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Differentiation of Facies in the Captain Creek Limestone Member
(Upper Pennsylvanian), Douglas and Johnson Counties, Kansas

by

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B.S., University of Nebraska, 1979

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For the Department

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ABSTRACT

Cluster analysis and nonmetric multidimensional scaling were used to delineate carbonate facies in the Captain Creek Limestone Member of the Stanton Limestone, Upper Pennsylvanian, in Douglas and Johnson counties, Kansas. Q-mode cluster analysis classified point-count data into 10 clusters on the basis of abundances of various constituents. These 10 clusters were combined to distinguish 6 facies, each representative of a distinct depositional environment: 1) a shallow, open-marine facies composed of foraminifera-bryozoan-echinoderm-brachiopod packstones, 2) a transitional facies containing encrusting foraminifera-Osagia wackestones and packstones, 3) a restricted, deep-water facies of phylloid algae wackestones, 4) a shoal facies of mixed skeletal grainstones, 5) an algal mound facies with foraminifera-phylloid algae packstones and sparry cement, and 6) a channel sequence defined by an exposed channel cut with a fining-upward sequence. The study area was influenced by transgressive seas depositing the widespread, shallow, open-marine facies followed by the more restricted deep-water facies. The remaining facies represent local variations responding to storms and temporary episodes of shoaling.

Introduction

The Captain Creek Limestone Member of the Stanton Limestone is extremely well exposed for approximately ten miles along recently completed Kansas Highway 10 in Douglas and Johnson counties, Kansas. Outcrops are complete and continuous enough to establish an equal-area sampling grid, making these rocks ideal for a statistical study. A detailed facies analysis of the Captain Creek in northeastern Kansas will provide a better understanding of other open-marine, transgressive Midcontinent rocks. This report uses a combination of statistical methods to identify carbonate depositional environments and to reconstruct the vertical facies sequence of the Upper Pennsylvanian Captain Creek Limestone in northeastern Kansas.

Cluster analysis is a multivariate technique that classifies objects by placing them into roughly homogeneous groups (Davis, 1973, p.456). In this study, samples containing similar biotic constituents in approximately equal amounts are grouped together, indicating similar environmental processes.

Nonmetric multidimensional scaling attempts to represent objects geometrically in space so that the interpoint distances correspond to dissimilarities between objects. The configuration produced demonstrates gradational relationships between the facies delineated by cluster analysis.

This combination of quantitative techniques has identified 10 clusters that have been geologically interpreted as representing 6 facies: 1) a shallow, open-marine facies of foraminifera-bryozoan-echinoderm-brachiopod packstones, 2) a transitional facies of encrusting foraminifera-Osagia wackestones and packstones, 3) a restricted, deep-water facies of phylloid algae wackestones, 4) a shoal facies of mixed skeletal grainstones, 5) an algal-mound facies of foraminifera-phyllloid algae packstones with sparry cement, and 6) a channel sequence represented by a fining upward progression with a corresponding increase in mud content. Thus, what appears on a regional scale to be a fairly monotonous, open-marine facies belt on an extensive carbonate shelf has considerable and sometimes subtle variability.

Multivariate Applications in Geology

The first multivariate analysis in carbonate petrology was a factor analytic study (Imbrie and Purdy, 1962) to interpret the structure within a variance-covariance matrix of multivariate data using eigenvalues and eigenvectors.

Cluster analysis simplifies some of the theoretical and operational concepts of factor analysis and presents results in easily interpreted visual displays.

Cluster analysis has been applied to both modern and ancient carbonate sediments (Purdy, 1963; Klovan, 1964; Bonham-Carter, 1965; and Behrens, 1965) and has recently been used in combination with other multivariate methods (Park, 1968 and 1974; Ekdale and others, 1976; and Smosna and

Warshauer, 1979).

This study uses Q-mode cluster analysis to group samples, R-mode cluster analysis to group variables, and an ordination technique to order samples in space to show gradational relationships among mutually exclusive clusters.

Geologic Setting and Previous Work

The Captain Creek Limestone Member is the lowest member of the Stanton Limestone, Lansing Group, Missourian Stage, Upper Pennsylvanian. It crops out from east-central Nebraska through southwestern Iowa, northeastern Missouri, and eastern Kansas to Oklahoma (fig. 1).

Regional lateral changes occur in the Stanton Limestone, and a framework of four major facies belts along the Kansas-Iowa outcrop region were recognized by Heckel (1968); (fig. 1). In the open-marine facies belt along the central region of the outcrop in northeastern Kansas and northwestern Missouri, Moore (1931, 1936, 1949, and 1950) first described the megacyclothem. Each depositional cycle records a single transgressive-regressive marine sequence and consists in ascending order of 1) thick, nearshore sandy or outside shale; 2) thin, transgressive or middle limestone; 3) thin, offshore or core shale; and 4) thick, regressive or upper limestone.

The Stanton Limestone comprises 5 members, 3 limestones separated by 2 shales (fig. 2). The underlying Vilas Shale together with all but the uppermost South Bend Limestone Member of the Stanton Limestone form a typical Kansas megacyclothem. The Vilas Shale is a nearshore shale resulting

Fig. 1 -- Outcrop of the Missourian Stage, Upper Pennsylvanian, in the Midcontinent (shaded region) divided into regional facies belts. Outcrop of the Stanton Limestone occurs along the western boundary of the shaded area in Kansas (adapted from Heckel and Baesemann, 1975, Fig. 3).

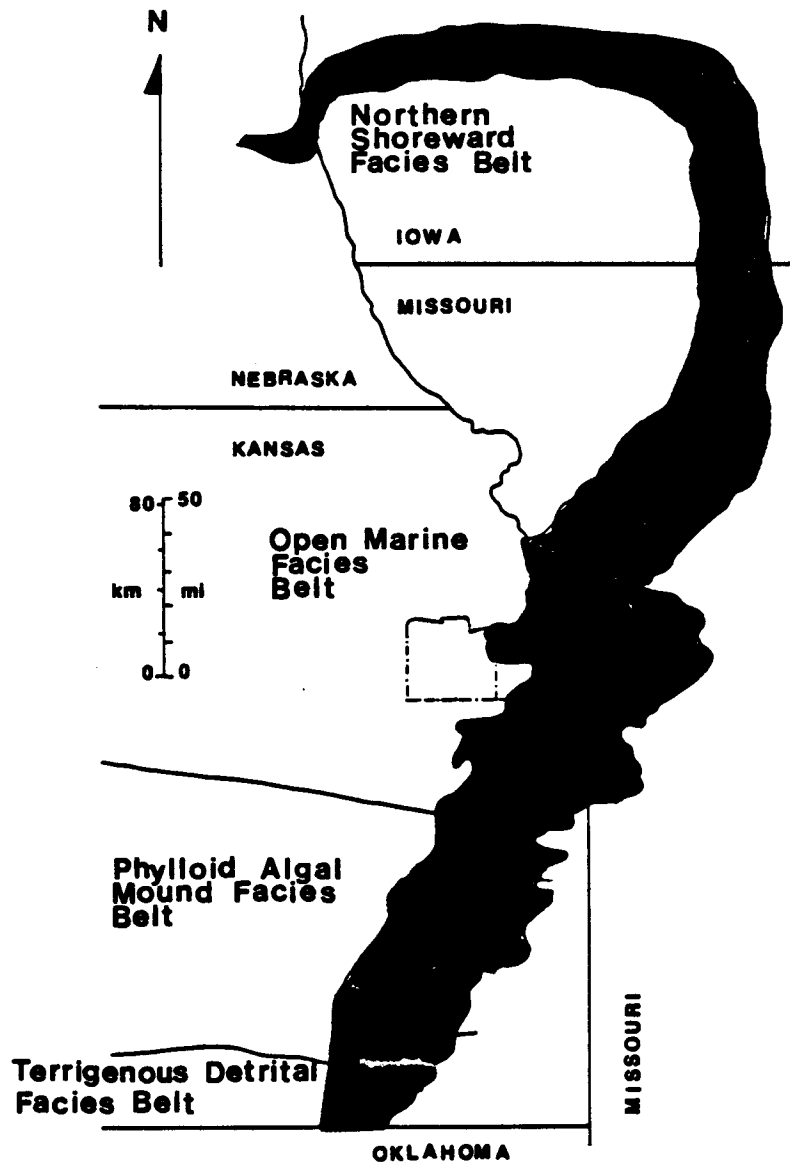
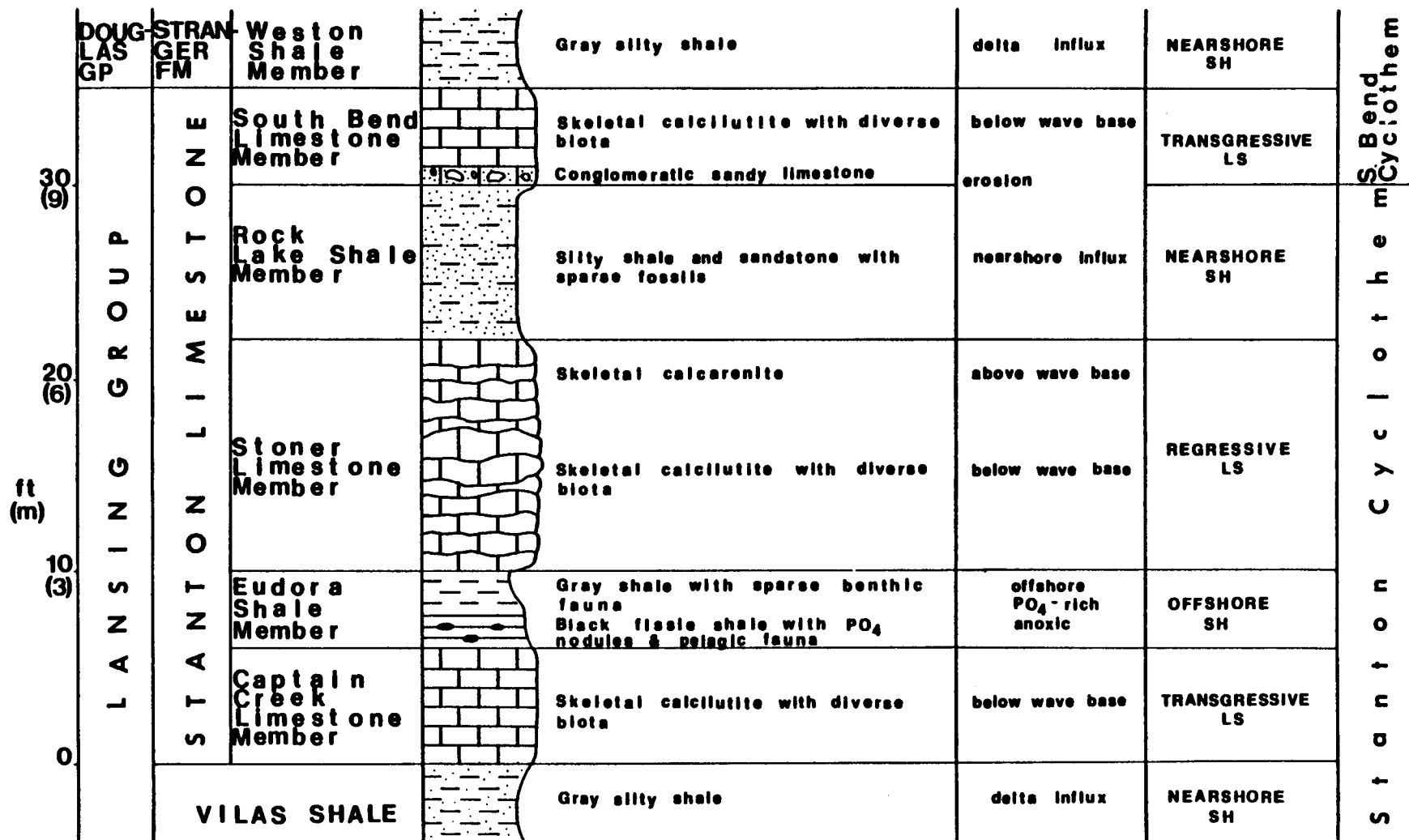


Fig. 2 -- Columnar section of Stanton
Limestone in open-marine facies belt of
northeastern Kansas (modified from Heckel,
1975a, Fig. 3a).



from influx of terrigenous material from deltas; the Captain Creek Limestone Member is a transgressive limestone deposited below wave base but still within the photic zone allowing proliferation of algae (Heckel and others, 1978); and the Eudora Shale Member is a black, offshore shale representing maximum transgression and deepest water.

Southward from the open-marine facies belt, the Captain Creek Limestone thickens to as much as 15 m and grades abruptly into the phylloid algal-mound facies belt. Most of the mound is sparry algal wackestones and packstones where spar-filled shelter voids occur beneath large algal blades and lime mudstone infills the remaining interstices. In southeastern Kansas and northeastern Oklahoma, the Captain Creek Limestone thins to 1 m of calcisponge-rich skeletal wackestones and packstones as the algal-mound facies pinches out and is replaced by the detrital belt. The absence of phylloid algae may have resulted from greater influx of terrigenous detritus (Heckel and others, 1978).

The Captain Creek Limestone grades northward from the open-marine facies belt to the northern shoreward facies belt in Iowa and Nebraska. Most evidence of shoreline deposition occurs at the top of the regressive Stoner Limestone Member where barren laminated limestone with birdseye fabric and desiccation cracks, commonly found on tidal flats, are developed (Heckel and others, 1979).

Within the open-marine facies belt, the Captain Creek Limestone Member is about 1.5 m to 3.5 m of medium-bedded mixed

skeletal wackestones and packstones (Zeller, 1968). It contains an abundant, diverse biota including bryozoans, encrusting and free-living foraminifera, molluscs, phylloid algae, Osagia, brachiopods, crinoid and echinoid debris, ostracodes, calcispheres, sponge spicules, and rare sponges and trilobites. The Captain Creek Limestone is similar to other stratigraphically lower limestone members. These underlying members are commonly exposed in outcrop, but where the distinctive Eudora Shale is missing, the Captain Creek Limestone is difficult to distinguish from them.

The study area (fig. 3) lies in Douglas and Johnson counties, Kansas, along Kansas Highway 10. This east-west traverse provides 10 miles of outcrop of the open-marine facies belt.

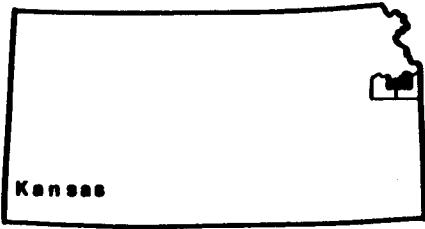
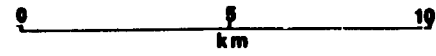
The Stanton Limestone has recently been intensively studied (Heckel, 1975, 1975a; Senich, 1975, 1978; Wood, 1977), but attention has been focused primarily on the phylloid algal-mound facies belt of southeastern Kansas. The open-marine facies belt has not been extensively studied, and most available literature is limited to brief lithologic and paleontologic descriptions (Ball, 1975; Heckel and others, 1978).

Methods

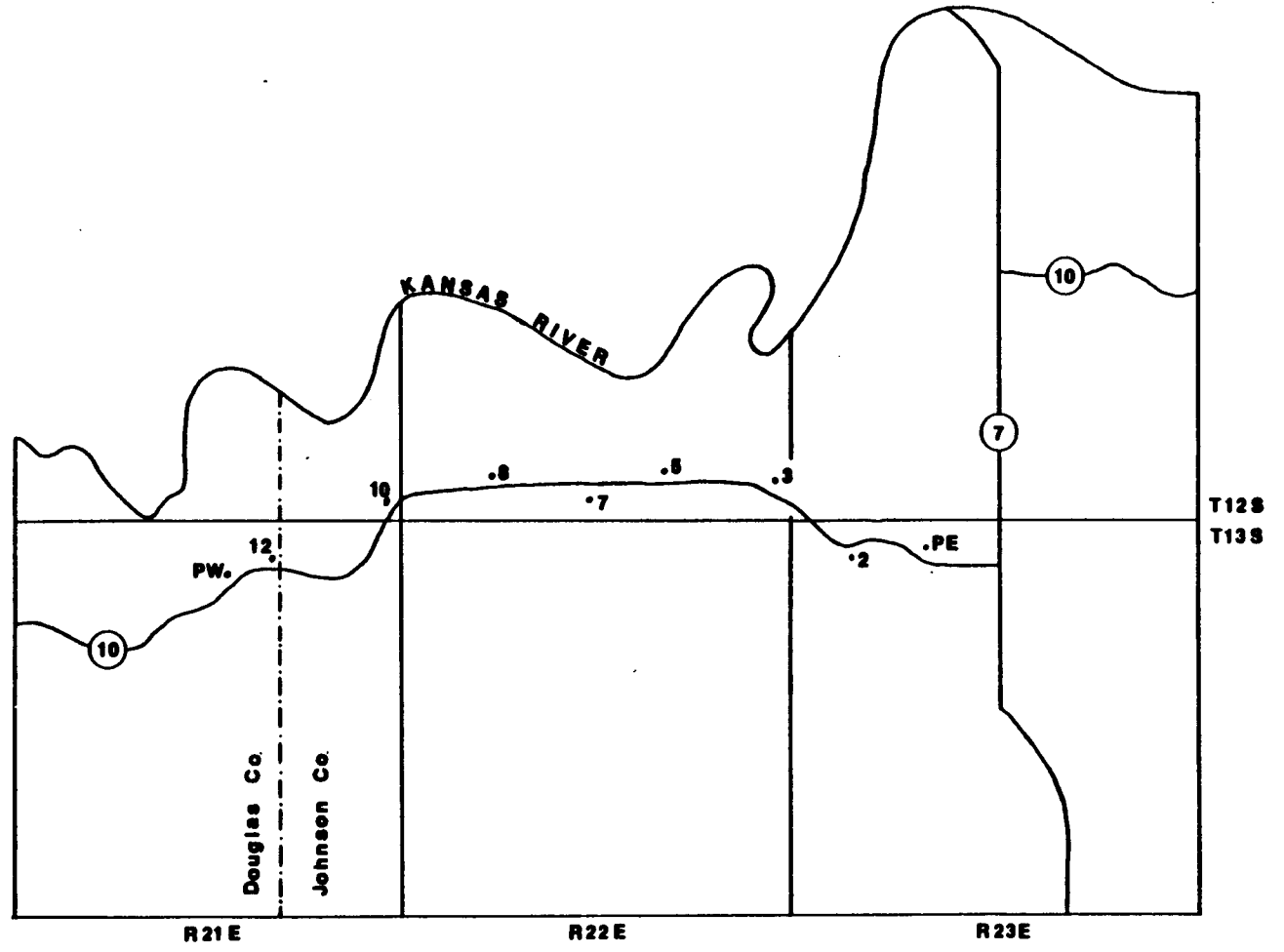
Preliminary Analysis of Data

Preliminary statistical procedures were used to determine

Fig. 3 -- Map of study area showing locations of the nine sampled sections of the Captain Creek Limestone Member along Kansas Highway 10 in Douglas and Johnson counties, Kansas.



