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Petrology and Paragenesis of the Spring Hill Algal Mound
(Plattsburg Formation, Upper Pennsylvanian)
at Neodesha, Kansas

by

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by

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ABSTRACT

Abrupt thickening of the regressive Spring Hill Limestone member to form a carbonate mound in the Fredonia-Neodesha area is accompanied by greatly increased lithologic and diagenetic diversity compared to offmound facies of the member. Four lithologic units are recognized, in ascending order: 1.) Skeletal-Sponge Calcilutite, 2.) Skeletal-algal Sparry Calcilutite to Sparite, 3.) Spar-Spot Skeletal Calcilutite, and 4.) Skeletal to Oolitic Calcarenite. Units 1 through 3 constitute the "mound facies" and are characterized by abundant, coarse, void-filling cements. These include, in sequential order, botryoidal calcite and needle cement rims, nonferroan calcite mosaic, very coarse ferroan calcite mosaic, and coarse, patchily distributed ferroan dolomite, which may also be replacive in origin. Botryoidal calcite is an abundant first-stage cement in the non-rigid, open, bryozoan-algal "framework" of Unit 2. It is interpreted as recrystallized precursor submarine botryoidal aragonite by virtue of its distinctive, finely radial, needle-like relict structure and high relict strontium content, both of which are observed in modern submarine botryoidal aragonite cements. Unit 3 contains distinctive "spar spots", which are 0.5 to 2.0 mm. irregular

to spherical structures that possess relict internal structure and strontium levels similar to those observed in botryoidal calcite void-filling cements. Spar spots are frequently fractured and occasionally possess poorly developed concentric lamellae. Spar spots have locally acted as depositional clasts, producing grain-supported fabrics that contain early, isopachous cement rims. Analogy with modern aragonite ooids of similar structure and irregular shape, but found only in low-energy hypersaline environments (the Persian Gulf), suggests a quiet to intermittantly agitated depositional environment for these "grains". Their irregular shape and poorly developed concentric lamination suggests that they are a somewhat reworked, syndepositional growth lying in a spectrum of origin somewhere between ooliths and early diagenetic spherulites.

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INTRODUCTION

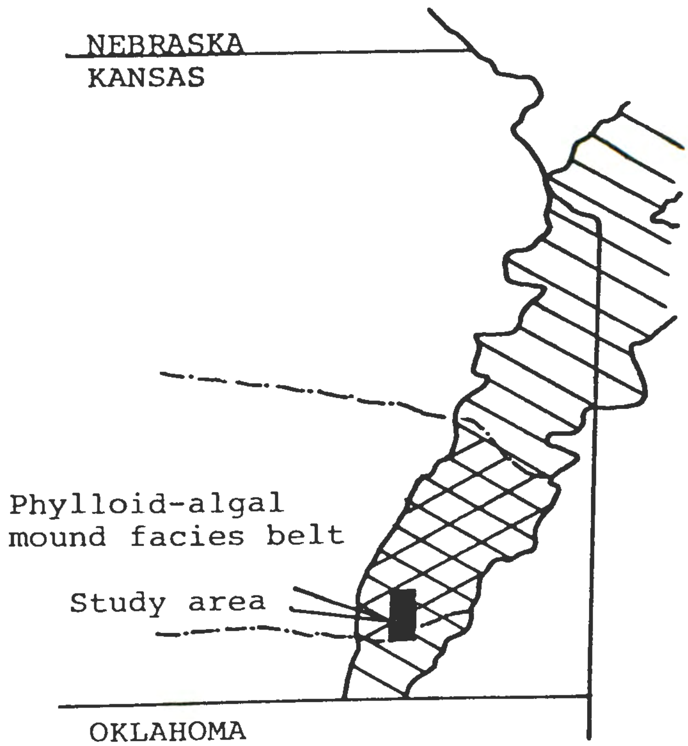
The Plattsburg Formation crops out across east-central Kansas (Figure 1a) as the basal unit of the Lansing Group in the Missourian Stage of the Upper Pennsylvanian Series. The Formation consists of three members, in ascending order: Merriam Limestone, Hickory Creek Shale, and Spring Hill Limestone (Figure 2), which are the transgressive limestone, offshore shale, and regressive limestone members respectively, of a typical Kansas cyclothem (Figure 3).

The subject of this study, the Spring Hill Limestone Member, forms a carbonate buildup in the Fredonia-Neodesha area within the phylloid-algal mound facies belt in south-eastern Kansas. This buildup attains a maximum thickness of approximately 27 meters (90 feet) at the K-96 roadcut, 3 miles southwest of Neodesha, Kansas (Figure 1b). The Spring Hill Mound is the most petrologically complex of all buildups in the phylloid-algal mound facies belt (Heckel, 1978). The most striking aspect of mounded Spring Hill is the large percentage of coarse, sparry calcite which is widespread through the buildup as large void fillings and locally massive sparite zones. Abundant cement-filled voids beneath algal and bryozoan umbrella structures contain several stages of coarse calcite, dolomite, dickite, and rare celestite crystals and attest to the high primary

Figure 1--Location of study area:

A.) Generalized outcrop belt (lined) of Missourian Stage in eastern Kansas showing Spring Hill study area (black rectangle) in phylloid -algal mound facies belt (cross hatched), (modified from Heckel and Baesemann, 1975, figure 3).

B.) Sample localities for Spring Hill Member within study area (modified from Harbaugh et. al., 1965, figure 21).



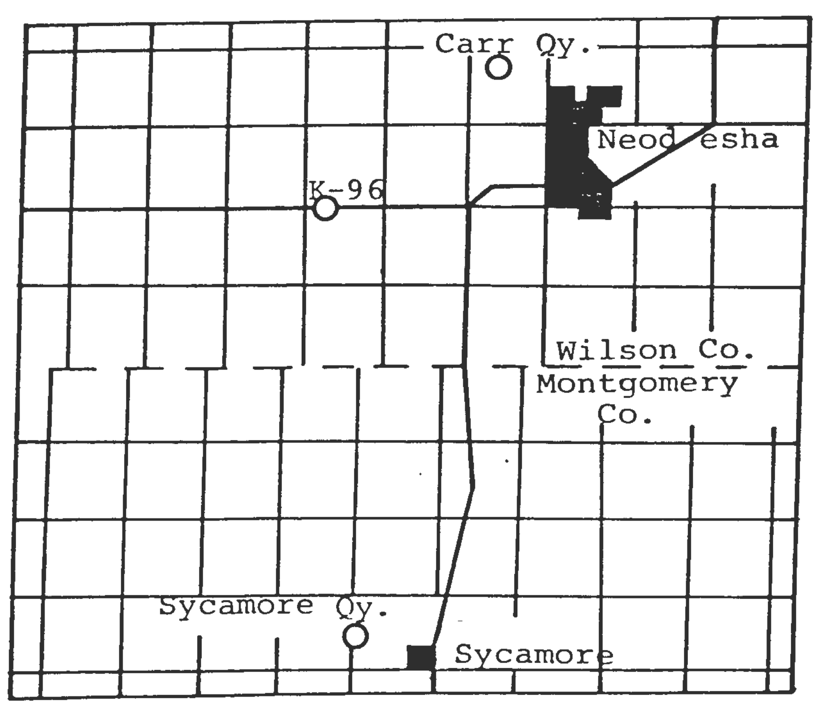


Figure 1 (A-upper, B-lower)

Figure 2--Stratigraphic distribution of mound-forming units in Lansing and Kansas City Groups. Plattsburg Formation at base of Lansing Group forms a carbonate buildup in Fredonia-Neodesha area (modified from Heckel and Cocke, 1969 figure 1).

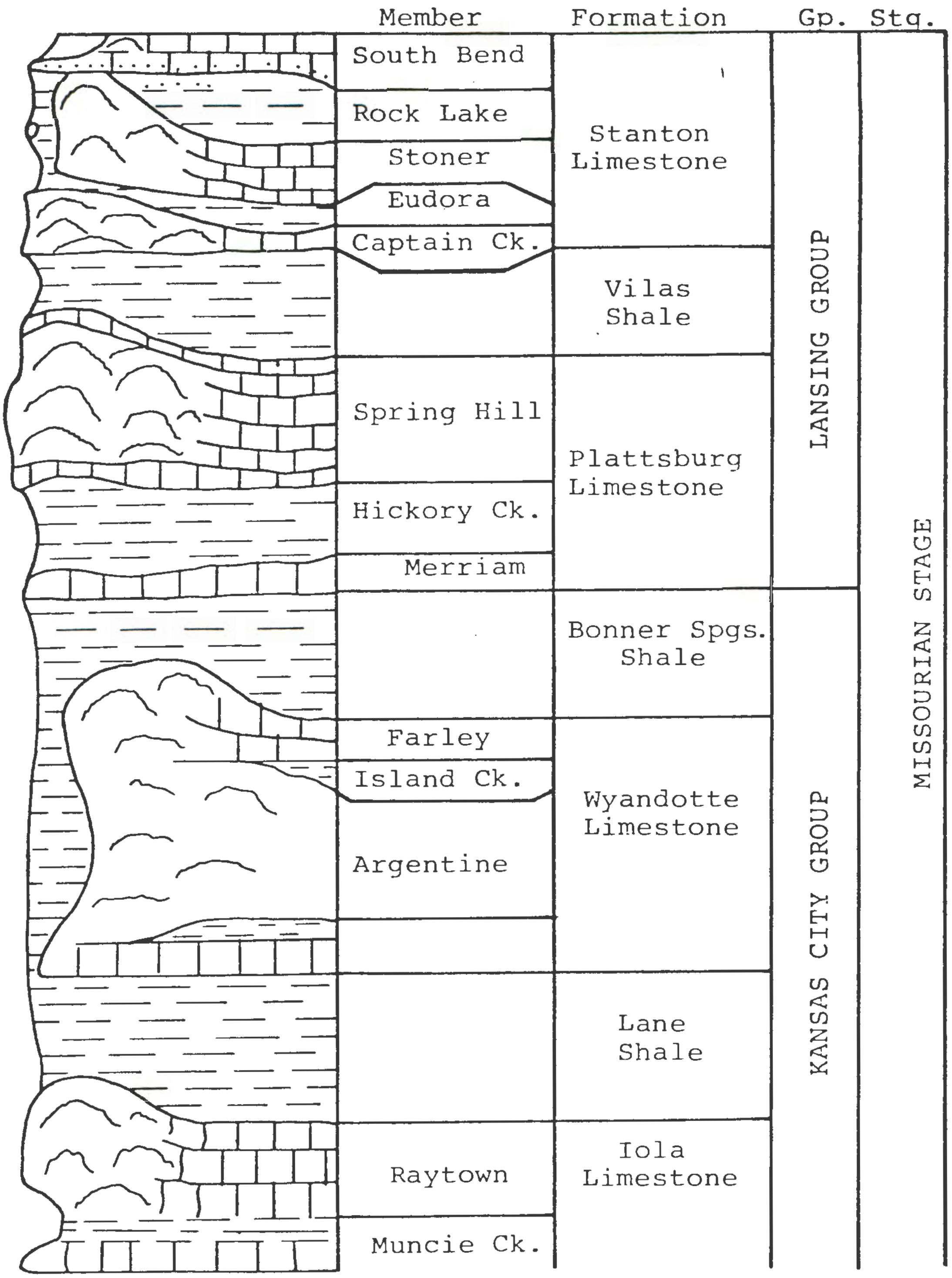
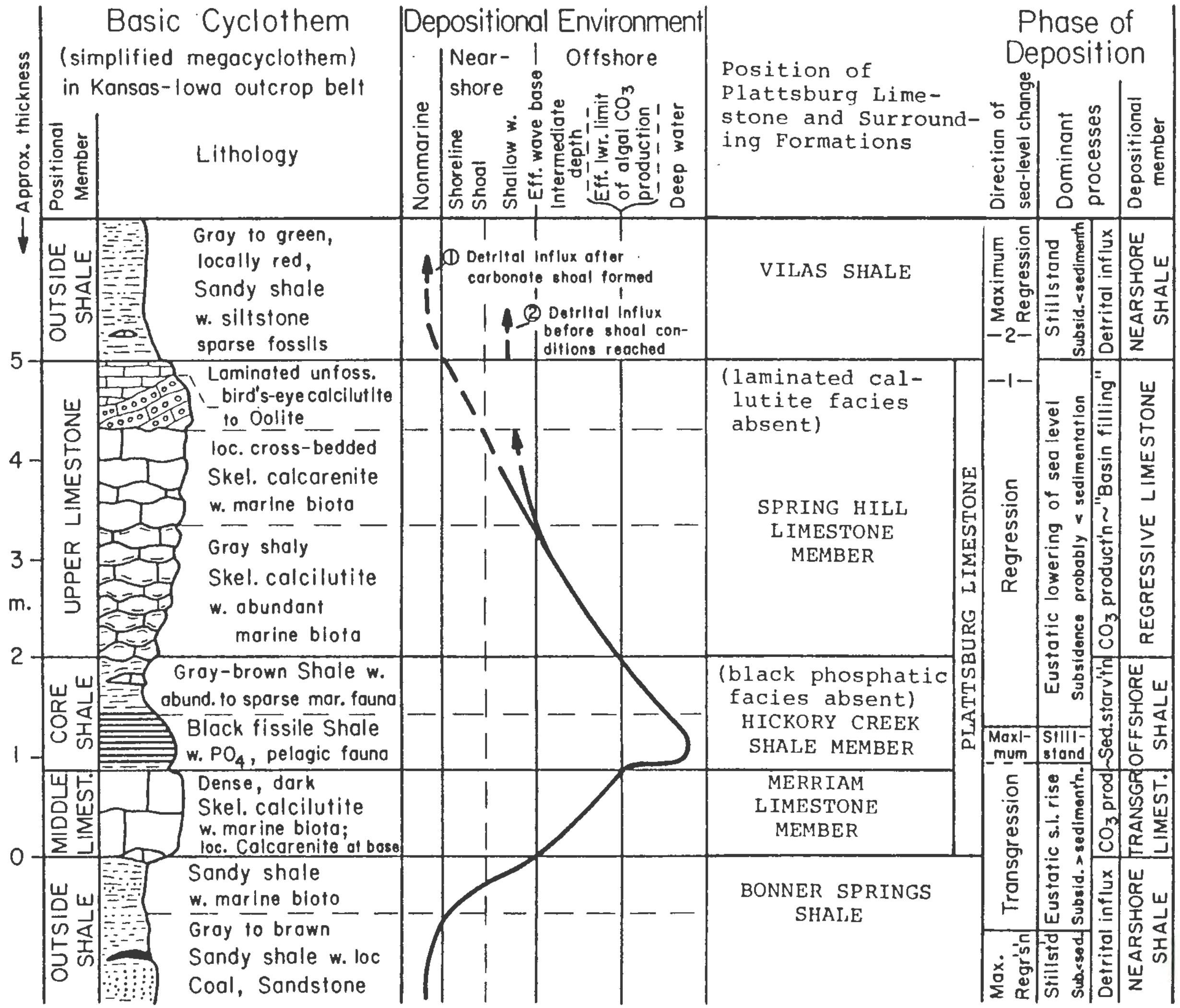

Member
Formation
Gp.
Stg.
South Bend
Rock Lake
Stoner
Eudora
Captain Ck.
Stanton Limestone
Vilas Shale
Spring Hill
Hickory Ck.
Merriam
Plattsburg Limestone
LANSING GROUP
Bonner Spgs. Shale
Farley
Island Ck.
Argentine
Wyandotte Limestone
Lane Shale
Raytown
Muncie Ck.
Iola Limestone
KANSAS CITY GROUP
MISSOURIAN STAGE

Figure 2

Figure 3--Idealized typical Kansas cyclothem (modified from Heckel, 1977 figure 2).

Figure 3



Basic Cyclothem
(simplified megacyclothem) in Kansas-Iowa outcrop belt
Approx. thickness
Positional Member
Lithology
Depositional Environment
Nonmarine
Near-shore
Shoreline
Shoal
Shallow w.
Eff. wave base
Offshore
Intermediate depth
Eff. lwr. limit of algal CO3 production
Deep water
Position of Plattsburg Limestone and Surrounding Formations
Phase of Deposition
Direction of sea-level change
Dominant processes
Depositional member
OUTSIDE SHALE
Gray to green, locally red, Sandy shale w. siltstone sparse fossils
① Detrital influx after carbonate shoal formed
② Detrital influx before shoal conditions reached
VILAS SHALE
Maximum Regression
Stillstand
Subsid.<sedimentn
Detrital influx
NEARSHORE SHALE
5
UPPER LIMESTONE
Laminated unfoss. bird's-eye calcilutite to Oolite
loc. cross-bedded Skel. calcarenite w. marine biota
4
Gray shaly Skel. calcilutite w. abundant marine biota
3
m.
(laminated calcilutite facies absent)
SPRING HILL LIMESTONE MEMBER
PLATTSBURG LIMESTONE
Regression
Eustatic lowering of sea level
Subsidence probably < sedimentation
CO3 product'n ~"Basin filling"
REGRESSIVE LIMESTONE
2
CORE SHALE
Gray-brown Shale w. abund. to sparse mar. fauna
Black fissile Shale w. PO4, pelagic fauna
(black phosphatic facies absent)
HICKORY CREEK SHALE MEMBER
Maximum
Stillstand
Sed.starv'n
OFFSHORE SHALE
1
MIDDLE LIMEST.
Dense, dark Skel. calcilutite w. marine biota; loc. Calcarenite at base
MERRIAM LIMESTONE MEMBER
Transgression
Eustatic s.l. rise
Subsid.>sedimentn.
CO3 prod
TRANSGR LIMEST.
0
OUTSIDE SHALE
Sandy shale w. marine bioto
Gray to brawn Sandy shale w. loc Coal, Sandstone
BONNER SPRINGS SHALE
Max. Regr'sn
Stillstd
Sub.<sed.
Detrital influx
NEARSHORE SHALE

porosity of this carbonate buildup. The Spring Hill Member is also characterized by numerous, poorly understood, complex diagenetic fabrics, the most distinctive of which consists of enigmatic radially structured "spar spots" of questionable origin.

Previous Work

Unpublished work by Newell (1933, *fide* Harbaugh, 1959) was the first documentation of anomalous thickening in the Plattsburg Formation near Neodesha. Subsequent work by Wagner and Harris (1953), and Harris (1954) culminated in publication of Geology of the Fredonia Quadrangle, which delineated the known outcrop areas of the Plattsburg and other units. Davis (1959) presented cross sections through the Plattsburg, and he interpreted the thickened limestone of the Plattsburg and overlying Stanton as barrier reef deposits.

Harbaugh (1959) delineated areal extent and thickness variations in the Plattsburg Limestone and noted thickening from an average of 20 feet in the offmound facies, to a maximum value of 115 feet in the mound facies. At the site of maximum thickness, which he interpreted as a "marine bank" rather than a barrier reef, the Spring Hill Member increased to 88 feet, whereas the Hickory Creek Shale Member increased to 45 feet; little change was noted in the Merriam Limestone Member.

Harbaugh (1960) studied marine bank development in 3 Lansing Group Limestones: the Spring Hill Member of the Plattsburg Formation, and the Stoner and Captain Creek Members of the Stanton Formation (Figure 2), with primary emphasis on the Spring Hill. This study delineated 6 carbonate lithologic varieties, 6 modes of porosity development, and, following petrographic criteria summarized by Bathurst (1959), he recognized two genetic types of crystalline calcite mosaic; void-filling and recrystallized. Harbaugh (1961) recognized 4 types of visibly crystalline calcite in the Lansing Group using some of his observations on Spring Hill fabrics to develop his ideas. Guidebook publications by Harbaugh and others (1962 and 1965) on marine bank limestones of southeastern Kansas contain syntheses of earlier publications on the Plattsburg.

Schroeder and Hayes (1967) studied the widespread occurrence of late-stage kaolinite and dickite void-fillings in Lansing Group algal limestones and related it to Tertiary intrusive activity adjacent to the Phylloid-algal mound facies belt.

Kettenbrink and Manger (1971) studied the external distortion of pisoliths within the offmound facies of the Plattsburg and related it to post-depositional modification of pisoliths in a plastic state prior to cementation. The most recent petrographic work on the Plattsburg Formation is a study by Conley (1977) on the origin of the same distorted pisoliths and ooliths. He found that the grains in this facies have been cemented by a complex sequence of cements found most straightforwardly developed within a large brachiopod, with stages of dissolution accounting for most observed distortion.

Purpose and Scope

It is only within the last 10-15 years that much energy has been directed toward understanding carbonate rocks and their diagenesis. Excellent reviews on the topic by Bathurst (1975) and Milliman (1974) have attempted to consolidate (and reconcile) theoretical and observed characteristics of carbonate systems. Environmental interpretation of carbonate rocks poses a unique challenge. Although contained fossils and sedimentary structures give the geologist indications of the paleoecologic and paleo-environmental parameters of a particular unit, the extreme susceptability of carbonate minerals to post-depositional modification often obliterates much of this direct evidence, making diagenetic reconstruction prerequisite to correct enviromental interpretation of some units.

In recent years, numerous papers have been written furthering our understanding of the complex geochemical and depositional aspects of this group of rocks. Carbonate literature is currently growing at an accelerated rate, with many of the more recent papers displaying a strong geochemical emphasis (e.g. Folk, 1974; Badiozamani et. al., 1977; Viezer, 1977; and Davies, 1977; to name but a few). It is the intent of this study to describe and interpret the diagenetic fabrics of the Spring Hill Limestone in light of recent advances in the understanding of carbonate diagenesis, geochemistry, and depositional environments. The specific objectives of this study are as follows:

1.) Present a detailed petrographic description of lithic units recognized within the Plattsburg buildup.
2.) Interpret and describe the diagenetic processes leading to the observed fabrics and establish a paragenetic sequence and to compare this with the sequence interpreted by Conley (1977) in the offmound facies.
3.) Delineate depositional facies within the mound complex and determine their relationship to patterns of diagenesis.
4.) Quantify geochemical trace element trends and attempt to correlate these to inferred original mineralogy, fabric, and environment.

Methods

Four weeks of field work subsidized by the Kansas State Geologic Survey were conducted during the summer and fall of 1977. Approximately 200 samples were collected from 3 outcrop locations (Figure 1b). The most detailed sampling (6-inch and 1-foot intervals) was accomplished at the K-96 roadcut. This 90-foot section represents the most complete exposure through the carbonate mound. Carr's and Sycamore quarries were sampled in less detail (1-foot and greater intervals) because the exposures are incomplete.

Specimens were slabbed and sprayed with acrylic lacquer for hand specimen observation. About 225 thin sections were prepared and stained following the methods of Dickson (1966). Thin section chips were sprayed and stained to aid in correlating features between hand specimen slabs and thin section. Quantitative trace element geochemistry of cement fabrics was obtained using an A.R.L. Electron Microprobe Analyzer; strontium was the element of primary interest.

Lithologic classification is that of a modified Grabau (1904) for megascopic description and Folk (1959) for petrographic description; some framework concepts and associated lithologic names from the Dunham (1962) system are also employed throughout the text.

STRATIGRAPHY

The Plattsburg Formation is the lower of two dominantly limestone formations in the Lansing Group of the Missourian Stage (Upper Pennsylvanian). The Plattsburg is separated from the upper limestone unit, the Stanton Formation, by the Vilas Shale. The Vilas is locally observed to interfinger with the upper portions of thickened Plattsburg; thus the two units are partial time correlatives of each other (Harbaugh, 1959). The Plattsburg Formation was divided into three members by Newell (1932), in ascending order: Merriam Limestone, Hickory Creek Shale, and Spring Hill Limestone.

Merriam Limestone Member

This member is a generally thin and relatively continuous transgressive limestone typical of Kansas cyclic deposits (Heckel, 1977). Thickness ranges from several inches up to ten feet locally (Moore et. al., 1951). Two lithologic divisions were noted by Newell (1932): 1.) a richly fossiliferous lower division up to 5 feet thick, dominated by brachiopods and pelecypods and containing common osagia zones that are locally oolitic, 2.) a poorly fossiliferous upper division, averaging 1 foot thick, is characterized by abundant clay-filled burrows in the top.

In the Neodesha-Fredonia area Harbaugh (1959) reports a thickness of 1 to 3 feet and a sponge-rich fauna for this member.

Hickory Creek Shale Member

The Hickory Creek Shale is a typical core shale of a Kansas cyclothem except for the absence of the phosphatic black shale facies and the presence of anomalous thickening in the Neodesha-Fredonia area (Heckel, 1977). Where thin, it carries abundant conodonts (Heckel and Baesemann, 1975); where thick, it is a locally carbonaceous, dominantly clay-shale containing abundant crinoids, sponges, and other invertebrates, and locally carrying interbedded limestones of variable thickness (Harbaugh, 1959).

Spring Hill Limestone Member

This member constitutes the main thickness of the Plattsburg Formation, especially where the Plattsburg is anomalously thick. In the open marine facies belt (Heckel, 1977) in northeast Kansas, the Spring Hill Member consists of 2 lithologic divisions (Newell, 1932): a thinly bedded lower unit averages 5 feet thick and is characterized by an orthid and spiriferid brachiopod-dominated fauna; the upper division, averaging 7 feet thick, consists of fossiliferous oolite and argillaceous limestone.

Thickened occurrences of this member in the Neodesha-

Fredonia area display increased lithologic complexity. Nevertheless, the lithologic succession in both northeast and southeast Kansas displays typical regressive characteristics. Lower units are dominantly calcilutite, containing abundant articulated fossils indicating quiet-water deposition; the uppermost units are either cross-bedded, grain-abraded calcarenite or oolite, reflecting turbulent shoal-water deposition.

SPRING HILL LITHOLOGIES NEAR NEODESHA

Four lithologic units can be recognized within the Spring Hill Member in the vicintity of Neodesha, Kansas, in ascending order:

Unit 1.) Skeletal-Sponge Calcilutite

Unit 2.) Skeletal-Algal-Sparry Calcilutite to Sparite (with abundant, coarse, void-filling, ferroan dolomite).

Unit 3.) Spar-Spot Skeletal Calcilutite (locally argillaceous and containing interbedded shales).

Unit 4.) Skeletal to Oolitic Calcarenite.

Contacts between the units are not clear except between units 3 and 4, which are separated by a thin shale. The contact between units 1 and 2 is not exposed at K-96 but is reported by Harbaugh (1959) to be indistinct at other exposures. Units 2 and 3 are similar, but differences in bedding style and fabrics are obvious; the contact between these units may be gradational over several feet, or it may be quite indistinct. Figure 4 illustrates the four units as observed at the K-96 roadcut.

Skeletal-Sponge Calcilutite (Unit 1)

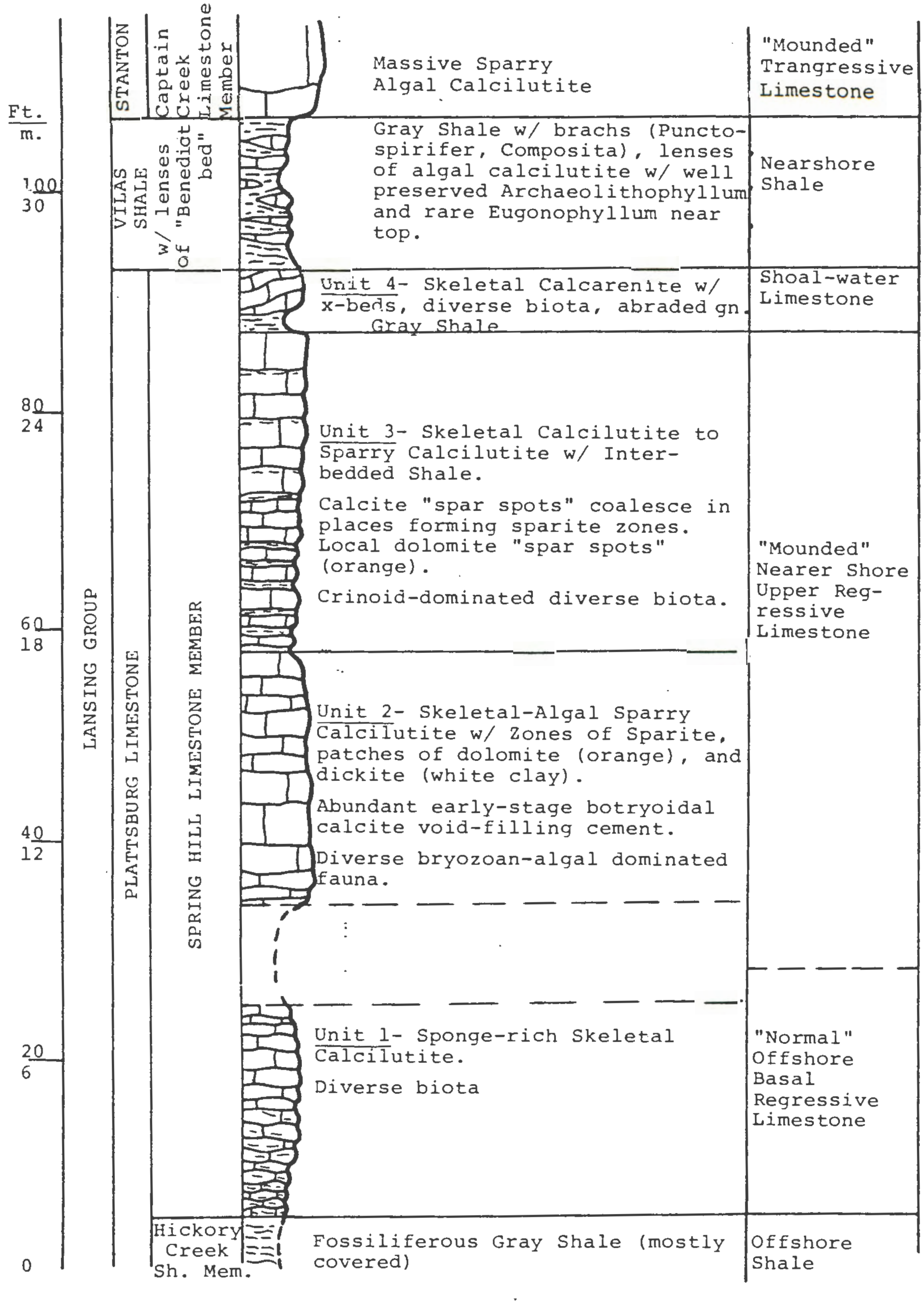
Rusty-orange to grey weathering, dense sponge-rich calcilutite constitutes the basal 21 feet of exposure at the K-96 roadcut. This unit is equivalent to Harbaugh's (1959) fragmental-pellet subdivision, which he reports observing at Sycamore and Carr's quarries as well as at the K-96 roadcut.

Discontinuous, wavy 2 to 10-inch-thick beds often are highly weathered to yield rubbly, fossil-rich bedding surfaces. Near the top of this unit, bedding surfaces are almost completely covered with assorted fossil debris; dominant constituents include crinoid stem segments up to 8 inches long, small sponge tubes, and nearly intact bryozoan fronds, some in apparent growth position. Brachiopods of several genera are common, frequently with both valves intact and articulated; the valves occasionally contain complex sequences of void-filling carbonates. Large heliosponges are present near the base of the exposure and smaller tubular and other sponges are present throughout the unit. Sponge skeletons are invariably altered to dark-brown sparry calcite. Although there is little recognizable algal material throughout most of the exposure of this unit, several local concentrations were noted.

Skeletal-Algal-Sparry Calcilutite to Sparite (Unit 2)

Twenty-six feet of medium to thick bedded (0.2-2.0 ft.) sparry-algal calcilutite overlies Unit 1, from which it is separated by a covered interval. Unit 2 is present at all 3 outcrop localities and is equivalent to the lower

Figure 4--Lithologic succession of Plattsburg and overlying Vilas and Stanton Formations at K-96 roadcut, 3 miles southwest of Neodesha, Kansas. Four lithologic units are recognized within Plattsburg Formation at this exposure.



