Petrography of Mississippian (Borden) Crinoidal Limestones at Stobo, Indiana

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PETROGRAPHY OF MISSISSIPPIAN (BORDEN) CRINOIDAL LIMESTONES AT STOBO, INDIANA[1,2]

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ABSTRACT

The basal siltstones of the Edwardsville Formation of the Borden Group in southern Indiana contain almost tabular bodies (2 miles long by 60 feet thick) of crinoidal limestones showing abrupt lateral contacts with the contemporaneous and surrounding siltstones. Microscopic investigation of these bodies, which are thought to have developed in shallow depressions of the sea bottom, shows that they consist essentially of numerous alternations of coarse bioaccumulated crinoidal limestones and partially dolomitized calcilutites almost entirely devoid of crinoids. The coarse beds, deposited in place, were protected from any clastic influx by the screening effect of crinoidal growth, whereas the calcilutites, interpreted as accumulations of algal dust generated by phytoplankton corresponded to definite encroachments of the surrounding clastics.

The temporary proliferation of the phytoplankton could result from the increased CO_2 concentration produced by the metabolism of the crinoids in combination with reduced circulation created by their growth. The algal precipitation of calcium carbonate would then make the environment lethal to the crinoids, and the related disappearance of the screening effect would allow an encroachment of the clastics, restricting the calcilutite area available for the next cycle of crinoidal growth. Repetition of this mechanism would lead to the gradual disappearance of the crinoids and to the burial of the carbonate body in the clastic sediments.

INTRODUCTION

Mississippian crinoidal limestones in Indiana were studied by P. B. Stockdale (1931a, 1931b) as part of a general study of the Borden Group. Stockdale proposed the name "Borden" and applied it to rocks in southern Indiana lying between the Rockford Limestone (Kinderhookian), or where the latter is absent, the interval between the New Albany Shale and the Harrodsburg Limestone (Warsaw). This group correlates approximately with Burlington-Keokuk rocks farther west, in the Mississippi Valley.

The Borden Group is divided into five formations. The New Providence, Locust Point and Carwood formations, comprising the lower part of the Borden Group, are a thick sequence (300–500′) of siltstones and sandstones containing local beds of crinoidal limestones. The upper two formations, the Floyds Knob and Edwardsville, have a combined thickness of 40 to 200 feet and possess striking lateral changes in lithology. In the area studied by the writers, the name Cisco Branch facies was used by Stockdale to include several lithologies present at the stratigraphic position of the Floyds Knob Formation that are too local to warrant individual names. These lithologies are arenaceous shale, calcareous shale, gray crinoidal limestone, sandstone, limestone conglomerate, oolitic limestone, ferruginous limestone, and siliceous limestone.

In this same area rocks of the Edwardsville Formation belong to Stockdale's Allens Creek facies. In it, developments of crinoidal limestones are abundant but are restricted to the lower 65 feet of the formation. They have been called "bioherms" by Stockdale because they do indeed fit the original definition of the word "bioherm" (E. R. Cumings, 1930, p. 207), which is "any dome-like, mound-like, lense-like or otherwise circumscribed mass, built exclusively or mainly by sedentary organisms such as corals, stromatoporoids, algae, brachiopods, molluscs, crinoids, etc., and enclosed in normal rock of different lithologic character." However, the term bioherm will not be used in this paper because the writers believe that the term should be restricted to any dome-like, mound-like, lense-like or otherwise circumscribed mass, built exclusively or mainly by *framework-building* organisms such as corals, stromatoporoids, and algae,

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[2] Presented at the AAPG-SEPM Annual Meeting, Denver, Colorado, April 1961.

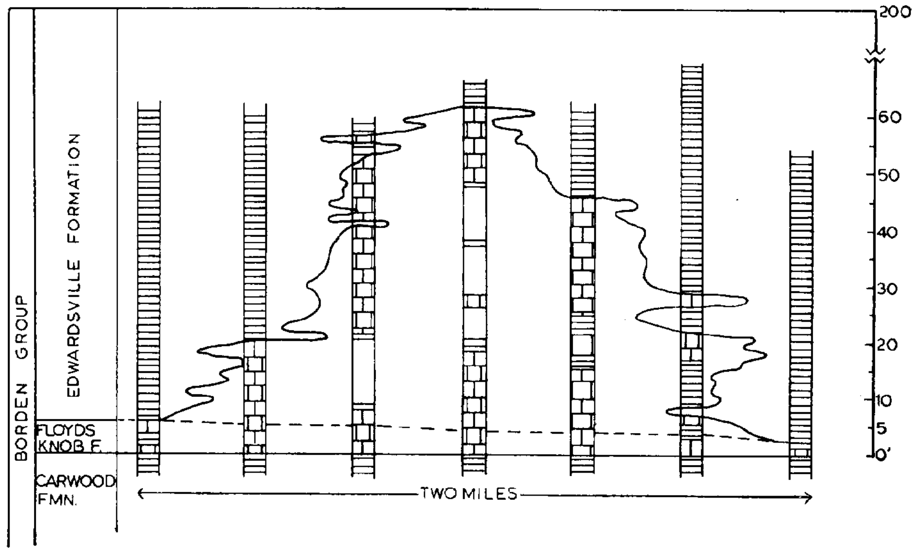


FIG. 1.—Cross-section of Allens Creek "bioherm" (after Stockdale, 1931).

and enclosed in normal rock of different lithologic character.

Seven mound-like masses of crinoidal limestones are present in the Floyds Knob and Edwardsville formations of Monroe, Brown, and Morgan counties. Stockdale studied one of these which is exposed along Allens Creek (fig. 1). The mass of crinoidal limestone is two miles in diameter and 65 feet in height, with its greatest thickness being approximately at the center. The lateral contacts with the contemporaneous siltstones are strikingly abrupt, but tongues and lenses of the latter are found interbedded with crinoidal limestone throughout the body. Stockdale's interpretation of the origin and development of this mass of limestone will be discussed later. The present paper deals with the detailed petrography and interpretation of another typical and better exposed example of these crinoidal masses located in sec. 4, T.8N., R.1E., and sec. 33, T.9N., R.1E., in Monroe County, Indiana, about 6 miles east of Bloomington. This area is included in the Unionville 7½ minute U.S.G.S. quadrangle topographic map. The name "Stobo" is from an old post office in the SW¼ NW¼ NE¼ sec. 4, T.8N., R.1E., now used as a dwelling (fig. 2).

The limestone beds forming the Stobo crinoidal mass are nearly flat, typically display sharp contacts, and interfinger with the surrounding siltstones. The actual dimen-

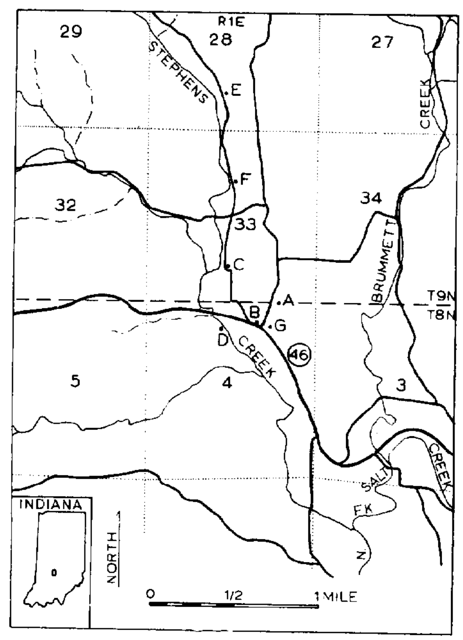


FIG. 2.—Location map.

sions of the body (2 miles long by 60 feet thick) show it to be tabular; the horizontal extent is 200 times the vertical dimension. In cross-section (fig. 3) the crinoidal mass appears asymmetrical but this is an illusion resulting mainly from the tangential location of the investigated sections. Seven of them were measured and sampled at intervals of approximately 11 inches. With the exception of section A, all begin at the top of the Carwood Formation and extend upward. Four sections extend through the crinoidal body into the overlying siltstones but section F is entirely in the siltstones and is located outside the crinoidal mass. The microscopic analysis included 235 non-oriented thin sections which were divided into seven microfacies on the basis of the statistical study of organic and inorganic parameters. X-ray diffraction patterns were obtained on selected samples of each microfacies.

