DIAGENETIC MODEL FOR CARBONATE ROCKS IN MIDCONTINENT PENNSYLVANIAN EUSTATIC CYCLOTHEMS[1]

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ABSTRACT: Diagenetic patterns in cyclic Midcontinent Pennsylvanian carbonates are readily explained in terms of a predictive diagenetic model derived logically from the eustatic depositional model for widespread Pennsylvanian cyclothems developed by Heckel (1977, 1980). Transgressive shoal-water calcarenites are characterized by pervasive overpacking of grains, neomorphism of originally aragonite grains (ooids, green algae, molluscs), and ferroan calcite and dolomite cement, which indicate movement from the marine-phreatic environment of deposition and diagenesis into the low-oxygen deeper-burial connate zone, with substantial compaction before any cementation. Offshore invertebrate calcarenites associated with offshore ("core") shales also are characterized by pervasive overpacking of grains and ferroan carbonate cements, which indicate a similar diagenetic history; their lack of discernible neomorphism relates to original absence of shallow-water aragonite grains (ooids, green algae), and probable removal of thin-shelled molluscs by dissolution during long periods of sediment starvation in cool water, which also corroded the edges of many calcite grains.

Regressive shoal-water calcarenites show a much greater variety of diagenetic features, including early marine cement rims and large-scale leaching of originally aragonite grains, often with subsequent collapse of micrite envelopes, grain fragments and overlying material in samples insufficiently stabilized by early cement rims. This was followed by pervasive cementation by blocky calcite before much further compaction, then by ferroan calcite and finally ferroan dolomite in remaining voids. This pattern indicates replacement of depositional marine-phreatic water by meteoric water, which dissolved unstable carbonate grains and then deposited stable carbonate cements in environments that eventually became increasingly oxygen depleted and otherwise chemically changed, probably as mixing-zone and deeper connate water moved back into the rock and replaced the meteoric water during and after the succeeding transgression. Trends in calcilutites are essentially similar to those in calcarenites of equivalent phase of deposition, with evidence of subaerial exposure and meteoric-vadose soil formation in strata at the top of many regressive limestones.

It is apparent that with the regression of the sea and emergence that terminated deposition of a cyclothem, meteoric water penetrated the permeable parts of the regressive carbonate and left its distinctive diagenetic patterns of early leaching and cementation before much compaction took place, but rarely did meteoric water penetrate the impermeable offshore shale, which acted as a "seal." This allowed associated offshore and underlying transgressive carbonates to become more deeply buried and substantially compacted before cementation took place, with unstable grains undergoing slow neomorphism in the absence of meteoric leaching.

INTRODUCTION

Recent syntheses of modern advances in recognizing and understanding the products and processes of carbonate diagenetic environments have facilitated the task of applying these findings to suites of ancient limestones, where several diagenetic environments may have left their mark. It is therefore timely to use these syntheses to organize the scattered observations made over the years (Heckel, 1978) on diagenesis of the cyclothemic limestones of the Midcontinent Pennsylvanian outcrop, and to relate the diagenetic patterns to the eustatic depositional model that has been developed for these rocks (Heckel, 1977, 1980), as Watney (1980) has begun to do for equivalent subsurface rocks in the oil fields of western Kansas.

EUSTATIC DEPOSITIONAL MODEL FOR PENNSYLVANIAN CYCLOTHEMS

The upper Middle and Upper Pennsylvanian sequence (Fig. 1) in Midcontinent North

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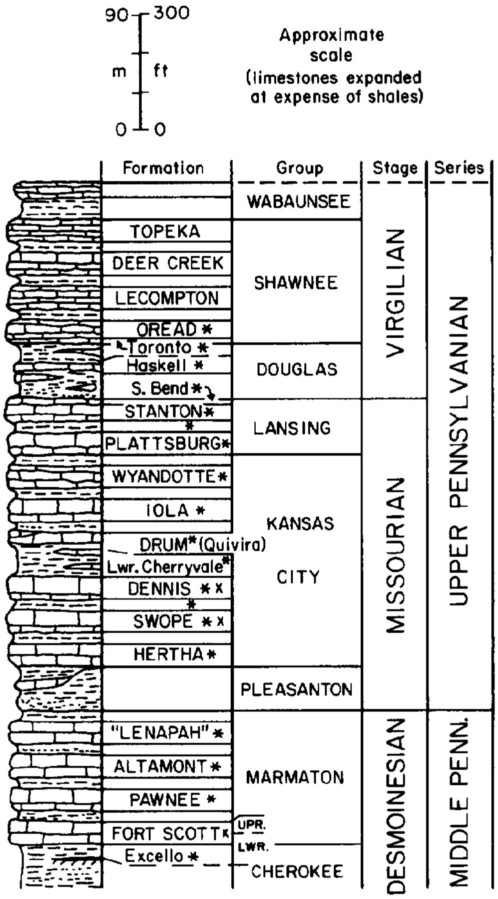

FIG. 1.—Generalized Pennsylvanian stratigraphic sequence in eastern Kansas. In formation column, capital names denote limestone formations that form most of marine part of eustatic cyclothems (Fig. 2); names in lower case are other (mainly member) names applied to similar cyclothems (modified from Heckel, 1980, Fig. 2). Asterisks denote units that have received petrologic study: Excello (James, 1970); Pawnee (Price, 1981); Altamont (Schenk, 1967); Lenapah (Parkinson, 1982); Hertha (Ravn, 1981); Swope (Payton, 1966; Mossler, 1971, 1973); Dennis (Payton, 1966; Frost, 1975; Railsback, 1983a, b); Cherryvale (Siebels, 1981); Drum (Stone, 1979); Iola (Mitchell, 1981); Wyandotte (Crowley, 1969); Plattsburg (Harbaugh, 1959, 1960; Nelson, 1978); Stanton and South Bend (Heckel, 1975, 1978); Haskell (Ball, 1964); Toronto (Troell, 1969); Oread (Toomey, 1969, Evans, 1967). X denotes units currently under detailed study at University of Iowa: Fort Scott (K. L. Knight); Swope (D. A. Nollsch, 1983); also Galesburg Shale, between Swope and Dennis, and Vilas Shale, between Plattsburg and Stanton (Schutter, 1983).

America consists generally of an alternation of widespread limestone formations that typically contain a thin, distinctive, laterally continuous shale member, and widespread sandy shale formations that locally contain coals, sandstones, and redbeds. Early workers recognized that the limestone formations were marine, whereas the shale formations were nearshore to nonmarine, and that the vertical succession shows cyclically repeating sequences of rock types termed cyclothems (Moore, 1929, 1936; Weller, 1930; Wanless and Weller, 1932).

The hypothesis of Wanless and Shepard (1936) that waxing and waning Gondwanan glaciation in the southern hemisphere caused sea-level changes that resulted in Pennsylvanian cyclothems was debated for some time (Moore, 1950; Weller, 1956). Nevertheless, the extremely widespread extent of the marine limestones, which remain discrete continuous units for hundreds of miles along outcrop and into the subsurface, delimited above and below by nearshore to nonmarine detrital deposits, has never been satisfactorily explained by any of the local sedimentological controls that adequately explain areally restricted cyclothems near major detrital sources (D. Moore, 1959; Ferm, 1970). This led Wanless (1967) and Heckel (1977, 1980) to propose a model for Midcontinent Pennsylvanian deposition in which the widespread, laterally extensive cyclic units are attributed to a series of eustatic marine inundations and withdrawals over much of the continent, with delta formation and abandonment forming local cycles wherever shoreline stood at the time. Thus deltaic (and fluvial) cycles are conspicuous around the margins of the Midcontinent region (for example, the Appalachians and southern Oklahoma), whereas eustatic cycles are most conspicuous farthest from the detrital source, particularly along the Midcontinent outcrop from Kansas northward. The eustatic model received strong support from Crowell (1978) who showed that periods of Gondwanan glaciation persisted from Late Mississippian to Mid-Permian time, which encompasses the Pennsylvanian when widespread cyclothems are well documented in North America and elsewhere (Wells, 1960).

As currently recognized and interpreted, the basic widespread eustatic "Kansas cyclothem" (Heckel, 1977), which characterizes the Pennsylvanian succession of the Midcontinent outcrop, consists of the following ascending sequence (Fig. 2): 1) thick, sandy nearshore to nonmarine ("outside") shale; 2) thin transgressive ("middle") limestone, typically skeletal

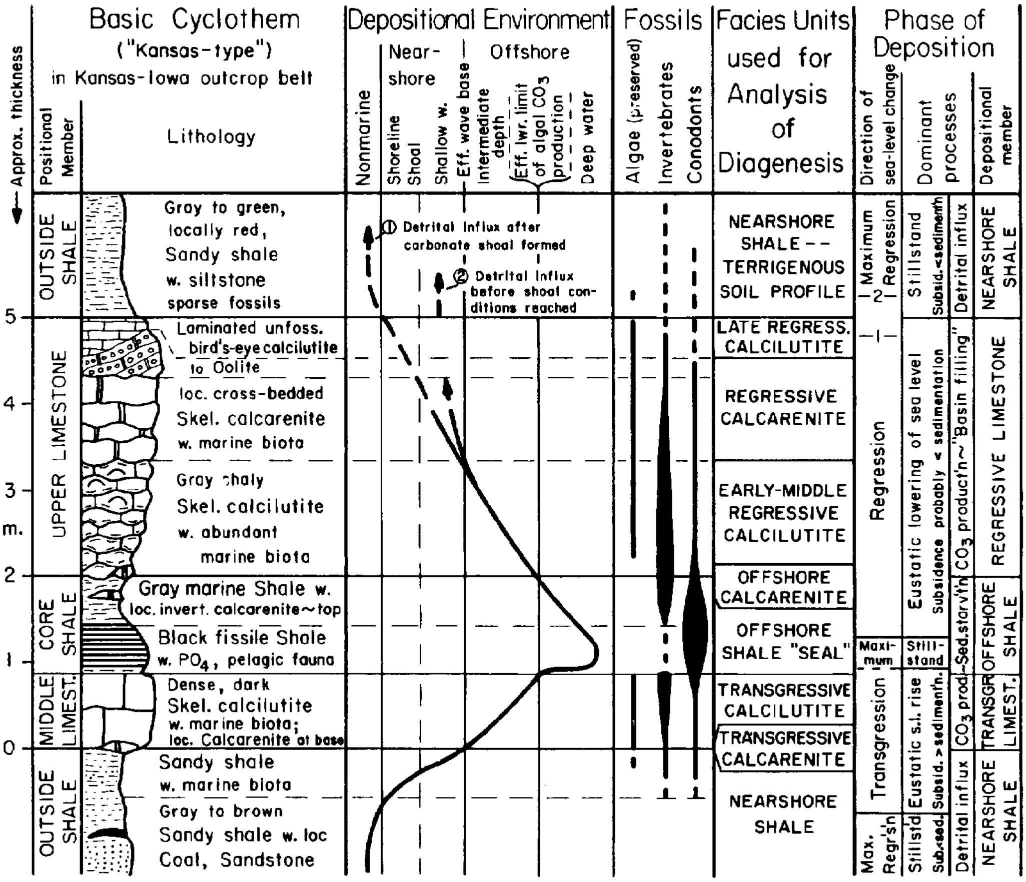

FIG. 2.—Basic sequence of eustatic Midcontinent Pennsylvanian "Kansas cyclothem" (modified from Heckel, 1977, Fig. 2), showing depositional interpretation, gross distribution of fossil groups, and lithic facies units used for analysis of carbonate diagenesis in current study.

calcilutite, but with local calcarenite at the base; 3) thin nonsandy offshore ("core") shale, commonly with phosphatic black fissile facies, and locally containing or overlain by thin calcarenite; 4) thicker regressive ("upper") limestone, typically skeletal calcilutite grading upward to calcarenite and muddy shoreline facies; and 5) thick, sandy nearshore shale again.

The thick, sandy nearshore shales represent the times of lowest sea-level stand at maximum regression between the marine inundations. Where marine, they typically contain sparse conodont and shelly invertebrate faunas of low diversity, reflecting fluctuating nearshore conditions of rapid sedimentation. Where nonmarine, some contain coals and well-preserved plant fossils; others are gray to red blocky mudstones, with local caliche and features of clay mineralogy that are characteristic of soil profiles (Schutter, 1983).

