PETROGRAPHY OF A CARBONATE TRANSGRESSIVE-REGRESSIVE SEQUENCE: 
THE BIRD SPRING GROUP (PENNYSYLVANIAN), ARROW CANYON RANGE, CLARK COUNTY, NEVADA

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ABSTRACT
A stratigraphic interval of 1846 feet belonging to the Lower and Middle Bird Spring Group and ranging from Lower Morrowan to Lower Missourian has been investigated petrographically in order to unravel the cyclic sedimentation of this miogeosynclinal limestone sequence.

More than 209,5 samples collected at an average interval of 10 inches were divided into eleven microfacies, given here in order of decreasing relative depth of deposition or increasing energy level: an almost pure calcisiltite (microfacies 0), a calcisiltite with scattered sand-size organic debris (microfacies 1), a calcisiltite with abundant scattered sand-size organic debris (microfacies 2), a grain-supported biocalcarenite with calcisiltite matrix (microfacies 3), a grain-supported biocalcarenite with clear calcite cement (microfacies 4), and a grain-supported oolitic biocalcarenite with clear calcite cement (microfacies 5). Microfacies designated as 0a, 1a, 2a, 3a and 4a are the detrital quartz-rich equivalents of microfacies 0 to 4 and include rocks with more than 10 percent of detrital quartz.

The following microscopic parameters were measured: frequency and elasticity of crinoid fragments, oolites, pellets (fecal, lithic and algal coated) and detrital quartz; frequency of debris of brachiopods and bryozoans, ostracodes, calcispheres, arenaceous benthonic foraminifers and pyrite. These data, together with symbols representing many other minor components were plotted alongside the columnar section as variation curves showing the stratigraphic behavior of the parameters. A combination of these measurements with the above textural classification of the microfacies led to the drafting of a relative bathymetric curve (expressing in this environment also the energy level) which represents the final interpretation of the oscillations in energy level and related water depth during deposition.

A total of 78 complete cycles were recognized. They are variants of 3 fundamental ideal cycles (or statistically most frequent successions of microfacies) established on the basis of the average values of all the measured parameters. Two of these ideal cycles characterize the Morrowan which consists of 46 cycles with features expressing a gradual transgression. A massive inflow of fine detrital quartz coincides with the deepest phase of the transgression. The third type of ideal cycle is typical of the Atokan-DesMoinesian-Missourian interval which consists of 32 cycles with features indicating a gradual regression. Therefore the investigated sequence is a complete major geological cycle of transgression and regression.

INTRODUCTION
This detailed petrographic description of a portion of the Pennsylvanian cyclic limestone sequence at Arrow Canyon is part of a continuing project, under the general direction of Prof. Ralph L. Langenheim, Jr., whose aim is to provide a complete reference section for Late Cambrian through Permian rocks in the southern part of the Cordilleran miogeosyncline.

The investigated stratigraphic interval (1846 feet) belongs to the Lower and Middle Bird Spring Group and ranges from the Lower Morrowan to the Lower Missourian. In the field it displays a steplike pattern of alternating benches and slopes which is characteristic of cyclic sedimentation.

Samples collected at an average vertical distance of 10 inches were studied petrographically and divided into eleven distinct microfacies which are repeated according to three major types of cycles. Variation curves of the clasticity and frequency of detrital and organic components were plotted alongside the stratigraphic column. An interpretative curve expressing the variation of the environmental energy and relative changes of depth was drawn. It emphasizes the characteristics of the 78 complete cycles recognized and shows the environmental evolution through time which corresponded to a major transgression followed by a regression.

LOCATION
Arrow Canyon is superposed across the northern end of the Arrow Canyon Range approximately 50 miles northeast of Las Vegas, Nevada (fig. 1). The Arrow Canyon Range is the principal topographic feature in the Arrow Canyon Quadrangle which is bounded by Latitude 36° 30' N. and 36° 45' N. and Longitude 114° 45' W. and 115° 00' W. A road entering the canyon joins U. S. Highway 93 from the west at the northern end of the irrigated valley along the Muddy River north of Glendale, Nevada.
FIG. 1.—Location map.
FIG. 2.—Stratigraphic nomenclature applied to late Paleozoic rocks of Southern Nevada. The asterisk indicates stratigraphic unit defined in the quoted paper. Stratigraphic column drawn to scale. Total thickness of Bird Spring Group is approximately 2400 feet.

The Pennsylvanian rocks investigated in this paper belong to the Bird Spring Group (Ches- terian through Wolfcampian) and are exposed in the lower, more open portion of Arrow Can- yon where it cuts the southeastern ridge of the Arrow Canyon Range. At the base the Bird Spring Group rests disconformably on Miss- issippian rocks of the Monte Cristo Group, and at the top it is truncated by the present topo- graphic surface. Outcrops also are bounded by recent alluvium and Tertiary sedimentary rocks. The investigated portion of the sequence dips approximately 40° southeast and is part of the northwestern limb of a partially overturned syncline. The syncline is, in turn, bounded to the northwest by a major thrust fault. The strata are abruptly flexed in the lower part of the canyon, however, and the uppermost portion of the Bird Spring Group displays gently dipping to horizontal rocks. Because of extreme aridity and rugged topography, essentially complete ex- posures of the entire sequence are readily ob- servable.

The numerous changes and the present status of the stratigraphic nomenclature for the Bird Spring Group at Arrow Canyon have been dis- cussed in great detail by Langenheim and Lang- enheim (1965) and may be conveniently repre- sented by a chart (fig. 2). Therefore only the stratigraphic location of the studied interval will be mentioned here.

The Bird Spring Group consists of the follow- ing formations from bottom to top:

1. Battleship Wash Formation (former BSa Formation): 80 ft
2. BSb Formation: 243 ft
3. BSc Formation: 2216 ft
4. BSD Formation: 320 ft
5. BSe Formation: 530 ft

The interval investigated in this paper begins 167 ft above the lower limit of the BSc For- mation and terminates at 139 ft above the lower limit of the BSD Formation. It reaches a total thickness of 1846 feet and consists of the follow-
ing time-rock units: Middle and Upper Morrowan (878 ft), Atokan (356 ft), Des Moinesian (434 ft), and Lower Missourian (178 ft).

PREVIOUS PETROGRAPHIC INVESTIGATIONS

The only detailed petrographic work comparable to the present one has been done by Rich, (1963, 1964), who investigated 7000 feet of carbonate rocks belonging to the Bird Spring Group in the Lee Canyon area, 45 miles south-southwest of Arrow Canyon. He originally collected the specimens for a fusulinid study (Rich, 1961) and, although never explicitly stated, seems to have sampled at ten foot intervals. His measured section ranges in age from Chesterian to Leonardian and consists of microfacies similar to those described in this paper. Rich has expressed the variations of microscopic organic and inorganic components by estimating the ranges of percent of area they covered in each thin section. This method was applied to fossil groups, total skeletal grains, total grains, autochthonous organic structures, matrix, other allochems and quartz. The ranges selected for foraminifers, corals, brachiopods, pelecypods and echinoderms were: less than 5, 5-10, 25-50 and over 50 percent. Sponge spicules, algal remains and ostracode valves were grouped as greater or less than 10 percent. The ranges for all parameters other than fossil groups were: 1-10, 10-25, 25-50, and over 50 percent of the total slide area.