DESCRIPTION OF MICROFACIES

The seven different microfacies which make up the Stobo crinoidal mass and its surrounding deposits are described below.

Microfacies 1 is a bioaccumulated crinoidal limestone (fig. 4, A) in which the fragments consist mainly of complete columnals and calyx plates, only rarely broken. None of these components shows any sign of abrasion. It is recognized that blastoid fragments may be present, but no attempt was made to distinguish them from crinoids. Associated with the latter are fragments of bryozoa, fish plates, occasional sponge spicules, brachiopod valves, and rare ostracod tests. Fish plates (fig. 4, B) appear as subrectangular to lenticular, calcified fragments, displaying a central line, on both sides of which extend superposed layers with wavy boundaries. These plates are similar to those described by L. Cayeux (1916, p. 495–499, pl. LVI, figs. 5, 6). Sponge spicules are present with smaller crinoidal fragments in some interstitial spaces; they are calcified and of monaxon type.

In most examples, the crinoid and other fragments are in reciprocal microstylolitic contact due to pressure welding. The central canals of the columnals are filled with crystalline calcite or calcilutite matrix, as are the bryozoan cells. Occasionally a complete

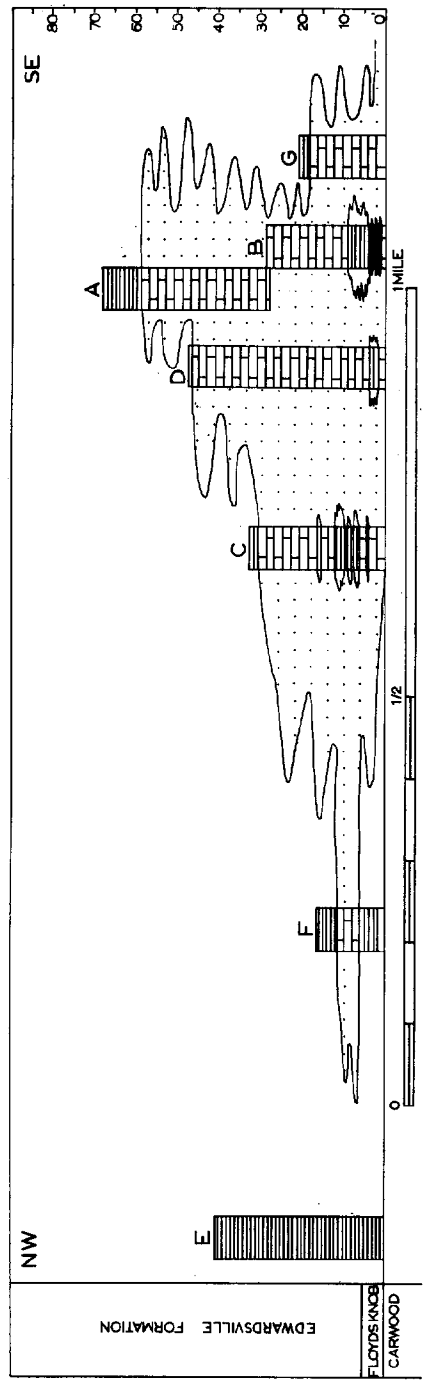
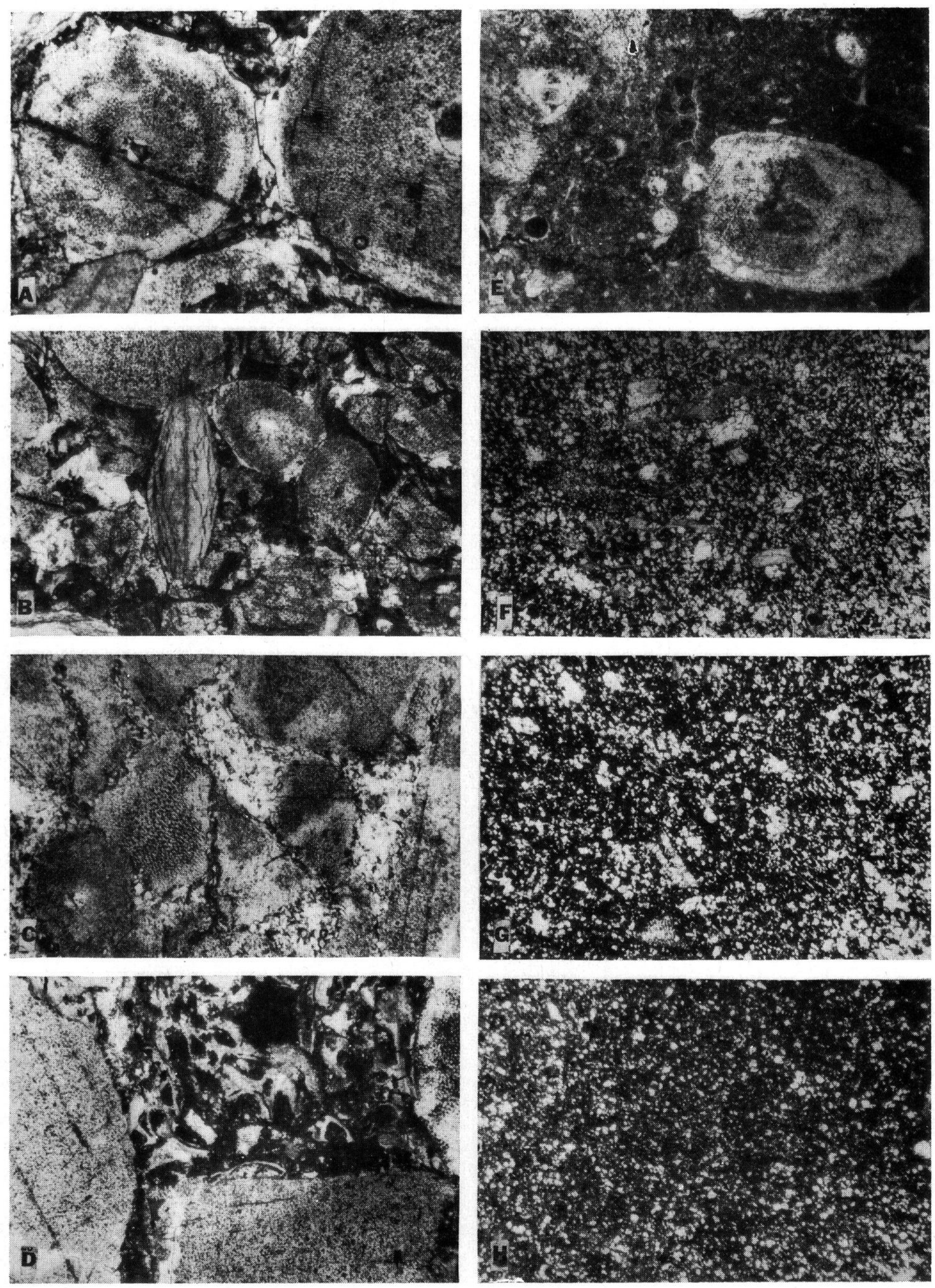


FIG. 3.—Cross-section of the crinoidal accumulation at Stobo, Indiana.


