (1975), Dubois (1979), and Schutter (1983). This study will examine the diagenesis of the Canville and Winterset Limestone Members by describing and interpreting the diagenetic facies recognized in those members. One hundred eighty-seven thin sections were prepared from 28 outcrop localities and 3 cores spread over an outcrop belt of 515 km in Iowa, Missouri, and Kansas (Fig. 2).

DENNIS DIAGENETIC FACIES

Distribution

Diagenetic Facies A, B, C, D, and E of the Dennis Formation form roughly subparallel regional units (Fig. 1). Facies A is the uppermost and northernmost facies, with B, C, and D progressively lower and farther south. Facies E occurs above the Stark Shale Member. Boundaries between facies are commonly gradational, and irregularities in the distribution of facies occur both in beds with higher primary porosities than surrounding strata and in beds isolated by shale partings. Examples include lowered portions of Facies B in unisolated oolite beds at localities 11 and 15, and perched portions of Facies C in oolite beds isolated by shale partings at localities 17 and 22 (Fig. 1).

Facies A

Grains.—Facies A consists of those rocks in which all originally unstable grains (phylloid algae, ooids, and molluscs) are devoid of relict internal structure. Phylloid algae consist only of clear, blocky spar, and the outlines of algal blades are commonly disrupted by brecciation of the surrounding mud, suggesting that the mud collapsed as coherent clasts into

TABLE 1.—*Summary of characteristics and interpreted processes and environments of diagenetic facies in Dennis Formation. Table omits marine cementation interpreted in Facies A, B, C, and D. Distribution of facies is shown in Figure 1*

Facies	Major Petrographic Characteristics	Interpreted Processes (in approximate temporal order)	Interpreted Environments (in temporal order) (* = longest duration in early diagenesis)
A	All unstable grains now clear, structureless calcite Fine dolomite at edges of primary voids Ferroan dolomite in primary and secondary voids Some interpenetrating grain-to-grain contacts	Precipitation of void-filling dolomite Leaching of all unstable grains Void filling Grain-to-grain pressure solution Fe dolomite void filling	Mixing zone *Unsaturated meteoric-phreatic and vadose Saturated meteoric-phreatic Burial
B	Most unstable grains as in Facies A; a few with preserved internal structure Ferroan dolomite in secondary voids Minor stylolites in algal rocks	Neomorphism of a few grains and some void filling Leaching of most unstable grains Void filling Pressure solution Fe dolomite void filling	Saturated meteoric-phreatic *Unsaturated meteoric-phreatic Saturated meteoric-phreatic Burial
C	Most unstable grains with some preserved internal structure; a few as in Facies A Ferroan dolomite in secondary voids Stylolites in algal rocks	Neomorphism of most unstable grains and some void filling Leaching of remaining unstable grains Pressure solution Fe dolomite void filling	*Saturated meteoric-phreatic Unsaturated meteoric-phreatic Saturated meteoric-phreatic Burial
D	All unstable grains with some preserved internal structure Many interpenetrating grain-to-grain contacts, fitted fabric, and broken grains	Neomorphism of all unstable grains Grain-to-grain pressure solution and grain breakage Minor void filling	*Stagnant, saturated meteoric-phreatic and/or burial
E	Dolomitic microspar matrix Very few unstable grains Crushed shells	Dolomitization of lime mud matrix Grain breakage Minor void filling	*Mg-rich, stagnant, saturated meteoric-phreatic and/or burial

the space originally occupied by the algae (Fig. 4A). Molluscs in Facies A consist of clear, blocky spar and can be recognized in some calcarenites only by micrite envelopes showing the original grain shape. Ooids in Facies A consist of clear, blocky spar.

Other grains in Facies A show few diagenetic effects other than interpenetrating contacts, rare grain breakage, and internal void filling.

Cements.—Cements in Facies A are almost entirely mosaics of clear blocky calcite that coarsen toward the centers of voids. Prismatic cements containing inclusions of microdolomite (Lohmann and Meyers 1977) are rare in this facies, in contrast to the facies described below.

Two distinct types of dolomite occur in Facies A, and one is unique to it. The unique type consists of clear, small (10–60 microns) rhombs of dolomite that occur at the edges of primary voids (Fig. 4B). This relationship suggests formation early in diagenesis. The second type occurs in both primary and secondary voids and is coarser, ferroan, and generally clear. It is separated from void walls in some cases by crystals of blocky or scalenohedral calcite, suggesting a formation later than that of the first type.

The top of Facies A north of Caldwell County, Missouri, consists of very rubbly, nodular calcilutite up to 1 m thick that contains pockets and fracture fillings of the overlying Cherryvale Shale (Fig. 1). Crystal-lined

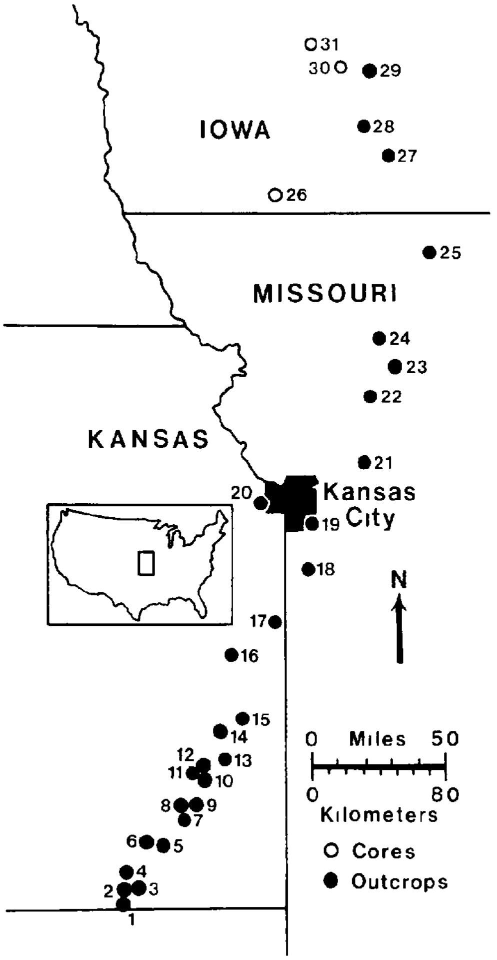

FIG. 2.—Outcrops and cores used in study. For exact locations, see Railsback (1983). Inset map shows location of study area within the continental U.S.

vugs occur in the meter below the rubbly zone at locality 28.