Kansas



sampling and techniques of point-counting thin sections. First, since point-counting of individual constituents (Table 1) was to be used to estimate volumetric abundances, how many points per slide should be counted and how many thin sections should be made per sample? Tests were run in which 400 and 800 points per thin section of 6 preliminary samples were counted and the data analyzed as a binomial distribution (Appendix I). Results showed that 600 points were few enough to be workable and provided a suitable estimate of constituent abundances. Another test was run on multiple thin sections made from each of these samples (Appendix II). Statistical analysis using Model II one-way analysis of variance (Sokal and Rohlf, 1969, p.201) showed that one thin section per sample was sufficient to represent the variation within each sample.

Second, did appreciable environmental changes occur, or is the study area simply underlain by a widespread homogeneous limestone? A two-way analysis of variance for paired comparisons (Sokal and Rohlf, 1969, p.328) was used on 12 preliminary thin sections (Appendix III). Results indicated that phylloid algae and brachiopods-molluscs were the only two constituents to show significant changes in abundance, changes too subtle to have been detected by direct field observations. Thus, one of the objectives of this study, to delineate facies, was compatible with existing information.

Finally, how many measured sections are necessary to encounter most of the variation? Sokal and Rohlf's (1969,

Table 1. Variables Point Counted in Thin Section

mud	echinoderm pieces****
fenestrate bryozoans	ostracodes
encrusting foraminifera	sponges
other types of foraminifera	sponge spicules
molluscs*	trilobites
brachiopods**	intraclasts
phylloid algae	void filling cement
<u>Osagia</u> ***	void space
other types of algae	quartz silt
calcispheres	unidentifiable grains

* Also includes brachiopods in preliminary analyses

** Primarily Enteleles

*** Any stromatolite-forming algae

**** Includes both crinoid and echinoid debris

p.247) method of determining the number of replicates needed to detect a given true difference between means was applied (Appendix IV). Nine sections were sampled on the basis of the results of this test.

The Final Analysis

Nine sections, each approximately 1.5 to 3 km apart along Kansas Highway 10, were selected for study (fig. 3, Appendix V). Samples were collected every 30 cm vertically through each section. A total of 71 thin sections were made, one from each sample. The thin sections were point-counted at 600 points per slide for 20 different variables (Table 1).

All point count data were converted into proportions and transformed using the arcsine transformation (Sokal and Rohlf, 1969, p.386). R-mode and Q-mode cluster analyses were computed using product-moment correlation coefficients and the unweighted pair-group method using arithmetic averages (Sokal and Sneath, 1963). The unweighted pair-group method usually imparts the least structural distortion that is inherent in displaying a multidimensional structure in two dimensions (Rohlf, 1970). Cophenetic correlation coefficients (Sneath and Sokal, 1973, p.278) were computed to measure the amount of distortion introduced during clustering.

The NT-SYS package of multivariate programs (Rohlf and others, 1972) and CLUSTAN (Wishart, 1975) were used for all computations, the latter to retrieve cluster diagnostics indicating abundant and deficient constituents in each cluster.

R-mode cluster analysis was computed to see if any variables provided redundant information that could be deleted from the data matrix. Redundancy represents a double weighting for a particular environmental response, thus, biasing the environmental model toward the effect (Park, 1974). High correlation (0.8 or 0.9) between constituents is considered to indicate redundancy, but none occurred.

Q-mode cluster analysis was used to classify samples into environmentally significant groups. The cluster diagnostics as determined by the CLUSTAN programs involved the T-value (Table 2). A large positive T-value indicates that the mean of a variable in a cluster of samples is significantly greater than its mean in the entire population of samples. That is, the variable is more abundant within the cluster than when averaged over the entire population. Conversely, a large negative T-value indicates that a variable is less abundant in the cluster as compared with its overall population mean.

The final multivariate technique used was nonmetric multidimensional scaling (Kruskal, 1964). This method represents data geometrically as points in space.

Results

Results of the redundancy test are shown by the R-mode dendrogram (fig. 4). The highest correlation between any two constituents is 0.55 for intraclasts and cement. All

Table 2. T-value Definition

$$\text{T-value} = (\bar{X}_{C,J} - \bar{X}_J) / s_J$$

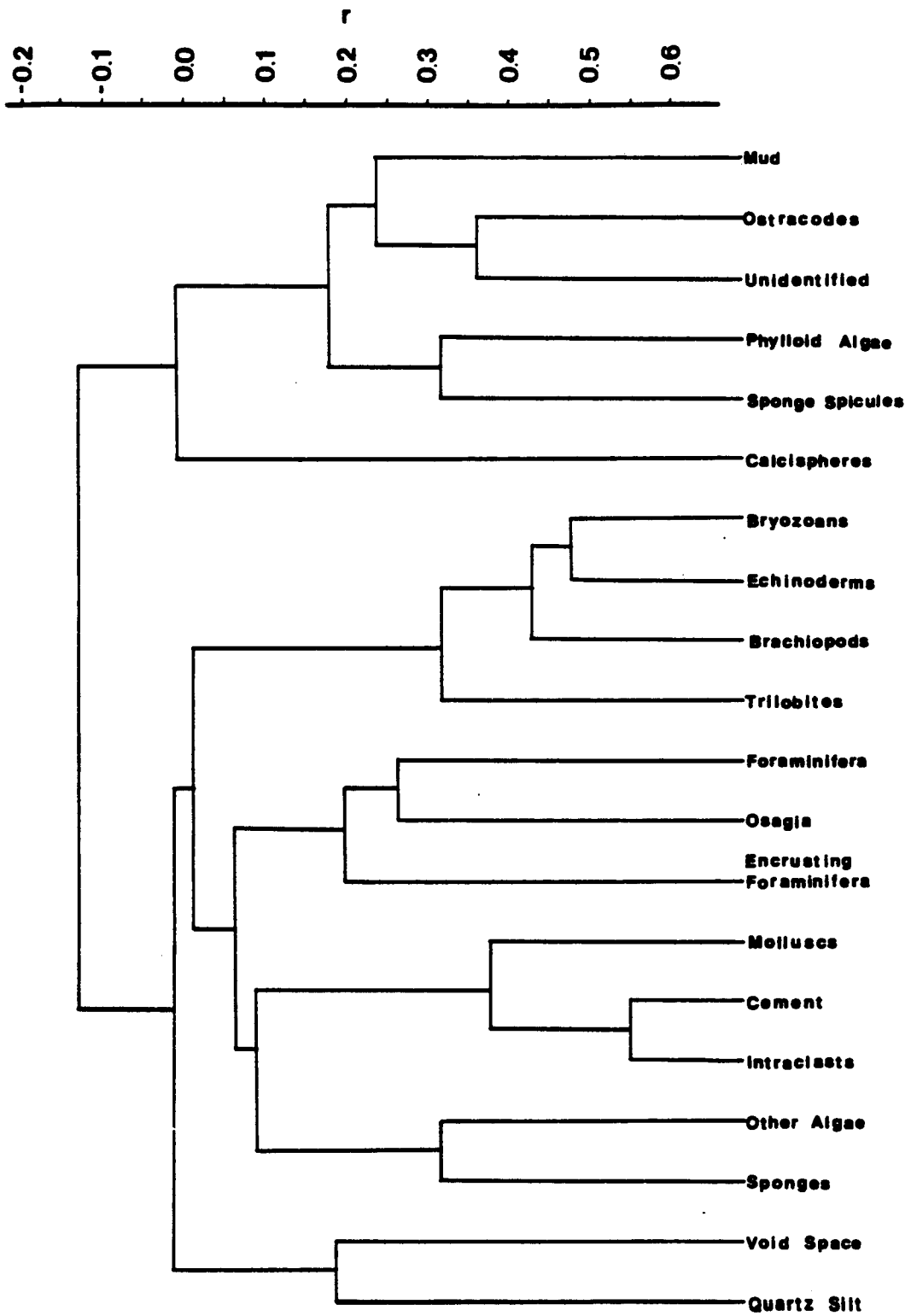
where:

\bar{X}_J = overall or population mean of continuous variable J.

s_J = overall or population standard deviation of continuous variable J.

$\bar{X}_{C,J}$ = mean of continuous variable J for a subset of samples comprising cluster C.

Fig. 4 -- R-mode cluster-analysis dendrogram for Captain Creek Limestone Member has grouped variables with similar distribution and abundance. The correlation coefficient ranges from +1 to -1, but only that portion of the scale where linkages occur is shown. No variable is considered redundant since all linkages are low level.



linkages occur at low levels of correlation, suggesting that none of the constituents provide redundant information.

Ten clusters were differentiated by Q-mode cluster analysis and are numbered as shown in figure 5. Several of the clusters have been geologically interpreted as belonging to the same depositional environments and have been combined. The original clusters and their associated facies are listed in Table 3. The geographic and stratigraphic distribution of these facies is shown in figure 6.

The cophenetic correlation coefficients, which measure distortion introduced during clustering, were fairly high indicating low distortion: $r = 0.702$ for R-mode and $r = 0.897$ for Q-mode.

Sediments and Paleoenvironments

The 71 samples collected were separated into distinct clusters on the basis of 20 variables. The samples within each cluster are highly similar and probably accumulated under similar environmental conditions. Geologic interpretations have differentiated 6 paleoenvironments: 1) a shallow, open-marine facies of foraminifera-bryozoan-echinoderm-brachiopod packstones, 2) a transitional facies composed of encrusting foraminifera-Osagia wackestones and packstones, 3) a restricted deep-water facies with phylloid algae wackestones, 4) a shoal facies of mixed skeletal grainstones, 5) an algal-mound facies with foraminifera-phylloid algae

Fig. 5 -- Q-mode dendrogram based on point-count data for the Captain Creek Limestone in Douglas and Johnson counties, Kansas. The analysis has grouped samples into clusters that are identified by numbers in the column on the right.

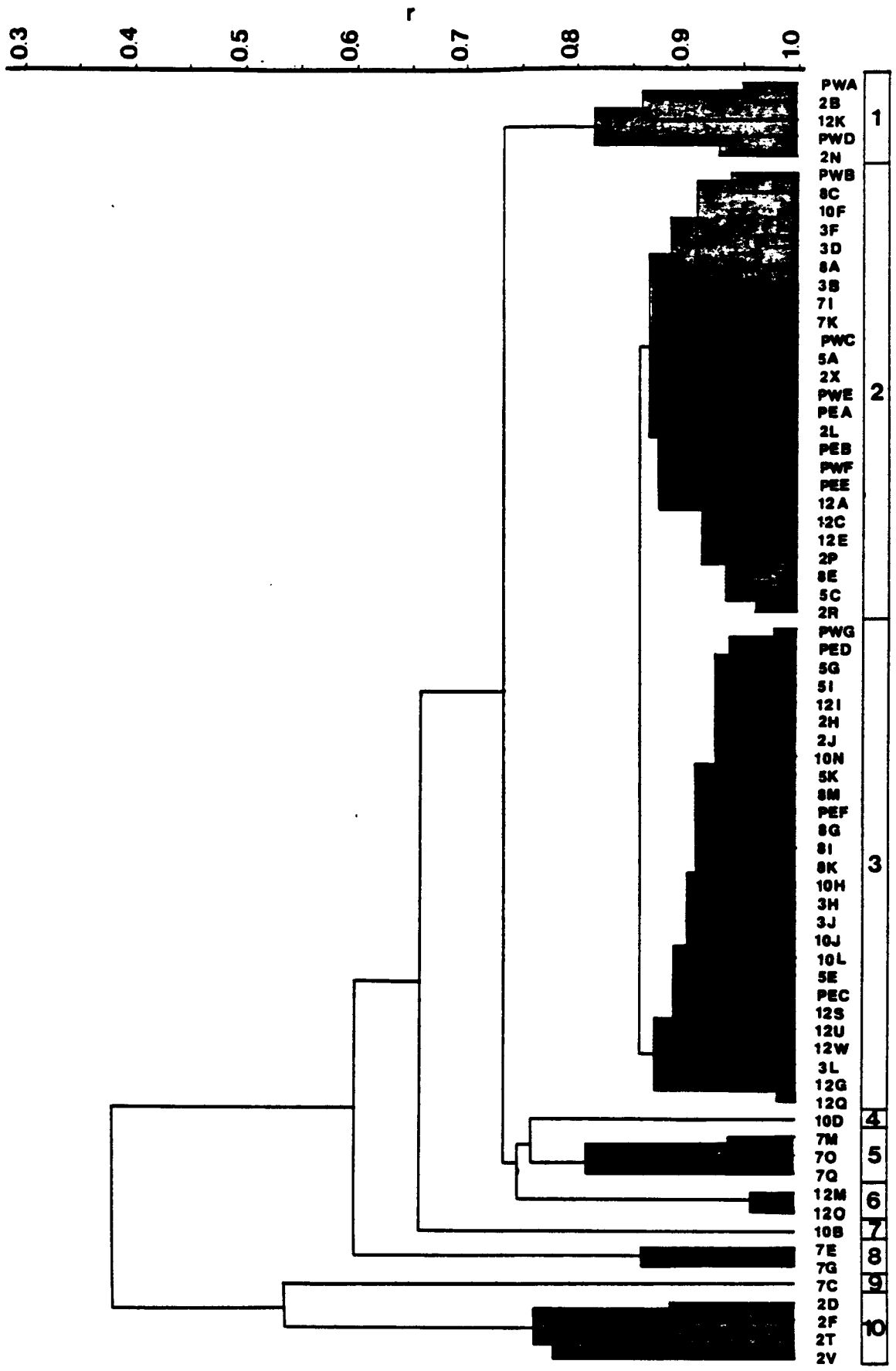
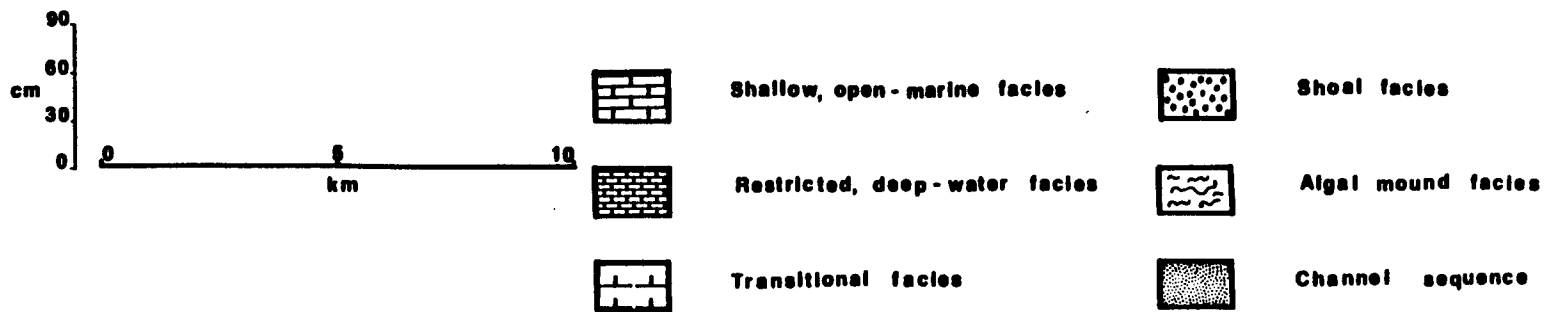
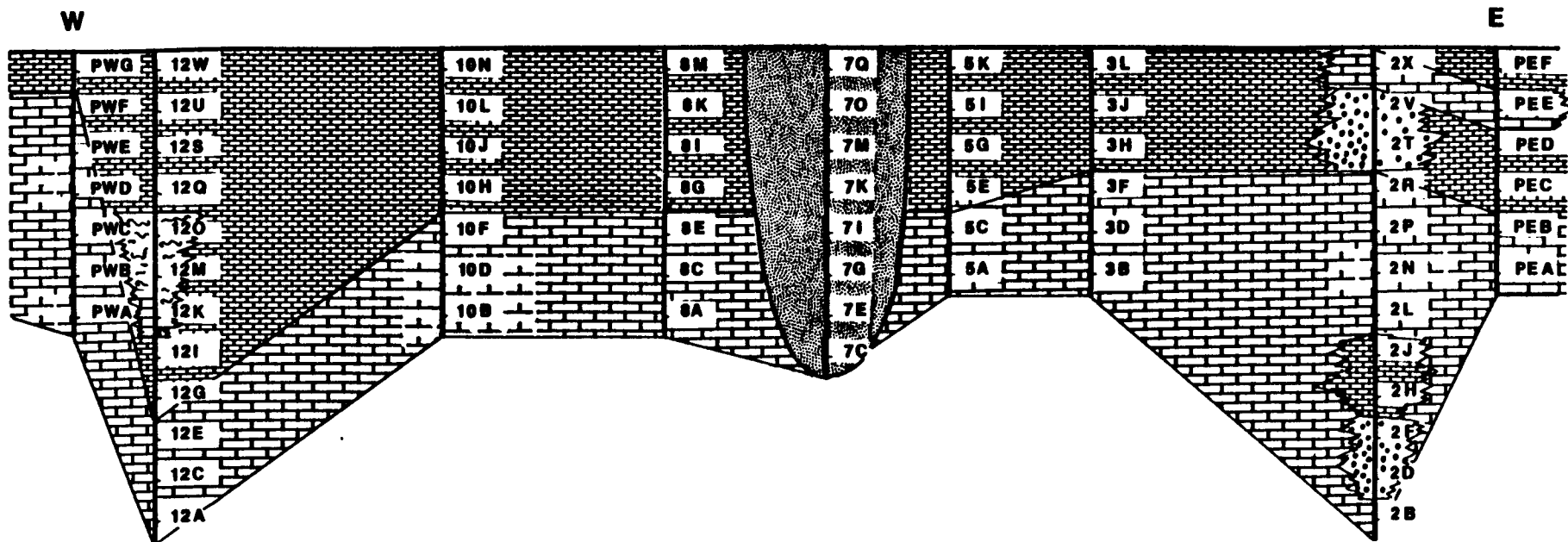


Table 3. Q-mode Clusters and their Associated Facies and Lithologies

<u>Cluster Number</u>	<u>Facies</u>	<u>Lithology</u>	<u>Number of Samples</u>
1	transitional	encrusting foraminifera- <u>Osagia</u> wackestones and packstones	5
2	shallow, open-marine	foraminifera-bryozoan-echinoderm- brachiopod packstones	25
3	restricted, deep-water	phylloid algae wackestones	27
4	transitional	encrusting foraminifera- <u>Osagia</u> wackestones and packstones	1
5	channel sequence	brachiopod-echinoderm-bryozoan packstone-wackestones	3
6	algal mound	foraminifera-phylloid algae packstones with sparry cement	2
7	transitional	encrusting foraminifera- <u>Osagia</u> wackestones and packstones	1
8	channel sequence	encrusting foraminifera- brachiopod packstones with quartz silt	2
9	channel sequence	brachiopod-intraclast-mollusc packstone-grainstone	1
10	shoal	mixed skeletal grainstones	4

Fig. 6 -- Restored stratigraphic cross section showing facies distribution in the Captain Creek Limestone along east-west line of outcrops in Douglas and Johnson counties, Kansas.



wackestones and sparry cement, and 6) a channel sequence that fines upward because of a gradual increase in mud content. The distribution of these facies is shown in figure 6.

