Reef petrography in the Beaverhill Lake formation, Upper Devonian, Swan Hills Area, Alberta, Canada

CAROZZI, Albert V.

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REEF PETROGRAPHY IN THE BEAVERHILL LAKE FORMATION,
UPPER DEVONIAN, SWAN HILLS AREA, ALBERTA, CANADA

ALBERT V. CAROZZI
University of Illinois, Urbana, Illinois

ABSTRACT

Statistical measurements of organic and inorganic parameters in thin sections reveal that the Swan Hills Member of the Beaverhill Lake Formation in the Shell Swan Hills 10-17 well is made up by the rhythmic alternation of eight carbonate microfacies. These rock-types are closely related and interpreted as a continuous sequence representing fore-reef, reef and back-reef conditions. The fore-reef environment shows dark-colored calcarenites whereas the reef itself consists of dark-colored bioconstructed limestones made up by cabbage-type stromatoporoids followed in shallower water by branching colonies of Amphipora. With these two organically constructed deposits are associated several types of biocalcarenites. The back-reef environment is represented by light-colored calcilutites containing scattered colonies of Amphipora and of mat-type stromatoporoids.

The vertical superposition of these microfacies displays seven rhythms of sedimentation during which an Amphipora-stromatoporoid reef community was established over a carbonate platform, developed and eventually disappeared. The rhythms seem to correspond to tectonically controlled phases of depth decrease.

INTRODUCTION

The object of the present investigation has been the petrographic description and environmental interpretation of the microfacies forming the Swan Hills Member of the Beaverhill Lake Formation in the Shell Swan Hills 10-17 well located in Twp. 64, Rge 13W 5th.

In the investigated locality, the Beaverhill Lake Formation has a thickness of 473 ft of which 438 ft were cored from the contact with the Middle Devonian Elk Point Formation upward through a large development of the Swan Hills Member as defined by Fong (1960), which here seems to occupy almost the entire Beaverhill Lake interval. In these organically constructed limestones and associated bioclastics 400 thin sections approximately at 1-ft intervals have been investigated with a total number of about 7000 statistical measurements. In spite of the fact that a fairly detailed knowledge has been obtained along a vertical line, the horizontal characteristics of these reef buildups are not well established, and their paleogeographic relations are still under discussion (Andrichuk, 1958 a,b; Edie, 1959; Illing, 1959).

METHOD OF INVESTIGATION

The author's method (Carozzi, 1950, 1958) can be designated as a statistical investigation of the microscopic components of carbonate rocks. It is based on the measurements of the apparent maximum grain size (or clasticity index) and of the frequency of the detrital components. These values are expressed as curves of variation drawn alongside the stratigraphic column and interpreted on the basis of their relations to the frequencies of benthonic and pelagic microfaunas. After completion of all the measurements, average values for the different parameters are computed for each of the microfacies distinguished in the investigated section. These average values appear characteristic to a varying degree of each of the microfacies and allow their classification according to a relative bathymetrical scale. Such a scale is used as a basis for drawing the relative bathymetrical curve which indicates the successive changes of depth which took place at the location of the investigated section. The relative bathymetrical curve is always located at the extreme right of the diagrams; it shows depth decrease from left to right and represents the final interpretation.

Curves of "main trend" (fig. 5 to 7) are presented here for the first time. Their func-
tion is to express the general evolution of the variation curve of a given parameter; this is particularly useful whenever the local fluctuations complicate the overall picture. The curves of main trend are of pure interpretative nature in contrast to the variation curves which express graphically the measurements of the microscopic parameters.

APPLICATION OF METHOD TO BEAVERHILL LAKE FORMATION

The term "reef" and related adjectives will be used in the discussion of the environment of deposition of the Beaverhill Lake Formation as a convenient designation for emphasizing the fact that constructive organisms such as stromatoporoids and Amphipora played a predominant role in the sedimentation.

In such a reef environment, detrital minerals are absent with the exception of the shale breaks R2 and R3 which display some angular grains of detrital quartz. The agitation and depth variations of this environment can nevertheless be expressed by measuring the maximum apparent grain size of the inorganic pellets of cryptocrystalline calcite. The measurements must be restricted to pellets entirely devoid of any organic fragments because the presence of the latter affects their size to a high degree. Such a value may be called index of general dasticity. It has the same significance as the elasticity of any detrital mineral grains as demonstrated in cases where quartz grains and pellets are associated (Carozzi, 1958).

