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APPLICATION OF COMPUTER TECHNIQUES TO THE PETROGRAPHIC STUDY OF OOLITIC ENVIRONMENTS, STE. GENEVIEVE LIMESTONE (MISSISSIPPIAN), SOUTHERN ILLINOIS AND EASTERN MISSOURI

BY

C. Prasada RAO and Albert V. CAROZZI [1]

ABSTRACT

Oolitic rocks present a critical problem of environmental interpretation because their oolites were not only deposited in the area where they were formed but also transported as detrital particles in adjacent areas.

For a reconstruction of the oolitic environments of the Ste. Genevieve Limestone about 800 thin sections, collected at an average interval of 12 centimeters from four sections, were studied by detailed petrographic investigation. Eight microfacies were recognized, given here in order of decreasing relative depth: 1. calcilutite and calcisiltite with scattered organic debris, 2. pelletoidal calcarenite with calcisiltite matrix, 3. biocalcarenite with calcisiltite matrix, 4. biocalcarenite with clear calcite cement, 5. pelletoidal calcarenite with clear calcite cement, 6. oolitic calcarenite with clear calcite cement, 7. oolitic-pelletoidal calcarenite with calcisiltite matrix, and 8. pure quartz sandstone with clear calcite cement.

The following microscopic parameters were measured: frequency and clasticity of complete oolites, broken oolites, pellets, lithoclasts, crinoid debris, and detrital quartz; frequency of bryozoan debris, ostracodes, calcispheres, and *Endothyra*; and percentages of oolite core composition.

The oolitic calcarenites with clear calcite cement, —52% of the total samples investigated— were divided into autochthonous and allochthonous calcarenites based on the petrographic characters and on the relationship of maximum oolite clasticity and maximum nonoolite (pellet, lithoclast, or crinoid debris) clasticity.

Three new computer programs were written for the plotting of microfacies parameters, the trend analysis and the plotting of parameter variations for autochthonous and allochthonous oolitic calcarenites with clear calcite cement. The trend analysis entails three specific tests of a pair of parameters: parallelism test, comparison test, and calculation of Spearman's correlation coefficient ρ.

Autochthonous oolitic calcarenites showed the following statistical relationships: 1. The maximum clasticity of oolites is independent of the clasticities of maximum nonoolites, pellets, and

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crinoid debris. 2. The clasticities of maximum nonoolites, pellets, and crinoid debris show in general a direct relationship. 3. The pellet, crinoid and bryozoan debris frequencies are generally opposed to the percent of oolites; directly related to the percent of nonoolites; and independent of maximum clasticity of oolites. The clasticities relationships seem to be due to the interplay ol local agitation and competence of currents bringing nonoolitic grains into the environment in which oolites are forming. The frequencies relationships might be due to the fact that the percentage of oolites in a sample is directly related to the maximum oolite clasticity, and as oolitization increases relatively more nonoolitic grains are oolitized.

Allochthonous oolitic calcarenites showed that the maximum clasticity of oolites is directly related to the clasticities of maximum nonoolites, pellets, and crinoid debris. All other clasticities and frequencies relationships observed in autochthonous oolitic calcarenites are found to be more closely related. These relationships are possibly due to the effects of sorting action during transportation. The percentage of broken oolites in this environment indicated the degree of transportation.

The ancient oolitic environment of the Ste. Genevieve Limestone bears many close similarities with the Recent oolitic environment of the Great Bahama Bank. In the Ste. Genevieve Limestone, the autochthonous and allochthonous oolitic calcarenites (microfacies 6) occur in discontinuous bars and shoals along the outer rim of a shallow platform. Microfacies 1 to 5 on the seaward slope correspond to the coralgal facies of the Bahama Bank, and the oolitic-pelletoidal calcarenites with calcisiltite matrix (microfacies 7) deposited mainly in the lagoon behind the bars to the pellet mud facies of the Bahama Bank which also contains transported oolites. However, in the Ste. Genevieve Limestone, microfacies 7 also occurs in the channels surrounding microfacies 6 and grades into a deltaic or estuarine pure quartz sandstone with clear calcite cement (microfacies 8). Furthermore, transported oolites and detrital quartz are distributed into microfacies 5 through 1 down the seaward slope, probably as an effect of tidal currents. This situation does not occur in the more protected conditions of the Bahama Bank where Andros Island does not act as a source area.

RÉSUMÉ

L'interprétation des conditions de dépôt des roches oolithiques est fortement compliquée par le fait que les oolithes n'ont pas été déposées seulement dans leur milieu de formation mais également transportées, à l'état de particules détritiques, dans les domaines avoisinants.

Dans le but de reconstituer le milieu de sédimentation oolithique du calcaire de Ste. Geneviève (Viséen), quatre coupes stratigraphiques ont été soumises à une étude pétrographique détaillée comportant l'examen de 800 coupes minces séparées par un intervalle vertical moyen de 12 cm. Les huit microfaciès suivants ont été distingués par ordre décroissant de profondeur relative de dépôt: 1. calcilutite et calcisiltite à débris organiques disséminés, 2. calcarénite pelletoïdale à matrice de calcisiltite, 3. biocalcarénite à matrice de calcisiltite, 4. biocalcarénite à ciment de sparite, 5. calcarénite pelletoïdale à ciment de sparite, 6. calcarénite oolithique à ciment de sparite, 7. calcarénite oolithique-pelletoïdale à matrice de calcisiltite, 8. grès quartzeux à ciment de sparite.

Les paramètres microscopiques suivants ont été mesurés: indices de clasticité et de fréquence des oolithes complètes, oolithes brisées, pellets, lithoclasts, débris de crinoïdes et quartz détritique; indice de fréquence des débris de bryozoaires, ostracodes, calcisphères et *Endothyra ;* composition en pourcentage des noyaux d'oolithes.

Les calcarénites oolithiques à ciment de sparite — 52% des échantillons — ont été divisées en calcarénites autochtones et allochtones sur la base des caractères pétrographiques et de la relation entre la clasticité maximale des oolithes et la clasticité maximale des particules nonoolithiques (pellets, lithoclasts ou débris de crinoïdes).

Trois nouvelles programmations à l'ordinateur ont été utilisées pour tracer les variations des paramètres des microfaciès, pour l'analyse de tendance (trend analysis) et pour tracer les variations des paramètres relatifs aux calcarénites oolithiques, autochtones et allochtones, à ciment de sparite. L'analyse de tendance comporte trois tests particuliers d'une paire de paramètres: test de parallélisme, test de comparaison et calcul du coefficient de corrélation ρ de Spearman.

Les calcarénites oolithiques autochtones ont montré les relations statistiques suivantes: 1. La clasticité maximale des oolithes est indépendante de la clasticité maximale des particules nonoolithiques et de la clasticité des pellets et des débris de crinoïdes. 2. La clasticité maximale des particules nonoolithiques, et la clasticité des pellets et des débris de crinoïdes montrent en général une relation réciproque directe. 3. Les fréquences des pellets, des débris de crinoïdes et de bryozoaires sont en général opposées au pourcentage des oolithes; directement liées au pourcentage des particules nonoolithiques; et indépendantes de la clasticité maximale des oolithes. Les relations entre clasticités semblent dues au jeu entre l'agitation locale et la compétence des courants apportant les grains nonoolithiques dans le milieu où les oolithes se forment. Les relations entre fréquences semblent dues au fait que le pourcentage des oolithes, dans un échantillon donné, est fonction directe de la clasticité maximale des oolithes, et que lorsque le degré d'oolithisation augmente, un nombre relativement plus grand de grains nonoolithiques est oolithisé.

Les calcarénites oolithiques allochtones ont montré que la clasticité maximale des oolithes est directement liée à la clasticité maximale des particules nonoolithiques, et à la clasticité des pellets et débris de crinoïdes. Toutes les autres relations concernant les fréquences et les clasticités observées dans les calcarénites oolithiques autochtones se sont montrées ici plus étroites, probablement à la suite d'effets de triage pendant le transport des particules. Le pourcentage des oolithes brisées dans ce milieu est un indicateur du degré de transport.

L'ancien milieu oolithique du calcaire de Ste. Geneviève montre des similitudes frappantes avec celui d'âge récent du Great Bahama Bank. Dans le calcaire de Ste. Geneviève, les calcarénites oolithiques autochtones et allochtones (microfaciès 6) forment des barres ou des haut-fonds discontinus le long du bord extérieur d'une plateforme peu profonde. Les microfaciès 1 à 5, déposés sur la pente sous-marine correspondent au « coralgal » faciès du Bahama Bank et les calcarénites oolithiques-pelletoïdales à matrice de calcisiltite (microfaciès 7), déposées dans des lagunes à l'arrière des barres, au « pellet mud » faciès du Bahama Bank qui contient également des oolithes transportées. Cependant, dans le calcaire de Ste. Geneviève, le microfaciès 7 s'est aussi déposé dans les chenaux qui entourent les zones de microfaciès 6, et passe vers le rivage au grès quartzeux à ciment de sparite (microfaciès 8), estuarien ou deltaïque. En outre, les oolithes allochtones et le quartz détritique ont été distribués dans les microfaciès 5 à 1, le long de la pente sous-marine, face au large, probablement par l'effet des courants de marée. Cette situation n'existe pas dans les conditions plus protégées du Bahama Bank, où Andros Island ne joue pas le rôle d'une source de particules détritiques.

INTRODUCTION

Knowledge of the present environments in which oolites are formed and where processes may be seen in action is naturally much better than the understanding of ancient depositional environments of oolites for which only completed rocks are available. Ancient oolites present the critical problem of having remained in the area of oolitization or of having been transported into adjacent environments as detrital particles prior to final deposition.

A method of distinguishing transported from nontransported oolites was proposed by CAROZZI (1957) for the study of unconsolidated oolitic sediments of the Great Salt Lake, Utah. It was subsequently modified and applied to oolitic rocks from three sections of the Ste. Genevieve Limestone in southern Illinois (LACEY and CAROZZI, 1967).

In this study further refinements have been introduced and the relationships between transported and nontransported oolites compared to all the other inorganic and organic components of the Ste. Genevieve Limestone in order to reach a complete understanding of an ancient typical oolitic environment.

PREVIOUS WORK

The transportation of oolites from places of accretion to adjacent environments as detrital particles has been substantiated for the Great Bahama Bank. SMITH (1940) and ILLINGS (1954) observed the migration, under the action of strong flood tides, of oolites across a shoal area toward the interior of the bank. However, PURDY (1963) reported appreciable transportation of oolites from the areas of oolite accretion along the barrier rim, into the pellet-mud lagoonal facies. Furthermore, KINSMAN (1964) noticed the transportation of oolites across an oolitic delta, near Abu Dhabi, Trucial Coast, Persian Gulf. This situation is also true for the Great Salt Lake (CAROZZI, 1957). In this case, it was shown that the maximum size of oolites and pseudoolites were unrelated in most of the sediments except in one area where the sizes were directly related and transportation by currents observed. It was concluded that the sorting action during transportation of an oolitic sediment would produce a direct relationship between the size of the oolites and the size of the pseudoolites; no such relationship would exist for nontransported oolitic sediments.

Such a mechanism of distribution of oolites was considered many years before it was evidenced in Recent sediments as shown by the works of DE LAPPARENT (1922), SWARTZLOW (1930), and CAYEUX (1935). The latter, in particular, emphasized that widespread saturation could not occur in ancient seas and that oolites had to be formed in relatively small saturated areas to be contemporaneously distributed radially as detrital particles. After these early works comparatively little attention was paid to this critical environmental problem until statistical petrography and computer techniques were applied to the investigation of the oolitic calcarenites of the Ste. Genevieve Limestone (LACEY and CAROZZI, 1967). The maximum apparent size and skewness of distribution of oolites and the maximum apparent size of the associated pseudoolites were used as criteria. A model was developed for all possible transitions from a rock entirely oolitic to entirely pseudoolitic. In nontransported oolitic rocks, the size of the oolites and the size of the pseudoolites were found to be independent, and the skewness was generally positive. Single origin transported oolites (types 1 and 2) were observed to be characterized by a direct relationship between the size of the oolites and that of pseudoolites, the skewness was slightly positive or negative. Multiple origin transported oolites (type 3) showed no relationship between the size of the oolites and that of pseudoolites, while the skewness was slightly negative. This study led to a sedimentary model for the Ste. Genevieve

Limestone in which zones of nontransported oolites were surrounded by proximal zones of transported oolites of type 1 followed by distal zones of type 2 and 3 according to a pattern of radially decreasing environmental energy. This particular work was essentially concentrated on the reciprocal behavior of oolites and pseudoolites in predominantly oolitic calcarenites and therefore did not take into account the entire spectrum of microfacies of the Ste. Genevieve Limestone, nor did it attempt to work out a general environmental picture.

DEFINITION OF TERMS

In the present study the term oolite is used to designate a grain which consists of a core (nucleus) and an accretionary envelope. The core may be of mineral, lithic, or bioclastic nature. In most of the investigated oolites the dominant cores are either a pellet, or a crinoid, or a bryozoan fragment. The oolite envelope may be either concentric or fibro-radiated, or both. In a broken oolite, the accretionary envelope may be completely broken or abraded, or both. The term total oolite is used to designate the total frequency of complete and broken oolites.

Pellets are defined as uncoated grains of micritic mud of lithic or faecal origin less than 2 mm in diameter, whereas the term lithoclasts is used for lithic grains larger than 2 mm. Whenever calcareous grains are almost spherical with no accretionary envelope the term pseudoolite is used.

Following the method of investigation proposed by Carozzi (1950, 1958, 1960) the index of clasticity is defined as the average apparent diameter of the six largest grains on the slide. The maximum oolite clasticity is the largest value of the index of clasticity of either a complete oolite or a broken oolite in a sample. The maximum nonoolite clasticity is the largest value of the index of clasticity among pellets, crinoids, or lithoclasts in a sample. This new parameter has been introduced to allow comparisons between the behavior of the largest oolites and the largest carbonate particles of any kind (mainly debris of crinoids and lithoclasts) which were not oolitized.

STATEMENT OF THE PROBLEM

The present study is a detailed petrographic investigation of all the microfacies represented in four sections of the Ste. Genevieve Limestone followed by application of computer techniques for the treatment of all the measured parameters. Trend analysis is used to differentiate transported from nontransported oolitic calcarenites. Each sample belonging to this particular microfacies is compared with the next sample, stratigraphically above.

Those samples which showed a relationship (a relative increase or decrease of clasticity) between the maximum oolite clasticity and maximum nonoolite clasticity were grouped as transported oolitic calcarenites. Those which showed no such relationship were grouped as nontransported oolitic calcarenites. The behavior of all parameter variations; in particular, the size and frequency relationships of clastic particles with each other and each with respect to the maximum oolite clasticity; the behavior of the frequency of nonoolitic grains with the percent of oolites in the sample were investigated. The percent of broken oolites and the core composition were also taken into consideration.

A synthesis of all these data led to a general environmental model for the Ste. Genevieve Limestone.