Interpretation.—All originally unstable grains in Facies A show no internal structure within clear, blocky calcite. The criteria of Bathurst (1975) suggest that such calcite had a void-filling origin, and the collapse of mud into some grains also suggests that extensive dissolution occurred.

The lack of relict structures in unstable carbonate grains in Facies A suggests that the sediments passed from the marine environment to an unsaturated meteoric environment without significant time in a saturated meteoric environment, which would have allowed neomorphism of at least some of those grains. The paucity of cements containing microdolomitic inclusions may have resulted similarly from dissolution of marine high-Mg cements in unsaturated water without prior neomorphism (Lohmann and Meyers 1977).

No cements suggesting vadose environments occur in Facies A, although Heckel (1983) has found possible meniscus cement in the upper Winterset in western Iowa; most cements are compatible with a phreatic origin. However, the rubbly, nodular beds at the top of Facies A north of Caldwell County, Missouri, suggest that extensive subaerial exposure occurred, and Siebels (1981) attributed the rubbly limestone to "soil-forming weathering processes." Thus the top of Facies A was in the unsaturated vadose environment for a considerable time, although the lower limit of that environment cannot be determined clearly.

The cements in Facies A suggest that, although all early fresh water was unsaturated with respect to $CaCO_3$, saturated fresh water later reached the facies. The compaction features noted in Facies A may have resulted from a lack of cement to stabilize primary intergranular porosity early in diagenesis.

The early formation of fine, rhombic, void-filling dolomite in Facies A (Fig. 4B) suggests that this dolomite formed in an environment between the marine-phreatic and meteoric-active environments. A possible dolomite-precipitating environment encountered in passage between these two is the meteoric-marine mixing-zone environment (Hanshaw et al. 1971; Badiozamani 1973; Land 1973). The ferroan nature of the later coarse dolomite suggests precipitation in a burial environment, where oxygen-poor conditions allowed ferrous iron to exist and enter the dolomite (Choquette 1971).

In summary, the diagenetic fabrics of Facies A are explained most readily by passage from the marine environment to a meteoric environment that was originally unsaturated with respect to $CaCO_3$ but saturated much later. The unsaturated meteoric environment extended upward to a vadose zone.

Facies B

Grains.—Facies B consists of those strata in the Dennis in which internal structures in

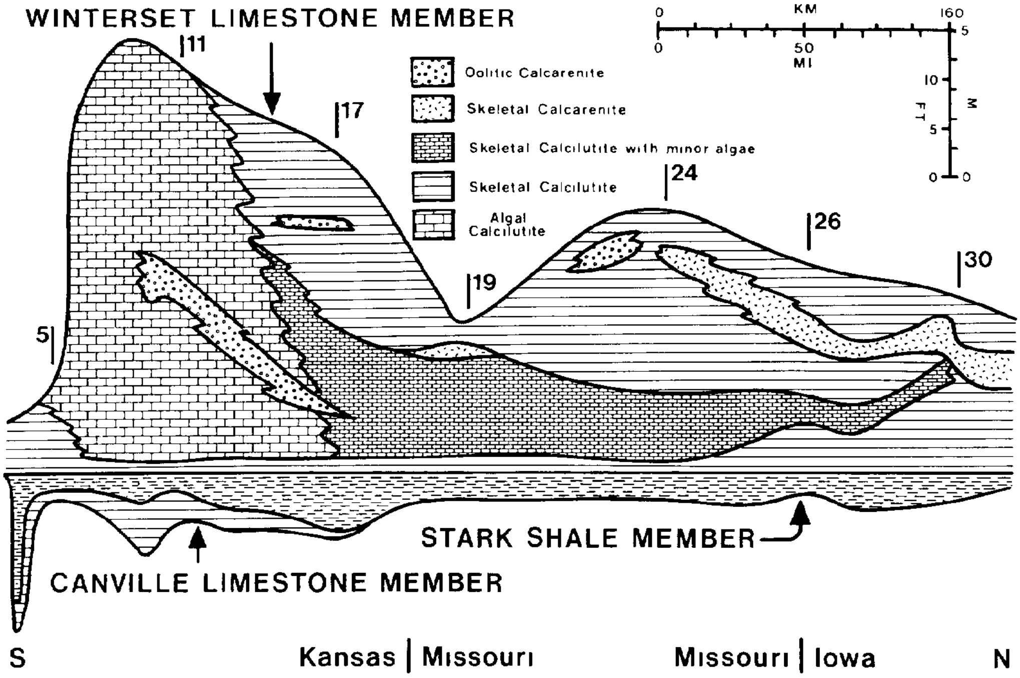

FIG. 3.—Stratigraphic cross-section of Dennis Formation showing major depositional facies. Datum is top of Stark Shale Member. Numbers by vertical lines match locality numbers in Figure 2. Compiled from Payton (1966), Frost (1975), and author's field notes.

originally unstable grains are rarely present or only poorly preserved, but it is distinguished from Facies A by at least minimal preservation. In the few cases where preservation is outstanding, original structures within similar grains nearby are completely obliterated (Fig. 4C). Phylloid algae and molluscs show complete internal structure very rarely but instead have remnants of such structures at their outer edges. In other cases, the spar composing them shows only cloudy areas parallel to the original structure of the grain.

Ooids generally show no more preservation of internal structure than do those in Facies A. Ooids in oolite beds in Kansas are blocky calcite as in Facies A, display concentric structure in a microspar fabric, or are represented only as voids (Fig. 4C) to form "oomoldic porosity" (Choquette and Pray 1970).

Cements.—Cements in Facies B consist largely of clear, blocky calcite. In some cases, grains are surrounded by rims of drusy scalenohedral calcite, with blocky spar in the centers of voids (Fig. 4D). Cements containing rims of microdolomitic inclusions around grains are more common in Facies B than in Facies A.