Ft.
m.
100
30
80
24
60
18
40
12
20
6
0
LANSING GROUP
STANTON
Captain Creek Limestone Member
VILAS SHALE
w/ lenses of "Benedict" bed"
PLATTSBURG LIMESTONE
SPRING HILL LIMESTONE MEMBER
Hickory Creek Sh. Mem.
Massive Sparry Algal Calcilutite
Gray Shale w/ brachs (Puncto-spirifer, Composita), lenses of algal calcilutite w/ well preserved Archaeolithophyllum and rare Eugonophyllum near top.
Unit 4- Skeletal Calcarenite w/ x-beds, diverse biota, abraded gn.
Gray Shale
Unit 3- Skeletal Calcilutite to Sparry Calcilutite w/ Inter-bedded Shale.
Calcite "spar spots" coalesce in places forming sparite zones. Local dolomite "spar spots" (orange).
Crinoid-dominated diverse biota.
Unit 2- Skeletal-Algal Sparry Calcilutite w/ Zones of Sparite, patches of dolomite (orange), and dickite (white clay).
Abundant early-stage botryoidal calcite void-filling cement.
Diverse bryozoan-algal dominated fauna.
Unit 1- Sponge-rich Skeletal Calcilutite.
Diverse biota
Fossiliferous Gray Shale (mostly covered)
"Mounded" Trangressive Limestone
Nearshore Shale
Shoal-water Limestone
"Mounded" Nearer Shore Upper Reg-ressive Limestone
"Normal" Offshore Basal Regressive Limestone
Offshore Shale

Figure 4

part of Harbaugh's (1959) crystalline limestone subdivision. The lower 6 feet consists of thick, massive beds ranging from 0.8 to 2.0 feet thick; above this, medium bedding dominates. Unit 2 is abundantly fossiliferous with crinoids, bryozoans, algae, and brachiopods in approximate order of decreasing abundance. The Unit is characterized by an extremely high percentage of largely cement-filled primary voids, created by bryozoan and phylloid algal umbrella structures; most of these voids are now occupied by multi-generation calcite and dolomite cements, internal sediments, dickite, and rare celestite. In localized areas, void-filling and recrystallization have combined, producing a nearly pure sparite lithology. Successive generations of cement can be distinguished by color variations in outcrop; milky calcite spar is usually followed by coarser clear spar; coarse, dark-brown calcite spar, orange-weathering ferroan dolomite, and white powdery dickite are common late-stage void fillings.

Spar-Spot Skeletal Calcilutite (Unit 3)

Unit 2 is overlain by 23 feet of medium to thick bedded (0.1 to 1.0 ft.), dense, tan to grey skeletal calcilutite with interbeds of shale; the limestone is locally argillaceous. Interbedded shales range from 1 to 4 inches thick and are often the sites of fossil accumulations. The transition between Units 2 and 3 is not sharp, but coincides with the first appearance of interbedded shales. Bedding in Unit 3 is more distinct and laterally continuous than is that of the more massive and crumbly underlying Unit 2. Unit 3 is equivalent to the upper part of Harbaugh's (1959) crystalline limestone subdivision. The most conspicuous fossils in the unit are crinoid ossicles, which commonly occur as long, articulated stem segments, brachiopods, bryozoans, and algae. Unique to this unit are abundant "spar spots", dark-brown sparry calcite spherules, locally coalescing to form subparallel sparite zones. Hematite staining and late-stage dickite void filling are also common. Dolomite void filling is present but only locally near the top is it as abundant as in the underlying unit. Unit 3 is present at all three sample localties but interbedded shales are best developed at the K-96 roadcut.

Skeletal to Oolitic Calcarenite (Unit 4)

Four feet of cross-bedded calcarenite caps the Plattsburg sequence at the K-96 roadcut, and is separated from underlying Unit 3 by a 1-foot-thick shale. This unit is equivalent to Harbaugh's (1959) calcarenite subdivision. At the K-96 roadcut Unit 4 consists of thick (0.8 to 1.2 ft.), dense beds extremely rich in fusulinids. Other common skeletal constituents include crinoids, bryozoans, brachiopods, pelecypods, and rare corals. Subparallel lineation of elongate skeletal grains is common. Low angle cross-beds are visible, dipping to the southwest. Dolomite is fairly abundant, often occurring as elongate zones resembling pelecypod casts.

An oolitic facies of this unit is present at the Carr's Quarry exposure, resting directly upon an irregular surface of Unit 3. The oolitic facies is highly weathered, forming a small-scale karst surface. Vadose dissolution has been very active as indicated by abundant oomoldic porosity. Several types of solution voids are well developed, usually completely or partially filled by multigeneration calcite cement. Hematite cement is also well developed in parts of this facies. The top of the oolite is characterized by an interesting ooid-algal lithology with complex void filling and what appears to be caliche development. The uppermost erosion surface of oolite at Carr's Quarry coincides with the Plattsburg-Vilas Shale contact; although the Vilas has mostly been eroded away, remnant patches are still preserved.

PETROLOGY OF SPRING HILL LITHIC UNITS

Skeletal-Sponge Calcilutite (Unit 1)

In hand specimen this lithology displays a dense mud-supported fabric rich in skeletal grains and sparry calcite. Color is highly variable, ranging from various shades of grey on fresh surfaces, to rusty-orange and yellow on highly weathered surfaces. Susceptibility to weathering of various rock components is variable. Weathering is most commonly expressed by oxidation of Fe-bearing carbonate minerals. Controls on selective oxidation and dissolution are related to the distribution of Fe-rich carbonates as well as inhomogeneity of permeability distribution, possibly due to infaunal burrowing. Pervasive small-scale color mottling, unrelated to weathering, results from abundant fragmented skeletal grains and the irregular, spotty distribution of sparry calcite in the matrix. Skeletal components are abundant and diverse, dominated by bryozoans, sponges, and crinoids with lesser amounts of algae, brachiopods, ostracodes, molluscs, and corals.

Thin section examination reveals a dominantly mud-support framework (often pervasively recrystallized) containing abundant skeletal grains and sparry calcite. The most typical fabric is characterized by a highly fragmental texture due to the cuts through numerous small sponges, disarticulation of crinoid stems, and fragmentation of bryozoan fronds (Figure 5a). Evidence of grain abrasion, however, is generally absent, and preservation of many delicate bryozoans and long, articulated crinoid stem segments intact attests to the lack of water agitation (Figure 5b).

The distribution of micritic matrix as irregular patches separated by skeletal grains and sparry calcite, imparts a mottled aspect in thin section (Figures 5a & c). The irregular mottled aspect is in part due to the abundance of what appear to be microspar-filled burrows (Figure 5c). Micritic patches are massive or, more commonly, consist of indistinct pellets (Figures 5c & 6b). Discrete pellets are fairly common (Figure 5d), and many of these may be of fecal origin. The pelleted aspect of much of the micritic matrix is accentuated by the presence of abundant Fe-oxide spots, which may be misidentified as pellets under transmitted light; observation under reflected light readily distinguishes these spots from pellets. Much of what was deposited as micrite has been recrystallized to microspar, especially that which occurs as internal sediment in sponge cloaca and in what appear to be small, irregular burrows (Figure 5c).

Depositional porosity has been greatly reduced by cementation yielding a dense fabric of low porosity common

Figure 5--Fabric of skeletal-sponge calcilutite. Bar in lower right hand corner is 0.5mm. long.

A.) Typical fragmental aspect of skeletal-sponge calcilutite. Skeletal constituents are dominated by bryozoans (B), sponge (S), and crinoid columnals (C). Matrix is dominantly microspar containing abundant micrite clots or patches.

B.) Excellent preservation of delicate fenestellid bryozoan. Note abundance of small and intermediate-sized sponges with spar-filled cloaca. Cloaca of small sponges across top of photo are filled with ferroan calcite. Walls of large sponges are altered to ferroan calcite and material between wall and cloaca is calcite.

C.) Abundant sponges in matrix rich in micrite and microspar, which appears to be localized in possible burrows. Internal geopetal sediment is recrystallized to microspar. Faint, indistinct pellets are present in dark micrite clots.

D.) Discrete pellets of possible fecal origin within a microspar matrix. Note interpenetrating dolomite rhombohedra (R) within bryozoan-encrusted sponge.

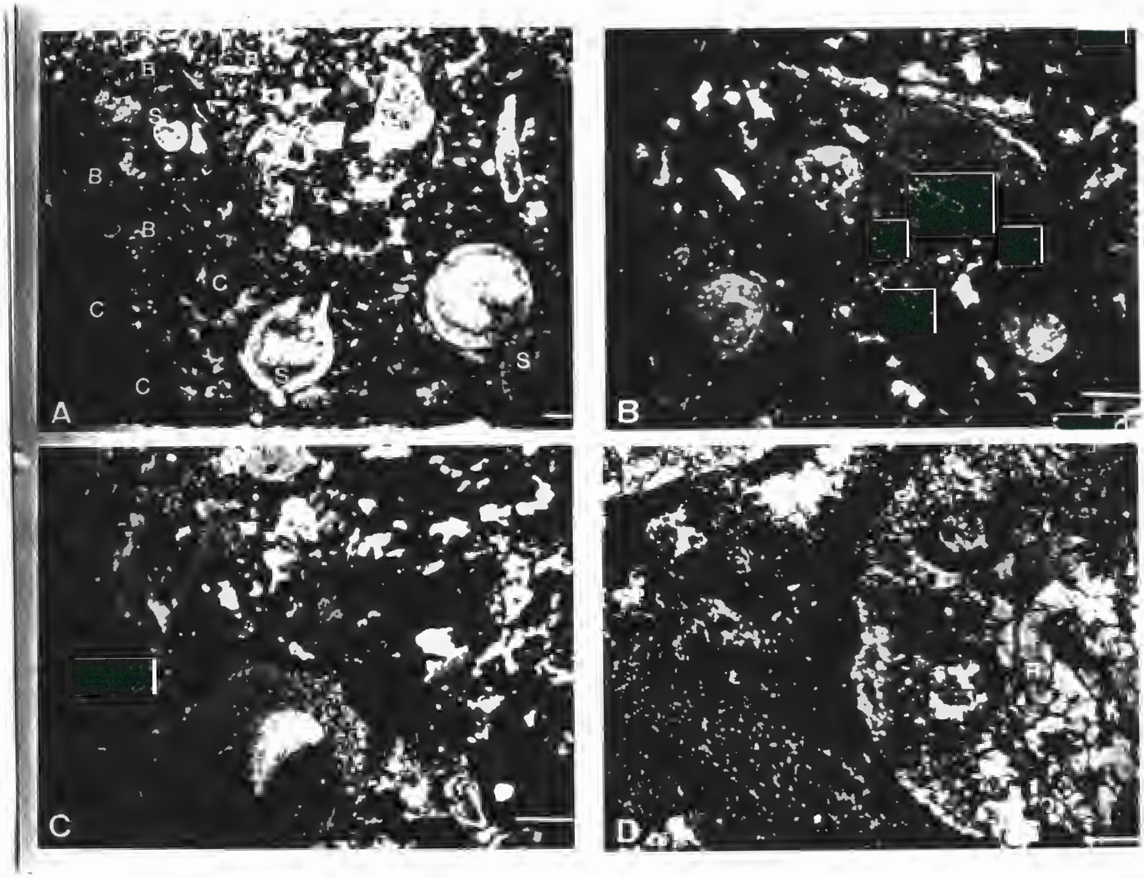


Figure 5

in many ancient calcilutites (Pray, 1960). Cement stratigraphy of intra- and interparticle voids may be simple (one generation), or complex (multi-generation). Complex cementation is the more common of the two types. Common cement minerals in Unit 1 include calcite and dolomite, both highly variable in iron content, and celestite.

Simple cementation is well developed in some large primary voids, especially in umbrella and geopetal structures (Figure 6a). This cement is demonstrably void-filling as it displays the following fabric criteria of Bathurst (1975, p. 417-418):

1.) Spar occupies the upper part of a cavity partially filled with internal (geopetal) sediment.
2.) The contacts between spar and particles are sharp.
3.) Coincidence of sparry calcite margins with the once free surfaces of skeletal grains (as in umbrella structures).
4.) The sparry mosaic possesses plane intercrystalline (compromise) boundaries.
5.) The optic or longest axis is preferentially oriented perpendicular to the original substrate (drusy fabric) and crystal size increases away from the initial substrate.
6.) The sparry mosaic consists of clear crystals lacking relict structures or abundant, minute inclusions (from general observation).

Figure 6--Cement fabrics in skeletal-sponge calcilutite. Bar in lower right hand corner is 0.5mm. long.

A.) Monomineralic drusy void filling of brachiopod shell. Cement has nucleated on and grown perpendicular to the shell substrate. Size of calcite blades increases rapidly away from the substrate, culminating in large, equant spar crystal in the center.

B.) Blocky calcite void-filling mosaic (B) between pelleted, clotted micrite (M) and sponges (S); isopachous first generation needle rim cement lines a void (V).

C.) Isopachous rim of tiny acicular calcite crystals is followed by final void filling of probable sponge cavity by 2 large crystals of calcite.

D.) Former acicular isopachous rim preserved as grey ghost outlining complex former void space. Rim has been incorporated in nearly complete optical continuity within a blocky calcite mosaic.

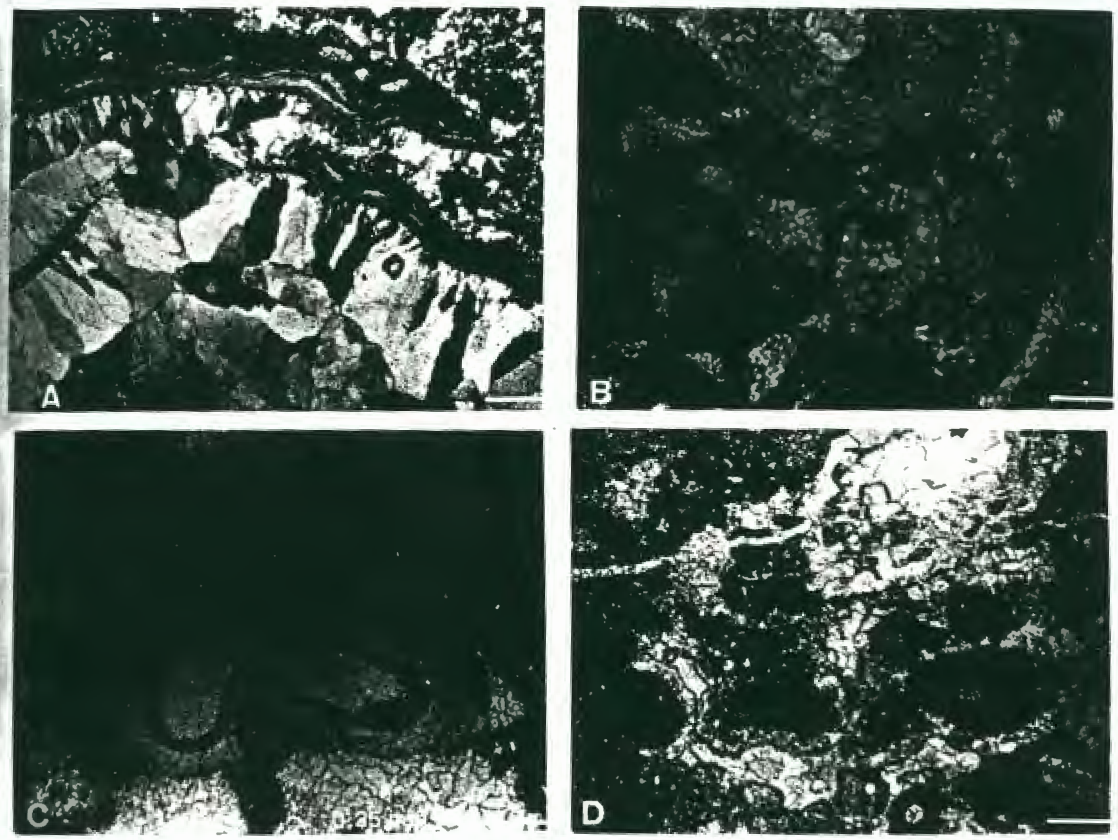


Figure 6

Figure 6a displays an ideal example of monomineralic cementation displaying the 6 criteria mentioned above. Often, it is difficult to distinguish successive generations of cements, and one could argue that Figure 6a represents a 2-stage monomineralic cement composed of an early drusy rim followed by large, equant crystals.

For the purpose of this study, complex cementation is defined as the presence of more than one definite stage of cement as distinguished by the presence of more than one mineral, or, distinctly different morphologies of monomineralic void-filling crystals. Complex cementation is widespread in Unit 1. The presence of more than one generation of cement is among the most unequivocal fabric criteria in support of a void filling origin for sparry calcite (Bathurst, 1975 p. 421).

The most common multi-generation cement sequence begins with an early-stage iospachous acicular rim cement lining intra- and interparticle voids, followed by blocky sparry calcite (Figures 6b & c). The early acicular cement consists now of either ferroan or nonferroan calcite, and is frequently incorporated (sometimes in optical continuity) within the later stage blocky calcite spar (Figure 6d); in these cases, the early rim cement is still readily identifiable as a ghost rim outlining primary void spaces.

Substrate control of cement fabrics is well developed with crinoid ossicles and ostracode shells. The prismatic shell structure of the ostracode shell provides an ideal crystal orientation perpendicular to the substrate, which promotes optical alignment or epitaxy of secondary cements. Quite often, early acicular cements are recrystallized and included in optical continuity within later stage calcite void fill (Figure 7a). Syntaxial overgrowths are generally well developed on crinoid ossicles. The overgrowth either fills pore space adjacent to the columnal, or grows by recrystallization of adjacent micrite. Syntaxial enlargement of crinoid columnals is a widespread observation in ancient carbonates (Evamy and Shearman, 1965). An interesting variation of normal epitaxial overgrowth is illustrated in Figure 7b where the expected epitaxial cementation of the internal void is interrupted by an early rim of acicular cement, which displays an optic axis orientation at 45 degrees to that of the columnals and its void fill. This suggests rapid crystallization of the early rim, perhaps as aragonite, to account for lack of substrate control.

Complex cementation involving 3 minerals; calcite, dolomite, and celestite is occasionally well developed (Figure 7c & d). First generation calcite cement consists of either large, sweeping botryoidal fans, or of blocky calcite mosaic displaying increasing crystal size toward the former void center. Celestite and dolomite fill the void center, and are commonly intergrown, with celestite localized on the edges of dolomite rhombohedra or along

Figure 7--Substrate control and complex cements. Bar in lower right hand corner is 0.5mm. long.

A.) Substrate control on bladed calcite void fill by favorably oriented prismatic microstructure of an ostracode shell. Acicular rim cement lining the inside and upper left outside edge of the shell are now optically continuous with the bladed void fill and prismatic crystals in the shell. Bladed void fill meets along serrate juncture in middle of shell, indicating a constant rate of crystallization from all walls of void.

B.) Anomalous lack of substrate control by monocrystalline crinoid ossicle on internal acicular calcite rim cement, which is 45 degrees off extinction with respect to both ossicle and final syntaxial void filling.

C.) Complex cement sequence consisting of large, early-stage botryoidal calcite fans (F) folled by later stage dolomite (D) and celestite (S).

D.) Calcite (C), dolomite (D), celestite (S) fill a large void of unknown origin.

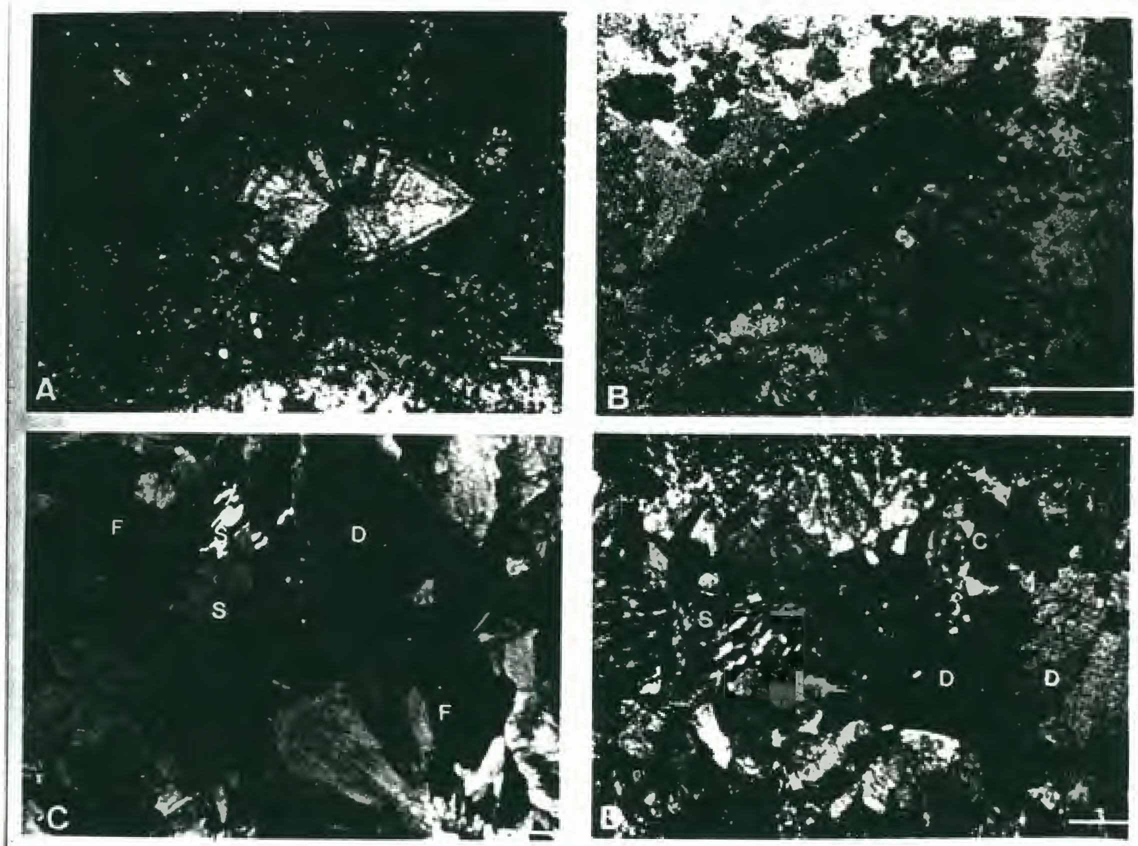


Figure 7

cleavage planes. When the two minerals occur as distinct void-filling components, celestite appears to be the latest stage.

Complex void filling involving distinct and/or gradational variations in the Fe^{+2} content of calcite and dolomite is widespread. A general trend evident from selective staining for iron, displays an increase in iron content in later stage calcites and dolomites.

Thin-section examination confirms the relative abundance of skeletal grains observed in hand specimen with only minor variation. The striking dominance of crinoids and bryozoans obseved in thin section is not surprising, because excellent preservation of microstructure due to inferred original stable mineralogies produces a bias in favor of these grain types. In addition, fragmentation and disarticulation can produce a large number of grains from one individual of these groups. The paucity of recognizable algae and molluscan grains noted in hand specimen is offset by the moderate frequency of casts and recrystallized ghosts of these grains in thin section. Ostracodes, rarely noted in hand specimen due to their small size, are fairly common in thin section.

Of all skeletal grains, sponges are the most petrologically complex. Sponges are generally preserved in recognizable gross form; only rarely have highly degraded ghost sponge-like grains been observed. The large volume of intraskeletal porosity associated with the sponge skeleton (cloaca and canals) provides ideal sites for localization of internal sediment, precipitation of void-filling cements, and excellent pathways for migration of pore fluids prior to complete cementation. In addition, intimate association between pore fluids and organic matter in the sponge skeleton, may have created microchemical environments which affected diagenesis.

Several sponge genera are present in this unit. The large, siliceous tubular sponge Heliospongia is generally well preserved. Internal sedimentation in internal canals, combined with calcitization of original siliceous spicules, has resulted in excellent preservation of this genus (Figure 8a & b). Most of the internal sediment that filled sponge canals is recrystallized to microspar, which occasionally contains indistinct micrite pellets (Figure 8a).

Calcitic sponges are abundantly well preserved throughout the unit. The fused spicular structure is generally preserved as a blocky mosaic of ferroan calcite, which is typically more coarsely crystalline and cloudier than associated cloaca and intraskeletal nonferroan void fill (Figure 8c). Ferroan calcite occupying the original sponge structure and the nonferroan calcite in intraskeletal voids are typically separated by acicular calcite rims (Figure 8c). Acicular rims are developed to varying degrees, frequently constituting a significant portion of the void-filling cement. Composition of acicular rims is variable,

Figure 8--Sponge petrology. Scale in lower right hand corner is 0.5mm. long unless otherwise indicated.

A.) Preserved structure of the siliceous sponge *Heliospongia*. Internal sediment recrystallized to microspar is localized in intraskeletal voids. Supportive spicules and tissue has been recrystallized to sparry calcite.

B.) Supportive structure of *Heliospongia* preserved through calcitization of siliceous spicules and connective tissue.

C.) Fused spicular structure of calcitic sponge preserved as ferroan calcite mosaic (grey). Internal voids are lined with a thin acicular ferroan calcite rim cement (darker) and filled by blocky, nonferroan calcite mosaic (white).

D.) Dolomite (white) of uncertain genesis is preferentially located in original sponge wall.

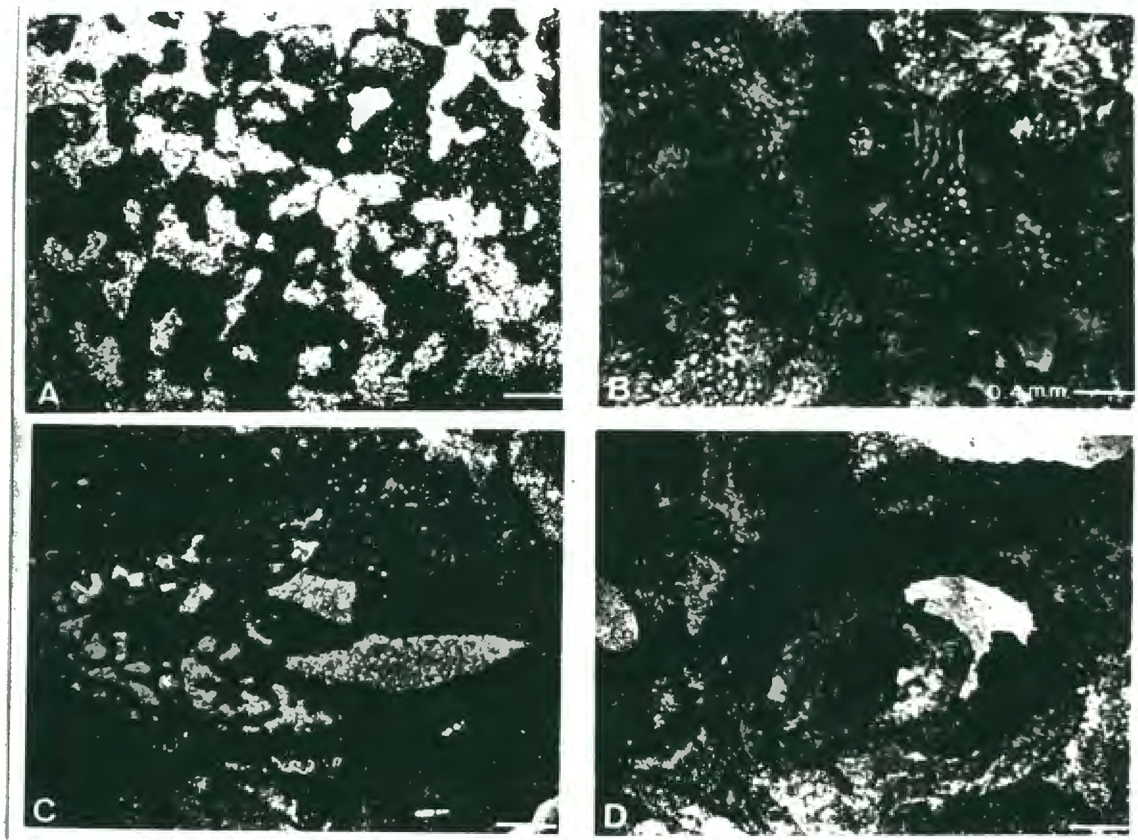


Figure 8

consisting either of ferroan or nonferroan calcite. In general, acicular ferroan calcite cement rims are observed on ferroan calcite sponge material while nonferroan rims are developed on nonferroan calcite sponge material.

Ferroan dolomite is occasionally observed in association with sponges. Dolomite may occur as discrete, euhedral rhombs, presumably of replacive origin (Figure 5d), as massive late-stage void filling (Figure 7c & d), and in massive forms of indefinite origin (Figure 8d).

Depositional Environments

A good case can be built for deposition probably below wave base in normal marine waters within the photic zone. The great abundance of inferred stenohaline crinoids (by modern analogy), and to a lesser extent the presence of corals as well as the diversity and abundance of the whole fossil assemblage strongly suggests normal marine salinity. Position of the environment within the photic zone is indicated by the in-place benthic habit of the algae, while the presence of abundant, intact bryozoans indicates quiet water. Bryozoans, as filter feeders, can tolerate only minimal turbidity, or clogging of the feeding aparatus results. Abundant mud within this environment would have been a ready source of turbidity if sedimentation were rapid; therefore one can safely assume slow deposition as well as quiet water.

Discussion of Diagenesis

Neomorphism of micrite to microspar is a widespread diagenetic response in many ancient calcilutites. The high surface area to volume ratio of micrite-sized particles renders them more susceptable to recrystallization than larger grains. An additional consideration involves the original mineralogy of the micrite component; if, as in modern carbonate environments, the original mineralogy was mainly aragonitic, this would increase the liklihood of recrystallization to a coarser mosaic (as opposed to calcite, which is more stable during diagenesis). Neomorphism of micrite to microspar is best observed in geopetal void fills. Neomorphosed internal sediment commonly consists of homogeneous equigranular mosaic, which displays a gradational size relationship with overlying void-filling calcite (Figure 9a & b). Micritic matrix generally contains remnant patches retaining original micrite texture (although much is now microspar) whereas internal sediment is usually pervasively neomorphosed (Figure 9a). Because internal sediment is mechanically deposited within a pre-existing framework, it may have been better sorted and contain less organic coating than primary micrite deposited inplace. This might explain the different diagenetic responses of the two different genetic types of mud. Another possibility is

Figure 9--Diagenetic considerations. Bar in lower right hand corner is 0.5mm. long.

A.) Geopetal void-filling beneath a brachiopod valve showing size gradation between recrystallized internal sediment (I) and overlying sparry void-fill (S). Dark micritic matrix (M) adjacent to the internal sediment is also recrystallized to microspar but less completely so; remnant patches of micrite-sized material remain.

B.) Well preserved algal blade (<u>Archaeolithophyllum</u>) showing patches of relict microstructure and conceptacle (C). Internal sediment of microspar size (I) occurs in geopetal structure between algal blades. Sponge with poorly preserved spicules beneath algal blade is encrusted by organism of unknown affinity, possibly blue-green algae (G).

C.) Extensive syntaxial crinoid overgrowth forming part of adjacent void-filling cement.

D.) Syntaxial crinoid overgrowth (O) transecting part of a sponge wall and growing into sponge cloaca as optically continuous void-fill.

E.) Botryoidal-like calcite recrystallized to a blocky to elongate calcite mosaic. Botryoids appear to have isolated patches of micrite within them which lacks radiating, needle-like structure of the more common botryoidal crusts in Unit 2. Botryoidal-like structures are cut by late-stage calcite-cemented fracture.

F.) Irregular bundles of botryoidal-like calcite (B) growing into void; crystals have nucleated on micrite as well as fragmented spherulitic structure (S) with finely needle-like structure identical to that of the "botryoidal" void-fill. On the grain note the micrite rim, clear void-fill (V), and needle cement rim (R).

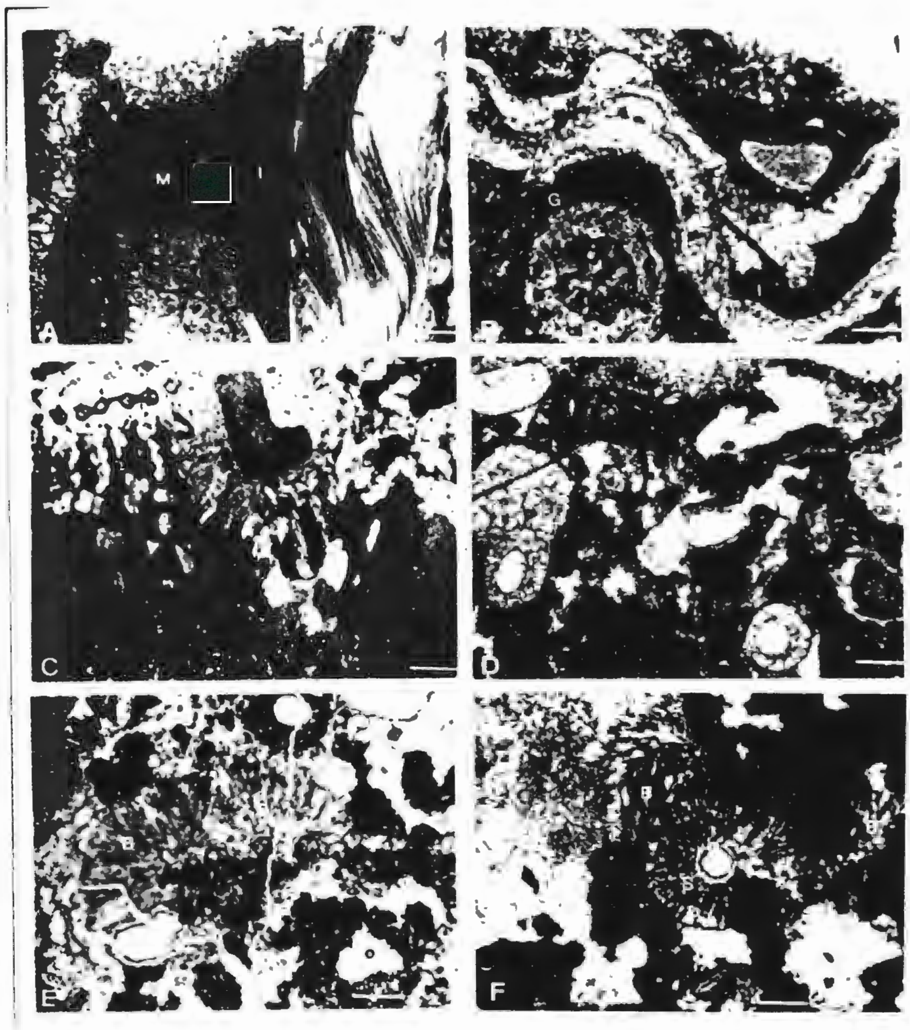


Figure 9

that the internal sediment was originally deposited as silt-sized crystals and has undergone little neomorphism. Continuous size gradation from micrite to microspar and spar in some internal sediment precludes this last possibility, unless the size gradation is a result of depositional size grading (Figure 9a).