Under reef conditions the organic growths of all sorts introduce numerous factors of perturbation in the distribution of detrital particles in relation to depth. In other words, it is expected that sometimes depth conditions will be expressed more by ecological relations of benthonic organisms than by the absolute values of the index of general dasticity. For instance, along channels protected by irregular ridges of stromatoporoids, the detrital particles may grade very quickly from calcarenites to calcilutites under practically similar depth conditions.

In the present investigation, the following organic parameters have been computed:

Benthonic components.—The frequency of stromatoporoids, Amphipora, and bryozoans has been determined over a thin section surface of 450 mm². The frequency of gastropods, brachiopods, and pelecypods (grouped together because of frequent lack of internal structure caused by recrystallization) has not been determined by actual counting but by a visual estimation resulting from the combination of binocular core description and thin section observation. This combination was necessary because most of these organisms are of macroscopic character and also because the effect of fragmentation would increase frequency values in an erroneous way.

Presence or absence has been reported for accessory components such as sponge spicules, Dasyycladaceae, arenaceous foraminifera, solitary corals, crinoids, and Chara stems which are not present in sufficient number to allow statistical measurements.

Pelagic components.—The frequency of ostracods and calcispheres has been determined over a thin section surface of 63 mm². It may be pointed out that the ostracods were originally benthonic elements but their tests have been floated by the currents and hence their behavior becomes that of pelagic components.

DESCRIPTION OF THE MICROFACIES

Eight microfacies form by their rhythmic alternations the investigated sequence. Five of them are basic types and three subtypes which may be missing locally. To this succession of eight carbonate microfacies must be added an argillaceous one forming the shale breaks R2 and R3.

Microfacies 1 (fig. 1A).—It is a dark to light-colored medium-grained calcarenite with a well-developed secondary cement of largely crystallized anhedral calcite. The abundant pellets have an average size of 0.494 mm; they are sub-rounded to well rounded and fairly well sorted locally. The pellets, which may be of accretionary origin, are predominantly composed of structureless cryptocrystalline calcite stained brown by bituminous matters and pyrite pigments. A few pellets contain fragments of smooth ostracods, echinoderms, and calcispheres. The recrystallization of the cement is demonstrated by indented pellets and residual ghost structures; however, the largely crystallized calcite may contain some per-
Fig. 1.—Typical microfacies of the Beaverhill Lake Formation, Nicols not crossed, X3. A: microfacies 1; B: microfacies 2; C: microfacies 2a; D: microfacies 3; E: microfacies 3a; F: microfacies 4; G: microfacies 4a; H: microfacies 5.
fectly preserved ostracod and gastropod tests. In some instances, the pellets appear to be surrounded by a thin layer of fibro-radiated calcite simulating a superficial oolite texture. Such a layer, however, may join several pellets to one another, indicating that it is a form of recrystallization of the cement.

**Microfacies 2 (fig. 1 B).**—It is a dark-colored stromatoporoid-constructed limestone with an interstitial fine-grained matrix of calcarenite. The organic framework consists predominantly of cabbage-type stromatoporoids with which are associated a few *Amphipora*. The interstitial calcarenitic matrix is made up of unsorted particles reaching an average grain-size of 0.185 mm which are predominantly angular fragments of stromatoporoids and *Amphipora* associated with a few reciprocally deformed pellets of dark cryptocrystalline calcite. Large zones of the organic framework may be recrystallized in a calcite mosaic. Dark stylolitic zones are concentrated along the boundaries between cabbages and the interstitial matrix.

**Microfacies 2a (fig. 1 C).**—It is a dark-colored fine-grained and unsorted calcarenite with a very reduced amount of detrital matrix. The average diameter of the particles is 0.225 mm. The particles are either angular fragments of stromatoporoids or subrounded pellets of cryptocrystalline calcite, closely packed and reciprocally deformed. Calcispheres are very abundant and a few broken ostracod tests may be noticed locally. The thin stylolitic zones display concentrations of bituminous matter and pyrite.