Some calcarenites in Facies B contain scattered poikilotopic cements that fill leached grains and the centers of intergranular voids (beyond fringing scalenohedral cements) (Fig. 4D). This suggests that the grains were leached after the precipitation of fringing scalenohedral cements but before the precipitation of coarse, blocky intergranular cements.

In the algal mounds, many algal blades are disrupted by brecciated mud, as in Facies A. Most voids in the mud are filled with clear, blocky calcite, but some are filled in part with clear ferroan dolomite. Ferroan dolomite may also extend into micritic areas, where it is not clear, suggesting that it has replaced carbonate mud rather than filled a void. Small stylolites or solution seams (Buxton and Sibley 1981) cut across some rocks in the algal mounds.

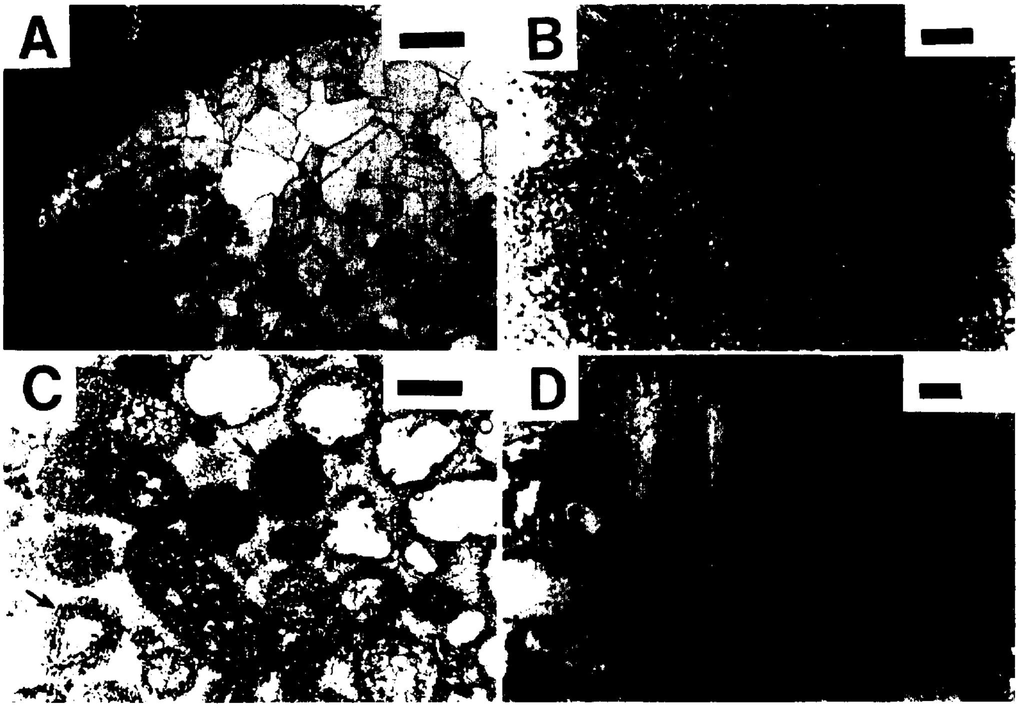

FIG. 4.—Diagenetic fabrics in Facies A and B. A) Brecciated lime mud in Facies A resulting from dissolution of unstable carbonate grain (probably phylloid algae) beneath smooth mud surfaces. Unattached, encrusting bryozoan (B) suggests former presence of firm support. (Plane-polarized light; scale bar is 1 mm.) B) Fine, rhombic dolomite (D) in Facies A occurring at edge of primary intergranular void and surrounded by calcite (C) that was precipitated later. (Plane-polarized light; scale bar is 25 microns.) C) Oolitic calcarenite in Facies B with oomoldic porosity (lower left) and ooids displaying preserved concentric structure (arrows). Heterogeneity of textures is similar to that described by Saller (1982). (Plane-polarized light; scale bar is 0.5 mm.) D) Skeletal calcarenite in Facies B cemented by isopachous rims of small calcite crystals followed by poikilotopic cement filling both primary (intergranular) and secondary voids. Areas labelled "P" are all one poikilotopic crystal. (Cross-polarized light; scale bar is .25 mm.)

Interpretation.—The poor but variable preservation of unstable grains in Facies B suggests that diagenesis in Facies B involved both dissolution and neomorphism, but that the former predominated.

The presence of some unstable grains with relict structures in Facies B suggests that the sediments were exposed to meteoric waters saturated with respect to $CaCO_3$, at least briefly in early diagenesis. Such an environment would have allowed slow replacement of aragonite by calcite to preserve internal structures, and would have allowed precipitation of fringing cements (Fig. 4D). Unsaturated water then dissolved all remaining unstable grains, and ultimately, saturated meteoric water returned to fill voids resulting from that dissolution of grains (areas labelled "P" in Fig. 4D). This suggests passage first to the saturated, active meteoric-phreatic environment (where minor neomorphism and some void filling occurred) and then to the unsaturated meteoric-phreatic environment before final passage to a saturated meteoric environment. In Facies B the first (saturated, neomorphosing) environment played a minor role in comparison to the second (unsaturated) environment.

Facies C

Grains.—Facies C consists of strata in which originally unstable grains display considerable internal structure, but at least some grains

