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Brigham Young University Geology Studies

Contents

Lower Ordovician Patch Reefs in Western Utah*

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ABSTRACT.—Small linear patch reefs in the Fillmore Formation (Lower Ordovician) of western Utah show an early occurrence of complex reef communities. The reefs are separated laterally at regular intervals of approximately 10 m and occur as discontinuous northeast-trending parallel mounds of fossiliferous, micritic limestone. Reef core dimensions are 1 to 1.5 m high, 2 to 3 m wide, and up to 30 m long.

Stromatolitic algae stabilized the substrate and provided a base for attachment of reef-building organisms. Anthaspidellid sponges, comprising one of the oldest varied assemblages of lithistid sponges in North America, and *Calathium,* a problematic organism considered a possible receptaculitid algae, constructed a rigid framework that bound carbonate sediment. Occurrences of trilobites, brachiopods, gastropods, nautiloids, crinoids, and burrowing structures within the reefs reveal a complex community of accessory organisms.

Interreef facies consists of ripple-marked bioclastic limestone and intraformational conglomerate with echinoderm debris and trilobite hash supporting intraclasts of micrite and fine bioclastic limestone. Abraded pieces of sponges and *Calathium* occur in the interreef beds near reef cores. Lateral contacts between reef cores and interreef facies have sharp contrast. Blocks fallen from reefs during Lower Ordovician time also have sharp contact with surrounding interreef bioclastic limestone, attesting to the rigidity of the patch reefs during reef growth.

Overlying and underlying shale indicates an overall period of low-energy conditions with a brief interruption of higher-energy conditions punctuated by reef growth and followed by a return to a low-energy environment and reef burial.

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INTRODUCTION

Because Cambrian and Ordovician multielement reefs are rare in North America, little is known of early reef development or of interactions among invertebrate populations with reef potential. Extensive multielement early Paleozoic reefs are remarkably well exposed in the Fillmore Formation of the Lower Ordovician Pogonip Group in the southern House Range and Yersin Hills in Millard County, Utah, and are the topic of the present investigation. These Lower Ordovician reefs contain a variety of organisms. Sponges, stromatolitic algae, and *Calathium* (a problematic organism considered a possible receptaculitid algae) are the primary reef builders. Vagrant or accessory forms show great diversity and include trilobites, nautiloids, brachiopods, crinoids, gastropods, and burrowing forms. Paleoecology of the organisms constructing and inhabiting the reefs is the primary emphasis in this study and only limited systematic paleontology has been done in this work.

The reef horizon crops out for approximately one mile along strike, with the reefs occurring laterally at regular intervals. Dense micritic fossiliferous limestone of the reefs contrasts markedly in lithology with interreef beds of bioclastic intraformational conglomerate. This contrast of lithologies provides excellent opportunity for detailed study of the reefs because interreef rocks weather more readily, leaving the resistant micritic reef bodies protruding from the outcrop.

Location and Geologic Setting

The patch reefs of this study are located on the eastern margin of the Lower Ordovician miogeosyncline (Hintze, 1973a). Shallow tropical seas, much like those found on the modern Bahama Bank, are believed to have covered much of western Utah during the time of reef development.

These reefs are extensively exposed at regular lateral intervals (Pl. 1, fig. 1) 52 miles southwest of Delta, Utah (Text-fig. 1), one mile north of U.S. Highway 50-6, T. 20 S., R. 13 W., in an area called the Amphitheater (Text-fig. 2).

The reef horizon occurs in the Fillmore Formation (Text-fig. 3) which consists of 548 m of dominantly intraformational conglomerate interbedded with shale and calcarenite and with minor small sponge-algal reefs at several different horizons within the formation. The unit characteristically weathers into thin-bedded ledges of intraformational conglomerates 25 to 100 cm high separated by slopes formed on interbedded shale.

Hintze (1951) named the Fillmore Formation and later divided it into six informal members (Hintze, 1973b). These members are, from the bottom up: basal ledge-forming limestone member, slope-forming shaly siltstone member, light gray ledge-forming member, brown slope and ledge member, calcarenite member, and *Calathium,* calcisiltile member. Hintze (1951) recognized fifteen distinct trilobite zones, A through N, in the Pogonip Group of western Utah, seven of these, zones D through I, occur in the Fillmore Formation.

The reef horizon of this study occurs in the lower part of the Fillmore Formation in the slope-forming shaly siltstone member, within trilobite zone G-1. Braithwaite (1969) studied the graptolites of the Pogonip Group and measured a section in the Amphitheater. He placed the reef horizon of this study 198 to 199 m above the base of the Fillmore Formation.

R. L. Ethington (1974, pers. comm.) of the University of Missouri has identified an assemblage of conodonts from the reef horizon that includes
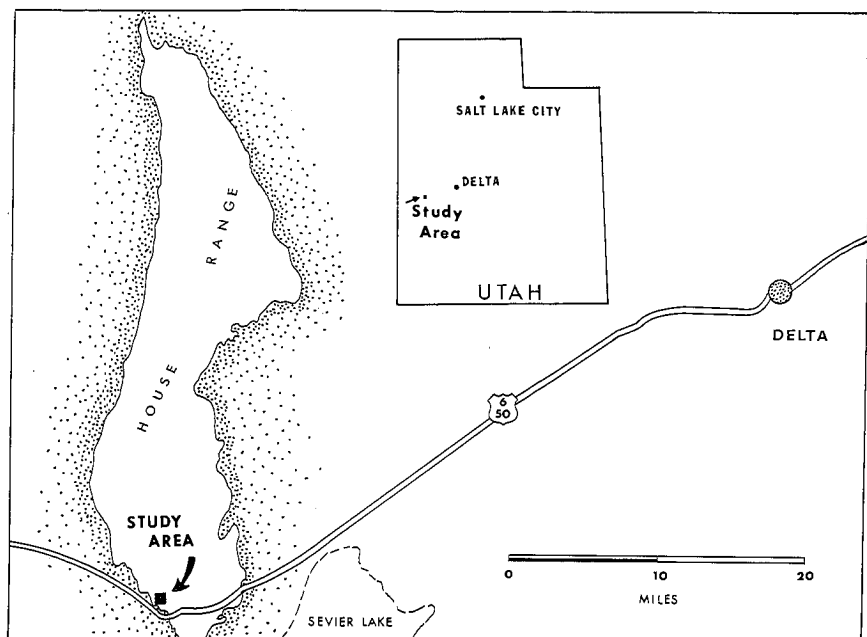
TEXT-FIGURE 1.—Index map, showing location of study area.