A
B
C
D
E
F
G
H

or partial ring of clear secondary calcite develops around the larger crinoidal columnals, in some cases by their peripheral replacement but always in optical continuity with them. These secondary enlargements may be transitional to the fillings of the interstitial spaces. The latter consist of much finer grained crinoidal debris (cirri, pinnules, etc.) set in a calcilutite matrix or in a well crystallized calcite cement, probably produced by biochemical precipitation. The calcilutite and the finer organic fragments usually show scattered rhombohedra produced by incipient recrystallization and dolomitization, but locally they are almost entirely recrystallized into a poorly organized calcite cement. Iron oxide pigments are common, especially where recrystallization has affected the matrix. Where this microfacies is chertified, the silicification, often with colloform structure, more frequently affects the matrix than the fragments.

Microfacies 2 is an arenaceous crinoidal calcarenite (fig. 4, C). The organic fragments are almost entirely crinoidal and bryozoan, incipiently sorted, and show traces of abrasion. Interstitial spaces are filled with fine-grained detrital quartz and iron oxide pigments with very few small organic fragments. Stylolitic contacts may be present between larger fragments, but welding of this sort is less obvious than in microfacies 1. The axial canals of the columnals may be filled either by crystalline calcite or by fine detrital quartz grains.

Microfacies 3 (fig. 4, D), an argillaceous crinoidal calcarenite, is similar to microfacies 2 in that the organic fragments are almost entirely crinoidal and bryozoan, incipiently sorted and abraded. However, the interstitial spaces are filled by argillaceous material, iron oxide pigments, fine-grained detrital quartz and locally by crystalline calcite. Much iron oxide pigment has penetrated the cellular networks of the crinoid fragments and stained then. Locally, small interstitial areas are filled with broken, fine, organic debris, including many bryozoan fragments.

Microfacies 4 (fig. 4, E) is a fine-grained calcilutite with scattered, "floating," relatively large fragments of crinoids and bryozoa, with their central canals and cavities filled with calcilutitic material. Crinoid columnals are often still attached to each other and form long segments, occasionally a foot or more in length. Most of these large segments appear not to have been disturbed after their deposition, with the exception of some local flattening produced by compaction. Sorting and abrasion are not apparent. The calcilutite often is incipiently dolomitized into small scattered rhombohedra.

Microfacies 5 (fig. 4, F) is a calcilutite, incipiently dolomitized with scattered very small rhombohedra. Minor amounts of clay minerals, detected by X-ray diffraction, are not visible microscopically because of the dark color of this microfacies. Small fragments of crinoids are irregularly scattered through the groundmass. Their peripheral recrystallization has produced irregular boundaries. Some samples contain calcified sponge spicules.

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FIG. 4.—Photomicrographs of typical microfacies. Nicols not crossed, ×16. A. Microfacies 1: bioaccumulated crinoidal limestone with large columnals displaying pressure welding or partial development of rings of secondary clear calcite, transitional to a poorly organized cement of recrystallized calcilutite and fine organic debris. B. Microfacies 1: bioaccumulated crinoidal limestone, with fish plate associated with smaller than average crinoid fragments, in a matrix of partially recrystallized calcilutite and fine organic fragments; note dominant pressure welding. C. Microfacies 2: arenaceous crinoidal calcarenite with incipiently sorted and abraded crinoid fragments, interstitial spaces filled with fine-grained detrital quartz and iron pigments. D. Microfacies 3: argillaceous crinoidal calcarenite displaying argillaceous material and fine-grained detrital quartz with high concentration of broken, fine bryozoan debris in the interstitial spaces between large crinoid fragments. E. Microfacies 4: calcilutite with scattered large crinoid fragments, associated with bryozoa and sponge spicules. The fragments appear to be floating in incipiently dolomitized calcilutite. F. Microfacies 5: calcilutite, with small crinoid fragments and sponge spicules. Groundmass generally incipiently dolomitized into randomly scattered rhombohedra. Boundaries of larger fragments are hazy as a result of peripheral recrystallization. G. Microfacies 6: siltstone with scattered crinoid fragments. Fine-grained detrital quartz and abraded small crinoid fragments are set in groundmass of clay particles. H. Microfacies 7: siltstone formed predominantly by silt-sized quartz grains and clay particles.

Microfacies 6 is a siltstone with scattered crinoid fragments (fig. 4, G). The rock is made up of extremely abundant silt-size grains of detrital quartz in a groundmass of clay particles in which there are irregularly scattered calcified or siliceous sponge spicules associated with abraded fragments of crinoids which commonly show rhombohedral cleavage along broken edges. Cavities in the fragments are filled with argillaceous material.

Microfacies 7 (fig. 4, H) is a siltstone predominantly composed of silt-size quartz grains and of clay particles. Fragmentary calcified or siliceous sponge spicules are locally present and rarely there are large brachiopod valves; crinoids and bryozoa are not present.

METHODS AND TECHNIQUES

Thin-sections were studied by the method used by Carozzi (1950, 1958), which consists essentially of the statistical measurement of size and frequency of inorganic and organic constituents. The measured values are expressed by curves of variation drawn alongside the stratigraphic column for each measured section. Curves have also been drawn to show the main trends of variation representing a generalized interpretation of the evolution of the components in a given section (Carozzi, 1961). Positions of thin sections are indicated by short lines extending from the right edge of the stratigraphic column.

ORGANIC CONSTITUENTS

Organic remains consist mainly of crinoid columnals and calyx plates, bryozoans, sponge spicules and fish plates. If present, blastoid fragments have not been distinguished from crinoid fragments. The frequency of crinoid fragments was measured with a low power petrographic or binocular microscope over an area of 900 square mm, except where the slide area was smaller, in which case an area of 450 square mm was used and the values were then doubled. Frequencies commonly ranged between 100 and 300 and exceeded 600 in only a few cases (table 1). The size of the crinoid fragments shown in the variation curves is the average of the 10 largest, usually chosen from at least 100 over an area of 900 square mm, or of five crinoid fragments over an area of 450 square mm.

The size and frequency of the crinoid fragments normally vary in a parallel way through the sequence of microfacies 1 to 7, and their variations indicate different conditions of deposition (fig. 5). In the bioaccumulated crinoidal limestone (microfacies 1), the crinoids have not been transported and display the highest values of size and frequency; this probably expresses the average size of the dissociated but unabraded crinoid fragments. The frequency remains almost the same in the arenaceous calcarenite (microfacies 2) and in the argillaceous calcarenite (microfacies 3). However, the detrital nature of these deposits is expressed by a size decrease which is greater in the arenaceous calcarenite, probably an effect of abrasion by quartz grains. Microfacies 4, a calcilutite with scattered crinoid fragments, displays fragments similar in size to those in microfacies 1, 2 and 3, but their frequency is considerably less. In microfacies 5, the last carbonate microfacies, crinoid size and frequency values are low. Lower values of crinoid size are found in the siltstone with scattered crinoid fragments (microfacies 6), and a slight increase of the frequency can be noted with respect to microfacies 5. No crinoid fragments are present in microfacies 7.

Frequency determinations of bryozoa and sponge spicules were made over 27.3 square mm. Fish plate frequencies were obtained in the same way as crinoids.

INORGANIC CONSTITUENTS

The clastic index of detrital quartz was obtained by measuring the apparent diameter of the 50 largest grains (out of at least 10,000) on each slide in which these constituents occur. Frequency determinations

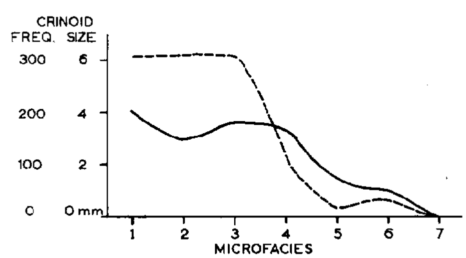

FIG. 5.—Relations between crinoid parameters and microfacies.