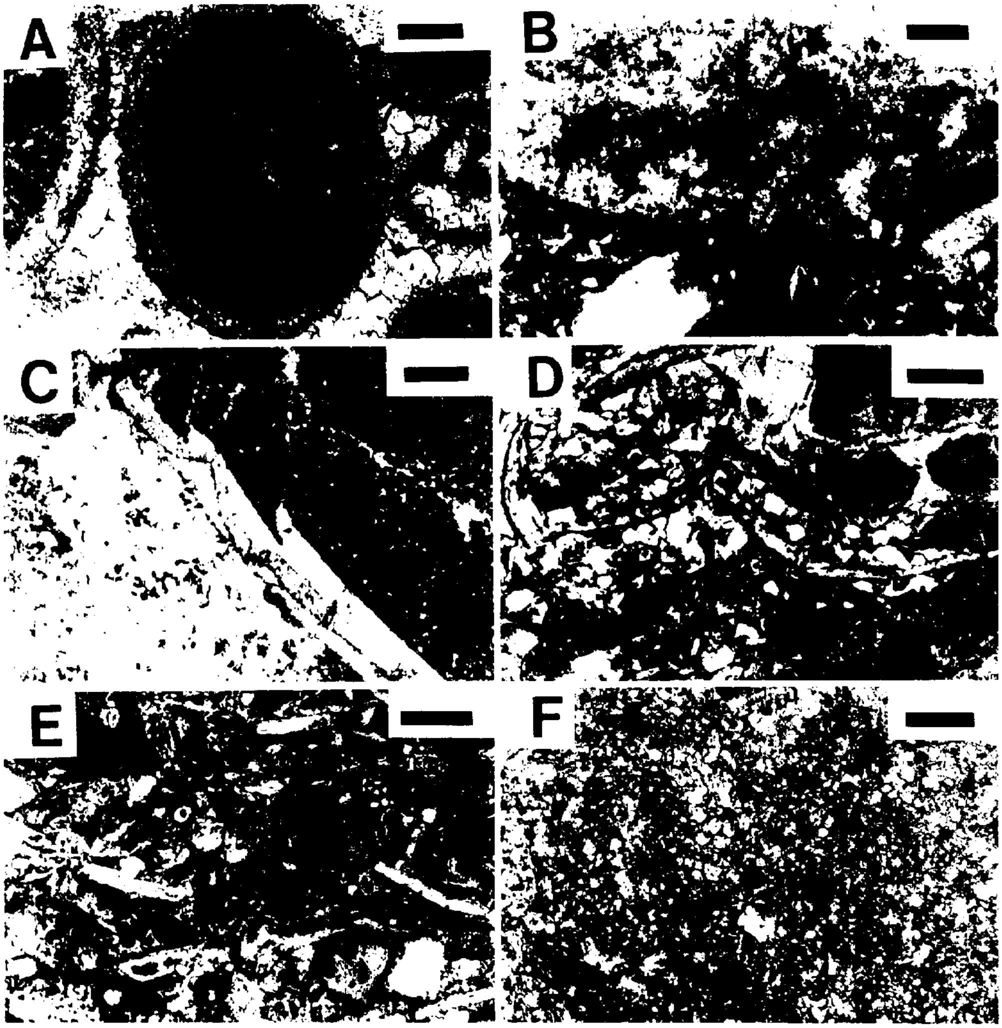

FIG. 5.—Diagenetic fabrics in Facies C, D, and E. A) Oolitic calcarenite in Facies C with ooids containing preserved radial and concentric structure. Contrast with Figure 4C, which shows ooids in Facies B with much less preservation of internal structure. (Plane-polarized light; scale bar is .15 mm.) B) Phylloid red alga in Facies C with partially preserved cellular structure. (Plane-polarized light; scale bar is 0.5 mm.) C) Clam with slumped internal structure in Facies C. This deformation may have resulted from partial neomorphism followed by dissolution of rest of grain by unsaturated water. This left a void into which preserved feature slumped. Mud to upper right then fractured to slump partly into void. (Plane-polarized light; scale bar is 0.5 mm.) D) Crushed brachiopod (arrows) in quartz-rich calcarenite in Facies D. Many carbonate grain-to-grain contacts are stylolitized. (Plane-polarized light; scale bar is 0.5 mm.) E) Calcarenite in Facies D with ubiquitous intergrown grain-to-grain contacts to give "fitted fabric" (Buxton and Sibley 1981). (Plane-polarized light; scale bar is 0.5 mm.) F) Microspar of inclusion-rich rhombs of ferroan dolomite in Facies E. (Plane-polarized light; scale bar is 100 microns.)

show none. This definition requires that the boundary with Facies B be gradational in many cases.

Ooids in Facies C exhibit well-preserved concentric structure or both radial and concentric fabrics (Fig. 5A). Phylloid algae show varying preservation. Some *Eugonophyllum* or similar green algae contain regular utricles at their edges, and red phylloid algae contain scattered, cellular structures (Fig. 5B). These structures are not outstanding but are more complete than those in Facies B.

Many molluscs in Facies C contain some internal structure, although it is commonly not complete. Some display curved structures in apparently broken voids, suggesting that the original organic structure of the grain has been preserved, but not in its original position (Fig. 5C).

Cements.—Most cements in Facies C are clear, blocky calcite, although some cements at edges of primary voids contain microdolomitic inclusions. Ferroan dolomite occurs in secondary voids (mostly clams, sparry areas in collapsed algal rocks, and some fractures).

Small stylolites occur in algal-mound rocks. These are associated commonly with spar that fills large voids, and they cut across both calcite and dolomite void fillings. Other compaction-related effects are rare in Facies C.

Interpretation.—The far better preservation of original structures in unstable grains in Facies C suggests that neomorphism was more important in the diagenesis of this facies than it was in Facies A or B. However, some leaching and void filling did occur.

The extensive preservation of structures within unstable grains in Facies C suggests that early in diagenesis the sediments were exposed to saturated meteoric water for a considerable time. The presence of some leached grains suggests that the sediment was eventually exposed to water unsaturated with respect to $CaCO_3$. Thus, the sediments passed from the marine environment to a saturated meteoric-phreatic environment and then to an active, unsaturated meteoric-phreatic environment, before returning saturated water filled most of the resulting voids. This sequence is the same as that for Facies B, but the more extensive neomorphism in Facies C suggests greater importance of (and presumably longer time in) the early saturated meteoric environment.

This sequence of diagenetic environments may explain the presence in Facies C of grains that have preserved but slumped internal structures (Fig. 5C). Neomorphism of such grains in the saturated environment may have been only partly complete when they passed into the unsaturated environment, where the rest of the grain dissolved to leave a void into which the neomorphosed or partly neomorphosed portion of the grain slumped.

Ferroan dolomite in both Facies B and C appears to fill voids that remained after most calcite void filling. Its occurrence in secondary voids and its ferroan nature suggest a late origin in an oxygen-poor burial environment. Stylolites in Facies C that are associated with spar-filled voids may have resulted from the elimination of remaining void space after precipitation of void-filling calcite and dolomite.