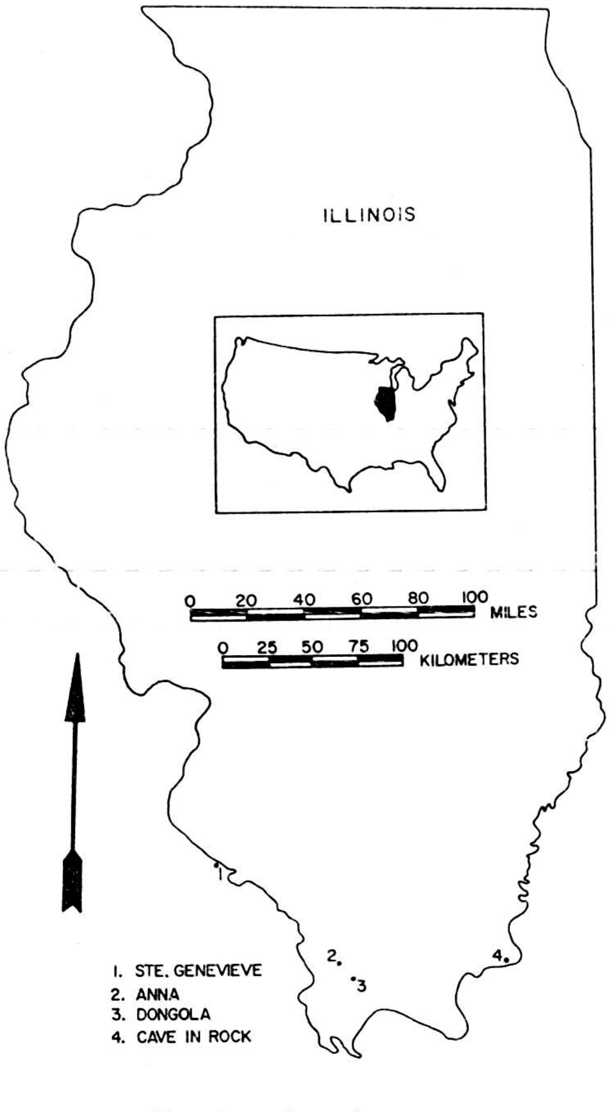

FIG. 1. — Location map.

LOCATION OF SECTIONS AND SAMPLING TECHNIQUES

The four exposures of the Ste. Genevieve Limestone (fig. 1) chosen for detailed sampling were the Midwest Stone Company quarry at Anna, Illinois; exposures in a roadcut along Interstate Route 57 approximately three miles north of Dongola, Illinois (HARRIS, 1961); the Rigsby and Barnard Quarry about a mile north of Cave In Rock, Illinois; and the type section of the formation, near Ste. Genevieve, Missouri (SHORT, 1962). At each location, closely spaced samples (average vertical distance of twelve centimeters) were taken in a vertical profile through all readily accessible zones (fig. 2). Thin sections oriented perpendicular to the bedding were prepared from each sample.

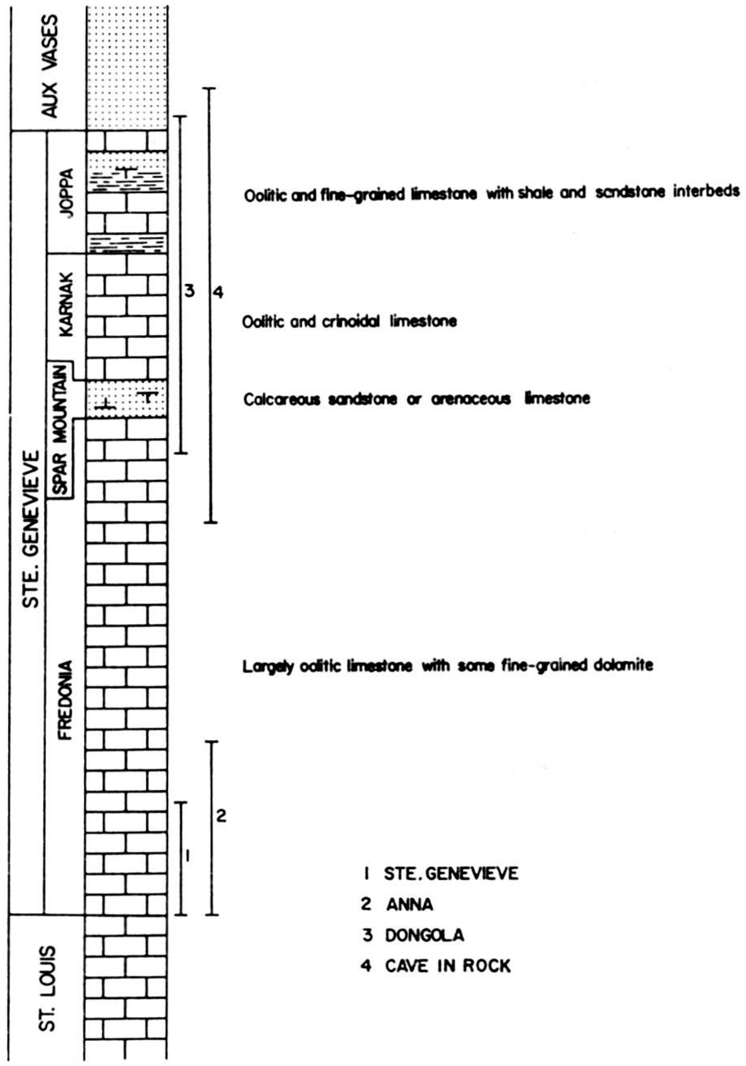

FIG. 2. — Sampled intervals.

MICROSCOPIC MEASUREMENTS

About 800 thin sections were studied by detailed petrographic investigation. Indices of clasticity (in ocular micrometer divisions) and frequency were computed for complete oolites, broken oolites, pellets, lithoclasts, crinoid debris, and detrital quartz. Frequency measurements on a constant surface of 181 sq. mm were also compiled for bryozoan debris, ostracodes, calcispheres, and *Endothyra.* A percentage estimate of the composition of oolite cores was expressed by the following major components: pellets, debris of crinoids and bryozoans. However, a few cores consisted of *Endothyra*, debris of echinoid spines, fragments of brachiopods, pelecypods, and detrital quartz. The presence and absence was recorded for the following components not abundant enough to undergo statistical measurements: brachiopods and their spines, pelecypods, gastropods, arenaceous foraminifers, echinoid spines, mica, glauconite, and cerebroid oolites (Carozzi, 1962). The behavior of these components was not represented graphically but was used as supplementary data for the final interpretation of the environment of deposition.

COMPUTER TECHNIQUES

Analysis, calculations, and graphic plotting of petrographic data for this study were expedited by the application of computer techniques. The digital computer facilities of the University of Illinois, Urbana, consisting of an IBM 360/75 computer were used for all computations. All data were plotted separately against the vertical stratigraphic position on 73 centimeter-wide paper using the Calcomp 763 Zip Mode Plotter. The Soupac computer installation was used in trend analysis. In the calculation of mean and standard deviation, and in the determination of Spearman's rank order correlation coefficient ρ, the SOUPAC statistical subroutines were used (Soupac Program Descriptions, University of Illinois, 1969).

Plotting of microfacies parameters

The petrographic raw data encoded onto punched cards were: all measured indices of clasticity (in micrometer ocular divisions), frequency, core composition, microfacies types, and sampling interval data. A Fortran IV program (Program 1) was written to reduce the above data to graphic form and to plot against the vertical stratigraphic position (figs. 12 through 16). The output obtained consisted of:

1. Indices of clasticity converted to natural size, expressed in mm.
2. Percentages of oolites, broken oolites, and pellets.

3. Variation parameter curves of:
   a) Clasticity of complete oolites, broken oolites, pellets, crinoid debris and detrital quartz.
   b) Frequency of complete oolites, broken oolites, pellets, crinoid and bryozoan debris, ostracodes, *Endothyra*, and detrital quartz.
   c) Composition of oolite cores expressed in percent of pellets, crinoid and bryozoan debris.
   d) Frequency expressed in percent of total oolites, and broken oolites with respect to total oolites.

As the coarse oolitic calcarenites are composed predominantly of closely packed oolites, the frequency index of oolites often decreases as the oolite size increases. Therefore, absolute frequency of oolites were replaced by a percentage. The percent of broken oolites with respect to total oolites and the percent of nonoolitic grains with respect to all components in the sample were also calculated.

Because of relatively similar stratigraphic position (fig. 2), the microfacies of the Anna-Ste. Genevieve and the Cave In Rock-Dongola sections were grouped separately. A statistical correlation subroutine was used to obtain mean of all measured components for each of the microfacies which were used to draw variation curves of average microfacies values (fig. 11).

Analysis and plotting of parameter variations for autochthonous and allochthonous oolitic calcarenites with clear calcite cement

The analysis of oolitic calcarenites with clear calcite cement is critical for reconstructing characters of environments of oolitization. A computer program (Program 2) to separate the autochthonous from the allochthonous oolitic calcarenites, to calculate mean and standard deviation of measured and computed parameters, and to plot parameter variations, was written.

The first step involved the separation of data pertaining to this particular microfacies from all sections, selection of the maximum clasticity of oolites and the maximum clasticity of nonoolites, and the conversion of their clasticities into mm. From the printed output the maximum oolite clasticity and the maximum nonoolite clasticity of a sample were compared with those of the succeeding sample. The samples which showed a relationship (a relative increase or decrease of clasticity) between the maximum oolite clasticity and maximum nonoolite clasticity were grouped as allochthonous oolitic calcarenites. Those which did not show such a relationship were grouped as autochthonous oolitic calcarenites.

In the second step, all previous plotted parameters including the maximum oolite clasticity and maximum nonoolite clasticity, pertaining to the autochthonous and allochthonous oolitic calcarenites were plotted separately in a " condensed stratigraphic order " within each of the four investigated sections as if no other microfacies were intercalated between them. These in turn were superposed in alphabetical order from bottom to top (figs. 6 and 8).

The third step consisted of computing total frequencies of oolites, nonoolitic grains, bioclastics, clastics (total of pellets, lithoclasts, and detrital quartz) and conversion of all frequencies into percentages and clasticities into mm. Mean and standard deviation of all parameters within these two groups were obtained using the statistical correlation program.

Trend analysis

Trend is defined as " any type of regularity in an ordered sequence of numbers or elements. Any ordered sequence of numbers or elements other than random shall be designated as a trend " (MILLER and KAHN, 1965, p. 325).

A computer program to analyze the trend of parameter variations of autochthonous and allochthonous oolitic calcarenites with clear calcite cement, arranged in a condensed stratigraphic order within each of the four investigated sections, was written (Program 3). This entails three specific tests: parallelism, comparison test, and Spearman's correlation coefficient ρ.

Parallelism of a parameter variation curve with respect to another was tested. This is expressed in the number of times both parameters behave similarly with an increase or decrease at each sampled point. If this value exceeds 50 percent of the total samples in the sequence, the variables are defined here as having a trend.

In the comparison test, individual values of a parameter variation were compared to the values of another parameter at each sampled point in the sequence. The result is the total number of " higher ", " equal ", and " lower " values of these parameters.

Spearman's rank correlation coefficient, which indicates a specific type of trend, namely a linear increase or decrease of a pair of parameters was determined. The Spearman's rank order correlation coefficient ρ ranges from -1 to 1 so that high positive values indicate the possibility of an upward trend whereas high negative correlation would indicate the possibility of a downward trend.

The output provided: trend of all parameters with respect to maximum oolite clasticity; trend of pellet and crinoid debris clasticity with respect to maximum nonoolite clasticity; trend of all parameters with respect to each other; comparison tests of clasticity of pellets, crinoid debris, and clasticity of maximum nonoolites, each with respect to maximum oolite clasticity; comparison tests of frequencies of broken oolites, pellets, crinoid and bryozoan debris, each with respect to complete oolite frequency. Spearman's measure of degree of association of all pairs of parameters in the sequence and the results are given in the form of values of Spearman's ρ.

In order to show graphically the relationships obtained by trend analysis of parameter variations for autochthonous and allochthonous oolitic calcarenites with clear calcite cement, parameter variations were plotted again in a condensed stratigraphic order within each of the four investigated sections as if no other microfacies were intercalated between them (Program 2, modified). These were superposed in an alphabetical order from bottom to top (figs. 8 and 9). The plotted parameters were:

1. Maximum oolite clasticity and maximum nonoolite clasticity.
2. Maximum oolite clasticity and pellet clasticity.
3. Maximum oolite clasticity and crinoid debris clasticity.
4. Maximum nonoolite clasticity, pellet clasticity, and crinoid debris clasticity.
5. Maximum oolite clasticity, total oolite and complete oolite frequency.
6. Maximum oolite clasticity and oolite percent.
7. Oolite percent and pellet frequency.
8. Oolite percent, crinoid debris frequency, and bryozoan debris frequency.
9. Pellet frequency, crinoid debris frequency, and bryozoan debris frequency.

ANALYSIS OF AUTOCHTHONOUS AND ALLOCHTHONOUS OOLITIC ENVIRONMENTS

Autochthonous oolites are defined as oolites which have remained within their environment of oolitization; while allochthonous oolites have been transported out of it, from a few hundred feet to several miles (LACEY and CAROZZI, 1967). The present analysis of oolitic calcarenites with clear calcite cement is the key for understanding autochthonous and allochthonous oolitic environments.

Parameter variations and their relationships in autochthonous oolitic environment

Autochthonous oolites are characterized by a general absence of abrasion of the outer concentric rings, a textural and compositional similarity of concentric rings of associated oolites, and a tendency of most oolites of a given sample to show the same maximum size. Autochthonous oolites are often associated with recoated broken oolites

Most of the oolites judged to be autochthonous, on the basis of the above characters, showed maximum clasticity of oolites and maximum clasticity of nonoolites to be unrelated. Autochthonous oolites, separated from allochthonous based on this observation, showed in the trend analysis and in the plot of comparison of parameter variations the following statistical relationships:

1. The maximum clasticity of oolites is independent of the maximum clasticity of nonoolites, the clasticity of pellets, and the clasticity of crinoid debris.
2. The maximum clasticity of nonoolites, clasticity of pellets, and clasticity of crinoid debris show a general direct relationship.

3. The pellet, crinoid and bryozoan debris frequencies are generally opposed to the percent of oolites; directly related to the percent of nonoolites; and independent of maximum clasticity of oolites.
4. The pellet, crinoid and bryozoan debris frequencies are generally related.

The above described clasticity relationships are shown in the Theoretical Model 1 (fig. 4); whereas the frequency of pellets, crinoid and bryozoan debris relationships with the oolite percent are shown in the Theoretical Model 2 (fig. 5).