Ulrichodina wisconsinensis (Furnish) and *Distacodus stola* (Lindstrom) and other specimens representing *Drepanodus* and *Scolopodus*. These forms represent a typical zone G-1 conodont assemblage.

Previous Work

Extensive literature describes Paleozoic reefs and reef organisms, particularly younger Paleozoic reefs (Bain, 1967; Jamieson, 1969; Myers, 1972). Cambrian stromatolitic structures have received attention in various areas of North America (Rezak, 1957; Kepper, 1972). Early Ordovician mounds have been studied and described in Texas and Oklahoma (Ham and Toomey, 1966; Toomey, 1970). These structures contain *Calathium* and *Archaeoscyphia*, a lithistid sponge (as do the western Utah reefs). Toomey (1970) described a three-stage developmental history of these early Ordovician mounds: a pioneer colony of dominantly rooted cystoids, a middle stage of stromatolites and algal-like components, and a climax community of the questionable coelenterate *Pulchrilamina*. Pitcher (1964) studied Middle Ordovician (Chazyan) reefs that appear to be transitional between Silurian and earlier reefs but notes that pre-Chazyan reefs are rare. Alberstat and Walker (1973) described a four-stage developmental pattern of later Ordovician reefs in Tennessee: a stabilization stage of pelmatozoan debris, algae, and bryozoans; a colonization stage of stromatoporoids, bryozoans, and pelmatozoan debris; a diversification stage of corals, stromatoporoids and bryozoans; and a domination stage of stromatoporoids and bryozoans. Alberstat and Walker related this pattern to the Chazyan reefs of Pitcher (1964) and older Ordovician mounds of Toomey (1970).

Organisms associated with the western Utah reefs have been studied by several workers: trilobites (Hintze, 1952; Demeter, 1973; Young, 1973), graptolites (Braithwaite, 1969), brachiopods (Jensen, 1967), nautiloids (Flower, 1968), conodonts (Ethington and Clark, 1971), and crinoids (Lane, 1970). Nitecki (1972) has studied the problematic *Calathium* from younger rocks and has described it as a receptaculitid algae. Bassler (1941) described a younger, though related sponge fauna from Ordovician rocks in central Nevada. These and other western Utah reefs have been briefly described by Roberts (1968). Rigby (1965) noted early sponge contributions to the development of these and younger western Utah Lower Ordovician reefs.

Methods

Field and laboratory work was conducted in the fall of 1973 and winter of 1974. Reef trends and spatial relationships were determined by using a Brunton compass and 100-foot steel tape. Continuous linear intercept traverses were conducted across reef structures and interreef beds using a 10-foot sample interval. Detailed stratigraphic columns of beds lying immediately over and under the reef horizon were constructed to aid in interpretation of events preceding and following reef development. Oriented samples of reefs were taken for laboratory study. These were etched with acetic acid to aid in description of interpretation of reef fabrics. Acetate peels up to 5 x 5 inches were made of polished slabs. Some peels were printed as 8 x 10-inch photographs using the peel as a
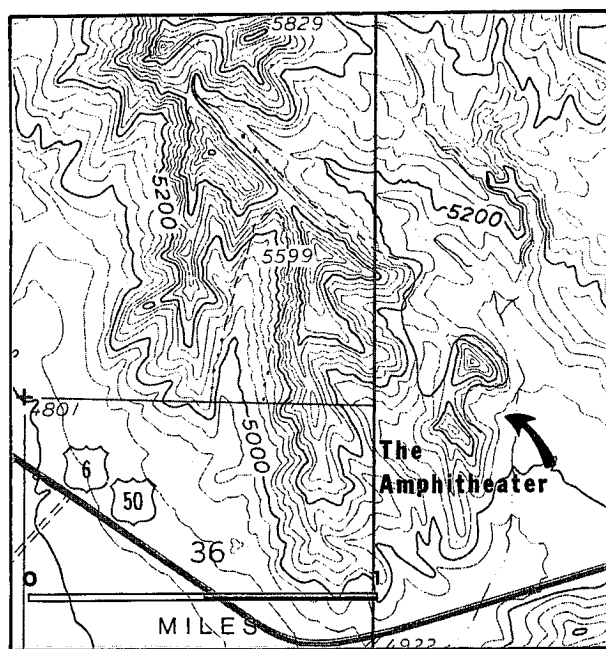
TEXT-FIGURE 2.—Outcrop map of reef horizons. Dashed line indicates change to biostromal development.
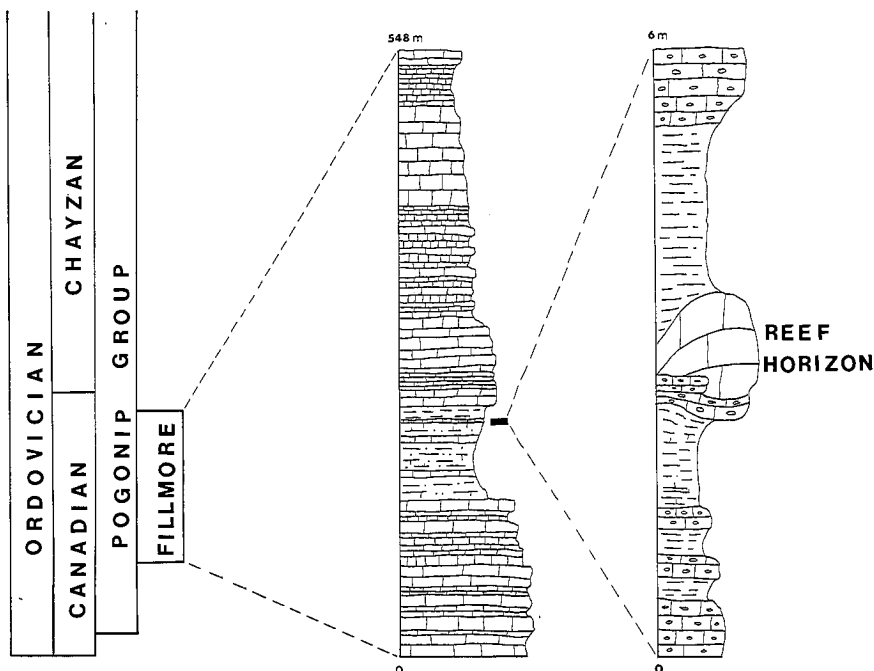
TEXT-FIGURE 3.—Stratigraphic column giving location of reef horizon.