In summary, the diagenetic fabrics of Facies C are explained most readily by passage through an extensive, active, saturated meteoric-phreatic environment, then an active, unsaturated meteoric-phreatic environment. The active, saturated environment returned later to allow calcite void filling before passage to the burial environment.

Facies D

Grains.—Facies D consists of rocks in which all unstable grains have retained some original structure. Molluscs in Facies D contain preserved internal structures, and spar in molluscs is not clear and generally has complex grain boundaries. Ooids do not occur in this facies, and phylloid algae are very rare.

All types of grains in Facies D display features resulting from compaction. Brachiopods commonly are crushed and lack much internal cement (Fig. 5D). Echinoderm fragments are divided into many smaller crystals, suggesting "degrading recrystallization" (Folk 1965). Grain-to-grain contacts are commonly intergrown and in some cases collectively form "fitted fabric" (Buxton and Sibley 1981) (Fig. 5E).

Cements.—Cements in Facies D are rare and generally occur only in intragranular voids. These cements are blocky calcite, although a few contain microdolomitic inclusions at the edges of voids. Fine-grained ferroan dolomite also occurs as a cement.

Interpretation.—Most spar within grains in Facies D is inclusion-rich jagged spar suggestive of neomorphic rather than void-filling processes. Spar that fills primary voids appears to have formed after compaction, suggesting that early cementation was negligible.

The lack of obviously leached unstable grains in Facies D suggests that the sediments either were never exposed to unsaturated meteoric water or were exposed only after stabilization of such grains. The extensive compaction in Facies D further suggests that much of the facies never entered the active, saturated meteoric-phreatic environment, where precipitation of cements would have made later breakage of grains and intergrowth at grain contacts unlikely. Thus, Facies D probably passed from the marine environment either to the stagnant meteoric-phreatic environment or directly to the burial environment.

Tucker (1981) has stated that "degrading neomorphism" (the recrystallization of large grains to many small ones) occurs only "in limestones which have been subjected to tectonic stress or very low grade metamorphism." Echinoderm fragments recrystallized to small crystals are common in Facies D, but they have been subjected to neither tectonic stress nor metamorphism. The most likely cause for the degrading neomorphism of echinoderms in Facies D is localized differential stress at point contacts between rigid grains during compaction (P. H. Heckel, pers. comm., 1981). In other facies such stress did not occur because earlier cementation provided a framework to distribute stress during loading.

Facies E

Facies E consists of rocks containing a matrix of finely crystalline (5 to 50 microns) rhombs of inclusion-rich ferroan dolomite (Fig. 5F). These rocks are generally devoid of grains of originally unstable mineralogies, prohibiting their classification in other facies. Facies E occurs just above the Stark Shale in the Winterset Member throughout the study area (Fig. 1). The same dolomitic texture also occurs locally near shale partings within the Winterset, and similar dolomite occurs in the Canville Member but is poorly developed.

Brachiopod shells and fragments and echinoderm fragments are nearly the only large grains in Facies E, and they are not dolomitized. Brachiopods are generally crushed with little internal cement.

Interpretation.—The general absence of originally unstable grains in Facies E makes determination of diagenetic environments difficult. The general lack of cement (and resulting crushing of many brachiopods) suggests that the sediment did not pass into the active, saturated meteoric environment. Thus Facies E entered only the stagnant meteoric or burial environments with little meteoric effect; the presence of ferroan dolomite suggests diagenesis in the burial environment.

The inclusion-rich ferroan dolomite that pervades Facies E apparently resulted from dolomitization of carbonate mud. The restriction of this fabric to facies adjacent to the Stark Shale or thick shale partings suggests that shales controlled the dolomitization by providing the magnesium (and iron) for that process. McHargue and Price (1982) and Schutter (1983) have proposed mechanisms for the transfer of Mg from shales to adjacent limestones.

DIAGENETIC HISTORY

Diagenetic Facies A, B, C, and D of the Dennis Formation represent a sequence from (1) strata characterized by complete alteration of unstable grains to clear, structureless, blocky spar, to (2) strata featuring unstable grains altered to inclusion-rich, jagged spar containing remnant internal structures. This suggests a corresponding sequence from diagenesis dominated by leaching and void filling to that dominated by neomorphism (Table 1).

These trends in diagenetic fabrics and processes are explained best by the introduction of fresh water into the unit, with the earliest occurrence of fresh water in the north. Facies A, B, C, and D represent different stages or environments in the interaction of that meteoric water with the carbonate sediments.

Development of Diagenetic Environments

Introduction of fresh water into the Dennis Formation is explained most easily by a regression that subaerially exposed the northern part of the Dennis first. Unsaturated meteoric water entered the northern upper Winterset and dissolved unstable carbonate grains until saturation occurred. This explains the development of Facies A in an initially unsaturated meteoric environment with weathering at the top of the unit (Fig. 6A).

Dissolution in Facies A allowed the development of saturated water farthest from the influx of fresh water. As regression con-