**Microfacies 3 (fig. 1 D).**—It is a dark-colored *Amphipora*-constructed limestone with an interstitial medium-grained matrix of calcarenite. The organic framework consists predominantly of branching types of *Amphipora* either complete or broken and oriented parallel to the bedding; their internal cavities and interstitial areas appear almost always filled by secondary calcite. The calcarenitic matrix consists of unsorted to incipiently sorted particles which have an average size of 0.307 mm. The particles are either angular fragments of *Amphipora* or subrounded to irregular pellets of cryptocrystalline calcite deeply stained by bituminous matters and pyrite pigments; local concentrations of calcispheres may be noticed. Numerous stylolites are present along the boundaries between the matrix and the *Amphipora* fragments and also between the different components of the matrix itself.

**Microfacies 3a (fig. 1 E).**—It is a dark to light-colored, coarse-grained calcarenite with a moderate amount of fine-grained matrix locally recrystallized in clear secondary calcite. The constituting particles, unsorted to slightly sorted, have an average grain size of 0.540 mm and are predominantly irregular to subrounded pellets of cryptocrystalline calcite. Scattered among them are larger fragments of *Amphipora* and concentrations of calcispheres.

**Microfacies 4 (fig. 1 F).**—It is a light colored, very coarse-grained calcarenite with a matrix largely recrystallized in clear secondary calcite. The constituting particles, which have an average size of 1.680 mm, appear unsorted to moderately sorted but in an irregular fashion. They consist again of *Amphipora* fragments and irregular to subrounded pellets of cryptocrystalline calcite. Among these particles are scattered numerous larger fragments of branching *Amphipora* filled with secondary calcite.

**Microfacies 4a (fig. 1 G).**—It is a light colored, medium-grained calcarenite with a very reduced amount of matrix. The constituting particles, which have an average size of 0.387 mm, appear unsorted to moderately sorted but in an irregular manner. They consist of *Amphipora* fragments and irregular to subrounded pellets of cryptocrystalline calcite. Among these particles are scattered numerous larger fragments of branching *Amphipora* filled with secondary calcite as well as concentrations of calcispheres and ostracod tests.

**Microfacies 5 (fig. 1 H).**—It is a light colored, very fine-grained calcarenite to calcilutite with the average diameter of the particles ranging from 0.104 mm to beneath the resolution power of the petrographic microscope. In the calcarenitic zones, angular organic fragments are associated with very small and well-rounded pellets of cryptocrystalline calcite which may be of faecal and algal origin. In the calcilutitic matrix are scattered large fragments of *Amphipora* and abundant mat-type colonies of stroma-
toporoids. Gastropods and local concentrations of entire shells of smooth ostracods, sponge spicules, and calcispheres may be noticed. Appreciable surfaces of the thin sections appear as mosaics of coarsely crystalline clear calcite of secondary origin; the latter replaces also organic fragments and fills original cavities between branching Amphipora and stromatoporoidal mats.

Table 1 summarizes the essential characteristics of the eight microfacies. Their identity is demonstrated not only by the organic parameters but also by their average values of the index of general clasticity which are remarkably characteristic for a reef environment where local anomalies are to be expected (fig. 2).

VERTICAL SUCCESSION OF THE MICROFACIES

The succession of the eight microfacies described above corresponds to an ideal sequence expressing a gradual shallowing of the environment of deposition. Such a succession has been indeed almost perfectly realized between 9884.5 and 10,001.5 ft. The variation of its microscopic parameters will now be described as a key for the interpreta-

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tion of the entire Beaverhill Lake Formation. Here will be only a description of the pattern of evolution of the curves, reserving the main interpretation for the discussion of the horizontal juxtaposition of the microfacies.

During the vertical superposition of microfacies 1 to 5, through 2, 2a, 3, 3a, 4 and 4a, the following features appear characteristic (fig. 3).

The index of general clasticity starts with a medium value in microfacies 1 and decreases to a first minimum in microfacies 2. The index then gradually increases upward until its maximum in microfacies 4; a rapid decrease follows until a second minimum is reached in microfacies 5.

The frequency of the stromatoporoids starts at a minimum in microfacies 1 and increases to its maximum in microfacies 2. It reaches a second minimum zone in microfacies 3 and 3a and then gradually increases toward a medium value in microfacies 5.