The actual parameter variations for autochthonous oolitic calcarenites with clear calcite cement in a condensed stratigraphic order (fig. 6) show no definite relationship between both the indices of clasticity and frequency of complete oolites, broken oolites, pellets, and crinoid debris. With a few exceptions, the detrital quartz was absent. Pellet, crinoid and bryozoan debris core percentages were observed to

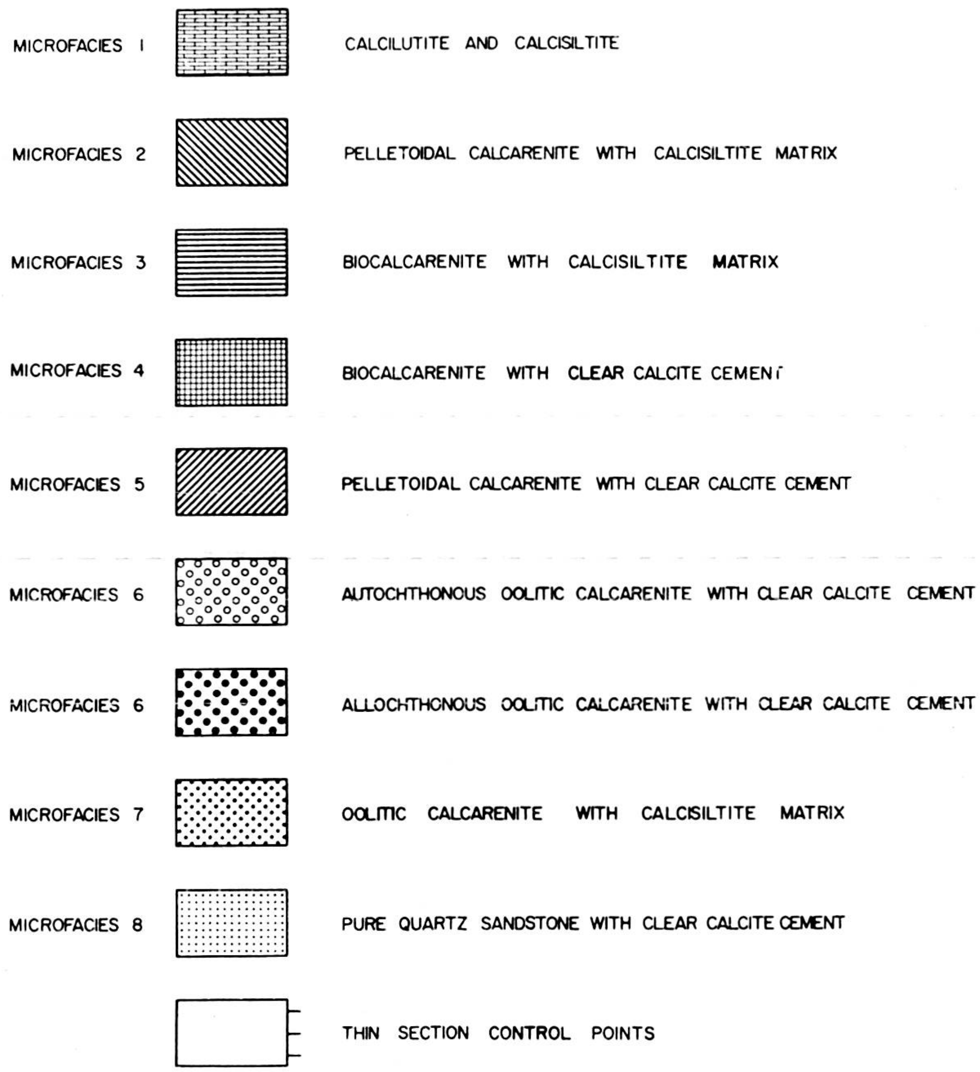

FIG. 3. — Symbol key.

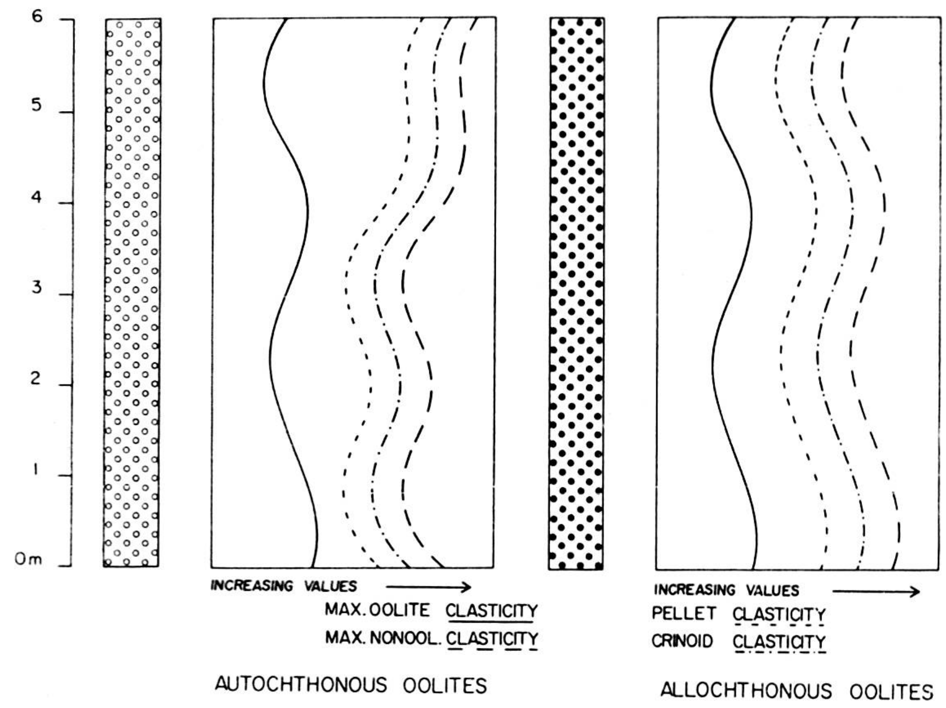

FIG. 4. — Theoretical model 1.

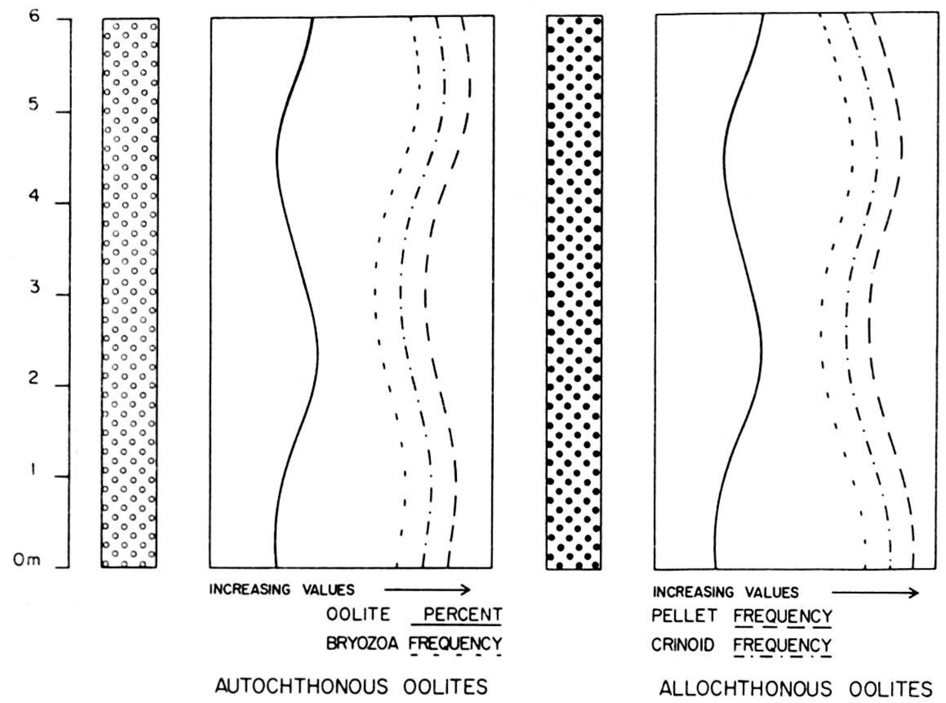

FIG. 5. — Theoretical model 2.

uncorrelated. However, the cores consisting of pellet and crinoid debris were relatively dominant over those formed by bryozoan debris, indicating the composition of the supply brought into the oolitic environment. Comparison of the percent of oolites in the sample and the percent of broken oolites with respect to total oolites showed that the percentage of broken oolites dominated in only a few cases, probably due to local turbulent conditions, swirling action, etc. Comparison of the maximum clasticity of oolites and the maximum clasticity of nonoolites (fig. 6, last column) showed the two curves to be independent.

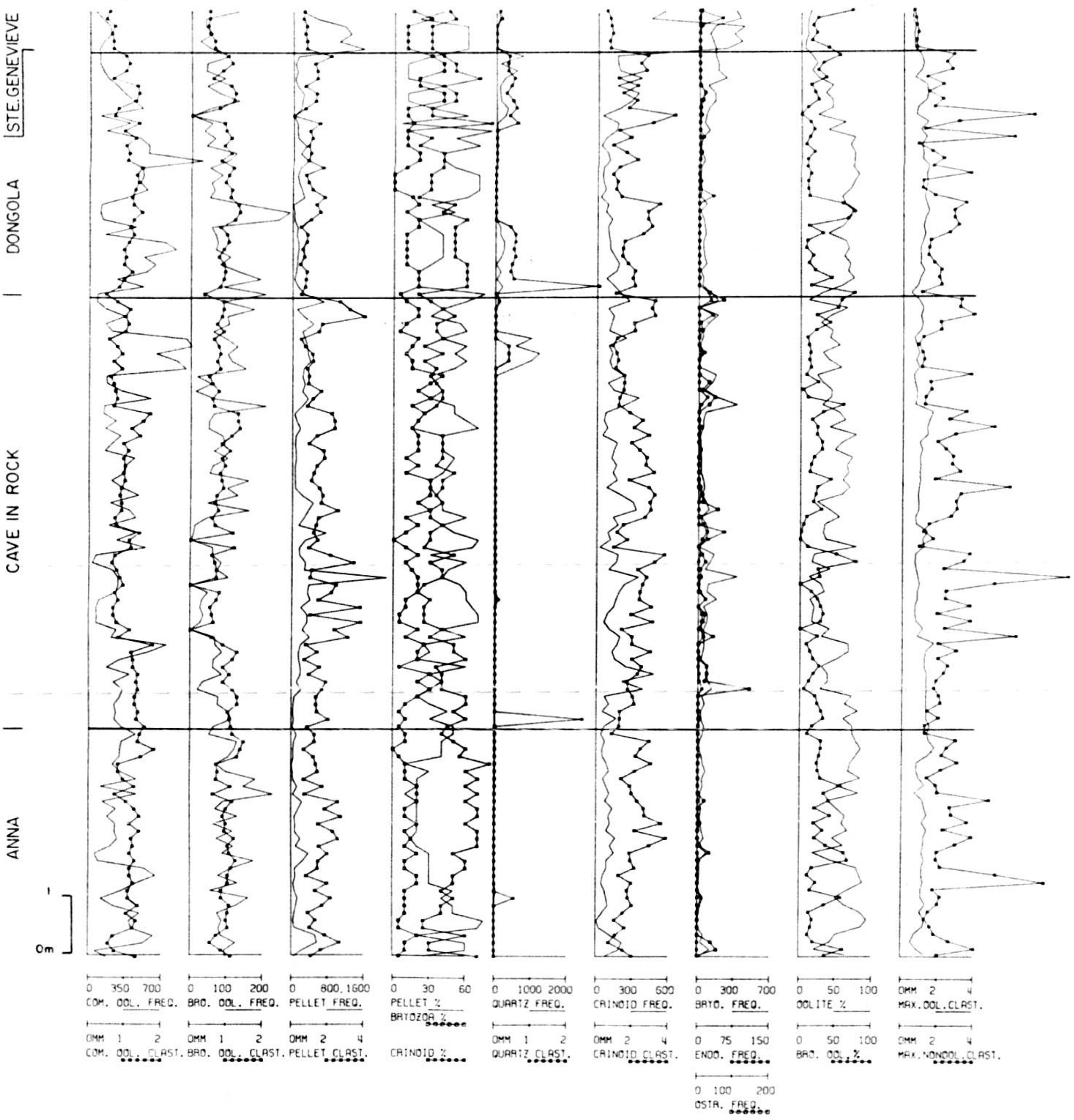

FIG. 6. — Parameter variations for autochthonous oolitic calcarenites (sections superposed in alphabetical order).

The actual behavior of the characteristic statistical parameters of the autochthonous oolitic environment, illustrated in the Theoretical Models 1 and 2, are shown graphically by the comparison of the natural parameters (fig. 7) and by the trend analysis. Comparison of the maximum clasticity of oolites with the maximum clasticity of nonoolites, clasticity of pellets, and clasticity of crinoid debris (fig. 7, first three columns), showed no trend (34.62 to 47.69%) and were characterized by low positive ρ values (0.14 to 0.18). Relationships of maximum clasticity of non-

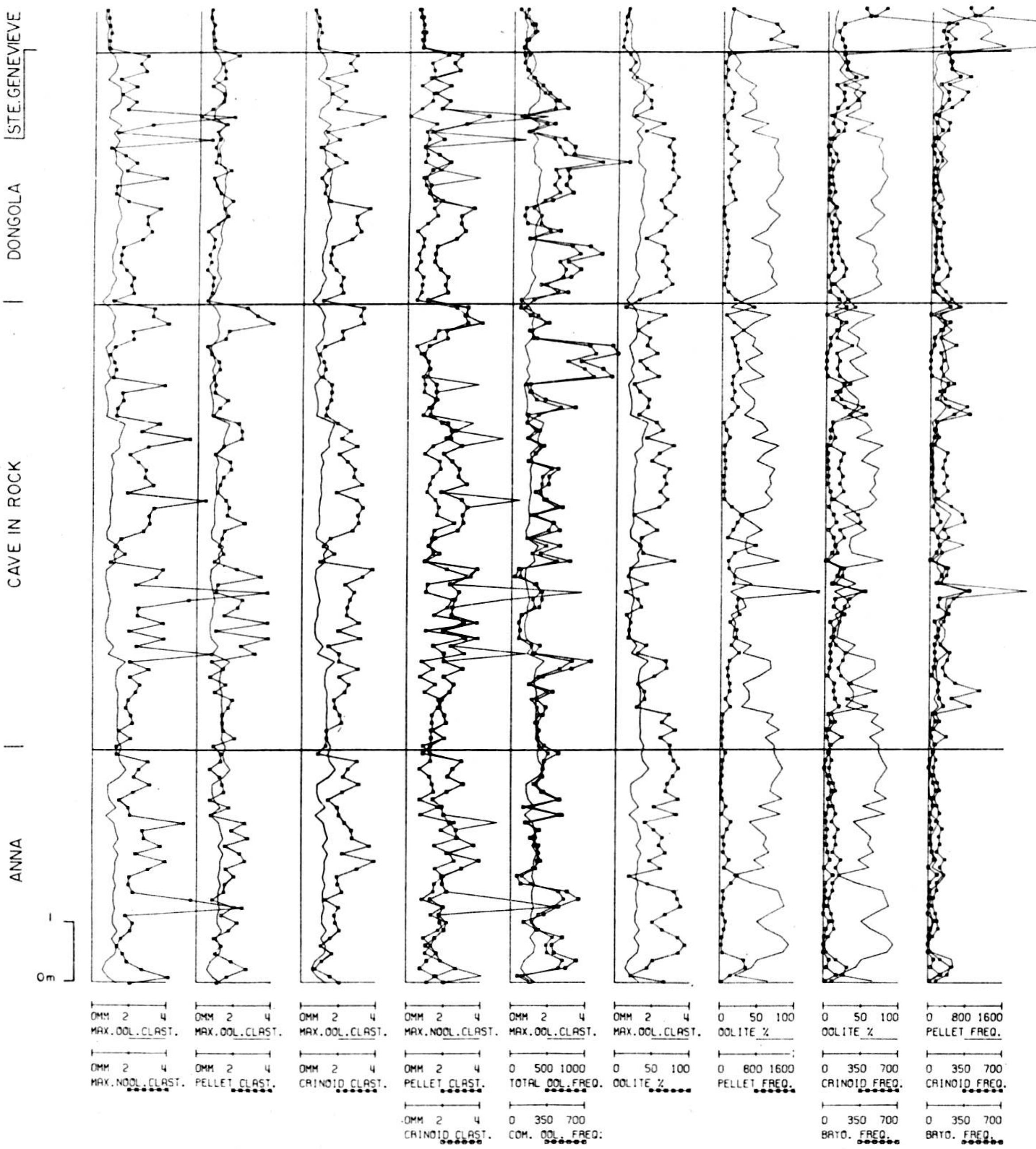

FIG. 7. — Comparison of parameter variations for autochthonous oolitic calcarenites (sections superposed in alphabetical order).

oolites, clasticity of pellets, and clasticity of crinoid debris are shown in the fourth column. These clasticities exhibited a trend (60.77 to 80.31%) and showed relatively high positive ρ values (0.52 to 0.80). Comparison of the clasticity of maximum oolites with the frequency of total oolites and complete oolites showed no trend (45.39%, 41.54%) and ρ values were low (0.16 to 0.20). However, the frequency of total oolites and complete oolites were well correlated, characterized by a good trend (90.0%) and a high positive ρ value (0.95). The maximum clasticity of oolites and the percent of oolites were related generally as indicated by a trend (54.62%) and a value of 0.52. The pellet, crinoid and bryozoan debris frequencies, when compared with the oolite percent, opposed the oolite percent curve (trend from 23.85 to 28.46%). Spearman's ρ values were relatively high and negative (-0.65 to -0.73). In the last column (fig. 7), where the frequencies of pellets, crinoid and bryozoan debris are plotted, the curves run nearly parallel to each other.