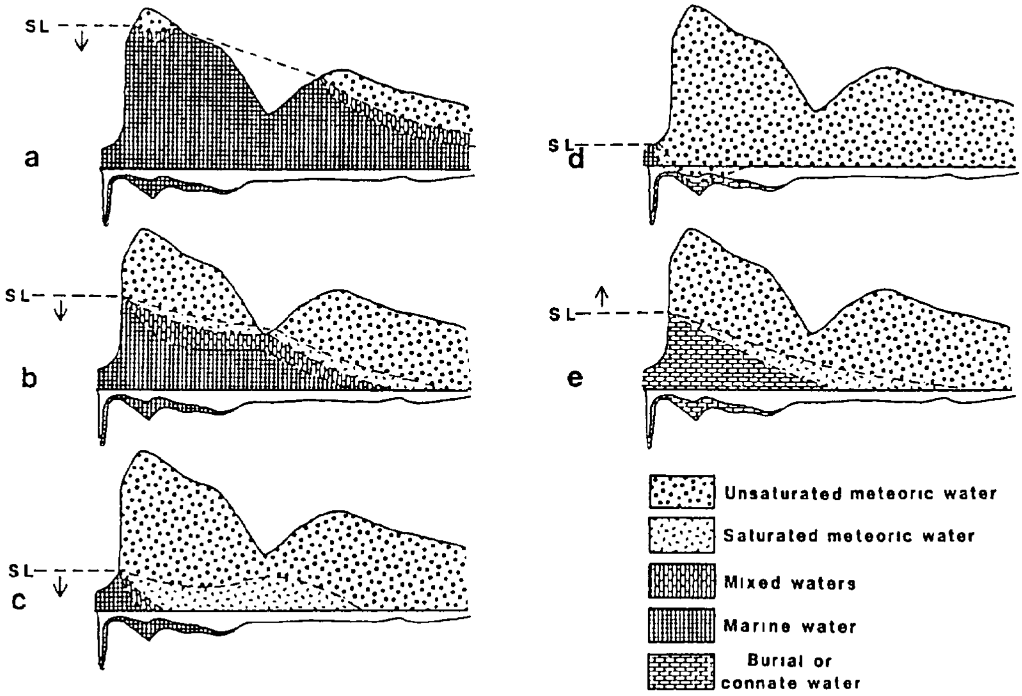

FIG. 6.—Interpreted progression of waters through Dennis Formation. Datum for stratigraphic sections is top of Stark Shale. A) Early regression brings unsaturated fresh water to Facies A, and a mixing zone develops between unsaturated fresh water and marine water. Unsaturated fresh water leaches unstable carbonate grains with no neomorphism. B) Further regression lowers level of marine-freshwater interface. Dissolution in Facies A creates a zone of saturated fresh water, which allows first neomorphism of unstable grains. C) Regression lowers level of fresh water further, and saturated freshwater lens grows. Larger saturated lens allows more extensive neomorphism lower in unit; later intrusion by unsaturated water leaches remaining unneomorphosed unstable grains or parts of grains. D) Maximum regression allows unsaturated water to reach its lowest level. E) Transgression causes saturated environments to return upward into formation. Sediments are progressively isolated in burial environment.

tinued, this saturated water passed farther into the Dennis as more unsaturated water entered at the exposure surface (Fig. 6B). Thus, Facies B and C encountered saturated meteoric water first and then unsaturated meteoric water, as petrographic evidence suggests. With time the saturated lens grew, allowing more stabilization of grains in strata it encountered later; greater preservation in Facies C supports this hypothesis (Fig. 6C). With maximum regression, unsaturated meteoric water penetrated to at least the bottom of Facies C after extensive stabilization in saturated water (Fig. 6D). There is no evidence that unsaturated water entered Facies D.

Ultimately, transgression caused a reversal of movement of diagenetic environments until all of the Dennis lay in the burial environment (Fig. 6E). This transgression allowed filling of some secondary voids as saturated environments returned upward, but its rapidity, if it was like other such transgressions (Heckel 1977), may have limited this void filling. In the burial environment, pressure solution and void filling by ferroan calcite and ferroan dolomite eliminated most remaining porosity.

Preservation of Marine Cements

Inclusion-rich prismatic cements, which are commonly interpreted as magnesian marine cements (Lohmann and Meyers 1977), are rare in Facies A but occur in Facies B, C, and D. This distribution may have resulted from dissolution of such cements in unsaturated meteoric water in Facies A (as was the case with unstable grains), whereas stabilization in saturated meteoric water in the other facies allowed the preservation of marine cements. Thus the present distribution of these cements may not reflect their original distribution but may instead result from later trends in meteoric dissolution and neomorphism.

Carbonate Transfer

The interpretation of changing diagenetic environments discussed above requires transfer of $CaCO_3$ through the Dennis, largely from Facies A (where leaching occurred in the unsaturated meteoric environment) to Facies B and C (where precipitation of fringing cements and stabilization of grains occurred before leaching of remaining unstable grains). Bathurst (1975) pointed out that, in such transfer, dissolution of aragonite grains alone cannot provide the volume of cement common in limestones. In the Dennis Formation, $CaCO_3$ was derived most likely from dissolution of both aragonite and calcite in the upper soil zone, allowing transfer of much $CaCO_3$ to the rest of the Dennis while total rock volume in the soil zone decreased.

This transfer of $CaCO_3$ allowed earlier and more extensive cementation in Facies B and C than in Facies A, where carbonate removal was the dominant early process. Thus, after early diagenesis, most primary porosity in Facies B and C was filled, whereas it remained open in Facies A. This difference in early void filling may explain the distribution of coarse ferroan dolomite, which appears to be a late burial cement because of petrographic evidence and its ferroan nature. Ferroan dolomite occurs in both primary and secondary voids in Facies A, but only in secondary voids in Facies B and C. Because of the transfer of $CaCO_3$, only in Facies A did considerable primary porosity remain to be filled by ferroan dolomite after early meteoric diagenesis. In contrast, only secondary porosity remained unfilled in Facies B and C, resulting in ferroan dolomite void filling or moldic porosity.

Transfer of $CaCO_3$ to Facies B and C also explains the distribution of types of pressure-solution effects. Stylolites, which are commonly interpreted as forming in lithified sediments (Buxton and Sibley 1981) occur in Facies B and C, where cementation occurred first and most extensively. On the other hand, fitted fabric, which is characteristic of uncemented sediments (Buxton and Sibley 1981), occurs in Facies D, where little cementation occurred because the active, saturated meteoric environment did not extend low enough. Less impressive but significant grain-to-grain pressure solution occurred in Facies A, where early cementation was not extensive because saturation was not achieved during regression. Thus, pressure-solution features in the Dennis Formation are predictable from bulk transfer of $CaCO_3$ and resultant cementation.

Anomalies in Regional Trends

Diagenetic Facies A, B, C, and D form roughly subparallel units (Fig. 1), suggesting relatively uniform passage of meteoric water through the Dennis Formation (Fig. 6). Anomalies in these trends occur in beds of oolitic calcarenite at localities 11, 15, 17, and 22. At localities 11 and 15, oolite beds in Facies B are surrounded by Facies C, suggesting that greater primary porosity in the oolites may have allowed earlier invasion by unsaturated meteoric water to give more moldic porosity and minimal preservation (Fig. 4C). These beds are not isolated by shale partings.