negative. Large, 2 x 3-inch, thin sections were made of several samples to determine microfabrics, petrology, and organism-to-organism relationships.

Terminology

Confusion has long plagued geologists on exactly what constitutes a fossil reef. Recent papers have reviewed the problem and the literature in an attempt to standardize terms and definitions related to reef structures (Heckel, 1974). Dunham (1970, p. 1931) divides reef terminology into two headings: ecologic reefs and stratigraphic reefs. The reefs of this study are considered in the context of Dunham's ecologic reefs as well as meeting C. Braithwaite's (1973, p. 1113) criteria by which fossil reefs can be recognized: "1. The structure can be shown to have risen appreciably above the sea floor at the time of maximum organic growth. 2. The structure was wave resistant, lying within the zone of wave action. 3. The organisms present include frame-building forms which can be shown to have functioned as frame-builders. 4. Both the frame-builders and associated vagrant organisms show a zonation consequent upon their near-surface position."

Carbonate classification used in this study is a modified form of that suggested by Folk (1959).

Acknowledgments

National Museum aided in brachiopod identification; Dr. Lee Braithwaite identi-
fied graptolites; Dr. N. Gary Lane of the University of Indiana gave preliminary
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LITHOLOGIES ENCOUNTERED

Reef Horizon

A petrologic study of the reef horizon reveals two distinct facies, a reef core
or micritic facies and an interreef or bioclastic facies.

Reef Core Facies.—Individual sausage-shaped reef cores throughout the exposed
belt are 1 to 1.5 m high, 2 to 3 m wide, and up to 30 m long. They consist of
a medium to medium-dark gray, dense, micritic, porcelaneous-weathering lime-
stone (Pl. 1, fig. 2).

Reef cores are characteristically crusted by a thin yellow brown iron-oxide-
stained rind of silicification that penetrates only a few millimeters into the dense
micritic limestone (Pl. 1, fig. 3). Fossils weather into relief in places on the
reef due to the outer silicification. Smooth to groove-marked or slickensided
surfaces are common on the silicified surfaces where differential compaction has
caused relative movement of overlying shales during early diagenesis. Reef cores
are dissected by joints running parallel to Tertiary Basin and Range features.
Silicification does not penetrate joints and does not crust recently exposed reef
surfaces resulting from weathering during uplifts and exposure following Basin
and Range diastrophism. The crust of silicification is present only where reef
cores have been in contact with overlying shale and appears to outline a Lower
Ordovician erosional surface. Silicic fluids may have had their origin from over-
lying shales and migrated along the reef core upper shale contact after being
compressed out of the shales due to compaction and settling.

Within the reef cores, originally siliceous sponge spicules have been altered
to calcium carbonate. *Calathium,* brachiopods, trilobites, and other skeletal
material have been altered to sparry calcite, while stromatolitic algae and matrix
have remained very fine microcrystalline calcite.