Shallow, Open-Marine Facies
Foraminifera-Bryozoan-Echinoderm-Brachiopod Packstones
(Plate I)

Description

This facies is represented by 25 samples and is one of the two major facies present in the study area. Sixteen of the 25 samples are classified as packstones and nine as wackestones. T-values indicate that cluster means for foraminifera, bryozoans, echinoderms, and brachiopods are slightly greater than the population means implying a greater abundance of these constituents within this facies as compared with the entire population of samples. The cluster mean for phylloid algae, however, is somewhat lower than the population mean, indicating a deficiency in the amount of this constituent as compared with the population. In general, the composition of this facies has considerable variability and is similar to average population abundances. This is shown by most T-values being close to zero.

The most widespread characteristic of this facies is the occurrence of grainy areas. These are localized pockets of very small, uniformly sized constituents, usually pellets and foraminifera, with very finely crystalline sparry cement

filling the interstices. The extent of these grainy areas varies between samples. They frequently interrupt a fairly homogeneous mud matrix and only rarely occur within the shelter of a larger carbonate grain. It is unlikely that these grainy areas are burrow fillings in many cases, since shapes are highly irregular. Faunal activity in the form of churning or actual burrows is another common feature. Abundant coated and encrusted grains are also present. A distinction has been made between these two grain types. A coated grain has a single layer of organisms completely surrounding the grain, and an encrusting grain has only limited surface area encrusted. Many of the samples contain grains showing moderate wear.

Interpretation

Packstones are abundant in this facies, indicating high energy at least occasionally. The wackestones were deposited in more sheltered or lower-energy environments and can be attributed to normal environmental fluctuations. Further evidence of a moderately high-energy environment is the abundance of coated and encrusted grains, which require sufficient energy to cause movement of grains. Wackestones and coated grains represent two energy extremes in this facies. This suggests significant variability in environment.

The kinds and amounts of bioclastic grains indicate open-marine conditions. High biotic diversity is the presence of many different kinds of organisms. All 14 faunal components that were point-counted are present. The most

common constituents, brachiopods and echinoderms, are common in open-marine environments. All bryozoans are fenestrate, which are found in moderate currents above wave base (Wilson, 1975, p.71). Considerable bioturbation also suggests an open-marine environment.

Abundant diverse fauna in predominantly grain-supported rocks are found in moderately high energy, normal-marine environments with unrestricted circulation. These conditions occur near wave base and are typical of a marine platform or shelf. Wilson (1975, p.65) has proposed a standard micro-facies in a shelf environment with open circulation. He described it as a coated and worn bioclast packstone-wackestone displaying textural inversion and dominated by particles found in high-energy environments. The foraminifera-bryozoan-echinoderm-brachiopod packstones were deposited in such an environment.

Transitional Facies
Encrusting Foraminifera-Osagia Wackestones and Packstones
(Plate II)

Three clusters have been combined on the basis of geologic interpretations. The 3 original subfacies or clusters comprising this new single facies are the encrusting foraminifera-Osagia packstone subfacies (cluster 1), the pellet-foraminifera packstone with coated grains subfacies (cluster 4), and the onkoid wackestone subfacies (cluster 7). These lithologies have been generalized under a single,

common heading of encrusting foraminifera-Osagia wackestones and packstones. (fig. 5 and Table 3). From the ordination diagram derived from faunal abundances, it is clear that each of these clusters is separate and distinct, removing the possibility of gradational relationships. Each cluster, however, can be interpreted as an outlier of cluster 3, the shallow, open-marine facies.

Each sample included in the transitional facies can be interpreted slightly differently based on its location and association with other facies (fig. 6).

Description

Four of the seven samples in this facies contain onkoids. These onkoids range in size from 1.5 to 2 cm in diameter, and, where identifiable, nuclei are usually fragments of brachiopod or mollusc shells. Coatings are either exclusively Osagia or Osagia and encrusting foraminifera consortiums that loosely surround the nuclei in crinkly layers. Two of these four samples are packstones with abundant pellets, foraminifera, gastropods, and crinoids. The remaining two samples are wackestones with a few smaller constituents but rarer in comparison to the packstones.

Three samples contain coated grains. Nuclei are variable and consist of brachiopods, bryozoans, phylloid algae, and crinoids. These samples also contain abundant pellets and numerous foraminifera. The character of these three samples differs slightly. One sample possesses grains coated with Osagia and encrusting foraminifera, and the other two samples

contain grains coated with only encrusting foraminifera. The sample from the base of section PW (fig. 6) differs from all the others in that the encrusting foraminifera have frequently become unattached and appear to float in the surrounding mud.

Interpretation

Those rocks containing onkoids were formed in somewhat protected areas with mild wave action that gently rolled the algal balls permitting loose concentric layers to form around the nuclei. The samples with coated grains were found in slightly higher-energy surroundings causing coatings to be tighter and more compact. Environments were still moderately protected but not to the same extent as where onkoids were produced.

All of these samples are associated either directly or indirectly with the shallow, open-marine facies. Five of the samples may be outliers or represent a temporary pause in sedimentation in the predominantly shallow, open-marine sediments. The sample from the base of section 2 (fig. 6) is overlain by rocks deposited in a shoal. It probably formed in a sheltered area in the lee of the shoal. The sample from section 12 marks a momentary higher-energy interruption of the establishment of the phylloid algal mound.

The Restricted, Deep-Water Facies
Phylloid Algae Wackestones
(Plate III)

Description

This facies is represented by 27 samples and is one of the two major facies present in the study area. The cluster mean for phylloid algae is significantly greater than the population mean. Petrographic examination reveals that phylloid algae are practically the only organic constituents in every sample. Only minor trace amounts of other components occur.

Nineteen of the 27 samples are wackestones, and the remaining 8 are packstones. Since 70% of the samples are mud supported, wackestone is the most appropriate term for this facies.

The phylloid algae in most of the samples are poorly preserved. Only rarely do the samples show long filamentous algae with distinctive and distinguishable internal structure. Usually, the algae appear as small, broken, angular, recrystallized debris. Identifications were made on the basis of shape and by elimination of all other possibilities.

Many of the samples have encrusted grains and horizontal grain orientation. Pellets are fairly common. Grain boundaries appear relatively unabraded. Evidence of burrowing is fairly limited, but where burrows occur, some are excellently preserved. Burrows occur only in sections 5 and 10 (fig. 6) and always within the uppermost 60 to 90 cm.

Interpretation

The dominant and deficient biotic components in this facies are reversed from those in the shallow, open-marine

facies. Constituents that are abundant in one facies are noticeably lacking in the other. This reversal indicates a change in environmental controls as the phylloid algae wackestones vertically replace the foraminifera-bryozoan-echinoderm-brachiopod packstones.

Wackestones dominate this environment. Mud-supported rocks possess a relatively low energy index (Dunham, 1962). Deposition of these rocks was in calm water where currents of removal were too weak to affect bottom mud. Grain boundaries show little wear from transport or agitation. Grains were produced at the site of deposition in calm, muddy water clear enough to permit light penetration.

The considerable abundance of phylloid algae and the corresponding scarcity of other organic constituents are the consequences of moderately restricted circulation. Pelleting is also a feature commonly associated with calm, restricted waters. Burrowing is confined to only two sections, emphasizing again the lack of normal-marine conditions.

The phylloid algae wackestone facies accumulated in quiet water generally below normal wave base but still within the photic zone. Circulation was somewhat restricted but not to the extent of eliminating other biotic constituents. Major biotic constituents and grain fabrics of all the samples are closely similar. This signifies a stable, uniform, and widespread environment.

Shoal Facies
Mixed Skeletal Grainstones
(Plate IV)

Description

This facies is represented by four samples from near the base and near the top of section 2. The cluster means for echinoderms, foraminifera, molluscs, Osagia, other types of algae, intraclasts, and cement are significantly higher than their population means. Mud and phylloid algae have a much lower abundance within the cluster as compared with their population means.

All four samples are grainstones, although they do not perfectly fit Dunham's (1962) definition. Grainstones should be grain-supported rocks with less than 1% mud. These samples, however, contain between 2 and 18% mud, but since these percentages are drastically smaller than in any other sample analyzed and classified as a packstone, grainstone seems the most appropriate designation.

All samples contain grains coated with Osagia and encrusting foraminifera. They include abundant fossils and display higher diversity than other samples. Most grains show evidence of moderate to extensive abraision. Pellets and foraminifera are extremely abundant in all samples, but only samples 2F and 2T show a distinct bimodal distribution of larger coated grains within a pellet-foraminifera matrix. Elsewhere, grain size and sorting are variable. Interstitial

cement is cloudy with an equidimensional crystal habit. The amount of lime mud is less in samples 2D and 2T than in 2F and 2V. Only 2T has geopetal features; gastropod chambers are floored with finely pelleted mud and the top is filled with the same cement as found in the interstitial areas.

Interpretation

All the characteristics of this facies, grain-supported fabric, coated grains, and considerable grain wear, indicate a high-energy environment. The fauna is also abundant and diverse, a feature of well-circulated, normal-marine waters. The mixed skeletal grainstone facies accumulated in a shoal environment with strong wave action.

Grain size distributions and sorting are highly variable in samples from this facies. Textures include well-sorted grains of large size, well-sorted small grains, poorly sorted finer fractions with mud, bimodal distributions with no mud, and localized patches of fairly homogeneous mud. The horizontal grain orientation in sample 2D suggests persistent wave action. Energy was generally high enough to wash away most of the mud.

This facies was deposited in shallow water at or above wave base in an environment subjected to fairly constant wave action. From the distribution of this facies (fig. 6), it appears that the shoal at the base of the section was temporarily covered by the shallow, open-marine facies and later re-established near the top of the section. The shoals are small and limited in vertical extent. The lower sample

in each of the two shoals has the highest energy as evidenced by a smaller amount of mud. This represents rapid establishment of shallow water. The upper sample in each shoal contains more mud indicating slightly lower energy and possibly deepening water. Following each shoaling episode, there was an abrupt return to the widespread marine environments of the shallow, open-marine facies or the restricted, deep-water facies.

Algal Mound Facies
Foraminifera-Phylloid Algae Packstones with Sparry Cement
(Plate V)

Description

This minor facies has a limited distribution and is represented by only 2 samples in the middle of section 12 (fig. 6). The cluster mean for cement is significantly greater than the population mean, and the cluster means for foraminifera and phylloid algae are slightly to moderately greater than the population means. Brachiopods, encrusting foraminifera, bryozoans, Osagia, and echinoderms are present in smaller amounts here than in the entire population of samples.

Both samples are packstones. The primary and most distinctive feature unique to these samples is sparry shelter cement. There are 2 generations of cement. The first is a radiaxial fibrous mosaic with elongate crystals and a preferred orientation of the longest axis normal to the cavity wall.

This is followed by a second generation of cement with equant rhombohedral crystal habit (see Bathurst, 1975, p.426). Both generations of cement are cloudy. These cements resulted from the infilling of sheltered voids, primarily beneath long filamentous algal blades, but also occur beneath other biotic components. Another common characteristic of this facies is thin, sparry compactional fractures visible in both mud and phylloid algae. Mud trapped between the algal blades is the result of both originally deposited and later infilled sediment.

Geopetal structures are common where gastropods occur. The bottoms of the chambers are filled with finely pelleted mud, and cloudy equant cement fills the upper part of the cavity. Pellets and foraminifera are abundant, but usually their occurrence is localized.

Interpretation

This facies has a composition similar to the phylloid algae wackestones surrounding it (fig. 6). The abundant shelter cement in the foraminifera-phylloid algae packstones, however, requires a different interpretation. This facies represents the climax of a limited and brief algal-mound build-up, similar in many respects to the major mound tract in southeastern Kansas. Heckel and others (1979, p.29) described early development of the massive mound facies as a sparry algal calcilutite with spar-filled voids containing pelleted geopetal mud fill beneath algal blades. This umbrella effect (Harbaugh, 1960, 1961, and 1962) formed when

individual algal blades caught lime mud on their upper surfaces, creating sheltered, water-filled voids beneath, which were later filled with coarse calcite cement. Compactional fractures are evident in mud and some skeletal fragments. These distinctive features occur on a much smaller scale in section 12. A small algal mound with its increased carbonate production also aids in the explanation of the considerable total thickness of section 12 as compared to the other sections (fig. 6).

Channel Sequence
Associated Subfacies
(Plate VI)

The three remaining clusters, 5, 8, and 9, occur at section 7 (fig. 5). They have been grouped together because all are interpreted to belong to a submarine channel sequence. The following subfacies can be differentiated in this sequence: the brachiopod-intraclast-mollusc packstone-grainstone subfacies (cluster 9), the encrusting foraminifera-brachiopod packstone with quartz silt subfacies (cluster 8), and the brachiopod-echinoderm-bryozoan packstone-wackestone subfacies (cluster 5) (Table 3).

Brachiopod-Intraclast-Mollusc Packstone-Grainstone Subfacies

Description: The most abundant constituents are indicated in the name of this subfacies. The cluster means for most of the

other constituents point-counted are significantly less than the population means. Shell debris is abundant and occurs in packed, grain-supported, horizontal layers. Very little mud is present; instead interstices are filled with cloudy, equidimensional marine cement. Crinoids display extensive syntaxial overgrowths, and the resulting cloudy, blocky appearance is similar to interstitial cement. Consequently, counting fewer crinoids than actually existed in the sample may have resulted due to operator error. Intraclasts are also abundant and occur as rounded homogeneous mud clasts that vary in size from 1 to 3 mm.

Interpretation: The sample representing this facies was taken from the finer fraction of a conglomerate with variably sized clasts. It contains the coarsest material in the entire section and has very little mud. Swift effective currents of removal commonly deposit sediments similar to these. Rounded intraclasts and broken shell debris also indicate high-energy transport for an extended distance. Fluvial environments with coarse-grained accumulations occupying the lowest part of a channel are usually interpreted as lag deposits (Keineck and Singh, 1973, p.231; Lattman, 1960). This subfacies also represents a basal lag deposit of a submarine channel.

Encrusting Foraminifera-Brachiopod Packstone with Quartz Silt Subfacies

Description: Again, the most abundant constituents are indicated in the subfacies name. All other constituents are either absent or possess cluster means significantly less than their population means. Both samples in this facies are similar in character and constituent types but differ in biotic proportions. The upper sample (fig. 6) has more abundant and diverse fauna and more prominent Osagia and encrusting foraminifera coated grains. The lower sample contains more terrigenous quartz silt and less mud. It also displays horizontal grain orientation and is well sorted.

Interpretation: This subfacies represents the lower portion of the fining-upward sequence. Current velocity decreased through time depositing the basal channel lag and progressing upward through silty lower-energy deposits with abundant quartz silt to sediments deposited under even lower-energy conditions, showing a decrease in quartz silt and an increase in mud. Terrigenous material was only found in section 7. The most likely source for this material is southeast Kansas, which was the site of the northern boundary of deltaic deposition produced by the weathering of the Ouachita, Wichita, and Amarillo Mountains.

Brachiopod-Echinoderm-Bryozoan Packstone-Wackestone Subfacies

Description: The 3 samples in this subfacies are characterized by abundant brachiopods, echinoderms, and bryozoans and rare trilobites and sponges. Remaining constituents are either

absent or significantly less abundant than biotic proportions in other samples from the channel sequence. This subfacies grades upward from packstones at the base to wackestones near the top (fig. 6). There is a noticeable upward decrease in shell debris. Crinoids are abundant and unabraded. The lowermost samples have rare encrusted grains and negligible amounts of quartz silt. The uppermost sample has more mud and coated grains and higher faunal diversity, but generally fewer bioclasts.

Interpretation: These samples represent the top of the fining-upward sequence. The upward vertical progression shows a gradual increase in mud that resulted from a corresponding decrease in current velocity. Grains have smooth, unabraded boundaries indicating little agitation or transport. A more drastic difference occurs at the top of the section, where mud becomes more abundant and sponges and trilobites appear for the first time. This part of the section was deposited during the final stages of Captain Creek deposition and probably represents the beginning of the transition into the overlying Eudora Shale, which is a black, phosphatic shale probably deposited in relatively deep water.

Evolution of the Carbonate Shelf

The facies of the Captain Creek Limestone Member vary both vertically and horizontally, revealing changes in the sedimentary environments through time and space. Now that

the paleoenvironments have been inferred, the geologic history of the carbonate shelf in northeastern Kansas can be unraveled.

Transgressive Sequence

Fifty-two of the 71 samples were clustered by Q-mode cluster analysis into one or the other of two major facies, the shallow, open-marine facies or the restricted, deep-water facies. These two facies represent the environmental conditions of transgressive seas on an epicontinental open-marine shelf.

Most authors agree that marine advancement was from the southwest. Seas spread eastward across southern Arizona and New Mexico, then north through the Texas and Oklahoma panhandles, across Kansas, Missouri, and Iowa to the Illinois basin (Elias, 1964; Wanless, 1972; and Heckel, 1980).

Sections PE, 3, 5, 8, and 10 (fig. 6) indicate a transgressive sequence. The lower half of each section is dominated by foraminifera-bryozoan-echinoderm-brachiopod packstones deposited in shallow, moderately high-energy water. The phylloid algae wackestones in the upper half of each section accumulated in deeper, more restricted waters. This progression is expected in the Captain Creek throughout northern Kansas except where interrupted by local variations such as channels or shoals. The expected occurrence of the vertical succession found in the Captain Creek Limestone can

be expanded to include other transgressive, middle limestones in Pennsylvanian cyclothems.

The term shallow with regard to the foraminifera-bryozoan-echinoderm-brachiopod packstones is used in a relative sense. The depositional environment of these rocks is shallower than that of the phylloid algae wackestones but considerably deeper than any nearshore environment. According to Heckel (1977), most middle limestones have fine grain size, diverse biota, and dark color, strongly suggesting deposition in the open-marine environment far enough offshore to be below effective wave base, but above effective base of the photic zone. He later portrays the depth at low sea level stand in epicontinental seas, when the underlying Vilas Shale was deposited, to be approximately 50 m and the depth at high sea-level stand, when the overlying Eudora Shale was deposited, to be approximately 150 m (Heckel, 1977, fig. 5). Presumably, the depth of deposition of the Captain Creek lies somewhere between these two values. These depths, which presumably apply to most of eastern Kansas, appear to be somewhat greater than the depths at which the units in Douglas and Johnson counties were deposited.