The thin offshore shales represent the times of highest sea-level stand at maximum marine inundation. These typically contain an abundant and diverse conodont fauna, reflecting extremely slow sedimentation under stable marine conditions. Some that are gray contain an abundant and diverse invertebrate fauna, which reflects a well-oxygenated sea bottom. Most contain a characteristic phosphatic black fissile facies, which lacks benthic fossils and reflects an anoxic sea bottom developed beneath a thermocline that became established in deep water at maximum transgression. Dark gray shale that is gradational vertically and laterally with the black facies contains a variable, sparse to abundant, restricted to locally diverse benthic fauna, which reflects dysaerobic conditions on the sea bottom intermediate between the other two facies (Malinky, 1982).

The two limestone members were deposited under water becoming either deeper or more shallow, between the lower depth limit for algal production (or preservation) of carbonate mud and the nearshore limit of significant detrital influx. In certain respects they are mirror images of one another. Lithologically, the offshore, diversely skeletal calcilutite facies, deposited below effective wave base in both limestones, lies adjacent to the offshore shale, whereas the various shoal-water calcarenite and other shoreline facies lie adjacent to the nearshore shale (Fig. 2). The nature of sedimentation under deepening water, when carbonate formation did not last long and clastics tended to be stranded progressively away from the site of deposition, differs from that under shallowing water, when carbonate formation intensified with time and detrital pulses from encroaching shorelines were brought readily to the site of deposition. This caused the transgressive ("middle") limestone to be thin and pure, but the regressive ("upper") limestone to be thick, shaly, and wavy-bedded, and these conspicuous characteristics have tended to obscure their converse relationship.

COMMON CARBONATE DIAGENETIC ENVIRONMENTS

The following summary of common carbonate diagenetic environments and their products is synthesized largely from Bathurst (1979, 1980a, b) and Longman (1980) with minimal specific citation. Diagenetic environments are classified fundamentally on the basis of two major factors: 1) whether pore space is saturated with water (phreatic), or unsaturated with water, resulting in a mixture of air and changing amounts of water among the grains (vadose); and 2) whether the water is derived from the sea and saline (marine), or derived from rainfall on the land and fresh (meteoric). The resulting combinations of these two factors yield four basic environments: marine-phreatic, marine-vadose, meteoric-phreatic, and meteoric-vadose (Fig. 3). These are further subdivided on the basis of such factors as amount of circulation of water through the pores and degree of saturation of pore water with respect to $CaCO_3$. Another diagenetic environment, the deeper-burial connate, is sufficiently distinct in terms of overburden, degree of oxygenation, and ion proportions from the marine-phreatic (from which it is derived) to be treated separately. A hybrid diagenetic environment, the mixing zone, is recognized between the marine- and meteoric-phreatic zones, where normal sea water is diluted to various portions by fresh water. A further distinct diagenetic environment is recognized where excessive evaporation causes marine pore water to become hypersaline brine in sabkhas, which lie landward of the marine-vadose environment in arid climates. Each of these basic environments and their subdivisions have characteristic diagenetic carbonate products.

Marine-Phreatic Environment

Most carbonate sediment is deposited and initially buried in the marine-phreatic environment, where all pore space is saturated with water of normal marine salinity. This environment was subdivided by Longman (1980) on the presence or absence of intergranular cements.

The "active" zone exists where sea water is forced into sediment by waves, tides, or currents, and where other factors, such as CO_2 loss by degassing or photosynthesis, are favorable, so that enough oversaturated pore water passes a certain point to precipitate cement on grains. This happens most commonly in coarse-grained sediments or internal cavities in upper-shoreface sediments that are strongly affected by waves and tides, and in topographic prominences such as buildups or shelf margins that partially obstruct currents. Marine cements are all aragonite or high-Mg calcite, in forms ranging from micrite and random needles, through isopachous fibrous rims with steep-sided rhombic to needlelike crystals, to botryoidal masses. Leaching of unstable grains is unlikely (at least in warm water). Because these cements form relatively rapidly with only shallow burial, essentially no compaction of grains takes place. Internal fine-marine sediment may be mobilized and redeposited on these cements.

The "stagnant" zone exists where water circulation or other factors are insufficient for intergranular cement to precipitate. This zone dominates the marine phreatic environment both in fine-grained sediments, where slow compaction expels water and further reduces permeability, and in coarse-grained sediments, where any of the circulatory or chemical fac-

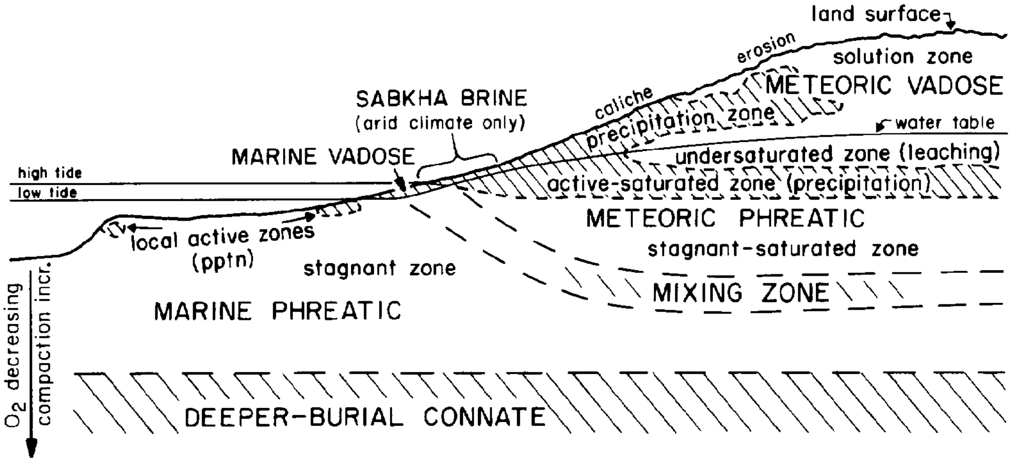

FIG. 3.—Common carbonate diagenetic environments present at any one time in partly emergent carbonate terrain (modified from Longman, 1980, Figs. 1, 3, 7, 14). Lined zones are those in which carbonate cements readily precipitate.

tors are lacking. Intragranular cement of aragonite and high-Mg calcite does occur within certain small pores and microborings in skeletal grains where only a little water is needed to provide cement, but such filling and "micritization" of grains occur in the active zone as well. The absence of intergranular cement allows compaction to begin as burial commences, eventually producing a number of distinctive features.

Deeper-Burial Connate Environment

The deeper-burial connate environment (Fig. 3), which has received little firsthand study, is inferred from the suggestions of Folk (1974), Bathurst (1980a, b), Moore and Druckman (1981), and McHargue and Price (1982). As marine sediments become progressively more deeply buried in the marine-phreatic environment, much more substantial compaction is possible before any significant cementation takes place. Calcarenites become greatly and pervasively overpacked, with increasing amounts of grain crushing and grain-to-grain contact, and increasing chances for grain welding, pressure solution, and stylolitization along these contacts. Remaining pore space might become so greatly reduced that any cement that eventually precipitates is finely crystalline and inconspicuous. There is increasing isolation from the sea-water reservoir and enough time for the chemistry of the interstitial connate water to change substantially. For example, K$^+$ tends to go into clays, and Mg^{++} into dolomite. The latter change removes the poisoning effect on growth of low-Mg calcite, which can become the major cement mineral in blocky equant form. Oxygen is soon depleted by organic decomposition, and the resulting reducing conditions permit existence of enough Fe^{++} in solution to form ferroan calcite and dolomite cements. Lime muds compact and lose pore water until they are cemented on a submicroscopic scale. Stylolites become laterally extensive. Also, there should be enough time for slow neomorphism of unstable aragonite grains and cements to blocky calcite mosaics while maintaining the critical balance of factors needed for retaining original aragonitic grain fabric.

Marine-Vadose Environment

A thin belt of carbonate sediment along shoreline is deposited in the marine-vadose environment, where tides and wave swash periodically fill aerated pores with sea water. Under the right conditions of CO$_2$ degassing, cements rapidly precipitate to form beachrock. Cements in beachrock are micritic to fibrous aragonite and high-Mg calcite, reflecting the marine origin of the pore water. Their form ranges from isopachous rinds, like those of the active marine-phreatic zone, to meniscus and pendent fabrics. Beachrock is continually broken into cobbles and boulders, which are easily rounded and often recemented into more beachrock by the the same kinds of cements.

Meteoric-Vadose Environment

Meteoric environments become established in marine carbonate sediment or rock upon emergence of the sea bottom. The meteoric vadose environment lies above the terrestrial water table (Fig. 3), where pore space is filled with air and variable amounts of fresh water. This environment was subdivided by Longman (1980) into two zones based on degree of saturation of pore water with respect to $CaCO_3$. As with previous subdivisions, these are end portions of a continuous spectrum, and particularly in the vadose environment, they are variably developed both geographically and temporally, depending on general climate and immediately preceding weather, respectively.

The "zone of solution" lies at and below the land surface in most humid climates where undersaturated rain water augmented by soil CO_2 moves downward. The major diagenetic process in this zone is solution of $CaCO_3$, with less stable aragonite affected before calcite and dolomite. Solution patterns commonly involve removal of aragonite grains from among calcite grains and from within calcite cements, and extend through etching and embayment of calcite grains, and pitting and channeling of calcitic limestones, to karst features ranging from small cavities to sinkholes and caverns.

The "zone of precipitation" may occur anywhere within the vadose environment where pore water becomes saturated with $CaCO_3$, which then precipitates on account of warming, evaporation, or other means of CO_2 degassing. In humid climates, pore water tends to be more saturated in the lower part of the vadose zone because of stronger downward flow. In drier climates, strong surface evaporation draws water up to form caliche in soils and on surface debris. In more intermediate climates and with irregular topography, groundwater movement and degassing leads to precipitation of tufa around springs and flowstone in caves. Extremely low Mg content of most meteoric water makes low-Mg calcite the main cement mineral. Cement form tends to reflect distribution of pore water in the presence of air, leading to meniscus cements concentrated at grain contacts, and pendent cements, ranging to microstalactites, on the undersides of grains, each type often lacking crystal terminations because of growth only to the water-air interface. Cement texture and fabric ranges from micritic in rapidly precipitated caliches, through intermediate sizes and equant to bladed shapes in calcarenites, up to extremely coarse crystals in slowly deposited cavern flowstones, where rinds of large growth-banded blades of "palisade" calcite are common.

Meteoric-Phreatic Environment

The meteoric-phreatic environment lies below the terrestrial water table, where all pore space is filled with fresh water containing variable amounts of dissolved $CaCO_3$. This environment was subdivided by Longman (1980) into several zones based on degree of saturation with respect to mineral species of $CaCO_3$ and the amount of water circulation needed to precipitate cement.

The "undersaturated" zone occurs below the water table (Fig. 3) where water entering from the vadose zone has not dissolved enough carbonate to become saturated. Water in this zone dissolves aragonite grains to form molds and, if undersaturated enough, it dissolves calcite as well to form irregular vugs. Neither form of void is distinguishable from similar porosity formed in the overlying meteoric vadose environment.

The "active-saturated" zone occurs below the undersaturated zone at the level where porewater becomes oversaturated with calcite, and is still actively circulating downward. In this zone extensive precipitation of low-Mg calcite cement takes place, both in primary pores, and in secondary molds of aragonite grains and solution vugs. Cement is typically clear and ranges from drusy dogtooth rims to blocky mosaics that derive from the early rims and tend to coarsen toward the middle of the void. Syntaxial overgrowths on echinoderms are considered particularly characteristic, as they are rare in the meteoric-vadose environment and not reported in shallow marine environments, although they can form in the deeper-burial connate environment.

The "stagnant-saturated" zone grades downward from the active zone below the level where significant water movement takes place. Because of slow movement of pore water in this zone in conjunction with its progressive equilibration with the surrounding sediment, probably little cementation takes place. Also because of this slow movement, neomorphism of aragonite to calcite may take place where solution of aragonite is delicately balanced by precipitation of calcite such that original aragonitic fabric is preserved, just as it may in the deeper-burial connate environment.