Recrystallization of skeletal grains to a coarse blocky mosaic of sparry calcite with retention of structure is well developed in sponges and rare algae (Figure 9b). Although rare, algae are occasionally well preserved, thus their paucity cannot be entirely accounted for by low preservation potential. In fact, molds of phylloid algae are also quite rare, indicating original low abundance of calcareous algae in this unit.

Syntaxial enlargement of crinoid grains is common in this unit (Figure 9c & d). Overgrowth is accomplished by several mechanisms: 1.) Syntaxial growth into adjacent void space (Figure 8b), 2.) Syntaxial growth by incorporation of adjacent micrite or sparry calcite (Figure 9c), and 3.) Syntaxial growth by incorporation of adjacent skeletal grains (Figure 9d).

Radiating fans of botryoidal calcite are observed as void-fillings; these are similar to primary aragonite cements described by Ginsburg and James (1976). Some of the fans are void-filling cement as they partially fill primary voids. In other cases the fans appear to be partially diagenetic as they occasionally isolate micrite patches and skeletal grains. Commonly the fans originate as void-filling cements with minor subsequent diagenetic growth into adjacent fabric components (Figure 9e). Botryoidal-like void-filling cements and spherulitic-structured "grains" are quite rare in the unit.

Although cement paragenesis is highly variable, several trends can be established:

1.) Early isopachous, acicular cement rims, now composed of either ferroan or nonferroan calcite commonly line inter- and intraskeletal voids.

2.) The mineralogy of cement rims in terms of iron content is usually the same as that of the substrate on which it nucleated. Ferroan clacite rims may be related to an original high magnesian calcite cement, which has the ability to hold greater amounts of iron in its lattice than does low magnesian calcite.

3.) Cement rims may be preserved as distinct acicular crystals or as recrystallized, turbid ghosts within a blocky calcite mosaic.

4.) Rare botryoidal-like structures are locally developed partially filling primary voids, the evidence suggests some diagenetic growth of this void-filling cement into adjacent fabric components.

5.) Ferroan calcite void fill is always a later stage than nonferroan void fill except in the case of acicular cement rims, where the ferroan content could possibly be related to a high magnesian calcite precursor. Late-stage ferroan void fill may be related to progressive concentration of Fe^{+2} as early nonferroan calcite precipitated from interstitial fluids of one origin (e.g. marine), or it may reflect a late-stage of cementation in a Fe-rich meteoric regime.

6.) Dolomite and celestite occur as late-stage void fills following ferroan and nonferroan blocky mosaics and acicular rim cements.

Skeletal-Algal Sparry Calcilutite to Sparite (Unit 2)

Unit 2 or its equivalent is present at all three sample localities but is best exposed at the K-96 roadcut, where it is medium to thick-bedded, locally massive skeletal-algal sparry calcilutite to sparite that forms the lower-middle 26 feet of exposed Spring Hill. It is separated from underlying skeletal-sponge calcilutite (Unit 1) by a covered interval (Figure 4). Several lithofacies not present at the K-96 cut can be observed in the Unit at the Sycamore Quarry (Figure 1b). Unit 2 is equivalent to the lower part of Harbaugh's (1959) Crystalline Limestone Subdivision.

The lower part of Unit 2 at the K-96 roadcut and Carr's Quarry consists of massive to thick-bedded (0.2 to 2.0 ft.), vuggy, light grey to yellowish-tan and orange-weathering spar-rich calcilutite. The fabric is dominated by coarse void-filling carbonate spar including calcite, ferroan calcite, and ferroan dolomite, which are localized in patches beneath numerous bryozoan and algal umbrella structures. In places, patches of this sparry carbonate locally coalesce to form zones of a massive crumbly sparite lithology. Sparite lithology is common to several other mound-forming regressive limestone in southeastern Kansas and is particularly coarse and well developed in the transgressive Captain Creek Limestone Member of the Stanton Formation in central Montgomery County (Ravn and Heckel, 1978).

Biota in the lower part of Unit 2 is dominated by large recrystallized algal blades and delicate fenestellid bryozoans, both of which are frequently nearly intact and unabraded. Other skeletal grains include locally abundant forams, several other types of bryozoans, large brachiopods, intact and disarticulated crinoid stems, molluscs, sponges, and corals.

The upper part of Unit 2 along K-96 locally consists of irregular, wavey, medium to thick-bedded skeletal calcilutite. This occurrence of upper Unit 2 displays a noticeable increase in mud with a corresponding decrease in coarse void-fills relative to lower parts of the Unit. The dense fabric weathers light grey and tan and contains abundant small spar patches, interpreted as casts or recrystallized fragments of algae and other skeletal grains. The upper part of Unit 2 is highly fossiliferous and carries a fauna dominated by crinoid columnals with abundant bryozoans, algae, brachiopods, molluscs, forams, sponges, and corals.

Two distinctive lithologies are present within Unit 2 at the Sycamore Quarry: 1.) Subparallel, algal-laminated sparite at the base of the Unit, and 2.) Fusulinid-rich, brecciated, sparry calcilutite in the upper-middle and upper part of the Unit. The lower-middle part of Unit 2 at Sycamore consists of mud-rich skeletal calcilutite. Algal-laminated sparite is very dark-brown and composed of subparallel, partially collapsed algal molds separated by coarse, dark-brown calcite, some of which displays botryoidal structures visible in hand specimen. The fabric is quite wavey and weathers to form thin, resistant zones within lighter colored sparry, algal calcilutite. Visual estimates indicate that the fabric is composed of up to 80 percent sparry calcite (Figure 10a). The type of algal preservation observed in algal-laminated sparite is significantly different from the typical case where algae are recrystallized (or solution-cast) to a sparry calcite mosaic that usually retains the blade-like morphology (Figure 10b).

Fusulinid-rich, brecciated sparry calcilutite is present in the middle and upper parts of the Sycamore

Quarry exposure. The lower exposure of this lithology is thicker bedded and less brecciated that the medium-bedded, knobby-weathering upper part. The knobby weathering of the upper part may be due to poorly developed shale interbeds largely removed by erosion and thus may actually be equivalent to Unit 3 at the K-96 roadcut. Nevertheless, due to the absence of both definite shale interbeds and spar-spot calcilutite and the modern erosional upper surface of the Sycamore section, footage is the only basis upon which correlation to the K-96 section can be made.

Brecciated calcilutite weathers light-grey at the base and yellowish-tan at the top. The fabric consists of coarse angular mud fragments separated by sparry calcite containing concentrations of intact, unabraded fusulinids (Figure 10c). Fusulinid concentrations are preferentially located within spar-filled voids beneath algal umbrellas and angular mud clasts, suggesting that the fusulinids were either mechanically deposited in the voids or that they preferred the sheltered habitat produced by the porous fabric of what may be a very early breccia.

Microscopic examination of the massive basal part of Unit 2 at the K-96 roadcut displays a coarsely crystalline spar-dominated fabric. Mud is present in moderate amounts and typically is pervasively recrystallized to microspar and spar. The diverse marine benthic biota is characterized by low numbers of individuals, except for the

Figure 10--Subparallel algal-laminated sparite and brecciated foram-algal calcilutite from Sycamore Quarry. Bar in lower right hand corner is 2.0 cm. for the hand specimens and 0.5 mm. long for the thin section.

A.) Mud-rich sample of algal-laminated sparite containing marine organisms within internal sediment (I), which is overlain by botryoidal calcite (B); this development of successive vertical geopetals is unique to this lithology.

B.) Thin section displaying typical preservation of algae in Unit 2; note branching morphology and apparent budding (B) (asexual reproduction). This common type of algal preservation contrasts with that observed in thin sections from sample 10A illustrated in photomicrgraphs 13a & c.

C.) Brecciated foram-algal calcilutite displaying concentration of fusulinids in sheltered void and small-scale collapse brecciated fabric.

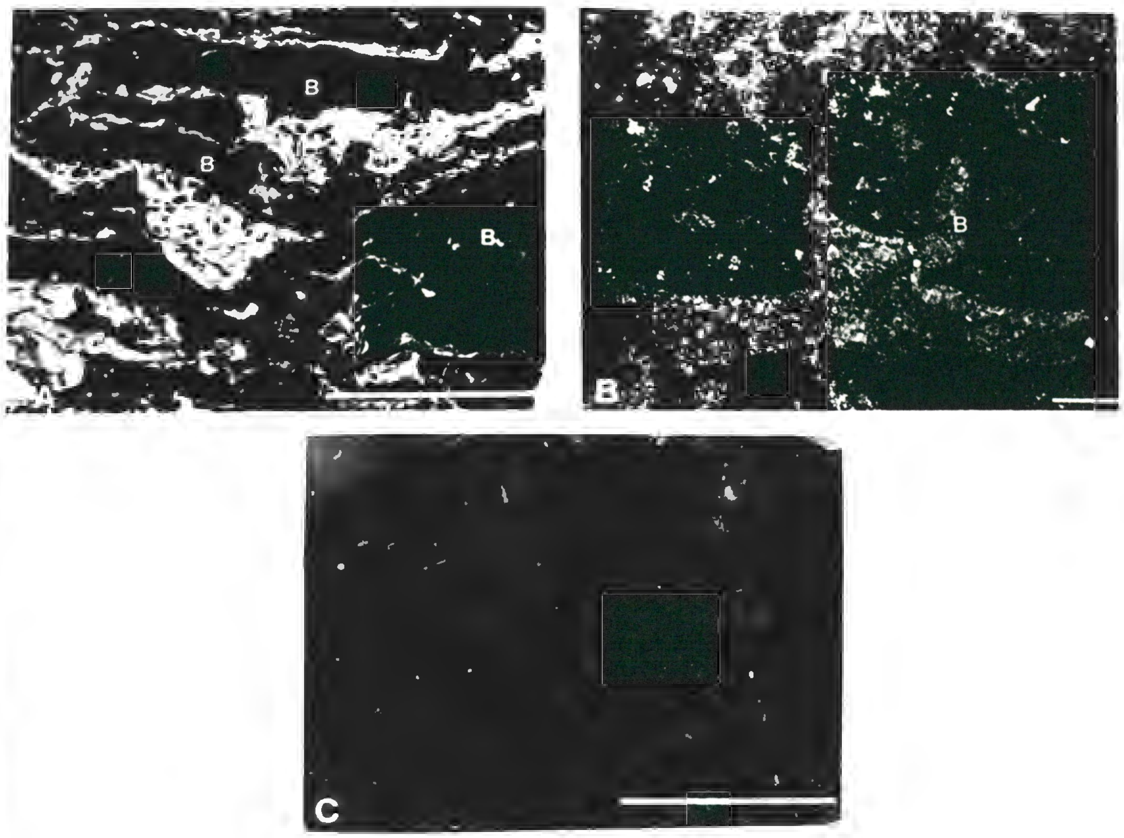


Figure 10

abundance of phylloid algae and several types of bryozoans (fenestellid in particular). The sheltering effect of phylloid and fenestellid bryozoans has produced a distinctive, locally grain-supported fabric of high depositional porosity, which is now occupied by multi-generational carbonate cements consisting of several mineralogies and textures. Although crystal texture, morphology, and the relationship between void-filling cements are quite varied, several dominant cement types are readily apparent.

Botryoidal calcite is a common first-stage void-filling cement throughout much of the basal part of the Unit. This cement displays many different degrees of recrystallization and retention of finely radial needle-like structure. Staining with Alizarin Red-S and potassium ferricyanide obscures botryoidal morphology and finely radial structure in some of the more recrystallized occurrences.

Botryoidal hemispheres commonly grow on top of one another to produce a bulbous, cauliflower-like mass, which partially or completely fills framework voids; remaining void space is typically cemented by irregular to equant calcite mosaic (Figure 11a). Botryoidal masses grow from the top as well as the floors and sides of voids and appear to lack substrate control as they nucleate on grains of different inferred original mineralogies. Botryoidal hemispheres appear to have grown in stages along concentric fronts; growth was periodically interrupted by deposition of internal sediment, which is preserved as dark, interlaminated zones within botryoids (Figure 11b). Relict internal structure of botryoids is preserved as finely radial needle-like inclusions, presumably along the edges of acicular aragonite, within a turbid, irregular, coarsely to unicrystalline calcite mosaic. Crystal terminations of botryoids are preserved as irregular needle-like fronts that extend into and are recrystallized within later stage blocky calcite void fill (Figure 11c). Needle-like terminations of juxtaposed botryoids commonly interfere and interpenetrate each other where they fill voids from opposite sides.

Botryoids are most commonly recrystallized to a coarse mosaic of highly irregular nonferroan calcite crystals, which display typically excellent finely radial needle-like relict structure (Figure 11d). In some cases, recrystallization to nonferroan calcite involves partial to complete loss of relict needle structure (Figure 12a). In cases where the botryoidal cement has been recrystallized to ferroan calcite or dolomite, complete obliteration of relict structure is the rule. Extreme recrystallization of botryoids commonly produces a unicrystalline ferroan calcite mass, sometimes with excellent preserved structure (Figure 12b), but often with inferred original structure completely destroyed (Figure 12c).

Botryoidal cement in the subparallel algal-laminated sparite near the base of Unit 2 at Carr's Quarry displays

Figure 11--Recrystallized botryoidal void-filling cements from the basal part of Unit 2. Bar in lower right hand corner is 0.5 mm. long.

A.) Cauliflower-like dark botryoidal hemispheres partially filling an umbrella void. Final stage of void fill consists of lighter, irregular calcite mosaic.

B.) Large botryoidal hemispheres showing discontinuous, dark concentric growth lines and relict needle-like structure. Edge of hemispheroids displays serrate crystal terminations. Final void filling is by irregular, coarse calcite (C) which has been patchily replaced or followed by ferroan dolomite (D).

C.) Relict botryoidal structure preserved as elongate rays of minute inclusions within calcite mosaic. Note irregular needle-like terminations preserved within later stage blocky calcite void fill (T).

D.) Same as 15c but with crossed polarizers. Botryoidal cement has been recrystallized to a coarse mosaic of straight-edged to highly irregular nonferroan calcite.

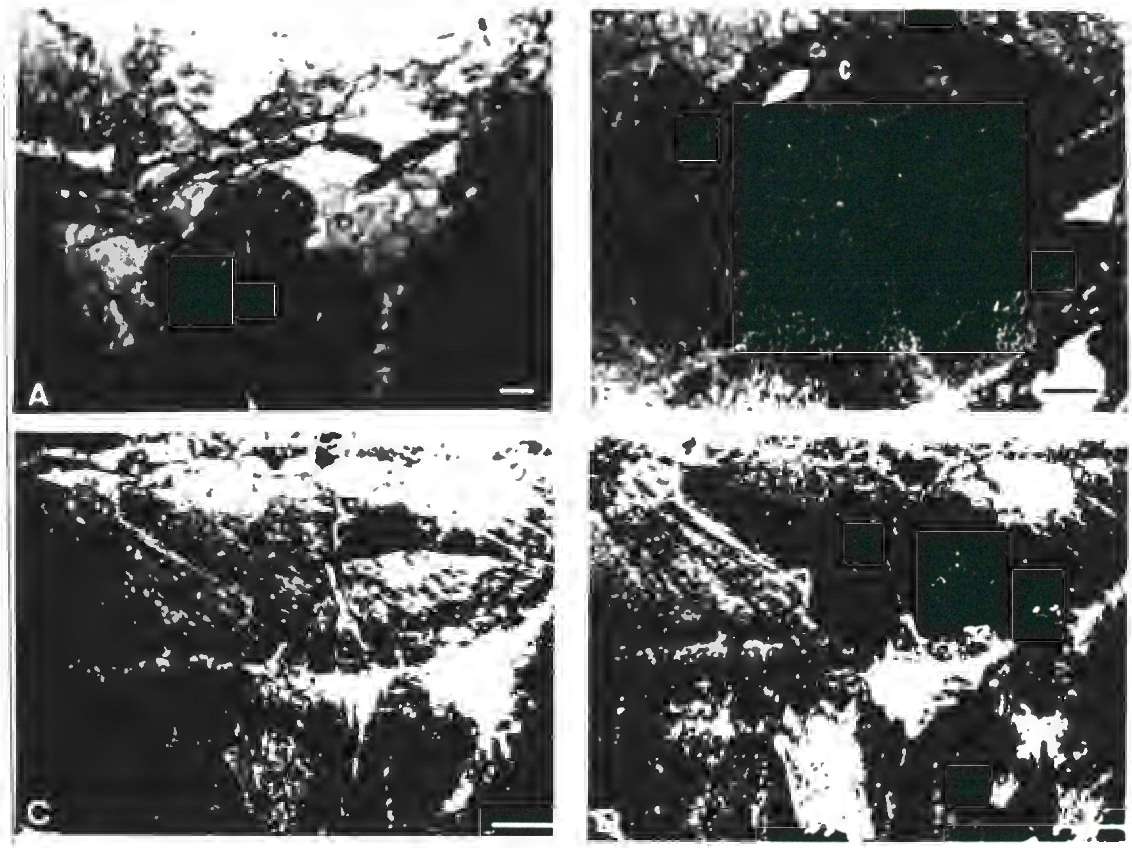


Figure 11

Figure 12--Variable retention of structure in recrystallized botryoidal fabrics, and relationship of botryoidal cements to framework. Bar in lower right hand corner is 0.5 mm. long.

A.) Partial loss of rayed needle-like structure through recrystallization. Dark, irregular zones are probably collapsed algal blades (D). From algal-laminated sparite at Sycamore Quarry.

B.) Unicrystalline botryoidal mass displaying excellent retention of needle-like structure. Crossed polarizers, 12° off extinction of unicrystalline botryoid.

C.) Botryoid apparently recrystallized to nearly unicrystalline mass of ferroan calcite with relict structure completely absent; only the hemispherical shape and irregular, serrate crystal terminations suggest originally needle-like structure.

D.) Probable collapsed algal blade (black) conforms to contour of botryoids due to either compaction or force of crystallization of early botryoidal cement, or, some combination of the two.

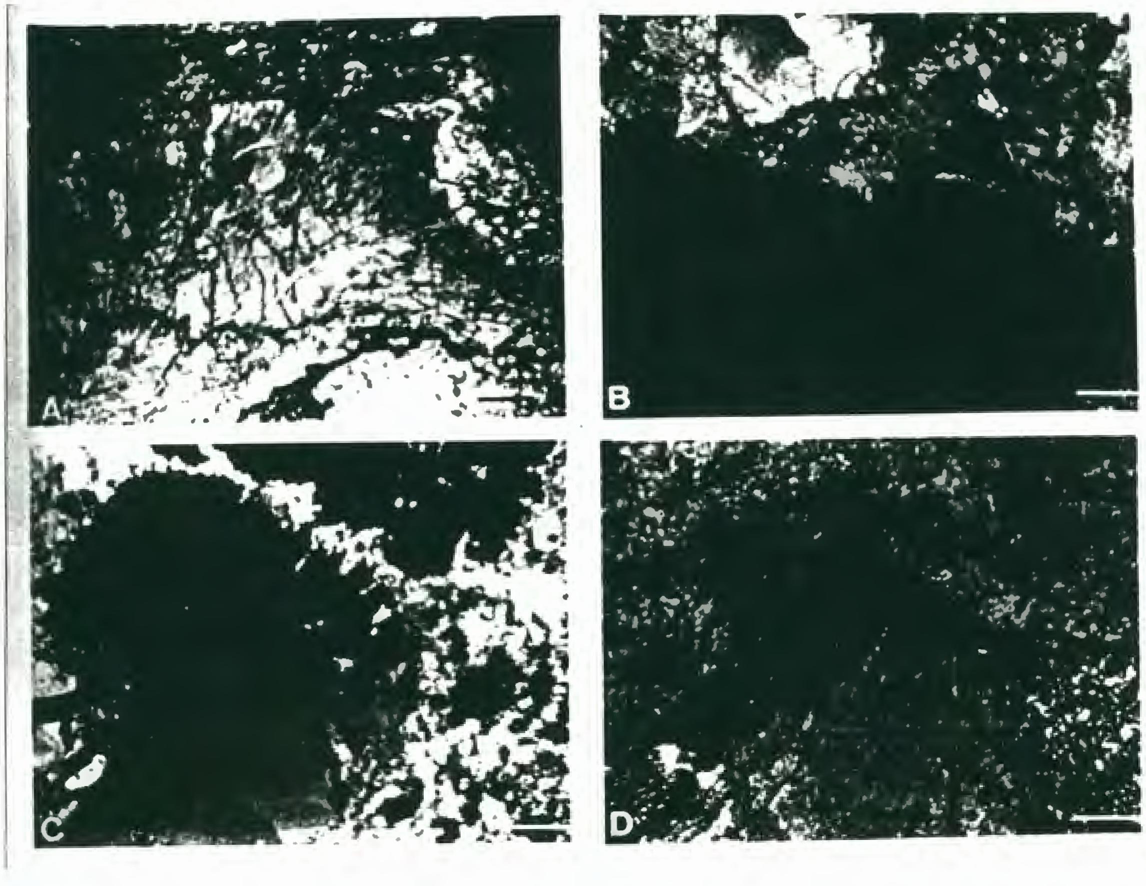


Figure 12

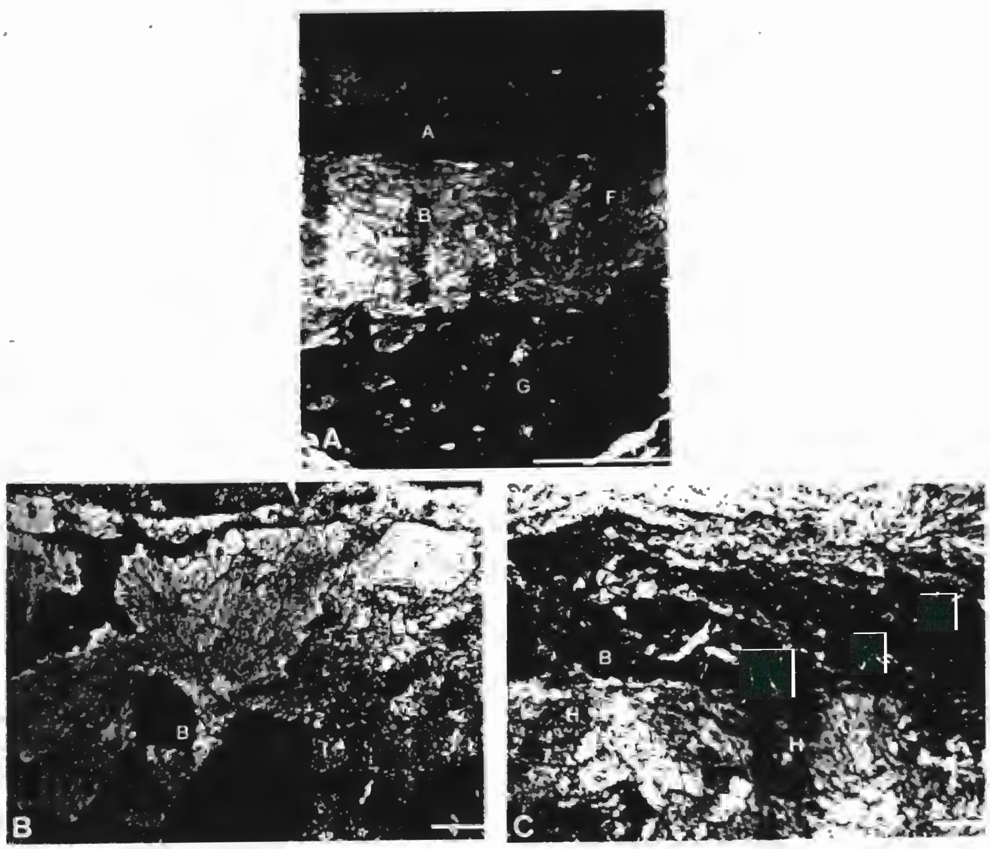


Figure 13

fabric relationships that suggest a very early, possibly synsedimentary origin for the cement such that it may have played a significant role in enhancing frame support in a very open depositional fabric (Figure 12d). It is possible that growth of synsedimentary botryoidal cement, through its force of crystallization, may even have played a role coincidnet with compaction in altering the depositional framework. The extremely high percentage of botryoidal cement in relation to visible framework in parts of the Spring Hill as well as other Kansas mound-forming limestones, suggests by itself the possible synsedimentary rigidifying role of this distinctive cement.

Fabric relationships between botryoidal cements, skeletal grains, internal sediment, and framework voids indicate an early submarine origin for the cement. Botryoidal cement in framework voids frequently overlies internal sediment of marine origin as indicated by contained marine invertebrates (Figure 13a); successive vertical alterations of these geopetal fabrics with collapsed algal voids indicates a marine origin for the cement. In addition, marine invertebrates are contained within individual botryoids (Figure 13 a & b). Evidence that botryoidal cement was a synsedimentary void fill, possibly coincident with compaction, and may have provided ridgidity and support by its force of crystallization is suggested by fractured skeletal grains (apparently fractured in-place) over- and

Figure 13--Botryoidal fabric relations. Bar in lower right hand corner is 0.5 mm. long.

A.) Botryoidal cement (B) completely fills an umbrella structure apparently formed by unidentifiable algae (A) preserved as dark, organic-looking concentration (possibly a green algae or collapsed red algal mold). Botryoidal cement overlies geopetal sediment (G) that contains numerous marine organisms. Note fragmented bryozoan (F) within botryoidal cement. Dark vertical lines are from thin section polishing machine.

B.) Bryozoan (B) enclosed within botryoidal cement mass suggests a marine origin for the cement.

C.) Bryozoan (B) apparently fractured by force of botryoidal cement crystallization; the offset, fractured perimeter of the bryozoan conforms to distal terminations of underlying botryoids.

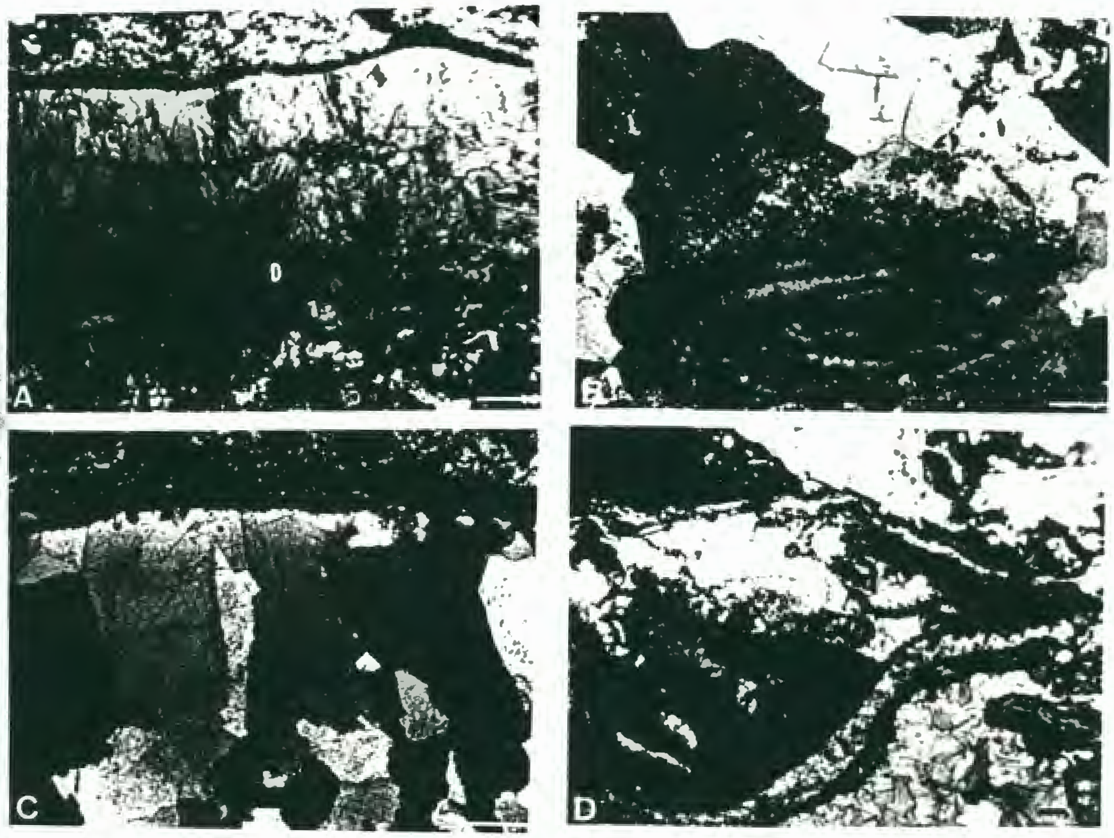


Figure 14

underlying unfractured botryoidal cements. Note that the termination of the botryoidal cement in these cases conforms to the fractured outline of the grain (Figure 13c)

Monomineralic nonferroan calcite void fillings typically display two end members of crystal morphology with gradations between them: 1.) Isopachous rims of bladed calcite, and 2.) Equant to drusy, blocky to irregular calcite mosaic. Bladed calcite cement fills fractures as well as solution and framework voids. Crystals are generally clear with straight borders: no inclusions or other relict features that would indicate replacive origin are observed in bladed calcite (Figure 14a). Bladed calcite void fill is always an early cement, which in many instances only partially fills voids.

Coarse equant blocky calcite mosaic, composed of clear crystals with straight borders is the common cement in the fusulinid-rich brecciated, sparry calcilutite at Sycamore Quarry (Figure 14b & c). Extensive cementation by very coarse nonferroan calcite is quite rare at the K-96 roadcut, where such void-filling is usually a finer, more irregular mosaic (Figure 14d). Nonferroan calcite cement at the K-96 exposure typically only partially fills voids, with final void-filling by coarser ferroan calcite (Figure 15a & b).

The most common and volumetrically important cement in the base of Unit 2 (other than botryoidal calcite) is very coarsely crystalline ferroan calcite. Ferroan calcite

Figure 14--Nonferroan calcite void-filling cements. Bar in lower right hand corner is 0.5 mm. long.

A.) Bladed calcite cement beneath umbrella of uncertain origin. Internal sediment is present at base of smaller overlying umbrella where void is cemented by irregular calcite mosaic (I). Irregular patches of partially oxidized dolomite (D) are present below the bladed-calcite-filled umbrella.

B.) Coarse, clear calcite cement in fusulinid-rich brecciated calcilutite at Sycamore. Intact, unabraded fusulinids displaying excellent preservation of microstructure are commonly concentrated in calcite-cemented fractures and sheltered voids.

C.) Coarse, nonferroan calcite cement filling algal encrusted umbrella void; algal blade has altered with only the encrustation as evidence of its former presence.

D.) Algal umbrella from K-96 roadcut. Encrusted algal blade has been altered to fine blocky calcite mosaic. Void beneath is cemented with an irregular calcite mosaic. Internal sediment trapped above the algal blade consists of microspar but appears finer grained because of large scale of photo.

usually occurs as a late stage void-filling cement, frequently following an earlier rim of blocky, drusy, or inequigranular nonferroan calcite (Figure 15a & b). Ferroan calcite void-filling is most commonly unicrystalline, with individual crystals measuring up to 8 cm. in long dimension; these crystals are commonly twinned and display excellent cleavage traces (Figure 15 a & b). Ferroan calcite void filling of adjacent voids are commonly in optical continuity with one another, such that large portions of thin sections exhibit unit extinction (Figure 15b).

Abundant rusty-orange-weathering dolomite lends a distinctive aspect to the basal part of Unit 2 at all three sample localities. That this dolomite is invariably ferroan is revealed by laboratory staining with potassium ferricyanide. Dolomite crystals are frequently partially oxidized, probably by modern weathering, with iron oxide concentrations localized along cleavage planes (Figure 16a); on fresher surfaces, some is unaltered (Figure 16a). In unstained thin sections, dolomite is readily identifiable by its sweeping to undulatory extinction (Figure 16d).