TABLE 1.—*Minimum, average, and maximum values of the parameters per microfacies*

Microfacies	1	2	3	4	5	6	7
Crinoid Minimum Size (mm)	0.90	1.58	2.97	1.69	0.57	0.57	—
Average Size (mm)	4.07	2.99	3.61	3.24	1.0	1.07	—
Maximum Size (mm)	9.52	5.1	4.25	5.0	5.2	2.03	—
Crinoid Minimum Frequency	55	164	255	52	0	12	—
Average Frequency	316	320	316	135	31	66	—
Maximum Frequency	1000±	621	432	426	135	170	—
Bryozoan Minimum Frequency	0	0	7	1	—	1	—
Average Frequency	18	12	22	6	—	1	—
Maximum Frequency	50	49	36	37	—	2	—
Sponge Spicule Minimum Frequency	0	0	0	0	0	0	0
Average Frequency	10	10	1	39	33	102	55
Maximum Frequency	227	52	4	213	321	285	436
Fish Plate Minimum Frequency	0	0	0	—	0	—	—
Average Frequency	1	0.2	1	—	0.32	—	—
Maximum Frequency	44	1	4	—	6	—	—
Quartz Minimum Clasticity (mm)	0.03	0.039	0.037	—	—	0.03	0.03
Average Clasticity (mm)	0.035	0.052	0.041	—	—	0.041	0.049
Maximum Clasticity (mm)	0.04	0.068	0.045	—	—	0.058	0.076

were not made because of the extremely arenaceous nature of the detrital quartz bearing rocks (microfacies 2, 3, 6, and 7), in which such measurements lose their significance.

Chert is present as nodules and as irregular zones replacing carbonates. Some of the nodules are hollow; some are almost completely filled. Replacements occur mainly in microfacies 1 and affects both matrix and fragments. The matrix is most frequently replaced and the result is a rock which is light blue in the hand specimen and orange-brown in this section under plane polarized light. Silicified fragments appear porous and chalky. Microfacies 5 may also be replaced by silica, especially where sponge spicules are abundant. Iron oxides occur primarily in the matrix of microfacies 2 and 3; no statistical study was made of them.

DESCRIPTION OF SECTIONS

Section A (figs. 6–8) is 38 feet thick and presumably is located at the highest stratigraphic occurrence of crinoidal limestone within the Stobo mass. This, the only stratigraphic section that does not start at the base of the Floyds Knob Formation, begins approximately 27 feet above the base. It shows alternating bioaccumulated crinoidal limestone (microfacies 1), calcilutite (microfacies 5), and the intermediate lithology (microfacies 4) to a height of 27 feet above

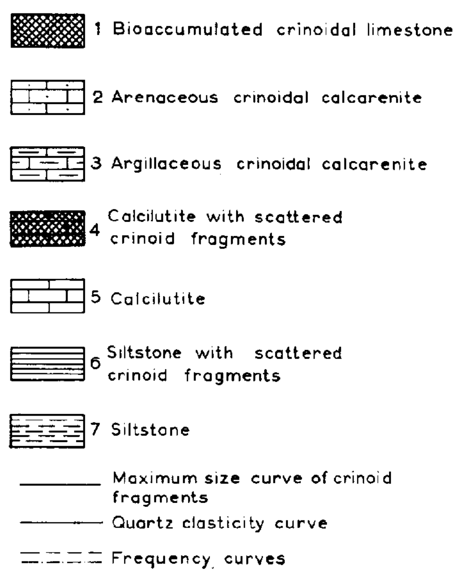

FIG. 6.—Table of symbols.

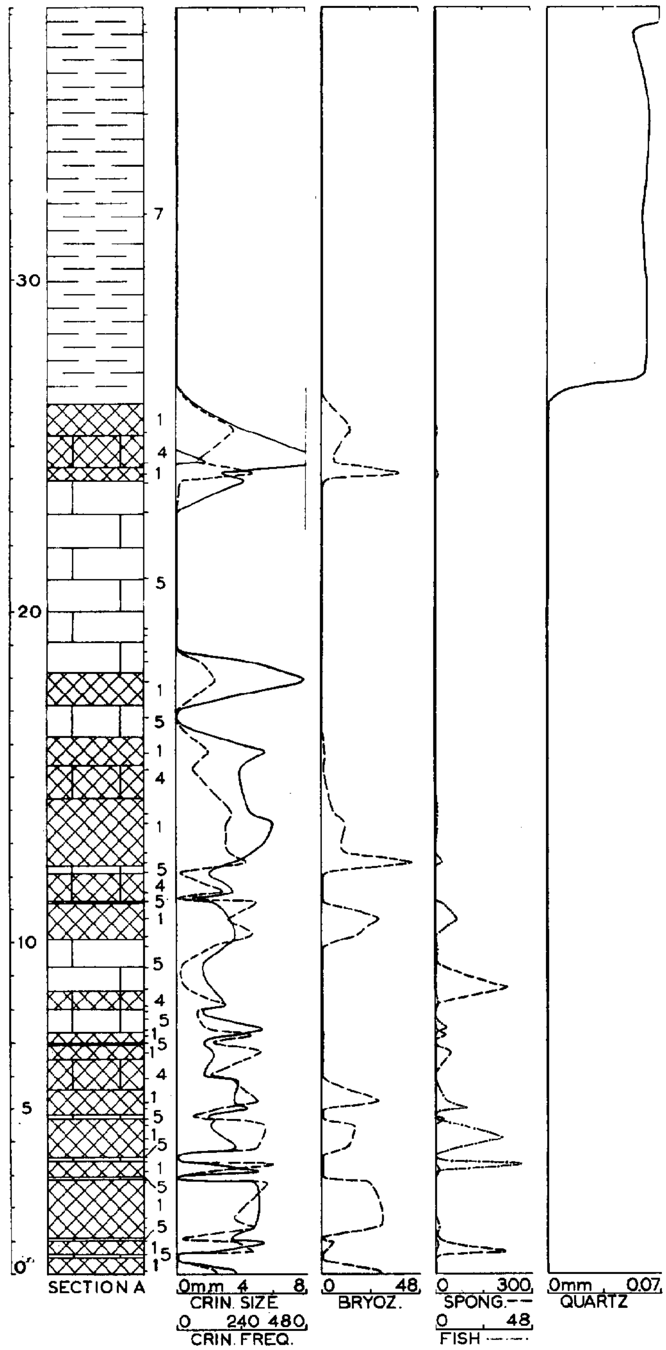

FIG. 7.—Section A; detailed curves.

which level the siltstone of microfacies 7 occurs.

There is a close correlation between the size and frequency of crinoid fragments. Both curves show peaks in microfacies 1 and 4 and low values in microfacies 5. An unusually large peak is noted at 25 feet in microfacies 4; otherwise, the relationships of size, frequency, and microfacies are normal (fig. 5). The bryozoan frequency curve is almost a duplicate of the crinoid frequency curve, with the exception that bryozoa are absent in the intervals from 6 to 10 feet, 11 to 12 feet, and 17.5 to 19 feet. Sponge spicules are irregularly distributed whereas fish plates are concentrated in microfacies 1. Detrital quartz is absent except in the overlying siltstone (microfacies 7).

The main variation trends in the different parameters (fig. 8) show that all the organic components have a tendency to decrease upward. A first zone of low size and high frequency of crinoid fragments occurs from the base upward to a height of 13 feet, also corresponds to a concentration of sponge spicules and fish plates. Above this level, high values of crinoid size are shown as two peaks separated hv low values located in the thick intervening development of microfacies 5 between 19 and 23 feet. Detrital quartz clasticity remains fairly constant with a value of 0.065 mm in the siltstone between 27 and 38 feet.