Mixing-Zone Environment

The mixing zone is characterized by brackish water formed from the mixing of marine and fresh pore water from the adjacent phreatic zones (Fig. 3). Like the boundaries of most other zones, it may fluctuate greatly in position with time, responding to such factors as seasonal variation in rainfall. Although little studied, leaching and neomorphism of aragonite and cementation like that in the adjacent phreatic zones is recognized. Cements range from micritic and bladed calcite at the freshwater end to isopachous high-Mg calcite rims at the marine end of the spectrum (Longman, 1980). An important effect of the slow, repeated fluctuation of salinities in this zone is the formation of dolomite at certain intermediate salinities, which are slightly undersaturated with calcite and oversaturated with dolomite. Another important effect is the probability that nodular cherts form at similar salinities, which also can be supersaturated with quartz while undersaturated with calcite (Knauth, 1979).

Sabkha Brines

In arid tidal flats and other dry shoreline environments, strong evaporation leaves behind a range of hypersaline porewater, which causes a complex variety of diagenetic features, including precipitation of evaporites and dolomite. Periodic flushing of such environments with seawater or fresh meteoric water can dissolve calcium sulphate, which raises Ca^{++} content and may ultimately result in replacement of dolomite by calcite, producing the fabric of "dedolomitization."

Summary of Criteria

Because few cement types or other individual diagenetic features are specifically diagnostic of a single diagenetic environment, a summary of exactly what the criteria do indicate is in order:

1. Original cement mineralogy reflects porewater chemistry at the time of precipitation. Early cloudy rims of fibrous aragonite and high-Mg calcite form only in Mg-rich water, and thus are characteristic both of early marine cementation (including beachrock) and of sabkha-brine cementation. In contrast, blocky low-Mg calcite cements form only in Mg-poor water, and thus are characteristic not only of the saturated, precipitating zones of the meteoric environments, but also of parts of the deeper-burial connate zone where Mg^{++} is removed by dolomite formation. Thus the common diagenetic fabric of cloudy, fibrous rim followed by clear, blocky filling indicates early marine cementation followed either by 1) emersion and migration of meteoric water, or 2) deeper burial and alteration of connate water chemistry, a duality of origin recognized by Folk (1974).

2. Relative uniformity of early cement rims helps distinguish vadose from phreatic environments of cementation. Isopachous rims reflect isotropy of the precipitating medium and therefore are best developed in phreatic environments, although they often occur in marine beachrock as well. In contrast, meniscus and pendent cements, especially those lacking good crystal terminations, will likely form only where water is confined by coexisting air to grain contacts or undersides, and thus are diagnostic of the vadose environments. Nevertheless, nonuniform aragonite botryoids, which seem to grow on any part of a cavity wall, are considered diagnostic of part of the active marine-phreatic environment.

3. Amount of compaction among grains depends on how early during burial the sediment became lithified. This should help to distinguish between early and late cements, and thus may aid in solving the problem of the dual origin of blocky calcite cements (as long as early cloudy rims thick enough to inhibit compaction are absent). Thus, a pervasively overpacked calcarenite with only blocky calcite cement suggests late cementation after substantial compaction in the deeper-burial connate zone, whereas a normally packed calcarenite with only blocky calcite cement suggests earlier cementation before much burial, and thus would be more likely in the saturated meteoric-phreatic environment. The type of partial overpacking illustrated by Watney (1980, p. 23) with retention of local large intergranular voids, on

the other hand, reflects solution etching of grains and selective enhancement of porosity in an unsaturated meteoric zone.

4. Ferroan calcites and dolomites record an aqueous environment low enough in oxygen that Fe^{++} can be incorporated into carbonate. Interstitial marine water can become reducing a short distance below the sediment-water interface if enough decaying organic matter is present to deplete the oxygen quickly. With increasingly deeper burial, even the low amounts of buried organic matter in calcarenites will eventually deplete oxygen. Thus ferroan cements should be common in the deeper-burial connate environment. In contrast, any vadose environment is highly oxidizing, and any mobile iron present would be in the form of ferric oxides or hydroxides. The meteoric-phreatic environment probably displays a range of oxidation, depending on the amount of organic matter and the rate of replenishment of oxidizing water from the vadose zone. Thus it may grade from oxidizing in the zone of active circulation at the top, to reducing in the stagnant zone at the base.

5. Discernible neomorphism of aragonite to blocky calcite reflects a slow enough reaction that the original fabric is preserved. Because neomorphism is more likely under relatively stagnant conditions, and also requires low Mg^{++}, it is probably characteristic of both the stagnant meteoric-phreatic and deeper-burial connate zones, but would be unlikely in Mg-rich marine zones or in the strongly leaching, undersaturated meteoric zones. Although it is probably also unlikely in those saturated meteoric-vadose zones where precipitation is rapid, it may take place where precipitation is slow.

6. Large-scale leaching of carbonate takes place only in the meteoric-vadose and undersaturated meteoric-phreatic and mixing zones, where voids ranging from aragonite-grain molds to solution vugs and caverns are formed. If the surrounding matrix is lithified and the voids become filled with cement, the void-space fabric will be preserved during deeper burial. In contrast, deeper-burial removal of carbonate involves solution under pressure and results in stylolites.

7. Evaporite minerals within carbonate sediment characterize brine environments. Blocky calcite pseudomorphs after molds of evaporite minerals indicate establishment of a low-Mg meteoric environment subsequent to a sabkha or other evaporitic environment. Calcite pseudomorphs after dolomite strongly suggest a similar sequence, in which Ca-rich water from solution of gypsum or anhydrite enhanced replacement of dolomite of any origin.

APPLICATION TO PENNSYLVANIAN EUSTATIC CYCLIC CARBONATES

Diagenetic Model

In order to apply the foregoing criteria to Midcontinent Pennsylvanian carbonates, the probable progression of diagenetic environments that moved through the deposits of a single transgressive-regressive cyclothem must be established (Fig. 4).

During marine transgression and the earlier part of regression, when marine sediment lay continually beneath sea water, all sediment was in the marine-phreatic diagenetic environment, probably largely stagnant, with active zones only near buildup margins and in parts of shoreface calcarenites. As higher parts of the regressive limestone emerged during later regression, meteoric environments became established in them. Thus, higher parts of the regressive limestone were slowly removed from the marine-phreatic environment and became subjected to, in order, first the marine-meteoric mixing zone, then the meteoric-phreatic environment (from stagnant, through actively precipitating, to unsaturated), and finally the meteoric-vadose environment, with or without carbonate precipitation. The top of this portion of the regressive limestone became a surface of subaerial exposure, often with local caliche and terrigenous residual soils. In some places, the marine-vadose (beachrock-forming) zone migrated through surface sediments just ahead of the emergent surface. Where the climate was more arid, the sabkha-brine environment may have become established locally in the top of the regressive limestone. This eventually would become flushed with fresher water.

How far down into the regressive limestone any of the meteoric environments became established would depend upon 1) how far the sea withdrew from the surface, 2) the patterns of permeability in the sediment, and 3) the amount of rainfall driving the meteoric water. Ideally, when the sea stood at its lowest level, the range of diagenetic environments shown in Figures 3 and 4 would have become established in the cyclothem. Because the ex-

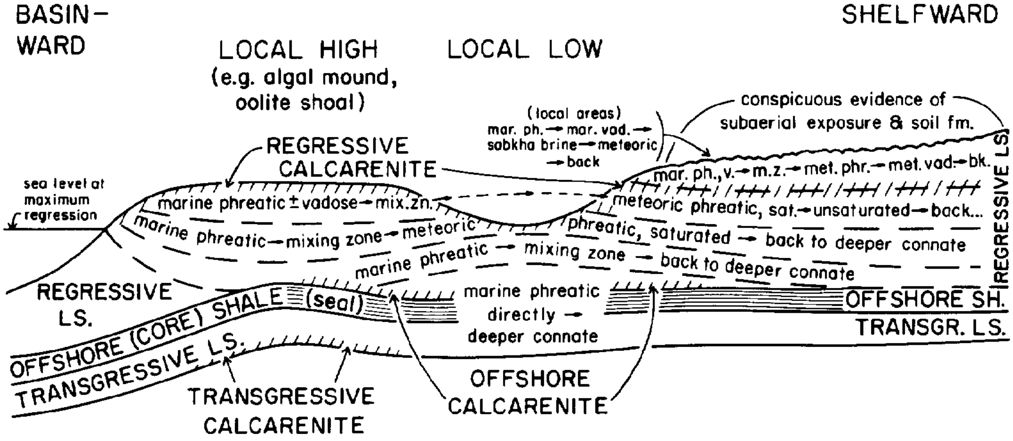

FIG. 4.—Progression of common carbonate diagenetic environments in different parts of typical Pennsylvanian eustatic "Kansas" cyclothem, shown at maximum regression terminating that cycle of deposition. Subsequent transgression reversed this progression and moved marine-phreatic environment back upward through the entire cyclothem as the next higher cyclothem began to be deposited. All parts of cyclothem eventually moved into deeper-burial connate environment. Modern exposure and weathering currently are bringing similar progression of diagenetic environments back through entire sequence of cyclothems on outcrop and in near-subsurface. The three horizons of calcarenite facies units named in Fig. 2 are diagonally lined and labeled, and the three horizons of calcilutite facies units are left blank.

tremely fine-grained core shale, even though normally quite thin, would have been an impermeable aquiclude or "seal," the meteoric environments were probably confined mainly to the regressive limestone above the shale. Thus the entire transgressive limestone and any thin limestones in the core shale would have been sealed off and would have remained continually in the marine-phreatic zone, rarely affected by meteoric diagenesis prior to the next transgression. They and topographically low parts of the regressive limestones would have moved directly into the deeper-burial connate zone. Intermediate levels of the regressive limestone would have become affected by only the mixing zone or only the mixing zone followed by the meteoric-phreatic zone before the next transgression. Only the upper parts of the regressive limestone, particularly in topographically high areas, would have been subjected to the entire progression of environments described in the ideal case.

The next transgression of the sea inundated the entire cyclothem with marine water again, with or without much of an intervening nearshore shale to act as a seal. This caused reversal of the progression of diagenetic environments, driven by marine-phreatic water moving back upward through the entire cyclothem. All sediment then moved slowly into the deeper-burial connate zone with time. The deeper zone thus eventually overprinted the meteoric fabrics that had become established in higher, but still permeable, parts of the regressive limestone.

Finally, modern meteoric weathering and exposure affect the entire range of depositional and diagenetic environments represented in the cyclothem on the outcrop, causing overprinting of the remaining permeable parts of the cyclothem with the products of meteoric environments. At the very least, ferroan carbonate minerals, which are unaltered in cores, become oxidized to ferric hydroxides for several feet below the modern soil zone and after only a few years on artificially exposed surfaces.

Although the possible fabrics developed from this sequence of events are potentially complex, even in the simple, ideal case described above, we can try to determine if the observations of diagenetic fabrics in the cyclic carbonates are compatible with the diagenetic model.

Observed Diagenetic Fabrics

Because diagenetic fabrics are most easily observed and interpreted in calcarenites, these facies provide most of the material for the present study, but certain interpretable observations on calcilutites are made as well. Three phases of calcarenite and three phases of calcilutite deposition are recognized in the basic Kansas cyclothem (Figs. 2, 4), in ascending order: *a*) local oolitic to skeletal calcarenite at the base of the transgressive limestone, deposited in shoal but deepening water; *b*) widespread skeletal calcilutite forming most of the transgressive limestone, deposited below the effective winnowing base in deepening but photic water; *c*) local offshore skeletal calcarenite within the upper gray facies of the offshore shale or at the base of the regressive limestone, deposited in deep water below the effective base of both winnowing and algal mud production and preservation; *d*) widespread skeletal calcilutite forming the lower-to-middle part of the regressive limestone, deposited below the effective winnowing base but in photic water becoming shallow; *e*) widespread but laterally variable skeletal-to-oolitic calcarenite in the upper part of the regressive limestone, deposited in water becoming shoal; *f*) local to widespread, sparsely skeletal to barren calcilutite at the top of the regressive limestone, deposited in shallow-lagoonal to muddy-shoreline environments.