The frequency of Amphipora begins at a minimum in microfacies 1 and gradually increases to its maximum in microfacies 3. Then a very gradual decrease occurs upward until a medium value is reached in microfacies 5.

The frequency of bryozoans reaches its maximum in the upper portion of microfacies 1 and gradually decreases to zero in microfacies 2.

The frequency of gastropods starts with a medium value in microfacies 1 and decreases through 2 and 2a to almost zero in microfacies 3. It increases again upward until it reaches its maximum in microfacies 5.

The frequency of brachiopods and pelecypods displays its maximum value in microfacies 1. It gradually decreases to its minimum in microfacies 3a and remains constant until microfacies 5.

The frequency of the smooth ostracods begins with a medium value in microfacies 1 and gradually decreases to almost zero in microfacies 3 and 3a. It then increases rapidly to its maximum in microfacies 5.

The frequency of the calcispheres starts with a relatively low value in microfacies 1 and increases rapidly towards its maximum in microfacies 2a. This peak is followed upward by a rapid decrease leading to a minimum in microfacies 3. The frequency then gradually increases to a relatively high and stable value in microfacies 5. The accessory components are represented by floated Chara stems which are found in all microfacies; by Dasyycladaceae in microfacies 1 to 4a; by arenaceous foraminifera restricted to microfacies 3 and 3a, and by sponge spicules present only in microfacies 5.

The variations of the index of general clasticity and their relations to the behavior of the benthonic and pelagic parameters appear sufficiently characteristic to allow a good prediction of the evolution of the sedimentation when a minimum of two microfacies are investigated statistically in a complete vertical succession as illustrated in figure 3.

**HORIZONTAL JUXTAPOSITION OF THE MICROFACIES**

The same pattern of evolution which has been described during a shallowing of the environment for a given point and during a certain span of time (fig. 3) applies also when the changes of sedimentation are studied laterally during an instant of time (fig. 4). The latter approach is well suited for a more thorough interpretation of the general environment of deposition. However, first the final conclusions must be anticipated by stating that the horizontal juxtaposition of microfacies 1 to 5 corresponds to a generalized section extending from fore-reef to back-reef conditions. This section displays a first group of dark-colored microfacies deposited in a reducing environment. Microfacies 2a and 3a are deposits which were laid down in relatively quiet conditions under the protection of the organically constructed ridges. The section shows a second group of light-colored microfacies deposited in an oxidizing environment. In this group microfacies 1 represents the fore-reef zone, microfacies 2a a ridge of cabbage-type stromatoporoids and microfacies 3 a ridge of Amphipora, both of which built the predominant part of the reef zone. Microfacies 2a and 3a are deposits which were laid down in relatively quiet conditions under the protection of the organically constructed ridges. The section shows a second group of light-colored microfacies deposited in an oxidizing environment. Microfacies 4 corresponds to the wave breaking zone, microfacies 4a is transitional toward 5 representing back-reef conditions where scattered mat-like colonies of stromatoporoids were growing in association with Amphipora.
ENVIRONMENTAL INTERPRETATION

The environmental significance of each computed parameter in relation to the horizontal juxtaposition of the microfacies will now be discussed (fig. 4).

The relatively high value of the index of general clasticity in microfacies 1 is rather surprising as one would expect a minimum size of the clastic components in the deepest environment. This microfacies is also the only one in the sequence displaying a fair sorting of its pellets; it is suggested that both features could result from an accretionary or faecal origin of the pellets. The index of general clasticity increases through microfacies 2, 2a, 3 and 3a until it reaches its maximum in microfacies 4 corresponding to the wave breaking point. Such an increase is consistent with the fact that Amphipora is known to live in shallower water than cabbage-type stromatoporoids and also with the transition from a deeper reducing environment to a shallower and oxidizing one. Microfacies 4a has a smaller value of the index of general clasticity because it was deposited in quiet waters in the back of the ridge built up by wave-accumulated larger fragments. Microfacies 5, extremely fine-grained, is a typical expression of protected back-reef lagoonal conditions.