Section B (figs. 9, 10), is 28 feet high, begins at the base of the Floyds Knob Formation, and is composed predominantly of successions of microfacies 1 and 7. From the base upward to a height of 3.5 feet, fairly thin beds of microfacies 1 and 7 alternate; from 3.5 to 9 feet microfacies 7 occurs. Suitable samples of microfacies 7 were unobtainable in these zones but the arenaceous character of the rock leaves no doubt as to its calssification. Overlying this development of microfacies 7 are further alternations of microfacies 1 and 7, extending to 13 feet, followed by a thick sequence of beds of microfacies 1 extending to the top of the section.

Crinoid size and frequency vary in a parallel fashion, with peaks in microfacies 1 and zero values in microfacies 7. At 18.5 feet, corresponding to the middle of the thick upper zone of microfacies 1, there is a decrease in size with a corresponding increase in frequency. It is important to point out that because of the indigenous nature of the bioaccumulated rock, this size decrease indicates an ecological change to a type of crinoid yielding smaller fragments. The bryozoan frequency parallels that of the crinoids, showing an important increase at the top of the section; this can easily be seen on the main trend curves (fig. 10). Sponge spicules and fish plates are not very abundant and are irregularly distributed, except that the latter occur only in microfacies 1.

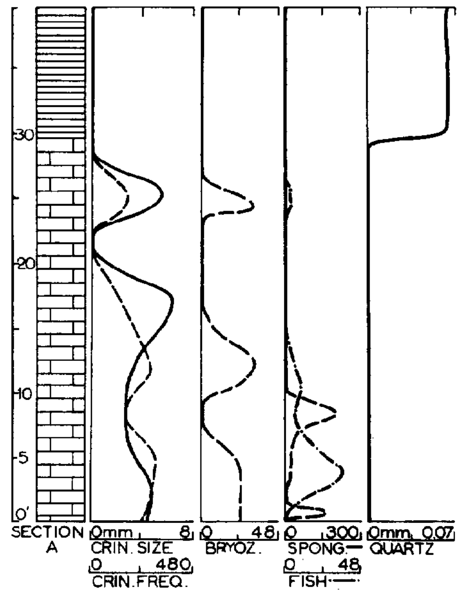

FIG. 8.—Section A; main trend curves. In all the figures showing main trend curves all the carbonate microfacies (1 to 5) have been grouped and given the standard limestone symbol.

Detrital quartz is found only in microfacies 7 and three peaks would show if samples of all zones had been obtainable. These three peaks have been reconstructed in the main trend curve.

Section C (figs. 11, 12) is 32.5 feet thick and divisible into three zones. The lowest one, extending upward to 9 feet, is principally composed of successions of microfacies 1, 6 and 7 with one bed of microfacies 3. Overlying this is a zone of microfacies 6 and 7 with a few thin beds of microfacies 3. The third zone begins at 13 feet and consists

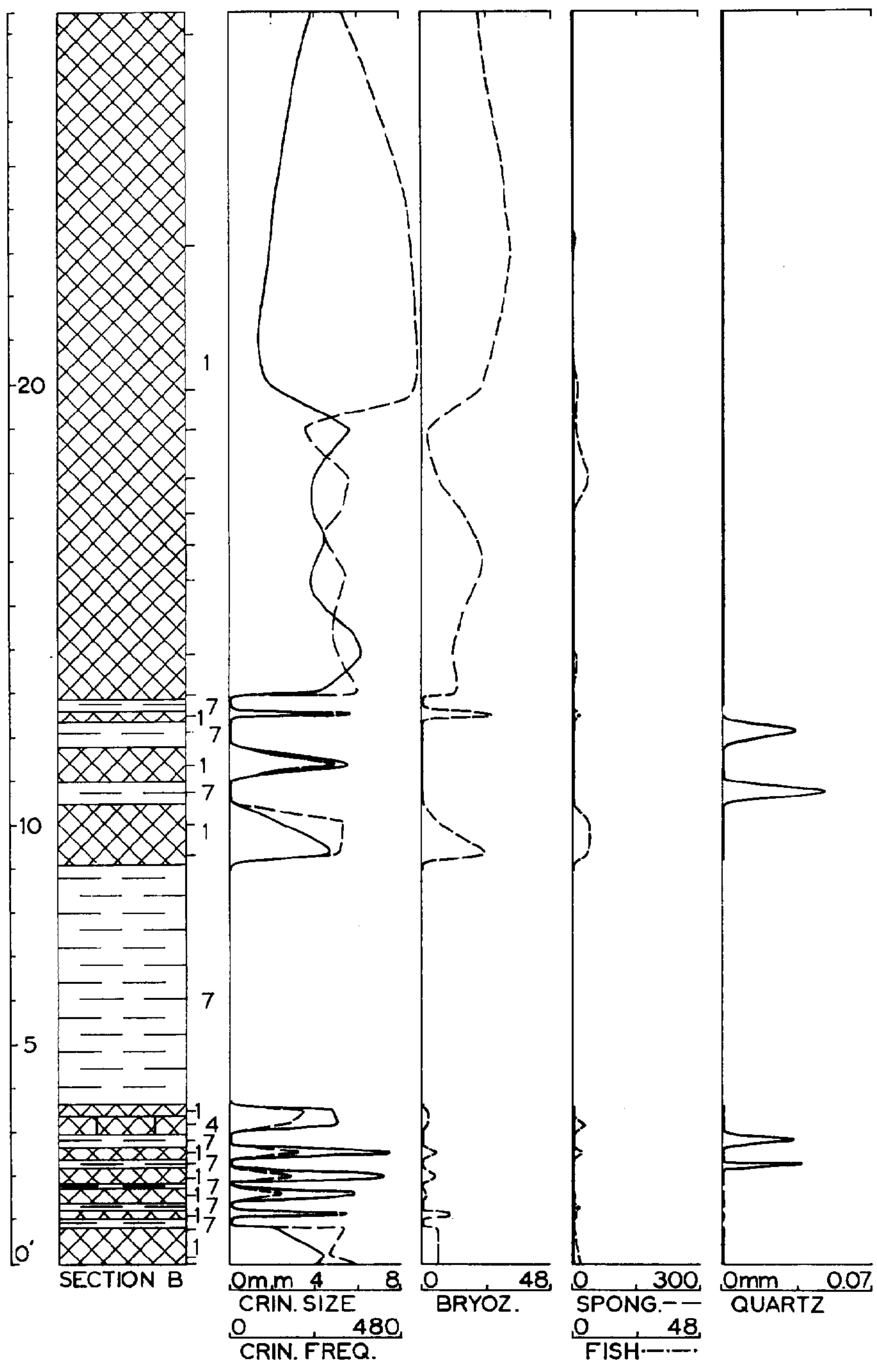

Fig. 9.—Section B; detailed curves.

mainly of microfacies 1, with beds of microfacies 5 and 7 in the lower part and beds of microfacies 2 and 7 at the top.

Again crinoid size and frequency show parallel variations with peaks in microfacies 1 and 3. The two parameters gradually decrease upward to 9 feet and then decrease rapidly. The decrease is followed upward by an increase of both curves, especially the frequency, culminating in high values throughout the thick development of microfacies 1. Bryozoan frequency is parallel with crinoid frequency, with more amplitude of variation in the uppermost zone. Sponge spicule frequency is high in the zone between 9 and 13 feet, and displays another small peak at the base of the thick development of microfacies 1. Fish plates are present in small numbers between 5 and 9 feet and in the thick zone of microfacies 1 in the top half of the section. Detrital quartz is concentrated in a zone between 6 and 18 feet, with peaks in microfacies 6 and 7.

The curves of main trend of crinoids (fig. 12) show a definite decrease in size at 13 feet and a correlative increase in frequency, similar to the one which occurred in section B at a point 6 feet higher in the latter section. Because of the irregular thickness and lenticular nature of the beds composing the body, these two points may well occupy the same stratigraphic position, indicating a simultaneous ecological change to a type of crinoid yielding smaller fragments.