Shallow water transgressive calcarenites.—Although uncommon and only local in the Midcontinent Pennsylvanian, calcarenites formed in transgressing seas are well developed in the basal Stanton (Captain Creek) Limestone (oolitic Benedict and Tyro beds), the basal South Bend (oolitic to conglomeratic), and the basal Hertha (Critzer) Limestone (abraded-grain skeletal calcarenite) (Heckel, 1975, 1978, Ravn, 1981).

Not only do these calcarenites lack conspicuous fibrous-rim cements, they all appear substantially and pervasively overpacked (Fig. 5–7), with crushed shells (Fig. 6), and welded to

FIG. 5.—Transgressive abraded-grain skeletal calcarenite with overpacked dasyclad green algal (d), mollusc (m), and other skeletal grains. Blocky ferroan calcite cement filled greatly reduced intergranular void space in deeper connate zone after compaction. Neomorphosed mollusc (m), now consisting of blocky calcite, shows conspicuous relict layering. Plane light; scale bar is 0.2 mm. Critzer Limestone (Hertha cycle) in roadcut east of La Cygne, Kansas.

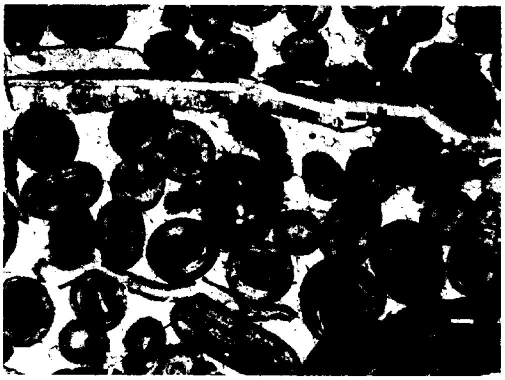

FIG. 6.—Transgressive fossiliferous oolite with overpacked ooids and crushed mollusc shells. Both grain types show welded grain contacts and neomorphism to blocky calcite while retaining relict lamellar and layered internal structure. Cement is blocky ferroan calcite emplaced in deeper connate zone after compaction. Plane light; scale bar is 0.2 mm. Benedict bed (Stanton cycle) in spillway southeast of Buffalo, Kansas.

FIG. 7.—Transgressive oolite with overpacked ooids, showing welded to stylolitized grain contacts, and dolomite replacement (clear) confined to certain lamellae. Cement is blocky ferroan calcite and dolomite emplaced in deeper connate zone after compaction. Plane light; scale bar is 0.2 mm. Tyro oolite bed (Stanton cycle) in quarry northeast of Tyro, Kansas.

stylolitized grain contacts (Fig. 7). The cement is almost entirely composed of an equant, blocky ferroan calcite spar in a greatly reduced pore space. The cement formed from syntaxial overgrowths on echinoderms is minor. Some cements contain ferroan dolomite crystals of probably both replacement and void-filling origin. No grain or intergranular pore space shows conspicuous leaching, even those grains reasonably assumed to have been originally aragonite, such as molluscs, green algae, and ooids. In fact, many molluscs and ooids display neomorphism to blocky calcite with retention of relict fabric (Fig. 5, 6). Some skeletal grains and ooids are replaced by ferroan dolomite, which maintains the original fabric, alternating with concentric layers of calcite in a few ooids (Fig. 7).

The pervasiveness of substantial overpacking of grains along with blocky calcite cement in these calcarenites reflects a high degree of compaction and indicates relatively deep burial before cementation in a Mg-poor environment. The dominance of ferroan cements (and replacements) indicating low-oxygen conditions supports relatively deep burial where oxygen replenishment is minimal during cementation. Widespread neomorphism and replacement of originally aragonitic grains with good retention of relict fabric indicates slow, delicately balanced processes, which are likely only in the stagnant phreatic zone below the level of active circulation. This pattern of diagenesis in transgressive calcarenites is strongly compatible with the proposed model, which regards these calcarenites as having remained continually in the marine-phreatic environment after deposition, moving slowly into the deeper-burial connate zone where all observed diagenetic patterns were developed. Also strongly supporting this interpretation is the conspicuous absence of early fibrous (or other precompactional) cement, or of large-scale meteoric leaching of grains, both of which are characteristic of shallow-zone diagenesis and common in depositionally similar calcarenites at the tops of regressive limestones.

Offshore calcarenites.—Calcarenites formed offshore in deeper water during or just after maximum inundation also are relatively uncommon in the Midcontinent Pennsylvanian. Examples can be found at the base of the regressive limestones (Stoner, Raytown) of the Stanton and Iola cycles, and the core shale (Mound City) of the Hertha cycle (Heckel, 1978; Mitchell, 1981; Ravn, 1981). These are unlike the calcarenites at the base of transgressive limestones and at the top of regressive limestones, which are commonly cross-bedded and contain algal and abraded grains, often with micrite envelopes, all features reflecting shallow, agitated environments. In contrast, the calcarenites in the "core" of the cyclothem consist entirely of invertebrate grains (chiefly echinoderms, bryozoans, brachiopods and encrusting foraminifers), which display no evidence of grain abrasion, cross-bedding, or definite algal structures. Thus, they formed in quiet water below the effective wave base and probably below the photic limit of much algal activity as well. The original absence or dissolution of algal carbonate mud accounts for their calcarenitic texture in contrast to the calcilutitic facies more commonly adjacent to the core shale in both limestone members.

Diagenetically, these calcarenites are typically greatly overpacked with welded-grain contacts. In some, the grains fit together as closely as pieces in a jigsaw puzzle, so that practically no intergranular material is present (Fig. 8). Many grains display evidence of surficial corrosion (Fig. 9). Cements are typically blocky ferroan calcite, derived from echinoderm overgrowths in a few examples. Ferroan dolomite is present in the matrix of a few specimens adjacent to core shales, and it predominates in specimens with a detrital mud-rich

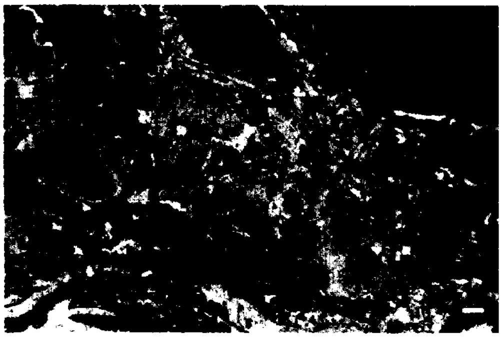

FIG. 8.—Offshore calcarenite consisting of echinoderms, brachiopods, bryozoans and encrusting foraminifers, all overcompacted such that they nearly fit together like a jigsaw puzzle, with minimal cement consisting of ferroan calcite emplaced in deeper connate zone after compaction. Plane light; scale bar is 0.2 mm. Basal Raytown Limestone (Iola cycle) in roadcut in Kansas City, Kansas.

FIG. 9.—Offshore calcarenite consisting primarily of echinoderm grains showing corroded surfaces (in contrast to abraded surfaces seen in shallow-water calcarenites). Cement is ferroan calcite emplaced in deeper connate zone after compaction. Plane light; scale bar is 0.2 mm. Basal Stoner Limestone (Stanton cycle) in quarry southeast of Buffalo, Kansas.

matrix, reflecting the association of dolomite and shale discussed by McHargue and Price (1982).

In one locality, the offshore calcarenite at the base of the Stoner Limestone displays a range of grain-packing from normal at the base to moderately overpacked at the top, which coincides with early drusy rims around grains at the base but disappearing upward. These drusy rims are bladed calcite (Fig. 10), with an initial fibrous precursor visible around echinoderm grains, and they cover small geopetal piles of marine mud resting on the tops of broad grains. Small, apparently neomorphosed, thin-shelled clams and snails are found only in the specimens with the drusy-rim cements.

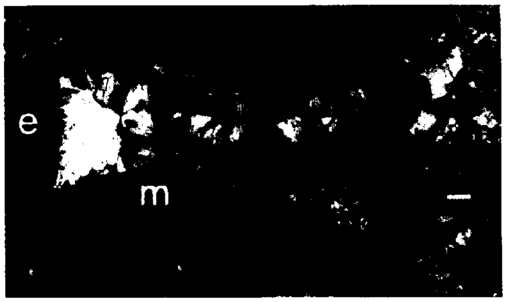

FIG. 10.—Offshore calcarenite in which geopetal mud (m) settled on tops of clam shells and other broad skeletal grains. Cement is bladed drusy calcite with initial fibrous precursor rimming mud surfaces and invertebrate grains, including echinoderm (e). This specimen underwent early cementation, probably during temporary impingement of mixing zone during regression, thus remained less compacted than other offshore calcarenites. Cross-polarized light, scale bar is 0.2 mm. Basal Stoner Limestone (Stanton cycle) in quarry northwest of Vilas, Kansas.

The extreme overpacking of grains and blocky ferroan carbonate cements in nearly all offshore calcarenites (Figs. 8, 9) reflect a high degree of compaction before cementation in a Mg-poor, low-oxygen environment, which would be expected in a sediment that moved directly from the marine-phreatic environment into the deeper-burial connate zone, just as the transgressive calcarenites did. The drusy-bladed rims and lack of grain compaction (Fig. 10) at one locality, however, indicate early cementation, possibly in the mixing-zone environment. The geopetal piles of cement-rimmed mud sediment attest to good circulation through this calcarenite horizon prior to cementation, and this would have promoted the early cementation. This evidence of permeability in conjunction with the position of these specimens in the base of a regressive limestone on a topographically high, transgressive algal mound tract (Heckel, 1978) allows early cementation to be attributed to greater penetration of the mixing zone here during maximum regression.

Furthermore, the presence of neomorphosed snails and clams in only the early cemented example of offshore calcarenite suggests that their absence in the late-cemented examples may have resulted from normal submarine dissolution of these thin, unstable aragonite shells in the undersaturated cooler-water, sediment-starved environment (see Alexandersson, 1978), where even the stable calcite grains eventually became corroded (Fig. 9). The absence of lime mud of any origin in late-cemented examples is similarly explained by dissolution. The absence of originally aragonite ooids and green algae in both the early and late-cemented examples of offshore calcarenites, on the other hand, confirms their expected absence in this deep-water depositional environment.

Shoal-water regressive calcarenites.—Calcarenites formed in shoal water as sea level fell are well developed at the tops of all regressive limestones in the Midcontinent Pennsylvanian. Only in these calcarenites did shallow marine and meteoric environments affect the sediment on a large scale and produce early shallow-zone diagenetic features.

Nearly all thin sections from regressive calcarenites display much looser packing of grains than either the transgressive or offshore cal-

FIG. 11.—Regressive skeletal calcarenite showing thin rim of drusy cement around echinoderm fragment (at extinction), suggesting initial cementation in Mg^{++}-rich marine environment. Echinoderm overgrowth (also dark) later filled final void space beyond drusy rim under subsequent low-Mg^{++} meteoric conditions. Crossed polarizers; scale bar is 0.2 mm. Upper Stoner Limestone (Stanton cycle) in roadcut west of Altoona, Kansas.

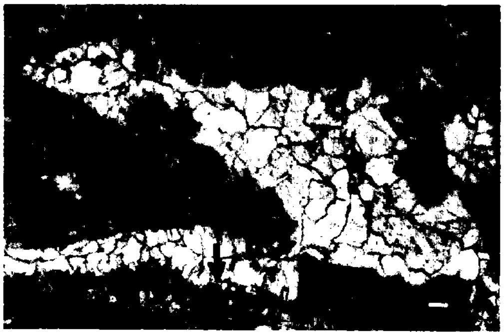

FIG. 13.—Regressive red-algal calcarenite showing dark cloudy cement rim with scalenohedral terminations and probable microdolomite inclusions, suggesting that rim was originally high-Mg calcite formed in marine environment. Breakage and offset of grains and rims (arrow shows movement) indicate minor collapse of framework prior to precipitation of clear blocky cement in low-Mg^{++} meteoric environment. Plane light; scale bar is 0.2 mm. Upper Stoner Limestone (Stanton cycle) in roadcut west of Independence, Kansas.

carenites. Grain-to-grain contacts are rare, and nearly all lack stylolitization or welding. This indicates that minimal compaction took place before cementation and that at least initial cementation must have taken place early, no later than shallow burial.