Ferroan dolomite seems to be both void-filling and replacive in origin, but the distinction between the two types is rarely unequivocal. One of the most common occurrences of dolomite is as irregular to hemispherical patches along the underside of algal and bryozoan umbrellas, where it appears to have replaced earlier cement generations

Figure 15--Late-stage ferroan calcite void-filling cement at K-96 roadcut. Bar in lower right hand corner is o.5 mm. long.

A.) Typically well preserved bryozoan forming an umbrella void. Early cement consists of finely crystalline, irregular, nonferroan calcite mosaic followed by later stage unicrystalline ferroan calcite. Ferroan calcite cement displays excellent cleavage traces. Recrystallized internal sediment overlies bryozoan.

B.) Adjacent voids filled by optically continuous ferroan calcite. Early-stage cement is finer blocky calcite . Algal blade forming lower umbrella structure has been dissolved internally and collapsed, with only thin, dark micritized rims preserved.

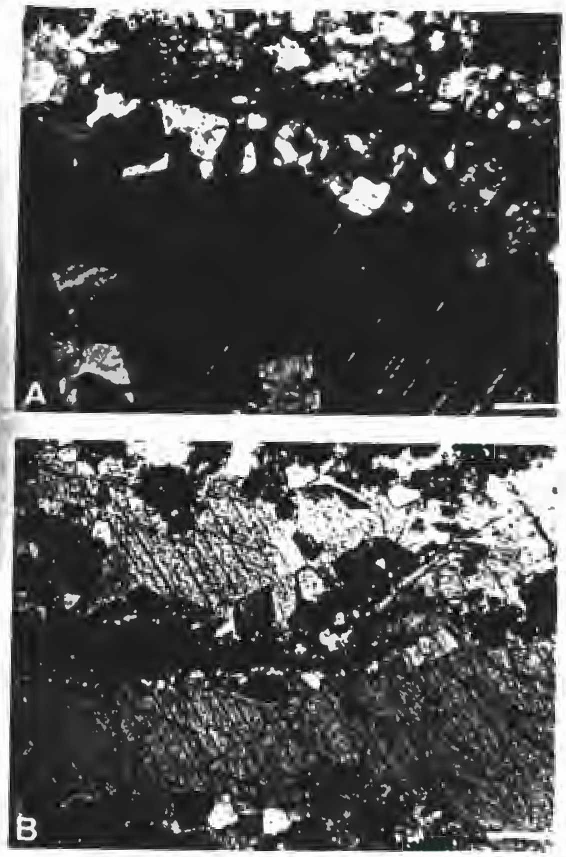


Figure 15

(Figure 16a & b). In some cases this occurrence may be a selective replacement or solution-precipitation reaction involving precursor botryoidal spar (Figure 16c & d); this is supported by the hemispherical shape, mode of occurrence as first generation cement on marine bioclasts, and irregular crystal termination similar to those of recrystallized botryoids (compare Figure 12c to 16c). If this occurrence of dolomite is in fact a replacement of botryoidal cement, it is apparently not pervasive as evidenced by ferroan calcite and dolomite hemispheres of identical morphology and mode of occurrence in the same void (Figure 16c & d).

Partial dolomite replacement of botryoidal cement typically involves retention of the irregular border of the precursor botryoid but obliteration of the finely needle-like relict structures so common to less altered botryoids (Figure 16e). This raises the possibility that botryoids could have been dissolved out as aragonite in the blocky calcite matrix, and then the voids were filled with ferroan dolomite. In many cases, dolomite occurs as isolated, irregular coarse crystals within umbrella void-filling calcite mosaic (Figure 16f); in these cases it is difficult to tell whether dolomite is replacive, or is filling solution voids formed by selective removal of some calcite crystals in the void-filling mosaic.

Figure 16--Typical occurrences of ferroan dolomite in basal part of Unit 2. Bar in lower right hand corner is 0.5 mm. long.

A.) Bryozoan umbrella with oxidized ferroan dolomite (D) along underside of blade, later stage void fill is irregular calcite mosaic (C). Oxidation of ferroan dolomite concentrates iron oxides along cleavage planes. Bryozoan forming the umbrella void is intact and displays excellent retention of microstructure. Upper void fill consists of internal sediment (I) recrystallized to irregular, fine calcite mosaic; coarse, blocky calcite mosaic (C), and very coarse ferroan calcite (FC).

B.) Same as 16a but with crossed polarizers.

C.) Umbrella void formed under partially collapsed micrite-rimmed algal blade (A) . Blade is now occupied by irregular fine calcite mosaic; broken fragments indicate that a void stage was involved. Void below blade is now occupied by hemispherical masses of ferroan calcite (FC) and ferroan dolomite (FD) with remaining void occupied by coarser ferroan calcite.

D.) Same as 16c but with crossed polarizers. Note sweeping, strained extinction of dolomite.

E.) Apparent replacement of botryoidal calcite (B) by ferroan dolomite (D). Dolomite replacement obliterates fine needle-like structure of botryoids but preserves dark, curved irregular termination rim of botryoid (T).

F.) Irregular, isolated dolomite patches (D) in calcite void-filling beneath algal umbrella.

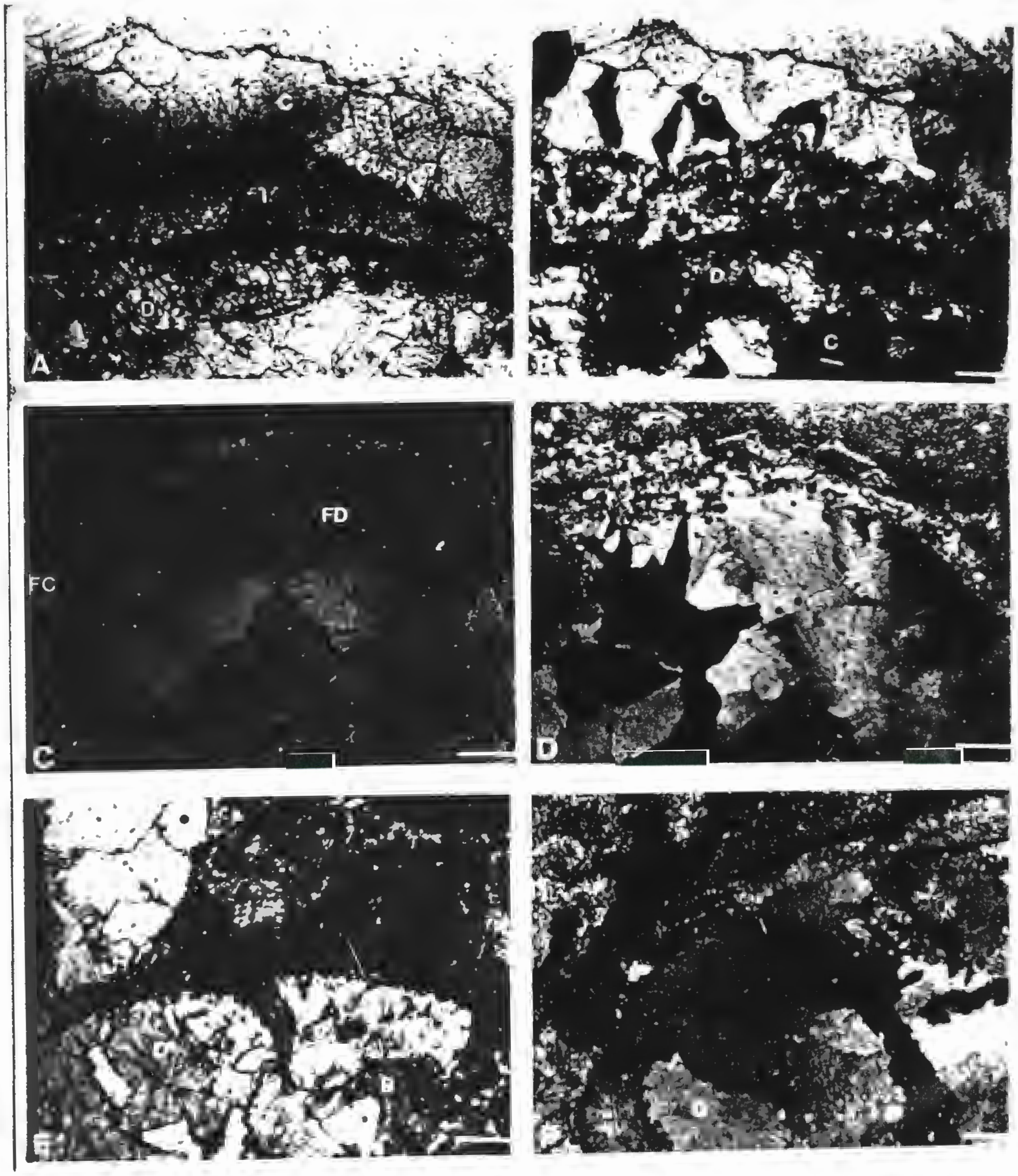


Figure 16

Preservation of skeletal grains is variable among major groups and can to some extent be related to inferred original mineralogy. Blade-like (phylloid) algae are invariably composed of equant to irregular calcite mosaic, if they are preserved at all. Preserved algal blades were nowhere observed to display definitive relict organic structure in the base of Unit 2, although buds that indicate coralline algal affinities are present in some blades (Figure 10b). Evidence of the original blade is restricted to micritized rims (Figures 14d, 15b, and 16c & f), algal, bryozoan, and foraminiferal encrustations of voids with blade-like morphology (Figure 14c & d), and preservation of the blade-like morphology itself as sparry casts. The absence of relict organic structure, combined with abundant occurrences of partially collapsed micrite envelops, indicates a solution-moldic stage followed by precipitation of void-filling calcite during diagenesis of many, if not all algal blades. A solution-moldic process of this type is compatible with the inferred original mineralogies of aragonite and very high magnesian calcite for green and red algae respectively. However, one might also expect that botryoidal calcite (of inferred original aragonitic composition) would also have dissolved if solution-moldic processes were the dominant mechanism of aragonite diagenesis. In fact, due to the presence of organic material surrounding carbonate minerals in biogenic carbonates (organic sheaths and membranes), one might expect such carbonates to resist dissolution to a greater degree than physically precipitated ones. Thus, in many diagenetic regimes one might expect the botryoidal aragonite to have dissolved before the biogenic aragonite of the algal blades. It is probable that the phylloid algae that consistantly show the effects of extensive dissolution and lack any relict organic structure are related to the Chlorophyta (green algae); many members of this group are only lightly calcified through impregnation of the outer cells, or simple coating by calcium carbonate (Wray, 1977 p. 79) and could thus be easily dissolved upon organic decay.

Bryozoans, brachiopods, fusulinids, and crinoid columnals are characterized by moderate to excellent preservation of microstructure. Bryozoans and fusulinids were nowhere observed to display obliteration of structure in the basal part of Unit 2 (Figures 14b, 15a & b), although minor recrystallization to very fine microspar was observed in a few specimens. The inferred original mineralogy of these groups by modern analogy is one of only moderate magnesian calcite, which is relatively stable during diagenesis; however, intense meteoric diagenesis is capable of altering even the structure of these stable groups, as seen in oolitic calcarenite of Unit 4 at Carr's Quarry. Crinoid columnals, composed initially of moderate magnesian calcite show excellent preservation due to their relatively stable mineralogy and unicrystallins structure. Progressive magnesium loss during diagenesis commonly converts ancient crinoid columnals to a low magnesian calcite without altering structure; evidence of originally higher magnesian content may be retained by exsolved inclusions of microdolomite in the columnal (Macqueen and Ghent, 1970).

Brachiopod preservation is generally quite good, although occasional partial loss of structure through recrystallization to irregular, equigranular calcite is observed. The original low magnesian calcite mineralogy of many brachiopods accounts for their generally excellent preservation.

Other skeletal elements are fairly rare. Presumably originally calcitic fusulinids are occasionally altered to equigranular blocky calcite mosaic which lacks relict structure, whereas small corals and ostracodes display excellent retention of structure. Molluscs are occasionally preserved as faint casts composed of blocky calcite.

Petrographic examination of the upper part of Unit 2 reveals an abundantly fossiliferous fabric composed of highly recrystallized skeletal grains. There is a noted decrease in large umbrella structures and associated coarse void-filling carbonates compared to the lower part of the Unit. Although umbrella voids are still common, they are characterized by decreased size and abundance. They are typically completely cemented by irregular nonferroan calcite mosaic (Figure 17a & b), although coarse ferroan calcite is still present as a late stage void-filling cement (Figure 15a). Decrease in abundance of ferroan calcite seems due primarily to nearly complete cementation of the smaller voids by earlier nonferroan calcite thus effectively eliminating potential sites for later precipitation of ferroan calcite. Dolomite is fairly abundant in the upper part of Unit 2 as small irregular patches, apparently randomly distributed throughout neomorphosed matrix and void-filling cements. Dolomite does not occur as a distinct stage within the overall void-filling sequence. While it is likely that dolomite is both of void-filling and replacive origin it is difficult to distinguish between the two types.

Algae are relatively abundant in the upper part of Unit 2, but their size is generally smaller than in the base. Algal preservation is the same throughout, with the blades composed of an irregular nonferroan calcite mosaic. Solution-moldic development, followed by partial collapse of the blade-like mold prior to complete void cementation by calcite is a common thread of algal diagenesis. This is indicated by the occurrence of fragmented, micritized algal rims within void-filling mosaics (Figure 17c).

The most distinctive aspect of the upper part of Unit 2 is ubiquitous development of micrite envelopes and abundance of highly micritized or recrystallized, unidentifiable grains (Figure 17c & d). Micrite rims are commonly developed on the grains of all fossil groups regardless of original mineralogy or degree of preservation. Irregular to spherical, unidentifiable sparry grains are second in abundance only to crinoid columnals. Many of these grains may be recrystallized skeletal grains; in fact, quite commonly one can find recognizable grains in various stages of alteration. Nevertheless, many of the altered grains seem to have formed through recrystallization of micrite intraclasts. Some of the recrystallized micrite grains (now partially sparry calcite) may not be true intraclasts, but could possibly have formed from precursor micritized skeletal grains formed through the boring activity of endolithic algae (Figure 17c-upper left, & 18a; Bathurst, 1975 p. 389).

Preservation of skeletal grains in the upper part of Unit 2 is generally quite poor. Recrystallization to an irregular calcite mosaic with complete loss of microstructure can be observed in all groups except crinoids. Foraminifers, bryozoans, and brachiopods are typically moderately well preserved but instances can be found where individuals of each group has been altered to the point where identification is possible only by overall morphology (Figure 18b & c). Extensive recrystallization has not only affected skeletal grsins, but has also pervasively recrystallized mud matrix to spar and microspar (Figure 18d).

Figure 17--Very fossiliferous sparry calcilutite from the upper part of Unit 2 at the K-96 roadcut. Bar in lower right hand corner is 0.5 mm. long.

A.) Sheltered void cemented with irregular nonferroan calcite mosaic (white). Small brachiopod in center is filled with coarse ferroan calcite, which is the common late-stage void fill. In the upper right-hand corner is an unidentifiable mass of cloudy, coarse, nonferroan calcite.

B.) Bryozoan-sheltered void cemented by irregular nonferroan calcite mosaic, the typical void-filling cement in upper part of Unit 2. Crinoid columnal in lower center of photo displays extensive development of micrite rim. Some sparry patches of various shapes are probably casts or replacements of skeletal fragments, but some may be burrows or borings.

C.) Collapsed micritized rims of algal umbrella (M) have fallen into sheltered void. Crinoid columnal (C), degraded forams (F), unidentifiable micrite blebs and micritized sparry calcite grains have accumulated on upper surface of blade, which is preserved as fairly intact micrite rim (M).

D.) Abundant micrite-rimmed grains including neomorphosed micrite blebs (now spar and microspar), micritized forams, crinoid, and numerous unidentifiable sparry grains.

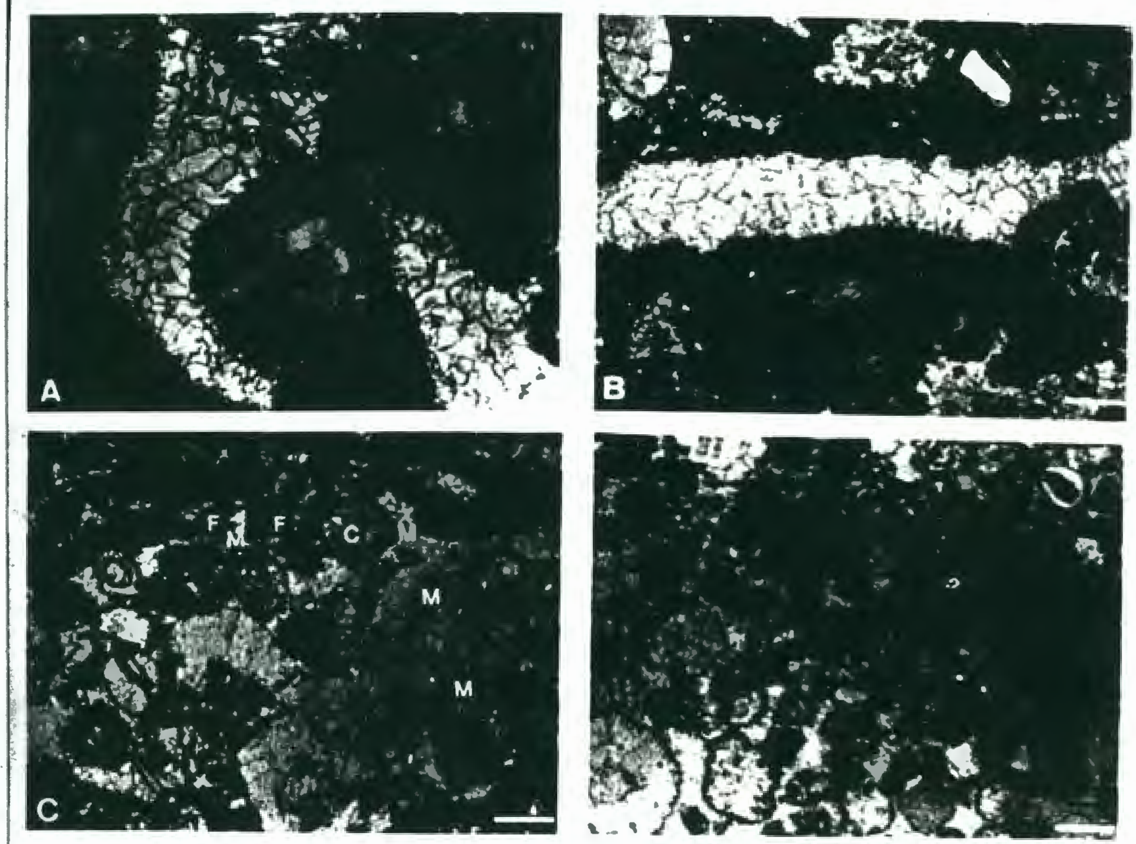


Figure 17

Figure 18--Altered grains and matrix in upper part of Unit 2. Bar in lower right hand corner is 0.5 mm. long.

A.) Highly altered grains with dark micrite rims. Some grains may have formed through aggrading neomorphism of precursor micrite clots and intraclasts whereas others may be micritized skeletal grains which were later partially recrystallized.

B.) Outline of calcitic sponge preserved as micrite rim, original sponge material as well as overlying void-filling (as suggested by fabric relationships) are composed of coarse, blocky calcite mosaic suggesting that the sponge structure may be a cast, which would require the internal micrite rim (R) to have remained coherent during moldic phase to prevent collapse of internal sediment (S) into mold.

C.) Matrix is pervasively recrystallized to microspar and spar, numerous small forams and bryozoans are altered to blocky calcite and typically well preserved fusulinid (F) is altered to microspar.

D.) Pervasive recrystallization of clotted, pelleted matrix to microspar and spar.

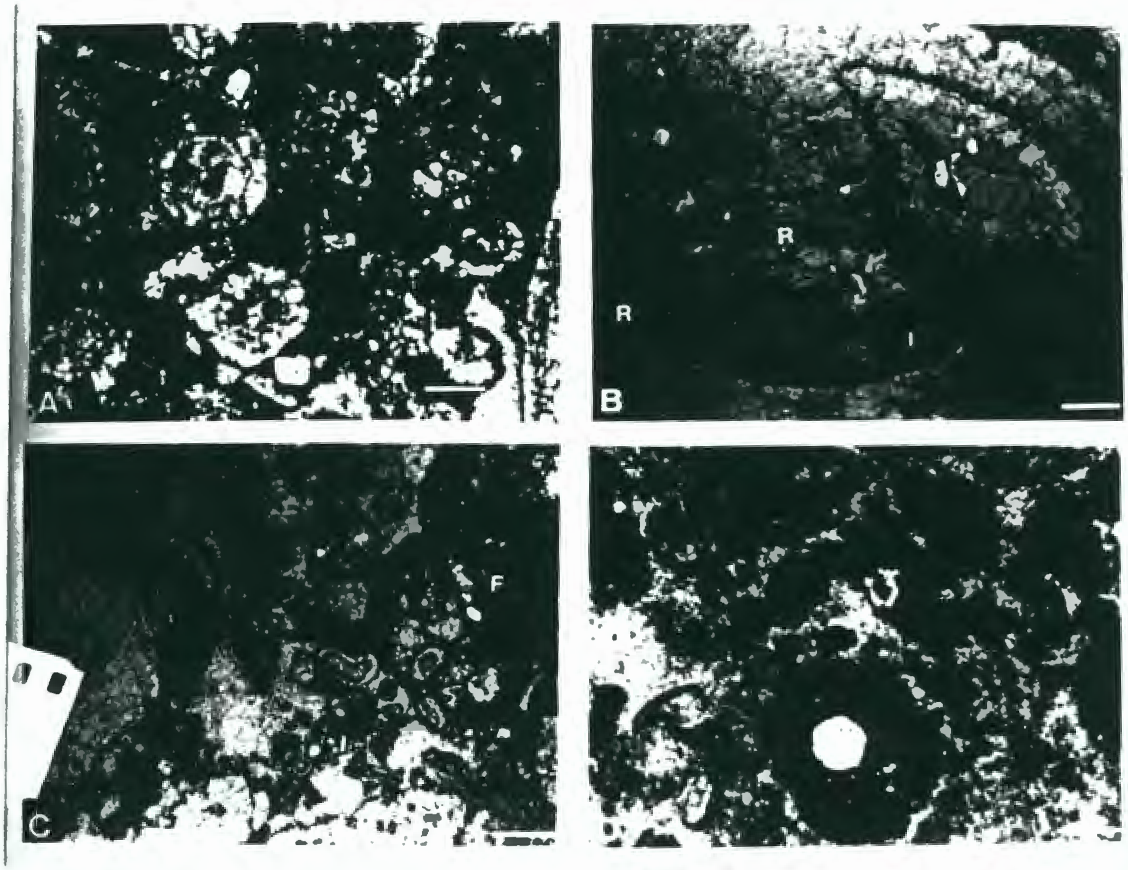


Figure 18

The highly altered aspect of many normally stable fossil groups in the upper part of Unit 2 is very similar to the type of preservation observed in the exposed oolite in Unit 4 at Carr's Quarry. The degree of alteration of skeletal grains in Unit 2 increases as one proceeds upwards toward the modern erosion surface which truncates the east side of the mound at K-96 roadcut. The net effect of long term meteoric exposure is to produce a fabric dominated by recrystallization of normally stable skeletal grains and micrite to an irregular calcite mosaic (Bathurst, 1975; figure 252 p. 328).

Fusulinid-rich, brecciated sparry calcilutite is present in the upper-middle and upper portions of the Sycamore Quarry exposure. The fabric consists mainly of 4 elements; 1.) abundant coarse, clear, euhedral nonferroan calcite void-fill, 2.) elongate to equant, angular, collapse-fractured mud fragments (pervasively recrystallized to 10 micron equigranular microspar), 3.) abundant well preserved fusulinid foraminifers, and 4.) casts and collapsed micrite envelopes of phylloid algae.

Fusulinids are characterized by excellent preservation of skeletal microstructure. They appear to be preferentially concentrated in voids beneath algal umbrellas (Figure 19a), but do occur distributed throughout microspar matrix as well. While they typically show no signs of abrasion, the tests are frequently fractured in place (Figure 19b).

In hand specimens, fusulinids and enclosing mud matrix are observed to be fractured as a unit, prior to complete void cementation by blocky calcite because the fractures do not transect final stage void-fillings. Although several stages of fracturing are present in the fabric, a very early stage can be inferred by the presence of numerous collapsed algal micrite envelopes and fractured first-stage isopachous cement which lines fusulinid intraskeletal voids (Figure 19b, c, & d).

Significant amounts of compaction have occured prior to complete void cementation by blocky calcite but after lithification of mud and contained bioclasts. Overall fabric relationships (e.g. unit fracturing of mud and bioclasts, fracturing of first-stage isopachous cement, and collapse of umbrella structures into uncemented voids) indicate early cementation, possibly syndepositional, followed by early compactive collapse of the porous framework prior to deposition of copious amounts of blocky void-filling calcite. A significant amount of solution-moldic removal of algal material also occurred fairly early.

Depositional Environments

Interpretation of rock fabric and faunal composition of Unit 2 , indicate normal marine deposition within the photic zone and in a quiet environment below effective wave base. The dominance of large, intact algal blades,

Figure 19--Brecciated foram-algal calcilutite from Sycamore Quarry. Bar in lower right hand corner is 0.5 mm. long.

A.) Fusulinid displaying early-stage isopachous rim composed of very fine acicular crystals. In-place fracturing due to compaction has interrupted both the test and early rim cement but not later stage unicrystalline void-filling, cementing this lithology. This suggests both early cementation and compaction of this calcilutite prior to final cementation.

B.) Preferential concentration of fusulinid tests within shelter porosity formed between collapse-brecciated mud fragments.

C.) Collapse of micrite component into algal blade-sheltered voids followed by cementation with coarse, blocky, nonferroan calcite.

D.) Micritized algal rims have collapsed into voids that they had previously bridged.

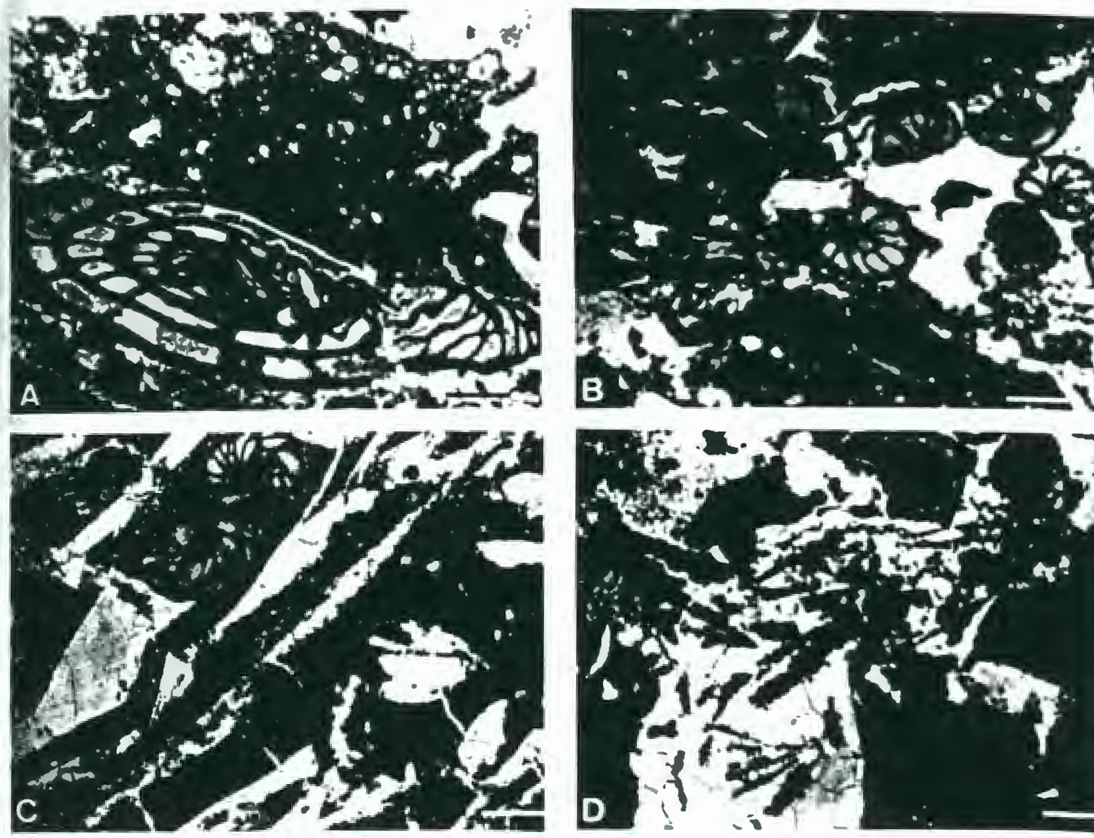


Figure 19

long crinoid stem segments (occasionally with cups) as bedding plane accumulations, and intact fenestellid bryozoans indicates quiet condition ecause crinoids generally disarticulate by scavengers even in a quiet environment, long crinoid stem segments are generally preserved in quiet conditions characterized by rapid deposition or by death in a protected place. Rapid mud sedimentation is highly unlikely as the general regime for this environment due to the great abundance of filter feeding bryozoans. Bryozoans are the major component in the base of Unit 2, thus one would expect optimum non-turbid conditions for their proliferation.

Even though the basal fauna in Unit 2 is dominated by bryozoans and algae, representatives of all major invertebrate groups are present in small numbers; this diverse marine benthic community is strongly indicative of unrestricted, normal marine conditions.

The abundance of bryozoans in the basal part of Unit 2 is a somewhat distinctive aspect of the Spring Hill mound, as opposed to some mounds that are composed of more algal dominated calcilutites. The importance and abundance of fenestellid bryozoans in the algal buildups of southeastern Kansas as well as late paleozoic "bioherms" in general, is becoming increasingly recognized (Frost, 1969; Cuffey, 1977). The local framework role of fenestellids (in conjunction with phylloid algae) within the base of Unit 2 is an inescapable conclusion. The highly porous depositional fabric produced by an environment favoring prolific development of large bryozoans and algae, played a major role in determining the types of cement fabrics that would later form; the relationship between paleoecologic communities and syndepositional and early diagenetic cement fabrics appears to be close.

A dramatic change in fabric and faunal content is noted between the lower and upper parts of Unit 2 on the east side of the mound at K-96. Although the Unit as a whole displays a diverse marine benthic community throughout, the upper part carries a fauna with a great abundance of individuals from all major invertebrate groups, whereas the basal part is dominated by fewer groups. Algae and bryozoans are still abundant upward, but are not nearly as dominant (in size and quantity) as in the basal part. Some slight change in ecologic conditions expanded the niches for other groups, perhaps due to development of conditions less favorable to prolific growth of large fenestellid bryozoans and large algal blades, both of which are smaller in the upper part of the Unit.

Discussion of Diagenesis

Preservation of what is believed to be former submarine aragonite cement, as indicated by relict structure and high relict strontium levels (by microprobe analysis), as coarsely recrystallized botryoidal calcite is an important diagenetic aspect of Unit 2. Studies on Recent marine sediments increasingly recognize early to synsedimentary cementation as a common lithification process (Shinn, 1969; Ginsburg and James, 1976). Documentation of the submarine origin of recrystallized botryoidal cements in the Spring Hill and other Upper Pennsylvanian limestones of southeastern Kansas (Ravn and Heckel, 1978), records yet another example of the importance of these cements in early porosity reduction and framework stablization of highly porous depositional fabrics in certain environments.

Recrystallized botryoidal hemispheres are localized in the depositionally highly porous basal part of Unit 2. They occur as a voluminous first-generation cement in framework voids, where they account for significant porosity reduction. This cement may have been important in providing support to a very open framework during initial compaction; post-formational compaction is evidenced by fractured hemispheroids cemented by later generations of cement.

Fabric relationships, mode of occurrence, and morphology of hemispherical masses is nearly identical to that of Holocene aragonite botryoids from Belize (Ginsburg and James, 1977), and of recrystallized botryoidal calcite from the Upper Paleozoic of the Canadian Arctic (Davies, 1977); other occurrences of of similar cements have been reported in the Capitan Formation (Permian) in the Guadalupe Mountains (Mazzullo and Cys, 1977), and in the Captain Creek Limestone (Upper Pennsylvanian) of Kansas (Ravn and Heckel, 1978).