Parameter variations and their relationships in allochthonous oolitic environment

Allochthonous oolites are characterized generally by evidences of abrasion of the outer concentric rings, a lack of a textural and compositional similarity of concentric rings of associated oolites and no tendency of most oolites of a given sample to show a common maximum size due to mixing of oolites from different sources. Allochthonous oolites often are not associated with recoated broken oolites.

Most of the oolites judged to be allochthonous, based on the above properties, showed the maximum clasticity of oolites and maximum clasticity of nonoolites to be directly related (a general increase or decrease of clasticity). Allochthonous oolites, separated from authochthonous oolites based on this observation, showed in the trend analysis and in the plot of comparison of parameter variations the following statistical relationships:

1. The maximum clasticity of oolites is directly related to the maximum clasticity of nonoolites, the clasticity of pellets, and the clasticity of crinoid debris.
2. The maximum clasticity of nonoolites, clasticity of pellets, and clasticity of crinoid debris show a direct relationship.
3. The pellet, crinoid and bryozoan debris frequencies are opposed to the percent of oolites; directly related to the percent of nonoolites; and opposed to the maximum clasticity of oolites.
4. The pellet, crinoid and bryozoan debris frequencies are mutually related.

The above described clasticity relationships are shown in the Theoretical Model 1 (fig. 4); whereas the frequency of pellets, crinoid and bryozoan debris relationships with the oolite percent are shown in the Theoretical Model 2 (fig. 5).

The actual parameter variations for allochthonous oolitic calcarenites with clear calcite cement in a condensed stratigraphic order (fig. 8) show that there is no

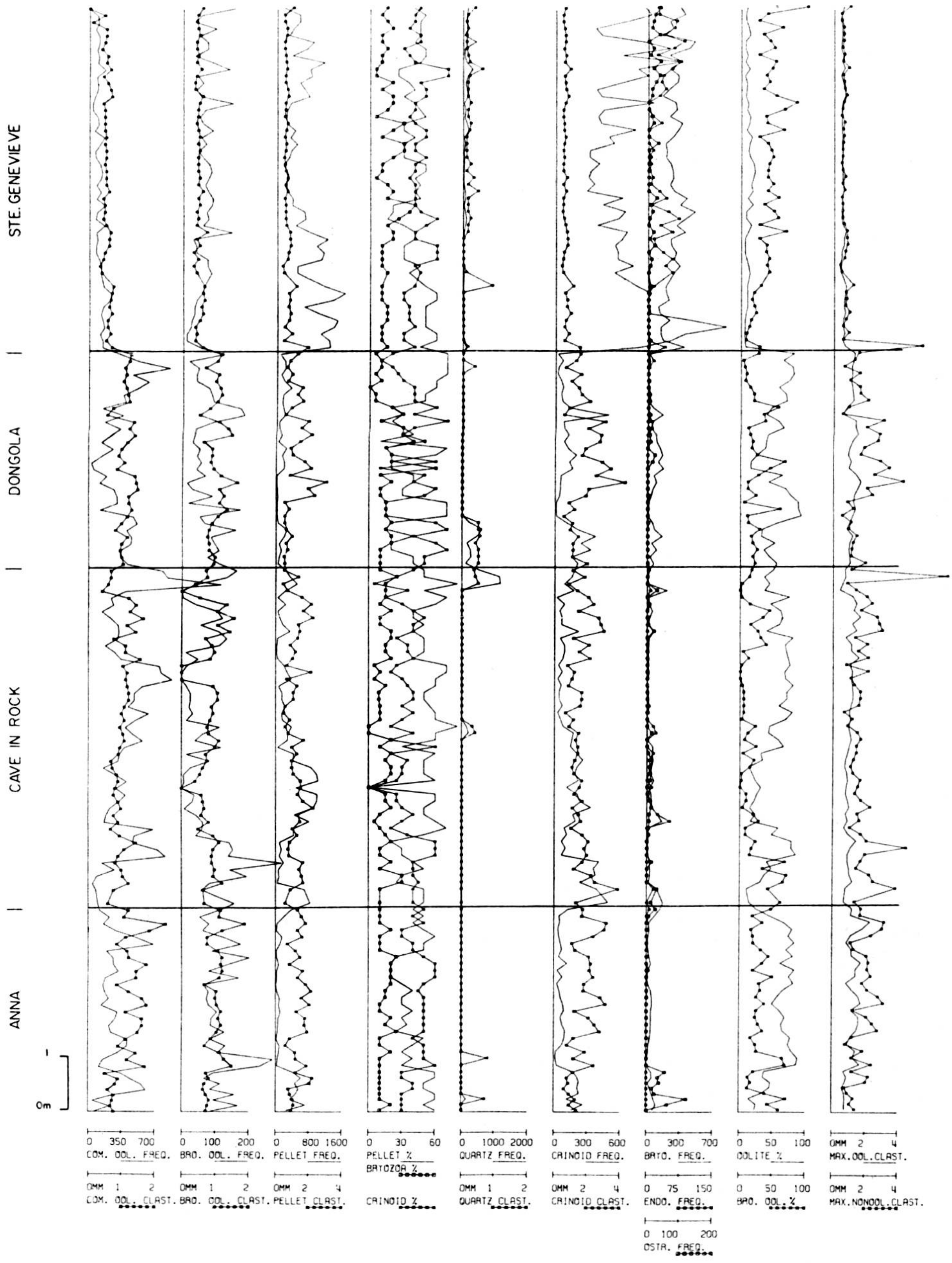

FIG. 8. — Parameter variations for allochthonous oolitic calcarenites (sections superposed in alphabetical order).

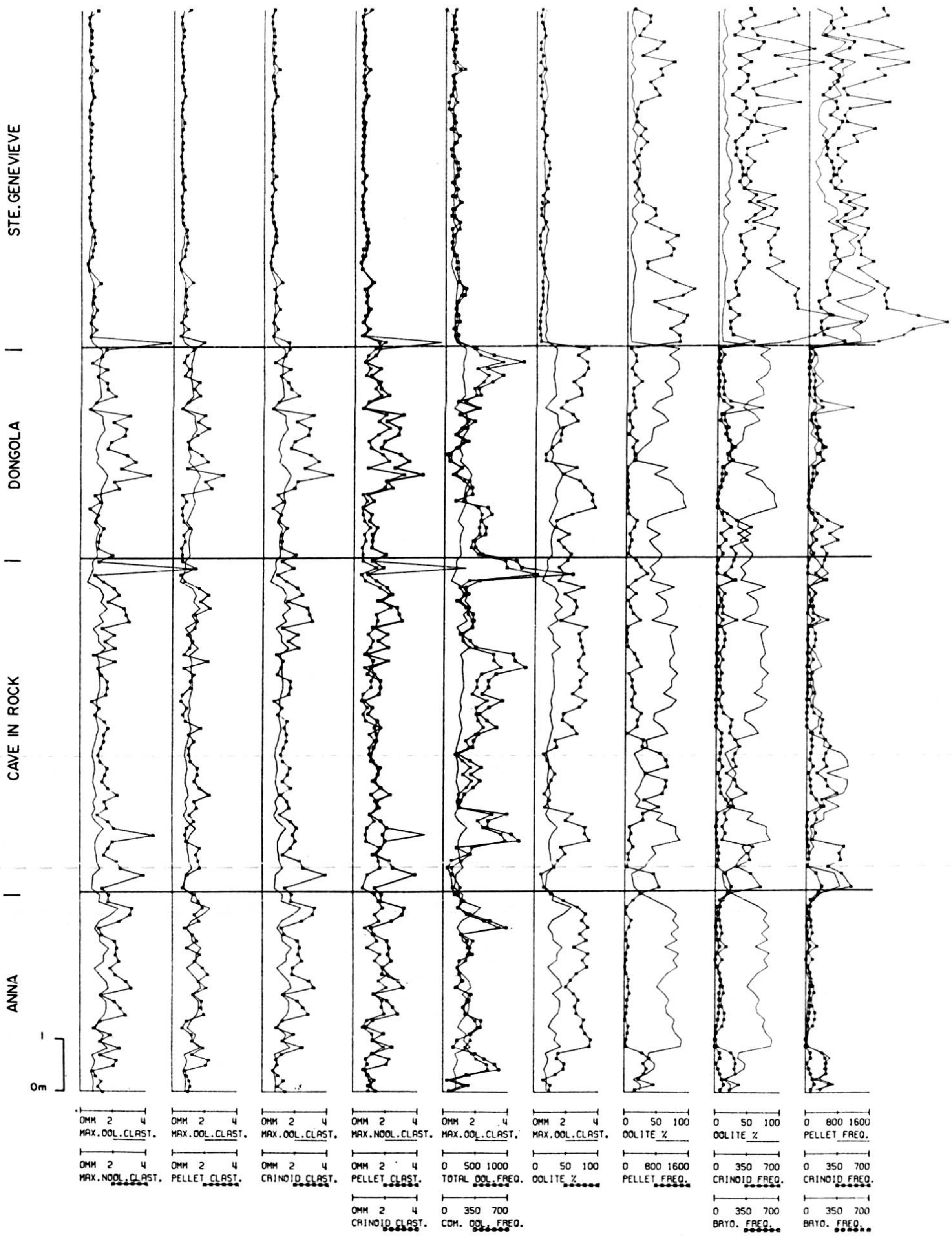

FIG. 9. — Comparison of parameter variations for allochthonous oolitic calcarenites (sections superposed in alphabetical order).

distinct relationship between both the indices of clasticity and frequency of complete oolites, broken oolites, pellets, and crinoid debris. Detrital quartz was generally absent except in the Ste. Genevieve section. The pellet, crinoid and bryozoan debris core percentages were observed to be random. This might be due to mixing of oolites from different sources or due to the composition of the supply brought into the environment of oolitization. Abrupt changes in oolitic core composition, however, might be considered as evidence of mixing of oolites from different sources. Upon comparison, the percent of broken oolites with respect to total oolites and oolite percent was found to be independent. An upward linear increase of broken oolite percent occurs in the Ste. Genevieve section. Therefore, where such a relationship is evident, the percent of broken oolites might be considered as an index of the degree of transportation. Comparison of the maximum clasticity of nonoolites (fig. 8, last column) showed the two curves to be directly related.

The actual behavior of the characteristic statistical parameters of allochthonous oolitic environment, illustrated in the Theoretical Models 1 and 2, are shown graphically by the comparison of the natural parameters (fig. 9) and by the trend analysis. Comparison of the maximum clasticity of oolites with the maximum clasticity of nonoolites, clasticity of pellets, and clasticity of crinoid debris (fig. 9, first three columns), showed excellent correlation as indicated by a good trend (62.58 to 77.30%) and high positive ρ values (0.70 to 0.82). The relationships of maximum clasticity of nonoolites, clasticity of pellets, and clasticity of crinoid debris are plotted in the fourth column. These clasticities were directly related and exhibit a good trend (71.78 to 83.44%) and high positive Spearman's measure of association (0.87 to 0.96). The comparison of the clasticity of maximum oolites with the frequency of total oolites and complete oolites showed no trend (35.58 to 37.42%) and ρ values (0.45 to 0.47) indicate neither a linear increase nor a linear decrease. However, the measure of association was higher than in autochthonous oolitic environment (0.16 to 0.20). The frequency of total oolites and complete oolites are well correlated as in the autochthonous oolitic environment, characterized by a good trend (81.60%) and a high positive value (0.95). The maximum clasticity of oolites and the oolite percent are related on the basis of high positive ρ value (0.78) though the trend (41.72%) was weak. Pellet, crinoid and bryozoan debris frequencies when compared with the oolite percent opposed the oolite percent (trend from 23.31 to 23.93%). Spearman's ρ values were high and negative (-0.81 to -0.92). The frequencies of pellets, crinoid and bryozoan debris are compared in the last column, and their frequencies appear related as the curves run parallel to each other.

INTERPRETATION OF PARAMETER VARIATIONS IN AUTOCHTHONOUS AND ALLOCHTHONOUS OOLITIC ENVIRONMENTS

Essential conditions for oolite growth

The required conditions for oolite growth may be summarized as follows (BATHURST, 1967):

(1) Supersaturation of a Ca CO_3 solution

(2) Availability of detrital nuclei

(3) Agitation

(4) Hydraulic and topographic controls

Supersaturation in $CaCO_3$ provides constant supply of inorganic material for oolite growth. The detrital nuclei afford surfaces on which the oolitic envelopes can develop. Agitation prevents the oolites from being cemented and keeps them in motion until the critical clasticity is reached. Beyond this size the oolites can no longer be lifted by currents or agitation, therefore cease to grow and settle on the bottom (CAROZZI, 1960). Hydraulic and topographic controls keep oolites on the oolite shoal (fig. 17).

The composition of supply

The composition of the sand-size detrital grains brought into the oolitic environment is shown by the composition of oolite cores and by the mean frequencies of nonoolitic grains. Both reveal pellets and crinoid debris to be more abundant than the bryozoan debris throughout the period of deposition of autochthonous oolitic calcarenites. Fluctuations in the composition of supply are reflected in the changes in the core composition, standard deviation and frequency curves of nonoolitic grains.

Model of oolite formation

CAROZZI (1957, 1960, 1967) proposed a simplified model of oolite formation, considering the interplay of two main factors:

1. The competence of the currents bringing uncoated grains into the oolitic environment where oolitization is taking place.
2. The local turbulence or agitation in the supersaturated environment in which oolites are forming.

He indicated that the maximum clasticity of oolites is directly related to the intensity of agitation in the oolitic environment, whereas the clasticities of nonoolitic grains are related to the supply brought into the oolitic environment. All grains set into motion by agitation are oolitized with the exception of the nonoolitic grains larger than the oolites. This interpretation is confirmed in the present study by the mean clasticity values of oolites (0.88 to 1.04 mm) and of nonoolitic grains (1.39 to 2.44 mm), and by the comparison tests with the maximum oolite clasticity. Out of 130 samples investigated, clasticities of 80 pellets, 115 crinoid debris, and 122 maximum nonoolites were larger than the maximum oolite clasticity. The maximum clasticity of non-transported oolites is unrelated to the maximum clasticity of nonoolites, the clasticity of pellets, and clasticity of crinoid debris because these clasticities are function of the above mentioned two independent factors in the environment of oolitization.