Common constituents in the shallow, open-marine facies and transitional facies are Osagia, other coated grains, and mixed skeletal components. The growth of Osagia or other stromatolite-forming algae occurs at depths of less than 30 m in salt water (Cloud, 1942). Blue-green and green algae, which are believed to include Osagia (Elias, 1964), are most

numerous in water less than 18 m deep (Newell and Rigby, 1957, see also Lane, 1958; McCrone, 1964). Therefore, the best estimate for the depth of deposition of the foraminifera-bryozoan-echinoderm-brachiopod packstones is 18 to 30 m.

The phylloid algal wackestone facies is probably composed of Archaeolithophyllum, a corallinacean or red alga, and Eugonophyllum, a codiacean or green alga (Bathurst, 1975, p.66). Some types of red algae are capable of forming banks in waters more than 30 m deep (Logan, 1961). Consequently, this facies may have been deposited at depths from about 20 m down to the base of the photic zone.

The Shoal

The shoal facies is represented by only four samples, all from section 2, where grainstones accumulated at two different times on a high-energy shoal (fig. 6).

Presumably, the shoal formed in response to some irregularity in the underlying Vilas Shale. Unfortunately, the Vilas Shale has insufficient outcrop to accurately determine its thickness in Douglas and Johnson counties to confirm this theory. Considerable work done in southeast Kansas, however, indicates that algal-mound build-ups were initiated by topographic control in the underlying Vilas Shale (Heckel, 1972). A similar situation may have existed in section 2, but wave energy was higher and grainstones were deposited instead of algal wackestones.

The transitional facies occurs at the base of section 2 (sample 2B). It is an onkoid packstone deposited under conditions of gentle wave action. The transitional facies is normally associated with the shallow, open-marine facies and, consequently, accumulated in similar environments. This sample represents the initial stages of shoaling. It accumulated near wave base where grains were rolled by weak, oscillatory motion that produced onkoids.

Shoaling continued resulting in the deposition of mixed skeletal grainstones in high-energy water above wave base (samples 2D and 2F, fig. 6). These samples have high diversity and abundant bioclasts suggesting that conditions were conducive to the growth and accumulation of biotic constituents.

The restricted, deep-water facies, represented by samples 2H and 2J (fig. 6), appears above the grainstones in section 2. This transition from grainstones to phylloid algae wackestones is too sudden to have resulted from deep-water deposition. Instead, deposition probably occurred in shallow, calm water on the lee side of the shoal.

Above the restricted, deep-water facies, there is a return to moderate energy, open-marine waters. The sediments deposited during this interval represent a suspension of shoal conditions as water deepened temporarily. A second shoal environment developed at the top of the section and was similar in duration and extent to the previous one.

The increased carbonate accumulation resulting from

the shoal caused total thickness to double.

Algal Mound

The vertical sequence of rocks in section 12 represents the establishment of an algal build-up and its subsequent replacement by the restricted, deep-water facies (fig. 6). The samples taken from the algal mound are distinguished from the similar phylloid algae wackestones by prominent shelter spar. This facies resembles, on a much smaller scale, the lithology described in the algal-mound tract in southeastern Kansas.

The base of section 12 follows the expected transgressive depositional sequence of foraminifera-bryozoan-echinoderm-brachiopod packstones beneath phylloid algae wackestones. The appearance of the transitional facies, which usually occurs within the shallow, open-marine facies, represents shallowing, slightly higher-energy waters that later favored the proliferation of algae. The foraminifera-phylloid algae packstones with sparry cement had limited duration and extent. They were replaced by the phylloid algae wackestones, which continued to be deposited throughout the rest of the Captain Creek. The algal build-up resulted in a two-fold increase in thickness of the section to 3.6 m.

The rocks in section PW deviate from the usual transgressive pattern in that the shallow, open-marine facies continues to near the top of the section before rocks of the

restricted, deep-water facies were deposited. This persistence of well-circulated, moderately high-energy conditions formed in response to the east-west transition from the shallow algal-mound facies in section 12 to the basin facies west of the study area.

In southeastern Kansas, algal mounds in the Captain Creek are bordered along their northwest extent by high-energy skeletal calcarenites found along a northeast-southwest trending rim (Heckel and others, 1978) (fig. 7). This rim coincides with the delta front slope of the underlying Vilas Shale where regional dip increases abruptly from 4 or 6 m/km to 38 m/km. Shoaling across this steep slope resulted in high-energy conditions and deposition of the skeletal calcarenite. Section PW is possibly a subdued northern extension of this rim.

During late Missourian time, a broad, flat, carbonate shelf formed a very abrupt shelf edge that extended across southern Kansas, northwestern Oklahoma, and the Oklahoma and Texas panhandles (Moore, 1979) (fig. 8). This shelf edge marked the farthest northward extent of an isolith hingeline separating paralic clastics from normal-marine carbonate deposition (Rascoe, 1962). As a consequence, the influence of the deltaic Vilas Shale reached its maximum northern extent in southeastern Kansas.

The Vilas Shale delta lobe provided considerable sediment influx to a broad, flat, carbonate shelf and could have extended for a considerable distance with a gradually

Fig. 7 -- Schematic diagram showing association between mound and basin facies in the Stanton Limestone in southeastern Kansas (adapted from Heckel, 1972, fig.3).

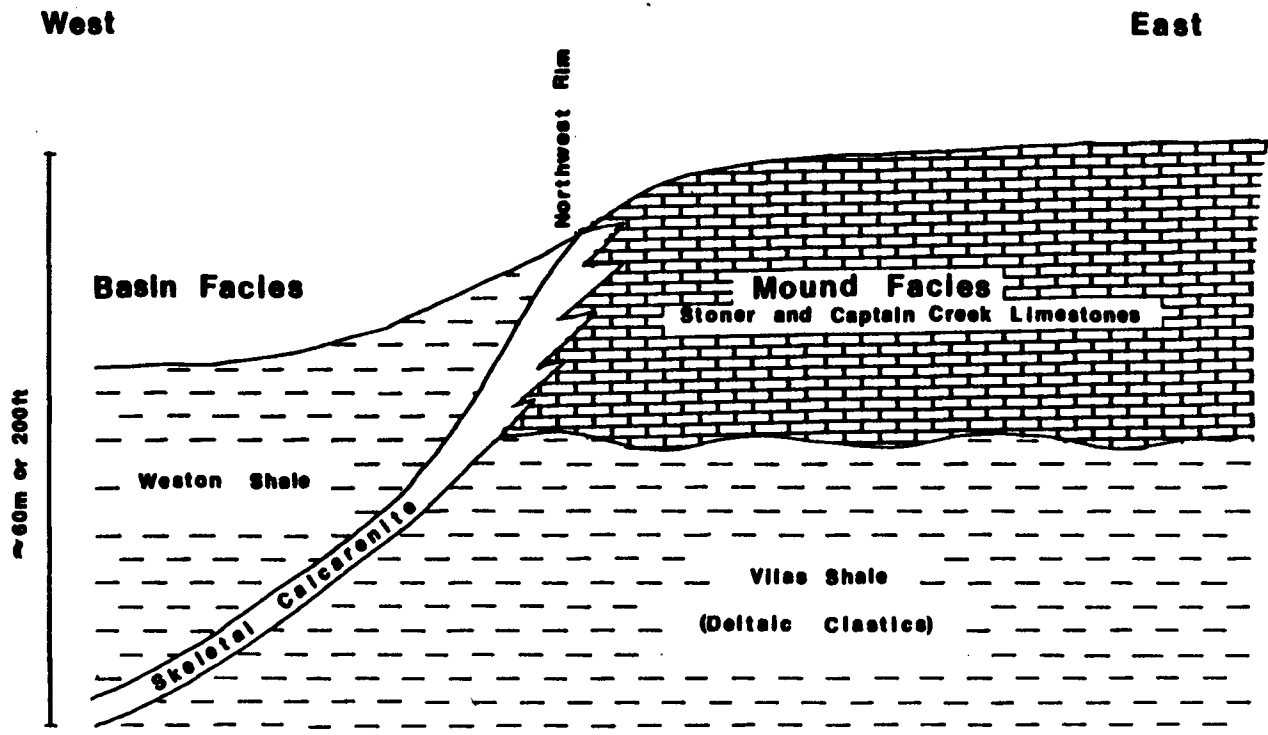
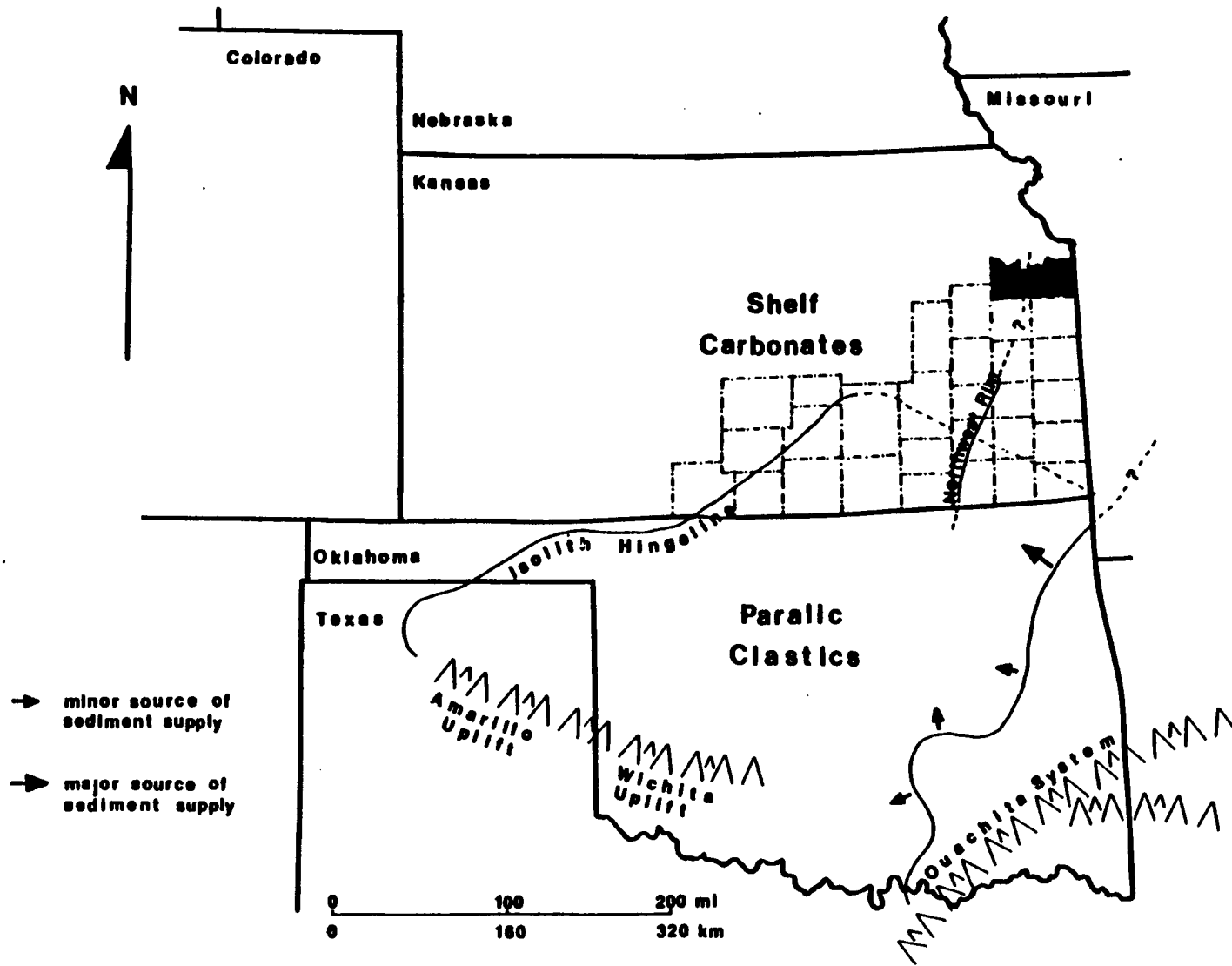


Fig. 8 -- Generalized paleogeography of sea in Late Pennsylvanian during limestone phase of cyclic deposition in Midcontinent North America (compiled from Heckel, 1972; Rascoe, 1962; and Moore, 1979).



decreasing slope. The northwestern rim, which coincides with the delta front slope, could have extended northward into Douglas County with greatly diminished dip. Within Douglas County, the Vilas Shale is thickest near Eudora where section PW was sampled but may be much thinner in the subsurface (O'Connor, 1960). This change in thickness could suggest the presence of the delta-front slope.

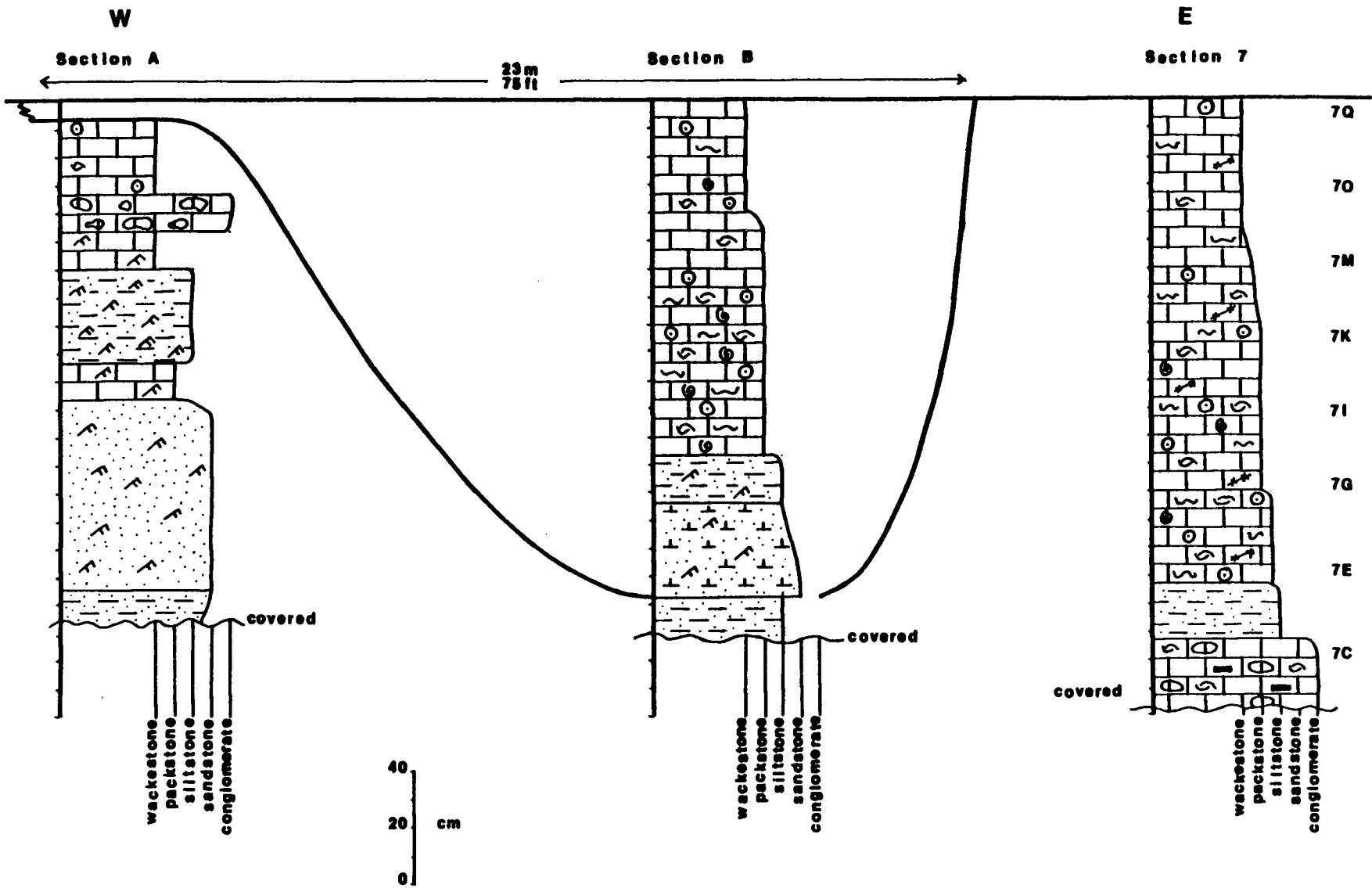
The proposed rim slope is much gentler at section PW, so the extremely high-energy calcarenites of southeastern Kansas are not expected. Instead, there is a persistence of moderate-energy conditions keeping pace with transgressing seas almost to the end of Captain Creek deposition.

Submarine Channel Sequence

The sequence of rocks in section 7 has been interpreted to represent a submarine channel (fig. 6). All samples have been clustered into specific channel subfacies, except for two samples near the center of the section, which belong to the shallow, open-marine facies. The association of these samples with the channel and their position in the section, however, makes it reasonable to include them in the channel fining-upward sequence.

The outcrop where section 7 was sampled also contained an exposed asymmetrical channel cut where 2 additional sections, A and B, were measured (fig. 9). Section A was measured on the convex bank, and section B was measured

Fig. 9 -- Channel sequence in the Captain Creek limestone Member (SE $\frac{1}{4}$, sec. 30, T.12S, R.22E.). Section 7 was sampled and included in statistical analyses. Sections A and B were measured and described to provide additional information for environmental interpretations.



within the channel cut-and-fill deposits. The entire 0.5 km-long outcrop shows a vertical sequence similar to section 7. The actual channel cut is laterally limited to a small portion of the outcrop and stratigraphically confined to the Captain Creek Limestone Member. Evidence of channel activity does not extend into the underlying Vilas Shale or the overlying Eudora Shale.

Section B is a fining-upward sequence ranging from rippled sandstone at the base to moderately fossiliferous wackestones at the top. The change from siltstone to packstone at 50 cm coincides with the introduction of abundant normal-marine fauna. The section gradually becomes less fossiliferous upward. This fining-upward sequence is similar in many respects to fluvial channel deposits. Despite the differences between a fresh water and a marine environment, the gradual upward progression from high to low flow-regime conditions is still expected in channels formed in both types of environments.

Section A contains three cycles that have been interpreted as fining upward sequences. The basal rocks are composed of rippled sandstone to siltstone in the lower two cycles and a limestone conglomerate in the upper cycle. These rocks are abruptly capped by rippled or fossiliferous wackestones in each cycle.

In a fluvial environment, these strata would be interpreted as crevasse-splay deposits. Crevasse-splay deposits result from water-cut channels that divert large quantities of

sediments during periods of high discharge. These deposits have an internal geometry of interfingering or overlapping lenses of coarse material, such as fine sand, capped by finer-grained deposits that accumulate during the falling stage (Reineck and Singh, 1973, p.246; Coleman, 1979; and Elliott, 1974).