The frequency curve of the stromatoporoids actually combines two stromatoporoidal communities living in different environments. A first community is of cabbage-type; it reaches its maximum development in the open sea reducing conditions of microfacies 2. This group is very well limited in space by rapid decreases in frequency both toward deeper conditions (microfacies 1) and shallower conditions (microfacies 2a, 3, and 3a). The second community is of a mat-type; it reaches its maximum development in the back-reef oxidizing conditions of microfacies 4a and 5. However, its frequency never reaches the high values of the first community.

The main development of branching Amphipora colonies takes place in open sea reducing conditions but at a shallower level than the stromatoporoids and in complete
opposition to the latter. After its maximum in microfacies 3, the frequency of the Amphipora decreases very slowly across microfacies 3a, 4, 4a, and 5. In these microfacies there is apparently an association of broken fragments and of individuals living in place. Wave action, particularly in microfacies 4, was probably very effective in moving many Amphipora from their position of growth and accumulating them in selected spots; consequently their present distribution in these microfacies may not be representative of their growth density.

The bryozoans have a very narrow zone of distribution. They reach their maximum frequency in microfacies 1 (that is, in fore-reef conditions) and disappear very rapidly as soon as the cabbage-type stromatoporoids begin to develop. In other words, they build the deepest organic zone of the investigated sequence.

The sponge spicules are typically monaxonlic types which are concentrated mainly in the back-reef environment of microfacies 5 with some rare occurrences in microfacies 4a. The quiet conditions of lagoonal waters are known to be favorable to their development.

Arenaceous foraminifera of relatively small size and thick shell have been observed only in microfacies 3 and 3a. They are considered to be rather typical of agitated conditions immediately below the zone of wave breaking and they do appear in such a position in the investigated section.

Fragments of large Dasycladaceae stems are scattered in very small number in all the microfacies except 5. Such conditions of occurrence indicate, as will be discussed later, that all the microfacies were deposited in the zone of photosynthesis.

Flated Chara stems are present in all the microfacies but in badly preserved condi-
tions indicating extensive floatation. Since they develop only in fresh-water to slightly brackish environments, their origin should be looked for in emerged portions enclosing fresh water ponds which would occur in back-reef conditions. From these zones, the *Chara* stems would be carried out to sea. A similar mechanism will be assumed later also to explain the distribution of the smooth ostracods.

The frequency curve of the gastropods combines actually two communities living in different environments in a similar way to the stromatoporoids. A first community, however not very abundant, reaches its maximum development in open sea reducing conditions, mainly in microfacies 1 to 2. This group is fairly well separated by a zone of low frequency (microfacies 2a, 3, and 3a) from the second community which reaches its maximum in the back-reef oxidizing conditions of microfacies 5. This second group always displays a greater frequency than the first one.

The frequency of the association brachiopod-pelecypod reaches its maximum in microfacies 1 in agreement with the fact that thick-shelled brachiopods are characteristic of fore-reef conditions. A gradual decrease of frequency is apparent across the reef environment, reaching complete stability from microfacies 3a on to the back-reef (microfacies 5).

The frequency curve of the smooth ostracods expresses two different environments. In the first one the ostracods have developed as benthonic components; in the second, they have been distributed passively by wave and current actions and behave as pelagic components. The conditions of preservation and the frequency relations to other parameters allow a fair discrimination of the origin of frequency maxima. Ostracods are extremely abundant in the quiet back-reef environment of microfacies 5 where they occur as perfectly preserved complete individuals indicating ideal conditions of development and preservation. Their frequency gradually decreases toward a minimum in microfacies 3; it may be pointed out that from microfacies 4 on, fragmentary individuals predominate over entire ones. The frequency increases and reaches a second peak in microfacies 1 where all the individuals are broken and often form the nuclei of accretionary pellets. This second maximum, always smaller than the first one, may be interpreted as a result of mechanical concentration of floated tests in the fore-reef environment away from the agitated conditions surrounding the constructed ridges. Such an interpretation implies a flotation of the ostracod shells from the back-reef toward the open sea as considered previously for the distribution of the floated *Chara* stems.