Rich’s method is very similar to that described in this paper although it emphasizes more visual estimations than absolute measurements of elasticities and frequency. Consequently variations within the chosen ranges cannot be detected and variations in the lower percentages are over-emphasized.

METHODS AND TECHNIQUES

Petrographic Analysis

In the field 2095 hand specimens were collected in a total thickness of 1846 feet corresponding to an average sample interval of 10 inches, and 693 field units were distinguished and described (Heath, 1965; Lumsden, 1965). Interspecimen distance was a function of lithology. Where units were thick and uniform the sampling distance was as much as two feet, where thinner, as close as five inches.

The hand specimen was unequipped except when finely laminated, in which case it was oriented vertically. Thin sections were also cut at random subject to the same exception. They were prepared in the routine fashion except for the use of an Ingrai-Ward thin section machine. All were cut to a thickness slightly above the standard value of .003 mm to allow better contrast among components. Before covering, one slide per field unit was selected and placed in a General Electric XRD-4 diffractometer and scanned from 22 to 40 degrees 20. This range includes the major peaks of quartz, calcite and dolomite.

The thin sections were studied following the method proposed by Carozzi (1950, 1958, 1961) which consists of measuring the indices of elasticity and frequency of all the detrital components and the frequency index of all the organic components of a carbonate rock.

The index of elasticity for any given component in a thin section is defined as its maximum diameter. Since we are dealing with an apparent diameter, except in the particular case where the section is cut through the center of the grain, the index of elasticity is the lowest numerical value of the maximum diameter. In order to obtain some degree of constancy in the measuring of the index of elasticity, the six largest grains from all the grains occurring in a particular thin section were selected and their diameters averaged. The occasional isolated grains notably larger than the grains making up the rock were considered to be due to local variations in the agents of deposition, and hence, though the diameters were measured, they were not entered into the tabulation of the index of elasticity.

The final expression of the index of elasticity is a numerical figure, given in millimeters, which represents the largest diameter of a grain that could be set in motion by the general forces acting in the environment of deposition.

The frequency index of a given component is defined as the number of its particles present in any given area of a thin section. In practice, this requires counting the number of grains found over a constant area on each thin section. The number must be in the order of at least 100 grains so that the measurements will be statistically reliable. A problem arises with the determination of the frequency index. If the rock is made up predominantly of closely packed grains of a particular clastic component, the frequency index will decrease as the grain size increases, thereby giving a misleading value. In order to overcome this, it was decided to choose an area for each clastic component which had a diameter of at least 10 times the average diameter of that component.

As a consequence of stratigraphic variations in the frequency of the major parameters, different surface areas had to be used.

In the Morrowan, the surface areas for the frequency index of crinoids, brachiopods, bryozoans, and ostracodes was 254 mm2. For area-
ceous benthonic foraminifers, oolites, pellets, quartz and pyrite, it was 56.5 mm. In the Atocon-DesMoinesian-Missourian interval, the surface area for the frequency index of quartz and pyrite, it was 20 mm.

The parameters occurring with sufficient frequency to be statistically valid were then plotted using appropriate scales, according to their position in the lithological column. By joining these points, a series of curves were obtained which trace the stratigraphic variation of each particular parameter. The presence of components not abundant enough to allow frequency measurements was designated by symbols drawn beside their position of occurrence in the lithological column.

On the basis of microscopic textures, presence of a detrital matrix or precipitated cement, average values and relationships of organic and inorganic parameters, the thin sections were divided into distinct microfacies.

The relative energy level at the time of deposition of each microfacies has been interpreted after considering all the data and respective positions of the microfacies in the cycles. The depositional textures in the cycles suggest a gradation from low to high energy levels and are believed to be the result of decreasing depth. An interpreted bathymetric curve for the entire measured section was prepared by plotting in a column the various microfacies arranged from left to right in order of increasing energy level or decreasing relative depth. This curve constitutes the basis for the interpretation of the environmental evolution through time of the investigated carbonate basin.

Components

In the description of the various microfacies, the term "grain" is used for discrete mineral or skeletal particles larger than .06 mm. Matrix or groundmass are used synonymously for the predominantly skeletal particles smaller than .06 mm. These display usually a microcrystalline texture which becomes microgranular wherever the granules are predominantly equal-sized.

Quartz occurs in two forms: as detrital grains or as secondary overgrowths. The latter were not tabulated unless they displayed visible cores in which case the latter were counted and measured as detrital particles. Although the distinction between primary and secondary quartz may become increasingly difficult as particle size diminishes, the problem has had no appreciable effect upon the microscopic measurements.

Chert is irregularly distributed but occurs in almost 70 percent of all field units, although very few beds are completely chertified. Chert appears to be most frequent in microfacies 0, 1, 2, less prominent in 3 and 4, and absent in 5. Chertified slides were identified as to microfacies, but only the parameters of detrital quartz were measured since it did not seem to have been affected by chertification. In a few slides it was possible to obtain the index of elasticity of crinoid fragments as the larger grains were not so easily replaced. The matrix, cement and finer material were always so thoroughly modified to make positive identification of all other components impossible.

Dolomite, identified by X-ray, seldom occurred in large quantities. The actual amount was not determined as the mineral could not be recognized under the microscope. Dolomite characterizes either single field units or broad stratigraphic zones consisting of several such units. It is most frequently found in microfacies 0 and 1, less commonly in 2 and 3, and very rarely in microfacies 4 and 5.

Pellets occur throughout the section studied and are of three types: fecal, lithic and algal coated.

Fecal pellets are most abundant in microfacies 1, 1a, and 2, 2a. They appear as spherical to ovoidal bodies formed of dark gray to black microto cryptocrystalline calcite devoid of internal structure. In a few pellets, fragments of other unidentifiable organic debris are discernible in the homogeneous groundmass.

Lithic pellets, or lithoclasts, are most abundant in microfacies 3, 3a and 4. The particles are irregular to well rounded, and made of dark gray to black cryptocrystalline calcite. In general these grains are larger than fecal pellets and their presence indicates reworking or churning of incipiently consolidated lime muds by current action. Many of these clasts contain detrital quartz grains or organic debris. The debris includes crinoid plates and occasionally columnals, brachiopod shell fragments, and rarely bryozoans, gastropod shell fragments, and arenaceous benthonic foraminifers.

Algal coated pellets (algal balls) are the largest pellets identified and most frequent in microfacies 4 and 5, less common in 3 and very rare in microfacies 2. They consist of a core made by the two preceding types of pellets or by an organic fragment, usually crinoid or brachiopod with blue-green algae of the Osagia type forming concentric laminated or vermicular coatings. The pellets are usually ovoid with their long axis parallel to that of the nucleus.
Phosphatic debris (francolite or collophanite) occur in a great number of thin sections, as irregularly shaped to sub-rectangular, isotropic bodies, with fibroradiated structure. They may be attributed to fish bony or scaly material. Although clay material may be present particularly in microfacies 0 to 3 and 0a to 3a, its particular composition was not determined.

DESCRIPTION OF MICROFACES

On the basis of the mean value of certain parameters, textural characteristics and the relative quartz contents, the slides were subdivided into two groups: a normal and a quartz-rich. The normal microfacies group contains 6 microfacies, 0 to 5, which will be defined below. Each slide included in this group is characterized by having less than 10 percent of its total surface area consisting of grains of detrital or secondary quartz.