CAROZZI (1960, p. 243-244) considered all types of transitions from a deposit entirely oolitic to a deposit entirely pseudoolitic and indicated the possible ways of inferring the local agitation. The oolitic calcarenites investigated here were not entirely oolitic or pseudoolitic, but fell within these two extreme cases. Therefore, it may be concluded that regardless of the intensity of agitation, the nonoolitic grains present in a sample fall within a certain size range. The minimum clasticity of nonoolitic grains approaches the maximum clasticity of oolites (1.04 mm) and the maximum clasticity of pellets, lithoclasts, and crinoid debris approach the maximum clasticity of nonoolites (2.44 mm). This behavior of clasticities of nonoolitic grains in autochthonous oolitic environment is clearly seen in the plot of comparison of parameter variations (fig. 7). In addition, the average clasticities of pellets (1.39 mm) and crinoid debris (1.98 mm) are within this range of 1.04 to 2.44 mm. Furthermore, the clasticities of pellets and crinoid debris show a positive linear increase with the maximum clasticity of nonoolites (0.65 to 0.73 ρ). Because the nonoolitic grains fall within the above mentioned range, the maximum clasticity of nonoolites, the clasticity of pellets, and the clasticity of crinoid debris are, in general, directly related to each other.

Degree of oolitization

The percentage of oolites in autochthonous oolitic calcarenites may be considered as an expression of the degree of oolitization. As the percentage of oolites increases, the frequencies and percentages of nonoolitic grains should decrease and vice versa. This behavior of frequencies of pellets, crinoid and bryozoan debris, illustrated in Theoretical Model 2 (fig. 5), is observed in the natural parameter variations (fig. 7). These frequencies are mutually parallel to each other but are opposed to the oolite percentage. The trend analysis of frequencies and percentages of all nonoolitic grains confirmed this relationship. Out of 130 samples investigated the frequencies and percentages of nonoolitic grains increased or decreased with the oolite percentage only in 11 to 38 samples. In other words, in a majority of the samples, the nonoolitic parameters increased and decreased with the decrease and increase of oolite percentage respectively. This reciprocal relationship is also reflected in the Spearman's ρ values, which show a linear decrease of nonoolitic parameters with the increase in oolite percentage (-0.53 to -1.0) and a linear increase of these parameters with increase in the nonoolite percentage (0.53 to 1.00).

The degree of oolitization seems to be related directly to the maximum clasticity of oolites, which is indicated by a trend (54.62%) and a positive correlation (0.54 ρ) between them. In addition, the behavior of frequencies and percentages of nonoolitic grains with respect to the oolite percentage mentioned above, is found valid (to a lesser extent) for the maximum oolite clasticity. The nonoolitic parameters in 42 to 55 out of 130 samples investigated show a trend, but in a majority of the samples these parameters show a reciprocal relationship with the maximum oolite clasticity. The possibility of linear decrease of nonoolitic parameters with the increase in the maximum oolite clasticity is indicated by Spearman's measure of association (-0.37 to -0.59 ρ).

In conclusion, the percentage of oolites (the degree of oolitization) generally is directly related to the maximum oolite clasticity (maximum agitation in the environment of oolitization) but opposed to the frequencies and percentages of nonoolitic grains. The percentage of broken oolites seems to suggest local turbulence, and swirling action.

Effects of transportation

The effects of prolonged transportation on any sediment may be summarized as follows: decline in size of particles, continuing abrasion, mixing of sediments from different sources, and increasingly better sorting of deposit. In the case of allochthonous oolitic calcarenites the effects of transportation are: a comparative decrease in the frequencies of total oolites, complete oolites, and broken oolites; an increase in the frequencies and percentages of nonoolitic grains; a decrease in the percentage of oolites in the sample; an increase in the broken oolites percent with respect to the total oolites; and a decrease in the indices of clasticity of oolites, maximum nonoolites, pellets, and crinoid debris.

a. *Decline in size*

All the average values of indices of clasticity showed a decline in size in the allochthonous oolitic environment. The average indices of clasticity of nonoolitic grains (1.05 to 1.48 mm) are still larger than the maximum oolite clasticity (0.92 mm), but both kinds of values are within a narrower range (0.92 to 1.48 mm) than in the autochthonous oolitic environment (1.04 to 2.44 mm). For instance, this range may be much smaller as in the Ste. Genevieve section (0.51 to 0.70 mm).

b. *Abrasive action*

The abrasive action is revealed by the presence of broken and abraded oolites, and general absence of lithoclasts. The amount of transportation seems to be indicated by the percentage of broken oolites with respect to total oolites. An upward linear increase of broken oolite percentage occurs in the Ste. Genevieve section. In other sections the amount of transportation fluctuated through time. The predominance of broken oolite percentage with respect to complete oolites is clearly shown in the microfacies which are not predominantly oolitic, where the oolites obviously have been transported out of their environment like ordinary clastic particles (figs. 12 through 16).

c. *Mixing of sediments from different sources*

In a few cases the clasticities of nonoolitic grains were smaller than the maximum oolite clasticity and the standard deviation of frequencies of nonoolitic grains was larger than in the autochthonous oolitic environment. The pellet, crinoid and bryozoan debris frequency curves furthermore show sudden fluctuations (fig. 9, last column), a similar behavior is shown by the composition of the cores (fig. 8). In a few instances *Endothyra* or detrital quartz or other core types dominated. In addition, samples showed poor sorting and a mixture of oolites of different sizes. All these observations seem to indicate that the allochthonous oolitic calcarenites were mixed occasionally with sediments from different sources.

d. *Sorting*

The association of large or small oolites with large or small uncoated grains (fig. 9) indicates the effects of sorting actions. These seem to have produced a direct relationship between the maximum clasticity of oolites and the clasticities of maximum nonoolites, pellets, and crinoids; and also between the clasticities of nonoolitic grains.

The frequency relationships observed in autochthonous oolitic calcarenites are more closely related in allochthonous oolitic calcarenites, another possible effect of sorting action during transportation.

DESCRIPTION OF MICROFACIES

Eight major but closely related microfacies characterize the Ste. Genevieve Limestone. Their subdivision is based on the values of measured components, combined with megascopic and petrographic textural variations. Pelletoidal microfacies are differentiated from bioclastic microfacies on the basis of an arbitrary limit of 50% of pellets with respect to the total pellets, lithoclasts, and bioclastics in the sample. Although incipient dolomitization was observed in all microfacies, it did not affect the textures sufficiently to influence the subdivision procedures.

The major features of the different microfacies are sufficiently illustrated in order of decreasing relative depth (Plate I) that only additional data will be given here.

Microfacies 1 (4% of the total samples investigated) contains silt-size angular grains of detrital quartz, muscovite flakes and a few oolites, invariably broken or abraded indicating transportation. The same applies to microfacies 2 (8%) which displays more than 50% of either faecal or lithic pellets. Microfacies 3 (10%) differs from microfacies 2 by having more than 50% of bioclastics, transported oolites and detrital minerals being similar to those of the preceding microfacies. Microfacies 4 (14%) is the first one showing more than 50% bioclastics set in a sparry calcite cement. Many organic debris with micrite coatings indicate reworking from microfacies 3. Lithic pellets are well rounded and the grains of detrital quartz are large (0.14 to 0.20 mm), subrounded and similar to those (0.27 mm) of the pure quartz sandstone (microfacies 8). Transported oolites are common. Microfacies 5 (6%) differs from the preceding one by having more than 50% of pellets associated with bioclasts which appear reworked from microfacies 2, the grains of detrital quartz are almost as coarse as in microfacies 4. Microfacies 6 (52%) is the typical oolitic sediment of the Ste. Genevieve Limestone. It consists of oolites (40%), some of which cerebroid (Carozzi, 1962), well rounded lithic pellets (23%), debris of crinoids (19%) and of bryozoans (8%); pellets and bioclasts are similar to those forming microfacies 4 and 5. Detrital quartz is fine-grained, subrounded and in small amount. This is also true for microfacies 7 (3%) which is almost equally lithic pelletoidal and oolitic, but contains numerous broken oolites (42%), indicating appreciable transportation. Microfacies 8 (3%) is a pure quartz sandstone with broken and abraded oolites associated with grains of glauconite, potassic feldspar and chert.

MICROFACIES RELATIONSHIPS

The above described microfacies follow each other in the investigated sections, and in order of decreasing relative depth, according to two distinct sequences (fig. 10). From a common starting point represented by a calcilutite and calcisiltite (microfacies 1), pelletoidal calcarenites (microfacies 2, 5) and bioclastic calcarenites (microfacies 3, 4) are derived at first with calcisiltite matrix and then with clear calcite cement, until both of them become oolitic calcarenites with clear calcite cement (microfacies 6). For environmental reasons to be discussed later in detail, the area of oolitization is partially surrounded by oolitic calcarenites with calcisiltite matrix (microfacies 7), formed almost entirely of allochthonous oolites, which provide the transition to the shallowest microfacies (8) consisting of pure quartz sandstone with clear calcite cement. In situations where microfacies 6 is not present, the two series of calcarenites grade into 8 through microfacies 7.

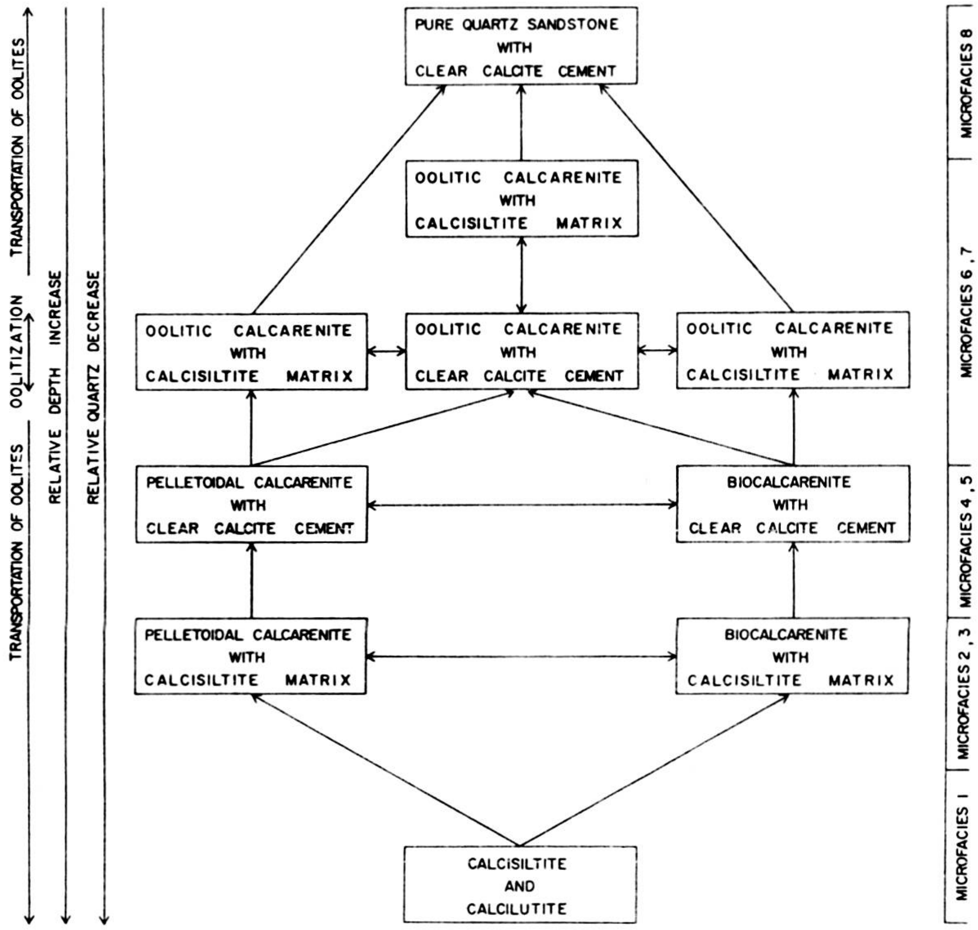

FIG. 10. — Relationships of microfacies.

Average values of all the parameters of the above described microfacies are plotted against the vertical succession, in order of decreasing relative depth, of the pelletoidal and bioclastic sequences (fig. 11). Because of stratigraphic reasons (fig. 2), the sections of Anna-Ste. Genevieve and Cave In Rock-Dongola have been grouped together.

The clasticity curves of complete and broken oolites are parallel to each other in both sequences. They increase linearly from microfacies 1 (0.25 mm, 0.18 mm) to a maximum value in microfacies 6 (1.03 mm, 0.86 mm), and linearly decrease to microfacies 8 (0.27 mm, 0.23 mm). In all cases these clasticities are smaller than those of pellets and crinoid debris. The frequencies of complete and broken oolites begin with low values in microfacies 1 (1, 2), follow the clasticity curves quite closely and also reach high values in microfacies 6 (358, 75). Whereas the frequency of complete oolites decreases from microfacies 6 to 8 (85), the frequency of broken oolites increases (125). Such variations indicate the generation of oolites in the environment of oolitization (microfacies 6) and their transportation into nonoolitic microfacies as detrital particles. The relative increase of broken oolites compared to complete oolites may suggest the degree of transportation.

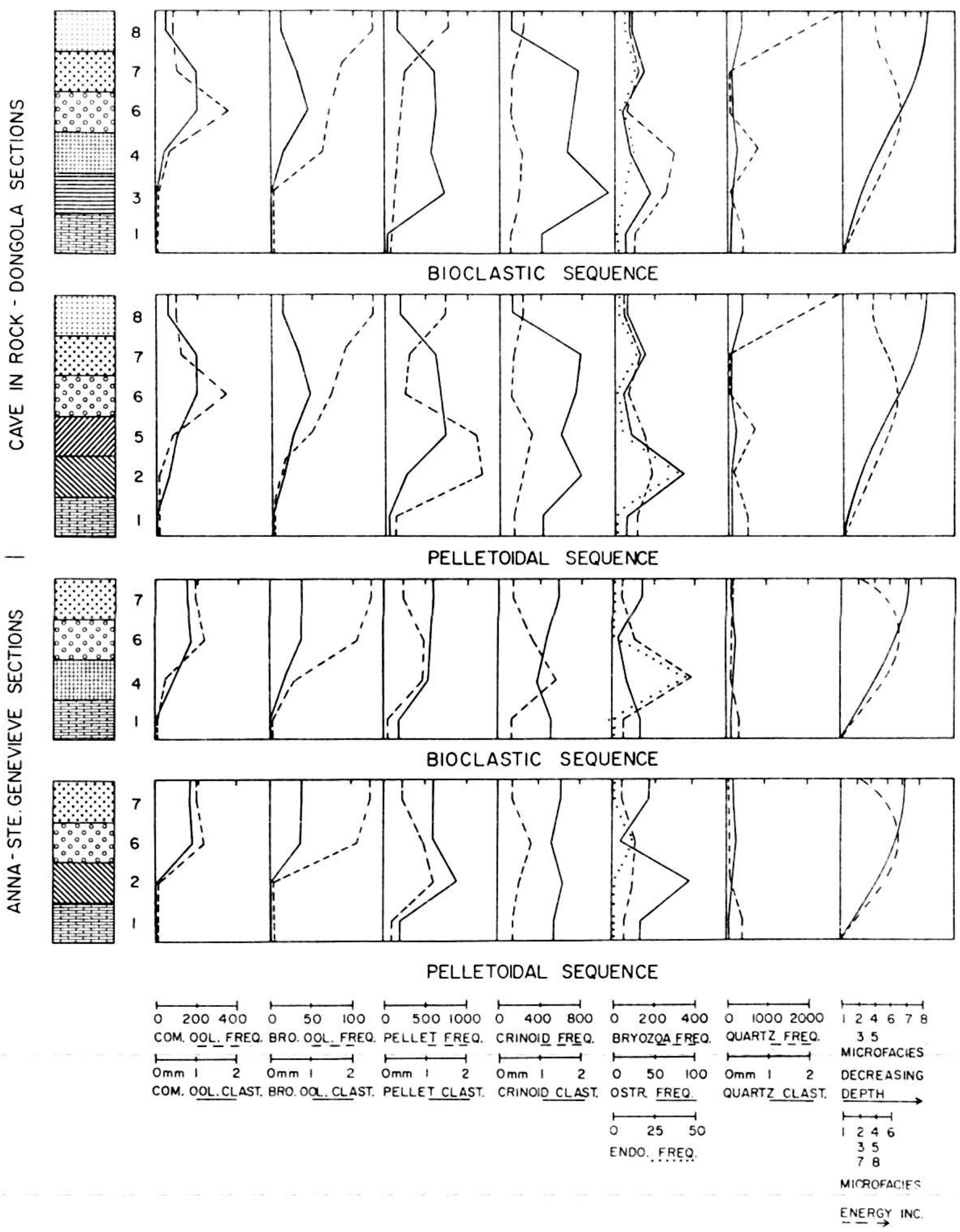

FIG. 11. — Variations curves of average microfacies values.