In contrast, oolitic calcarenites high in the Winterset at localities 17 and 22 are in Facies C but are surrounded by Facies A and B, respectively (Fig. 1). These beds have thick shale partings both above and below, suggesting that entry into the oolite beds was impeded by relatively impermeable barriers long enough to allow neomorphism of ooids (Fig. 5A). Better preservation of ooids in the lower half of the oolite bed at locality 17 may have been caused by density stratification of saturated and unsaturated waters.

These examples suggest that paleohydrologic controls caused local variations in regional diagenetic trends within the Winterset Member. The general absence of meteoric effects in the Canville Member (i.e., below the relatively impermeable Stark Shale) is a more obvious and larger-scale effect of paleohydrologic controls on diagenesis (Heckel 1982).

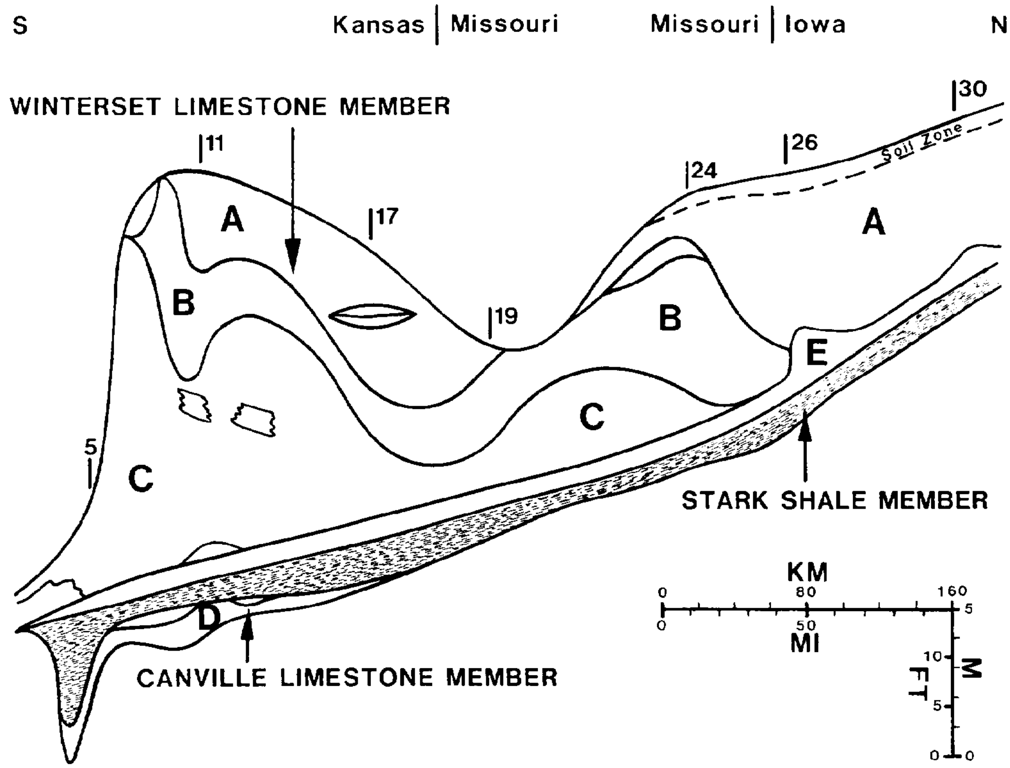

Fig. 7.—Inferred paleotopography of Dennis Formation. Arrangement shown has areas of greatest meteoric influence (i.e., Facies A) highest to give earliest and longest subaerial exposure; areas of little meteoric influence are lowest. Horizontal datum is parallel to sea level (compare with Fig. 6). Numbers by vertical lines match locality numbers in Figure 2.

Paleotopography

The stratigraphic cross-sections in Figure 6 contain nonhorizontal orientations of interpreted sea level, suggesting that such cross-sections do not represent true paleotopographic relations. Figure 7 is a cross-section reconstructed to show paleotopography as suggested by diagenetic facies and to reorient sea level to horizontal. This interpretive cross-section places Facies A (and particularly the northern soil zone) highest so as to allow the most prolonged subaerial exposure. It places the Dennis relatively low in the Kansas City area and in southernmost Kansas, where Facies A is thinnest or does not occur (Fig. 1).

This paleotopographic cross-section based on diagenetic facies of the Dennis Formation is in accord with that derived from depositional evidence by Heckel (1977) for Upper Pennsylvanian cyclothems. It also agrees with the claim (again based on depositional evidence) of Heckel (1980) that the Kansas City area was the "lowest part of the shelf" that extended southwestward from Iowa to the Kansas-Oklahoma border.

CONCLUSIONS

1) Differences between the carbonate diagenetic facies of the Dennis Formation resulted from passage through differing sequences of diagenetic environments (Table 1).

2) Development of Dennis diagenetic environments was governed by the interaction of the carbonate sediments with incoming fresh water that was unsaturated with respect to $CaCO_3$ (Fig. 6). Influx of fresh water during

regression caused extensive leaching in Facies A, and that leaching allowed development of a saturated meteoric lens that caused progressively more neomorphism in Facies B and C before unsaturated water entered those facies. Unsaturated water did not affect Facies D. Later transgression caused saturated environments to pass up through the Dennis Formation rapidly before burial conditions set in.

3) Paleohydrologic variation resulting from contrasting permeabilities caused irregularities in the distribution of Dennis diagenetic facies.

4) Transfer of $CaCO_3$ and resulting patterns of dissolution and void filling during early diagenesis governed later patterns of both pressure solution and void filling by ferroan dolomite.

5) Paleotopography derived from interpreted diagenetic environments agrees with paleotopographic interpretations derived from depositional evidence (Fig. 7). The regression during and after Winterset deposition that is required by diagenetic interpretations also agrees with depositional evidence (Heckel 1977).