The quartz-rich microfacies group is limited to the upper part of the Morrowan, and includes only 5 microfacies, 0a, 1a, 2a, 3a and 4a; microfacies 5 of the normal microfacies group not being represented. In this group the detrital and secondary quartz together account for 10 to 80 percent of the total surface area of the thin section. The high quartz content causes a reduction in the frequency of all organic fragments, matrix, and cementing material.

Normal Microfacies Group

Microfacies 0—Megascopically, this limestone occurs in thin to massive beds which are poorly resistant. The rock is nonfossiliferous and fine grained. The weathered surface is light gray, tan to light brown, while the fresh surface is tan or medium to dark gray. Chert is abundant as nodules or discontinuous layers. Dolomite occurs in 25 percent of the samples studied, but seldom in great quantities. This microfacies is almost pure calcisiltite with less than 3 percent of organic debris (fig. 3, A). The groundmass is crypto- to microcrystalline, dark brown to almost black calcite, colored by pyrite and organic matter. Some samples display an extremely fine calcilutitic groundmass. Angular grains of detrital quartz are common, particularly when the groundmass is microgranular. Pyrite particles are more common in this microfacies than in any other within the normal microfacies group. They tend to be evenly distributed, and often responsible for iron oxide staining. Mica flakes are euhedral, small, and associated with relatively large quantities of detrital quartz grains.

Organic debris are limited to calcified monoaxonic sponge spicules, small subangular crinoid plates and columnals, brachiopod shell fragments, and more rarely bryozoans, ostracode valves and worm tubes. The fecal pellets are usually subrounded and small.

Microfacies 1—Megascopically, this limestone is fine grained and occurs in thin to massive beds of over ten feet. Some of them are very resistant, and display a step-like pattern. The weathered surfaces are brown or light gray to dark gray, and smooth. A few units show cross bedding, and are poorly fossiliferous. The fresh surface displays a gray color with blue and green cast. Chert is very extensive as nodules or layers. Dolomite occurs in minor quantities in almost all samples. This microfacies is a calcisiltite which contains 3–30 percent sand-size organic debris floating in a fine grained matrix (fig. 3, B).

The groundmass consists of a uniform mosaic of microcrystalline calcite, stained by organic matter and pyrite particles. Some samples contain a very fine calcilutitic matrix. Angular, fine grained detrital quartz grains are ubiquitous and occur in variable amounts. Small pyrite particles are abundant in all slides, but euhedral flakes of mica are rare.

Organic debris are usually scattered in a random fashion throughout the groundmass. A few slides, however, show debris with preferred orientation concentrated into narrow bands, bound on either side by dark gray calcisiltite similar to that described in microfacies 0. Angular to subangular fragments of crinoid plates and columnals, brachiopod shells and spines and bryozoan fronds constitute most of the larger sand sized particles. The smaller particles are mainly of similar composition, together with ostracode valves, pelecypod shell fragments, and arenaceous benthonic foraminifers. Some slides show minor quantities of calcispheres, trilobite debris, echinoid plates, gastropod shells, and calcified monoaxonic sponge spicules. Dark gray small fecal pellets are very common and associated with some subrounded to well rounded lithic pellets.

Postdepositional disturbance of the fine grained matrix, shown by the irregular and often spiral distribution of the organic debris in some slides, suggests reworking by scavengers or currents.

1 Since pure calcisiltite may have a different environmental position when associated with other microfacies suites, it has been given the symbol "0" to meet such conditions in the future synthesis of the Paleozoic of Arrow Canyon (See similar procedure used for the Devonian, in Cariss and Carozzi, 1965).
Microfacies 2.—Megascopically, this medium grained limestone occurs in thin to medium beds which are poorly resistant. The weathered surfaces are light to dark gray or brown. The fresh surfaces are medium gray. The rock is fairly fossiliferous and sometimes shows cross bedding. Chertification is fairly common. Dolomite is rare and identified in only minor quantities.

This microfacies is a calcisiltite with abundant sand-size scattered organic debris (fig. 3, C). The matrix consists of a brown to dark gray mosaic of microcrystalline calcite stained by organic matter and pyrite pigments. Detrital quartz occurs as small angular grains, a few of which show secondary overgrowths. Pyrite particles are common, whereas the small euhedral mica flakes are rare.

The bioclastic material accounts for about 30-50 percent of the slide surface area and some grains show signs of welding by pressure-solution. Crinoids, brachiopods and bryozoans constitute the majority of the larger bioclasts, while smaller particles are made of similar material together with trilobites, gastropod shells, pelecypod shells and some unidentifiable fragments. The crinoid columnals and plates tend to be angular and some have poorly defined margins resulting from syntaxial growths of clear calcite spar. Brachiopod valves and small shell fragments are numerous and show signs of preferred orientation parallel to bedding. Brachiopod spines are variable in size and scattered throughout the slide. Ostracode valves, arenaceous benthonic foraminifers, gastropod shells, and calcified monoaxonic sponge spicules are relatively abundant while coral septa fragments, pelecypod and phosphatic debris occur in minor quantities. Lithic and fecal pellets are erratically distributed in about equal number. Some large algal coated pellets are found in a few samples, and show crinoid, brachiopod or pelecypod shell fragments as cores.

The irregular and spiral-like arrangement of the bioclastics in some slides indicates the reworking action of scavengers. Other varieties display a laminated texture made up of alternating layers rich and poor in fragmental material.

Microfacies 3.—Megascopically, this limestone appears coarse grained, light to medium gray with thin to massive bedding. The rock is resistant and occurs in step-like outcrops. The fresh surfaces are light to dark gray and reveal a very wide variety of easily identifiable fossils. Cross bedding is rare. Chertification is not prominent. Dolomite is found in very few samples and in only minor quantities.

This microfacies is a grain-supported biocalcareous calcisiltite with calcisiltite matrix (fig. 3, D, E and F). The larger organic debris are dominated by fragments of crinoids, brachiopods and bryozoans. The crinoid plates and columnals frequently exhibit pressure welding and incipient recrystallization with syntaxial growth along the fragment edges forming clear spar. Brachiopod shells are often distorted while the spines are widespread throughout the samples studied. Bryozoans tend to be restricted to the coarser clasts, and some occur as complete fronds. Small fragments are less conspicuous and are probably obscured by other particles. Other minor components are arenaceous bentonic foraminifers, calcispheres, phylloid algae, pelecypod shells, and coral septa fragments. Calcified monoaxonic sponge spicules, ostracode valves, and gastropod shells are less frequent than in microfacies 2. The particles show even distribution, little or no sorting and grain orientation is rare. There is no clear evidence of reworking.

All three types of pellets occur in this microfacies. The fecal pellets are small and well-rounded, the lithic, which predominate, are subangular to rounded and their intraformational origin is well shown by the numerous organic debris they contain. Rather large algal coated pellets are locally predominant. Their algal material is wrapped around crinoid plates and columnals, gastropod and brachiopod shells, and less often rounded lithic fragments and quartz grains.

The matrix usually consists of microcrystalline calcite stained by organic pigmentation to a brown or gray color. In a few slides, the matrix is a mosaic of coarser grained light gray calcite. This texture appears to be frequently associated with the algal coated pellets described above. In a few cases, welding by pressure-solution has been so extensive as to eliminate nearly all of the cementing material. Many slides show signs of recrystallization of the calcisiltite into clear spar. The recrystallization occurs in patches of only a few microns in diameter, or replaces up to 30 percent of the dark gray calcisiltite. The resulting spar is fine grained and clear, but has a gray cast, which may be a reflection of the organic pigmentation associated with the original calcisiltite mud.