The rocks in section A may be crevasse-splay deposits formed by three successive storm surges. They have a structure similar to fluvial crevasse-splay deposits, and their limited occurrence at only the convex side of the channel makes any other explanation unlikely. The conglomerate in the upper cycle is too coarse to be a crevasse-splay deposit. Instead, a temporary diversion of discharge from the major channel could have deposited this basal, storm-lag conglomerate.

The channel cut-and-fill of section B eroded the deposits of section A (fig. 9). Presumably, the rocks in section A were deposited by another channel, and the channel in section B was cut and filled later, near the end of Captain Creek deposition. Rocks at section 7 are similar to rocks found throughout the rest of the 0.5 km-long outcrop. The base of this section is a conglomerate with variably-sized clasts beneath a silty shale (fig. 9). Both of these units probably occur beneath sections A and B also, although the conglomerate is covered. Above this, fossiliferous packstones with terrigenous quartz silt grade upward into fossiliferous wackestones at the top. Source material for

some Upper Pennsylvanian sandstones and siltstones is considered to originate from the north or northwest (Mudge, 1956). Moore (1979), however, has reconstructed the paleogeography, and shown that during late Missourian, clastics shed by the Ouachita Mountains were a major sediment source in northern Oklahoma and extreme southern Kansas (fig. 8). The shift to a northern sediment source did not begin until later in the Pennsylvanian.

The sequence of events producing these channel-associated deposits in Johnson County began with a powerful storm surge that scoured a wide, slightly sinuous to straight channel. Rounded limestone or mud pebbles were transported from nearshore environments to the east or south. This was followed by a period of quiescence during which silty shale was deposited above the lag conglomerate found at the base of all three sections. After this, major current flow was confined to a much smaller portion of the channel similar to the exposed channel of section B. Three small storms increased discharge within the smaller channel, producing the crevasse-splay deposits of section A. The original broad scour channel funneled transgressing seas and helped move large quantities of sand out onto the shelf. Slightly higher energy conditions resulted, and sediments similar to those in section 7 were deposited. The major deltaic sand bodies deposited in Oklahoma during lower stands of sea level were drowned during rising sea level. The resulting transgression accompanied by shelf currents moved sands and

silts offshore (see Reading, 1978, p.258).

Relationships Between Facies: Ordination

Nonmetric multidimensional scaling (MDS) is defined as placing t points in a space of k dimensions so as to minimize stress, S , between distances between points in the configuration and the original distance matrix (Kruskal, 1964). Nonmetric MDS is superior to other ordination methods (e.g. principal component analysis and principal coordinate analysis) because it more accurately displays interpoint distances as judged by cophenetic correlation (Rohlf, 1972). The stress is represented by a fraction or a percent indicating whether a monotone relationship exists between dissimilarity and distance. The stress calculated for figure 10 is 0.20 where a value of 0.00 indicates a perfect monotone relationship.

The MDS ordination (fig. 10) demonstrates the gradational nature of systematic changes in environmental variables. Samples in each cluster are segregated on the MDS ordination. When arranged in 3-dimensional space, clusters are found to be closer in position to some clusters than to others. These observed associations are the basis for reconstructing environmental gradients.

Relative depositional energy decreases from left to right in figure 11. Rocks deposited during two episodes of shoaling in section 2 and the channel lag deposits at the base of section 7 were deposited in the highest energy

Fig. 10 -- Three dimensional Q-mode ordination
by nonmetric multidimensional scaling of seventy-
one samples. (See Table 2 for facies associations.)

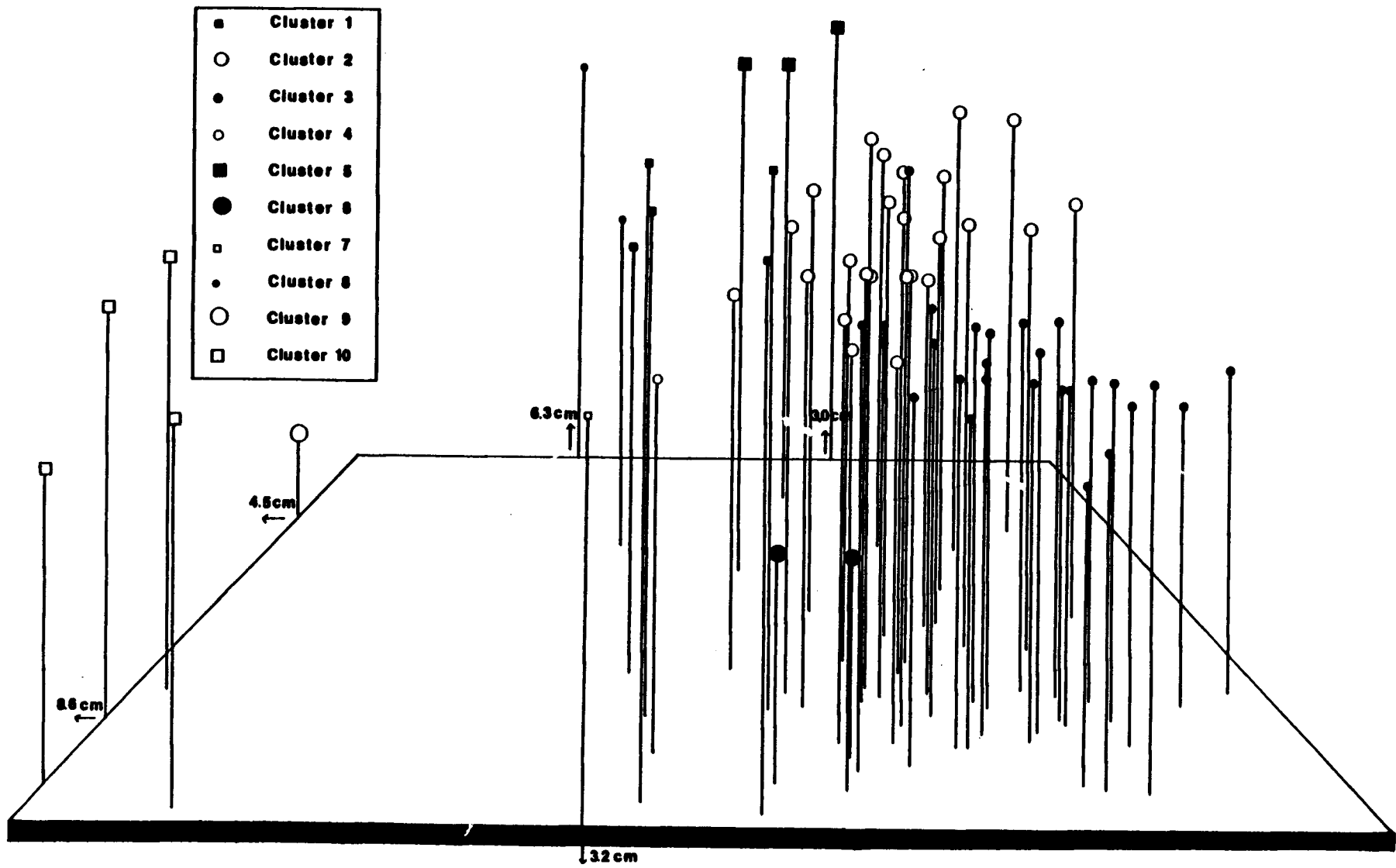


Fig. 11 -- Lines illustrate energy ranges for numbered clusters as determined by MDS ordination. (See Table 2 for facies associations.)

HIGH ENERGY	MODERATE ENERGY	LOW ENERGY
--------------------	------------------------	-------------------

10 and 9

8

7, 1, and 4

5 and 6

2

3

environments and the restricted marine phylloid algae wackestone facies in the lowest. All the other facies fall somewhere between with either a unique or an overlapping energy relation as indicated.

Another relationship illustrated by the ordination is the gradational change from the shallow, open-marine facies to the restricted, deep-water facies. There is no sharp break between the range of one and the range of the other of these two major facies, clusters 2 and 3. Instead, there is overlap. This situation agrees with the interpretation of slowly deepening water that would have resulted from the transgressing seas.

Conclusions

1. A combination of multivariate and statistical methods was used to determine carbonate depositional environments and to reconstruct the vertical facies sequence of the Upper Pennsylvanian Captain Creek Limestone Member of the Stanton Limestone in Douglas and Johnson counties, Kansas.
2. The combination used was Q-mode cluster analysis to group samples, R-mode cluster analysis to group lithologic constituents, and ordination by nonmetric multidimensional scaling. These first methods classified samples; the second then ordered them in space to show gradational relationships among mutually exclusive clusters.
3. Seventy-one thin sections from nine measured sections

were point counted for a variety of constituents to provide data for the multivariate procedures. The R-mode analysis concluded that none of the variables was redundant. The Q-mode analysis classified the 71 samples into 10 clusters. 4. The 10 clusters were combined to represent 6 depositional environments as a result of geologic interpretations: 1) a shallow, open-marine environment with unrestricted circulation in moderate energy water near wave base composed of foraminifera-bryozoan-echinoderm-brachiopod packstones; 2) the transitional facies where encrusting foraminifera-Osagia wackestones and packstones represent outliers within the previous facies; 3) a somewhat restricted, deep-water facies within the photic zone consisting of phylloid algae wackestones; 4) a shoal facies represented by mixed skeletal grainstones deposited in shallow water with fairly constant wave action at or above wave base; 5) an algal mound composed of foraminifera-phylloid algae packstones with sparry cement, which developed when shelter voids formed beneath large algal blades; and 6) a channel sequence which fines from a basal shell lag upward to fossiliferous wackestones.

5. Deposition on the carbonate shelf in Douglas and Johnson counties was controlled primarily by transgressing seas during the time when Captain Creek sediments were accumulating. Generally, the most widespread vertical succession is from the shallow, open-marine facies upward to the restricted, deep-water facies. Estimates of water depth based upon fauna and hydrodynamic conditions suggest that early Captain Creek

deposition occurred in approximately 18 to 30 m of water and late deposition occurred from approximately 20 m of water down to the base of the photic zone.

6. The remaining facies are the result of local fluctuations in environmental conditions. Temporary and gradual shallowing produced an algal mound and a high-energy shoal. The channel sequence occurred in response to conditions outside the study area. A large storm probably originated in east-central to southeastern Kansas, scoured a wide channel that extended into northeastern Kansas. Flow continued in a restricted portion of this broad channel depositing cross-bedded sandstones and siltstones. The remainder of the channel acted as a funnel for the transgressing seas and moved large quantities of nearshore sediment northward into Douglas and Johnson counties.

Acknowledgements

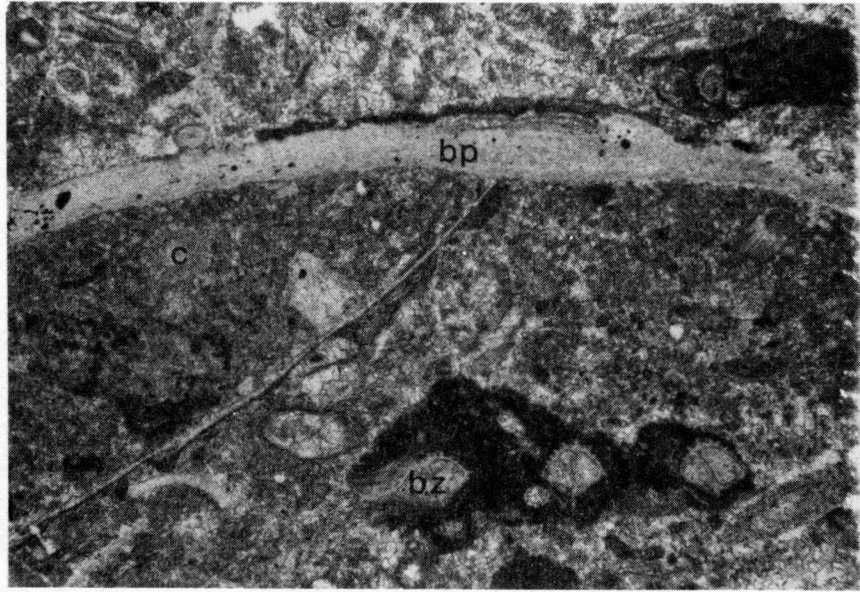
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Plate I: Shallow, Open-Marine Facies
Foraminifera-Bryozoan-Echinoderm-Brachiopod Packstones

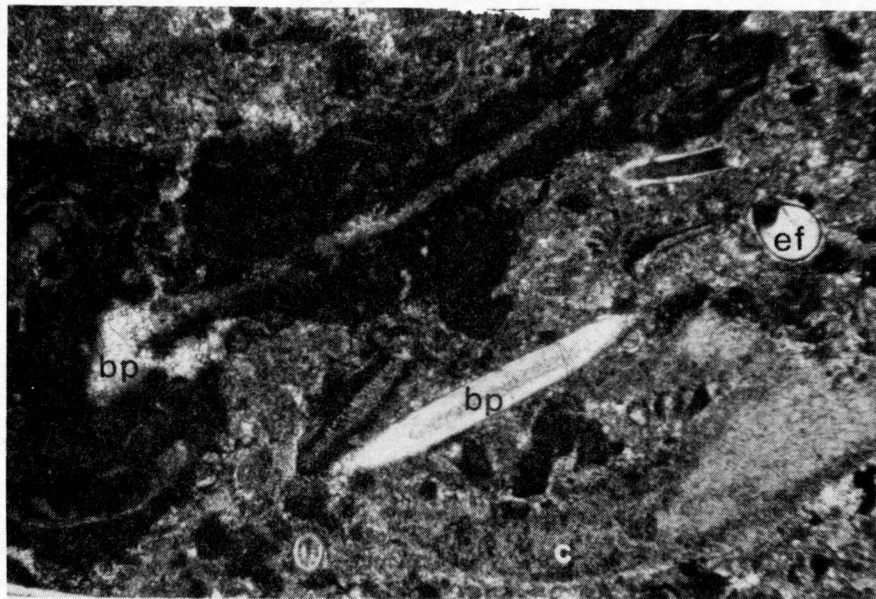
- A. Abundant, diverse bioclasts consisting of bryozoans (bz), crinoids (c), and brachiopods (bp) indicate normal-marine environments with unrestricted circulation.
- B. A recrystallized brachiopod fragment (bp) coated with Osagia and encrusting foraminifera. Also present are a longitudinal section through a brachiopod spine (bp), a crinoid (c), and an unattached encrusting foraminifer (ef).



A

0.2 mm

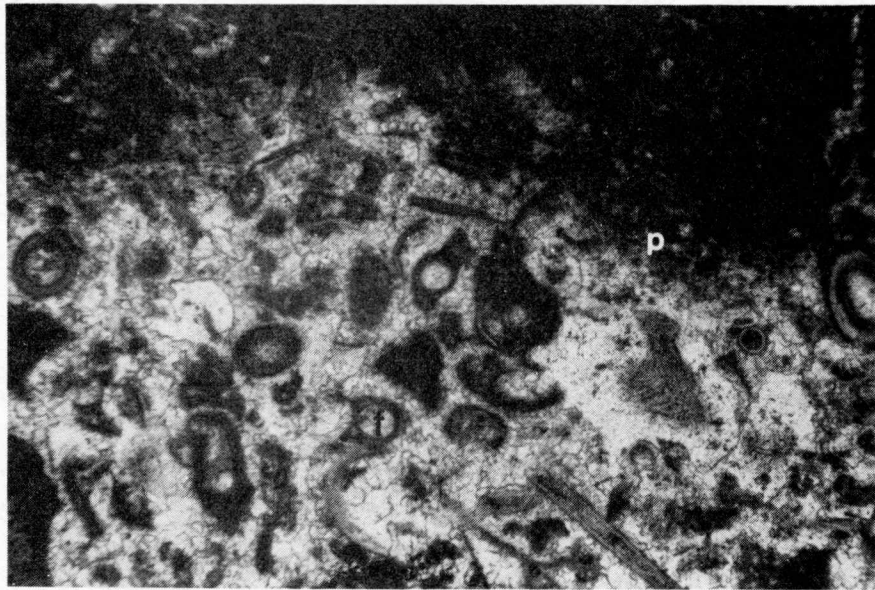
B



(cont.)

C. Grainy areas, characteristic of this facies, are localized pockets of small, uniformly sized constituents, usually pellets (p) and foraminifera (f), surrounded by finely crystalline sparry cement.

D. Pelleted fossiliferous packstone suggests deposition in moderately high-energy environments near wave base, which is typical of a marine platform or shelf.



C

0.2 mm

D

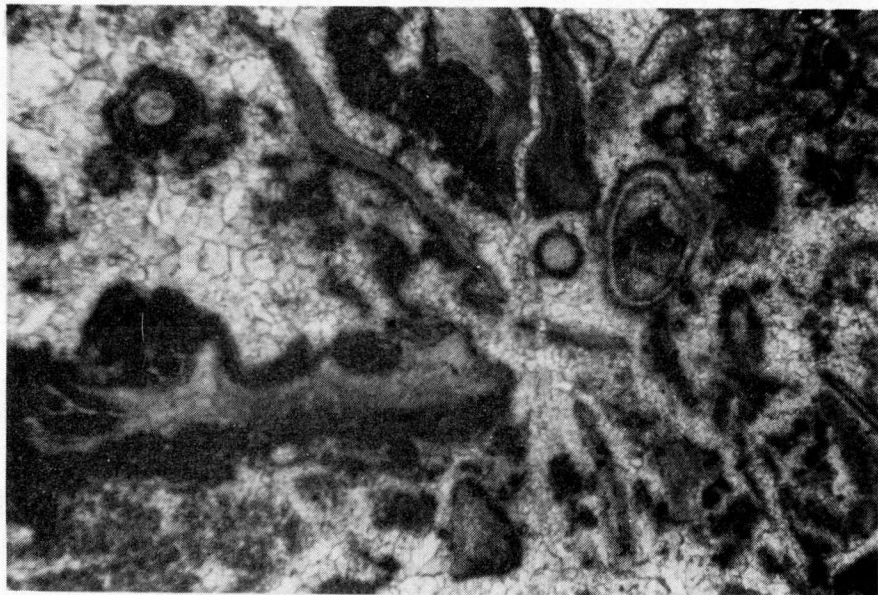
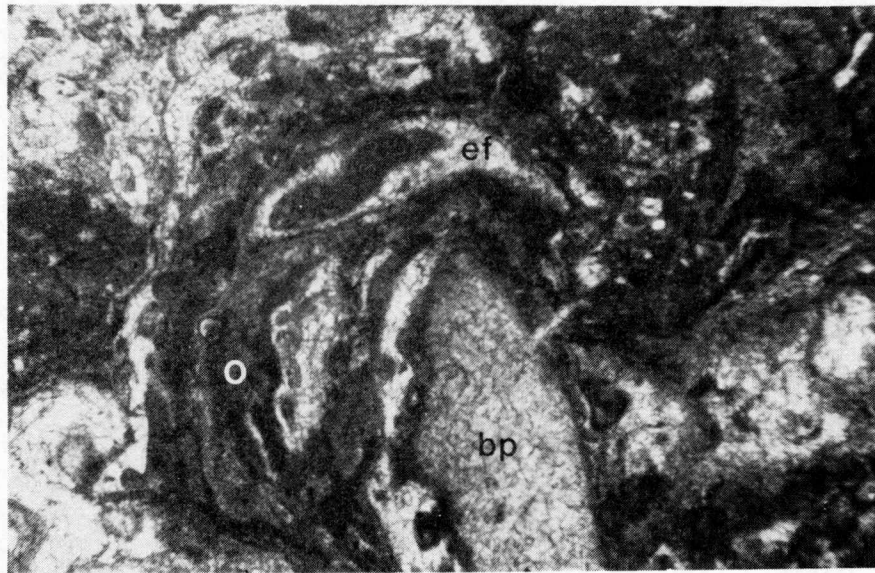


Plate II: Transitional Facies
Encrusting Foraminifera-Osagia Wackestones and Packstones

A. Portion of an onkoid with recrystallized brachiopod shell nucleus (bp) coated with Osagia (o) and encrusting foraminifera (ef).