Section D (figs. 13, 14) displays two zones, a lower one, up to a height of 4.5 feet, composed of microfacies 4, 1 and 7, and an upper one, extending to the top of the section at 46 feet, composed mostly of microfacies 1, with thin intercalations of 2, 3, 4 and 5.

The size and frequency of crinoids vary in a parallel and normal way. At 16 feet the frequency increases and the size decreases and these remain fairly constant throughout the rest of the section except for extremely high frequency peaks at 18 and 28 feet. Bryozoan frequency is in general parallel to crinoid frequency except for the absence of high peaks at 18 and 28 feet. Sponge spicules and fish plates are not abundant in this section and are irregularly distributed. Detrital quartz peaks occur in all microfacies except 4 and 5, and at about 17 feet two

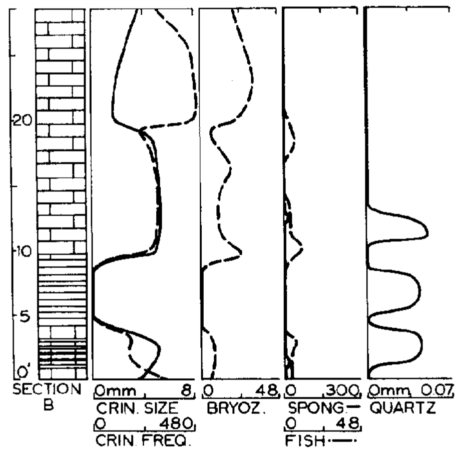

FIG. 10.—Section B; main trend curves.

peaks occur in microfacies 1. These are the only two occurrences of detrital quartz in this microfacies.

The main trends (fig. 14) of the crinoid parameters in this section clearly show the size drop and frequency increase at 16 feet, indicating an ecological change to a type of crinoid yielding smaller fragments. This is similar to the changes observed in sections B and C, but the position in section D is intermediate to those in B and C.

Section E, located entirely outside the limestone accumulation, exhibits only microfacies 7 and has been investigated solely for comparative purposes. Section F, 14 feet thick, occupies an intermediate position between E and C. It contains one zone of crinoidal material (microfacies 2) which is a tongue of the major crinoidal accumulation. Crinoid size, although not large when compared with the developments of microfacies 1 at the same stratigraphic level, is still large for microfacies 2. Section G, 18 feet thick, is composed of microfacies 1 displaying typical values for crinoid size and frequency and comparable to the lower zones of sections B, C and D, where crinoid size is high and frequency low.

Sections F and G are not suitably exposed for statistical study, but they furnish valuable information concerning the size and shape of the crinoidal body.

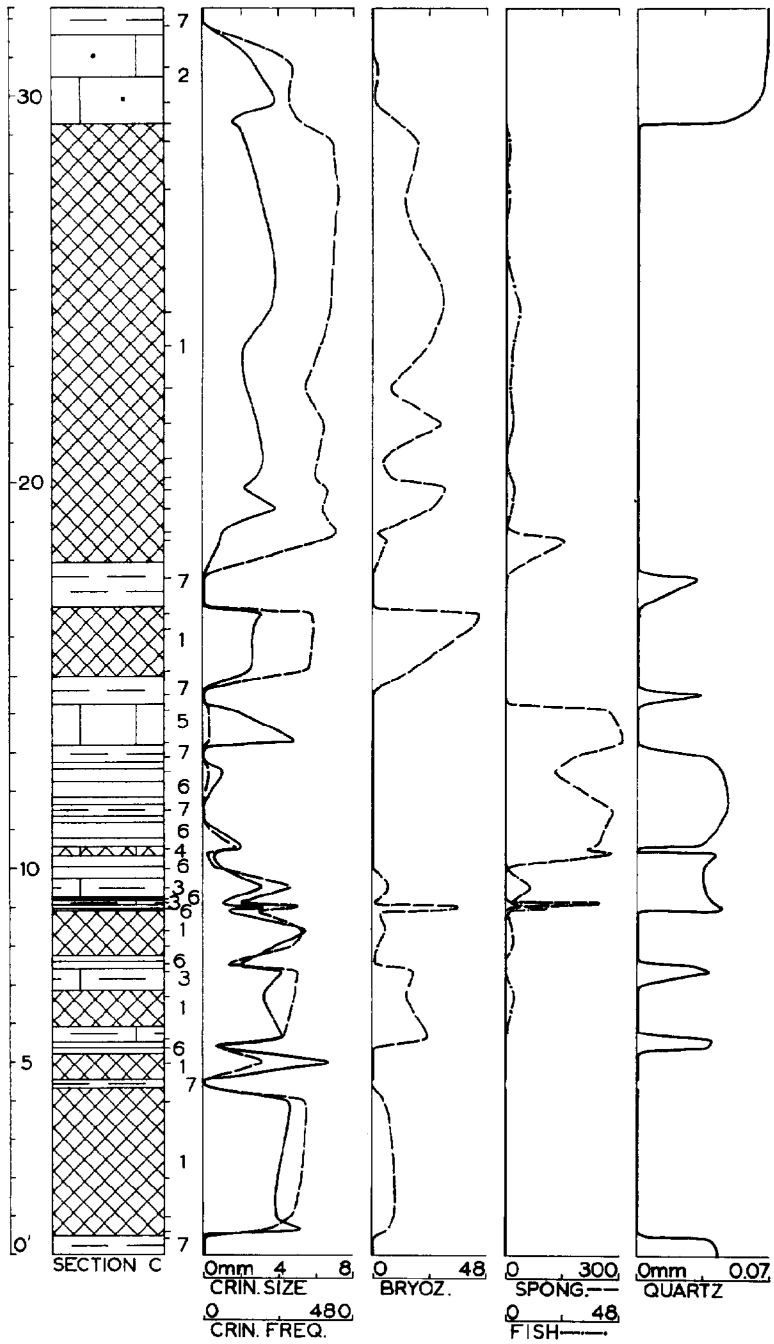

FIG. 11.—Section C; detailed curves.

COMPOSITE SECTION

A composite section (fig. 15) has been drawn by superposing sections A and D. These were chosen because they display the maximum development of crinoidal limestone as well as features pertinent to the development of the body as a whole. With the amount of lateral change present in the body, no one section can accurately summarize the entire limestone development, whereas the composite section does portray the essential characteristics of the central portion of the crinoidal accumulation and gives an indication of the general evolution of the sedimentary environment.

It is quite noticeable that crinoids and bryozoa (the most important constituents) decrease in frequency upwards, This indicates that conditions of development were very favorable in the beginning but gradually became unfavorable. The relation between the size and frequency of the crinoids shows also that three zones succeeded each other in time. The first 16 feet of the section contain relatively large crinoid fragments; the second zone, from 16 to 44 feet, has small crinoid fragments; the third, from 44 to 59 feet, is another zone of large fragments. The best development of sponge spicules and fish plates coincides with the zone of small crinoid fragments. Peaks of detrital quartz appear to be related to the zonation based on crinoid size which extends through the entire bioaccumulated body (fig. 16).

ENVIRONMENTAL INTERPRETATION

It is of the utmost importance in the environmental interpretation to stress that the Stobo crinoidal body is not a homogeneous mass, but rather is composed of numerous alternations of coarse and fine lithologies.

The coarse lithology is represented by crinoidal, bioaccumulated limestones in the center of the body (microfacies 1), which grade laterally into crinoidal calcarenites (microfacies 2 and 3), which in turn are abruptly replaced laterally by siltstones (microfacies 6 and 7). Occasional thin tongues of siltstones may extend well inside the crinoidal body. Crinoidal bioaccumulated layers are followed upward by pure calcilutites, sometimes preceded by the intermediate microfacies 4 (calcilutite with scattered crinoid fragments). The fine-grained lithology is represented by pure calcilutites (microfacies 5) in the core of the body, grading laterally into siltstones (microfacies 7).