The frequencies and clasticities of pellets and crinoid debris are random; this is interpreted as reflecting the behavior of particles which are not involved in oolitization. The bryozoan debris, ostracodes, and *Endothyra* frequencies decrease in microfacies 6 because they are winnowed away as an effect of the high energy. In the bioclastic sequence of Cave In Rock-Dongola sections the bryozoan debris frequency linearly increases from microfacies 3 (259) to a maximum value in microfacies 4 (290), whereas the frequency of crinoid debris shows no appreciable change (203, 210). This may be interpreted as being an expression of the increased disintegration of the delicate bryozoan debris with increasing energy in the environment, whereas the resistant crinoid columnals were only sorted according to size but not appreciably broken. The frequency of detrital quartz oscillates and abruptly increases from microfacies 7 to 8, expressing the pure quartz sandstone with clear calcite cement.

The microfacies (fig. 11, last column) are arranged from left to right at arbitrary equal intervals in order of decreasing relative depth showing that the two types of sequences indicate a regular decrease of depth upwards. The interpretation by relative energy is based on the assumption that the lowest energy is represented by microfacies 1, followed by the pelletoidal, bioclastic, and oolitic calcarenites with calcisiltite matrix (microfacies 2, 3, and 7); the pelletoidal, bioclastic calcarenite with clear calcite cement (microfacies 4, 5) and the pure quartz sandstone (microfacies 8), the maximum energy is represented by the oolitic calcarenite with clear calcite cement (microfacies 6). Therefore, the two sequences show an upward increase of energy to a peak followed by a decrease. Further discussion of environmental conditions will be given later on.

DESCRIPTION OF SECTIONS

The environmental evolution of the four investigated sections is illustrated by the variation curves of all measured parameters, of the percentage of oolites (the degree of oolitization), and of the percentage of broken oolites with respect to complete oolites (the degree of transportation). The composition of oolite cores expressed in the percent of pellets, crinoid and bryozoan debris is shown in the fourth column (figs. 12 through 16). On the relative bathymetric curve the " main trend curve " is superimposed as a dashed line to show the general evolution of sedimentation. Although only closely spaced vertical samples are studied in each section, the lateral distribution of microfacies may be inferred, provided no major breaks in the sequence are present, according to Walther's Law, which states that " the horizontal migration of the facies is responsible for the differences in the rocks superposed vertically in a given section " (1894). Since the behavior of parameters in autochthonous and allochthonous oolitic calcarenites with clear calcite cement and in all the microfacies has already been discussed in some detail, attention here is directed only to the most characteristic features of each section.

Ste. Genevieve section

This is the type section of the Ste. Genevieve Limestone corresponding to Short's section 1 (Short, 1962) and shows only microfacies 6 (in particular the allochthonous type), 4 and 2.

The Ste. Genevieve section (fig. 12) is characterized by a marked parallelism between the clasticity curves of complete oolites, broken oolites, pellets, and crinoid debris. The frequencies of pellets, crinoid and bryozoan debris are parallel to each

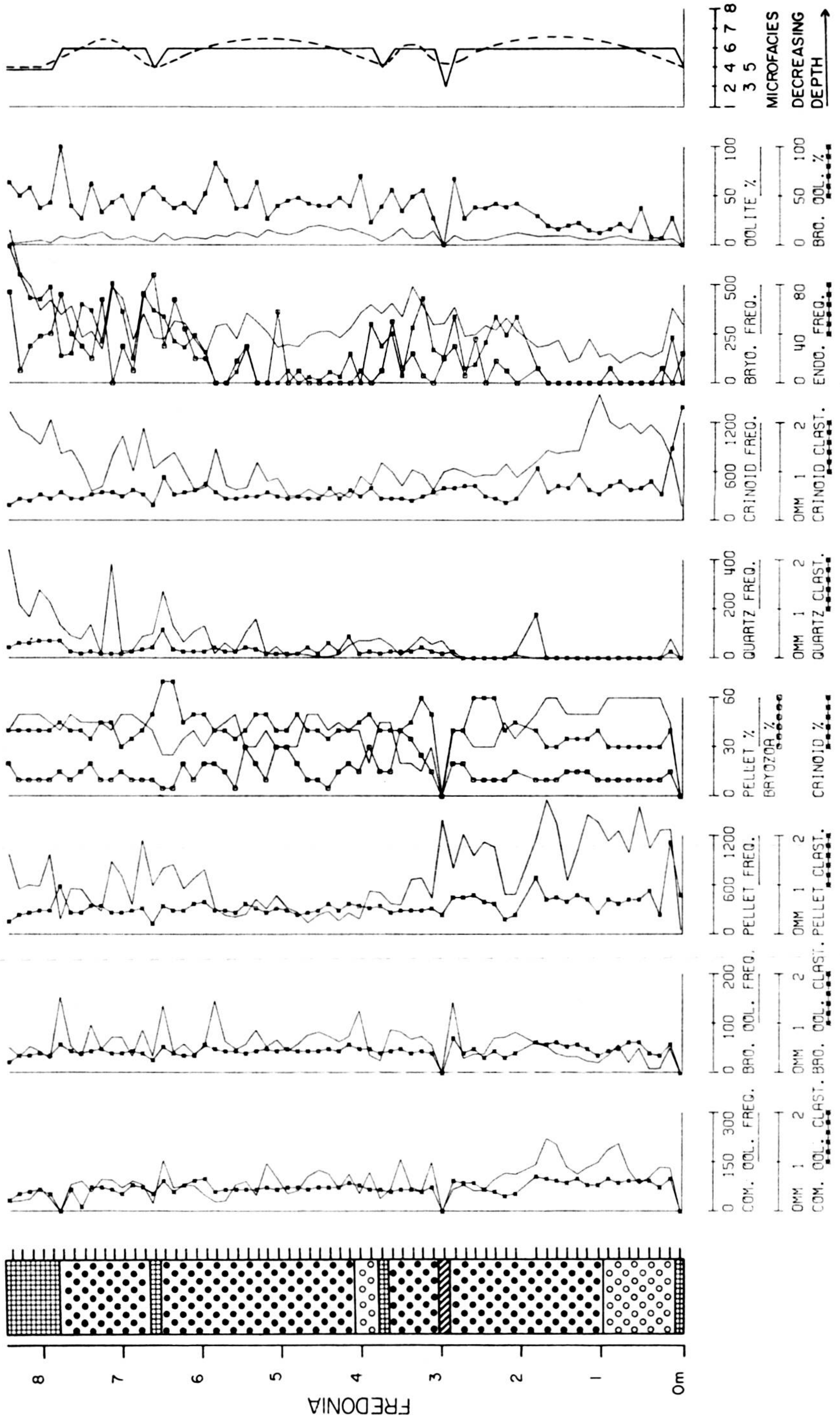

FIG. 12. — Variation curves, Ste. Genevieve section.

other and opposed to the oolite percentage. The clasticity and frequency curves of each component are unrelated. The behavior of all the parameters indicates a typical allochthonous oolitic environment. Furthermore, the percentage of broken oolites shows a linear increase upwards and the bryozoan debris frequency increases whereas the frequencies of pellets and crinoid debris decrease, indicating disintegration of the delicate bryozoan fronds with increasing transportation. Oolite core composition fluctuates from 2 meters upwards suggesting the mixing of oolites of different origin during transportation. From this point the quartz clasticity and frequency increases upwards, and microfacies 4 at the top is arenaceous.

In the autochthonous oolitic zone at the bottom (0 to 1 m) the clasticities of oolites are independent of those of the pellets and crinoid debris, the composition of oolite cores is stable and dominated by pellets, oolite frequency increases whereas the broken oolite percentage decreases.

This section shows a lower portion from 0 to 4 m consisting of 2 cycles, a long and a short. The longer consists of microfacies 4 overlain by autochthonous and followed by allochthonous oolitic calcarenites. This pattern is again repeated in the upper part (4 to 8 m) ending in microfacies 4. The main trend curve reflects a general shallow water environment with only slight fluctuations to relatively deeper conditions.

Anna section

The lower part of the Anna section is characterized by a predominance of allochthonous oolitic conditions as in the Ste. Genevieve section (fig. 13, 0 to 8 m). It begins with a terminal part of cycle consisting of oolitic calcarenite succeeded by three cycles often changing from the deepest environment to shallow oolitic conditions. These cycles, though different in amplitude, correspond to the two long and two short cycles of Ste. Genevieve section. Such oscillations in the bathymetric curve seem to suggest a possible stratigraphic correlation between these sections. This assumption is justified because both sections are temporal equivalents (fig. 2).

The Anna section might be considered an example of formation of oolites in an autochthonous environment, and of distribution of these oolites in allochthonous environment and in microfacies 7.

The oolitic zone between 0.5 to 2.5 m illustrates alternating autochthonous and allochthonous conditions, clearly shown by the peaks of broken oolite percentage corresponding to allochthonous zones and by the direct relationship between the clasticities of oolites, pellets and crinoid debris due to sorting action during transportation.

The next succeeding oolitic zone (3.25 to 5.75 m) is an example of generation of oolites in autochthonous environment, followed by their distribution into both allochthonous environment and microfacies 7. The effects of transportation has resulted in a linear increase in the broken oolite percentage.

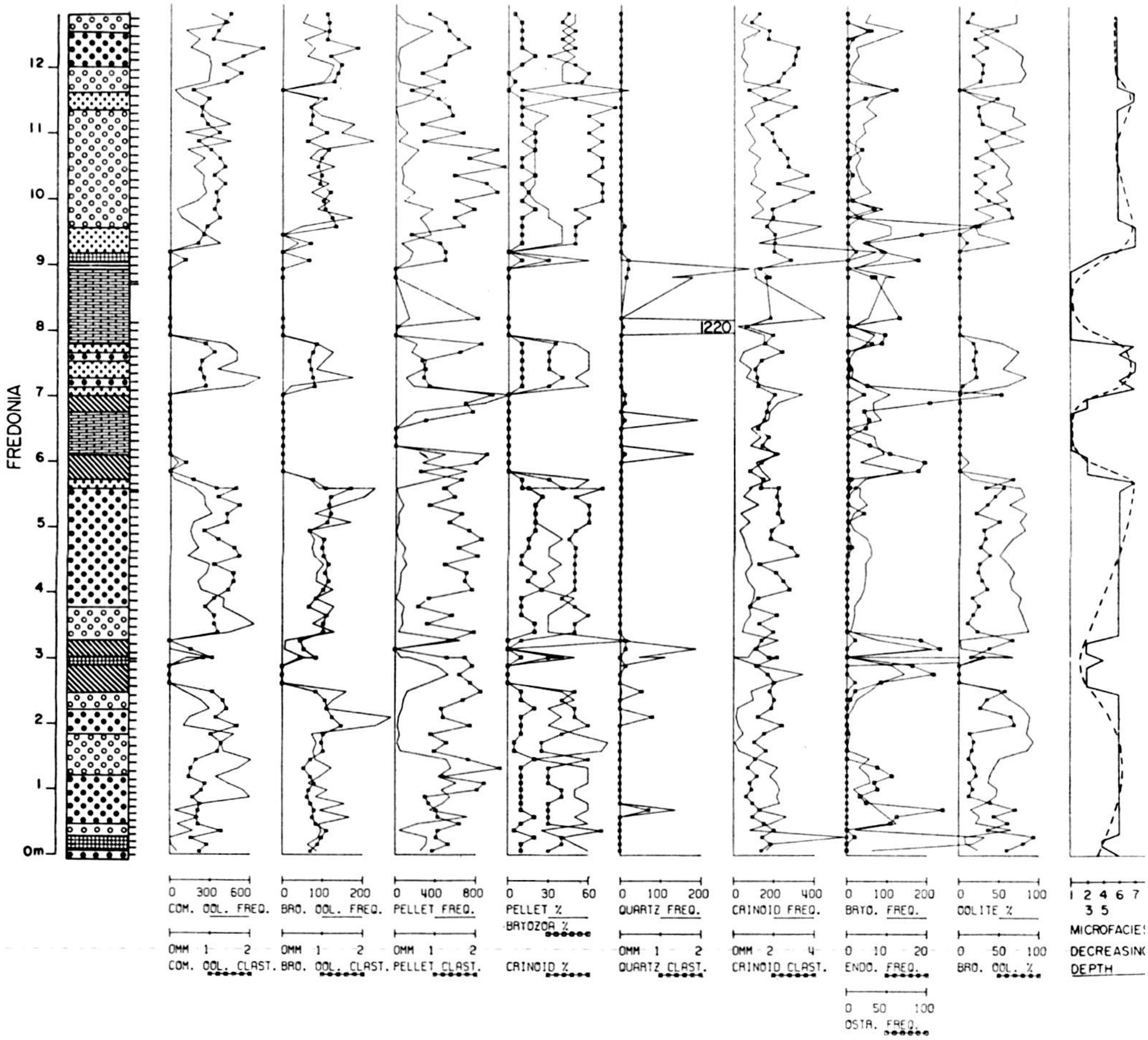

FIG. 13. — Variation curves, Anna section.

A complete cycle, between 6 and 8 m, from microfacies 1 to 7 and back to 1, is expressed by a general decline of all components, except detrital quartz, in the deeper water conditions. Furthermore, the peak of the cycle consists of alternation of allochthonous microfacies 6 and 7 in which the oolites are transported.

Above 8 m, the sequence evolves from microfacies 1 into a biocalcarenite, first with calcisiltite matrix (microfacies 3) then with clear calcite cement (microfacies 4) and eventually into microfacies 7 and 6. Oolitization of the bioclasts results in the linear decrease of crinoid and bryozoan debris, and a linear increase in the crinoid debris component of the cores. As the agitation can only lift grains smaller than or equal to the maximum oolite clasticity, pellets larger than the maximum oolite clasticity are left behind, as reflected in the high clasticities of pellets. Predominance of pellet cores in microfacies 7, intercalated between these two autochthonous zones, must be due to mixing of oolitic sediments from different sources.

The main bathymetric trend curve shows essentially shallow water conditions from 0 to 5 m, whereas upwards, oscillations range from microfacies 1 to 7.