The frequency curve of the pelagic calcispheres appears to be entirely opposed to the curve of the index of general clasticity. The frequency is very low in microfacies 1 and increases toward its maximum in microfacies 2a which corresponds to a fairly protected environment in the back of the stromatoporoidal ridge where the index of general clasticity is very low. The frequency of the calcispheres decreases rapidly in microfacies 3 and then increases gradually toward a medium value in microfacies 5. This last trend can be interpreted by the assumption that the calcispheres did not accumulate in the agitated conditions where the *Amphipora* developed but were gradually washed into the back-reef as some pelagic foraminifera (*Globigerina*) are trapped today in atoll lagoons. Phases of transportation in such a direction probably alternated with others during which ostracods and *Chara* were floated in an opposite direction.

**BATHYMETRICAL INTERPRETATION**

A bathymetrical comparison between Mesozoic reefs and present ones is possible only in a very broad manner (Carozzi, 1955a). When a similar comparison is attempted for Paleozoic reefs, the problem becomes quite difficult because of the lack of data concerning the bathymetrical distribution of stromatoporoids and *Amphipora* which are the predominant colonial organisms.

The only information in our possession is a relative one corresponding to the fact that in order of decreasing depth, one finds successively a bryozoan, a stromatoporoid, and an *Amphipora* belt before reaching the wave breaking zone and back-reef conditions. However, one absolute fact is known, it is
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the depth distribution of the Dasycladaceae which stops at 135 ft depth, the lower limit of the photosynthesis zone. The presence of Dasycladaceae even in microfacies 1 indicates that the latter was still deposited above 135 ft. The distribution of the arenaceous foraminifera in microfacies 3 and 3a is also consistent with such a relation (Carozzi, 1954, 1955b). In conclusion, the sequence of microfacies 1 to 5 was deposited in an environment which did not reach more than 150 ft in depth as far as can be assumed from the present stage of our knowledge of Paleozoic reefs.

DESCRIPTION OF THE RHYTHMS OF SEDIMENTATION

The Beaverhill Lake Formation of the investigated section can be subdivided into seven well defined rhythms of sedimentation on the basis of the succession of microfacies and of their microscopic parameters (figs. 5-7).

Rhythm 1, 10,050'-10,001', (fig. 5).—Its sequence starts with microfacies 1 followed by an alternation of 2 and 2a; the rhythm ends with several thin alternations of microfacies 1 and 3. The general trend of the sedimentary evolution is 1, 2, 2a, 3 in an upward direction. Such an evolution is clearly displayed by the organic components; indeed frequency peaks of bryozoans, cabbage-type stromatoporoids, and Amphipora follow each other. Brachiopod, pelecypod, and gastropod frequencies decrease gradually upwards as do also the fragments of ostracods. The frequency of the calcispheres reaches a peak in microfacies 2a before decreasing upward. The index of general elasticity decreases in the middle portion of the rhythm before increasing again near the top.

Rhythm 2 starts by a subsidence during which its basal microfacies 1 is deposited on top of the shallowest microfacies 3 of the first rhythm. The succession is then a gradual and complete depth decrease through microfacies 2, 2a, 3, 3a, 4, 4a, and 5. For the first time in our sequence, the depth decrease has overpassed the wave-breaking zone (microfacies 4) and reached back-reef conditions.

Rhythm 3, 9884.5'-9825.5', (fig. 6).—This rhythm is relatively simple. It starts with a rather symmetrical portion in which microfacies 3 is preceded and followed by 4a; it ends with another symmetrical portion in which microfacies 4a is preceded and followed by 5. The organic parameters have a normal behavior; the Amphipora maximum related to microfacies 3 is well realized; mat-like stromatoporoids are very abundant in microfacies 5, as well as important concentrations of whole ostracods and calcispheres. Among the accessory components, a few solitary cup corals are present and sponge spicules are locally concentrated in the lower part of microfacies 5. The index of general elasticity reaches a maximum in microfacies 5 and decreases gradually throughout 5 until the top of the rhythm. The lower part of this rhythm is a subsidence period during which the back-reef conditions developed on top of rhythm 2 were interrupted by an increase of depth which temporarily re-established the environment favorable to Amphipora colonies (microfacies 3). The upper half of the rhythm is a new depth decrease during which the back-reef environment again became predominant. It may be pointed out
Fig. 6.—Variation curves of microscopic parameters in the Beavertail Lake Formation (rhythms 2, 3, and 4).
that microfacies 5 of the upper half of this rhythm corresponds to the last presence of back-reef conditions in the investigated sequence.