EXPLANATION OF PLATE 1
FIELD VIEWS AND PHOTOMICROGRAPH OF REEF-INTERREEF CONTACT

FIG. 1.—Outcrop of reef cores, showing lateral separations.
FIG. 2.—Fabric of reef cores as seen in the outcrop.
FIG. 3.—Reef core surface crusted by thin rind of dark iron-oxide stained silicification.
FIG. 4.—Photomicrograph of sharp contact between interreef bioclastic limestone and fos-
siliferous, micritic reef block fallen from reef during Lower Ordovician time. Mean-
dering burrow occurs in the reef block, x2½.
FIG. 5.—Loading and compaction of the lower shale resulting in sagging of the intra-
formational conglomerate reef supporting bed.
FIG. 6.—Stromatolitic-bound intraclasts providing the foundation for a reef core.
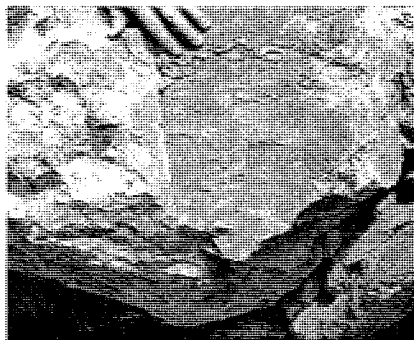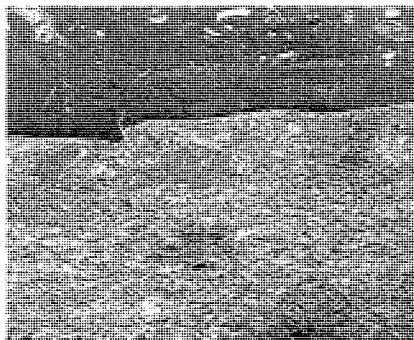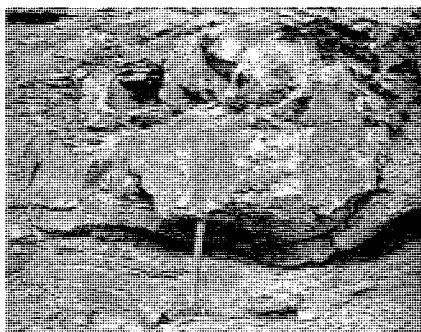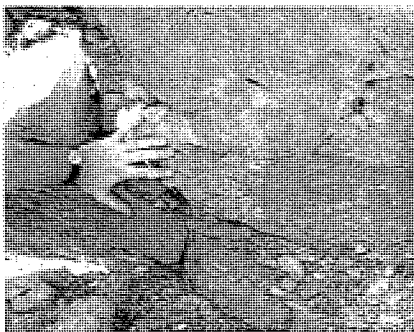
PLATE 1

Sharp contacts (Pl. 1, fig. 4) between obviously lithified solid reef core blocks, 20 to 30 cm high and wide, fallen from reefs during Lower Ordovician time, and surrounding interreef beds indicate the rigid, firm nature of the reef materials during their period of growth. One fallen reef block shows interior organisms oriented upside down with subsequent growth of individual organisms oriented upright occurring on the same block where attachment of reef organisms and growth took place on the block after it had fallen from a reef core.

Interreef Facies.—Laterally equivalent rocks of the reef cores are bioclastic limestone and intraformational conglomerate. The bioclastic limestone consists chiefly of echinoderm debris and trilobite hash supporting intraclasts in varying amounts and cemented by calcite spar. The interreef facies has sharp contacts laterally with contemporaneous reef cores. Reef cores rise approximately 1 m above equivalent bioclastic rocks. Abraded fragments of sponges and *Calathium* occur in bioclastic rocks adjacent to reef cores. Bedding planes of the interreef facies are ripple marked, and beds coarsen in grain size downward into an intraformational conglomerate bed underlying the reef cores. Algal material is abundant throughout the bioclastic limestone. Trilobite hash and echinoderm fragments have been altered to sparry calcite. The bioclastic limestone is tightly cemented by sparry calcite with some limonitic grains occurring in the matrix.

Overlying and Underlying Beds

Intraformational Conglomerate.—A thin layer of intraformational conglomerate, 15 to 25 cm thick, underlies the reef cores throughout the study area. The unit is medium-light gray to light olive gray. Pebble diameter is variable, ranging from 4 cm to coarse sand-sized particles of 1 mm. The conglomerate grades into overlying finer-grained bioclastic interreef beds, where it thickens to 30 to 45 cm. Intraclast pebbles are all well rounded and are discoidal to flat. Pebbles are generally microcrystalline calcite or fine-grained bioclastic limestone. The unit is atypical of units in the Fillmore Formation, having a low silica content.

The intraformational conglomerate bed has sagged as much as 50 cm downward under the dense reef masses into the underlying shale (Pl. 1, fig. 5). This is considered to be related to adjustment to differential loading in the underlying shale.

Contact between the conglomerate unit and overlying reefs shows sharp contrast in most exposures; however, some reef cores contain intraclasts in their lower portions (Pl. 1, fig. 6). Contact between the intraformational conglomerate and overlying bioclastic interreef beds is difficult to differentiate because of the gradational nature of the contact. Generally the intraclasts become smaller in the upper interreef bed approaching coarse sand grain size. Trilobite hash and echinoderm debris support intraclasts of intraformational conglomerate with calcite spar as the cement.

Lower Shale.—A thin-bedded medium-light gray to light olive gray, calcareous, clay shale lies immediately under the intraformational conglomerate. It is approximately 2 m thick and contains thin calcareous silty layers. This lower shale unit contains *Dictyonema* and other dendroid graptolites that are the subject of a study by L. Braithwaite (1969). Fragments of asaphid trilobites occur with the dendroids. Surfaces of shale partings are uneven and mottled. Repichnid burrows 5 mm in diameter are compressed on some bedding surfaces. Occasional discoidal shaly pebbles occur throughout the unit.
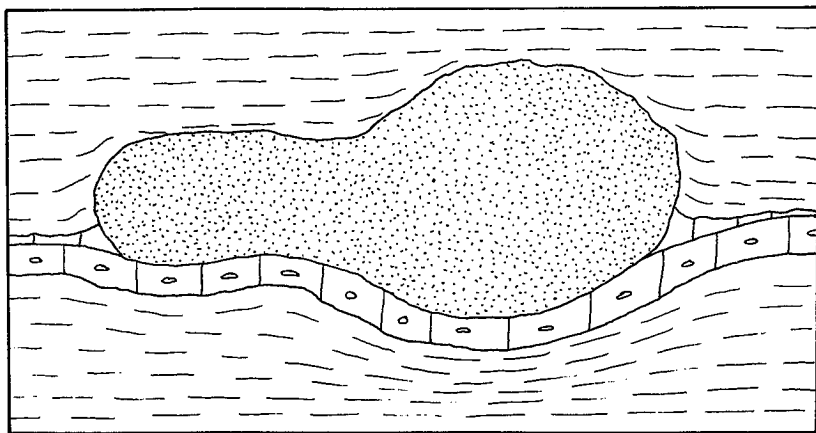
TEXT-FIGURE 4.—Idealized cross section of a reef core 1.5 m high, showing its relationship to adjacent rocks.