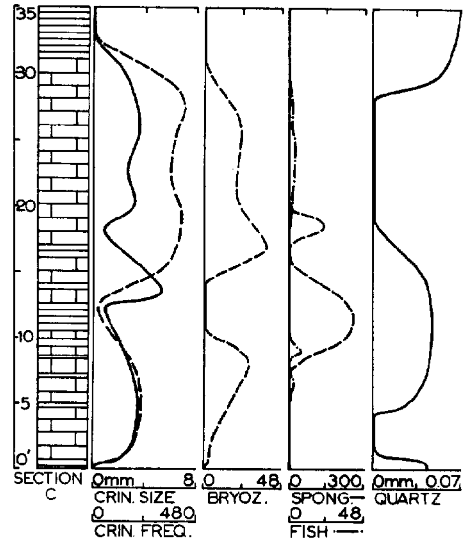

FIG. 12.—Section C; main trend curves.

The crinoidal bioaccumulated layers indicate times of optimum conditions for the development of crinoids and associated bryozoa and fish. Essentially clastics were unable to penetrate the environment because of the screening effect of dense crinoid colonies. This also explains the abruptness of the lateral contacts with the siltstone facies. The calcilutitic matrix of the bioaccumulated crinoidal limestone may be recrystallized minute fragments of crinoids or biochemically precipitated algal dust as discussed below.

The calcilutites superposed on each bioaccumulated layer are generally devoid of crinoid or other fossil debris. The crinoids cannot be responsible for the massive genesis of these deposits because their metabolism does not create conditions directly favorable to the precipitation of calcium carbonate. The microscopic texture of the calcilutites suggests that they developed from "algal dust" (Carozzi, 1960, p. 208–209) produced by phytoplankton. The temporary

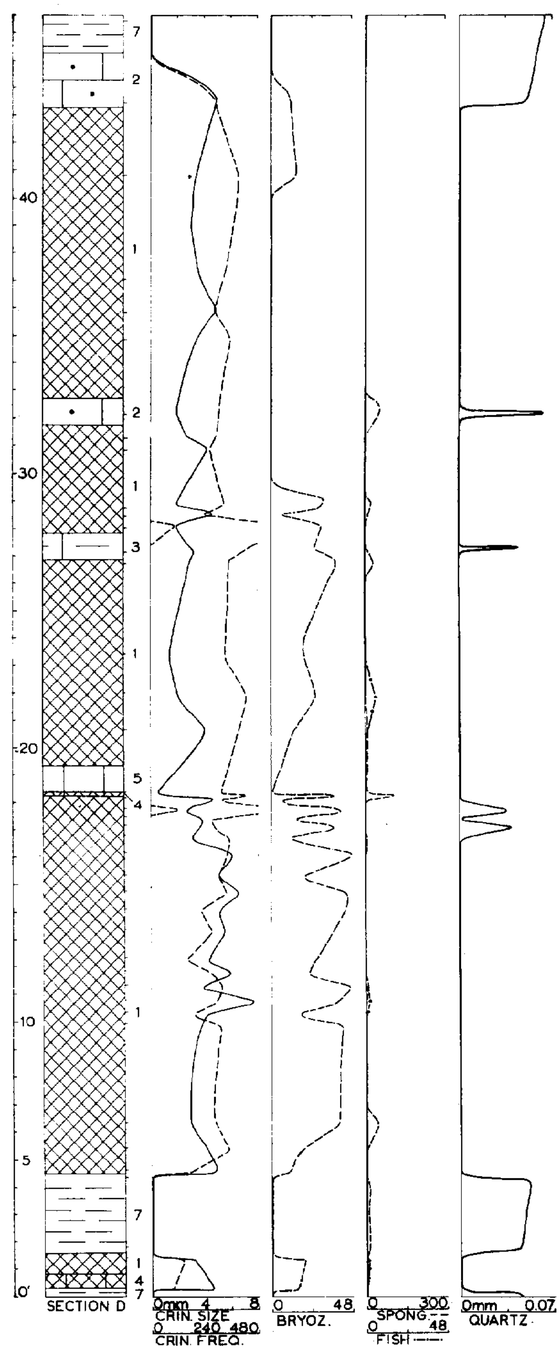

FIG. 13.—Section D; detailed curves.

and abundant proliferation of the latter could result from the increased CO_2 concentration developed by the metabolism of the crinoids, combined with the restricted circulation created by their growth. The algal precipitation of $CaCO_3$ would then make the environment lethal to crinoids, and during the deposition of the calcilutites the maximum encroachment of clastic sediments from the outside would take place, restricting the area available for the next cycle of crinoidal development. The slow currents of the environment, no longer filtered by the crinoids, would gradually disperse the algal plankton, stopping calcilutite deposition. Crinoid larvae then become reestablished preferentially on the freshly deposited calcilutite.

These numerous alternations of coarse, bioaccumulated crinoidal limestone and calcilutite display a general evolution, expressed by the three zones of different crinoid fragment size. The uppermost and lower-

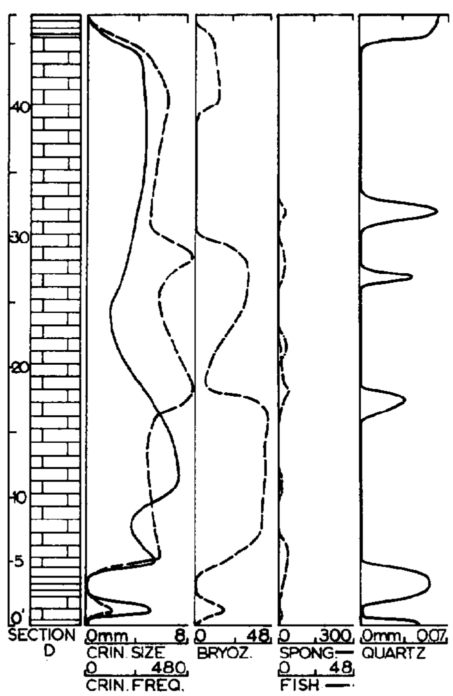

FIG. 14.—Section D; main trend curves.

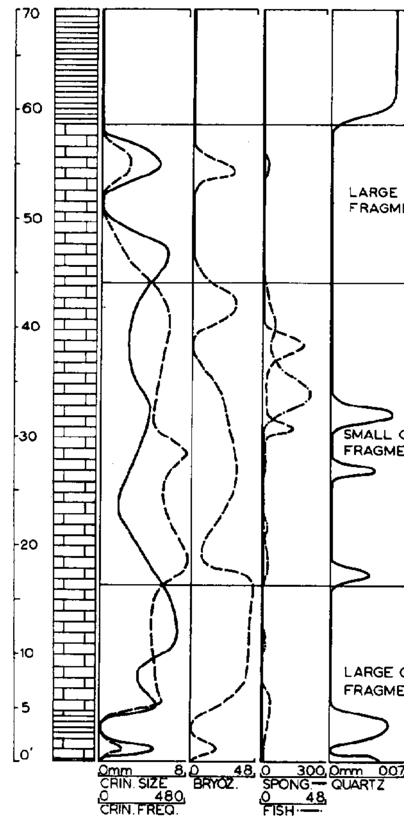

FIG. 15.—Composite section.

most zones contain large crinoid fragments; in the middle zone a smaller crinoid size is displayed, accompanied by a correlative increase in frequency (figs. 15, 16) because of a change in the type of crinoid to one yielding smaller fragments. This would decrease the screening effect, evidenced by contemporaneous peaks in the frequency of sponge spicules and fish plates, and appearance of grains of detrital quartz, possibly due to a temporary deepening of the environment.

The presence of chert in the crinoidal accumulation and its complete absence from the surrounding clastic sediments suggests a possible biochemical origin and a quiet physical environment for its deposition.