Detrital quartz is not abundant in this microfacies, but occurs either as very fine angular grains or as coarser subangular to subrounded grains, which seem to be of a different origin. Both types may form cores for secondary overgrowths or crystals. Pyrite particles are less frequent than in previously described microfacies, and scattered throughout the matrix. Small euhedral flakes of mica are very rare.
Microfacies 4.—Megascopically, this limestone is found in thin to massive beds, fairly resistant and very fossiliferous. The weathered surface is light gray to medium gray and sometimes shows cross-bedding and a fretted aspect. The fresh surface is light to dark gray, and displays dark rounded debris in a fine matrix. Dolomite is very rare.

This microfacies is a grain-supported pelletoidal biocalcarenite with a cavity-filling clear spar cement (fig. 3, G, and H; fig. 4, A). The bioclasts show a high degree of roundness and apparent sphericity, and may cover 60 to 80 percent of the slide's surface area. They include fragments of crinoid plates and columns, brachiopod shells, and spines, bryozoans. Cavities in crinoid columnals and brachiopod spines are frequently filled by calcisiltite mud indicating reworking processes. There is a sharp reduction in the frequency of pelecypod shells, ostracode valves, gastropod shells, arenaceous benthonic foraminifers, and calcispheres.

Pellets of all varieties are numerous and may account for up to 70 percent of the slide surface area. The lithic pellets which predominate tend to be well rounded and their shape is often controlled by that of the enclosed organic debris. These are fragments of crinoid plates and columnals, brachiopod shells, algal fragments, and less commonly arenaceous benthonic foraminifers. Some organic fragments show thin coatings of lithic material representing the late stage in pellet destruction by agitative forces.

The fecal pellets are darker and smaller than the lithic pellets. Algal coated pellets are much larger than the lithic or fecal pellets and although less abundant they reach their maximum frequency in this microfacies. They are well-rounded, ovoid, and the algal material often coats fragments of crinoids, brachiopod shells, and gastropods.

Cavity-filling spar cement is characteristic of this microfacies and occurs in two varieties. The first is clear, coarsely crystalline, and seems to have been precipitated as a cavity-filling cement. The contacts between the grains and spar are sharp and clearly defined. The second form of spar is found where coarse grained debris have welded together by pressure-solution. In such cases the boundaries of the adjacent grains have been destroyed by a syntaxial growth of clear and coarsely crystalline spar, which merges...
into the grains without sharp boundaries. In some slides the cementing spar shows a clotted texture which may be due to recrystallization of residues of primary calcisiltite matrix. The latter also occurs as patches and stringers.

Quartz is limited to scattered particles with frequent secondary overgrowths and crystal outlines. The majority of the grains are angular, fine grained and similar to those previously described. However, a few slides contain large subangular to subrounded sand-sized grains. Pyrite is rare and restricted to the edges of particles and occasionally to the inside of algal coated pellets.

**Microfacies 5.**—Megascopically, this limestone is thin to medium bedded, medium grained, and its oolitic texture is not visible in outcrop. The weathered surface of the fairly resistant beds is light gray, while the fresh surface is light to medium gray. Chert and dolomite are absent.

This microfacies is a grain-supported, oolitic biocalcarenite with a cavity-filling clear spar cement (fig. 4, B and C). The sandsize debris are predominantly normal oolites with some superficial oolites. The normal oolites consist of numerous concentric layers of fibro-radiating crystalline calcite coating cores made by fragments of crinoid stems and columnals, brachiopod shells, ostracode valves, lithic and fecal pellets. The oolites, although in reciprocal contact, do not show effects of pressure-solution.

Halfmoon oolites (Carozzi, 1963) formed by partial internal solution with consequent settling of the core to the bottom of the cavity, are quite widespread. The random orientation of the cores indicates that an earlier phase of post solution reworking must have occurred before final deposition.

The frequency of nonoolitized organic fragments is inversely proportional to that of the oolites. Wherever present these debris are dominantly crinoid plates and columnals, together with brachiopod shells and spines. Bryozoans and arenaceous benthonic foraminifers occur in minor quantities while gastropod shells, pelecypod shells, and echinoid spines are rare. All organic particles, regardless of composition, are smaller than those found in microfacies 0-4, some of them show a fine coating of lithic material indicating that they represent the late stage of destruction of lithic pellets. The latter tend to be subrounded, generally ovoid, and contain fragments of gastropods, ostracode valves, crinoid plates or brachiopod shells. Fecal pellets are small, and well rounded, but not
common. Algal coated pellets, abundant in some slides, have cores of the same composition as those found in the lithic pellets.

Cavity-filling spar cement is predominant, and like in microfacies 4 it may show in places a dotted texture indicating the recrystallization of patches of calcisiltite material.

Grains of detrital quartz are small, angular and rare, so is pyrite which occurs in algal coated pellets and along the margins of bioclasts.

Quartz-rich Microfacies Group

This group represents the quartz-rich equivalents of the microfacies 0-4 of the normal microfacies group, and each equivalent has been given the suffix "a." The description will be limited to variations introduced by the abundance of detrital quartz. In general, microfacies 0a-4a contain much less bioelastic material than their counterparts in the normal microfacies group, since the abundance of quartz grains leaves less space for organic debris, and also may have had some destructive effect upon the organic remains during sedimentation.

Microfacies 0a.—Megascopically, this limestone is similar to microfacies 0 except that the weathered rock is generally tan, and friable. The units tend to be thin bedded. Dolomite is rare.

This microfacies ranges from a quartz-rich calcisiltite to a calcite cemented quartz siltstone (fig. 4, D).

The groundmass which may account for 40-80 percent of the slide's surface area, consists of crypto- to microcrystalline yellow to tan calcite. The color results from clay particles, organic pigmentation or iron oxide staining. The high percentage of quartz in many of the slides causes the calcite to look like lithic pellets, but these blebs can be separated from genuine pellets by their texture, color and hazy boundaries.

Detrital quartz dominates the microfacies and may cover 10-80 percent of the total slide surface area. The grains show no secondary growth and are typically angular. Pyrite particles are numerous in all slides, and mica occurs as small, euhedral flakes.

The rare organic debris include small fragments of crinoid plates, brachiopod shell fragments and a few ostracode valves. A few fecal pellets occur as small subrounded structureless particles.

Microfacies 1a.—Megascopically, this limestone is similar to microfacies 1 except for the absence of bedding. Dolomite is very rare.

The microfacies is a quartz-rich calcisiltite with scattered sand-size debris (fig. 4, E). The groundmass is crypto- to microcrystalline brown stained calcite. Euhedral flakes of mica occur in minor quantities. The detrital quartz, which may account for 10-40 percent of the total area, is angular and tends to be either evenly distributed or to show local concentrations or banding. The irregular trend of the banding often indicates post-depositional disturbance and reworking by organisms and currents. The larger grains tend to be coarser than the detrital quartz in microfacies 0a. No secondary overgrowth or recrystallization was noticed. Pyrite particles are common, but less frequent than in microfacies 0a.