Early rims of drusy cement range from thin to thick, around all types of grains, including echinoderms (Fig. 11). Some are cloudy and fibrous (Fig. 12) and appear to neomorphosed from aragonite. Others are cloudy but blockier, and in places show ghost scalenohedral (dogtooth) crystal forms (Fig. 13), which display possible microdolomite inclusions under high power, suggesting that they probably were originally high-Mg calcite (Lohmann and Meyers, 1977). Both types of cloudy rims reflect early marine cementation. Although the generally isopachous nature of these cements might suggest the marine-phreatic environment, and definite vadose features are not apparent, the marine-vadose environment is not ruled out because meniscus and pendent cement fabrics can be masked by further cement growth and neomorphism, and thin sections may miss edges of recemented beachrock clasts.

Clear drusy to blocky cement rims and echinoderm overgrowths are common. Many rims are inconspicuous because they grade into the final blocky crystals filling the pore, but some have a distinct line of scalenohedral terminations (Fig. 14), and others become visible when an echinoderm grain with substantial overgrowth is at extinction (Fig. 15). These are probably originally low-Mg calcite formed in a meteoric environment, because lack of significant compaction rules out deeper burial. Locally toward the north are possible meniscus cements (Fig. 16) and pendent cements (Fig.

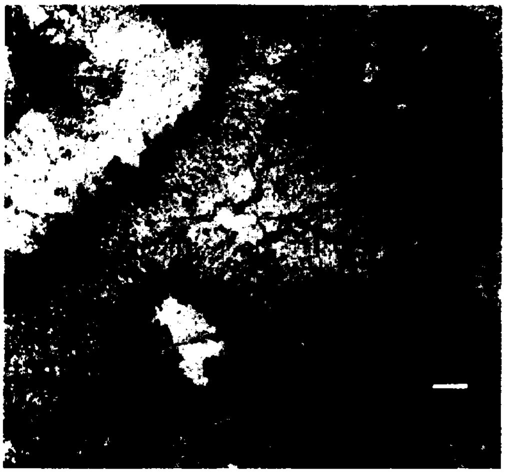

FIG. 12.—Regressive abraded-grain skeletal calcarenite showing thick cloudy rim of drusy, fibrous, probably originally aragonite cement around all grains, and indicating substantial early cementation in marine environment. Plane light; scale bar is 0.1 mm. Top of Stoner Limestone (Stanton cycle) in streambed northeast of Buffalo, Kansas.

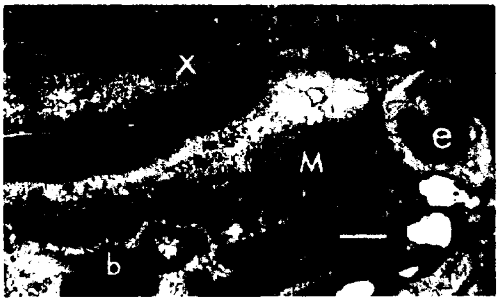

FIG. 14.—Regressive skeletal calcarenite showing thin early rims of clear drusy calcite cement with scalenohedral terminations along tops of bryozoan grain (b) and leached partially collapsed grain (x), and syntaxially around echinoderm grain (e), emplaced during first passage of saturated meteoric phreatic zone through sediment. Then original aragonite of grain x was leached as meteoric water became undersaturated, after which its remaining micrite envelope partially collapsed. Emplacement of intergranular geopetal sediment that became microspar (M) may have taken place in vadose zone, as it resembles "crystal silt" interpreted as vadose by Dunham (1969). Final blocky calcite filling above microspar and within grain x was precipitated probably as saturated phreatic environment moved back through rock during succeeding transgression. Plane light, scale bar is 0.5 mm. Upper Stoner Limestone (Stanton cycle) in roadcut southwest of Buffalo, Kansas.

17), which indicate initial cementation in the meteoric-vadose environment.

Leaching of unstable grains is evident in all cyclothems. Red algal grains of original high-Mg calcite are commonly only partially leached (Fig. 18). Green algae, ooids, and molluscs of original aragonite are more commonly totally leached, although some oomolds contain dropped nuclei, reflecting leaching of only the outer cortex (Fig. 19). In some calcarenites,

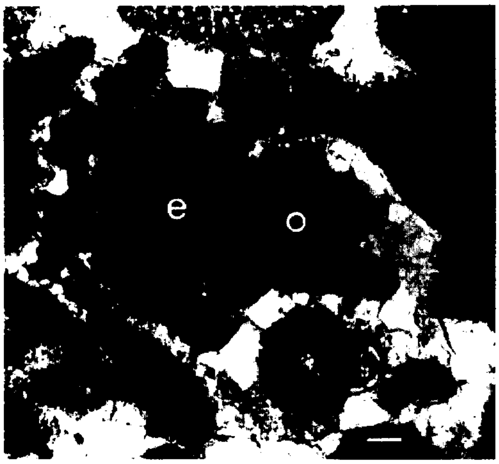

FIG. 15.—Regressive skeletal calcarenite showing clear drusy blocky calcite rim cement on bryozoan grains, with scalenohedral terminations visible where adjacent large syntaxial overgrowth (o) on echinoderm grain (e) is at extinction, both cements probably formed in active saturated meteoric phreatic environment. Crossed polarizers; scale bar is 0.1 mm. Middle Stoner Limestone (Stanton cycle), in quarry south of Roper, Kansas.

FIG. 16.—Regressive abraded-grain skeletal calcarenite showing possible meniscus cement, indicated by thickening and concentration of blocky calcite cement crystals at grain contacts (esp. arrows), and reflecting precipitation in meteoric vadose environment. (Compare with Longman, 1980, p. 471, Fig. 9A). Plane light; scale bar is 0.1 mm. Upper Winterset Limestone (Dennis cycle) in quarry at Crescent, Iowa.

FIG. 17.—Regressive osagia-grain calcarenite showing clear pendent drusy calcite rim cement around possibly solution-enlarged, intergranular void in which rim is substantially thicker along top (t) of void than along base (b), strongly suggesting precipitation in meteoric vadose environment. Crossed polarizers, with final void-filling crystals at extinction; scale bar is 0.2 mm. Top of Raytown Limestone (Iola cycle) in streambank north of Pammel Park, near Winterset, Iowa.

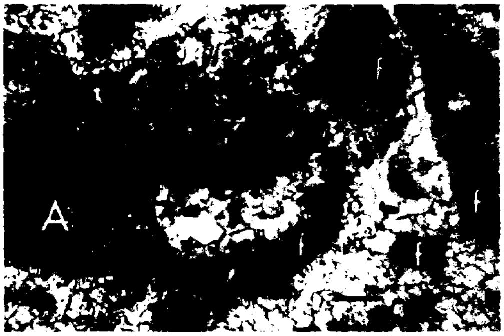

FIG. 18.—Regressive red-algal calcarenite showing partially leached thallus (center) of *Archaeolithophyllum*, with left portion (A) neomorphosed to blocky calcite that retains cellular structure, and right portion fractured and partially collapsed, resulting in offset fragments (f). Thin rims of drusy calcite cement on thallus and some fragments formed in saturated meteoric water, possibly both before and after leaching in associated undersaturated meteoric environment. Plane light; scale bar is 0.5 mm. Upper Hertha Limestone in roadcut south of Uniontown, Kansas.

grains were leached out of their micrite envelopes or accreted coatings, which then collapsed partially (Fig. 14) or completely (Fig. 20) prior to much cementation. Some minor collapse took place without leaching in rocks consisting of long, thin blades of red algae, even after an early rim of cement (Fig. 13). In rocks rich in green algae, early leaching commonly left mainly micrite envelopes, which along with overlying layers of coherent mud, collapsed partially to totally into underlying void space to produce a "brecciated" fabric, with geopetal piles of broken micrite envelopes often the only remaining direct evidence of algal blades (Fig. 21). In a few cases, leaching was intense enough to remove large areas of matrix, cement and grains, and form solution vugs (Fig. 22). All leaching is considered to have taken place in the undersaturated zones of the meteoric-phreatic and vadose environments.

In a few calcarenites with large open spaces between grains, a ghostlike partial filling of geopetal cloudy microspar crystals is visible (Fig. 14). This may be transported "crystal silt," interpreted by Dunham (1969) to be meteoric-vadose in origin.

Some samples of regressive calcarenites show moderate grain compaction and no definite evidence of shallow-zone diagenesis. These probably did not begin to cement early enough to preserve any early diagenetic features (such

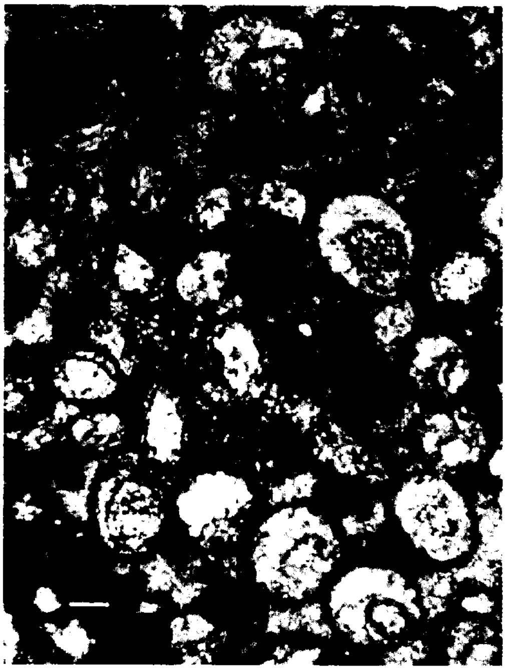

FIG. 19.—Regressive oolite showing blocky calcite spar-filled ooids, in many of which nucleus dropped to bottom of void after cortex was leached in undersaturated meteoric environment, then became cemented into later void filling as water became saturated. (Nuclei displaced to sides or tops of oomolds apparently contrary to gravity, illustrated by Payton 1966, p. 581, from similar calcarenites, may have been displaced by crystals growing into void from opposite side.) Plane light; scale bar is 0.2 mm. Top of Bethany Falls Limestone (Swope cycle) in roadcut east of LaCygne, Kansas.

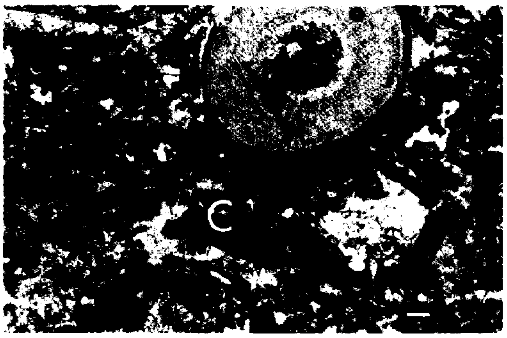

FIG. 20.—Regressive skeletal calcarenite showing crushed coating (c), out of which presumably aragonite grain had been leached in undersaturated meteoric environment, prior to compactional crushing. Plane light; scale bar is 0.2 mm. Middle Stoner Limestone (Stanton cycle) in roadcut west of Altoona, Kansas.