The occurrence of recrystallized botryoidal calcite in shelf-edge carbonates and bryozoan reefs in Upper Paleozoic strata of the Canadian Arctic is well documented by combined petrographic and geochemical studies (Davies, 1977); fabric relationships shared in common by Spring Hill botryoidal cements and those reported from both Belize and the Canadian Arctic are as follows:

1.) Botryoidal cement occurs as a first generation cement on marine bioclasts.
2.) Botryoidal cement occurs with interlaminations of internal sediment of inferred submarine origin.
3.) Botryoids are observed to have nucleated on sediment-floored geopetals which contain marine invertebrates.
4.) Foraminifers are observed totally encased within individual botryoidal hemispheres.
5.) Vadose indicators such as miniscus cement are absent, suggesting cementation in a phreatic regime.

The above observations confirm a marine phreatic system during formation of botryoidal cement in Unit 2. The observed irregularly crystalline botryoidal calcite fabric is interpreted as a replacement of former submarine botryoidal aragonite needle cement for the following reasons:

1.) The relict finely radial needle-like structure of the botryoids are similar to those observed in known syn-sedimentary cements from Belize.
2.) This relict needle-like structure is characteristic of aragonite, but not calcite.
3.) Identical cements from the Canadian Arctic contain trace element strontium levels averaging 7,500 ppm., which is characteristic of marine precipitated aragonites (Belize samples average 8,300 ppm.) and is 7 to 8 times greater than strontium levels characteristic of primary marine calcites; relict strontium levels of Spring Hill botryoidal calcite are similar to those of the Belize and Canadian Arctic occurrences.
4.) The mere presence of excellent relict structure within an irregular calcite mosaic indicates either recrystallization or replacement of a precursor metastable carbonate phase such as aragonite or high magnesian calcite.

From a predictive standpoint, by comparison with the geochemical trace element data of Davies (1977), one would expect high strontium levels within the recrystallized mosaic if indeed the precursor was high strontium aragonite. On the other hand, absence of such high levels in some or all of the specimens would not preclude a strontium-rich precursor due to the tendency for strontium loss during recrystallization (inversion) of strontium-bearing carbonates.

While there are many similarities between Spring Hill botryoidal cements and those reported from Belize and the Canadian Arctic, a significant difference does exist. In the case of both Belize and the Canadian Arctic, botryoidal aragonite cements formed in highly porous, rigid boundstone frameworks in a shelf-edge setting. In the Spring Hill as well as other Upper Pennsylvanian mound-forming limestones in southeastern Kansas, botryoidal cements are developed in fabrics that are only locally grain-supported yet still contain fairly abundant large voids.

It can be seen by the Belize occurrence that botryoidal cement is forming in a somewhat unique hydrologic regime, namely, that of the reef front. It is likely that a combination of favorable fabric and hydrologic conditions promotes formation of botryoidal cements in the Belize case. Likewise, the Canadian Artic occurrences of botryoidal cement are found in a similar shelf edge setting. However, the fabric of the bryozoan "reefs" is likely transitional between that of the rigid Belize boundstones and less rigid Spring Hill "bank" deposits. While the Spring Hill fabrics are locally similar to those of the two analogs, there are cases where the fabric containing botryoids does not appear to have been frame supported in the sense of a lithified, rigid, boundstone framework. In fact, there is good evidence that the cement provided rigidity and support to what was an extremely open framework, especially in cases of massive botryoidal sparite such as algal-laminated lithology from Sycamore Quarry and that described by Ravn and Heckel (1978) from the Captain Creek Limestone Member; without the support provided by early precipitation of botryoidal aragonite on a large scale, the open frameworks of these lithologies might not have maintained their integrity upon even slight compaction. Thus, the indication is that this distinctive cement can occur in buildups in at least two different paleogeographic regimes: marginal shelf-edge reef front and organic buildups in an epeiric sea. In these two regimes the cement may play slightly different functions; merely void-filling in an already rigidly structured framework in the former, and further rigidifying a looser sedimentary framework as well as void-filling in the latter. The occurrence of distinctive botryoidal cements in deposits of these two regimes, points out the gradational nature between rigid reefs and nonrigid banks (Heckel, 1974).

Bladed, fibrous calcite is locally developed as an early-stage void filling. As suggested by Kendall and Tucker (1973) on petrographic grounds, some forms of bladed calcite reflect an aragonite (probably marine) precursor.

Bladed calcite cement, as suggested by Folk (1974), may also have formed through recrystallization of precursor aragonite which posessed fibrous morphology due to selective poisoning of sideward crystal growth by high Mg/Ca ratios. Observation of relict isopachous bladed rims within later stage blocky calcite void-fillings in other parts of the Member, suggests that some occurrences of bladed cements consisted of unstable precursor mineralogies. However, lack of fine needle-like relict structure similar to that observed in cements interpreted as former aragonite botryoids, does not favor an aragonite precursor for most observed bladed calcite.

Nonferroan, more or less equant, calcite void-filling cements display three modes of occurrence:

1.) A second stage of cement following botryoidal calcite that frequently fills the remaining void.
2.) The first stage of cement, composed of an irregular mosaic of fairly equant crystals, that forms in the absence of botryoidal void-filling.
3.) The first stage of intergranular cement (preceeded by isopachous rim cement selectively developed on most foraminifers), composed of coarse, clear, equant calcite mosaic that completely fills intergranular voids (as in brecciated calcilutite at Sycamore Quarry).

It is not possible to determine whether nonferroan calcite mosaic was precipitated in a marine or nonmarine diagenetic regime. This cement is demonstrably void-filling as evidenced by incomplete void fillings, local development of drusy fabric, the clear, sharp-bordered habit of the mosaic, and the absence of replacement features.

The upper part of Unit 2 is characterized by a first generation of irregular, equant nonferroan calcite. The absence of well developed first-generation botryoidal calcite in the upper part of the Unit on the east side of the mound at K-96 may be related to the decrease in abundance of large voids; the change in fabric between the upper and lower part of the Unit thus may account for observed differences in cement stratigraphy.

Ferroan calcite is the common late-stage cement in voids not completely occupied by previous cement generations. This cement is present in both the upper and lower parts of the Unit, but it is much more abundant in the basal part. The absence of numerous, large voids in the upper part of the Unit apparently reduced potential sites for extensive development of ferroan calcite void-fill, by allowing nearly complete cementation by earlier generation equant, irregular calcite mosaic.

Ferroan dolomite is a late-stage mineral, occurring either as void fillings within, or as replacements of preexisting cements and skeletal grains. That ferroan dolomite emplacement occurred after the other cements is evidenced by its isolated occurrence internally to other stages of cement and mud matrix. In the basal part of Unit 2, dolomite generally occurs as irregular isolated patches, or as large, coarsely crystalline masses. That some of the large masses are of void-filling origin is evident from rare incomplete void-fillings; in terms of texture and crystal morphology alone, however, these occurrences cannot always be distinguished from probable replacive dolomite. The replacive origin of some dolomite in Unit 2 can only be suggested from interpretation of gross fabric relationships; relict structure within what might be dolomite replacements of earlier cements is usually absent. Rare instances of isolated needle-like structure within ferroan dolomite masses and the highly irregular boundary between some dolomite patches and surrounding carbonates, suggests a replacive origin for at least some of the dolomite.

Solution processes have been active in Unit 2 as evidenced by the presence of thin stylolites and occasional inferred casts of molluscan grains. Observation on stylolites where they cut botryoids, indicates that little material has been removed during stylolite genesis. The most abundant evidence for small-scale solution is provided by frequent crushed micrite envelopes of phylloid algal blades. At the K-96 roadcut, solution-compaction has not been developed to such an extent that it produces a megascopically compacted fabric. In contrast, however, lithofacies from Sycamore Quarry show that significant compaction, following early partial lithification and moldic porosity development, has taken place. Small scale brecciation is ubiquitous in the upper-middle and upper parts of the Sycamore exposure. Solution-moldic porosity was provided by removal of algal material, whereas framework porosity was formed by abundant algal umbrella structures; significant collapse of angular mud fragments has occurred into both types of voids. That the collapsed mud fragments display little sign of deformation other than fracture may indicate that they were fairly well indurated; however, laboratory experiments (Shinn et. al., 1977) indicate compaction of non-indurated lime muds does not always involve conspicuous deformation of compacted fragments. In the case of Spring Hill breccia, it is evident that matrix was well enough indurated that included fusulinids were fractured along with mud upon collapse of the fabric.

Spar-Spot Skeletal Calcilutite (Unit 3)

Skeletal to sparry skeletal calcilutite forms Unit 3, the upper-middle 28 feet of exposed Spring Hill mound at the K-96 roadcut (Figure 4). Unit 3 is underlain by skeletal-algal sparry calcilutite to sparite (Unit 2), and is overlain by two feet of shale and four feet of skeletal calcarenite (Unit 4); the shale bed is unassigned as to Unit (Figure 4). Unit 3 lithologies at Carr's Quarry are similar to those at K-96, but there are some differences in stratigraphic succession. At Carr's Quarry no thin shale separates Units 3 and 4, and Unit 4 consists of oolite in contrast to skeletal calcarenite at K-96. The interbedded limestone-shale sequence that characterizes Unit 3 at K-96 and Carr's Quarry is absent at Sycamore Quarry. The uppermost exposure at Sycamore Quarry consists of medium-bedded, knobby weathering, brecciated foram-algal calcilutite; although this lithology does contain interbedded shales as in Unit 3 at K-96 and Carr's Quarry, they are not developed to the same degree. Futhermore, the carbonate lithology and fabrics in the interval at Sycamore Quarry are significantly different than those in Unit 3 at the other 2 localities; thus, although the two shale-parted lithofacies may be partial time correlatives of each other, correlation between them remains indefinite.

The contact between Units 2 and 3 at K-96 and Carr's Quarry is picked at the lowest traceable shale interbed. Strata above the contact consist of dense, bedded, grey skeletal calcilutite with distinctive brown calcite "spar spots", which are sparry circular to irregular cross-sectioned grains up to several millimeters in diameter; strata below the contact consist of thick-bedded to massive, crumbly, tan, sparry calcilutite. Unit 3 consists of distinctly bedded, dense, grey-weathering, skeletal to sparry calcilutite. Bedding ranges from medium to thick (3 inches to 2 feet) and is locally massive near the top.

The most well defined and continuous beds in the mound complex (except for the capping calcarenite facies) occur in the basal 12 to 15 feet of Unit 3 due to the presence of somewhat continuous shale interbeds.

Unit 3 is fossiliferous throughout, carrying a diverse marine benthic fauna dominated by crinoid columnals and containing echinoid plates and spines, bryozoans, molluscs, brachiopods, coralline red algae, foraminifers, corals, and shark teeth; identifiable phylloid algae are quite rare in this Unit. The major invertebrate groups seem homogeneously dispersed throughout the Unit. The only readily apparent biotic trend is a sizable increase in abundance of fusulinid foraminifers in the top few feet of the Unit.

Shale interbeds and limestone bedding planes are preferential sites of fossil accumulations. Large, intact crinoid stem segments and calyces, articulated brachiopods, intact fenetellid and other bryozoans, and apparent in-place accumulations of echinoid plates and spines occur often in shaley pockets and depressions on the bedding planes.

Unit 3 calcilutites are significantly different from other Spring Hill mound-forming calcilutites in the followin respects:

1.) Their distinct, moderately laterally continuous bedding style.

2.) The presence of discontinuous, wispy quartz-silt stringers several centimeters long.

3.) The presence of discrete thin shale interbeds (2 to 6 inches thick).

4.) Their dense, low-porosity fabric.

5.) The presence of abundant circular to irregular cross-sectioned, dark-brown "spar spots".

Discontinuous, dark-grey to tan silt stringers several millimeters thick commonly display a subparallel orientation to bedding (Figure 20a). Silty stringers are most abundant in the interbedded limestone-shale lower part of the Unit where one might suspect them to be argillaceous in composition; testing with dilute hydrochloric acid indicates that they contain appreciable carbonate. Less abundant but more unoriented, equant to irregular "pockets" of silty material are present in the more massive upper part of the Unit.

The abundance and mode of occurrence of sparry calcite is variable throughout Unit 3. Large Umbrella structures and associated coarse void fillings similar to those in underlying Unit 2 are rare in Unit 3. However, sparry calcite is relatively abundant in this Unit, occurring as small-scale void-fillings, intergranular cement in fossil-rich zones, neomorphosed mud matrix, replacements of bioclasts, and the numerous circular to irregular brown calcite "spar spots".

Spar spots are composed of brown ferroan calcite and clear to milky (occasionally turbid) ferroan calcite; occasional highly irregular ferroan dolomite spar spots are also observed (as revealed by laboratory staining of hand specimens). Calcite spar spots are most abundant in the lower (interbedded limestone-shale) part of the Unit, where they occur as discrete grains or coalesced masses of several grains floating in carbonate mud matrix or in sparry void-fillings; their distribution is generally random but occasionally they display preferred arrangement subparallel to bedding planes and associated silt stringers (Figure 20b). In hand specimen aided by a hand lens, the spots display irregular outer perimeters that give the appearance of having grown into surrounding matrix. Local concentrations of spots coalesce to form patches of brown spar up to several centimeters across. Only in rare instances can samples be found where the spar spots display a grain supported fabric similar to what one would see in an oolite. The above considerations give the impression, upon hand specimen examination, of probable diagenetic origin for this distinctive fabric.

Visibly crystalline calcite and ferroan dolomite are the common void-filling minerals in Unit 3; the calcite displays a variety of colors that include brown, irridescent brown, milky, and clear. The dolomite is typically white on fresh surfaces and weathers rusty-orange.

Figure 20--Hand specimen appearance of silty stringers and spar spots. Bar in lower right hand corner is 2.0 cm. long.

A.) Subparallel silt stringers (light zones) within calcilutite

B.) Crudely parallel accumulations of spar spots.

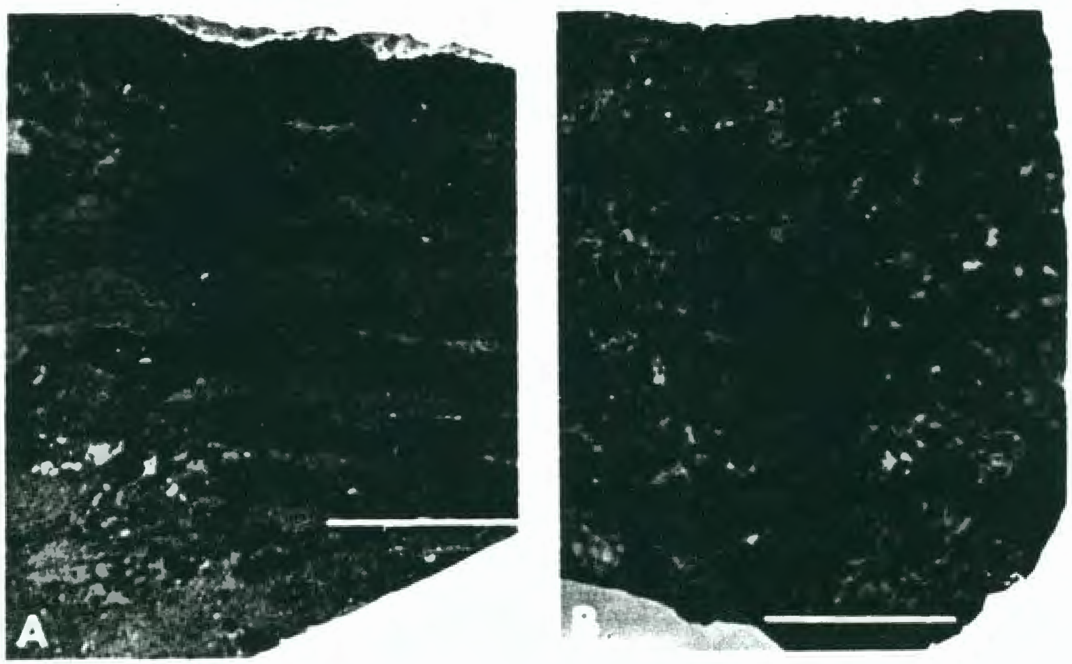


Figure 20

Other less common void-filling minerals include celestite, barite, and rare fluorite. Dickite (white clay) is a ubiquitous late-stage hydrothermal void-filling mineral located in small voids and frequently associated with ferroan dolomite (Hayes and Schroeder, 1968). Ferroan dolomite occurs as small, irregular to subcircular, coarsely crystalline patches and sharp-bordered late-stage void-fillings. Some of the irregular ferroan dolomite patches appear replacive in hand specimen because they transect earlier cement generations. However, in many cases the origin (replacive versus void-filling) of coarse patchily-distributed ferroan dolomite cannot be determined with certainty in hand specimen.

Although multi-generation cement sequences seem quite varied, several trends can be noted from hand specimens:

1.) Dickite appears to be a later stage void-filling mineral than either calcite or most dolomite, and emplacement of dickite may have involved partial replacement of previous carbonate generations as evidenced by irregular relationship between co-existing dickite and carbonate cements.

2.) Ferroan dolomite occurs as both a late-stage void-filling and as replacements of earlier cement generations.

3.) Calcite may have formed both early and late.

Void-filling of a large articulated brachiopod shows a complex multi-generation cement sequence within this Unit. First-stage cement displays a bladey to acicular morphology composed of clear to milky isopachous calcite; remaining void space is lined by irridescent-brown curved rhombohedral isopachous calcite; large schalenohedral calcite aggregates up to 4 cm. long incompletely occupy the void center, and acicular to platey celestite and an unidentified metal oxide (possibly manganese) occur nucleated on schalenohedral calcite.

Petrographic examination of the sequence immediately below the lowest shale interbed at the base of Unit 3 displays fabrics transitional to those observed in Units 2 and 3, illustrating the gradational nature between arbitrary lithologic units in the Spring Hill mound. The 5-foot thick section below the contact displays bedding characteristics (thick to massive and crumbly with ill-defined bedding) and a bryozoan-rich fauna characteristic of Unit 2. However, large-scale umbrella voids with coarse, sparry void fillings and the highly altered-grain fabrics characteristic of the lower and upper parts of Unit 2 (respectively) on the east flank of the mound are absent. The transitional section does contain irregular botryoidal void-fillings but they are rare and typically not as well developed as in the base of Unit 2, probably due to absence of large original voids conducive to their formation. Rare spar spots and fragments of spar spots characteristic of Unit 3 are also present in this section. Some of these features display characteristics reminiscent of void-filling, which when combined with an internal structure (finely radial and needle-like) similar to that of botryoidal cements produces the potential for mis-interpretation of some of the structures as void fillings. Consideration of gross fabric relationships as well as differences in external morphology, size, and texture of recrystallized mosaics, usually is sufficient to distinguish between the 2 occurrences of calcite mosaic with finely radial, needle-like internal structure (Figure 21a).

Petrographic examination of stained thin sections reveals that silt stringers, which appear argillaceous in hand specimen, are composed of approximately 80 percent carbonate, dominated by nonferroan calcite with lesser amounts of nonferroan dolomite. Other minerals in the stringers include quartz, clays, and unidentifiable silicates, all of which are silt-sized or smaller. Dolomite and quartz occur as highly irregular silt-sized grains apparently detrital in origin. Occasional rhombohedral dolomite is observed, which is possibly due to diagenetic enlargement of detrital dolomite. Silty layers are moderately to abundantly fossiliferous with biota identical to that of the enclosing calcilutite; small spar patches are also ubiquitous within the stringers (Figure 21b).

Figure 21--Spar spots and associated fabric. Bar in lower right hand corner is 2.0 mm. long.

A.) Irregularly shaped grain (G) composed of irregular calcite mosaic with finely radial structure in a matrix of spar, microspar, and pelleted mud. While having the appearance of a hemispherical botryoidal void-filling, fabric relationships suggest this is a fragment of a spar spot. An unidentifiable circular grain, possibly a sponge tube, occupies the center of the photo.

B.) Silt stringer (center) containing bryozoan fragment (B) and small sparry calcite patches. Many of the very small white areas in the silty zone are irregular quartz and dolomite grains; dolomite does not appear to stain positive for ferroan content, but this could be an artifact of fine texture. Two spherulitic spar spots (S), one irregular and the other fairly circular, appear to have been compacted or grown diagentically into the underlying silty zone.

C.) Two circular spar spots with interfering micritized perimeters. Relict needle-like radial structure is evident within their irregular nonferroan calcite mosaic. Central spot displays a foraminiferal nucleus with an early isopachous intraskeletal rim (white) followed by unicrystalline calcite void filling (dark). Spot on left engulfs irregular pelleted micrite patches.

D.) Irregular spherulitic calcite structures with cerebroid, micritized rims, surrounded by sparry calcite void filling. Internal micrite lines (dark) gives a concentrically laminated aspect to the structures. Accumulation of recrystallized internal sediment (I) upon the structure might suggest deposition as grains except for the presence of similar micrite on the underside of the void roof (I).

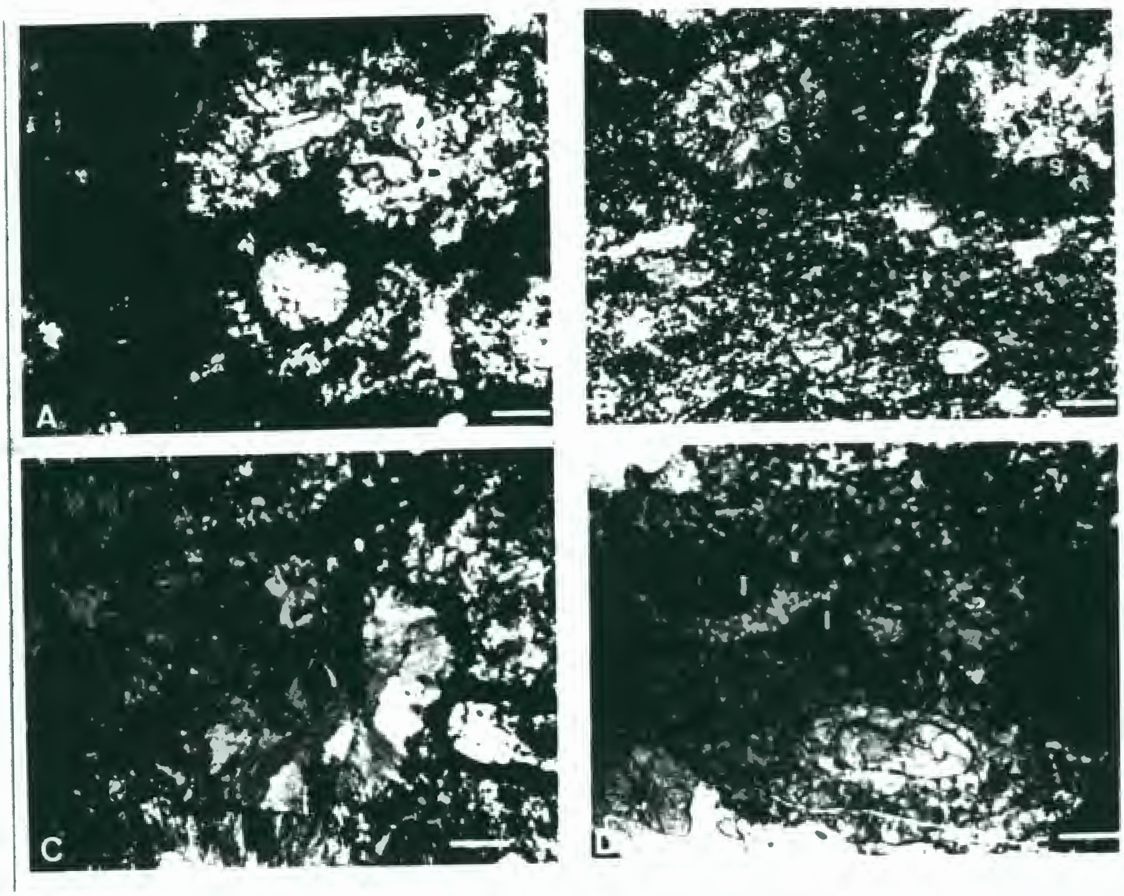


Figure 21

The presence of abundant circular to irregular spar spots throughout the Unit produces a distinctive texture not generally observed in other Upper Pennsylvanian mound-forming limestones in southeastern Kansas (P.H. Heckel, personal communication 1977). Their internal structure generally is radial, consisting of needle-like lines of minute inclusions within regular to irregular crystals and is hereafter termed "spherulitic". Their genetic interpretation is often quite equivocal, for not only do the structures display numerous mineralogies and degrees of alteration suggesting comples paragenesis, but also their fabric relationships suggest a complex perhaps polygenetic origin, both primary and secondary, as well as combinations of the two.

Possible origins for the structures worth considering include:

1.) Recrystallized, radially structured ooliths similar to hypersaline ooids described from the Great Salt Lake (Sandberg, 1975) and Persian Gulf (Loreau and Purser, 1973).

2.) Altered fragments of red algal buds without internal structure.

3.) A diagenetic enlargement of a depositional grain such as ooids or bioclasts.

4.) A slightly reworked (intraclastic) synsedimentary growth (i.e. a true spherulite).

5.) A late diagenetic spherulitic growth produced through recrystallization of lithified sediment. The goal in investigating this distinctive spherulitic fabric is to determine whether the features are primary or secondary in origin, or some combination ot the two; considerations will include internal structure, external morphology, and gross fabric relationships.

The most common external morphology of spherulitic spar spots is circular in cross section (Figure 21c) but irregular, fragmented, compound, and coalesced morphologies are also noted (Figures 21d, 22a, and 22b). Many of the irregular spots display sharp discontinuities in external morphology and internal structure suggesting fragmentation prior to deposition, and implying that whatever their origin, they eventually behaved as depositional grains (Figure 22a).

The perimeter of individual grains may be irregular with individual, or bundles of, bluntly terminated crystals extending into adjacent materials, but most commonly the perimeters are micritized and frequently display cerebroid undulations (Figures 21c, 21d, and 22a). In rare cases grains contain one or two internal micrite layers, which give the impression of relict concentric lamination (Figure 21d). One occurrence of what appears to be an oolitic outer cortical layer was noted; however, the curved rectangular crystal mosaic and absence of relict radial structure

Figure 22--External morphology of spherulitic grains. Bar in lower right hand corner is 2.0 mm. long.

A.) Irregularly shaped spherulitic spot displaying cerebroid perimeter with dark, micritized rim, part of which could possibly be an organic encrustation (E). The spherulitic grain, along with bryozoans, an ostracode, and numerous fuzzy micrite pellets and altered skeletal grains appear as a detrital accumulation within a spar-cemented void; finely crystalline rims preceeding later-stage blocky void fill are visible on many grains.

B.) Irregular spherulitic spot (lower right) along with other indistinct spherulitic spar spots (S), large crinoid columnal, and dark foram or bryozoan fragments. Large concentrically laminated oolith has undergone alteration of inner cortical layers producing a void into which preserved outer cortical layer has collapsed with compaction onto underlying spar spot; part of collapsed layer is visible (arrow). Preserved cortical layer is composed of blocky, rectangular calcite that conforms to concentricity of the laminae. This type of preservation contrasts sharply to irregular calcite mosaic that makes up spar spots.

C.) Part of a spar spot with an irregular, micritized rim displaying a possible highly neomorphosed encrustation. Outer boundary of left-hand spot is highly neomorphosed to microspar, whereas the other spot is less altered and displays faintly visible relict radial structure. Spherulitic spar spots seem depositional because of relationship with adjacent void-filling calcite, which displays distinctly finer rims surrounding the spar spots.

D.) Subparallel, coalesced spar spots floating in both pelleted matrix and clear, coarse void-filling calcite. Some spots contain fuzzy micrite pellets.

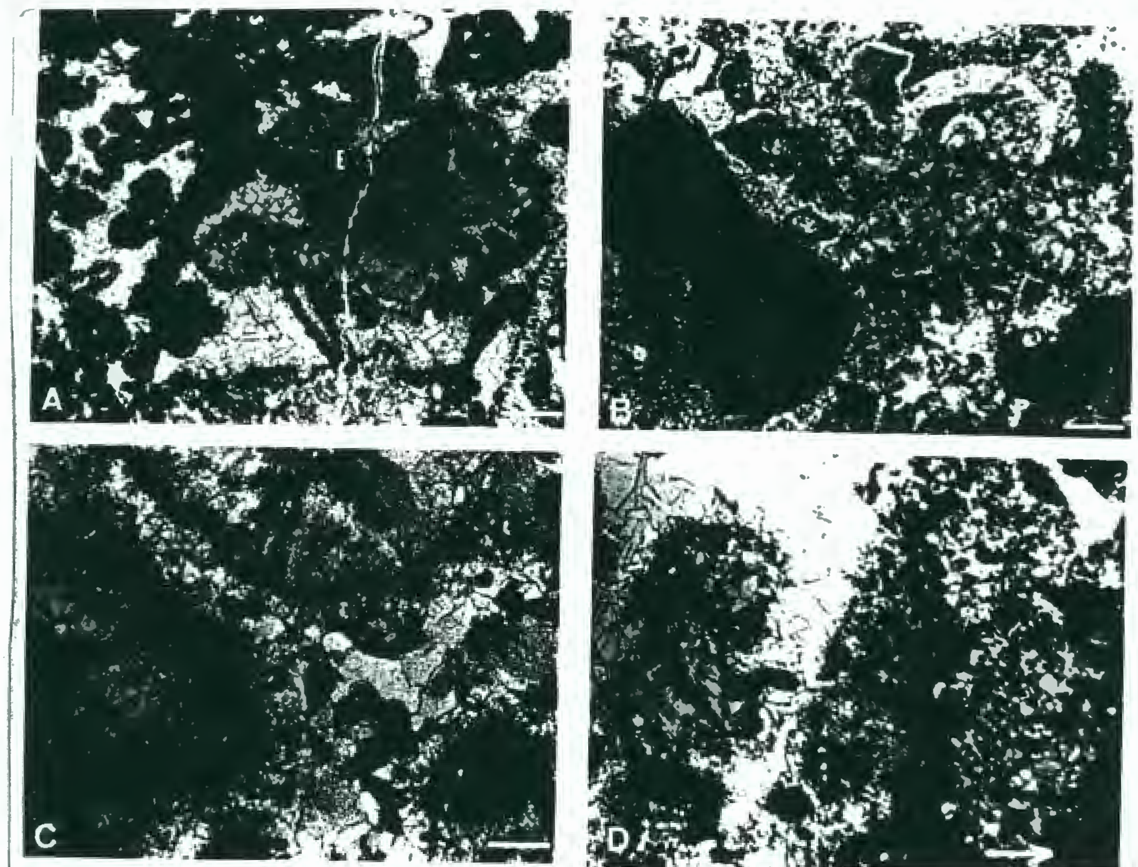


Figure 22

in this grain (Figure 22b) is in striking contrast to the majority of spherulitic grains (for example Figures 21c, 22d, and 22a). If this identification is correct, it means that these spar spots were deposited as grains in a marine environment, thereby eliminating the possibility of a very late diagenetic origin for these particular structures. Although the most common shapes are grossly spherical in cross section, elongate shapes with cerebroid perimeters are locally developed as isopachous crusts on altered bioclasts, in what appears to be, at least partially, a void-filling relationship (Figure 23c).

The internal structure of spherulitic spots consists of finely radial, needle-like inclusions in an irregular, blunt-crystal terminated calcite mosaic (Figure 21c and 22a). Retention of relict structure is variable within irregular, nonferroan calcite mosaics and is typically better developed in the coarser grained ones (compare Figures 21c and 22a with 22d). Some of the spots possess nuclei, and with no concentric laminations, appear to have grown outward along irregular fronts into surrounding material (Figure 21c). The most common recognizable nuclei are gastropods and forams; the general rarity of recognizable nuclei is probably due to a combination of the statistical liklihood in favor of tangential cuts, diagenetic alteration, and possibly lack of an original macroscopic nucleus.

The internal structure of most spherulitic spots is nearly identical to that of interpreted marine botryoidal cements, formed through recrystallization of inferred precursor botryoidal aragonite. However, several differences do exist:

1.) Inferred botryoids are grey in transmitted light, whereas spherulitic mosaics are invariably goldish-brown, possibly due to contained organic matter like one might expect in recrystallized ooliths.
2.) Botryoids typically display longer relict needles than do the spherulitic grains.
3.) Spherulitic spots are commonly recrystallized to a finer, more irregular calcite mosaic than are botryoids.

Fabric relationships of spherulitic spots are varied, and display aspects indicative of both primary and secondary origin, as depsitional clasts, void-filling cements, and diagenetic growths. Fabric relationships commonly indicate that most spherulitic structures, especially ones with circular cross sections, were deposited as discrete grains of possible oolitic or early, reworked diagenetic origin.

Grain-packed fabrics (typical of oolite) composed of spherulitic spots are occasionally developed within Unit 3 (Figure 23a); when present, they suggest that the spots could be a detrital accumulation; the presence of local grain-supported fabrics containing fractured spherulitic spots also favors this interpretation (Figure 22a). The

Figure 23--Fabric relationships of spherulitic spots. Bar in lower right hand corner is 2.0 mm. long.