Organic debris are much less common than in microfacies 1 and the fragments tend to be smaller and more rounded. Crinoid plates and columnals are uncommon and occur with less frequency than the fragments of brachiopod shells. Ostracode valves and arenaceous benthonic foraminifers show great variations in frequency. Gastropod remains, bryozoa, brachiopod spines are rare. Fecal pellets tend to be fairly small, subrounded, and sometimes occur in greater frequency than any other particle, except detrital quartz. The less common lithic pellets are small and usually well rounded.

Microfacies 2a.—Megascopically, this rock is similar to its equivalent, but devoid of cross bedding. Dolomite is very rare.

This microfacies is a quartz-rich, calcisiltite with abundant scattered sand-size organic debris (fig. 4, F). The groundmass consists of a brown to dark gray mosaic of microcrystalline calcite. The detrital quartz grains are angular and slightly coarser than those found in microfacies 0a, and 1a, and show a greater range in grain size. In some slides bands of quartz grains alternate with others consisting of poorly oriented bioclasts. Numerous pyrite particles are irregularly scattered throughout the matrix which also displays rare euhedral flakes of mica.

The bioclasts are much smaller, less numerous and show less faunal variety than those found in microfacies 2. They consist mainly of fairly small subangular fragments of crinoid plates and brachiopod shells. Crinoid columnals, brachiopod spines, arenaceous benthonic foraminifers, ostracode valves and bryozoan fragments are rare. Small fecal pellets predominate over subrounded, dark gray lithic pellets which rarely contain organic debris.

Microfacies 3a.—Megascopically, this limestone is similar to microfacies 3 except for a sharp reduction in fossil content and the absence of
cross bedding. The weathered surface is rough because of the increased quartz content. Dolomite is very rare.

This microfacies is a quartz-rich, grain-supported biocalcarenite with calcisiltite matrix (fig. 4, G). The bioclasts are less common and smaller than those in microfacies 3, but are larger than the organic debris in microfacies 2a. The fauna is very restricted with crinoid plates and columnals, together with brachiopod shell fragments accounting for over 85 percent of all particles present. Brachiopod spines are uncommon, and this may be a reflection of their inability to withstand the abrasion by quartz grains. Some bioclasts are coated by lithic material, and represent, as in previous microfacies, the late stage in pellet destruction. Small numbers of ostracode valves, arenaceous benthonic foraminifers, and bryozoan fragments occur in all samples. Gastropod shells, echinoid fragments and trilobite remnants are rare.

Lithic pellets are fairly abundant and range from large, subrounded individuals, often containing organic debris, down to poorly rounded ones with none. Fecal pellets occur as smaller, well rounded, dark bodies which are less frequent than the lithic types.

Detrital quartz occurs with less frequency than in previously described microfacies within this group, and may cover 10-20 percent of the slide's surface area. The grains are angular and occur in bands or evenly distributed. Secondary growth features are rare. Abundant pyrite particles are scattered throughout the matrix.

Microfacies 4a.—Megascopically, this limestone is identical to microfacies 4 except that the surface is rough due to scattered coarse grains of detrital quartz. Dolomite is absent.

This microfacies is a quartz-rich, grain-supported biocalcarenite with a cavity-filling clear spar cement (fig. 4, H). An appreciable portion (30-50%) of the bioclastic material has recrystallized to a mosaic of microcrystalline clear calcite, with destruction of the internal structure of many fragments.

The coarse grained bioclasts, fairly well-rounded, consist of columnals and plates of crinoids associated with brachiopod shell remains and spines. Recrystallization is most widespread among these particles. Echinoid spines, arenaceous benthonic foraminifers, trilobite debris, pelmepod shell fragments, and lithic pellets devoid of organic debris, are rare.

The sand-size particles are cemented together by coarsely crystalline calcite, which shows cavity-filling textures, but is not stained by organic pigmentation.

Detrital quartz grains are much coarser than in any other microfacies and may reach a maximum size in excess of .20 mm. The grains are usually subangular, although a few show a higher degree of rounding. The detrital grains are evenly scattered among the bioclastics or concentrated in irregular bands or stringers. No secondary growth was noticed. Pyrite particles are relatively rare and occur in little clusters or scattered in the cement of sparry calcite.

IDEAL CYCLES OF THE MORROWAN

The six normal microfacies described above and their five quartz-rich equivalents are all represented in the Morrowan. They express different environments of carbonate deposition which grade into each other vertically and horizontally. Their relationships display a consistent pattern 0 to 5 to 0, and 0a to 4a to 0a indicating the presence of two ideal cycles which may be used for the general interpretation of the environmental evolution. Only the pattern of the 0 to 5 and 0a to 4a sequence, corresponding to a general shallowing and increase in environmental energy will be described (fig. 5) since the other halves are mirror images.

From the general behavior of the organic components and their relationships with depositional textures it appears that wave-base may be correlated with the gradual disappearance of the silt-size matrix and its replacement by cavity-filling calcite (fig. 7).

The lithologic sections represent the relative thickness of each microfacies in the two groups as expressed by their respective number of samples. The curves show the variation of the average frequency and elasticity for a given component obtained from 10 to 20 thin sections of each microfacies.

Normal Microfacies Group

In this group, microfacies 1 accounts for 37.8 percent of the lithologic section, followed by microfacies 3 with 26.8 percent, 2 with 16.5 percent, 4 with 10.4 percent, 0 with 6.7 percent, and 5 with 1.8 percent.

The crinoid frequency curve shows an increase from 7 per unit area in microfacies 0 to a maximum of 305 in microfacies 2 and then declines to 230 in microfacies 4. The elasticity curve runs almost parallel to the frequency curve with the smallest fragments averaging .22 mm in microfacies 0 and increasing to 1.22 mm in microfacies 3 and then declining to microfacies 4. There is however, a sharp increase in microfacies 5 where the elasticity is 1.24 mm. A general increase in elasticity with increasing energy level is clearly displayed. The crinoids apparently preferred the environment corresponding
to microfacies 2, followed by 3 and 4 and therefore lived on either side of wave base, although preferably below where water circulation was still fairly good and could carry food to the static crinoids.

Brachiopods show an increase from 6 in microfacies 0 to the maximum of 448 in microfacies 2 and then decline to microfacies 5. Therefore these organisms found optimum conditions just below wave base, but their range appears to
BIRD SPRING GROUP (PENN SYLVANIAN), NEVADA

have been the same as that of the crinoids.

Bryozoans are least numerous in microfacies 0, while the maximum of 29 per unit area in microfacies 4 is followed by a decline to 9 in microfacies 5. Although bryozaons prefer highly agitated conditions well above wave base, the steady increase of their frequency from microfacies 0 to 4 indicates a wide range of tolerance.

Arenaceous benthonic foraminifers are absent in microfacies 0, but increase to a maximum of 16 in microfacies 3 and then decline to microfacies 4 and 5. The curve is similar to that of the oolites, with the maximum frequency of the foraminifers occurring near wave base.

Ostracodes behave as free floating organisms. They occur in maximum numbers (25) in microfacies 1 with a sharp decline to microfacies 0 and a more gentle one to microfacies 5. It seems likely that the valves, which upon death, dropped into the agitated water zones above wave base, were gradually destroyed with increasing agitation, while those dropping onto the sea floor below wave base were preserved in the softer calcisiltite mud.