Upper Shale.—A thin-bedded, medium gray to medium-dark gray, calcareous, clay shale approximately 1.5 m thick overlies the reef core and interreef beds. This upper shale unit lies flat on interreef beds but progressively overlaps reef cores until it buries the cores. The reefs penetrate approximately one meter upwards into the overlying shale (Text-fig 4). Surfaces of shale partings are characteristically flat and even. Texture of the overlying shale is less silty than that of the underlying shale. Trilobite fragments of *Psalikilus,* the small articulate brachiopod, *Glyptotrophia,* and *Westonia* and other small inarticulate brachiopods occur in the upper shale. Burrows in the shale are lined or filled with skeletal material.

SEDIMENTARY STRUCTURES

Bedding planes of interreef facies and the intraformational conglomerate are ripple marked, and intraclast pebbles are truncated by ripple-marked erosional surfaces (Pl. 2, fig. 2). Osmond (1963) studied ripple-marked erosional surfaces on Lower Ordovician pebble conglomerates of the Garden City Formation in the Stansbury Range, Utah. He described the ripple-marked surfaces as being scoured by the motion of silt-laden bottom waters. Osmond states that the movement of pebbles did not take place as normally occurs in loose clastics and that crests were rounded and troughs cut into an indurated pebble limestone. The intraformational ripple-marked surfaces of this study closely resemble those of Osmond's study. Pebbles are rounded except where they are beveled at ripple-marked surfaces, and the arrangement of the intraclasts is independent of the ripple-marked surface whether positioned in the troughs or on the ridges of the surface. The ripple-marked surfaces of this study, however, are not overlain by silicious silt, the agent considered necessary by Osmond to cut through hard indurated limestone pebbles.

The ripple-marked conglomerate surfaces of this study are considered to be the result of scouring on *in situ* pebbles as described by Osmond (1963), not of movement by pebbles into ripple crests. The pebbles, however, are considered to have been soft, not indurated as suggested by Osmond (1963, p. 106) for those pebbles of his study.
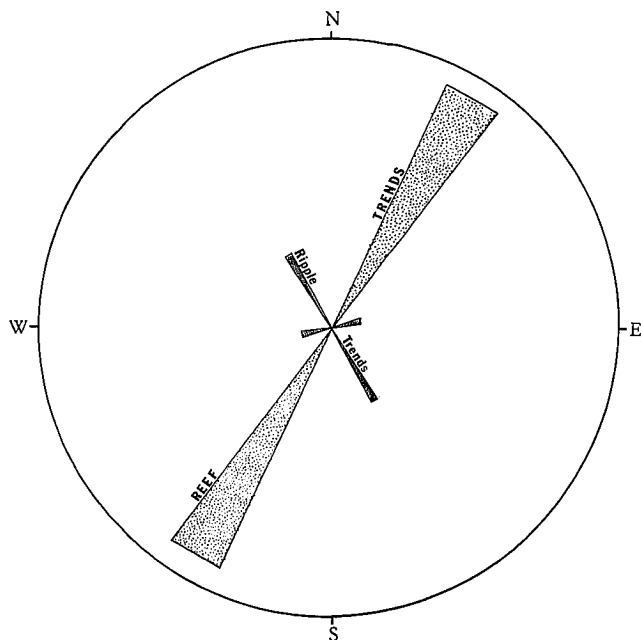
Text-figure 5.—Rose diagram of 17 reef lineament trends and 7 interreef bed ripple-mark trends.

In contrast to ripple-marked surfaces formed on the intraformational con-glomerate beds, ripple marks formed on the bedding surface of the interreef clastic carbonate bed were formed in loose drifting material, and grains were moved by currents from ripple troughs to ripple crests. Unfortunately, talus cover makes observations of ripple marks on interreef beds difficult because of limited exposure.

Directional trends of ripple marks at 7 localities are plotted on a rose dia-gram in relation to reef trends (Text-fig. 5). Two ripple-mark trends were observed. The dominant one at 5 localities has a direction of N 31° W and