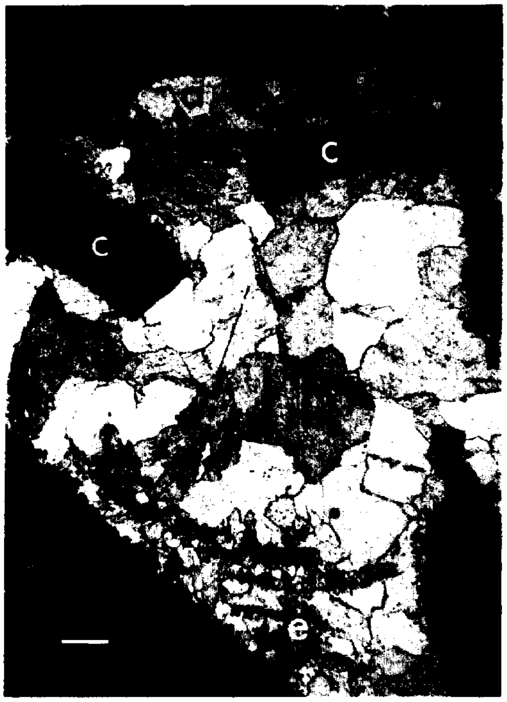

FIG. 21.—Calcarenitic zone in regressive phylloid algal mound showing geopetal pile of broken micrite envelopes (e) in bottom of void originally sheltered by leached algal blade that provided broken envelopes and formerly was positioned beneath partially collapsed mud clasts (c). Above these, another leached algal blade (a) and overlying mud are also partially collapsed, farther down on left. Leaching and collapse took place in undersaturated meteoric environment prior to void filling by drusy to blocky calcite in saturated meteoric phreatic environment, which probably passed back through sediment during subsequent transgression; both processes resulted in sparry, brecciated appearance of most algal-mound facies. Plane light; scale bar is 0.5 mm. Upper Stoner Limestone (Stanton cycle) in roadcut southeast of Elk City, Kansas.

as leached grains) that may have formed prior to final compaction and cementation. An overcompacted regressive calcarenite illustrated by Watney (1980, p. 23) shows solution-enhanced intergranular porosity, which distinguishes it from the pervasively overcompacted transgressive calcarenites.

Neomorphism is apparent in some grains, particularly red algae (Fig. 18), which, originally as high-Mg calcite, were less likely than aragonite to be removed entirely in the meteoric-leaching environment. A number of presumably original aragonite ooids also escaped meteoric leaching long enough to undergo neomorphism (Fig. 23), perhaps in early passage of the stagnant phreatic zone or because early cement sealed them off from the path of leaching pore water. Nevertheless, neomorphism is much scarcer in regressive than in transgressive calcarenites.

The final void filling in most cases is typically clear, relatively coarse, blocky nonferroan calcite, occasionally with interior ferroan calcite (see Conley, 1977, p. 556). Many of these crystals are syntaxial overgrowths of nearby echinoderm grains (Figs. 11, 15). In some voids, crystals of strained ferroan (baroque) dolomite form the final filling. The final calcite filling probably took place anywhere from the meteoric phreatic to the deeper connate environment, with ferroan calcite forming later as oxygen dwindled. The ferroan dolomite may have formed anywhere from the

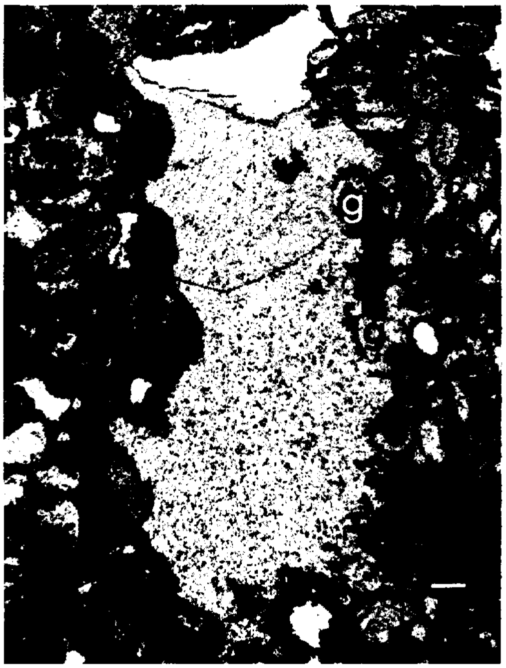

FIG. 22.—Regressive oolitic skeletal calcarenite showing solution vug in which entire grains, matrix and early cement were leached in strongly undersaturated meteoric water after initial induration of sediment. Some grains bordering vug on right (g) were leached from their micrite envelopes, fragments of which settled to bottom of vug. Coarse blocky calcite that fills vug and adjacent leached grains was emplaced in saturated meteoric phreatic environment, which probably passed back through rock during subsequent transgression. Plane light; scale bar is 0.2 mm. Upper Stoner Limestone (Stanton cycle) in core from Bedford, Iowa.

FIG. 23.—Regressive oolite showing probable diagenetic history of: thick cloudy early cement rim in marine phreatic environment, neomorphism of early rim and at least outer parts of accessible ooids in stagnant saturated meteoric phreatic zone, then leaching of remaining aragonite interiors of ooids in unsaturated meteoric zone. Most oomolds apparently remained open in subsequent diagenetic environments that passed through rock with succeeding transgression, but some received thin irregular nonferroan blocky rims and micritic coatings (arrows), probably in modern meteoric phreatic and vadose environments. Plane light; scale bar is 0.1 mm. Upper Drum Limestone (Quivira-Drum cycle) in quarry southeast of Independence, Kansas.

mixing zone to the deeper connate environment, as long as Mg^{++} was present and oxygen depleted.

Several of the previously described features are often present in a single sample of regressive calcarenite in what may first appear to be a bewilderingly complex fabric. Three examples of oolites offer a glimpse of the variety of fabrics, with reasonable interpretations relating all of them to the general pattern of diagenesis expected form the depositional-diagenetic model.

Grains in an oolite specimen from the upper Drum Limestone received an early rim of marine cement. After further regression and emergence, incoming saturated meteoric-phreatic water first neomorphosed the early cements and at least the outer parts of many accessible ooids (Fig. 23) in the stagnant zone, then precipitated clear calcite in remaining primary void space in the active zone, as overgrowths on the neomorphic replacement crystals of the original cement. Eventually the meteoric water became undersaturated with carbonate and leached the remaining aragonite of the ooids and molluscs, leaving only the originally calcite brachiopods, bryozoans and echinoderms, in addition to the neomorphosed cements and ooids. Succeeding transgression and burial eventually brought in deeper connate water that apparently was undersaturated, as most oomolds remained open. Modern percolating meteoric water may have deposited the irregular, thin, blocky nonferroan calcite rims and micrite coatings currently visible around the interiors of some oomolds (Fig. 23).

Grains in an oolite at the top of the Bethany Falls Limestone (Swope cyclothem) received a thin, early rim of fibrous to bladed cement (Fig. 24), probably mostly after emergence, when saturated mixing-zone water moved through. Then meteoric water moved in and, in the stagnant zone, neomorphosed a few accessible ooids and the large clam shells that lie at several levels in the oolite. Eventually the active zone became established and completely filled the intergranular void space with blocky calcite. Then undersaturated meteoric water moved through and leached the remaining aragonite cortex of the ooids. Unleached nuclei dropped to the bottoms of many oomolds, but collapse of the oomoldic fabric was prevented by both the intergranular cement and the early neo-

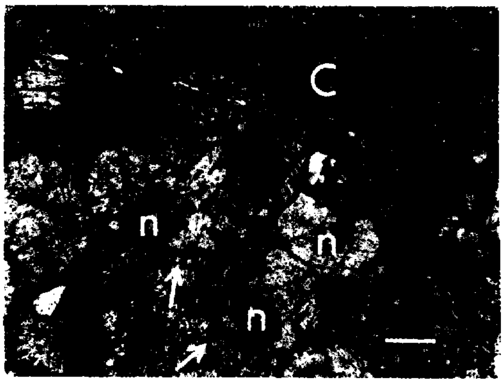

FIG. 24.—Regressive fossiliferous oolite showing probable diagenetic history of: early bladed calcite cement rims (arrows) probably in mixing zone, followed by neomorphism of clam shells (c) in stagnant saturated meteoric phreatic zone, precipitation of final blocky intergranular filling in active saturated meteoric phreatic zone, then leaching of aragonite cortex of ooids in unsaturated meteoric zones, resulting in geopetal collapse of ooid nuclei (n). Finally, after subsequent transgression, ferroan dolomite filled oomolds and replaced dropped nuclei in low-oxygen water somewhere from mixing zone to deeper-burial connate zone. Plane light; scale bar is 0.2 mm. Top of Bethany Falls Limestone (Swope cycle) in Canville Creek, west of Stark, Kansas.

FIG. 25.—Regressive marine pisolite showing probable diagenetic history of: settling of thin layer of lime mud (m) on tops of pisoliths, followed by precipitation of thin fibrous to thicker clear, strained-bladed cement rim (r) around grains and on top of settled mud, in marine phreatic to mixing zone. Then roughly half of aragonite cortex of pisoliths was leached on lamellar scale in undersaturated meteoric zone, leaving rim-cement-supported framework weakened at grain contacts where compactional fracture occurred. This resulted in collapse of cement rims that remained coherent between grain contacts, into partially leached pisomolds to produce chain of crushed pisoliths (see Conley, 1977), with fracture of cement "ram" in one place (x). Eventually, as saturated water with decreasing oxygen passed back through rock during succeeding transgression, remaining pisolith aragonite neomorphosed to ferroan calcite, with some concentric lamellar fabric preserved, and centers of intergranular pores were filled with ferroan calcite (f). Plane light, scale bar is 0.2 mm. Top of Spring Hill Limestone (Plattsburg cycle) in Verdigris River valley between Benedict and Altoona, Kansas.

morphism of the clam shells. Succeeding transgression and burial in this case brought back phreatic water that, somewhere between the mixing zone and the deeper connate environment, became depleted of oxygen and precipitated ferroan dolomite in most of the oomolds, incorporating the dropped nuclei in many of them.

Grains in an intermound-marine pisolite (Fig. 25) at the top of the Plattsburg Limestone received a thin layer of marine mud on their upper surfaces, followed by a rim of drusy-fibrous to clear-bladed cement, probably mainly in the mixing zone, as it moved through after regression and emergence of the nearby mound. With further emergence, undersaturated meteoric-phreatic water moved through the rock and partially dissolved the aragonite of the pisoliths. Then enough burial took place for compactional stress to fracture the cement rims that maintained the outer shapes of the partially dissolved pisoliths, where they were weakest, at grain contacts. This caused the upper rims along a line of grains to shift slightly and collapse into the line of lower rims as far as the remaining aragonite pisolith material would let them, resulting in a chain of crushed pisoliths, as discussed by Conley (1977) from this unit. The cement rim continued to grow as saturated environments moved back through the rock after the succeeding transgression. Final, blocky ferroan calcite and ferroan dolomite filling of remaining voids, and neomorphism of the remaining pisolith aragonite, preserving its concentric lamellar structure, completed the diagenetic pattern in this specimen, probably in the oxygen-depleted deeper connate zone.

Even though these three regressive oolites display dominance of different features, all show a similar succession of diagenetic processes that is reasonably explained by the eustatic depositional-diagenetic model: 1) deposition during regression in shallow water with precipitation, in some, of different thicknesses of early marine cement rims; 2) emergence of the carbonate sediment surface and influx of meteoric water in various amounts and degree of saturation, resulting in different amounts of mixing-zone to meteoric-phreatic cementation and neomorphism, followed by meteoric leaching of the remaining aragonite grains; 3) compactional collapse, in one, at certain weak points of the partly cemented leached-grain framework; 4) resubmergence during the succeeding transgression and return of meteoric through mixing-zone to deeper connate water, resulting in precipitation of different types and amounts of later, progressively more ferroan cements in the remaining voids as O_2 generally decreased with time; 5) reemergence to modern meteoric weathering, which started filling the remaining voids with nonferroan calcite and oxidizing the Fe^{++} in ferroan cements. The latter process is conspicuous in the rusty color of ferric hydroxides on modern exposed ferroan carbonate surfaces.

Variations in effects of these processes in this facies, both within and between cyclothems, relate to paleotopography, facies distribution, patterns of permeability, and to exact chemistry of the local succession of ambient water. The latter two factors were influenced by paleoclimates, the geographic and temporal extent of regression, and the environment of deposition of the overlying nearshore to nonmarine shale, which varied from place to place and from cyclothem to cyclothem.