A.) "Grain"-supported fabric composed dominantly of 0.5 to 1.0 mm. diameter subspherical spar spots with spherulitic internal structure. Other grains include crinoid and bryozoan fragments. Matrix is dominantly neomorphosed (microspar) pelleted mud.

B.) Indistinct spar spots in varying degrees of alteration, some containing pelleted micrite. Isopachous rims of drusy, bladed calcite (B) are nucleated on spar spots (S), reflecting possible substrate control by original radial structure. Final void-filling is accomplished by blocky calcite mosaic (B).

C.) Bioclast, possibly red algae, encrusted by irregular blocky calcite rim with internal structure of fine needle-like rays similar to that observed in botryoids; matrix is pelleted microspar. Cerebroid crust on underside appears to be a void filling, except that bottom of "void" is irregular. Presence of crust on top (with possible detrital pellet accumulation) as well as bottom of bioclast implies formation of crust prior to final deposition of clast.

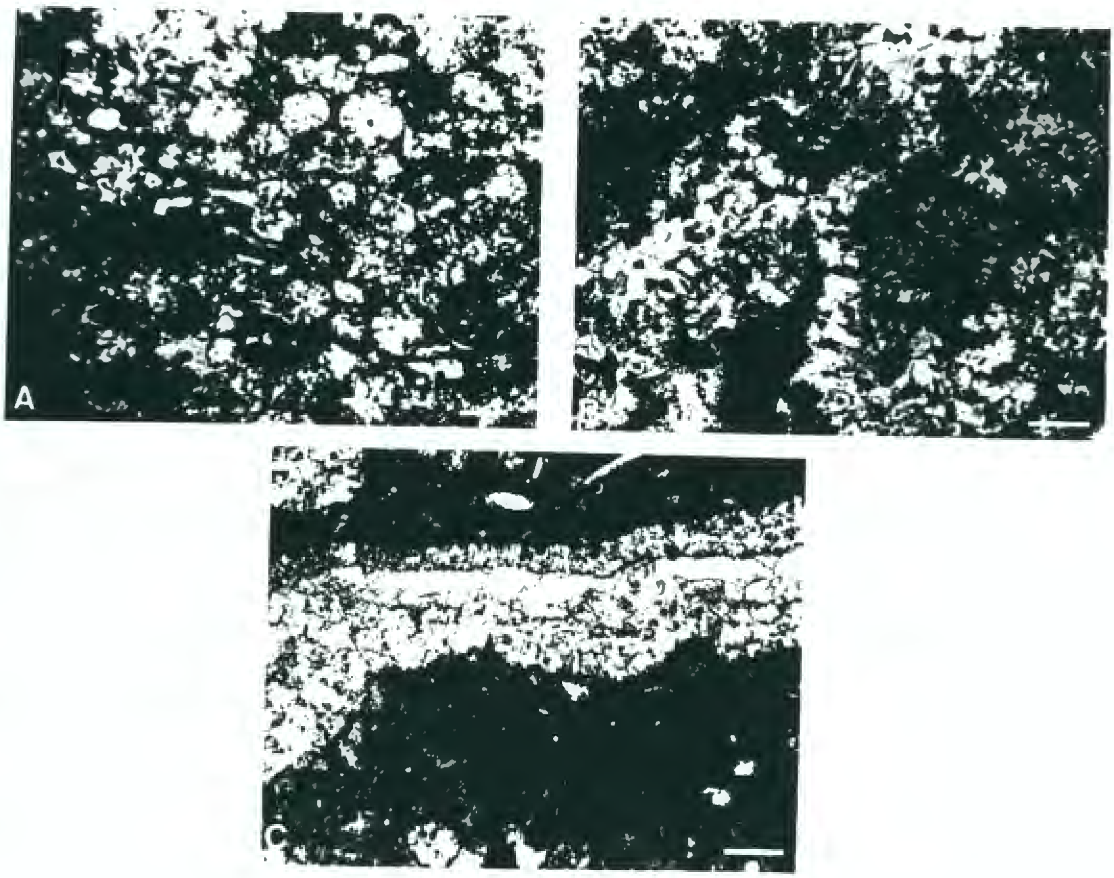


Figure 23

most conclusive evidence of detrital origin for the spots is provided by intergranular cement relationships. The presence of early-stage isopachous, bladed calcite rims followed by final void-filling blocky calcite shows that the spherulitic spot provided a substrate for void-filling cements and therefore must have acted as framework grains (Figure 23b). The above fabric relationships are exceptional, however, differing from the common situation in which the spar spots occur as isolated, coalesced, or juxtaposed structures (occasionally subparallel to bedding), 2-dimensionally suspended in neomorphosed pelleted microspar matrix, sparry calcite void-fill, or silt stringers; fabric relationships of the common occurrence frequently suggests a secondary origin for spar spots (Figures 22d and 21b).

Spherulitic calcite spots display numerous stages of alteration involving processes of recrystallization, replacement, and solution-mold development; these processes are polymineralic and include ferroan and nonferroan calcite and dolomite, and minor silica. The first stage in paragenesis involves recrystallization of a primary needle-like, radial fabric, producing an irregular calcite mosaic with relict radial structure preserved as fine radial lines of minute inclusions. The relict rayed structure in conjunction with blunt crystal termination in some of the fabrics are highly suggestive of an aragonite precursor. Similar relict structure has been interpreted as preservation of minute inclusions deposited within and between aragonite crystals during growth of the original needle-like fabric (Davies,1977).

The most common type of alteration following initial recrystallization to irregular calcite mosaic consists of solution and replacement processes, which produce unicrystalline (or nearly so) calcite and ferroan calcite spar spots; these processes typically involve complete loss of relict radial structure within the larger crystals (Figure 24a & b). Spots of both compositions (ferroan and non-ferroan calcite) frequently occur in the same thin section along with other spots that still retain their relict structure within irregular, nonferroan calcite mosaics; thus, this stage of alteration seems to be random. One distinct fabric composed entirely of large, unicrystalline ferroan calcite spar spots with well developed cleavage traces, contains turbid geopetal-like concentrations in the bottoms of the crystals, which is evidence for a distinct solution and void phase in genesis of these spar spots (Figure 24b). In other cases, ferroan calcite spar spots contain irregular to bladed inclusions of presursor calcite mosaic, implying that replacement also has been an active process in development of ferroan calcite spar spots (Figure 24c & d). Preferential retention of precursor calcite mosaic around the perimeter of ferroan calcite-replaced spar spots indicates that the replacement process began in the grain interior and moved outward (Figure 24c & d). Retention of patches of fine, irregular calcite mosaic in the center of ferroan calcite replacements may indicate that replacement of the radially structured part of the spheres was selective over that of the nucleus, which generally lacks radial structure.

Coarse ferroan dolomite is commonly localized within spar spots in all states of alteration. It may display sharp or highly irregular crystal interfaces with adjacent calcite, ferroan calcite, and silica (Figure 25a & b). It is difficult to determine whether ferroan dolomite associated with spar spots is void-filling or replacive. Some occurrences isolate calcite grains and display highly irregular perimeters, which embay adjacent unicrystalline ferroan calcite and suggest a replacive origin; in other cases the contacts between the two are sharp and straight, suggesting possible void-filling origin. Some dolomite patches display regular boundaries with ferroan calcite composing the spar spots and highly irregular boundaries with adjacent calcite mosaic void-fill (Figure 25c); thus the nature of the crystal contacts between dolomite and other phases is probably not a reliable indicator in determining replacive versus void-filling origin of dolomite. The typical occurrence of ferroan dolomite in both sparry void-fillings and neomorphosed matrix is one of highly irregular patches, which frequently isolate irregular, embayed

Figure 24--Spherulitic calcite spar spots altered to unicrystalline ferroan and nonferroan calcite. Bar in lower right hand corner is 2.0 mm. long.

A.) Nonferroan and ferroan calcite unicrystalline (or nearly so) spar spots (center and right respectively) in spar and neomorphosed pelleted matrix. Irregular perimeters and absence of relict structure characterize this type of recrystallization.

B.) Fractured, unicrystalline ferroan calcite spar spots in sparry pelleted matrix. The dark geopetal accumulation (G) in the lower half of some of the spots suggests solution-void-internal sedimentation-reprecipitation diagenesis. Entire sample is composed of mutually interpenetrating ferroan calcite spar spots.

C.) Two large spar spots displaying varying degrees of alteration. Central one is partially recrystallized to unicrystalline ferroan calcite with partial retention of precursor calcite mosaic (and crude radial structure) around perimeter and in the center; other spar spot is composed of highly irregular calcite mosaic but has lost any relict spherulitic structure.

D.) Replacement of spar spot by coarsely twinned unicrystalline, ferroan calcite with partial retention of spherulitic structure and bluntly terminated crystals around perimeter. Isolated inclusions of nonferroan calcite mosaic with traces of relict structure strongly suggest replacive nature of coarse ferroan calcite.

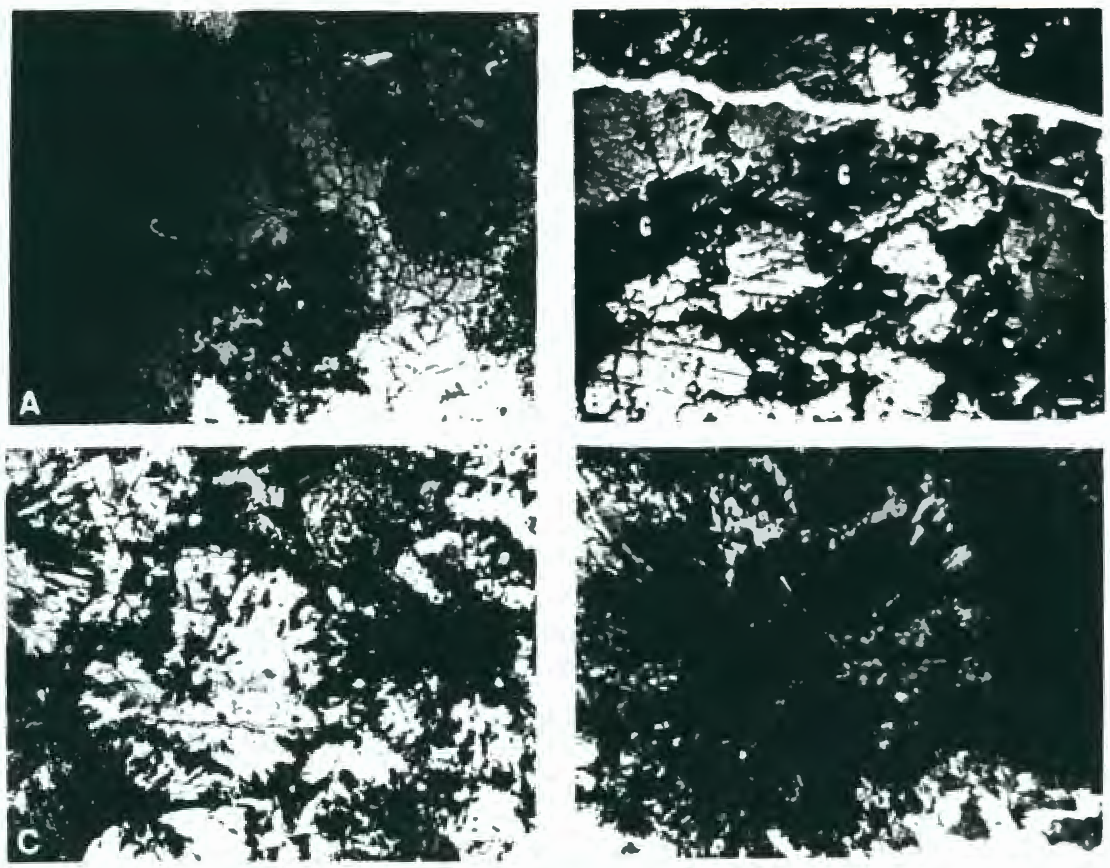


Figure 24

patches of calcite, suggesting a replacive origin (Figure 25d).

Dolomite displays several other modes of occurrence aside from that of irregular, coarsely crystalline patches. As previously mentioned, silt-sized dolomite of probable detrital origin is present in silty stringers. Silt-sized euhedral rhombs are present as possible diagenetic enlargements of detrital dolomite, pervasive replacements of fine-grained matrix (rare), and also, quite rarely as replacements of unicrystalline ferroan calcite occupying some spar spots. Replacive rhombs in unicrystalline spar spots occur as unidentifiable concentrations of inclusions under low power (Figure 26a); inspection under high power displays their sub- to euhedral crystal habit (Figure 26b). An interesting feature of this replacement is that the rhombohedra are nearly all in optical continuity with the ferroan calcite host, suggesting host control over crystallization of replacive dolomite.

Replacive silica is present in small amounts near the middle of the Unit. It displays the fibrous, feathery texture typical of chalcedony. Replacement by silica is apparently nearly nonselective because all fabric components except bioclasts are observed in various stages of replacement. Borders of silica masses may be irregular (Figures 25a-d, 26c, and 26d) or planar (Figure 25a); borders are locally observed conforming to step-like cleavage traces

Figure 25--Replacive silica and coarse ferroan dolomite. Bar in lower right hand corner is 1.0 mm. long.

A.) Replacive silica (S) with isolated ferroan calcite remnant (F). Note irregular border between silica and dolomite (D) and fairly regular border with large ferroan calcite crystal. Large ferroan calcite crystal contains numerous minute inclusions which may represent relicts of former recrystallized spherulitic calcite mosaic except that the inclusions are not radially aligned.

B.) Silica (S) displaying step-like boundary which conforms to dolomite (D) cleavage, sharp, straight border (with minute embayments not readily visible in photo) with ferroan calcite crystal (F) and highly irregular border with microspar (M).

C.) Straight, step-like boundaries between dolomite and large ferroan calcite crystal (black), highly irregular boundary between ferroan dolomite (D) and adjacent fine mosaic (M)

D.) Large patch of coarse ferroan dolomite with long rod-like pendant of calcite mosaic (C) extending into dolomite patch; this suggests a replacive origin for much of the coarse dolomite that displays this common relationship.

All photomicrographs are with crossed polarizers.

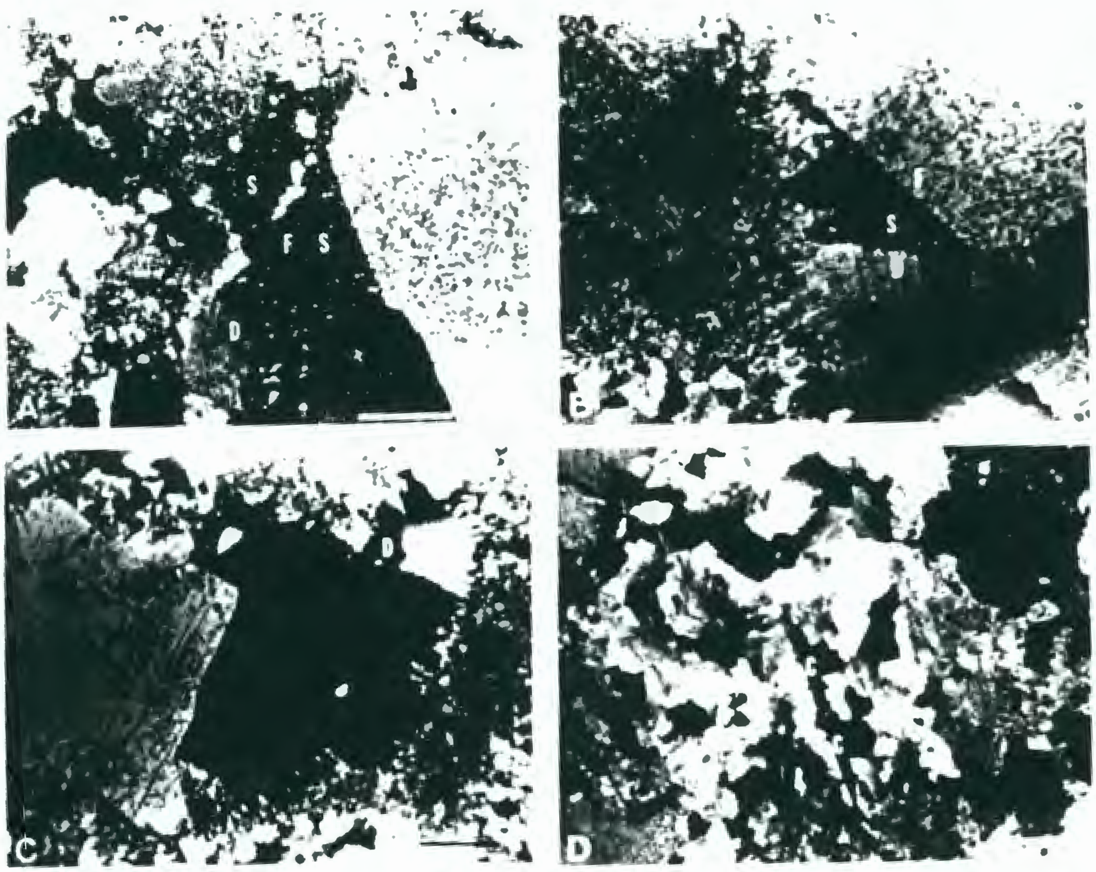


Figure 25

of ferroan dolomite (Figure 25b). Silica is locally observed isolating irregular dolomite and calcite patches (Figure 25a). In rare cases one can observe nearly complete silicification of precursor unicrystalline ferroan calcite spar spots (Figure 26c). Comparison of silica boundaries reveals a trend toward more planar boundaries adjacent to large unicrystalline, ferroan calcite and dolomite, and toward highly irregular boundaries adjacent to finer calcite mosaics and neomorphosed matrix; although irregular boundaries also occur adjacent to unicrystalline masses, they are less common. This relationship of boundaries to crystal size in partially replaced fabrics presumably results from lesser stability in the diagenetic regime (and hence higher reactivity) of finer-grained materials of a particular mineralogy.

Inter- and intragranular cement morphologies and sequences are quite varied within Unit 3. The most voluminous cement consists of clear, blocky, nonferroan calcite which is particularly well developed in geopetal voids (Figure 27a) and interstitially in local calcarenite fabrics (Figure 22a). While this cement fabric can be observed to completely fill voids, it is frequently preceded by earlier generation cements with different morphologies. The most common morphologic predecessor consists of a thin irregularly developed rim of equant to crudely bladed morphology (Figure 22c); in some cases this rim may just

Figure 26--Replacive dolomite rhombohedra and silicification. Bar in lower right hand corner is 1.o mm. long.

A.) Ferroan calcite spar spot with concentration of minute inclusions.

B.) Same as "A" but under high power. Numerous 10 micron dolomite rhombs displaying sub- to euhedral morphology; most rhombohedra are optically continuous with host ferroan calcite.

C.) Nearly complete silicified spar spot. Silica is definitely replacive as evidenced by isolated calcite grain (C). Some unreplaced but spherulitic mosaic is still present around perimeter of silica, with highly irregular contact.

D.) Spar spot recrystallized to a nonuniform calcite mosaic displaying only poorly developed relict structure; center of spot is occupied by replacive silica (black with white specks).

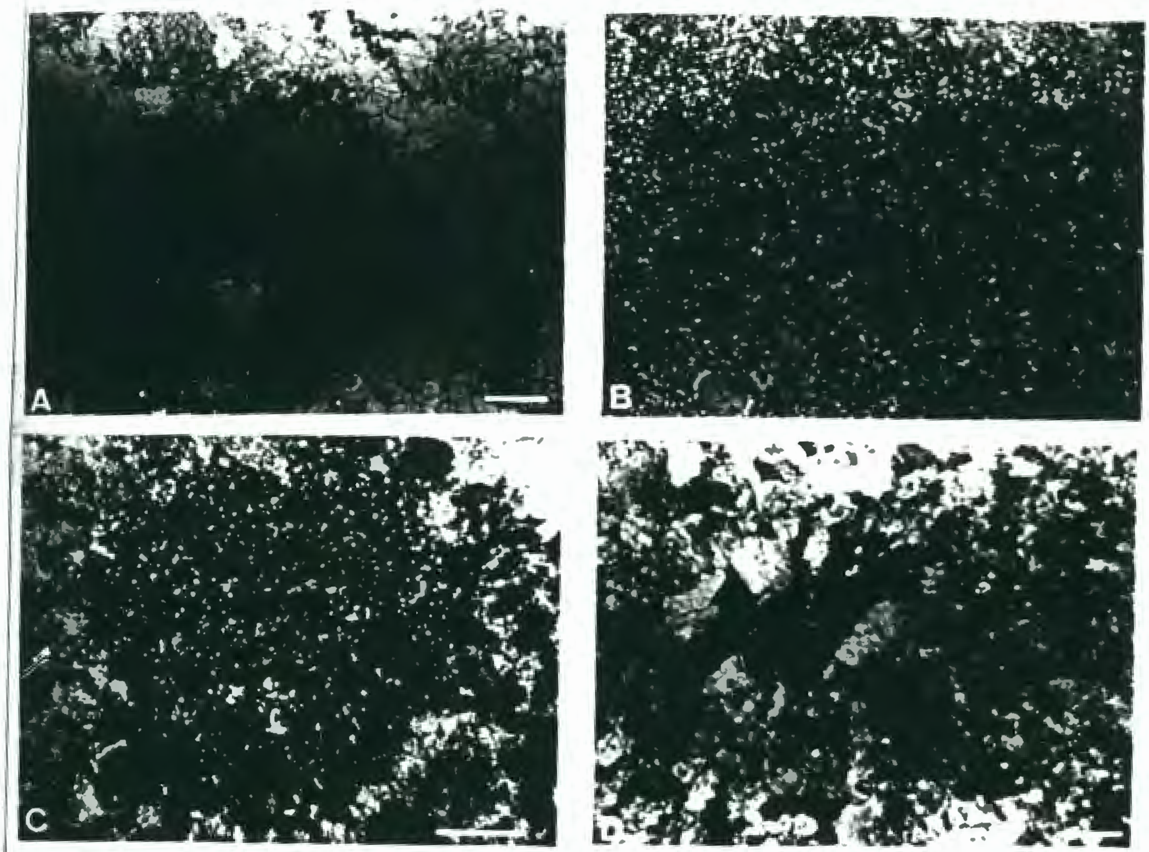


Figure 26

represent finely crystalline initial nucleation of the blocky mosaic and not a separate stage of cementation. In other cases, fairly extensive acicular needle-rim cements are developed locally on foraminifers and bryozoans, and represent as early stage of cement with excellent expression of substrate control on crystal orientation and morphology, but not necessarily mineralogy; the acicular habit of these rims is suggestive of aragonite or high magnesian calcite precursors, whereas preservational evidence suggests that most foraminifers and bryozoans were initially calcite (Figure 27b). Another early morphologic cement stage that precedes blocky mosaic consists of bladed isopachous cement rims which fill significant portions of adjacent void space (Figure 23b). These bladed rims do not display relict turbid, needle-like inclusions as do similar bladed rims in the overlying calcarenite. The bladed morphology could be a reflection of substrate control either by the original aragonitic rays constituting the spherulitic grains, or the narrow, blunt-tipped crystals to which distal ends of the spherulitic structures have been recrystallized. Other distinctive, although less common, cements include large blades composed of constituent rayed subcrystals with optic axes that diverge away from the substrate (Figure 27c), and equant, blocky rims followed by very coarse ferroan calcite with strained extinction (Figure 27d).

Figure 27--Void-filling cement fabrics. Bar in lower right hand corner is 2.0 mm. long.

A.) Gastropod composed of blocky calcite typical of molluscan casts. Geopetal internal sediment consists of pellets and an ostracode whose interior is filled with bladed calcite crystals that meet along a serrate central junction, reflecting substrate control exerted on the void fill by the fibrous microstructure (perpendicular to the shell wall). Gastropod shell is filled with common void-filling irregular to blocky calcite mosaic characterized by an increase in crystal size away from the substrate.

B.) Fibrous, acicular rim of inferred precursor aragonite on bryozoan reflects substrate control on the orientation (but not mineralogy) of early cementation; final void-filling is blocky calcite.

C.) Complex cement sequence. Early stage recrystallized botryoidal hemisphere (B) with a very thin, fine-grained, blocky rim is followed by large compound blades composed of individual subcrystals with optic axes that diverge away from the substrate. Final void filling is by coarse ferroan calcite. Microspar material on which blades nucleated contains abundant replacive dolomite rhombohedra (many of the bright white specks).

D.) Void-filling sequence begins with very fine blocky calcite followed by coarse, equant, blocky calcite, with final stage void-filling of large crystals of ferroan calcite containing strained to elongate subcrystals.

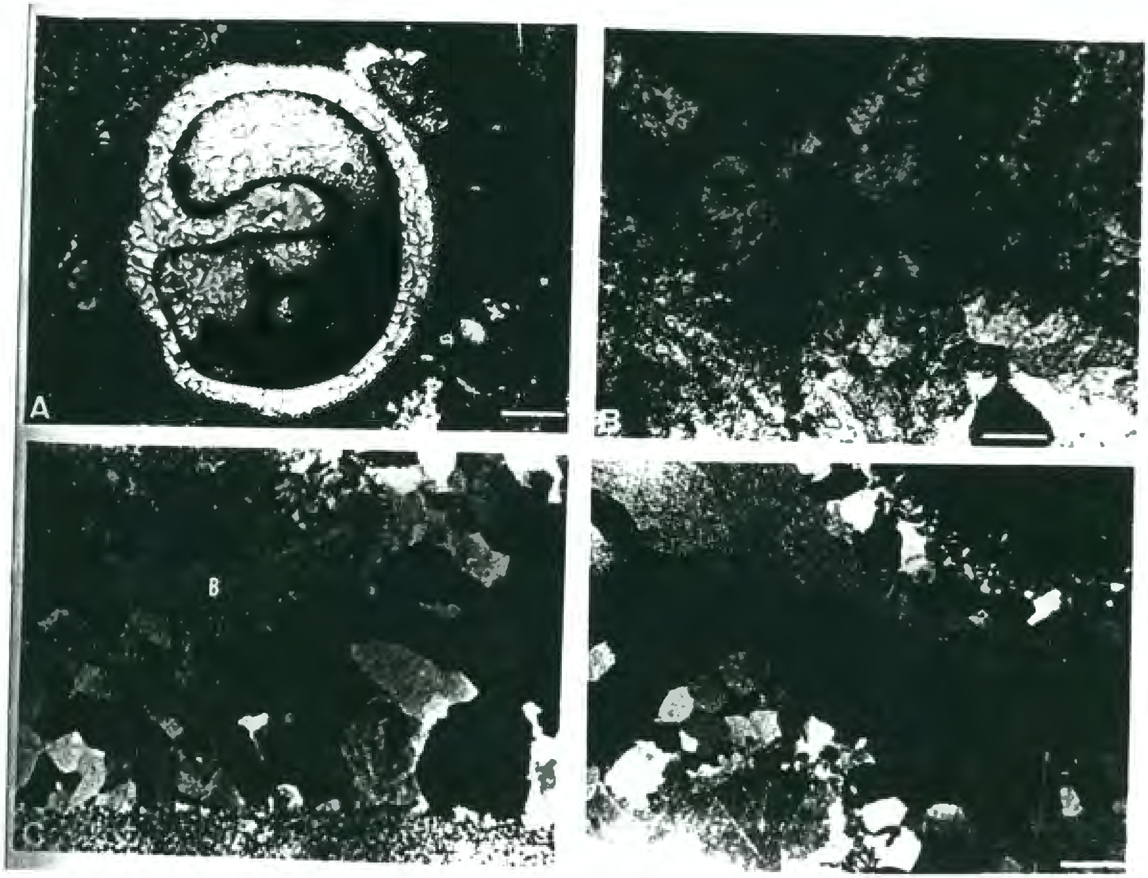


Figure 27

One occurrence of equant, blocky mosaic displays the close relationship between processes of neomorphism and void-filling. An excellent gradation in crystal size passing from a void into adjacent micrite can be observed in Figure 28a. It is difficult to tell where so-called void-filling stops and neomorphism begins. Fluids from which the void filling crystallized may have permeated micropores within adjacent micrite causing crystal growth of some grains with incorporation of remaining grains in the fine sediment.

Substrate control of void-filling cements is developed to varying degrees. As previously mentioned, acicular rims are occasionally developed on bryozoans and forams, and bladed rims occur on many local occurrences of grain-packed spherulitic spar spots. Crinoid columnals typically display well developed syntaxial overgrowths, with occasional slight variations involving bladey, though nearly syntaxial overgrowth (Figure 28b); this type of overgrowth is especially well developed when the serrate structure on the edge of the columnal acts as the substrate.

Skeletal preservation is variable but related to differences in original mineralogy, as discussed in previous sections. Crinoids are typically well preserved, as are fusulinids, and, to a lesser extent, bryozoans (Figures 22b, 28c, and 27b respectively). Molluscs are typically poorly preserved and occur as probable casts occupied by clear,

Figure 28--Miscellaneous fabric elements. Bar in lower right hand corner is 2.0 mm. long.

A.) Size gradation from very fine microspar into blocky calcite void-filling mimics neomorphism. Large-scale view of thin section reveals that coarse spar occupies a void. Some recrystallization of micrite has occurred possibly due to interaction between void-filling fluids and microporosity within mud at base of void. Distinction between processes of neomorphism and void-filling is more one of scale than mechanism.

B.) Nearly optically continuous but distinctly bladed crinoid overgrowth partially cementing small sheltered void. Clear rim of blocky calcite has nucleated on mud forming base of void.

C.) Well preserved fusulinids in microspar and patchy coarser calcite matrix. Most minute bright white spots in microspar matrix are nonferroan dolomite rhombs. Curved streaks are artifact of thin-sectioning.

D.) Partially preserved pelecypod valve displaying selective preservation of prismatic calcite layer (P). Aragonite and calcite valve was initially incrusted by forams (F) prior to dissolution of aragonite shell layers. Mold was then filled as individual prisms of the preserved prismatic layer grew into the void, followed by unicrystalline final void fill (U). Note excellent preservation of fine lines (probably organic matter) perpendicular to prisms in the calcite layer. This selective preservation of prismatic calcite was noted also in overlying calcarenite of Unit 4.

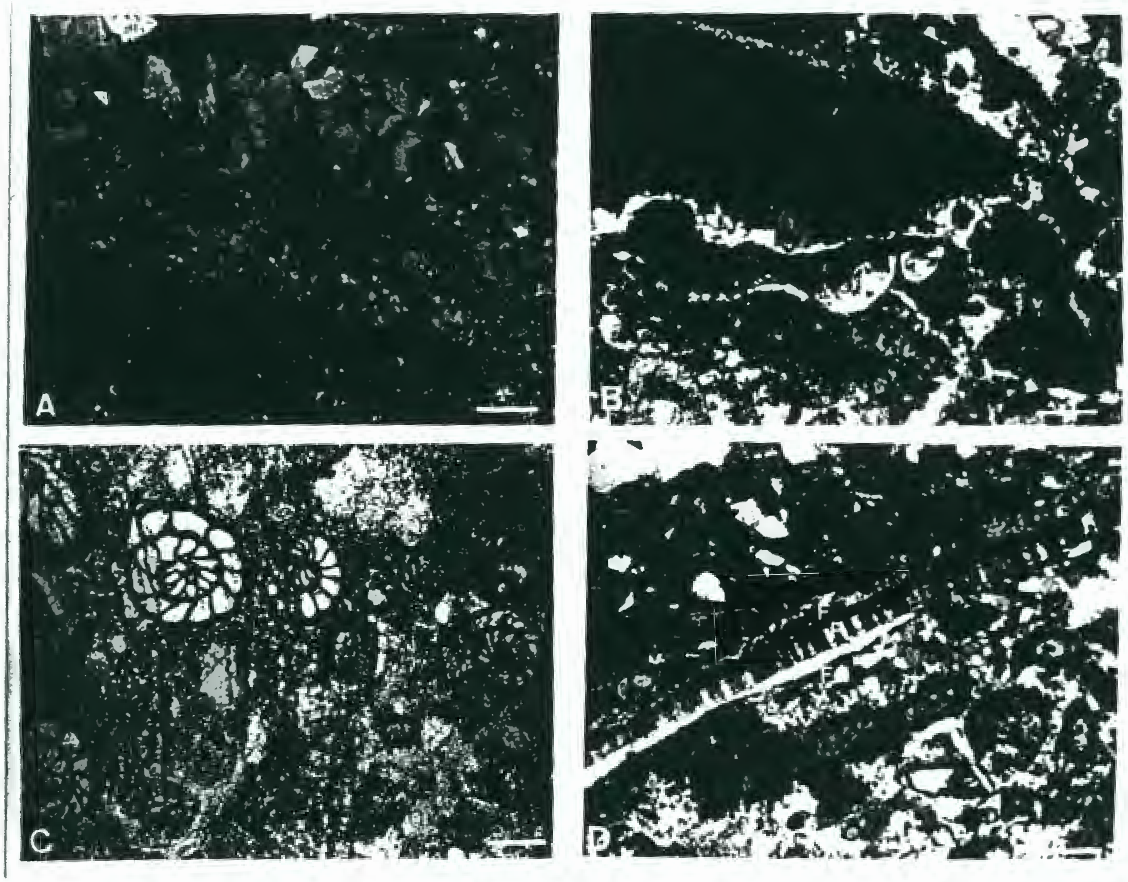


Figure 28

blocky, void-filling calcite (Figure 27a) that displays no relict structure; in rare cases, preservation of the prismatic calcite layers characteristic of particular bivalves is observed, while associated layers of original aragonite have dissolved (Figure 28d).