Rhythm 4, 9825.5'-9769.5' (fig. 6).—This rhythm is a complex association of microfacies 3, 3a, and 4a in which the general trend of sedimentary evolution shows a sequence 3, 3a, to 4a upward. The rhythm shows in its lower portion a shale break (R2) after which microfacies 3 becomes predominant, until it is replaced at the top of the sequence by a large development of microfacies 4a.

The organic parameters follow the lithological evolution; the maximum of Amphipora is well displayed in the middle of the rhythm and followed upwards by that of mat-type stromatoporoids. The frequency of the ostracods and calcispheres increases upward. The index of general clasticity does not vary much because the difference of indexes between microfacies 3, 3a, and 4a is not very significant.

Rhythm 5 starts with a subsidence which definitely ends back-reef conditions and establishes again an environment favorable to Amphipora growth (microfacies 3), this subsidence is accompanied by the shale break R2. The middle and upper portions of this rhythm correspond to a depth decrease during which Amphipora becomes predominant followed by microfacies 4a, indicating a tendency toward back-reef conditions which were never fully realized. In other words, after the shale break R2, depth decreased and organic growth started again.

Rhythm 5, 9769.5'-9717' (fig. 7).—This sequence is again an association of microfacies 3, 3a, and 4a similar to the preceding one but without any basal shale break. The general trend of sedimentary evolution is also 3, 3a, to 4a upwards with a large predominance of the latter microfacies.

The organic parameters of this rhythm are fairly well displayed; the Amphipora maximum occupies the lower half of the sequence whereas the mat-like stromatoporoid maximum appears in the upper half. The ostracod frequency normally increases slightly upwards but the calcispheres have an abnormal behavior by steadily decreasing in frequency upward; such erratic conditions are to be expected occasionally with pelagic components. The index of general clasticity does not vary much, as in the preceding rhythm, because the indexes of 3, 3a, and 4a are not very different from one another.

Rhythm 5 starts with a slight subsidence during which microfacies 3 and 3a are deposited on top of microfacies 4a, forming the top of the preceding rhythm. Depth decreases upwards and rapidly reaches microfacies 4a which builds the last thick unit in the described sequence, indicating a tendency toward back-reef conditions.

Rhythm 6, 9717'-9657.5' (fig. 7).—It is a rather complex sequence starting at the bottom with a thick shale break (R3) and consisting of an association of microfacies 1, 2, 2a, 3, and 3a. However, the general trend of sedimentary evolution shows a predominance of microfacies 3 and 3a in the lower portion of the rhythm, of microfacies 2 in the middle, and of microfacies 1 in the upper portion.

The variations of the organic parameters are entirely in agreement with the microfacies distribution. The Amphipora maximum in the lower part of the rhythm is followed by that of the cabbage-type stromatoporoids which re-appear here again after their last occurrence in the lower part of rhythm 2. Gastropod, brachiopod, and pelecypod frequencies increase upward; the fragments of ostracods vary in the same way. The calcispheres, after having reached a peak in microfacies 2a, decrease gradually upward in frequency. The index of general clasticity oscillates in a somewhat irregular way.

This rhythm is the first one of the investigated section during which depth increases gradually upward through a sequence 3a, 3, 2a, 2, and 1. Such an evolution is separated from microfacies 4 of the preceding rhythm by the shale break R3, indicating by itself a rupture of equilibrium in the carbonate deposition.

Rhythm 7, 9657.5'-9612' (fig. 7).—This probably incomplete rhythm has a symmetrical appearance. Its lower and upper portions are constituted by microfacies 2, whereas the center displays an alternation of microfacies 1 and 3.

Among the organic parameters two maxima of cabbage-type stromatoporoids
Fig. 7. Varied sections of microconglomerate in the Beaverhill Lake Formation (Rhythms 5, 6, and 7).
surround a central maximum of *Amphipora* indicating a predominant influence of microfacies 3 against 1. The behavior of the ostracods is abnormal whereas the calcispheres display a very strong maximum only in the upper part of the rhythm where microfacies 2a is present. The index of general clasticity shows a peak in the middle of the sequence.

Rhythm 7 which is probably only a fraction of a larger unit extending beyond the investigated core is a simple oscillation reaching by depth decrease microfacies 3, starting and ending in microfacies 2.