Transgressive calcilutites.—Calcilutite was deposited below effective wave base in the transgressing sea of nearly every cyclothem. All transgressive calcilutites have been noted as "dense" on outcrop. In thin section, pellets are rare and mostly confined to sheltered void space. Both characteristics suggest that substantial compaction preceded lithification. All transgressive calcilutites are dark colored, which suggests minimal oxidation of organic matter before cementation. Most are relatively thin and well burrowed, and thus spar-filled primary voids exist mainly within skeletal cavities, where the microenvironment may be conducive to cement precipitation in any of the major diagenetic environments. Both micrite and microspar are present in these calcilutites, but no explainable pattern is yet recognized. The pervasive fine-grained ferroan dolomitization of matrix in the tops of several of these calcilutites is related by McHargue and Price (1982) to Mg^{++} availability from the overlying shale. Dense nature, dark color and ferroan mineralization all point to long-term compaction and maintenance of low-oxygen conditions before final cementation, as would be expected in direct movement from the stagnant marine-phreatic to the deeper connate environment, just as with transgressive calcarenites.

From early transgressive calcilutites of the Stanton cyclothem, equivalent in phase to the Benedict and Tyro oolites mentioned previously, Wray (1964) described extremely well preserved red algae, which are neomorphosed to a blocky calcite spar that preserves exquisite detail of original structure. A more recently discovered specimen of green algae provides evidence as to how this neomorphism may have taken place (Fig. 26). The internal algal structures appear confined to what looks like an organic film that partially collapsed away from the upper boundary with the matrix after the original aragonite was at least partly dissolved but before the present calcite was completely precipitated. This indication of substantial void space during neomorphism strongly suggests that perhaps the critical difference between neomorphism and void filling in this example was maintenance of a filmy organic template during the void stage. This idea may or may not apply to other examples of neomorphism (see Saller, 1982; Steinen, 1982). In any case, the abundance of neomorphosed grains in transgressive calcilutites is as consistent as the neomorphosed ooids in transgressive calcarenites with a diagenetic history of moving slowly from the stagnant marine-phreatic into the deeper connate zone, where delicate chemical balances are more likely maintained and where delicate organic films would not be oxidized, or swept away by rapid water movement.

FIG. 26.—Transgressive calcilutite with green alga *Eugonophyllum* showing internal tubules as well as peripheral utricles. Clearer area along left top (x) seems to have been void space remaining after partial falling away of upper part of algal blade from mud matrix. This suggests that internal algal structures were preserved as an organic film that remained after original aragonite was at least partially dissolved but before present blocky calcite was completely precipitated, probably all occurring in low-oxygen connate water. Photo by J. E. Barrick; plane light; scale bar is 0.5 mm. Benedict bed equivalent (basal Stanton cycle) in roadcut west of Neodesha, Kansas.

Of the few transgressive limestones that developed algal mounds, the Captain Creek Member of the Stanton has a widespread spar-rich facies that was described briefly by Ravn and Heckel (1978). In this sparite facies, botryoidal aragonite (Fig. 27) was precipitated early in cavities beneath large algal blades, which collected mud on their tops. This early botryoidal aragonite apparently stabilized the open

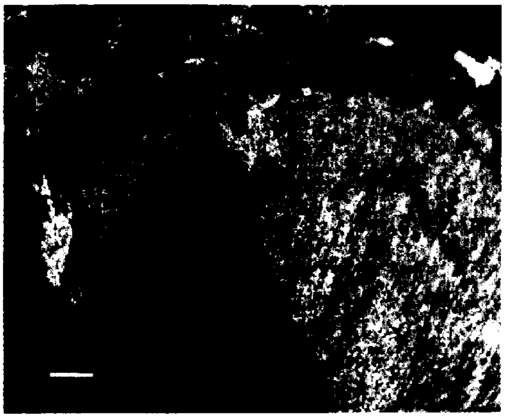

FIG. 27.—Sparite facies in transgressive algal mound showing relict fine radial structure of former aragonite botryoid expanding upward, with former crystal terminations still visible in places along upper edge. Botryoid was neomorphosed to irregular crystals of calcite (different shadings), probably in stagnant marine phreatic to deeper connate water. Plane light, scale bar is 0.5 mm. Captain Creek Limestone (Stanton cycle) in roadcut southeast of Elk City, Kansas.

framework and prevented much compactional loss of original void space (Ravn et al., 1978). Modern botryoidal aragonite is known in buildups where enough water flux is thought to maintain the active precipitating zone of the marine-phreatic environment down to 120 m depth (Ginsburg and James, 1976), which is analogous to the occurrence of the Captain Creek sparite facies at the margin of a transgressive algal buildup. Later diagenesis of the Captain Creek sparite involves some breakage of algal blades, fracturing of coherent overlying mud clasts, collapse of these into remaining void space, neomorphism of the botryoidal aragonite to calcite (Fig. 27) and final filling of the remaining voids with small, blocky to large, strained crystals of calcite. As far as presently determined, these processes could have taken place while the locally rigid, extremely permeable sediment-rock mass was moving from the active marine-phreatic into the deeper connate zone. The early cements, both the conspicuous botryoidal masses and the probable fine intergranular forms in the eventually fractured mud layers, apparently kept this sparite from overcompacting as the other transgressive and offshore deposits did before they underwent any cementation.

Early-middle regressive calcilutites.—Calcilutites deposited in shallowing water up to effective wave base form most of the limestone in most cyclothems. They generally underwent the greatest variation in diagenetic history, depending on intensity of development of meteoric environments during regression and the depth to which these affected the sediment. Lower parts may have gone directly from the marine phreatic into the deeper connate zone as the transgressive limestones did. Middle parts may have been subjected to only the mixing zone or to only the mixing zone and stagnant meteoric-phreatic zone before reversing back into the marine-phreatic and moving into the deeper connate zone. The highest parts of most, however, were probably subjected to the actively precipitating and leaching zones of the meteoric environments as were most of the overlying regressive calcarenites.

Available thin sections reveal a variety of micrite, microspar and pseudospar, and burrowed, pelleted, clotted, dolomitized, and silicified mud fabrics, some illustrated by Harbaugh (1960), Payton (1966), Mossler (1971), Nelson (1978), Mitchell (1981), and McHargue and Price (1982), and most of which are beyond the scope of this report. The dolomite and chert are, to be sure, compatible with the presence of the mixing zone in these calcilutites.

Although most spar fabrics involve algal blades and molluscs consisting of blocky calcite of uncertain origin, a number of the features seen in the overlying regressive calcarenites are present in voids sheltered by skeletal pieces in the algal-mound facies. Early cloudy rims are visible around some sheltered cavities. Leaching of algal blades followed by collapse of fluid sediment (Fig. 28), micrite envelopes, other algal fragments, and "clasts" of overlying mud (Fig. 21) are evident in many of the sheltered cavities. Just as in regressive calcarenites, these cavities are filled by blocky calcite, often starting with conspicuous dogtooth rims, becoming coarser and more ferroan inward, and followed in some cases by coarsely crystalline ferroan dolomite, as illustrated by Mossler (1971, p. 967).

A few algal mounds in the regressive limestones contain sparite facies, in which ghost radial botryoidal structures in irregular blocky calcite probably represent former aragonite early cavity-lining cements. These were described from the Plattsburg limestone by Nelson (1978) and include the "cauliflower algal crusts" illustrated by Harbaugh (1959, p. 308). Sparite zones in several mounds contain, in addition

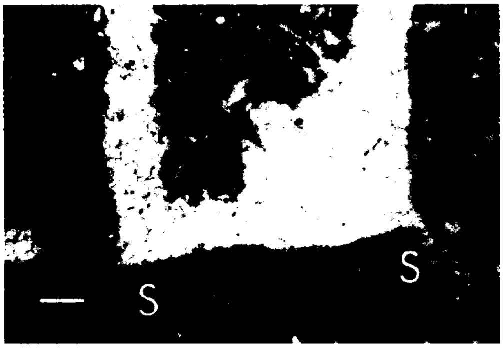

FIG. 28.—Upper regressive sparry algal calcilutite showing molds of two nearly vertical algal baldes that were leached early enough, probably in unsaturated meteoric phreatic zone, that bottoms were filled with geopetal sediment (s) similar to matrix and possibly derived from collapsed area between blade molds. Voids were later filled with blocky calcite, probably as saturated meteoric-phreatic zone moved back through sediment during following transgression. Plane light; scale bar is 0.5 mm. Upper Hertha Limestone in roadcut south of Uniontown, Kansas.

to neomorphosed botryoids, void-filling patches of ferroan dolomite, some of which display ghost geopetal fabrics of small crystals at the base and coarser crystals above (Heckel, 1978, p. 77, pl. 2g; Mitchell, 1981, p. 152–162). These dolomite patches attest to deeper connate water movement through remaining pathways of permeability in the buried mounds, and the conspicuous rusty-weathered patches of this dolomite preserve a spectacular view of the deep "plumbing system" of this facies on outcrop.

A general upward trend in the regressive calcilutite and calcarenite facies is apparent in the Stoner Limestone of the Stanton cycle. Early fibrous cement rims were noted only in the higher calcarenites (Fig. 11), with the thickest rims in the highest samples (Fig. 12). In lower calcarenites (Fig. 15, 20) and in much of the algal-mound facies (Fig. 21), the only early rims are calcite, and there is much more evidence of aragonite-grain leaching and collapse of material into voids. This trend reflects the greater tendency toward early marine cementation in the shallowest water during later regression, and these early marine cements minimized collapse after meteoric leaching of grains. Below the level of early protective cements, however, the greater effects of meteoric leaching and cementation are apparent in the more widespread collapse of unsupported material (including fractured mud "clasts"), and in the pervasive blocky calcite cement, which formed from meteoric water after leaching and collapse but before much more compaction took place, and which preserves the brecciated appearance of the algal-mound facies.

Late-regressive shoreline calcilutites.—Deposits of muddy shorelines, including lagoons and other protected embayments, as well as the familiar tidal-flat laminates with distinctive birdseye-fenestral fabric and mudcracks, are well developed at the tops of regressive limestones in most cycles, particularly higher on the shelf toward the north. These deposits should have undergone the most intense subaerial exposure and meteoric-vadose soil-forming processes of any facies in the cyclothem, and should be the facies most likely affected by evaporitic environments.

Lamination, birdseye vugs, and, less commonly, subpolygonal cracks are typically conspicuous on outcrop, and in a few cases the last two features are filled with overlying shale. Most birdseye vugs are filled with blocky calcite, often following a drusy rim. In some samples, spar-filled small-scale nontectonic fracturing of the muddy matrix often joins birdseye vugs and appears incipient to in-place brecciation. From similar horizons in western Kansas cores, Watney (1980) described well developed in-place brecciation with fitted clasts, clotted-to-laminated texture, circumgranular cracks, "crumbly fractures," fossil-root casts and shale-filled solution cavities. All these features, especially in combination, are regarded as results of subaerial-to-vadose desiccation and leaching.

A bed of "rubbly" limestone capping the regressive Bethany Falls Limestone of the Swope cycle near La Cygne, Kansas, consists of poorly sorted, pelleted to vaguely pisolitic mud "clasts" (Fig. 29). These display circumgranular cracks and irregular accretionary layers around the outsides, which in places join clasts to one another. Irregular fractures join spar-filled cavities, some with geopetal silt layers (Heckel, 1978, p. 77, pl. 2c) and some with early blocky rims in meniscus fabrics. A few clasts contain birdseye vugs and may be the remains of a once continuous tidal carbonate bed. Below the rubbly bed, a crinkly-laminated, siliceous, micrite-to-microsparite crust (Fig. 30) is welded to the eroded top of an oolite. The rubbly bed and laminated crust are interpreted as paleocaliche formed by precipitation of the crust, clast accretionary layers, and meniscus cements in a saturated vadose zone that devel-

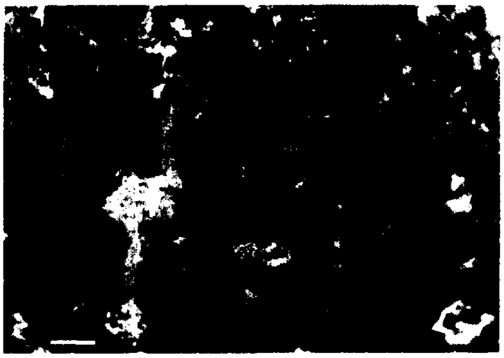

FIG. 29.—Late regressive "rubbly" calcilutite showing poorly sorted pelleted to vaguely pisolitic fabric with circumgranular cracks (white layers) connected to irregular fractures that join cavities, some of which contain possibly vadose carbonate silt (gray). This fabric is characteristic of caliche formed around eroded fragments in meteoric-vadose zone. Plane light, scale bar is 0.5 mm. Capping bed of Bethany Falls Limestone (Swope cycle) in roadcut east of La Cygne, Kansas.

oped after subaerial erosion reduced the tidal bed to clasts and leached the underlying oolite. In support, Schutter (1983) has stratigraphic and mineralogic evidence that the thin, overlying Galesburg Shale is a soil profile throughout this region and northward. Similar crinkly-laminated, micritic-to-vuggy crusts at the tops of regressive limestones in western Kansas cores also probably represent paleocaliche, and are overlain by shales having the characteristics of paleosoils (Watney, 1980). Paleocaliche features, including possible rooting structures (rhizocretions), recently were described by Mitchell (1981) from the top of the Iola Limestone in Iowa and Nebraska cores.