EXPLANATION OF PLATE 2
PHOTOMICROGRAPHS OF SEDIMENTARY STRUCTURES AND REEF FABRICS
AND A REEF CREST ASSEMBLAGE

Fig. 1.—Photomicrograph of graded bedding in the interreef beds, x2½.
Fig. 2.—Photomicrograph of a ripple-marked erosional surface truncating intraclasts of an intraformational conglomerate, x2½.
Fig. 3.—Photomicrograph of *Calathium* attached to a tubular lithistid sponge and sur-rounded by stromatolitic algae, x2½.
Fig. 4.—Photomicrograph of a lamellar lithistid sponge encrusting *Calathium*, x2½.
Fig. 5.—Crinoid-nautiloid-sponge assemblage occurring in an Ordovician erosional depres-sion on a reef crest. "Cake platter" sponge is 8 cm in length.
Fig. 6.—Photomicrograph of sponge fragment incorporated by algal growth, x2½.
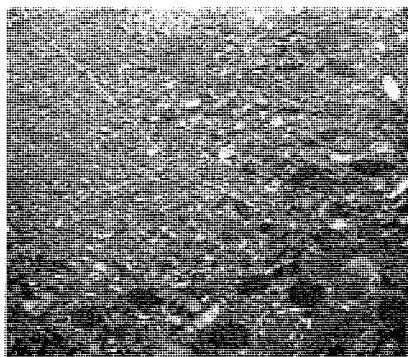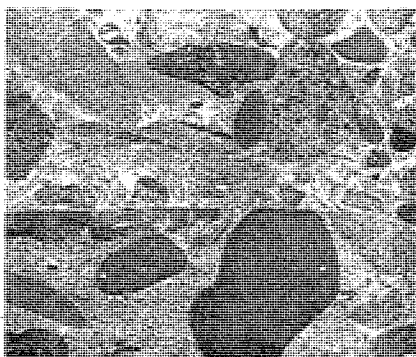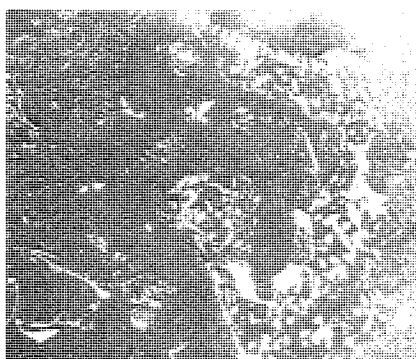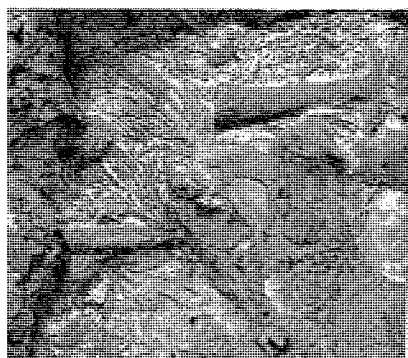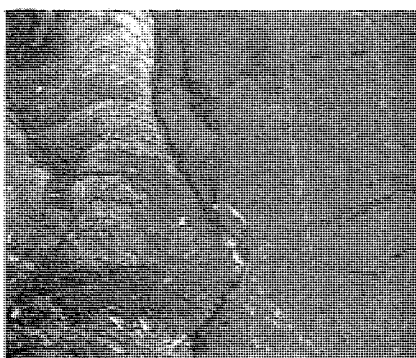
PLATE 2

a range of 4 degrees with currents moving to the northeast. The subdominant trend, measured at 2 localities, has a direction of N 74° E and a range of 3 degrees, with currents moving to the southwest. Both subdominant ripple marks were associated with dominant trend ripple marks as interference ripple marks, with ripple-crest amplitudes smaller than amplitudes of the dominant ripple-trend crests.

Graded bedding is present in the intraformational conglomerate and overlying interreef beds (Pl. 2, fig. 1). Although a general fining of sediments takes place from the bottom of the intraformational conglomerate upwards to the top of the interreef beds, no single continuous graded structure occurs. Grading bedding attributed to single sedimentary pulses are observed only through thicknesses of about 8 cm. The intraformational-conglomerate–interreef-bed sequence is composed of 3 or 4 of these 8 cm graded bedding structures. Those shown (Pl. 2, fig. 1) in the photomicrograph occur in the upper part of the interreef bed.

REEF TRENDS AND SPATIAL RELATIONS
Reef Trends

Most of the 57 studied reef cores are exposed in cross section where the beds have eroded normal to the long axis of the reefs; only 17 are exposed so that the longitudinal axes of reef cores are evident. One reef is exposed for a length of 30 m. Axial directions of these 17 reef cores are plotted on a rose diagram (Text-fig. 5). Reef trends average N 31° E with a total range of 12°.

Reef Spatial Relations

A graphic representation of lateral separation of 16 reef cores normal to their axial trends is plotted in Text-figure 6. Modal distance of separation is approximately 10 m. Abnormal variance in wider separations of the reefs, as shown in Text-figure 6, is possibly the result of talus cover burying existing intervening reef cores. Such interpretation is supported by the occurrence in some places of micritic reef blocks in loose debris at approximately the modal separation distance. *In situ* reef material was not seen, however. Another possible explanation for abnormally wide separations of reef cores is that the traverse passed through one of the many gaps in the discontinuous cores. A graphic representation of reef distribution for this area would be expected to approach a normal bell curve with an approximate range of separation of 5 to 15 m if all the reef cores were exposed.

Reef cores occur regularly for at least 900 m along a straight-line distance across the width of the reef horizon exposure normal to the average reef trend of N 31° E. Reef structures become less prominent to the northwest and are not easily distinguishable from biostromal units because of talus cover. Where the bed is well exposed, however, micritic reef structures appear as biostromal structures 35 to 40 cm thick. Horizontal separation measurements of the low mounds were not obtained because of widespread talus cover.

A straight line distance from the most northeasterly reef core exposure to the most southwesterly, parallel to the reef trends, is 400 m.