Fecal pellets and lithic pellets (lithoclasts) seem in a general manner to exclude each other by occurring in distinctly different environments and therefore only one set of composite curves has been used for both as discussed below. Algal-coated pellets (algae balls) are usually not abundant enough to undergo a valid statistical treatment and consequently their distribution has no appreciable influence on the behavior of the other two types of pellets.

Pellets are the only components showing bimodal distribution, with maximum frequency peaks of 63 in microfacies 1 and 278 in microfacies 4. The peak in microfacies 1 represents the maximum frequency of the fecal pellets, which declines thereafter, whereas the peak in microfacies 4 corresponds to the maximum frequency of lithic pellets which also declines in microfacies 5 in response to the generation of oolites which have often pellet cores. The pellet clasticity curve is almost parallel to the frequency curve and also shows a bimodal distribution, with the maximum clasticity of the fecal pellets in microfacies 2 and the largest lithic pellets in microfacies 4. Obviously the smaller fecal pellets are more important in the relatively quiet environment well below wave base, while the larger lithic pellets predominate above wave base where reworking by water agitation is extensive. The distribution of the fecal pellets may indicate either that the related organisms lived only in quiet conditions or that the pellets were destroyed in agitated environment.

Oolites are restricted to microfacies 5 and reflect the highest energy zone and the shallowest conditions attained with corresponding saturation in calcium carbonate. As a consequence of intense oolitization, the frequency of all the other components is drastically reduced.

Detrital quartz shows a steady decline in frequency from a maximum of 156 grains per unit area in microfacies 0 to 4 in microfacies 5, with a slight flexure between microfacies 2 and 3. The clasticity increases on the other hand from .04 mm in microfacies 0 to a maximum of .07 mm in microfacies 4, before decreasing to microfacies 5. The decreasing particle size with increasing water depth suggests that the detrital quartz grains have been winnowed out from the zone above wave base and have been redeposited in the deeper and quieter water, leaving the larger grains as lags in the region at or above wave base. The intersection of the frequency and clasticity curves and the opposite behavior of their trends is characteristic of an insufficient supply of detrital quartz grains into the environment (Carozzi, 1958). The presence of very minor quantities of small grains in microfacies 5, suggests that they were trapped between bioclastic grains, and therefore not winnowed out like the rest of the quartz grains.

Pyrite steadily declines in frequency from 602 in microfacies 0 to 80 in microfacies 5, and produces a curve almost parallel to that of the quartz frequency which typifies the close relationship between these two minerals of extra-basinal origin (Carozzi, 1958). The decrease which reflects an improvement in the water circulation reaches its maximum gradient at wave base between microfacies 3 and 4.

The relative bathymetric curve expresses the reciprocal relationships between the various microfacies in terms of energy level and decrease in water depth. These conditions may be summarized as follows:

Microfacies 0: Very quiet conditions of deposition characterized by a high concentration of very fine quartz grains and pyrite particles, together with a dearth of organic debris.

Microfacies 1: Quiet conditions of deposition with a marked increase in organic debris and particularly the highest frequency of ostracodes and fecal pellets. There are lesser increases in crinoid, brachiopod and bryozoan remains, while quartz and pyrite decrease in frequency.

Microfacies 2: Weakly agitated conditions with the highest frequency of crinoids, and brachiopods, together with the first appreciable development of lithic pellets. Bryozoans and arenaceous benthonic foraminifers are also increasing, while ostracodes, fecal pellets, quartz grains and pyrite particles are declining in importance.

Microfacies 3: Moderately agitated conditions corre-
sponding to a greater variety of debris than in any other microfacies and typified by a maximum concentration of arenaceous benthonic foraminifers together with numerous crinoids, brachiopods, bryozoans, and lesser quantities of ostracodes and lithic pellets.

Microfacies 4: Agitated conditions characterized by the highest frequency of bryozoans and lithic pellets together with a sharp decline of arenaceous benthonic foraminifers, and pyrite.

Microfacies 5: Well agitated conditions corresponding to a predominance of oolites with minor quantities of crinoid with maximum size and brachiopod remains.

Quartz-rich Microfacies Group

In the quartz-rich group, microfacies 1a comprises 43 percent of the lithologic section, while microfacies 0a accounts for a further 41.9 percent, and is followed by microfacies 2a (6.8%). 3a (5.4%) and microfacies 4a with 2.9 percent. The major effects of a massive inflow of silt-size detrital quartz in the environment of the preceding series of microfacies are a general reduction of the abundance of organisms and a shifting of some of the frequency peaks in shallower conditions.

Crinoid frequency is at a minimum in microfacies 0a, increases to the maximum of 251 in microfacies 3a and then decreases to 114 in microfacies 4a. The crinoid clasticity is bimodal, and decreases from .96 mm in microfacies 0a to .73 mm in microfacies 1a and then increases again to a second maximum of 1.10 mm in microfacies 2a before decreasing a second time. The frequency and clasticity curves run nearly parallel to each other and show similar characteristics as those exhibited in the normal microfacies group. Also in this environment, the crinoids lived on either side of wave base, but with the optimum conditions in microfacies 3a. A drastic frequency reduction in comparison with the normal microfacies group is obvious.

Brachiopod debris show a steady increase in frequency from 4 in microfacies 0a to 349 in microfacies 4a, thereby showing a distinct preference for shallow water, high energy conditions above wave base. This is a deviation from the normal microfacies group. The brachiopod and quartz frequency curves show an inverse relationship which indicates that quartz was detrimental to the brachiopods, particularly below wave base.

The bryozoans occur in very minor quantities and apparently could not withstand the quartz invasion. There is a gentle increase from a minimum of nil in microfacies 0a to the maximum in microfacies 4a of 14 per unit area. The curve runs parallel to that in the normal microfacies group and has its maximum in the same microfacies.

Arenaceous benthonic foraminifers are rare, but show a maximum in microfacies 3a, which again coincides with that of the crinoid frequency. The curve is similar to its counterpart in the normal microfacies group although there is a sharp reduction in frequency. This may be due to the mechanical destruction of the foraminifer tests by the detrital quartz grains.

Ostracodes show a bimodal distribution with maxima in microfacies 1a and 3a. The peak in microfacies 1a coincides with that of the normal microfacies group, but the cause of the second peak and of the generally erratic behavior is unknown.

Pellets, unlike those in the normal microfacies group, do not exhibit a bimodal distribution, but show a steady increase from microfacies 0a (11) to a maximum of 264 in microfacies 3a, followed by a sharp drop to microfacies 4a which contains almost no pellets probably as a consequence of destruction by mechanical action. The elasticity of the pellets is .06 mm in microfacies 0a and 1a, then increases to the maximum of .33 mm in microfacies 3a. Apparently the pellets in microfacies 0a and 1a are essentially of fecal origin; those in microfacies 2a both of lithic and fecal origin, whereas microfacies 3a contains mainly lithic pellets. Therefore a general correlation exists with the evolution of the pellets in the normal microfacies group where the fecal pellets reach their peak in microfacies 1a and the lithic pellets in microfacies 4a. Oolites are entirely absent in this group of microfacies.