6) The simple application of Longman's (1980) diagenetic environments to the Dennis Formation and their agreement with depositional evidence indicates that the concepts of diagenetic environments and resulting diagenetic facies can be useful in studying carbonate diagenesis.

ACKNOWLEDGMENTS

Philip H. Heckel of the University of Iowa supervised the thesis work from which this paper is derived, and Robert L. Brenner and Keene Swett served on the examining committee. The Kansas Geological Survey provided funds for field work in Kansas, and the Iowa Geological Survey allowed access to cores in its possession. Franz O. Meyer of Shell Oil Company assisted in preparing some of the photographs. Discussions at the University of Iowa with David A. Nollsch, Elaine C. Winfrey, Kimbell L. Knight, and Stephen R. Schutter improved the study considerably. Philip W. Choquette (Marathon Oil Company) and Thomas Freeman (University of Missouri) reviewed the article for JSP.

REFERENCES

BADIOZAMANI, K., 1973, The Dorag dolomitization model—application to the Middle Ordovician of Wisconsin: Jour. Sed. Petrology, v. 43, p. 965–984.

BATHURST, R. G. C., 1975, Carbonate sediments and their diagenesis: Developments in Sedimentology No. 12: Amsterdam, Elsevier, 658 p.

BUXTON, T. M., AND SIBLEY, D. F., 1981, Pressure solution features in a shallow, buried limestone: Jour. Sed. Petrology, v. 51, p. 19–26.

CHOQUETTE, P. W., 1971, Late ferroan dolomite cement, Mississippian carbonates, Illinois Basin, U.S.A., *in* Bricker, O. P., ed., Carbonate Cements: Baltimore, Johns Hopkins University Studies in Geology No. 19, p. 339–346.

CHOQUETTE, P. W., AND PRAY, L. C., 1970, Geological nomenclature and classification of porosity in sedimentary carbonates: Amer. Assoc. Petroleum Geologists Bull., v. 54, p. 207–250.

DUBOIS, M. K., 1979, Factors controlling the development and distribution of porosity in the Lansing-Kansas City "E" Zone, Hitchcock County, Nebraska [M.S. thesis]: University of Kansas.

FOLK, R. L., 1965, Some aspects of recrystallization in ancient limestones, *in* Pray, L. C., and Murray, R. C., eds., Dolomitization and Limestone Diagenesis: Soc. Econ. Paleontologists Mineralogists Spec. Publ. 13, p. 14–48.

FROST, J. G., 1975, Winterset algal bank complex, eastern Kansas: Amer. Assoc. Petroleum Geologists Bull., v. 59, p. 265–291.

HANSHAW, B. B., BACK, W., AND DIEKE, R. G., 1971, A geochemical hypothesis for dolomitization by ground water: Econ. Geol., v. 66, p. 710–724.

HECKEL, P. H., 1977, Origin of phosphatic black shale facies in Pennsylvanian cyclothems of Mid-Continent North America: Amer. Assoc. Petroleum Geologists Bull., v. 61, p. 1045–1068.

———, 1980, Paleogeography of eustatic model for deposition of Midcontinent Pennsylvanian cyclothems, *in* Fouch, T. D., and Magathan, E. R., eds., Paleozoic Paleogeography of West-Central U.S.: Rocky Mountain Section, Soc. Econ. Paleontologists Mineralogists, p. 197–215.

———, 1982, Diagenetic model for carbonate rocks in Mid-Continent Pennsylvanian eustatic cyclothems (abs.): Amer. Assoc. Petroleum Geologists Bull., v. 66, p. 580.

———, 1983, Diagenetic model for carbonate rocks in Midcontinent Pennsylvanian eustatic cyclothems: Jour. Sed. Petrology, v. 53, p. 733–759.

HORNE, J. C., 1965, Environmental study of the Bond Formation of the Illinois Basin and Kansas City Group of the northern and central Mid-Continent [M.S. thesis]: University of Illinois.

LAND, L. S., 1973, Holocene meteoric dolomitization of Pleistocene limestone, North Jamaica: Sedimentology, v. 20, p. 411–424.

LOHMANN, K. C., AND MEYERS, W. J., 1977, Microdolomite inclusions in cloudy prismatic cements: a proposed criterion for former high-magnesium calcites: Jour. Sed. Petrology, v. 47, p. 1078–1088.

LONGMAN, M. W., 1980, Carbonate diagenetic textures from nearsurface diagenetic environments: Amer. Assoc. Petroleum Geologists Bull., v. 64, p. 461–487.

McHargue, T. R., and Price, R. C., 1982, Dolomite from clay in argillaceous or shale-associated marine carbonates: Jour. Sed. Petrology, v. 52, p. 873–886.

Payton, C. E., 1966, Petrology of the carbonate members of the Swope and Dennis Formations (Pennsylvanian), Missouri and Iowa: Jour. Sed. Petrology, v. 36, p. 576–601.

Railsback, L. B., 1983, Diagenetic history of the carbonate members of the Dennis Formation (Missourian, Upper Pennsylvanian) in Iowa, Missouri, and Kansas [M.S. thesis]: University of Iowa, 129 p.

Saller, A. H., 1982, Patterns of dissolution and neomorphism in Pleistocene limestones of Enewetak Atoll, Marshall Islands (abs.): Geol. Soc. America Abstracts with Programs, v. 14, p. 607.

Schutter, S. R., 1983, Petrology, clay mineralogy, paleontology, and depositional environments of four Missourian (Upper Pennsylvanian) shales of Midcontinent and Illinois basins [Ph.D. thesis]: University of Iowa.

Siebels, C. J., 1981, Petrology, clay mineralogy, and conodont distribution of the Cherryvale Formation, Upper Pennsylvanian, Midcontinent [M.S. thesis]: University of Iowa, 164 p.

Tucker, M. E., 1981, Sedimentary Petrology—An Introduction: Oxford, Blackwell Scientific Publications, 252 p.

Watney, W. L., 1980, Cyclic sedimentation of the Lansing-Kansas City groups in northwestern Kansas and southwestern Nebraska: Kansas Geol. Surv. Bull. 220, 72 p.