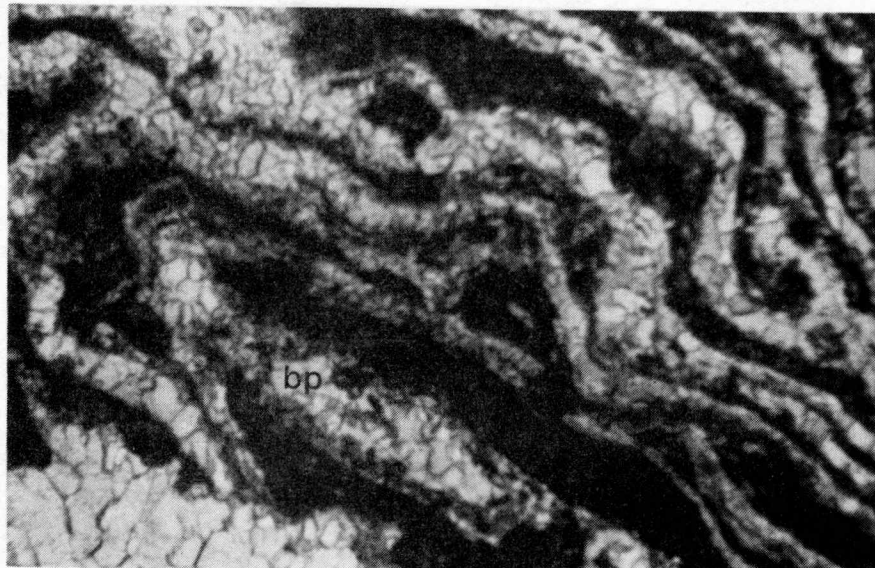
B. Another onkoid with a brachiopod shell nucleus (bp). Coatings are crinkly, recrystallized algal (Osagia?) layers. Onkoids are usually formed in somewhat protected environments with mild wave action to gently roll the grains.



A

0.2 mm

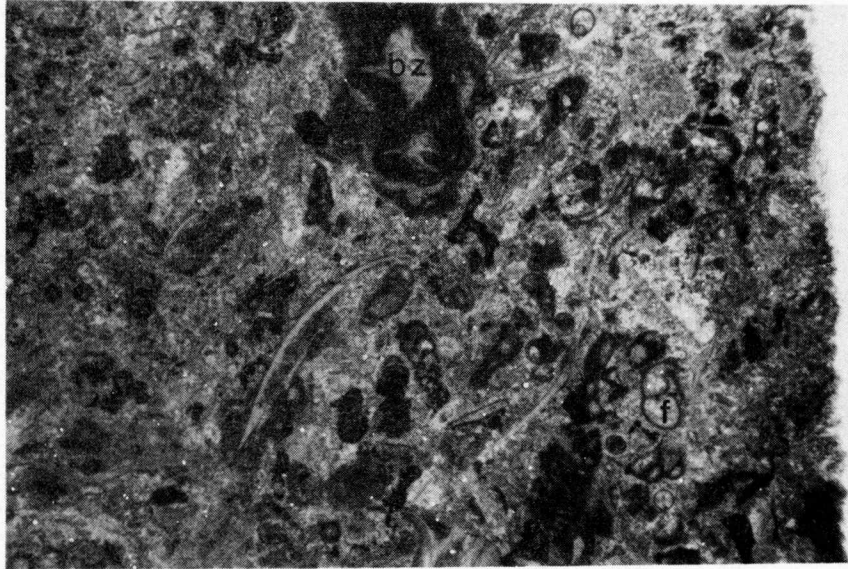
B



(cont.)

C. Abundant encrusting foraminifera (f) that have become unattached and appear to float in the surrounding mud.

Also present, a bryozoan (bz) coated with Osagia.



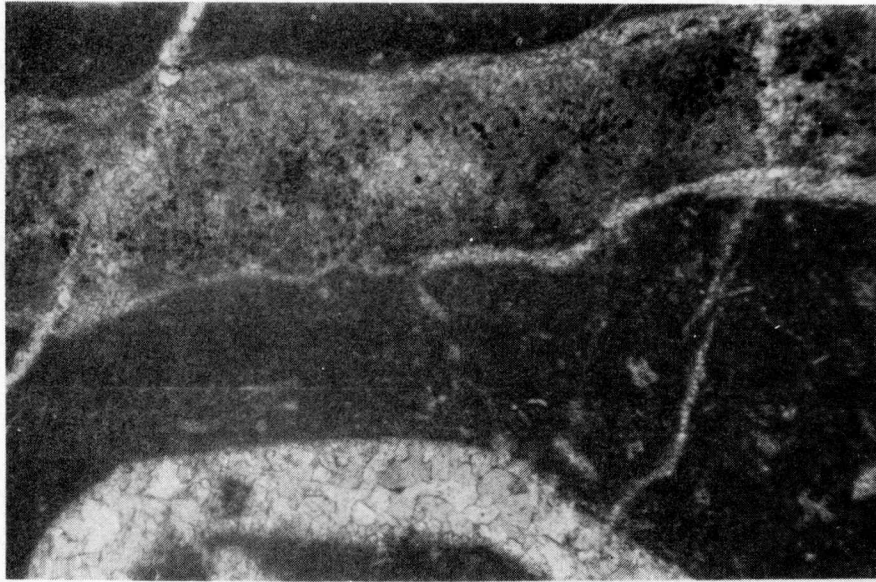
C

0.2 mm

Plate III: Restricted, Deep-Water Facies
Phylloid Algae Wackestones

A. Rare, well preserved, long filamentous phylloid algae with distinctive internal structure.

B. Phylloid algae usually occur as small, broken, angular, recrystallized debris, which accumulated in quiet water generally below wave base but still within the photic zone.

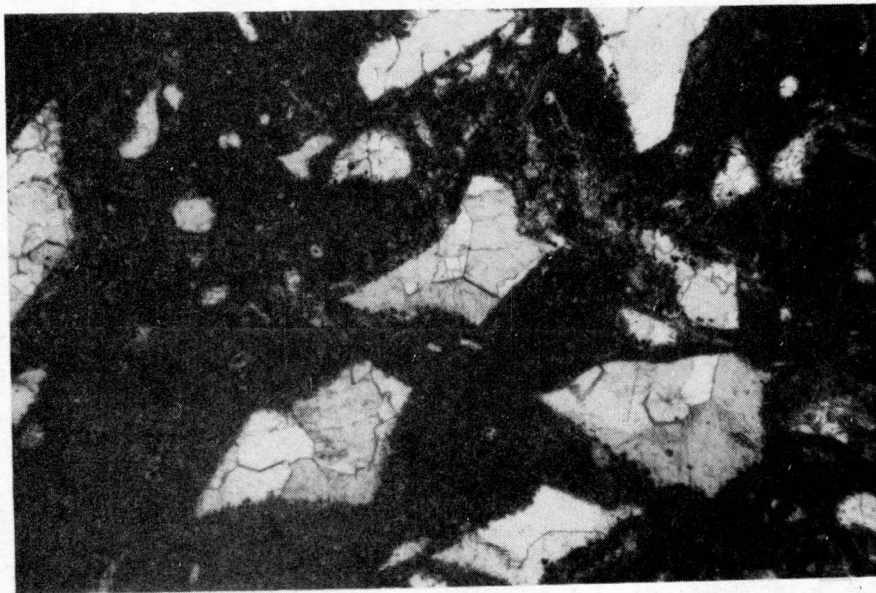


A

0.2 mm



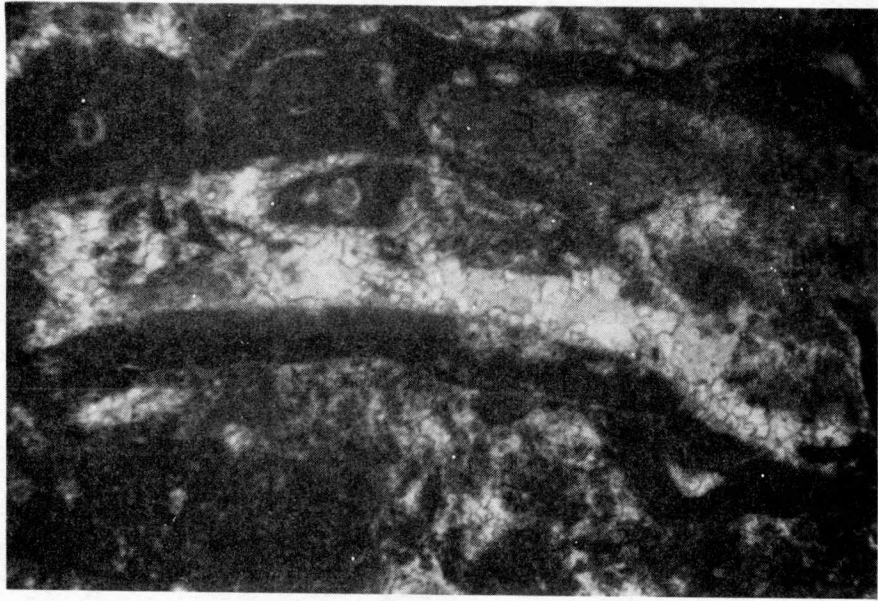
B



(cont.)

C. Phylloid algae are commonly oriented horizontally and occasionally encrusted with foraminifera.

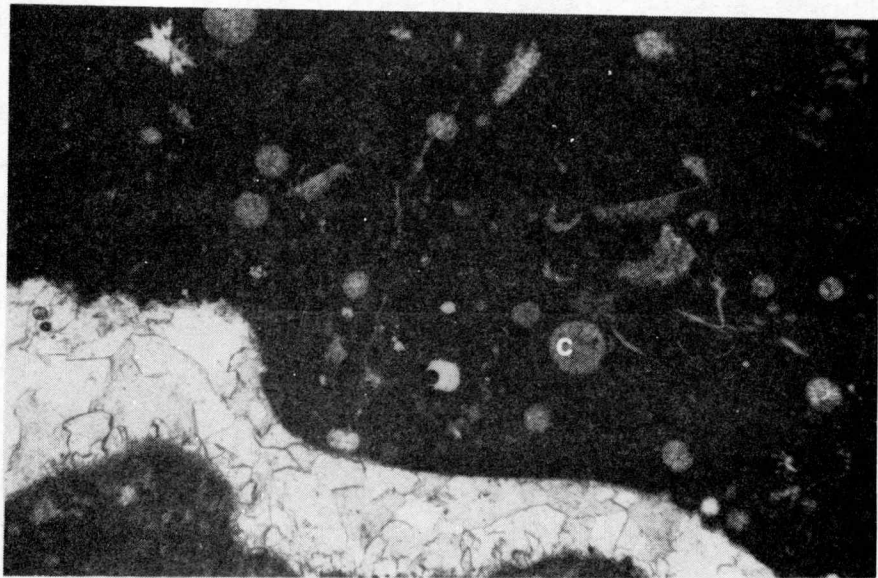
D. Calcispheres (c) are locally abundant in the mud surrounding the phylloid algae.



C

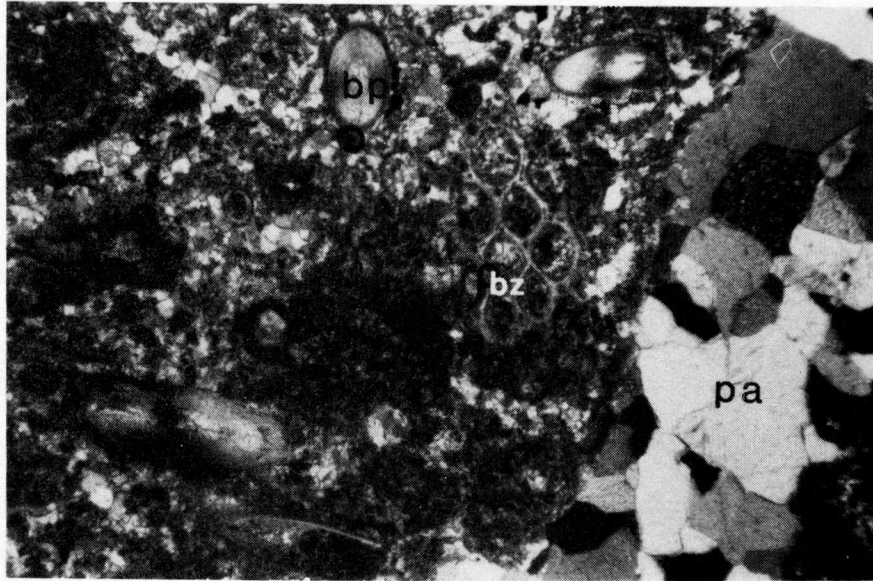
0.2 mm

D



(cont.)

E. The dominance of phylloid algae (pa) suggests that circulation was somewhat restricted but not to the extent of eliminating other biotic components, bryozoans (bz) and transverse sections through brachiopod spines (bp).



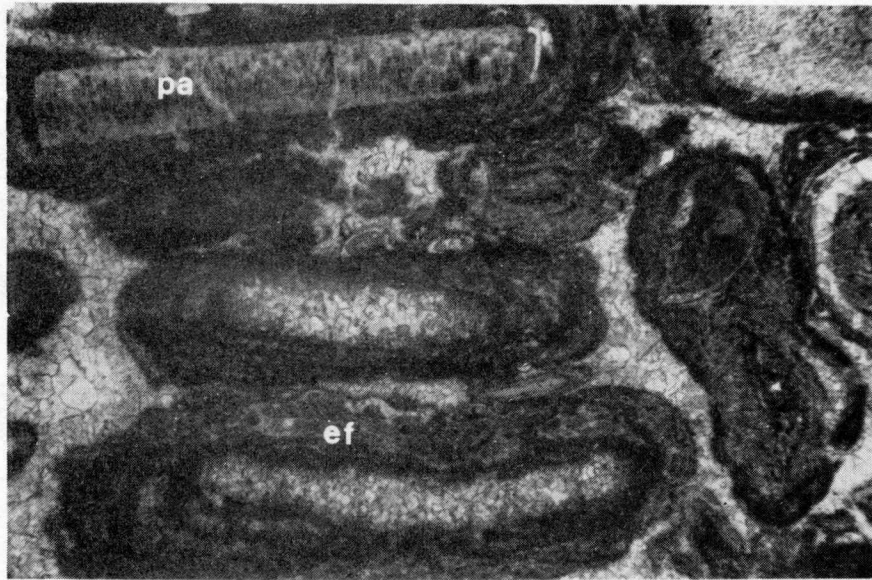
E

0.2 mm

Plate IV: Shoal Facies
Mixed Skeletal Grainstones

A. Coated grain grainstone with phylloid algae (pa)
nuclei and encrusting foraminifera (ef) coatings.

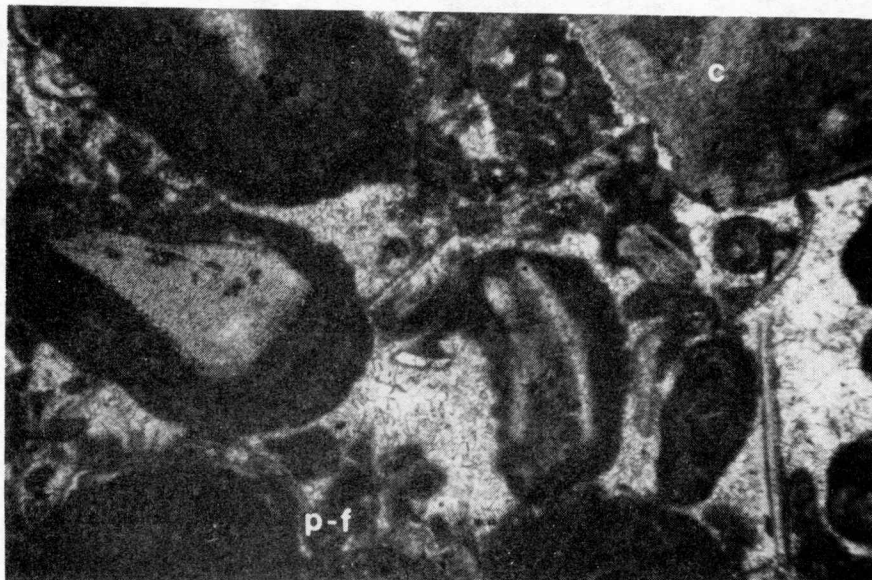
B. Bimodal distribution of large coated crinoids (c)
and other bioclasts within a pellet-foraminifera (p-f)
matrix.



A

0.2 mm

B



(cont.)

C. Gastropod geopetal floored with small bioclasts and finely pelleted mud. Top of chamber is filled with cloudy, marine cement similar to that found in the interstitial areas.

D. Large crinoid (c) with irregular grain boundary indicating abrasion: Abundant, diverse fauna in rocks with abraded grains and little mud were deposited in shallow water at or above wave base in an environment subjected to fairly constant wave action.