INTERPRETATION OF LOCAL LOWER ORDOVICIAN TOPOGRAPHY

Data represented on the graphs in Text-figures 5 and 6, along with observations made in the field, were used to construct a block diagram (Text-
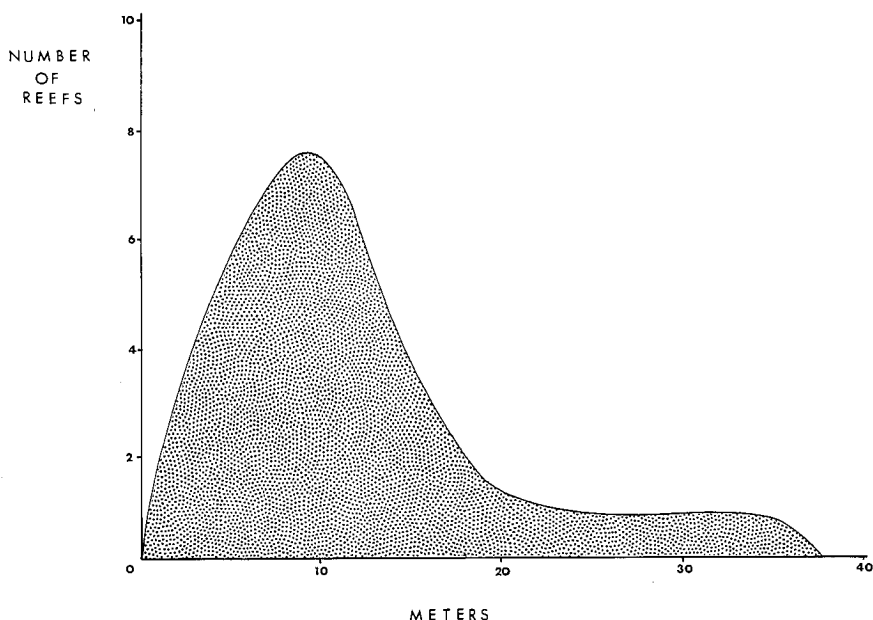
TEXT-FIGURE 6.—Line graph showing distances of lateral reef separation on the reef horizon.

fig. 7) showing probable paleotopographic relations during Lower Ordovician time. Reef growth developed in a reef field containing 80 to 100 parallel, discontinuous rows of reefs over a width of 900 m with a modal-reef separation distance of 10 m. Actual extent of the reef field is unknown, but probably it included a greater area during Lower Ordovician time, particularly extending to the southeast and south of the study area.

Uniform alignment of the reefs was produced by preferred orientation and density of the bottom-stabilizing or sediment-trapping organisms. Such preferences were a direct effect of environmental factors, in this study thought primarily to be existing currents. Current directions, as indicated by ripple trends measured in the top of the interreef beds, were likely affected by the reefs, rather than being a cause of reef lineaments. Currents that existed at the inception of the reefs are probably not reflected by these readings at the top of the interreef beds and have left little impression other than reef alignment. Currents that existed in Lower Ordovician seas controlling reef lineaments may have resulted from prevailing winds.

The Ordovician equator is thought to have a trend passing through the central United States in a northeasterly direction (Irving, 1964; Whittington, 1972), somewhat parallel to the trend of these reefs. The western Utah area in which these reefs developed would have been the 5° to 10° north latitude where low-latitude equatorial winds may have had an effect on current directions that affected reef lineaments (Text-fig. 8). Modern low-latitude winds, the trade winds, significantly influence modern currents, causing a strong equatorial drift of westward-moving water parallel to the equator.

Lower Ordovician shoreline configuration may also have had an effect on current directions and reef lineaments. To the east of the reef belt, the 0
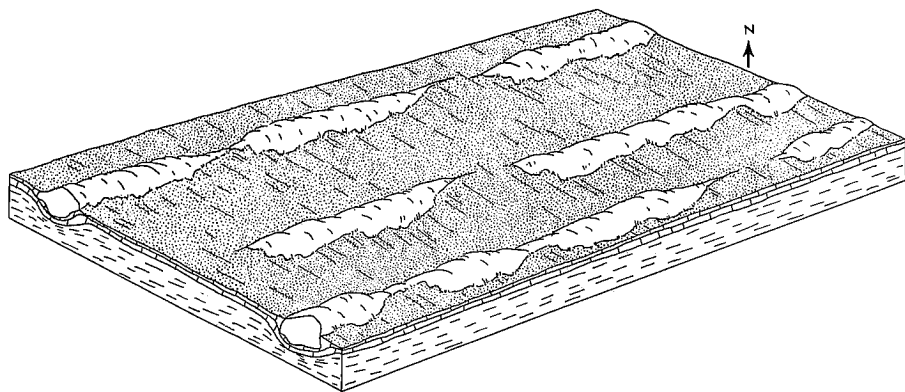
TEXT-FIGURE 7.—Conceptual block diagram of reef occurrences on the reef horizon.
    Reefs are 1 to 1.5 m high and 10 m apart.

isopach line of Lower Ordovician marine sediments has a general northeasterly
trend through Utah (Text-fig. 8) that may indicate the gross trend of the then-
existing shoreline.

Regular lateral separations of the reefs present an enigma. Heckel (1974,
p. 103) discusses the effects of organic stabilization and hydrodynamic influ-
ence on the formation and buildup of reef structures. In his estimation, growth
of organic buildups implies that local elevation of the sea floor provides more
favorable hydrodynamic conditions for organic growth than do surrounding
areas. This observation holds true for the reefs of this study after stromatolitic
algae had stabilized the substrate and subsequent growth of attaching organ-
isms; however, on the basis of information presently available, initial spacing
of the stabilizing organisms cannot be directly related hydrodynamically to
local highs on the substrate. The intraformational conglomerate underlying
the reef structures maintains a constant thickness both under the reef cores
and laterally from the reef cores where it grades upward into interreef beds.
Hydrodynamic factors other than those related to bottom topography must
have influenced the regular spacing of the initial stabilizing organisms. Such
factors would have to control currents that provide nutrients and oxygen.