Fig. 8.—General schematic evolution of the microscopic parameters in relation to relative depth (amplitudes of curves not to scale, compare with Figs. 5 to 7).
It appears interesting to point out that during the depositional history of the investigated core, most of the microscopic components display a general evolution which is superposed as a larger scale mechanism on the rhythmic patterns described above. This corresponds actually to the determination of the large scale trend of the different curves of main trend (compare fig. 8 with figs. 5-7).

The overall evolution of the index of general clasticity indicates an increase until the middle of rhythm 2 where microfacies 4 is reached for the first time. A minimum is apparent during rhythm 3 and relatively low values predominate in the rest of the sequence with a slight increase upwards. In other words, the index of general clasticity shows lower values during rhythms 3 to 7 than during 1 to 2.

This upward decrease of the index of general clasticity can be readily explained by the fact that rhythms 4 to 7 and particularly 4 and 5 do not display microfacies 4 (wave-breaking zone) but 4a. Such conditions indicate that the upper portion of the investigated sequence was deposited in a generally less agitated environment than the lower one during which the reefs were established. It seems as if the organic constructions had influenced the sedimentary history in an irreversible way.

The frequency curves of the stromatoporoids and *Amphipora* do not show any general evolution. The general evolution of the frequency of the gastropods indicates an increase until rhythm 3 followed by a decrease in the rest of the section. There is a tendency for the gastropods to be less abundant in the upper half of the sequence than in the lower one. The general evolution of the frequency curve of brachiopods and pelecypods shows stability over most of the sequence with increases toward top and bottom.

The overall evolution of the frequency of the ostracods displays an increase until rhythm 3 after which there is a general decrease. However, a slight increase may be noted within the upper field of low values. In other words, the ostracods are definitely less abundant during rhythms 4 to 7 than during 1 to 3. This decrease of general fre-
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frequency starts with the disappearance of the typical back-reef microfacies 5 from which the ostracods seem to have originated. The general evolution of the frequency of the calcispheres shows a gradual decrease upwards. Here again, the values are lower during rhythms 4 to 7 than during 1 to 3. This decrease is difficult to understand because increasing open sea conditions should give rise to an increased frequency of these pelagic organisms. It is possible that one faces here an effect of dispersal whereas during the ascending phase of the reef (rhythms 1 to 3) the calcispheres were concentrated by waves and currents in the immediate vicinity of the growing colonies which had wave breaking effects.

GENERAL BATHYMETRICAL INTERPRETATION

The general bathymetrical history of the investigated sequence is definitely an asymmetrical one comprising seven rhythms of sedimentation which are also themselves predominantly of asymmetrical character (fig. 9).

Rhythm 1 is a gradual depth decrease starting in fore-reef environment and ending with reef no. 1. An abrupt subsidence starts rhythm 2, bringing back fore-reef conditions. A gradual depth decrease leads then to the development of reef no. 2 followed by its back-reef facies.

Rhythm 3 is actually an interruption of back-reef conditions by a subsidence re-establishing an open sea environment rapidly followed by a return of the back-reef facies. The latter is abruptly interrupted by a subsidence during which clay materials (shale break R2) are brought into the carbonate environment. In spite of this unfavorable foreign inflow, colonial organisms grew up again, apparently in a more quiet environment than before, during the gradual depth decrease which forms most of rhythm 4. A rapid subsidence inaugurates rhythm 5 during which another depths decrease corresponds to a second regrowth of organic colonies.

Rhythm 6 is in itself a continuous depth increase bringing back fore-reef conditions. It was certainly a major rupture of equilibrium since it begins with a second and very important inflow of clay materials (shale break R3). Rhythm 7 is a simple oscillation corresponding to a relatively short-lived reef no. 3. The asymmetrical character of most of these sedimentary rhythms which seems to correspond to a gradual decrease of depth followed by a rapid subsidence (provided constant sedimentation rates are admitted) appears as a typical feature of tectonically controlled oscillations (Carozzi, 1950). In spite of the fact that such a pattern has not yet received a satisfactory explanation, it leads to six natural breaks in the Beaverhill Lake Formation among which two correspond to the deposition of argillaceous material brought from outside the carbonate environment.

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