C

0.2 mm

D

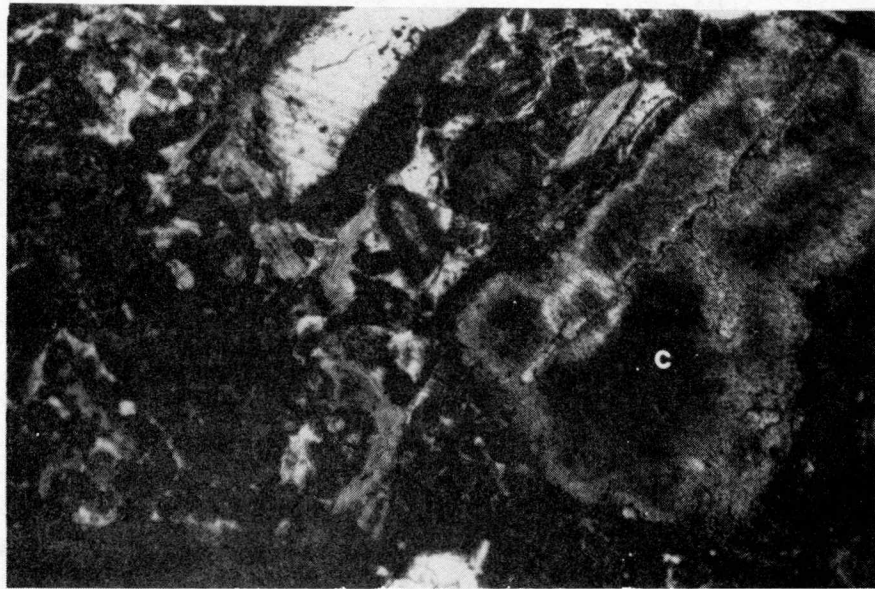
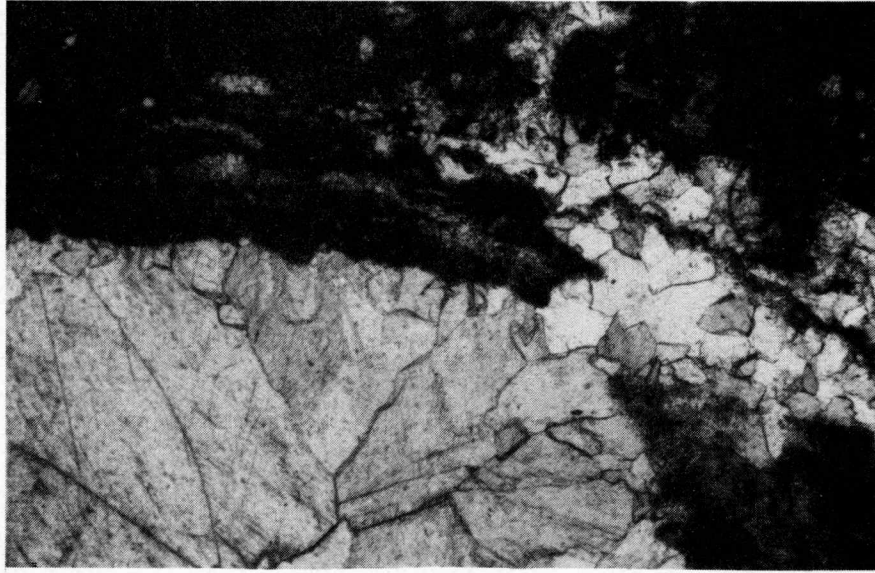


Plate V: Algal Mound Facies
Foraminifera-Phylloid Algae Packstones With Sparry Cement

A. Sparry shelter cement beneath recrystallized phylloid algae is characteristic of this limited and brief algal-mound build-up.

B. Shelter spar beneath brachiopod shell under crossed polars. Two generations of cement are present: 1) a radiaxial mosaic with elongate crystals and a preferred orientation of the longest axis normal to the cavity wall, and 2) cement with equant rhombohedral crystal habit.

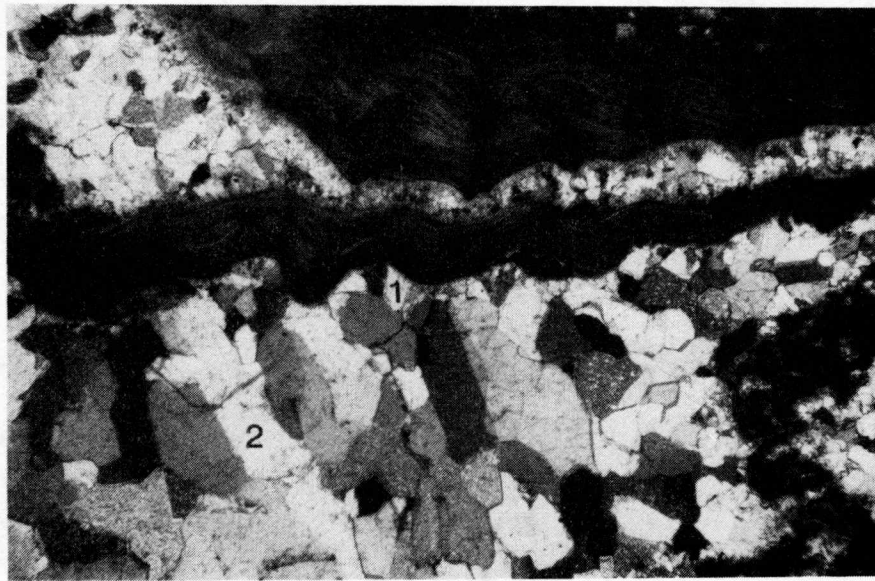


A

0.2 mm



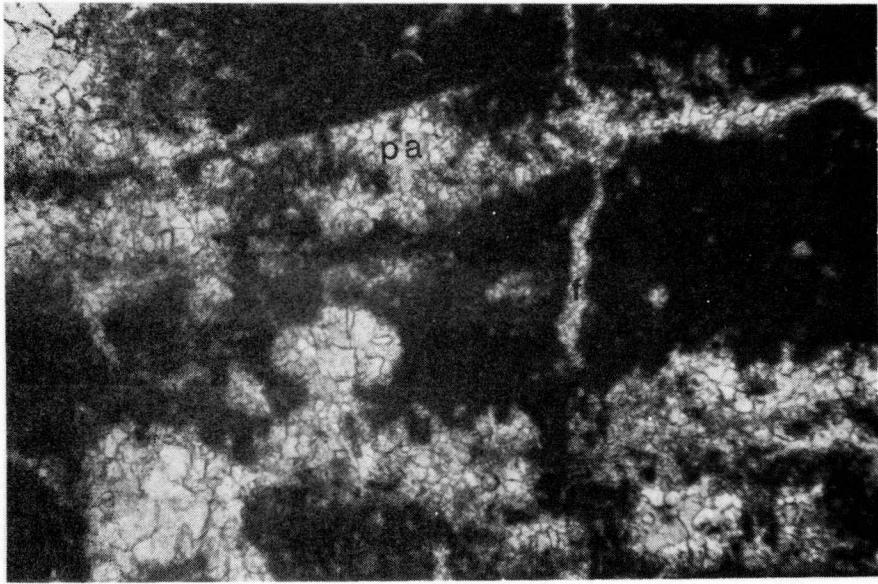
B



(cont.)

C. Thin, sparry compactional fractures (f) visible in mud and phylloid algae (pa) are another common feature of this facies.

D. Localized occurrences of pelleted mud are the result of both originally deposited and later infilled sediment.



C

0.2 mm



D

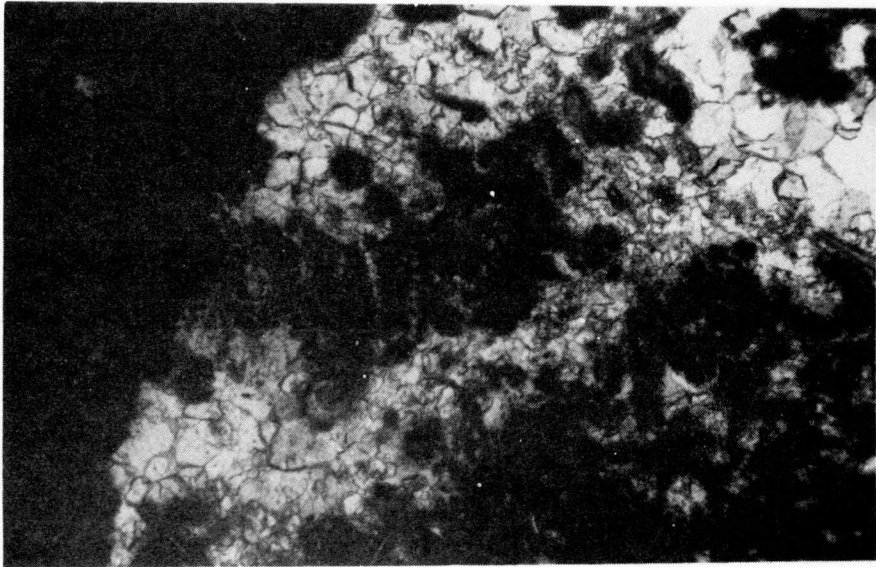
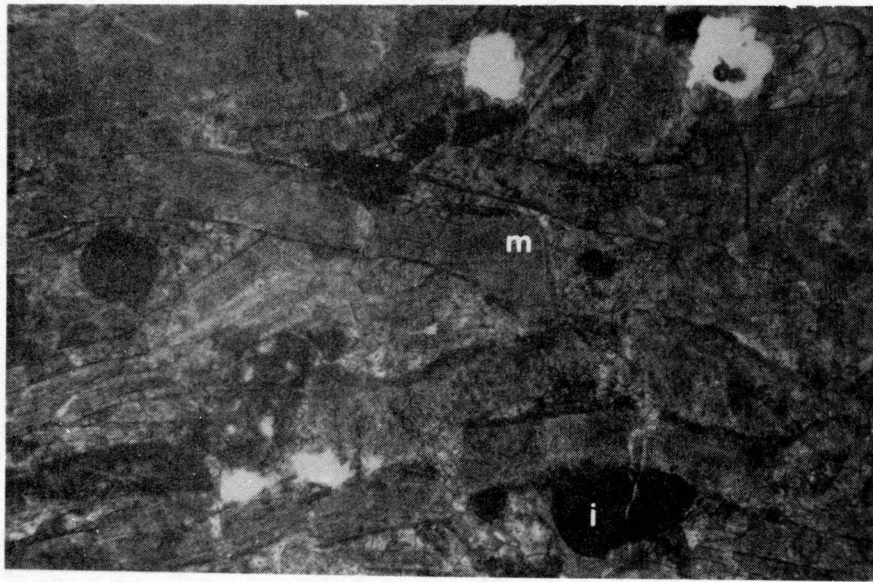


Plate VI; Channel Sequence

A. Intraclast (i)-mollusc (m) grainstone, sampled from the base of section 7, represents a basal lag deposit of the submarine channel.

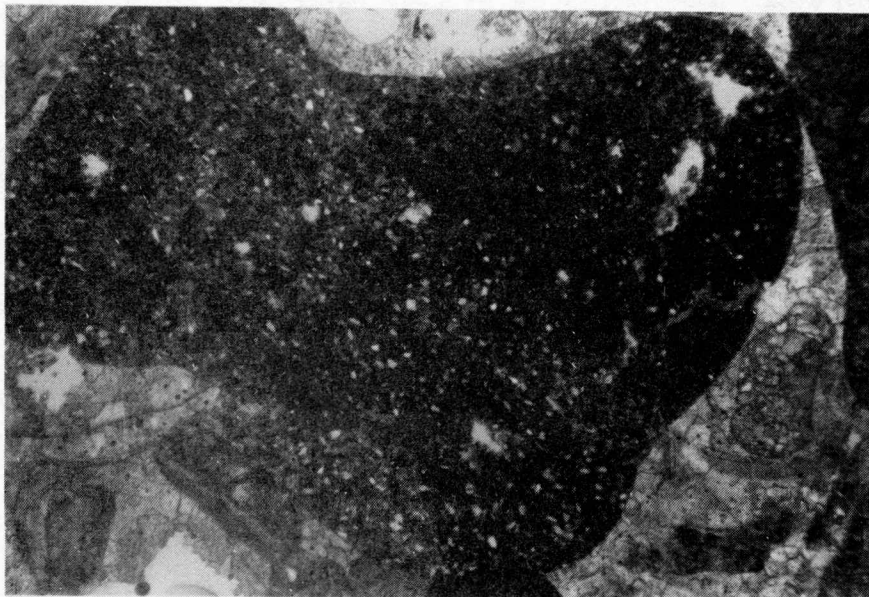
B. Large intraclast containing fine terrigenous quartz silt, also from the base of section 7, suggests high energy transport.



A

0.2 mm

B



(cont.)

C. Abundant terrigenous quartz silt surrounding crinoids

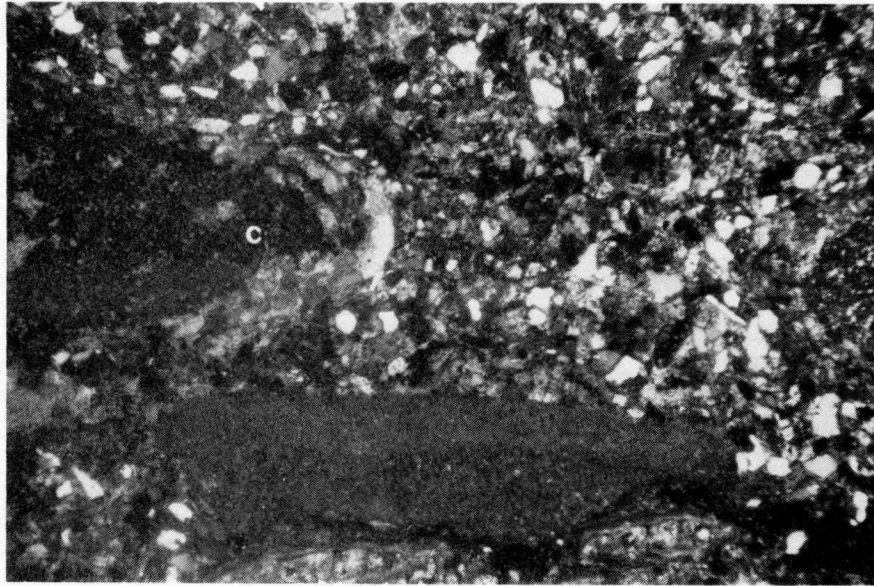
(c). Sampled from the center of section 7.

D. Quartz silt incorporated into the Osagia-encrusting

foraminifera layers coating a brachiopod shell. This

sample, also from the center of section 7, represents

the lower portion of a fining-upward sequence.

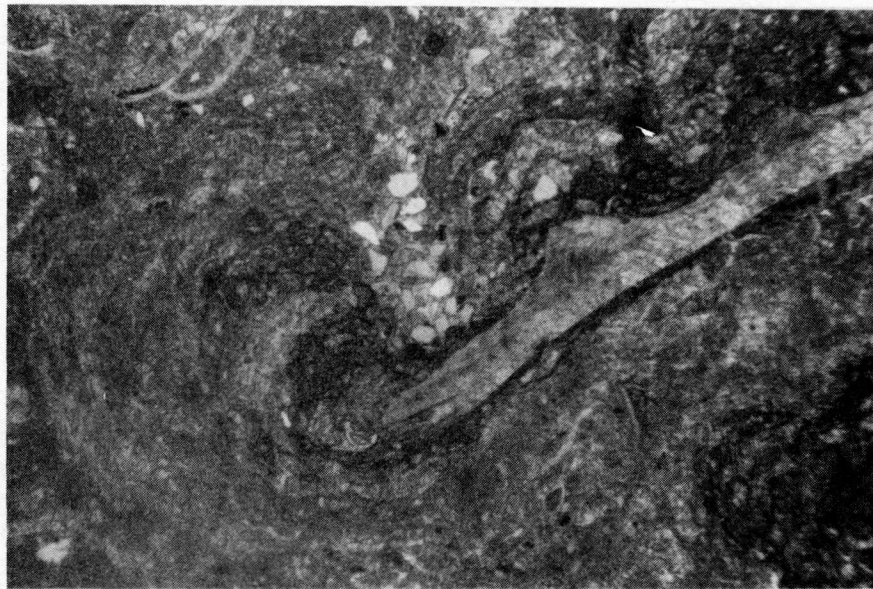


C

0.2 mm



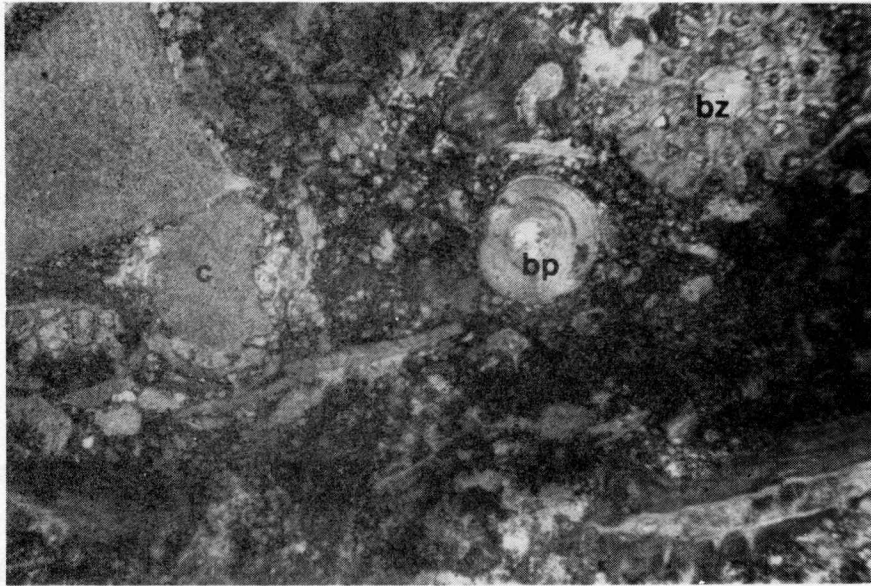
D



(cont.)

E. Fossiliferous packstone with crinoids (c), bryozoans (bz), and a brachiopod spine (bp) sampled near the top of section 7.

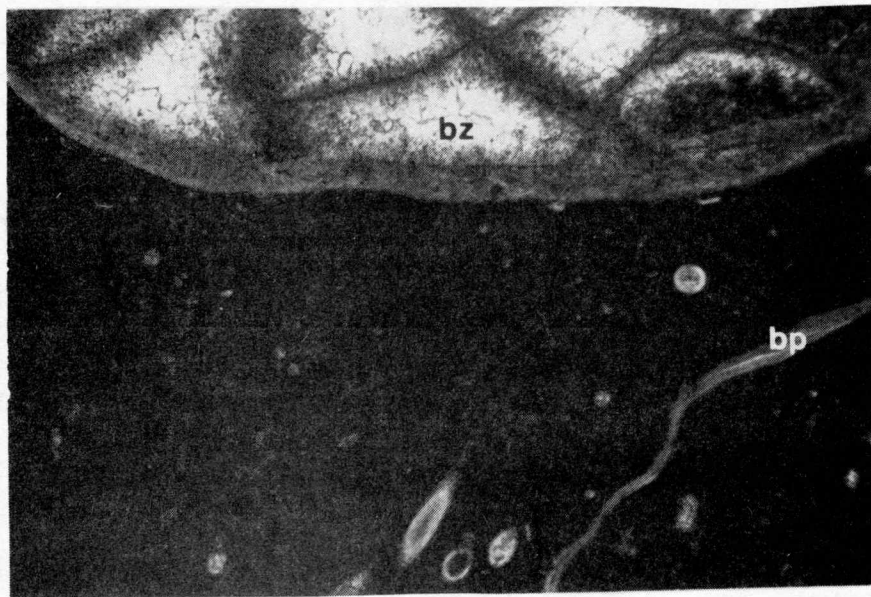
F. Fossiliferous wackestone with large bryozoan (bz), thin brachiopod shell (bp), and a few crinoids (c).
This sample came from the top of section 7 and represents the top of the fining-upward sequence.