The quartz frequency curve has three peaks, although two are small, with one maximum of 3461 in microfacies 0a, representing the concentration of winnowed quartz particles, a second in microfacies 2a of 2436, and a third in microfacies 4a of 1408. The peak in microfacies 2a represents the sum of the detrital quartz in the sediment and the quartz winnowed out of sediments above wave base and deposited below it, while the third small peak is a reflection of the large subangular to subrounded detrital quartz grains which are part of the lag deposit caused by winnowing. These grains have an average diameter of .23 mm and are the largest in either group. The clasticity decreases down to .08 mm in microfacies 0a. The quartz supply is no longer insufficient and both parameter curves are not really opposed but they still intersect in the same microfacies (2a) as in the normal microfacies group, just below wave base as a result of winnowing in microfacies 4a.

The pyrite frequency curve has a maximum of 802 in microfacies 0a and a minimum of 123 in microfacies 4a. The curve runs almost parallel to
the quartz frequency curve, and except for its greater values is almost parallel to the equivalent curve in the normal microfacies group.

The relative bathymetric curve, as in the normal group, expresses the reciprocal relationships between the various microfacies in terms of energy level and decrease in water depth. These conditions may be summarized as follows:

Microfacies 0a: Very quiet conditions of deposition characterized by a lack of organic debris, except for a few large crinoid fragments, and a high concentration of fine quartz grains and pyrite particles.

Microfacies 1a: Quiet conditions corresponding to the maximum frequency of ostracodes and fecal pellets, but with little else except quartz and pyrite, which are declining.

Microfacies 2a: Weakly agitated conditions marked by crinoid fragments with high parameters and the increase in the pellet parameters, due to the appearance of the lithic types.

Microfacies 3a: Moderately agitated conditions corresponding to the highest concentration of coarse-grained crinoid bioclasts, in association with the maximum parameters for pellets which are essentially lithic. The microfacies is also marked by highest frequencies for arenaceous benthonic foraminifers, ostracodes and pellets under the effect of mechanical actions.

Microfacies 4a: Agitated conditions with the highest frequencies in bryozoans and brachiopods, and the maximum quartz clastclty, together with a decline in crinoid parameters and pyrite particles, and a disappearance of arenaceous benthonic foraminifers, ostracodes and pellets under the effect of mechanical actions.

**Ideal Cycle of the Atokan-DesMoinesian-Lower Missourian Interval**

In this stratigraphic interval only microfacies 1 to 5 are present and there are no quartz-rich equivalents. An ideal cycle can be established, similar in a general fashion to the one of the normal microfacies group on the Morrowan but with its distinct peculiarities (fig. 6).

The lithologic section shows the relative thickness of the different microfacies. Microfacies 1 comprises 48.8 percent of the columnar section, while microfacies 3 accounts for 27.4 percent and is followed by microfacies 2 (14.2%), microfacies 4 (5.2%) and microfacies 5 (4.4%).

The measured parameters are the same as in the Morrowan, however calcispheres have become abundant enough to be tabulated. The average values of size and frequency have been obtained as previously.

Crinoid frequency varies in a straight line from an average of 14 fragments in microfacies 1 to 96 in microfacies 4. Crinoid clastclty is nearly a straight line but with a change of slope in microfacies 2. There is a strongly marked in-
increase in size of crinoid debris with increase in environmental energy, from .46 mm in microfacies 1 to .72 mm in microfacies 4.

Size and frequency curves of crinoids show a general parallelism as well as a linear relationship with the environmental energy. These conditions indicate a preferred habitat above wave base in shallow and high energy environments, much shallower than in the Morrowan. Crinoid debris as such disappear in microfacies 5 as an effect of intense oolitization processes which have changed all the organic debris into oolites.

Brachiopods do not show a linear variation but increase from six per unit area in microfacies 1 to fifty-one in microfacies 3 and back down to eighteen in microfacies 4. This is due to their preference for a relatively quiet environment from wave base to just below it. The brachiopods in the Morrowan reached their peak of frequency in slightly deeper conditions (microfacies 2).

Bryozoans show a trend parallel to that of the brachiopods with a maximum frequency in microfacies 3, but are fewer in number. This is a different behavior than the bryozoans of the Morrowan which had their maximum frequency in more agitated conditions (microfacies 4).

Arenaceous benthonic foraminifers trend from one per unit area in microfacies 1 to twenty in microfacies 3 and 4. The curve is similar to that of crinoids indicating a preferred habitat in shallow and high energy environments.

Calcispheres vary from one per sample in microfacies 1 to ten in microfacies 3 and back down to three in microfacies 4. These fragile pelagic organisms survive best in the environment of limited activity situated below wave base (Carozzi, 1961; Cars and Carozzi, 1965). Ostracodes behave as free floating organisms and display a bimodal distribution. They range from three in microfacies 1 to twelve in microfacies 2 down to ten in microfacies 3 and back up to twelve in microfacies 4. This is due to their observed tendency to occur as single valves in non-pelletoidal rocks, and as complete shells in pellet-bearing samples. The peak in microfacies 2 is due to the better survival potential of single valves in a lime mud deposit while the second peak in microfacies 4 reflects the better survival of complete shells in an agitated environment...

Pellets are rare in microfacies 1 and 2 but increase in frequency rapidly to 564 in microfacies 3 and 1070 in microfacies 4, finally decreasing to 184 in microfacies 5. Pellet clasticity increases from microfacies 1 through 2 and reaches its peak at 1.07 mm in microfacies 3, declining from there to .66 mm in microfacies 5.

Like in the Morrowan pellets account for the bulk of those in microfacies 1 and 2, while lithic and algal coated pellets form the vast majority in microfacies 3 and 4. The maximum frequency in microfacies 4 results essentially from intraformational reworking. The sharp decline in frequency in microfacies 5 is due to intense oolitization through which most of the lithic pellets became nuclei of oolites. The decrease in clasticity in microfacies 4 and 5 is due to the abrasion and rounding of the lithic pellets by the active environment.

Oolites are found only in microfacies 5. Their nuclei consist essentially of pellets and crinoid fragments.

Detrital quartz varies in opposition to all previous parameters. Its maximum frequency occurs in microfacies 1, 390 per unit area, with a steady straight line decrease to 43 in microfacies 4. Its clasticity varies in opposition to frequency ranging from .062 mm in microfacies 1 to 0.82 mm in microfacies 4. This is the typical behavior of detrital particles in a poorly supplied environment (Carozzi, 1958). Like in the Morrowan the fine silt-size quartz is winnowed out of the agitated environment and concentrated in quiet water leaving only a few larger grains in the high energy microfacies.

Pyrite declines from a high of 160 in microfacies 1 to 15 in microfacies 4, following the quartz frequency curve. This is a typical behavior which emphasizes the close relationship between these two minerals of extrabasinal origin (Carozzi, 1958). The relative bathymetric curve shows a steady increase in energy level and decrease in water depth. The reciprocal relationships between microfacies characteristics may be summarized as follows:

Microfacies 1: Quiet conditions of deposition with peaks in the frequency of pyrite and detrital quartz, and very few fossil debris.

Microfacies 2: Weakly agitated conditions with increased abundance of all the organic components. Note the frequency peak of the ostracodes (single valves) and the predominance of fecal pellets.

Microfacies 3: Moderately agitated conditions corresponding to the frequency peaks of brachiopods, bryozoans, arenaceous benthonic foraminifers, calcispheres, and to the maximum size of lithic pellets.

Microfacies 4: Agitated conditions with frequency peaks of crinoids, ostracodes (complete shells), arenaceous benthonic foraminifers, and lithic pellets. To the clasticity peak of detrital quartz is related a sharp drop in the size of the lithic pellets.