Neomorphism of fine-graind matrix is pervasive throughout the Unit. Pellets and intraclasts are typified by fuzzy, indistinct borders and are commonly recrystallized to microspar and spar.

Depositional Environments

Unit 3 as a whole carries a diverse marine benthic fauna indicating fairly normal marine conditions throughout deposition. Periods of shale deposition did not produce a noticeably restrictive effect on the observed faunal distribution. Fully marine organisms that are abundant include inferred stenohaline crinoids and to a less certain extent corals. Abundant suspension-feeding echinoderms, bryozoans, and corals indicate fairly low turbidity during deposition of most of the Unit, although lithologic considerations indicate there must have been periods of at least slightly increased turbidity associated with silt stringers, and periods of potentially great turbidity (unless shale deposition was very slow) associated with shale interbeds.

Though dominantly calcilutitic in lithology, the local zones of calcarenite, silt stringers, and well developed shale interbeds in Unit 3, record the transition from the quiet, clear-water environments below wave base, of underlying Units 1 and 2, to the highly agitated calcarenitic environments of overlying Unit 4. The transition was characterized by more conspicuous detrital accumulation which produced the shale interbeds. These interbeds may indicate periods of greatly increased detrital influx from the southwest that temporarily overwhelmed the normal rate of carbonate mud production within a dominantly carbonate regime, or the shale interbeds may represent a slowly deposited accumulation during periods of decreased carbonate mud production.

In addition to the shale interbeds, detrital influx was also responsible for the numerous silty stringers that contain detrital quartz and dolomite as well as lesser amounts of clays. The silty stringers contain a diverse biota, which might imply that the deposition of silt as distinctive accumulation resulted from a decrease in the normal rate of carbonate mud production. Another possibility for the origin of silt stringers is that they represent storm deposited sediments which accumulated in depositional lows; the wispy, discontinuous nature of these features may favor this second possibility as to their origin.

Associated spherulitic spar spots display many similarities to hypersaline ooids described from Great Salt

Lake (Sandberg, 1975). If, in fact, spherulitic spar spots were of hypersaline origin, it would require a restricted source from which they could have been derived along with the observed detrital quartz and dolomite. The mixed-calcilutitic nature of the limestone and disarticulated nature of much of the contained biota (except in shaley pockets and interbeds) might suggest that much of the calcilutite could be a transported, rapidly deposited part of the Unit. Although a more thorough discussion on the possible origin of spar spots follows, there is no evidence to date of restricted hypersaline environments within the Upper Pennsylvanian Kansas sequence that could have acted as a source of hypersaline ooids; the closest potentially restricted area would be to the southeast on or around the Ozark Dome. The overall direction of detrital encroachment into the Kansas carbonate sequence was from the southwest off the Ouachitas; therefore, conjecture as to a possible intermittent source of hypersaline sediment from the south-east, would require a 90 degree shift in source direction, which could possibly be accomplished by storms.

The occurrence of intact crinoid stem segments and calyces as well as echinoid plates with spines, which appear to be in-place post-mortem accumulations, indicates rapid burial by the shale. Thus, fossil accumulations not only reflect mortality related to periods of increased turbidity, but also support the possibility of storms as a mechanism of rapid detrital influx.

Discussion of Diagenesis

The most distinctive and problematical diagenetic structures in Unit 3 are the spherulitic spar spots. There are enough structural similarities between spar spots and botryoidal void-fillings to imply that even though the two fabric elements now represent different textural components, there may have been similarities in the chemical systems from which they crystallized; these similarities are twofold:

1.) They both possess relict structure expressed as finely radial lines of minute inclusions in recrystallized mosaics; this relict structure is similar to the structure observed in certain modern aragonite void-filling cements, most notably botryoidal aragonite from Belize (Ginsburg and James, 1977); it is also similar to structures observed in other Upper Paleozoic strata, which has been interpreted as original aragonite.

2.) The structure is best retained in coarse, nonferroan calcite mosaics; subsequent alteration to dolomite and unicrystalline ferroan calcite typically involves loss of structure.

Although similar in structure, major differences between botryoidal void-fillings and spar spots lie mainly in their genesis and fabric role:

1.) Fabric roles are distinctly different with botryoids forming as a submarine, void-filling cement, and spar spots possibly growing as syndepositional spherulites in sediment with later deposition as clasts.

2.) Morphologically the structures are different. Botryoids generally occur as hemispheroids with a large external surface of nucleation and attachment, whereas spar spots are typically spheroids with completely free external surfaces. The locally irregular surfaces of the spheres display small-scale cerebroid perimeters similar to the botryoids; they also possess a nucleation surface, but it is internal and 3-dimensional.

3.) The scale of the two fabric elements is quite different with botryoids being noticeably larger. Internally, individual needle-like structures are much longer and more continuous in botyoids.

4.) Both structures possess internal laminations, which appear to be due to internal sedimentation upon growing botryoids and a type of micrite envelope in the spar spots. In spar spots, laminations are concentric and rare, whereas in botryoids they are hemispherical, reflecting gross morphology, and quite common.

5.) While both initially recrystallized to calcite mosaics that preserve relict structure, the mosaic of botryoids is very coarse to unicrystalline whereas that of spar spots is less coarse and is characterized by nearly complete loss of relict structure upon recrystallization to very coarse mosaics or single crystals.

6.) Botryoids occasionally contain intact marine invert-abrates within them, which have not been identified with certainty (except as nucleii) in spar spots.

7.) Botryoids are typically dark-grey in transmitted light whereas spar spots are an organic-appearing goldish-brown.

It can be seen that the two structures are genetically distinct in some respects. However, it is probable that similar chemical systems may have prevailed, one within voids and the other possibly on the open sea floor, during crystallization of the two mineralogically and structurally similar crystal fabrics. The differences may be more of degree than kind. It is also possible that the same minerals could produce similar structures in relatively distinct chemical microenvironments within the same marine regime.

Several possibilities exist as to the origin of spherulitic spar spots, some of which were outlined earlier. A discussion and evaluation of these possible origins are now presented.

One possibility is that they are algal. The nonferroan calcite mosaics that constitute most spar spots and retain internal structure, as well as other fragments composed of similar mosaics and lack structure, possess a distinctive reddish to goldish-brown color similar to that observed in many coralline and rarer solenoporid red algae found in Upper Pennsylvanian rocks of Kansas (Heckel, 1975). As a matter of fact, I have been able to consistantly use this seemimgly tenuous criterion to identify red algae in the overlying skeletal calcarenite (Unit 4) at the K-96 cut. In the calcarenite, grains are initially identified by color, and closer inspection under high power usually reveals the characteristic algal cellular microstructure. The problem with this potential source for spar spots is primarily that solenoporid algae possess a radial, needle-like structure only on certain cuts, whereas all spar spots that display structure are radial. Also, the needle-like structure of the spots displays no other orgnic structures of the solenoporids that Heckel (1975) illustrated, such as cross partitions. Some of the irregular spot-like fragments that consist of irregular calcite mosaic, posses the characteristic color, but lack relict rayed structure, may be red algal fragments, but these constitute only a small porportion of the grains.

The possibility that the structures are a true spherulitic growth (i.e. post depositional and formed in place through neomorphism or metamorphism) deserves some consideration but can nevertheless be discarded for most spar spots. Although the carbonate mound has been subject to low-grade hydrothermal metamorphism, which could potentially produce such a structure, many of the spots have obviously been transported and deposited as clasts, as evidenced by fractured grains, and depositional fabrics displaying intergranular cement rims followed by later-stage blocky calcite void filling. It is nevertheless possible that hydrothermal induced factors could have played a role in later diagenesis of the structures.

The most reasonable origin, based on inductive reasoning and simplicity, is one of an ooid or ooid-like origin. By modern analogy we can induce that ancient nonskeletal depositional spheroids probably invlove processes similar to those observed today. Also, for reasons of simplicity, we will see that this origin does not require us to invoke any new hypothetical or previously unobserved mechanism, but rather just some minor modifications of already described mechanisms.

Considering possible oolitic origin, modern ooids typically form in agitated environments that produce a dominantly tangential orientation of crystallites favoring development of a concentrically laminated cortex. This type of mechanically abrasive control is well documented in many occurrences of Recent oolite formation. The problem in applying this type of agitated ooid formation to the Spring Hill spar spots is that they generally lack concentric lamellae, and when it is present it is only superficially developed. Although we might assume that any tangential structure has been destroyed during diagenesis, when concentric structure is developed, it consists of 3 or less distinct concentric rings separated by radially oriented relict structure; this suggests that tangential concentric structure was never extensively developed. Other lines of evidence against this type of ooid formation are gained by inspection of definite ooliths in both mound and offmound facies of the Plattsburg. Thin sections of the pisolitic facies of the Plattsburg (also see Conley, 1977) as well as the oolitic facies in the upper Spring Hill at Carr's Quarry are characterized by relict concentrically laminated cortices. In neither case were ooliths from these localities observed to display relict radial orientation. Thus, it would seem that the agitated environment of formation of these ooids, all in clean calcarenites, did not produce the spherulitic spheroids found in Unit 3 at the K-96 roadcut. Therefore, we must investigate other possible environments of ooid formation.

The internal radial needle-like structure of the spar spot spheroids is very similar to that of aragonite ooids reported from hypersaline environments in the Great Salt Lake (Kahle, 1974; Sandberg, 1975) and restricted coastal embayments and lagoons of the Persian Gulf (Loreau and Purser, 1973). The radial structure of Great Salt Lake ooids is periodically interrupted by concentrically laminated zones composed of clays or finely textured, unoriented aragonite crystals. The Spring Hill structures display cerebroid boundaries similar to those illustrated by Sandberg (1975, figure 14), but lack recognizable clay concentrations in the saddles. Nevertheless, it is likely that clay or some other accumulation initiating cerebroid development was not preserved.

Aragonite ooids forming in restricted shoreline embayments and lagoons in the Persian Gulf possess well developed radial orientations because the environment of formation is very quiet; thus much of the growth takes place with the spheres sitting on the bottom (Loreau and Purser, 1973). Intermittant to mild agitation does produce poorly developed concentricity in some of the ooids, but in general they lack internal lamellae and commonly possess irregular spherical shapes due to lack of mechanical abrasion during their formation.

Inferring a hypersaline origin for spherulitic spar spots in Unit 3 on the basis of modern analogy to those formed in the Persian Gulf involves a major problem of potential source for the ooids. To date there are no strata within the Missourian sequence in Kansas that display evidence of significantly restricted hypersaline conditions. The strata in Unit 3 that contain the highest concentration of spherulitic spar spots are interbedded with shales and contain silty stringers rich in detrital quartz and dolomite. This reflects detrital influx from outside the algal-mound belt, and implies fresh water influx as well. Two possible detrital sources at this time were the Ouachita fold belt to the south and the cratonic Ozark uplift to the east. It is generally accepted that detrital sediments that encroach onto the carbonate environments of southeastern Kansas did so from the southwest as evidenced in the Plattsburg by southwestward gradation of the Spring Hill mound into shale within two miles of both the K-96 and Sycamore Quarry exposures. We might conjecture long distance storm transport of hypersaline ooids from potentially restricted environments around the Ozarks to the east, but evidence for this is lacking because the Plattsburg is at its eastern erosional limit in the present study area.

The relict internal structure, irregular cerebroid morphologies, and general lack of concentricity suggest formation of finely radial structures in quiet environments. That some transport subsequent to formation has occurred, is evidenced by fractured spar spots. A logical possibility for origin of spar spots is recrystallization of radially-structured ooids in a local environment, which, in view of the associated biota, must involve nearly normal marine salinities. The work of Lees (1975) indicates that modern oolite distributions are controlled both by salinity and temperature such that as water becomes progessively warmer, ooids can form under slightly lower salinities. Nevertheless, Lees' data suggests that ooids are not likely to form in salinities much less than those of the most saline open marine environments. Thus the possibility of ooids forming in warm, quiet water under normal marine conditions seems possible though not strongly supported.

From the possibilities discussed, the most likely origin for many of the ooid-like structures is as apparently chemically precipitated aragonite growths (supported by high strontium levels) formed on a somewhat stable substrate in a quiet environment, probably in warm water in shallowing seas at or slightly above normal salinities. This is supported by the stratigrahpic position of Unit 3 between more offshore Units 1 and 2 and shoal-water Unit 4.

Spherulitic spar spots display many degrees and types of alteration involving replacement of spherulitic-structured calcite mosaic by ferroan calcite, ferroan dolomite, and silica, as well as extensive solution-mold development followed by precipitation of void-filling calcite, ferroan calcite, and possibly ferroan dolomite. Figure 29 illustrates a diagramatic representation of spar spot paragenesis, beginning with the inference that spar spots were originally composed of radially-structured

Figure 29--Flow diagram illustrating paragenesis of spherulitic spar spots.

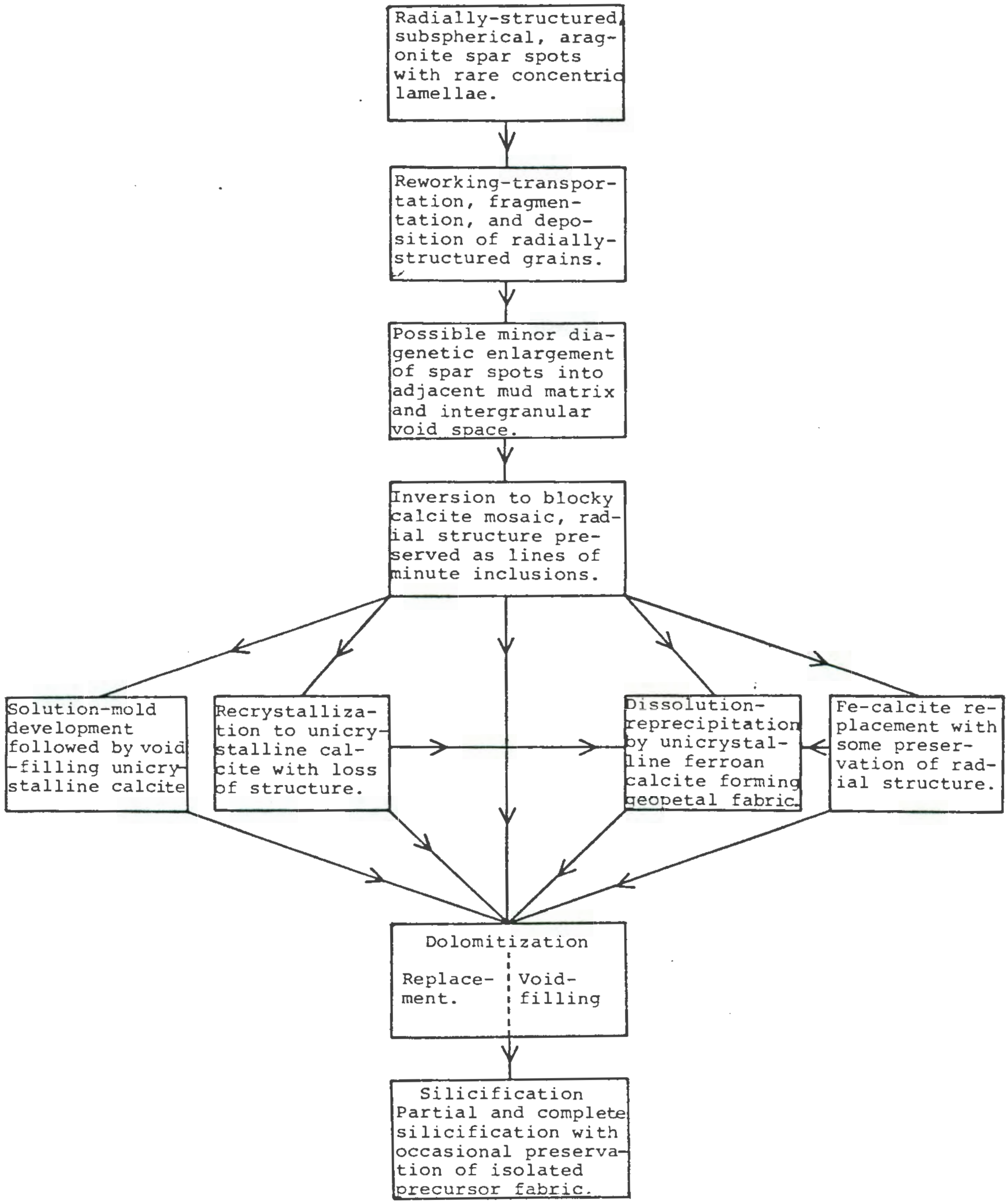

Radially-structured, subspherical, aragonite spar spots with rare concentric lamellae.
Reworking-transportation, fragmentation, and deposition of radially-structured grains.
Possible minor diagenetic enlargement of spar spots into adjacent mud matrix and intergranular void space.
Inversion to blocky calcite mosaic, radial structure preserved as lines of minute inclusions.
Solution-mold development followed by void-filling unicrystalline calcite
Recrystallization to unicrystalline calcite with loss of structure.
Dissolution-reprecipitation by unicrystalline ferroan calcite forming geopetal fabric.
Fe-calcite replacement with some preservation of radial structure.
Dolomitization
Replacement.
Void-filling
Silicification
Partial and complete silicification with occasional preservation of isolated precursor fabric.

Figure 29

high-strontium aragonite and were deposited as clasts in a marine regime.

The paragenetic stages illustrated in Figure 29 are by no means presented as a rigid linear evolution of fabrics. The alteration processes are frequently incomplete as evidenced by occurrence of all stages within the same sample. This can be attributed to the apparent randomness of the chemical processes and the overall inhomogeneity of the rock fabrics of Unit 2. The above steps (Figure 29) do not necessarily represent discrete phases of diagenesis; some may have acted simultaneously in various parts of the fabric due to variance in microchemical systems. Also, there may have been several times throughout the history of diagenesis that some of the processes were active, although evidence for this is not readily apparent. The response of the original radial aragonite crystal textures and the resultant fabric are complex, and many aspects of their evolution (especially with respect to chemical parameters and mechanisms) must remain problematical in a study of this scope

Stages of Void Filling

Early-stage cements include thin acicular rims, thick acicular fibrous rims, bladed isopachous rims, botryoidal hemispheres, large compound bladed rims, and botryoidal-like crusts on some skeletal grains. Thin acicular rims are rare and typically occur as isopachous first-stage cements lining intraskeletal voids and the outer perimeter of foraminifers (Figure 21c) and occasionally bryozoans. The short needle-like morphology is oriented perpendicular to substrate due possibly to a preferred microstructural orientation of the discrete crystallites forming the test. The morphology of this cement is typical of high magnesian cement rims observed in modern environments and probably reflects mineralogic and associated morphologic controls by the high magnesian mineralogy and microstructure of the substrate.

Large, acicular fibrous cement rims, consisting of loosely packed divergent crystals, though rare, are developed on bryozoans and fusulinids (Figure 27b). The orientation of constituent crystals is similar to relict structure in spherulitic spar spots, although in spar spots the rayed inclusions are finer and form a much tighter fabric. The size, morphology, and overall fabric of these rims, by comparison to structure in spar spots, suggests an aragonite precursor and would thus reflect lack of mineralic substrate control as they form often on what appear to have been originally calcite organisms.

Skeletal crusts with relict needle-like structure (Figures 23c and 30b) identical to that in spar spots are relatively rare. Some display cerebroid morphologies similar to the outer periphery of many spar spots and they also seem to be a small-scale version of some compound botryoids. The crusts also occur lining the interior and exterior of a small clam. The internal crusts pre-date internal sediment within the geopetal structure (Figure 30d) and is thus demonstrably void-filling in origin. The occurrence of a similar, though thinner crust on the exterior of the shell in direct contact with mud in a relationship that does not suggest presence of a former void in the space now occupied by the crust, suggests formation of the rim prior to deposition. Also, the clast is floating in micrite in a nongrain-support relationship, eliminating the possibility of free surfaces available for nucleation after deposition.

Bladed isopachous rims are developed in local pockets of grain-packed spherulitic spar spots within the dominantly calcilutite lithology. The rims commonly interfere with one another and form a significant portion of the void-fill in these fabrics. They also provide unequivocal evidence that the spar spots on which they nucleated were deposited as discrete clastic particle and not formed, at least in their present locations, as diagenetic growths (Figure 23b).

Botryoidal void-filling is relatively rare in Unit 3, presumably due to the rare occurrence of large voids which appear to favor its growth. The rare occurrences that are noted (Figure 30a) serve to illustrate fabric and structure between this cement and spherulitic spar spots, which occur in the same sample. The discussion and interpretation of botryoidal void-fillings has been considered in detail in the previous section (Unit 2) and need not be re-evaluated here because botryoidal cements in Unit 3 display no significant differences from those in Unit 2 other than a slightly more irregular, less hemispherical shape.

Large, compound bladed rims are rare, but when present they are quite spectacular. Their structure is one of radiaxial fibrous calcite; they are usually isopachous and frequently are preceded by earlier cement generations (Figure 27c).

The abundant occurrence of coarsely crystalline dolomite as small, randomly distributed, locally coalesive patches appears to be dominantly a replacive fabric as evidenced by frequent isolation of calcite patches as well as the general aspect of the overall fabric (highly irregular embayed crystal contacts, irregular shapes and patchy distribution in unsupported "voids" etc.). Void-filling and replacive characteristic, as both coarsely crystalline ferroan dolomite and fine-grained rhombic nonferroan dolomite, suggest a polygenetic origin for dolomite. Coarsely crystalline dolomite is invariably ferroan with up to 10 weight percent FeO (by microprobe analysis, n=2).

Figure 30--Void-filling cements, relict structures, and altered spar spots. Bar in lower right hand corner is 2.0 mm. long.

A.) Partial alteration of spar spot to unicrystalline ferroan calcite (FC), with some retention of precursor mosaic and blunt-end to needle-shaped crystals. Botryoidal calcite (BC) fills part of a void and displays fine needle-like structure.

B.) Faint retention of poorly developed concentric structure in two spar spots. Note apparent nuclei (N) and clear intergranular calcite mosaic

C.) Spar spot (S) partially recrystallized to unicrystalline ferroan calcite, containing isolated parts of original calcite mosaic and surrounded by relict structure (RS) around grain periphery.

D.) Geopetal structure in clam showing vague needle-like structure in crusts (C) present on both interior and exterior of valves. Crusts pre-dates internal sediment which pre-dates final void-filling of clear, coarse, blocky mosaic of nonferroan calcite.

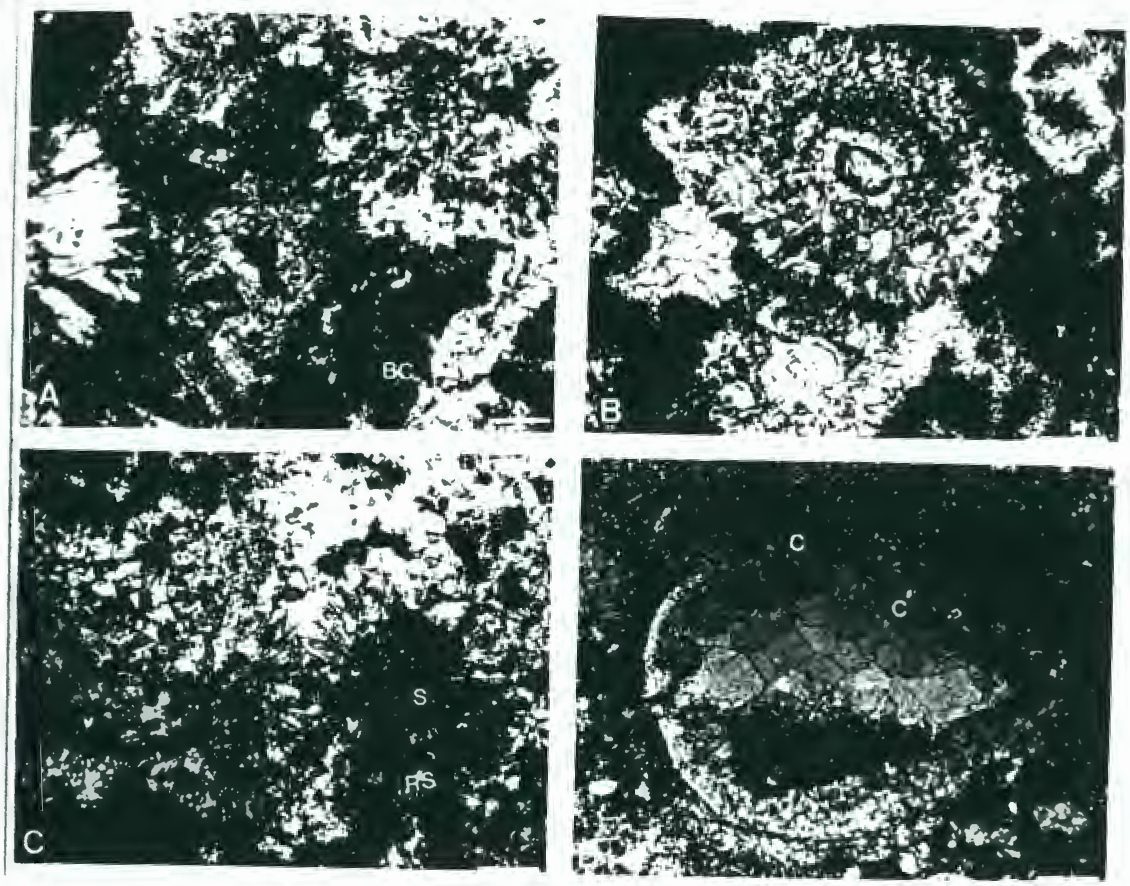


Figure 30

Skeletal to Oolitic Calcarenite (Unit 4)

Calcarenite is the uppermost lithologic Unit in mounded Spring Hill, completing the regressive succession (Figure 3). Although calcarenite is most commonly skeletal in origin, various amounts of intraclasts and oolite are present locally. On the basis of grain composition and rock fabric, two calcarenite facies can be distinguished. A tightly packed oolitic facies is present at Carr's Quarry, while the K-96 roadcut is characterized by a skeletal facies containing only minor amounts of ooliths and thin horizons rich in intraclasts. Calcarenite facies are well sorted and contain little mud except for that in intraclasts and internal sediment beneath algal umbrellas near the top of Carr's Quarry exposure.

These two lithologies are approximate time equivalent lateral facies of the same depositional phase within the regressive Spring Hill succession. The correlation is justified by their similar stratigraphic position between underlying Spring Hill mound facies and overlying Vilas Shale. Lithologic successions at the two outcrops is identical except for the presence of a thin shale underlying K-96 calcarenite, which is absent at Carr's Quarry. The two facies differ, however, not only in grain composition but also in degree of meteoric diagenesis. Skeletal calcarenite at the K-96 raodcut is conformably overlain by Vilas Shale and Captain Creek Limestone. The upper surface of the oolite at Carr's Quarry however, is dominantly a modern erosion surface with only remnant patches of impermeable Vilas Shale. Long term absence of much impermeable shale over the oolite at Carr's Quarry has subjected the facies to more intense meteoric diagenesis, for perhaps much of the Quaternary, producing a somewhat karsted upper surface as well as changes in mineralogy and fabric.

Four feet of grey, cross-bedded, abraded-grain skeletal calcarenite caps the Spring Hill succession at the K-96 roadcut. This dense lithology forms a resistant exposure of 0.8 to 1.2 foot thick beds, which are easily distinguished from underlying mound rock by their granular outcrop expression, large-scale low-angle crossbeds, and position between two shale units (overlying Vilas and underlying thin shale of variable thickness in the Spring Hill).

Grain size varies among skeletal calcarenite samples, ranging from coarse to fine sand-sized, with the most common size lying between 0.5 and 2.0 mm. Rare horizons up to 5.0 cm. thick, consist of fine to very fine grains displaying excellent sorting. Size grading, consisting of a coarse basal shell layer with progressive decrease in grain size upwards is present in some beds; however, no overall grain size trend in the unit as a whole is apparent.

Skeletal calcarenite consists of diverse array of commonly abraded skeletal grains cemented by one or more stages of calcite spar. The most abundant grains include fusulinids, several types of bryozoans, and crinoid columnals, all of which show excellent preservation of shell microstructure (Figure 31a & b). Other skeletal grains include abundant molluscan fragments, characterized by highly variable preservation and selective dolomitization of less stable microstructural layers (Figure 31c), several genera of small foraminifers (locally abundant), red algae, brachiopods, and rare ostracodes.

Calcareous red algae are a common to locally abundant grain type that is easily distinguished in thin section by its distinctive brownish-red color. Red algae are typically recrystallized to an irregular, equigranular mosaic similar to that of adjacent intergranular cement. Cellular structure is typically preserved within the recrystallized mosaic (Figure 31d).

Nonskeletal grains are dominated by altered calcilutite intraclasts and ooids, with trace amounts of quartz and opaques. Quartz is present as detritus within most intraclasts and also as authigenic growths in intraskeletal voids (especially bryozoan zooecia); although some quartz is authigenic, the majority of it accurs as detritus within intraclasts.

Figure 31--Skeletal Calcarenite from K-96 roadcut. Bar in lower right hand corner is 0.5 mm. long.

A.) Abundant, well preserved bryozoans of several different types. Matrix consists of 0.15 to 4.0 mm. mosaic of irregular, sharp bordered ferroan calcite.

B.) Representative fabric showing excellent preservation of common fusulinids. Note incorporation of recrystallized pelecypod fragments (P) within syntaxially enlarged crinoid grain.

C.) Differential preservation of pelecypod microstructure layers. Faint retention of layering, possibly organic matter, is present within prismatic original and blocky altered layers as sharp, thin lines. Quartz-rich lithoclasts (Q) with authigenic muscovite lying below valve.

D.) Grain with curved, cross-partitioned cellular structure faintly visible (R); suggesting origin as Solenoporid red algae.

E.) Typical large calcilutite intraclast (I) containing a recrystallized Archeolithophyllum fragment (A).

F.) Fine-grained intraclastic grainstone. Several genera of small forams are a ubiquitous component of this grainstone.

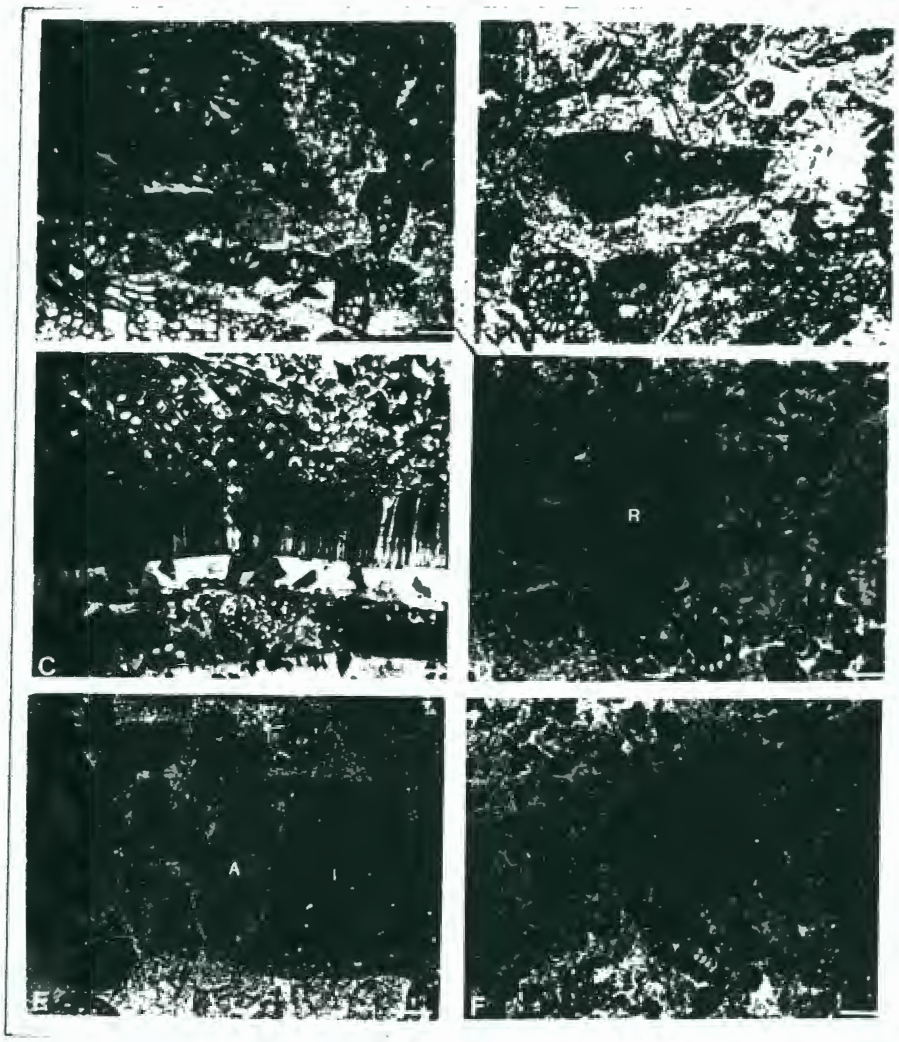


Figure 31

Intraclasts are distinctive in thin section due to their grey color, conspicuously rounded morphology, and microspar texture (Figure 31e). They rarely show signs of compaction, indicating either deposition in a fairly lithified state or early framework stablization due to early cementation. A distinctive intraclastic texture composed almost entirely of small clasts and forams in the 0.25 to 0.5 mm. size range is present as local thin horizons (Figure 31f)

Ferroan calcite is the most common intergranular cement in the skeletal calcarenite facies. This cement typically displays two morphologies: 1.) Irregular, more or less equigranular mosaic, and 2.) Recrystallized, isopachous, acicular cement rims. Distribution of the two cements is variable; acicular cement in particular is not everywhere developed. Void space may be completely occupied by either type of cement, but most commonly, acicular cement occurs as an early stage isopachous, drusy rim followed by irregular, equigranular mosaic (Figure 32a & b). Cement rims, when present, constitute a significant portion of void-filling component occupying up to 60% of intergranular void space in some samples.