E

0.2 mm

F



Appendix I; Determination of number of points to be counted in carbonate thin sections from the Captain Creek Limestone

The objective of this statistical procedure was to find the minimum number of points feasible to count that would provide a sufficiently representative estimate of the actual proportions of constituents.

Method

A binomial distribution can be used to compute the percentages of various constituents obtained from carbonate point counting. Objects within samples must occur in only one of two possible classes; a kind of constituent is either present or absent in each trial or advance of the stage. Six thin sections sampled at 1 m intervals horizontally from section PW were chosen to obtain percentages of constituents in samples. The Captain Creek Limestone is fairly monotonous laterally in this area, so samples taken at 1 m intervals were considered to have been deposited within the same environment. Thus, data from each of the six thin sections were averaged and mean constituent percentages were used in all calculations. Each slide was counted with 400 and 800 points per slide so that the entire slide was traversed. Grid spacing was 1.32 mm for 400 counts and 0.99 mm for 800 counts. The standard error was calculated to determine the deviation between sample estimates of mean percentages of constituents and the true or population parameters of these quantities using the formula:

$$S_e = \sqrt{\frac{pq}{n}}$$

where;

p = probability that a constituent is present.

q = (1-p) = probability that a constituent is absent.

n = number of points counted (400 or 800).

A binomial sampling equation was used to determine how many points need to be counted so that a constituent with a given mean abundance would be overlooked only a certain percent of the time (5%).

$$y = (1-p)^n$$

where;

y = risk of failure = 0.05

p = mean constituent abundance

n = sample size (number of point counts)

We are assuming three things by using these methods.

1) Samples are random. This was accomplished by using systematic sampling. The slide was divided into intervals or cells, a random location was selected, and each traverse was continued at a specified increment.

2) Events are independent. This assumption was not always met. A count of a high-volume constituent was usually followed by another like count. This situation did not seem to occur frequently enough to deserve serious concern, however.

3) The six sample thin sections were taken from the same population. Based on field observations, this assumption

does not seem unwarranted.

Conclusions

It was decided that the four constituents that make up less than 1.8% (intraclasts, ostracodes, molluscs, and sponge spicules) are not important enough to adjust the point count number in order to predict their proportions with acceptable accuracy. Even though we may be willing to sacrifice an accurate estimate of abundances of these minor constituents, we do not want to completely miss counting them when they are present. To accommodate this situation, the binomial sampling equation suggests that a count of 600 points per slide will allow us to miss a constituent that makes up 0.5% of the total only 5% of the time.

Of the remaining 10 constituents, the decision to allow a standard error of $\pm 30\%$ of the actual mean proportion of each particular constituent was made. Consequently, a count of 800 points per slide will yield a smaller standard error than is required. A smaller than required standard error results for 400 points per slide for 7 of the 10 constituents. Encrusting foraminifera, however, seem to be environmentally significant even though they are not very abundant. The appropriate standard error for this constituent is obtained by counting some number of points between 400 and 800. Thus, 600 was selected as an appropriate number for most constituents.

Descriptive Statistics

	points per slide	mean %	Std. error (%)	<u>+30%</u> of mean
intraclasts	400	0.08	0.14	0.02
	800	0.21	0.19	0.06
ostracodes	400	0.46	0.34	0.14
	800	0.50	0.25	0.15
molluscs	400	0.83	0.45	0.25
	800	0.81	0.32	0.24
foraminifera	400	1.96	0.69	0.59
	800	1.35	0.41	0.40
phylloid algae	400	16.96	1.88	5.10
	800	16.02	1.30	4.80
<u>Osagia</u>	400	5.30	1.12	1.59
	800	4.40	0.72	1.32
encrusting foraminifera	400	1.96	0.69	0.59
	800	1.84	0.47	0.55
mud	400	37.42	2.42	11.20
	800	41.50	1.74	12.45
pellets	400	18.88	1.96	5.66
	800	18.19	1.36	5.46
echinoderm pieces	400	4.42	1.03	1.33
	800	4.22	0.71	1.26
sponge spicules	400	1.25	0.56	0.38
	800	0.96	0.34	0.29
brachiopods	400	3.46	0.29	1.04
	800	2.53	0.55	0.75
cement	400	3.00	0.85	0.90
	800	3.42	0.64	1.02
bryozoans	400	2.29	0.75	0.69
	800	2.08	0.50	0.63

Binomial Sampling:

If we are willing to miss 5% of the time, a constituent that makes up 1% of the total;

$$p = 0.01$$

$$y = \text{risk of failure} = 0.05$$

n = sample size or number of points counted

$$y = (1-p)^n$$

$$n = \frac{\log y}{\log (1-p)}$$

$$n = \frac{\log 0.05}{\log (1-0.01)} = 300$$

If we are willing to miss 5% of the time, a constituent that makes up 0.5% of the total;

$$p = 0.005$$

$$y = 0.05$$

$$n = \frac{\log 0.05}{\log (1-0.005)} = 600$$

If we are willing to miss 5% of the time, a constituent that makes up 0.25% of the total;

$$p = 0.0025$$

$$y = 0.05$$

$$n = \frac{\log 0.05}{\log (1-0.0025)} = 1200 \quad (\text{this is not feasible})$$

Appendix II; Determination of number of thin sections to be made per sample (all tests correspond to procedures of Sokal and Rohlf, 1969)

The objective of this statistical study was to determine if one thin section per sample was adequate to represent the variation within each sample.

Method

Three thin sections were made from each of 6 samples from the same stratigraphic level from the top of section PW taken at 1 m intervals. A Model II one-way analysis of variance was used to test each constituent to see if the means were from the same population and to isolate the variance components. Assumptions of analysis of variance (normality and equal variances) were met by most of the data.

Results

The results of the analysis are summarized in Table 1. Preliminary treatment using the Rankit method determined that the distributions of all the constituents were normal with the exception of phylloid algae and mud-pellets. The F_{\max} test was used to test for homogeneity of variances. Again, the equal variance assumption was satisfied for all constituents except phylloid algae and mud-pellets. Mud-pellet data was transformed using the arcsine transformation to produce normally distributed data with equal variances. An appropriate transformation for phylloid algae could not be found so a nonparametric test was substituted. (This

test allowed the rejection of the null hypothesis, but the variance components could not be isolated.)

Each sample was considered a group, and the 3 thin sections from each sample were considered replicates within each group. The null hypothesis for the anovas was H_0 : all samples are from the same population. If the hypothesis was accepted (as with foraminifera), all samples were considered to have come from the same population and, consequently, one thin section was adequate to represent this. If the hypothesis was rejected, the variance components were isolated. If the within group variation (WG) was less than the between group variation (BG), most of the changes could be attributed to sample distribution instead of differences within samples, reducing the importance of multiple thin sections per sample. Within group variation, however, is a function of mean, so an arbitrary value of $WG/\bar{Y} < 10$, where \bar{Y} is the mean, was set as the critical value. All constituents had values less than 10, so it was concluded that one thin section per sample was sufficient to represent the variation. (Ostacodes failed this test, but were ignored since they were considered to be environmentally insignificant without refined taxonomic identifications.)

Table 1; Data Summary for Model II One-Way Analysis of Variance for Determination of Number of Thin Sections to be Made per Sample.

<u>Constituent</u>	<u>Anova Assumptions</u>		<u>Anova Results</u>	<u>Variance</u>	<u>Mean</u>	<u>WG/\bar{Y}</u>
	<u>Normality</u>	<u>Variance</u>	<u>H₀</u>	<u>Components</u>	<u>%</u>	
foraminifera	normal	equal	accepted			
ostracodes	normal	equal	rejected	WG=49%	1.15	42.60
phyllloid algae	not normal	not equal	rejected using	BG=51%		
			a nonparametric test			
<u>Osagia-encrusting foraminifera</u>	normal	equal	rejected	WG=42%	5.41	7.76
mud-pellets	not normal	not equal	rejected	BG=58%	62.41	0.34
echinoderms	normal	equal	rejected	WG=21%	4.58	4.80
brachiopods	normal	equal	rejected	BG=79%	3.42	9.36
bryozoans	normal	equal	rejected	WG=32%	2.30	8.26
				BG=68%		
				WG=19%		
				BG=81%		

Appendix III: Preliminary determination of changes of abundances of constituents in the Captain Creek Limestone

The objective of this statistical study was to determine if any differences in abundances of constituents could be detected that indicated environmental change.

Method

Before this research could be undertaken, a general idea of which constituents, if any, changed in abundances was necessary. If no changes existed and the entire limestone was highly monotonous, a study to differentiate facies would have been unwarranted.

In this test, a two-way analysis of variance for paired comparisons was used to compare the easternmost (section PE) and the westernmost (section PW) sections (Sokal and Rohlf, 1969). This method tested for differences between the two localities (columns) and differences between beds (rows). Differences in abundances of constituents reflect spatial changes in environment as well as environmental changes through time. A supplementary analysis was also performed using a one-way analysis of variance on six samples taken at 1 m intervals horizontally from the tops of each section.

Two assumptions of anovas were tested on all data: normality and equality of variances. If data did not meet these assumptions, either they were transformed or a nonparametric test was substituted, which is indicated in the computations.

Conclusions

The results of the 2-way anovas for paired comparisons appear in Table 1. There was no significant difference in the abundances of foraminifera, echinoderm pieces, brachiopods-molluscs, bryozoans, and Osagia-encrusting foraminifera between the two sections. Phylloid algae was the only constituent that showed a significant change between these eastern and westernmost sections. Ostracodes and mud-pellets were not considered to be environmentally sensitive and were not tested. Brachiopods-molluscs showed a significant change through time (rows or beds), but other constituents did not (with the exception of foraminifera which exhibited only a very slightly significant difference).

The supplementary 1-way anovas between the tops of the eastern and western sections (Table 2) did not confirm these results, perhaps due to an increased sample size in this analysis. These results showed that only Osagia-encrusting foraminifera displayed a significant difference in abundance.

Both of these analyses indicated that only minor faunal changes were detectable. If it was possible to delineate facies, they would be quite subtle and probably unrecognizable from direct field observations. The statistical approach to this particular limestone was not only preferable but necessary.

Table 1: 2-Way Anovas for Paired Comparisons Between the Westernmost and Easternmost Sections (* indicates statistical significance, $p \leq 0.05$; n.s. indicates not statistically significant, $p > 0.05$)

foraminifera

<u>source of variation</u>	<u>df</u>	<u>SS</u>	<u>MS</u>	<u>F_s</u>
columns (locations)	1	0.187	0.187	0.433
rows (beds)	5	12.171	2.434	5.620*
error	5	2.165	0.433	(barely significant)
total	11	14.524		

phylloid algae

<u>source of variation</u>	<u>df</u>	<u>SS</u>	<u>MS</u>	<u>F_s</u>
columns (locations)	1	305.122	305.122	9.19*
rows (beds)	5	582.862	116.572	3.51 n.s.
error	5	166.070	33.214	
total	11	1054.053		

echinoderm pieces

<u>source of variation</u>	<u>df</u>	<u>SS</u>	<u>MS</u>	<u>F_s</u>
columns (locations)	1	0.701	0.701	0.107 n.s.
rows (beds)	5	81.456	16.291	2.490 n.s.
error	5	32.660	6.532	
total	11	114.817		

Table 1: (cont.)

brachiopods-molluscs

<u>source of variation</u>	<u>df</u>	<u>SS</u>	<u>MS</u>	<u>F_s</u>
columns (locations)	1	0.546	0.546	0.316 n.s.
rows (beds)	5	60.115	12.023	6.966*
error	5	8.630	1.726	
total	11	69.291		

bryozoans

<u>source of variation</u>	<u>df</u>	<u>SS</u>	<u>MS</u>	<u>F_s</u>
columns (locations)	1	0.301	0.301	0.064 n.s.
rows (beds)	5	45.618	9.124	1.960 n.s.
error	5	23.300	4.660	
total	11	69.218		

Osagia-encrusting foraminifera

Data do not meet assumptions of normality. A nonparametric test was used; Wilcoxon signed ranks test for two groups, arranged as paired observations (Sokal and Rohlf, 1969, p.400).

paired difference between E and W

- 3.22
+ 7.17
- 4.00
+ 1.50
- 8.84
- 5.67

rank

- 2
+ 5
- 3
+ 1
- 6
- 4

Tabled value indicates that the difference in abundances of Osagia-encrusting foraminifera between E and W is n.s.

$$\begin{aligned} \sum + \text{ranks} &= + 6 \quad \text{-- } T_s \\ \sum - \text{ranks} &= - 15 \end{aligned}$$

Table 2: One-Way Anovas for the Top of the Easternmost and Westernmost Sections (* indicates statistical significance, $p \leq 0.05$; n.s. indicates not statistically significant, $p > 0.05$).

Analysis confined to same bed

BG = between group

WG = within group

foraminifera

<u>source of variation</u>	<u>df</u>	<u>SS</u>	<u>MS</u>	<u>F_s</u>
BG	1	0.018	0.081	0.034 n.s.
WB	22	11.866	0.539	
total	23	11.884		

phylloid algae

<u>source of variation</u>	<u>df</u>	<u>SS</u>	<u>MS</u>	<u>F_s</u>
BG	1	206.756	206.756	3.96 n.s.
WB	22	1149.016	52.228	
total	23	1355.773		

Osagia-encrusting foraminifera

<u>source of variation</u>	<u>df</u>	<u>SS</u>	<u>MS</u>	<u>F_s</u>
BG	1	40.921	40.921	17.70 ** (highly significant)
WG	22	50.763	2.310	
total	23	91.684		

echinoderm pieces

<u>source of variation</u>	<u>df</u>	<u>SS</u>	<u>MS</u>	<u>F_s</u>
BG	1	0.8911	0.8911	0.158 n.s.
WG	22	124.0715	5.6400	
total	23	124.9626		

Table 2; (cont.)

bryozoans

<u>source of variation</u>	<u>df</u>	<u>SS</u>	<u>MS</u>	<u>F_s</u>
BG	1	0.0003	0.0003	0.000015 n.s.
WG	22	44.3834	2.0170	
total	23	44.3837		

brachiopods-molluscs

Data did not meet assumptions of equal variance. Used nonparametric Wilcoxon two-sample test (Sokal and Rohlf, 1969, p.392).

Results indicate that the difference in abundances of this constituent within a single bed is not significant.

Appendix IV: Determination of number of sections that must be sampled.

The objective of this statistical study was to determine how many sections needed to be sampled to represent the preliminary estimates of constituent variability.

Method

After the data had been analyzed (Appendix III), it was necessary to make an estimate of the number of additional sections needed to delineate facies with a specified amount of certainty. If each section was considered a replicate, Sokal and Rohlf's (1969, p.247) method of determining the number of replicates needed to detect a given true difference between means was applicable. The 18 thin sections from the top of the westernmost section (3 thin sections from each of 6 samples taken from the same stratigraphic level) were used to estimate the standard deviation among constituents (Table 1).

Conclusions

A total of 9 sections were sampled based on the results of the test to determine the number of replicates. Since phylloid algae had the largest standard deviation, it was used to estimate σ . At a 5% significance level, we wanted to be 80% certain of detecting a 10% difference between any two means. The calculations suggested that 9 or 10 sections were needed. Nine was selected since the total distance along the study area traverse could be halved 3 times to get

the proper distribution.

Table 1; Standard Deviation for each Constituent Based on Data from the 18 Thin Sections at the Top of the Westernmost Section

<u>Constituent</u>	<u>s</u>
foraminifera	0.6867
phylloid algae	7.75
<u>Osagia</u> -encrusting foraminifera	1.513
mud-pellets	6.683
echinoderm pieces	1.914
brachiopods-molluscs	0.999
bryozoans	1.4197

Number of replicates needed to detect a given true difference between means:

$$n \geq 2(\sigma/\delta)^2 \{t_{\alpha}[\nu] + t_{2(1-P)}[\nu]\}^2$$

σ = true standard deviation; estimate this from the 18 thin sections

δ = smallest difference we want to detect. A 10% difference between any two means was used.

ν = df = a(n-1) where: a = groups or beds = 6

α = significance level = 0.05

P = we want to be 80% certain of detecting the 10% difference between means

Since phylloid algae has the largest standard deviation, it will yield the largest number of replications. This is the n value that will be used to determine the number of sections to be sampled.

Start with $n = 5$; $v = a(n-1) = 6(4) = 24$

$$n \geq 2 \left(\frac{7.75}{10} \right)^2 \{ t_{0.05}(24) + t_{2(1-0.8)24} \}^2$$

$$n \geq 1.20125 (2.064 + 0.857)^2$$

$$n = 10$$

Next try $n = 9$: $v = a(n-1) = 6(8) = 48$

$$n \geq 2 \left(\frac{7.75}{10} \right)^2 \{ t_{0.05}(48) + t_{2(1-0.8)48} \}^2$$

$$n \geq 1.20125 (2.01 + 0.849)^2$$

$$n = 9.8$$

This is close to the previous solution indicating that we have iterated to stability. It appears that 9 sections are necessary for this study.

Appendix V; Locations of the nine sampled sections

Douglas County

- Section PW SE, SE, SW, Sec. 3, T.13 S., R.21 E.
(north side of K-10, 1 mi. east of Eudora)
- Section 12 SE, SE, SE, Sec. 3, T.13 S., R.21 E.
(north side of K-10, 1 mi. west of
Evening Star Road exit)

Johnson County

- Section 10 NE, SE, SE, Sec. 36, T.12 S., R.21 E.
(north side of K-10, county road exit,
1 mi. east of Evening Star Road exit)
- Section 8 C. of W line of SW $\frac{1}{4}$, NW, SE, Sec. 32,
T.12 S., R.22 E. (north side of K-10,
0.5 mi. west of DeSoto exit)
- Section 7 NW, SE, SE, Sec. 33, T.12 S., R.22 E.
(south side of K-10, 0.1 mi. east of
Kill Creek)
- Section 5 SW, NW, SE, Sec. 34, T.12 S., R.22 E.
(north side of K-10, Kill Creek Road
exit)
- Section 3 SW, NW, SE, Sec. 35, T.12 S., R.22 E.
(north side of K-10, 1.1 mi. east of
Kill Creek Road exit)
- Section 2 SW, NE, SE, Sec. 6, T.13 S., R.23 E.
(south side of K-10, 0.4 mi. west of
103rd Street exit)
- Section PE SW, NW, SE, Sec. 5, T.13 S., R.23 E.
(north side of K-10, 0.3 mi. east of
103rd Street exit)

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