Microfacies 5: Well agitated conditions corresponding to a predominance of oolites with almost complete disappearance of crinoid and brachiopod remains.
GENERAL BATHYMETRIC RELATIONSHIPS

Although the ideal cycles, just described, represent the ideal vertical sequence of the rocks studied, the same relationship may be expressed in a horizontal form by application of Walther’s Law (1894). The horizontal representation (fig. 7) shows in particular the fundamental relation, previously mentioned, between the position of wave base on one side and the distribution of organic components and types of interstitial material on the other side, both of which expressed by the various microfacies. The interstices of the carbonates deposited above wave base are filled by a cement of clear calcite spar, while those below are filled by a matrix of silt-size bioclastics or consist almost entirely of that same matrix with scattered sand-size organic fragments. The inferred relationship between microfacies and the environment is summarized below.

Microfacies 0: is a calcisiltite deposited in very quiet marine conditions and with poor circulation, which results in a sparse fauna.

Microfacies 1: is a calcisiltite with scattered sand-size organic debris and is deposited in quiet water with limited circulation and containing a restricted faunal assemblage.

Microfacies 2: is a calcisiltite with abundant scattered sand-size organic debris deposited in weakly agitated conditions, and still below wave base. The groundmass is a microcrystalline calcite mud, but the larger bioclasts and more extensive fauna suggest improved circulation and conditions more amenable to life.

Microfacies 3: is a grain-supported pelletoidal biocalcarenite with calcisiltite matrix. This microfacies has been deposited in moderately agitated conditions corresponding practically to wave base level. It contains the most abundant fauna and the largest variety of species.

Microfacies 4: is a grain-supported biocalcarenite with sparry calcite cement, and is a reflection of agitated conditions above wave base. The fauna is more limited in variety than in microfacies 3, but has about the same frequency.

Microfacies 5: is a grain-supported oolitic calcarenite with sparry calcite cement, deposited in the most agitated conditions attained in the sequence. This microfacies consists essentially of oolites with organic and pelletoidal cores.

Microfacies 0a–4a occur in identical environments to microfacies 0–4, but display abundant angular grains of detrital quartz, brought into the carbonate environment at a particular time of its evolution.

DESCRIPTION OF THE CYCLES OF THE MORROWAN

The Morrowan (fig. 8) like the overlying section consists of numerous repetitions of its constitutive microfacies,2 which in fact represent more or less complete variants of the ideal cycles described above. These changes of environment are summarized by the oscillations of the relative

2 Three tables listing the average parameter values for all the described microfacies and 30 figures giving the detailed graphical representation of the variations of all the measured parameters as well as gross lithological data which could not be included in figures 9 and 10 for reasons of graphical scale have been deposited as Document 9216 with the American Documentation Institute, c/o Library of Congress, Washington 25, D. C. Copies may be secured by citing the Document Number and remitting $5.00 for photocopies or $2.25 for 35 mm microfilm. Advance payment is required.
Fig. 8.—Example of detailed graphical representation of the microscopic parameters for a typical portion of the Morrowan.
bathymetrical curve, which in this particular environment expresses also the variations of energy level (fig. 9).

The Morrowan section consists of 46 complete cycles, each reflecting changes from relatively deep water to shallow water and back to deep water conditions. The climax of each cycle is the shallow water stage which for reference purposes has been numbered 1 to 46 from bottom to top.

The cycles of the Morrowan may be divided into three major groups according to the characteristics of their relative bathymetric curves and the distinct environments they represent. Cycles 1 to 15 are short period curves with high amplitudes. The relative position of the curves reflects a high energy and shallow water environment reaching several times conditions for the generation of oolites.

The second group, consists of cycles 16 to 29 which are long oscillations with amplitudes, periods and relative positions indicating lower energy and greater depth. These conditions correspond to a decline in faunal frequency and variety.

The last group includes cycles 30 to 46 which display high amplitudes and short periods associated with a considerable variation in the relative position of the curves. Although a temporary shallowing of the sea is apparent, the general trend is still a continued deepening of the environment. This last group of cycles is characterized by a massive inflow of fine-grained detrital quartz which began in cycle 29 but was preceded by a few isolated ones in cycles 2, 3, 12 and 23. This abundance of detrital quartz had a profound effect on the conditions of deposition and resulted particularly in a further distinctive reduction of the fauna.

The environmental evolution of the Morrowan (fig. 9, A) shows a general trend toward increasingly deeper and quieter conditions which are emphasized by the envelope curve drawn as a tangent to the maxima of the 46 constitutive cycles (fig. 9, B) and by a second envelope curve drawn as a tangent to the preceding one (fig. 9, C). In conclusion the Morrowan represents a major transgression.

DESCRIPTION OF THE CYCLES OF THE ATOKAN-DESMOINESIAN-LOWER MISSOURIAN INTERVAL

This stratigraphic interval like the underlying Morrowan consists of numerous cyclical repetitions of its constitutive microfacies. A total of 32 complete cycles have been recognized (fig. 10) which may be divided into 2 major groups according to the characteristics of their relative bathymetrical curves and the distinct environments they represent. It should be pointed out that this stratigraphic interval corresponds to distinctly shallower conditions than those of the Morrowan as shown by the absence of microfacies 0 and the greater frequency of microfacies 5, the shallowest of the sequence.

Cycles 1 to 15 build the first group in which a middle section (cycles 3 to 13) consists of short period curves with high amplitudes preceded and followed by longer period cycles. The relative position of the curves indicates intermediate depth conditions which never extend above microfacies 4. Nevertheless the environment is shallower than the underlying terminal portion of the Morrowan. Cycles 16 to 32 show a predominance of long period cycles but with a great variety in amplitudes although in many instances the shallowest conditions favorable to the formation of oolites were generated. This group of cycles corresponds to a much shallower environment than the underlying one.

The generalized bathymetric curve and its two envelope curves (fig. 10, A, B, and C) emphasize the fact that the upper portion of the section (Upper DesMoinesian and Lower Missourian) is generally shallower than the lower part (Atokan and Lower DesMoinesian). This gradual trend toward an increasingly shallower environment corresponds to a general regression which combined with the transgression displayed by the underlying Morrowan builds a complete major geological cycle.

CONCLUSIONS

The detailed petrographic investigation of a stratigraphic interval of 1846 feet ranging from Lower Morrowan to Lower Missourian has demonstrated the cyclic character of the miogeosynclinal limestone sequence called the Bird Spring Group.

Eleven distinct microfacies are repeated in 78 complete cycles which correspond to oscillations in energy level and related water depth expressed by size and frequency variations of environment. The cycles are variants of three fundamental types, one of which displays the effects of a massive inflow of fine-grained detrital quartz.

The environmental analysis shows that the evolution of the characteristics of the 46 cycles forming the Morrowan corresponds to a gradual transgression with a massive inflow of detrital quartz coinciding with its maximum. The Atokan-DesMoinesian-Lower Missourian interval consists of 32 cycles with an evolution of their characteristics indicating a gradual regression. Consequently, the investigated sequence forms a complete major cycle of transgression and regression.
Fig. 9.—Generalized bathymetric curves of the Morrowan.
Fig. 10.—Generalized bathymetric curves of the Atokan-DesMoinesian-Lower Missourian interval.
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