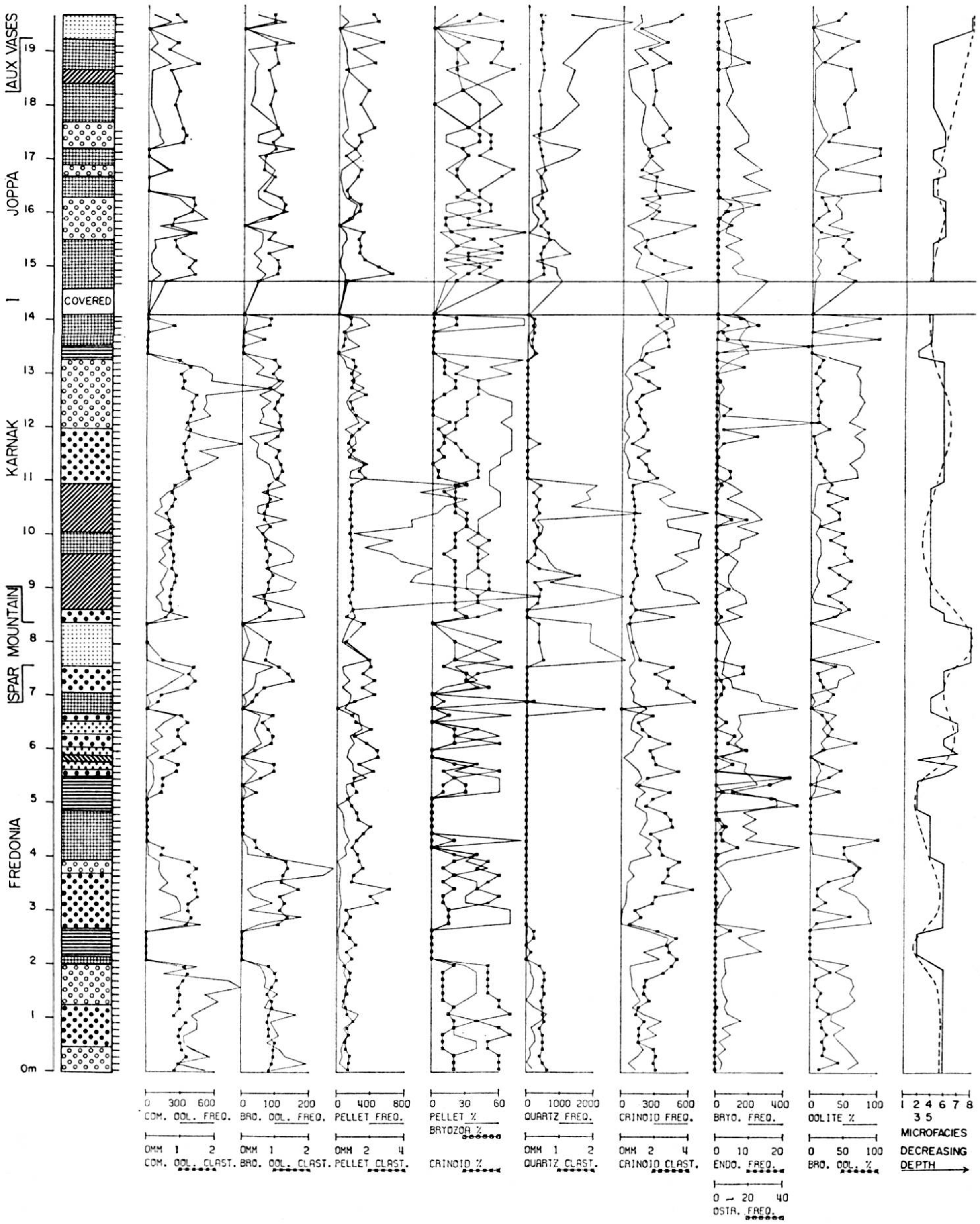

FIG. 14. — Variation curves, Dongola section.

Dongola section

The lower part of this section (fig. 14, Fredonia) is characterized by the predominance of microfacies 6 in four distinct zones with intercalated abrupt changes to microfacies 2, 3, and 4. In these oolitic zones, the parameter variations behave typically as in autochthonous and allochthonous environments. The lowermost zone (0 to 2 m) is characterized by the presence of medium-grained detrital quartz and the absence of ostracodes and *Endothyra.* The core composition is stable in the autochthonous zones, but fluctuations in the allochthonous zone indicate mixing of oolites of different origin. The next oolitic zone (2.75 to 4 m) is essentially allochthonous with a small autochthonous zone at the top. Mixing of oolitic sediments of different origin is again shown by fluctuations in the core composition. The third zone (5.5 to 6.5 m) is an intermixing of allochthonous oolitic calcarenite with clear calcite cement (microfacies 6) and oolitic calcarenite with calcisiltite matrix (microfacies 7), as clearly evidenced by the rapid fluctuations of core composition and higher broken oolite percentages. The last oolitic zone (7.0 to 7.5 m) is entirely allochthonous and grades to pure quartz sandstone (Spar Mountain) in which the oolite core composition is random and the broken oolite percentage reaches the maximum (100%). This is succeeded by another allochthonous zone (8.5 to 8.75 m), indicating transitions between microfacies 6 and 8.

In the nonoolitic zones, above 9 m and until the top of the section, particularly in microfacies 4 and 5, the clasticities of all components are close to each other and show a parallel trend, because these sediments are well-sorted and located above wave-base. The broken oolite frequency and its percentage are higher than those of complete oolites, indicating the transportation of oolites into these environments as detrital particles. In both autochthonous and allochthonous environments (11 to 13.25 m) the oolite core composition is predominantly pellets and the percentage of broken oolites is low, possibly due to a little transportation prior to final deposition. In the three zones of autochthonous oolites above 15 m, the oolite cores are predominantly crinoid debris instead of pellets.

In this section, the main bathymetric trend curve shows six major cycles, reaching every time the shallowest depth corresponding to the generation and distribution of oolites.

Cave In Rock section

Four distinct oolitic zones, as in the Dongola section (Fredonia), occur below the arenaceous calcisiltite, equivalent of Spar Mountain between 0 to 7 m of the Cave In Rock section (fig. 15, Fredonia). This indicates a possible stratigraphic correlation of these sections, which is justified because they are temporal equivalents (fig. 2).

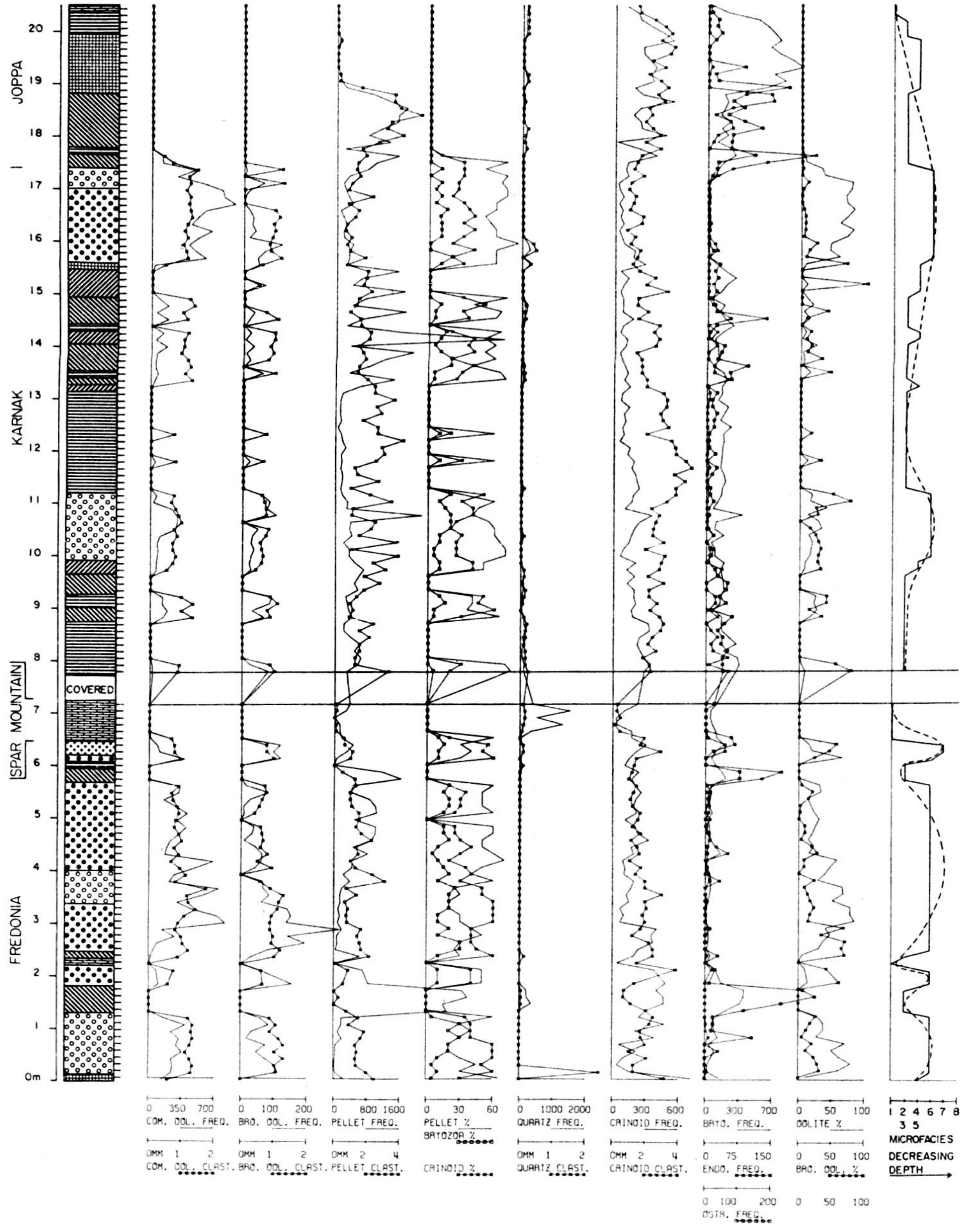

FIG. 15. — Variation curves, Cave In Rock section.

The middle part of this section (8 to 20 m) consists essentially of pelletoidal and bioclastic calcarenites with transitional terms and only two oolitic zones. In the nonoolitic zones the broken oolites are more abundant than complete oolites, suggesting an appreciable deposition of oolites transported as detrital particles. The frequencies of pellets, crinoid and bryozoan debris abruptly decrease in the oolitic zones, as in the previous sections, due to the effect of the oolitization process. In both autochthonous and allochthonous zones the oolite core composition is stable and dominated by pellets, showing that even in the case of allochthonous environment the transportation was small (low percentage of broken oolites) and little mixing occurred.

Between 20.5 to 30.5 m (fig. 16), a complete cycle from calcisiltite to oolitic calcarenite with calcisiltite matrix and back to calcisiltite (microfacies 1-7-1) shows bioclastic microfacies gradational to pelletoidal ones. As in other parts of this section,

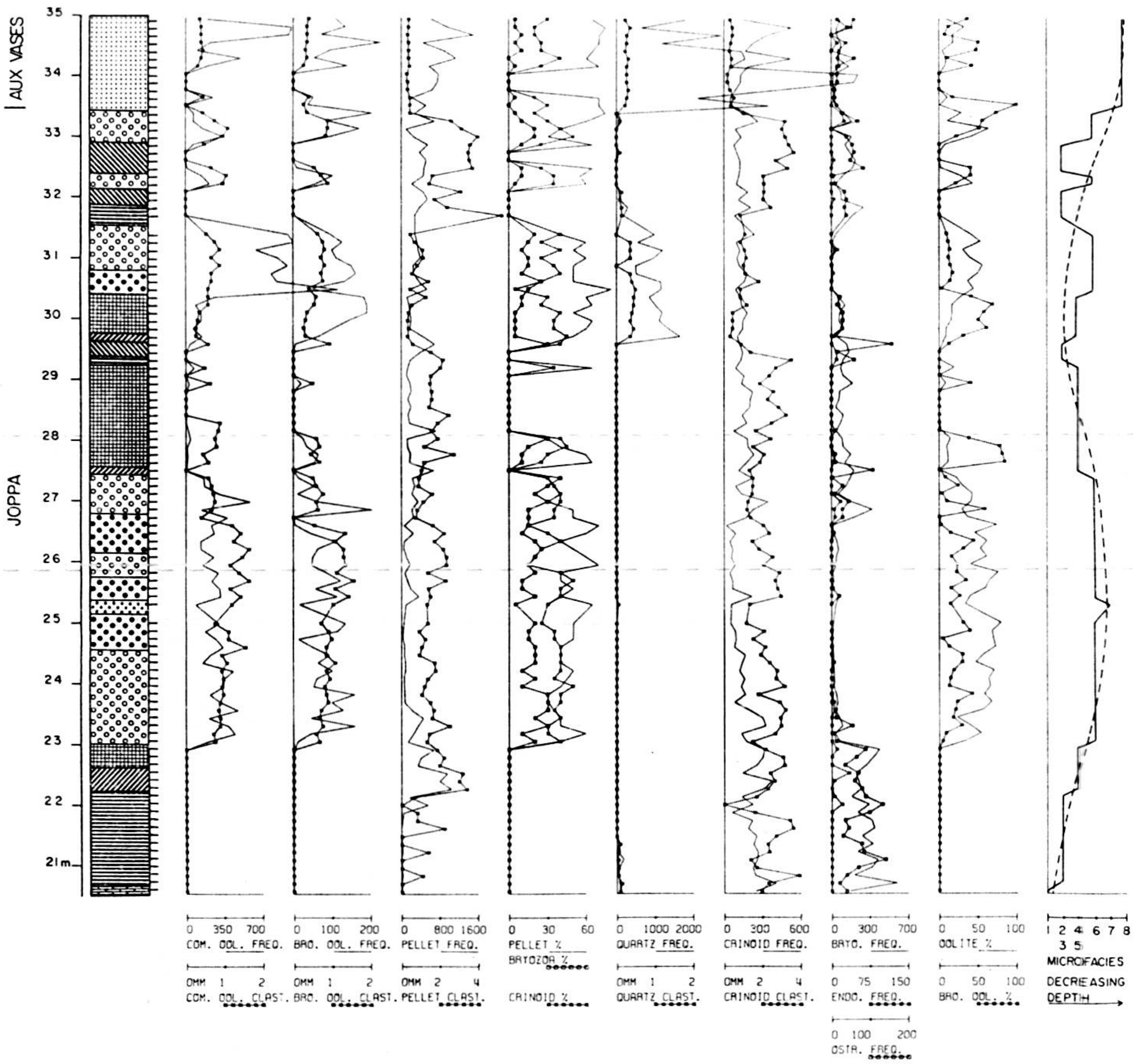

FIG. 16. — Variation curves, Cave In Rock section (Cont.).

the frequencies of nonoolitic grains decrease near the oolitic zones due to the fact that part of these grains are oolitized. The peak of the cycle (23 to 27.5 m) shows autochthonous and allochthonous oolites and their distribution in microfacies 7. Changes in the composition of supply and mixing of oolitic sediments of different origin during transportation is reflected in the oscillation of the core composition. Higher up in the section, the elevated percentage of broken oolites in the autochthonous oolitic calcarenites (33 m) might be due to local turbulence, swirling action or to transition to pure quartz sandstone.

The main bathymetric trend indicates predominantly shallow water conditions in the lower part of the section (0 to 7 m), while the middle part (8 to 20 m) is characterized successively by a short oscillation and a long oscillation with amplitude ranging from deeper to shallow conditions. Between 20.5 to 30.5 m, a complete cycle from the deepest to the shallowest environment occurs. The final phases of sedimentation represent a transition from an oolitic environment to a deltaic situation.