FIG. 30.—Late regressive siliceous (light), micrite (dark) to bladed microsparite (gray) crust, which lies below "rubbly" calcilutite of Fig. 29, above eroded top of regressive oolite (Fig. 19), and is interpreted as laminar caliche horizon, perhaps formed at water table after meteoric cementation of subaerially leached oolite. Plane light; scale bar is 0.5 mm.

Pervasive microcrystalline nonferroan dolomitization was recognized in the capping muddy carbonate shoreline facies in the Iola by Mitchell (1981) and in several subsurface units by Watney (1980). These dolomites are regarded as the result of oxygen-rich schizohaline environments in tidal shorelines, where protodolomite crystals formed initially in Mg-rich brines and became stabilized to dolomite in the mixing zone when meteoric water affected the sediment. In support, dolomitization in a sample of laminated carbonate from the top of the Bethany Falls (Swope cycle) in Iowa is confined to certain fine-grained laminae, which indicates an original close depositional control on the process, and stands in contrast with the more diffuse shale-associated microcrystalline ferroan dolomitization described by McHargue and Price (1982) from offshore calcilutites that went directly from the marine-phreatic to oxygen-poor deeper connate environments.

The only evidence of evaporites reported so far from Midcontinent cyclothems are a calcite pseudomorph after a lath-shaped probable evaporite mineral (Mitchell, 1981, p. 83) in laminated carbonate near the top of the Iola in Nebraska, and anhydrite, both filling voids and replacing dolomite, in upper regressive carbonates in western Kansas cores (Watney, 1980). Evaporitic diagenetic features should become more abundant northwestward in the drier Pennsylvanian climatic belt (Heckel, 1980), where evaporites are reported from the subsurface of western South Dakota.

CONCLUSIONS AND IMPLICATIONS

Although these observations on the rich variety of diagenetic fabrics in Midcontinent Pennsylvanian limestones require further testing with more systematically collected samples and geochemical analyses, they do show that the proposed diagenetic model is a viable, working hypothesis, with the following significant trends and implications:

1. Transgressive and offshore calcarenites show evidence of diagenesis mainly in the deeper-burial connate environment, where cementation took place in low-oxygen water only after enough burial for substantial compaction.

This resulted in conspicuous overpacking, crushing of thin shells, grain-contact welding and stylolitization, and finally ferroan cements. The characteristic dense nature and dark color of transgressive calcilutites are explained similarly by increasing compaction under decreasing oxygen as the sediment moved directly into the deeper connate zone prior to any cementation. Transgressive calcilutites show early spar cements only in organic buildups from a depositional regime like that in which modern organic buildups contain similar botryoidal precipitations.

2. In contrast, a great variety of shallow-zone diagenetic features characterizes the shallow, regressive calcarenites and upper, regressive calcilutites. These features include early marine cements in the topmost beds, resulting in maintenance of a normally packed fabric. They also include evidence of meteoric leaching of unstable aragonite grains, from both early cemented calcarenites and lower, not-yet-cemented calcarenites and calcilutites. Leaching led to local collapse of fluid mud sediment, micrite envelopes, shell fragments, and clasts of coherent mud sediment. Collapsed material was cemented by blocky calcite, mostly in the oxidizing portion of the returning saturated meteoric-phreatic environment, before much more compaction took place. Remaining voids were filled by later ferroan calcite and coarsely crystalline ferroan dolomite in increasingly oxygen-depleted deeper-burial environments.

3. This contrast in diagenetic history between transgressive and regressive limestones is partly responsible for their long obvious differences in density and color on outcrop. Petrographically this contrast is particularly well illustrated in the conspicuous differences between the overpacked, neomorphosed, ferroan-cemented transgressive oolites (Fig. 6, 7) and the normally packed, early cement-rimmed, oomoldic to blocky calcite- and dolomite-filled oocastic regressive oolites (Figs. 19, 23, 24).

4. Meteoric-vadose meniscus and pendent cements, paleocaliche and other evidence of subaerial erosion and soil-forming processes, and also evaporite minerals, are found only in the tops of regressive limestones, particularly toward the north end, which was higher on the shelf. Similar patterns were pointed out by Watney (1980).

5. Lack of extensive marine cements (except in buildup margins), and particularly lack of evidence of meteoric diagenesis or subaerial exposure in transgressive limestones or in calcarenites associated with core shales, form another line of evidence favoring the depositional model of Heckel (1977, 1980) for Pennsylvanian cyclothems and countering the brackish to fresh, shallow-water nearshore interpretation of black core-shale deposition of others (e.g., Zangerl and Richardson, 1963; Merrill, 1975; Merrill & Martin, 1976).

6. The strong evidence of large-scale meteoric diagenesis in many regressive limestones indicates periodic widespread emergence and strongly supports the glacial-eustatic model for deposition of widespread cyclothems. Because this model must apply worldwide to this part of the Pennsylvanian, it seems appropriate for workers in Texas to integrate eustatic changes with the delta-avulsion model that has been extensively applied there, but which must apply only to the shoreline area, and probably was depositionally significant mainly during regressive phases (Heckel, 1980; Malinky and Boardman, 1983). Recognition of eustatic sea-level drops in the Texas sequence may help explain the extensive meteoric diagenesis noted by Dutton (1982) in the distal marine-reworked facies of a succession of Missourian fan-delta sandstones in northwest Texas more readily than the delta model alone.

7. Differences in paleotopography of the depositional surface, amount of sea-level drop, annual rainfall, catchment area, permeability of the sediment, etc., would have controlled the depth that meteoric water penetrated into any part of the cyclothem during maximum regression. Meteoric diagenesis would have extended much deeper on paleotopographic highs into the regressive limestone (explaining the early cemented offshore calcarenite in Figure 10), and possibly in a few areas it may have breached the core shale "seal" and affected the transgressive limestone. Watney (1980) noted that subsurface core shales were affected by meteoric water only higher on the Cambridge Arch. At its northernmost fresh quarry exposure in Iowa, the entire 1.2 m Plattsburg Limestone is cut by red shale-filled fractures, which reflect post-Plattsburg Pennsylvanian leaching and oxidation from the red base of the overlying shale down into the reddened top of the underlying marine shale (B. E. Robinson, pers. commun., 1981). On the

other hand, in topographically low areas, meteoric diagenesis may not have visibly affected even the top of the regressive limestone, if it was barely awash or became overlain by a nearshore marine shale "seal" during regression. Thus distribution of diagenetic patterns in regressive carbonates may be utilized to detect subtle ancient paleotopographic features delineated by partial marine withdrawals.

8. Differences in the amount of marine regression that terminated different cyclothems, and in marine versus nonmarine environments of the overlying shale, would account for widespread diagenetic differences in the homologous regressive facies of the different cyclothems. For example, Payton (1966, p. 581) observed that ooids in the upper Winterset Limestone (Dennis cycle) in Missouri and Iowa are generally neomorphosed, whereas ooids in the upper Bethany Falls Limestone (Swope cycle) are generally leached. This is readily explained by the fact that nearly the entire Galesburg Shale above the Bethany Falls is a soil profile along outcrop (Schutter, 1983), indicating that the sea withdrew from much of the Midcontinent at this time, allowing undersaturated meteoric water into the Bethany Falls; in contrast, the lower Cherryvale Shale above the Winterset is nearshore marine along much of the outcrop, with evidence of weak soil formation only toward the north (Siebels, 1981), suggesting that the upper Winterset may have been affected mainly by stagnant marine to saturated meteoric-phreatic water, which is more conducive to neomorphism. Thus differences in diagenetic patterns between homologous carbonates in different cycles should help in determining such factors as how far the sea withdrew between cycles.

As another example, the black Excello Shale (core shale of lower Fort Scott cyclothem) in Iowa is essentially oxidized in terms of organic geochemistry, whereas the next lower widespread black shale (below the Ardmore Limestone) is unoxidized (J. R. Hatch, pers. commun. 1981). This is readily explained by the swamping of lower Ardmore limestone deposition by marine prodeltaic shale in Iowa, thus protecting the sequence from meteoric diagenesis, whereas the Blackjack Creek Limestone above the Excello is overlain by an underclay-coal sequence, which suggests that precoal meteoric diagenesis probably penetrated the entire Blackjack Creek and affected the black Excello Shale as well.

9. Fossils composed originally of stable calcite tend to be well preserved throughout the sequence (except where surficially corroded in slowly deposited offshore calcarenites). Fossils composed originally of metastable aragonite are best preserved mainly in transgressive limestones, where they underwent slow neomorphism with fair retention of original structure. In contrast, they apparently often dissolved in the cool ambient water of the offshore calcarenites, and they tend to be largely leached out in the upper parts of regressive limestones, where they were affected by undersaturated meteoric water.

Applying the depositional-diagenetic model to plants and soft-bodied animals, which decompose too quickly to be well preserved as fossils, one can predict that rapid burial in transgressive deposits would prevent much seafloor decomposition. Subsequent covering with an impermeable transgressive limestone or offshore shale "seal" would then protect them from the highly oxidizing meteoric diagenesis that typically ravages regressive limestones and nearshore shales soon after deposition. It is in the transgressive portions of two cyclic sequences that two notable, uncommon fossil assemblages are found. The Garnett, Kansas, biota of plants, insects, and vertebrates (Heaton, 1980) occurs in a transgressive channel-filling of Rock Lake Shale into underlying regressive Stoner Limestone (Stanton cycle) and is overlain by later transgressive South Bend Limestone, followed by thick marine to prodeltaic shale.

The famous Mazon Creek, Illinois, biota of plants and soft-bodied animals, occurs in the Francis Creek Shale, a rapidly deposited deltaic complex (Baird and Shabica, 1980), which overlies coal and is overlain (where the sequence is continuous) by a widespread black shale. Although interpreted by some as a shallow-water nearshore deposit, this black shale is probably the offshore deposit of maximum transgression. This makes the Francis Creek Shale a transgressive marine delta (Heckel, 1980, p. 209; Baird and Shabica, 1980), which was sealed off by the overlying anoxic marine shale from meteoric oxidation and leaching until after the fossils became protected by formation of siderite concretions and the muds became compacted and less permeable. (Were the Francis Creek a regressive delta, there would have been less time for compaction to reduce permeability before pervasive penetration by oxidizing meteoric water, which tends to destroy nonmineralized organic remains before concretion formation, as is the general case in regressive deltaic deposits). In support, Baird and Shabica (1980) reported preliminary findings of similar well-preserved fossils in rapidly deposited transgressive shales in other Midcontinent cyclothems.

10. It is becoming increasingly apparent that deciphering the diagenetic history of a rock is critical to understanding the timing and pathways of hydrocarbon migration, and ultimately to predicting present hydrocarbon distribution. I hope that consideration of this depositional-diagenetic model will aid in the efficient exploration and production of hydrocarbons in the subsurface Pennsylvanian rocks that underlie most of the western Midcontinent and that already produce substantial quantities of oil and gas.

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