Isopachous cement rims are universally recrystallized to a coarse drusy mosaic which preserves the initial acicular morphology as turbid rays within bladed crystals (Figure 31a & c). The relict acicular morphology and mode of occurrence of this cement is very similar to that of early submarine and beachrock cements observed in Recent environments (Bricker, 1971). Analogy with these Recent cements indicates an initial metastable mineralogy of either high magnesian calcite or aragonite. Occurrence of the cement rim as recrystallized turbid inclusions within syntaxial crinoid overgrowths indicates that the cements was not initially crystallized in optical continuity with the columnal (Figure 32c & d). That the columnal did not exert its typical substrate control to produce an initial syntaxial rim suggests that the rim was initially of a different mineralogy than the columnal (namely aragonite) or, that the cement was crystallized too rapidly to allow optical alignment of the acicular crystals with the uni-crystalline crinoid columnal. It is likely that the rim was deposited rapidly as syndepositional aragonite cement due to its acicular habit, lack of control by high magnesian calcite substrate, and by analogy to modern occurrences of similar cements in Recent environments.

Dolomite is moderately abundant throughout the skel-etal calcarenite facies. It is preferentially located as casts or replacements of molluscan grains (Figure 33a). Frequently it occupies only part of the space of the original shell, presumably due to selective replacement or dissolution-precipitation of less stable microstructural layers (Figure 32b). Gastropods are typically

Figure 32--K-96 skeletal calcarenite intergranular cements. Bar in lower right hand corner is 0.5 mm. long.

A.) First generation acicular, isopachous cement rim is followed by irregular calcite mosaic. Early cement rim is preserved as turbid, short, needle-like inclusions within larger crystals comprising the void fill.

B.) Same as "A" but with polarizers crossed. Early isopachous rim is recrystallized to bladed calcite, which extends further into initial void than did precursor acicular rim.

C.) Early acicular rim (A) recrystallized by syntaxial crinoid overgrowth; portion not including early rim has filled surrounding void as a clear, incomplete, unicrystalline void filling

D.) Same as "C" but with polarizers crossed and grain at extinction. Outline of original grain (C), acicular rim (A), and final syntaxial void filling (S) are preserved within the final optically continuous mass.

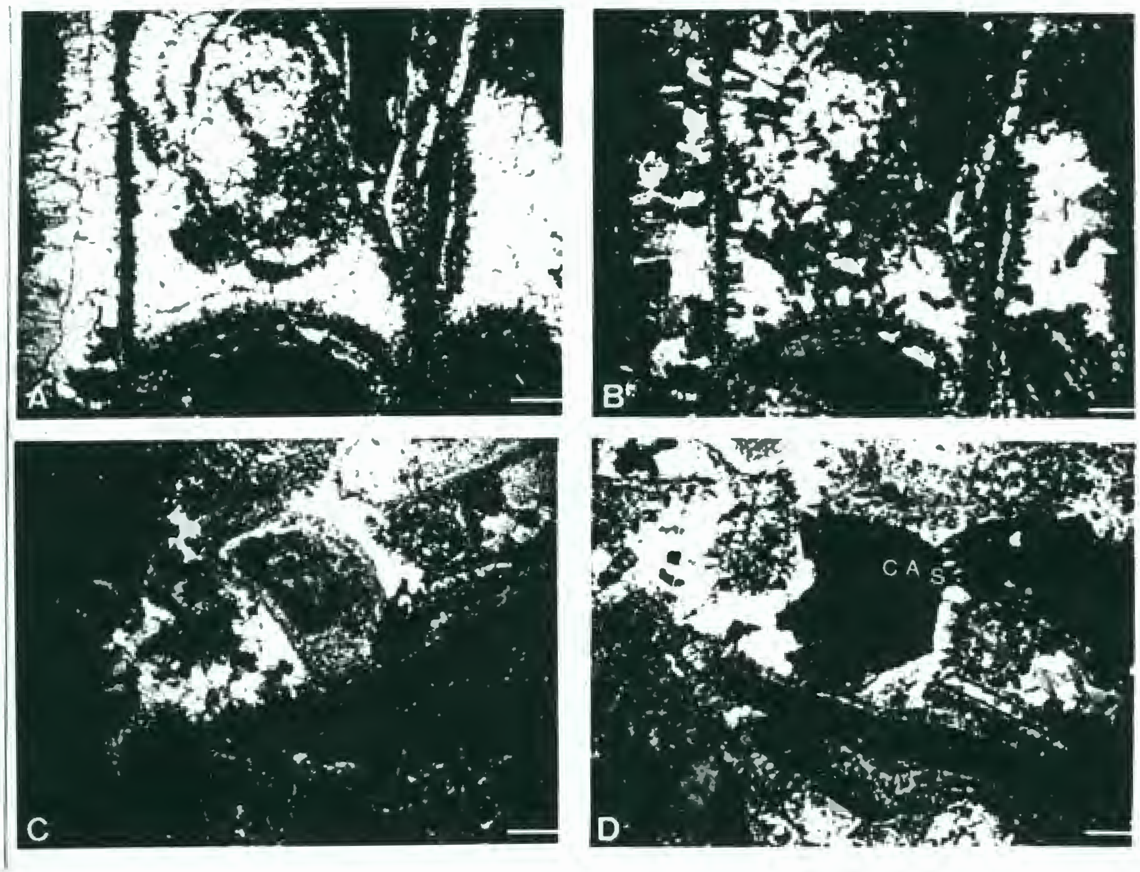


Figure 32

completely composed of dolomite, whereas pelecypods may be completely dolomite or calcite, or contain both dolomite and original-appearing calcite layers. It appears that dolomite is preferentially localized in former aragonitic molluscan shell layers.

Calcitization of dolomitic molluscan grains is well developed in some cases. It is indicated by calcite embayments around the perimeter and often extending into the interior of some molluscan grains (Figure 33 c & d).

A variable thickness of highly weathered oolitic calcarenite caps the Carr's Quarry exposure. The upper surface is erosional with small, karst-like pits, while the lower contact is irregular and may be either sharp or gradational with underlying mound facies. Rock fabric is dominated by tightly packed ooliths with minor amounts of superficially coated grains and skeletal fragments. Intense meteoric diagenesis has produced a highly altered lithology with significant development of oomoldic porosity in exposed sufaces. Oomoldic porosity is expressed by selective removal of nuclei and inner cortical layers, but complete dissolution of individual ooliths is not well developed. Locally extensive dissolution produces a soft, somewhat chalky rock into which the hammer readily sinks.

Alteration of ooliths has rendered nuclei indistinguishable in many cases. A noted exception to this is foraminiferal nuclei which apparently, due to their

Figure 33--Dolomite in K-96 skeletal calcarenite. Bar in lower right hand corner is 0.5 mm. long.

A.) Preferential localization of dolomite (D) as casts or replacements of molluscan grains.

B.) Selective dolomitization of less stable, presumably aragonite layers. Dolomite (D) consists of large crystals with sweeping extinction. Prismatic layer (P) is preserved as original calcite.

C.) Calcite embayments around perimeter of dolomite casts. Calcitization has not destroyed the original grain outline (O).

D.) Advanced calcitization with calcite embayments (C) extending into grain interior.

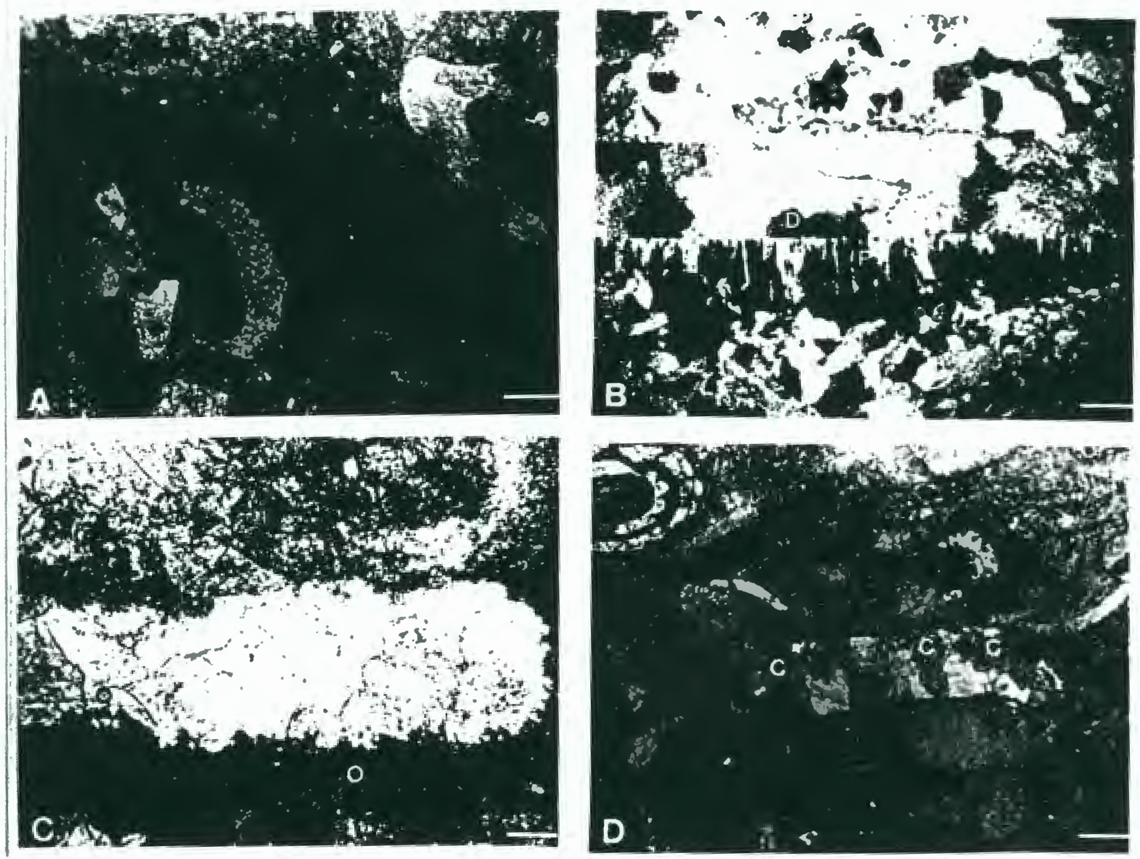


Figure 33

stable intermediate magnesian calcite mineralogy, have in most cases resisted alteration (Figure 34a).

Oolith cortices are typically recrystallized to several large calcite crystals displaying relict lamination in most cases (Figure 34b). The degree of recrystallization of cortices is highly variable. In some cases a significant thickness of cortex, or even the entire oolith consists of one crystal; in these cases relict lamellar structure is usually absent.

Intergranular cement generally consists of isopachous hematite or calcite rims followed by an irregular blocky calcite mosaic (Figure 34c). Occasionally the entire intergranular void is occupied by hematite cement (Figure 34c). Hematite cement rims are identical in mode of occurrence to early-stage acicular, ferroan calcite cement rims observed in K-96 skeletal calcarenite. Early calcite rims in the oolitic facies are occasionally hematite-stained or partially replaced by hematite. In light of these considerations, the logical explanation for hematite cement rims is that they are an oxidized precursor ferroan calcite rim. It seems probable, however, that significant amounts of iron have been added during meteoric diagenesis to account for the abundance of hematite in the oolitic facies. That early acicular cement rims are replaced preferentially to later stage coarse, irregular mosaics, may be due to the finer crystal size or higher ferroan content of the rim.

Figure 34--Oolitic calcarenite facies from Carr's Quarry. Bar in lower right hand corner is 0.5 mm. long

A.) Preserved foraminiferal nuclei.

B.) Recrystallized cortical layers composed of several large crystals, some with vague concentric lamellae (L).

C.) Early cement rim, now hematite (H), followed by blocky calcite (white) in lower half of photo. Hematite cement completely fills intergranular voids in the upper half of photo.

D.) Two fusulinids in various states of alteration. Complete recrystallization to blocky calcite (left). Partial recrystallization to blocky calcite with outer portion (dark) retaining some structure (right).

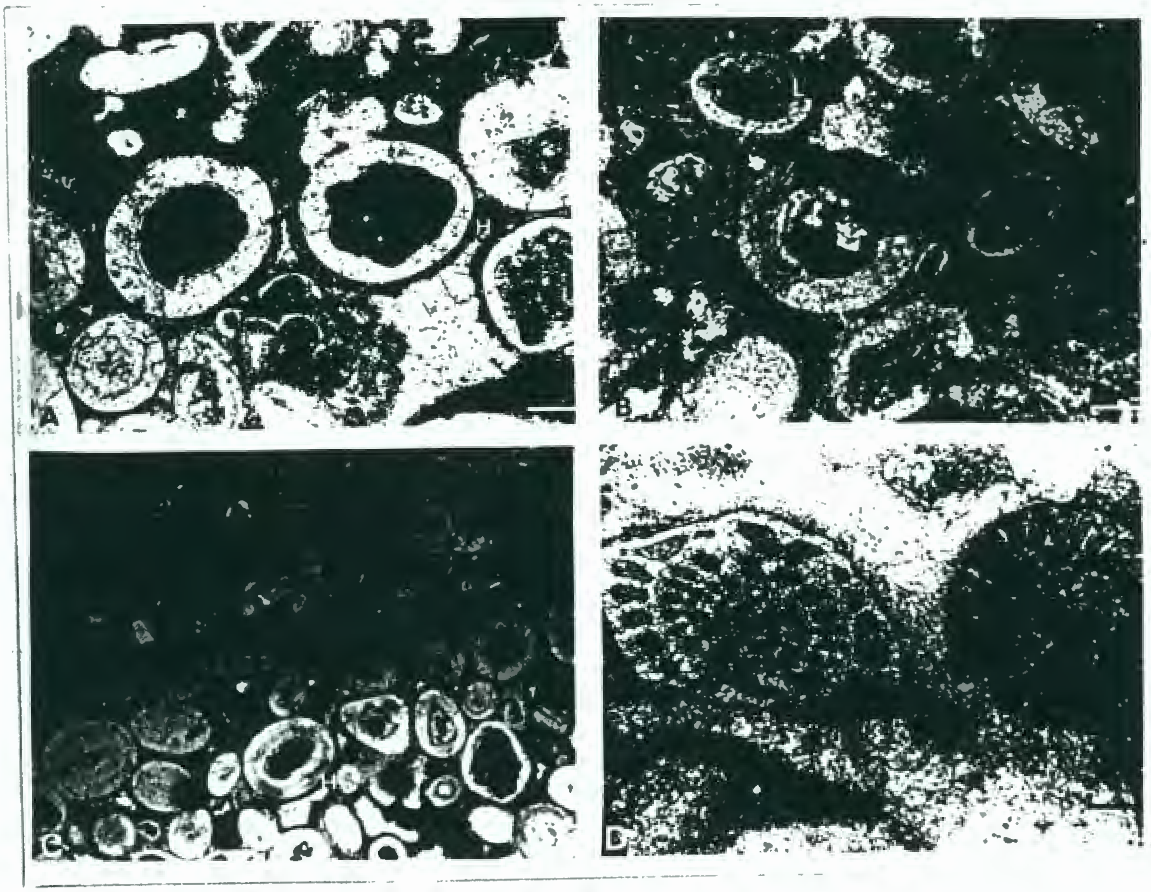


Figure 34

The oolitic facies appears to represent an advanced stage of meteoric diagenesis with respect to the skeletal calcarenite facies. This is supported by the apparent long term exposure to meteoric waters by virtue of early erosional removal of overlying shale in the unprotected hillside that is the site of Carr's Quarry. This situation facilitated development of oomoldic porosity and the recrystallization of more stable skeletal elements such as fusulinids (Figure 34d), which are unaltered in the other facies.

Near the top of the oolite exposure a unique oolith-algal lithology is developed (Figure 35a & b). This lithology is characterized by abundant algal umbrellas partially filled by dolomite and calcite with some caliche development, and by small-scale karst-like solution pits. Oolith-algal lithology is patchily developed as zones of concentrated algal material in association with abundant ooliths and internal sediment. It is not possible to determine whether the algae represent a once-living accumulation on a stablized oolite substrate, or whether they are allochthonous clasts codeposited with the ooids by some form of hydraulic concentration. Many of the algal blades are large, intact, and unabraded suggesting relatively quiet conditions or possibly a rapidly storm-laid deposit of all sizes available. If deposited under continually agitated conditions one might expect a homogeneous

Figure 35--Oolith-algal and void-filling fabrics from the top of Carr's Quarry. Bar in lower right hand corner is 0.5 mm. long.

A.) Well preserved algae displaying relict microstructure. Internal sediment is localized between algal blades in a partial umbrella structure. Aggregate ooids in upper-center appear to be "welded" at points of contact

B.) Cast of branching phylloid-algal blade; dissolution and partial collapse of algal mold was followed by void-filling blocky calcite.

C.) Complete cementation beneath umbrella structure by dolomite (D) and calcite (C). Lower surface of blade that forms void coincides with dark upper rim (R) upon which some internal sediment may have accumulated.

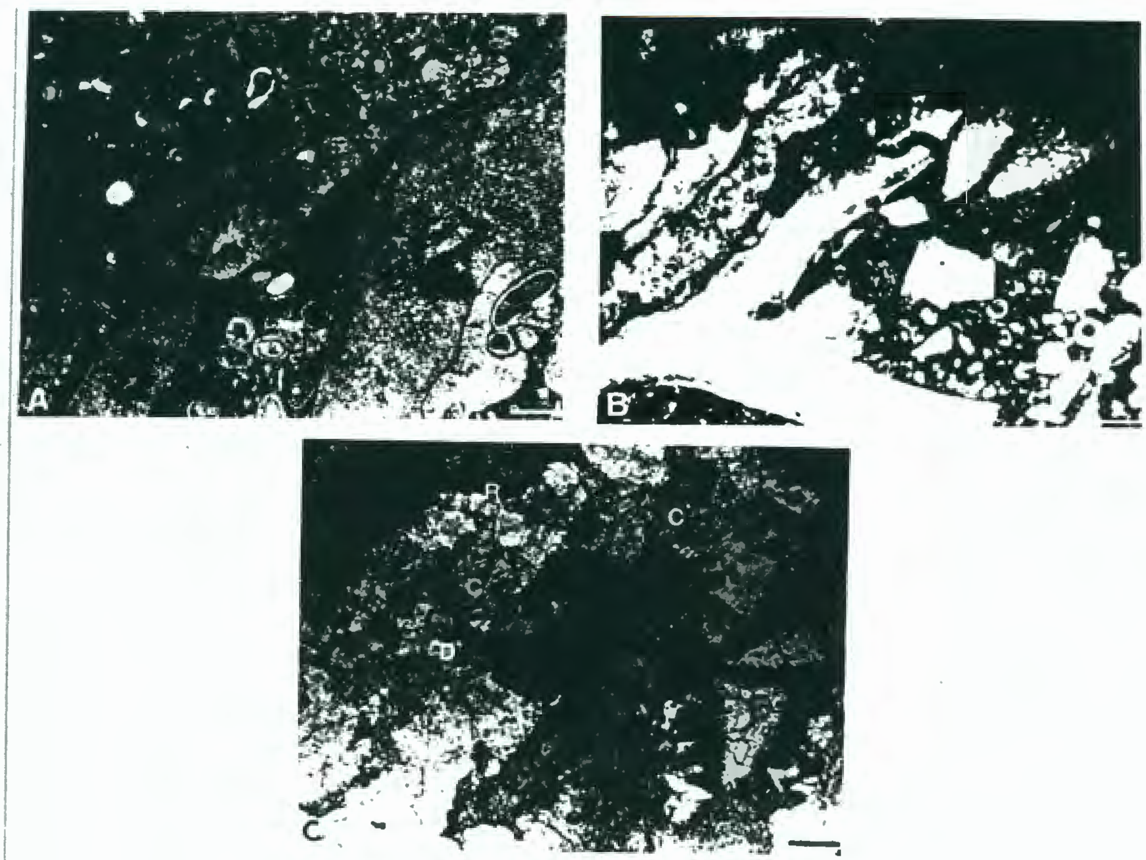


Figure 35

distribution of small algal clasts as in the calcarenite facies at K-96.

Partial and complete void filling beneath algal "umbrellas" is seen at the very top of the Carr's Quarry exposure. Void-filling is accomplished either by calcite or calcite and dolomite with commonly several stages involved (Figure 35c). Interpretation of some of the complexities seen in the photos seem beyond the scope of this study.

Depositional Environments

Environmental interpretation of the calcarenite facies is the most straightforward of all the Spring Hill lithologic units. Depositional fabrics consisting of well-washed and sorted grains, often highly abraded, and with large scale crossbeds point to deposition in agitated to turbulent water of shoal environments that culminated regressive Spring Hill deposition in areas of mound development. Presence of several fining upwards layers within calcarenite may indicate possible storm deposition for part of the Unit. The presence of large, rounded, intraclasts throughout the skeletal facies may indicate "normal" day-to-day reworking of storm -deposited sediments. Fossil content of intraclasts indicate derivation from an environment similar to that of deposition, but with a source of detrital quartz nearby.

Many features of skeletal calcarenite facies are similar to those of the younger Westphalia Limestone (Virgilian) of Kansas, which has been interpreted as a possible ancient storm deposit (Ball, 1971). The most notable similarities include extreme concentration of fusulinid tests, abundant intraclasts (about half the size of those observed in the Westphalia), well developed current lineation, and abraded and polished grains. While these criteria are compatible with storm deposition, they are somewhat nondefinitive. Nevertheless, that fact that storm activity is an important if not dominant modifying process in the inter- and shallow subtidal regimes is strongly supported by studies on the frequency and effects of Recent storms in similar settings (Hayes, 1967).

Discussion of Diagenesis

The well-washed calcarenite facies (Unit 4) was well cemented by several stages of calcium carbonate cement. Initial framework stablization was accomplished by isopachous, acicular cement rims, which produced a fabric generally devoid of compaction features. Although not everywhere developed, this early cement rim is a significant void-filling component accounting for early porosity reduction. Early cement rims in this facies are similar those observed in both modern beach rock and early submarine-cemented masses in its acicular morphology and isopachous mode of occurrence. This cement now is typically recrystallized, preserved as turbid ghosts in bladed crystals and crinoid overgrowths. This suggests a precursor unstable mineralogy that most probably was originally aragonitic. The original cement rim is now composed of ferroan calcite, which may be a recrystallization product of either freshwater meteoric or marine regimes. Ferroan content could reflect either relict iron content of the precursor cement, or iron added during later meteoric diagenesis.

Diagenetic fabrics differ greatly between the two calcarenite facies due to the degree of meteoric diagenesis to which the two facies have been subjected. Intense meteoric diagenesis at Carr's Quarry, due to early erosional exposure, has resulted in recrystallization of some normally stable low magnesian calcite fossil grains, local development of oomoldic porosity, recrystallization of remaining ooids, iron oxide replacement of calcite cements, and dissolution and collapse of algal molds followed by subsequent void-filling. Extensive replacement of cement rims as well as later-stage blocky cement by iron oxides, developed possibly in response to more recent meteoric diagenesis.

Dolomite is fairly abundant as void-filling cement beneath algal umbrellas at Carr's Quarry, and as either replacements or casts of molluscan grains in the K-96 exposure. Dolomite associated with molluscan grains displays preferential localization in less stable microstructural layers originally of aragonitic composition. Relict structure of dolomitic molluscan fragments is absent, thus it is difficult to ascertain whether the solomite is replacive or void-filling in origin. Subsequent calcitization of dolomite is developed in varying degrees throughout the calcarenite facies.

GEOCHEMISTRY

A limited amount of trace element analysis for strontium content of spherulitic spar spots and botryoidal calcite was run usingan A.R.L. microprobe; for the samples discussed, beam current was held within one percent of the mean, yielding data generally considered to be accurate within 2 percent of the total. Weight percent oxide has been converted to parts per million; these values will be considered accurate to within 100 ppm., although the accuracy may actually be greater than this. For the purpose of this discussion raw data has been rounded to the nearest 100 ppm.

Samples probed include four spar spots from a "tight" argillaceous calcilutite within the interbedded limestone-shale part of Unit 3, a unicrystalline botryoid from the lower part of Unit 2, as well as one sample of massive Captain Creek sparite for comparison. Values for the 4 spar spots ranged from a low of 6,700 ppm. to a high of 10,700 ppm. with an average of approximately 8,200 ppm. Sr^{+2}. These values compare favorably with average values from modern marine aragonite botryoids from the Belize reef of 8,300 ppm. Sr^{+2} (Ginsburg and James, 1976). These levels of strontium are nearly identical to those observed by Davies (1977) in Upper Paleozoic reefs of the Canadian

Arctic. Davies' samples came from botryoidal masses with structure similar to that of spar spots and were interpreted as neomorphosed botryoidal aragonite, which had retained its original high strontium content through diagenesis in a closed microchemical system as suggested by Kinsman (1969). Botryoidal cements similar to those described by Davies are present in the Captain Creek Limestone (Ravn and Heckel, 1978) and in the Spring Hill. The one Captain Creek sample probed contained 3,500 ppm. Sr^{+2}, and a sample from the subparallel algal-laminted sparite at Sycamore Quarry carried 7,300 ppm.; these values are comparable to those already discussed from modern and ancient examples. They are considerably higher than maximum levels of approximately 1,000 ppm. characteristic of marine calcites (Davies, 1977) and suggest a precursor of marine aragonite for these fabrics. The somewhat lower value, comparatively, for the Captain Creek sparite sample can be readily accounted for by the advanced state of recrystallization of this fabric; similar unicrystalline fabrics in the Spring Hill yielded values of 1,000 and 1,800 ppm. However, these values are still in striking contrast to those in associated blocky void-filling calcite and spar spots now occupied by ferroan calcite, which have gone through a definite moldic stage; these fabrics are characterized by little or no strontium (less than 1,000 ppm.).

Although additional data on the strontium range within finely radial, needle-like fabrics of inferred precursor marine aragonite is needed, as well as data on co-existing diagenetic fabric elements, the present data (limited though it may be) in conjunction with petrographic consideration indicates a precursor marine aragonite origin for both botryoidal void-filling calcite and radially structured spar spots.

SUMMARY AND CONCLUSIONS

Abrupt thickening of the Spring Hill Limestone Member forming a carbonate buildup in the Fredonian-Neodesha area, is accompanied by greatly increased lithologic diversity and diagenetic complexity with respect to the offmound facies of the member. The Spring Hill mound at the K-96 roadcut consists of a regressive lithologic succession characterized by a diverse, marine invertebrate fauna which records normal marine conditions throughout and is dominated by calcilutite deposition, below wave base and within the photic zone, except for the presence of shoal water calcarenite, which caps the sequence.

The member is divided into 4 lithologic units characterized by different diagenetic fabrics and dominated by different faunal elements. Dense, skeletal-sponge calcilutite at the base of the member (Unit 1) is overlain by a high porosity fabric (Unit 2) formed through the interaction of large fronds of bryozoans and large blades of algae dominating the biota and affecting carbonate mud sedimentation. The loose framework role of this biota produced abundant shelter porosity, which served as sites for localization of coarse, sparry calcite and dolomite which form zones of distinctive, massive crumbly sparite. This sparite of Unit 2 is characterized by massive, early submarine cementation by botryoidal aragonite now preserved as botryoidal calcite. The marine aragonitic origin is suggested by modern morphologic analogy, relict internal aragonite-like structure, and high relict strontium levels characteristic of modern marine precipitated aragonites.

Although botryoidal cements are present in small amounts in underlying skeletal-sponge calcilutite of Unit 1 and the overlying spar-spot skeletal calcilutite of Unit 3, their extensive development in the base of Unit 2 probably results from development of a depositional fabric of high porosity, which gave extensive cements room to form. Modern aragonite botryoids from the Belize barrier reef form within highly porous, shelf-edge boundstones; this geographic setting is distinctly different from that of a shallow epicontinental sea in which the Spring Hill was deposited. Although a reefoid boundstone might seem quite different from the non-rigid mound structure, the common thread between the modern and ancient occurrences is development of a highly porous depositional fabric. Botryoidal cements reported from shelf-edge bryozoan "reefs" in the upper Paleozoic of the Canadian Arctic (Davies, 1977) were formed in a paleogeographic setting similar to that of the Belize reef front, but in structure these bryozoan "reefs" are probably more closely allied to the carbonate buildups of southeastern Kansas than to the boundstone of a barrier reef; once again, the control seems more to be the presence of a porous framework than one of paleogeographic setting.

Aside from early-stage botryoidal cements, the very porous bryozoan-algal fabric of Unit 2 contains abundant coarse, blocky calcite, which is usually followed by uni-crystalline ferroan calcite and ferroan dolomite. Ferroan calcite is volumetrically perhaps the most important cement in the buildup as a whole. It is present in all 4 units in large amounts and is commonly the material that seals up many voids. Its maximum development is apparently also tied to the presence of large voids; where these exist, ferroan calcite is extensively developed because earlier cement generations were not capable of completely sealing intergranular void space. The exception to this is the brecciated fabric at Sycamore Quarry, which contains abundant large voids, but nearly all have been cemented by coarse, blocky, nonferroan calcite. Final-stage cement, following coarse ferroan calcite, usually consists of coarse ferroan dolomite. Ferroan dolomite is extensively developed within the high porosity fabrics of Unit 2. The cement sequence beginning with blocky calcite, followed by coarse ferroan calcite, and finally ferroan dolomite has been observed to be a common sequence in the offmound pisolite facies of the Plattsburg by Conley (1977). In the mound facies however, blocky nonferroan calcite is frequently a second-stage cement following early-stage botryoids or acicular calcite. The sequence noted by Conley (1977) is definitely present throughout the mound facies of the Spring Hill, but in slightly more complex form than in the offmound facies.

Fabric elements with structure similar to that of botryoids but of more likely depositional-clast origin are termed spherulitic spar spots. These structures are ubiquitous in the lower third of Unit 3. While they display occasional features suggestive of diagenetic or void-filling origin, gross fabric relationships and intergranular cementation strongly suggests that most of these structures are depositional in origin. The exact mechanism and environment in which they were formed is open to discussion, but that some were subject to marine depositional processes is fairly definite. Their structure closely resembles that of modern aragonite ooids, which have been observed forming only in hypersaline environments. The finely needle-like structure of these grains, nearly identical to that of botryoidal calcite, is very reminiscent of aragonite; when this is combined with the consistantly high strontium levels of the four specimens probed (avg. 8,2oo ppm.) little doubt remains as to their marine aragonitic origin. Once we have shown that these structures were originally aragonite, we reinforce our hypothesis that they are a form of quiet water ooid (in conjunction with previously mentioned morphologic and structural data), or possibly a a synsedimentary oolitic growth that grew intermittently embedded (stablized) within mud sediment; the distinction between the two need not be very great. The fact that skeletal grains in addition to bioclastic nuclei of spar spots possess spherulitic-structured crusts, indicates that the spherulitic structure is pre- rather than postdepositional; also, the presence of crude, poorly developed concentric lamellae suggests at least some minimal degree of periodic agitation or cessation of growth.

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