GENERAL ENVIRONMENTAL INTERPRETATION

The general horizontal environmental reconstruction of the Ste. Genevieve Limestone (fig. 17) is a synthesis of all the petrographic, statistical, and stratigraphic data combined with the concept of environments of autochthonous and allochthonous oolitic calcarenites. This model ranges from subtidal to intertidal and consists of a seaward slope, discontinuous oolitic bars and shoals, a lagoon and finally a delta or estuary. These environments are expressed by six microfacies subdivisions. The general depth decreases from microfacies 1 to 8, while the energy increases from microfacies 1, reaches its maximum in microfacies 6, and decreases again from microfacies 6 to 8.

The first subdivision consists of calcilutite and calcisiltite with scattered organic debris (microfacies 1). It corresponds to relatively quiet conditions below wave base, at the lower part of the slope with poor or limited circulation of water. The faunal assemblage consists of moderate amounts of crinoid and bryozoan debris, ostracodes, and rare *Endothyra*, and is associated with a limited number of transported oolites and fine-grained detrital quartz.

The second subdivision is represented by pelletoidal and bioclastic calcarenites with calcisiltite matrix (microfacies 2 and 3). These deposits are poorly-sorted and indicate moderately agitated conditions corresponding to wave base level and contain abundant crinoid and bryozoan debris, ostracodes, *Endothyra*, and small amounts of angular to subangular, silt-size detrital quartz and transported oolites.

As depth decreases, the second division grades into the third subdivision (microfacies 4 and 5). This group of pelletoidal and bioclastic calcarenites is characterized by a clear calcite cement, which reflects the agitation conditions above wave base. Consequently, the sediments become well-sorted, and the fauna predominantly consists of crinoid and bryozoan debris, while the ostracodes and *Endothyra* have been eliminated by winnowing, and concentrated in the deeper microfacies. Relatively more transported oolites occur in this subdivision because it is adjacent to the oolitic bars or shoals where oolites are generated as the ascending cold currents reach shallower waters.

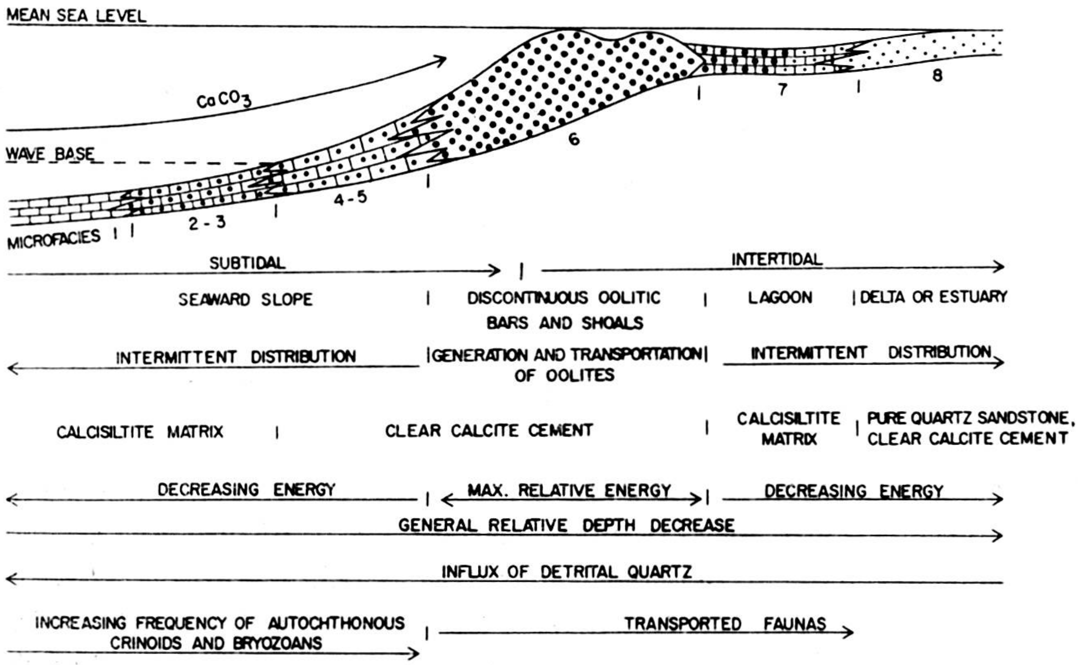

FIG. 17. — General horizontal interpretation of microfacies relationships.

The fourth major subdivision consists of oolitic calcarenites with clear calcite cement (microfacies 6). Autochthonous oolitic calcarenites indicate the highest energy and shallowest water conditions along discontinuous bars and shoals in the intertidal level, where the water was warmer and supersaturated with $CaCO_3$. The supply of nuclei was from microfacies 4 and 5. Bryozoan debris were winnowed out of this high energy conditions, with the result that the oolite core composition is predominantly pellets and crinoid debris rather than bryozoan debris. The oolites formed in this environment are transported along marginal channels and on both sides of the outer platform resulting in allochthonous oolitic calcarenites grading into the next subdivision (microfacies 7).

The fifth subdivision consists of oolitic-pelletoidal calcarenite with calcisiltite matrix (microfacies 7). It represents intertidal lagoonal conditions in the back of bars and in the marginal channels surrounding microfacies 6. It contains abundant pellets, allochthonous oolites, and crinoid and bryozoan debris. The calcisiltite matrix indicates a relatively lower energy.

The sixth subdivision is a pure quartz sandstone with clear calcite cement (microfacies 8). It interfingers with microfacies 7 and indicates deltaic or estuarine conditions.

In the channels between oolitic bars, microfacies 4 and 5 grade through microfacies 7 into microfacies 8. Because of this transition the microfacies 4 and 5 become extremely arenaceous in certain parts of the investigated sections.

The ancient oolitic environments in the Ste. Genevieve Limestone bear many similarities with Recent oolitic environments of the Great Bahama Bank. The oolitic facies in the Bahama Bank occur along the barrier rim with coralgal facies on the seaward slope, and pellet mud lagoonal facies in the back of the barrier rim. Appreciable transportation of oolites was observed to occur only from the barrier rim into the pellet mud lagoonal facies (PURDY, 1963).

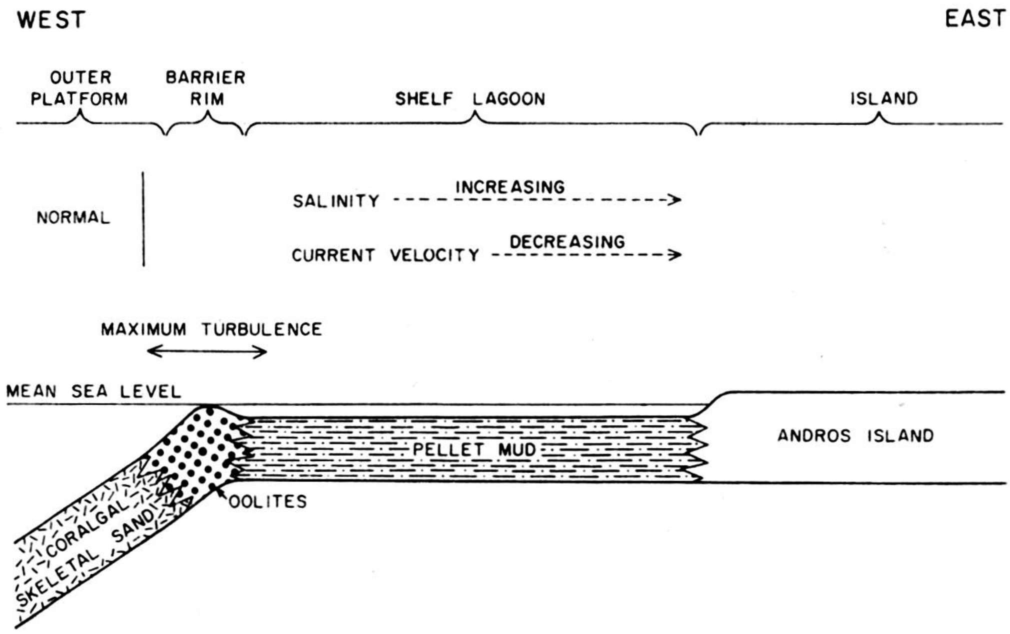

FIG. 18. — Simplified partial model of Great Bahama Bank (modified after E. G. Purdy, 1963).

In the Ste. Genevieve Limestone, the autochthonous and allochthonous oolitic microfacies 6 occurs in discontinuous bars and shoals along the outer rim of a platform. Microfacies 1 to 5, on the seaward slope, correspond to the coralgal facies of the Bahama Bank, and the oolitic-pelletoidal calcarenite with calcisiltite matrix (microfacies 7) in the channels surrounding microfacies 6 correspond to the pellet mud facies of the Bahama Bank. However, in the Ste. Genevieve Limestone microfacies 7 grades into a deltaic or estuarine pure quartz sandstone (microfacies 8). Furthermore, the allochthonous oolites are not only transported into the shelf-lagoonal microfacies 7 as in the Bahama Bank and in the marginal channels but also occur from the shallowest to the deepest microfacies (8 to 1), though their frequency strongly decreases in both cases, in particular in the deepest water conditions (microfacies 1). Such a mechanism of distribution of transported oolites and detrital quartz in all the seaward microfacies seems to result from a system of alternating tidal currents which reached the lagoonal area and also contributed to drain the influx of freshwater from the deltaic area. This situation does not occur in the case of the Bahama Bank (fig. 18) because the pellet mud lagoon appears more protected and Andros Island does not act as a source area in any respect.

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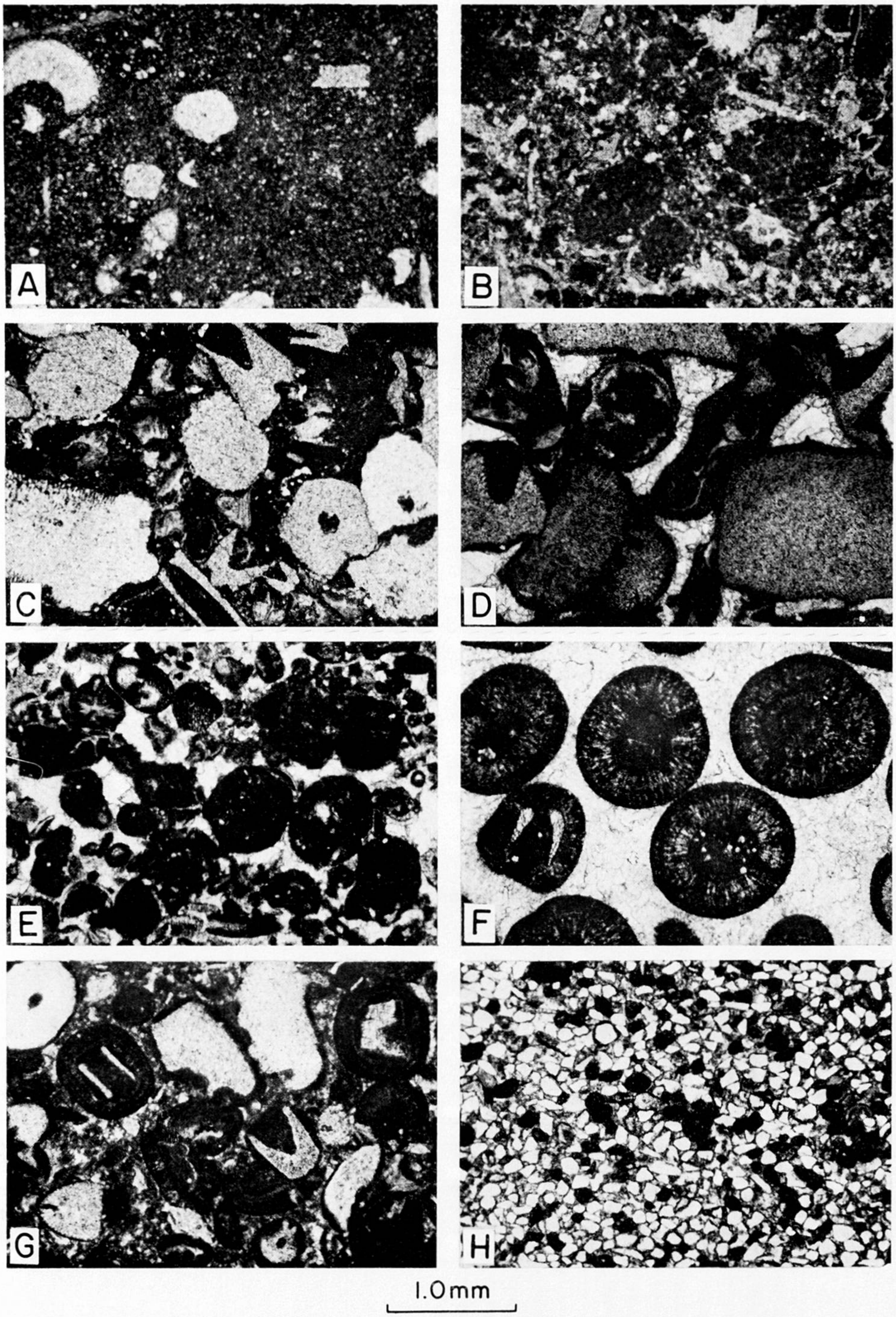
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PLATE 1

A. Microfacies 1. Calcisiltite with scattered debris of crinoids, bryozoans. Anna section. Nicols not crossed.

B. Microfacies 2. Grain-supported pelletoidal calcarenite with calcisiltite matrix. Matrix, rather coarse and bioclastic. Note poorly-sorted, angular to subangular pellets (lithic), debris of crinoids and bryozoans, and ostracodes. Anna section. Nicols not crossed.

C. Microfacies 3. Grain-supported biocalcarenite with calcisiltite matrix. Note poorly-sorted, pressure-welded, sand-size crinoid and bryozoan debris whose canals and zooecia are filled with calcisiltite matrix. Cave In Rock. Nicols not crossed.

D. Microfacies 4. Grain-supported biocalcarenite with clear calcite cement. The well-sorted, coarse sand-size crinoid columnals and bryozoan debris are filled with microcrystalline calcite and have similar envelopes. Pressure-welding contacts. Cavity filling sparry calcite cement. Dongola section. Nicols not crossed.

E. Microfacies 5. Grain-supported pelletoidal biocalcarenite with clear calcite cement. Well-sorted, rounded, lithic pellets with debris of crinoids and bryozoans. Note irregular mosaic of sparry calcite cement. Cave In Rock. Nicols not crossed.

F. Microfacies 6. Grain-supported oolitic calcarenite with clear calcite cement. Well-sorted, coarse sand-size complete oolites show numerous accretionary envelopes with fibro-radiated structure. Cores are lithic pellets similar to those of the previous microfacies, and crinoid debris. Note typical cavity filling sparry calcite. Cave In Rock. Nicols not crossed.

G. Microfacies 7. Grain-supported oolitic-pelletoidal calcarenite with calcisiltite matrix. Poorly-sorted, transported oolites, lithic pellets, crinoid and bryozoan debris. Note abundance of broken oolites. Cave In Rock. Nicols not crossed.

H. Microfacies 8. Pure quartz sandstone with clear calcite cement. Moderately-sorted, subangular to subrounded grains of quartz, pellets and crinoid debris (0.27 to 0.36 mm). A few small broken oolites. Sparry calcite stained by organic matter and iron oxides. Cave In Rock. Nicols not crossed.