GEOLOGICAL EVOLUTION

The first interpretation of the Borden

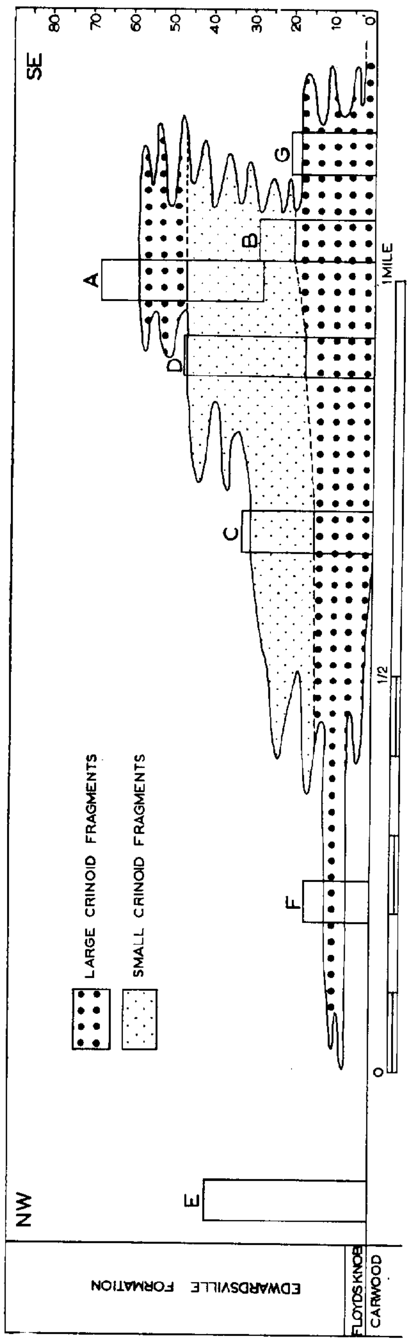

FIG. 16.—Zonation of the crinoidal accumulation.

crinoidal bodies was given by P. B. Stockdale (1931a, 1931b, p. 251–268). He postulated the presence of restricted areas of clear waters in which crinoid colonies established themselves, these surrounded by turbid waters depositing clastic sediments. He did not specify the origin of these patches of clear water. Crinoidal growth was supposed to be continuous, suffering only temporary constrictions by the influxes of clastic material.

However, it should be pointed out that the establishment of a crinoid colony requires an undisturbed substratum. Such conditions could have been provided in a sea bottom such as was present in Borden time only in local depressions below wave base, where previously deposited sediments are not subjected to continuous reworking and to much additional sedimentation. Crinoid larvae are apparently able to survive only in the depressions.

The intermittent crinoidal growth is part of a regional geological evolution which may be explained as follows. Once a colony is established, the vigorous growth of the crinoids creates a screening effect which essentially stops any penetration of clastic particles, whether brought in by suspension or by traction. After this stage is reached, clear water may exist above the depression (fig. 17, stage 1). The concept of locally depressed areas is supported by the observation that quartz grains were occasionally brought into the margins of the colony whereas crinoidal debris (of undoubtedly low density) were not moved outwards.

Because of the continuous production of CO_2 by the metabolism of the crinoids, conditions are generated over the depression which are very favorable to the proliferation of phytoplankton. The algal dust precipitated by the latter gradually creates lethal conditions for the crinoid colony. The crinoidal debris liberated by the in place decay of the animals generates a bioaccumulated crinoidal layer, overlain by calcilutitic algal dust. When the screening effect dispappears, the currents bring clastics into the depression, making it smaller and dispersing the phytoplankton (fig. 17, stage 2). The same currents also introduce crinoid larvae which establish a new colony on the firm calcilu-

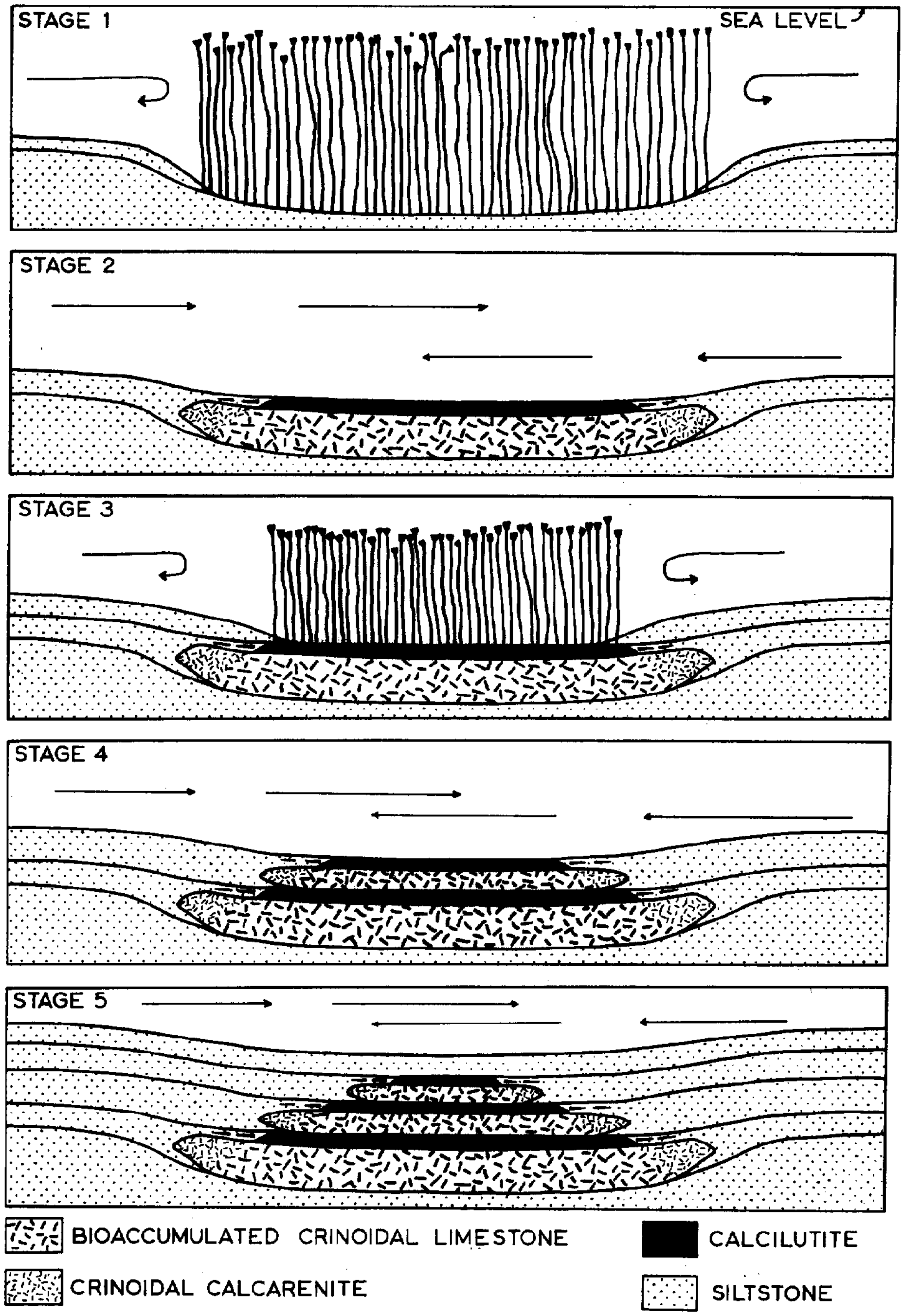

FIG. 17.—Schematic diagram illustrating the sedimentary evolution of the crinoidal accumulation.

titic bottom, and the succession of events described above is repeated (fig. 17, stages 3 and 4).

As time progresses, the periodic influxes of clastic material gradually decrease the area available for crinoid growth, until the carbonate body is completely buried in clastic sediments (fig. 17, stage 5). This coincides with a general shallowing of the environment, possibly achieved solely by sedimentation.

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