The factors that influenced consistent reef lineaments and lateral separa-
tions were long lasting. Younger horizons of reef development in Middle
Ordovician (Chayzan) age rocks of western Utah also show northeasterly reef
trends and consistent lateral separations of the reefs (Rigby, 1974, pers.
comm.).

The tendency of these Lower Ordovician reef cores to diminish in size
westward and to grade to a biostromal occurrence indicates a change of environ-
ment affecting the reef-building organisms. Waters were likely becoming deeper
and may have been quieter toward the northwest.

ENVIRONMENTS OF SEDIMENTATION

Dominant rocks associated with the reef horizon are shale into which the
reef horizon was introduced. The dominance of shale throughout this part of
the Fillmore Formation indicates an overall period of low-energy waters charged
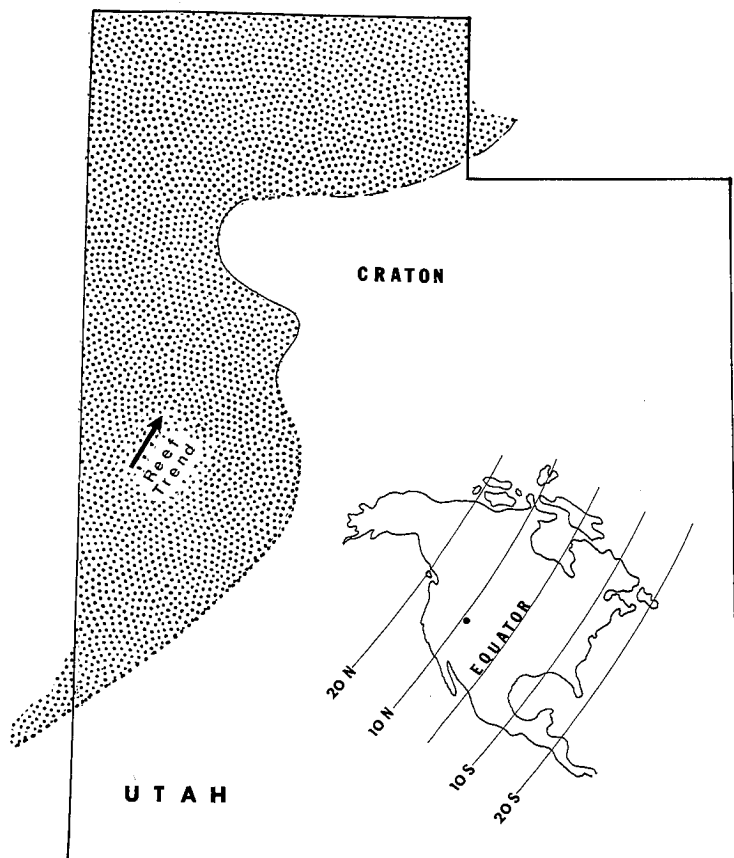
TEXT-FIGURE 8.—Possible geographic relationships existing during Lower Ordovician time; arrow indicates trend of reef lineaments, line separating stippled area from plain area is 0 isopach line of Lower Ordovician rocks (after Hintze, 1973a) and may reflect gross shoreline trend; possible Lower Ordovician equator position (after Irving, 1964) is indicated on inserted sketch of North America.

with terrigenous sediment. The abrupt change from the lower shale unit to intraformational conglomerate is attributed to greatly increased current activity. Higher-energy conditions are thought to have cleared waters of terrigenous sediments, allowing carbonates to dominate and allowing an increase of fauna. Ripple-marked surfaces, presence of algae, and small reef size are thought to be a result of shallow water depths. Clear waters allowed sunlight to reach the substrate, where stromatolitic algae flourished. High-energy conditions made it advantageous for organisms with reef potential to construct wave-resistant structures elevated from the substrate. Vigorous current activity and sedimentary pulses, possibly the result of occasional storms, continued and scattered reef debris and other bioclastic material between reefs, forming bioclastic interreef beds. Growing reef structures acted as baffles and trapped carbonate muds winnowed from the interreef beds. Reef growth continued until a maximum

relief of 1.5 m above the substrate was reached. During this time only 10 to 15 cm of interreef beds accumulated. Reef development is thought to have involved a period on the order of a few decades. At the maximum state of reef development, energy conditions changed. Had conditions remained constant, reef growth would have continued, if not upward because of shallow water restriction, then laterally (Heckel, 1974, p. 143). Environmentally favorable conditions changed to a low-energy state and terrigenous sediments choked out the reef growth of sediment-sensitive sponges and algae. Heckel's (1974, p. 143) model for nearshore, shallow-water reef growth applies to these reefs. "In nearshore shallow water regimes where major factors such as terrigenous influx are quite variable, environments favorable for organic proliferation rarely last long enough for buildups to grow to large height, even with continual subsidence."

REEF PALEONTOLOGY AND PALEOECOLOGY

Reef-dwelling organisms can be separated into two main divisions: (1) frame-building organisms, those organisms that contributed to the construction of the rigid reef mass, both binding the loose sediment together and trapping fine carbonate muds; (2) vagrant or accessory organisms, those organisms that dwell on or near the reef buildup to gather preferred food but contributed to the reef mass only by adding skeletal remains upon their demise.

Frame-Building Organisms

Three groups of organisms comprise the principal frame builders of the reef masses: sponges, algae, and *Calathium*.

Sponges.—Sponges acting as frame builders in the reefs are lithistid sponges belonging to the family Anthaspidellidae. The sponge assemblages of these reefs comprise the oldest known varied occurrence of lithistid and anthaspidellid forms that begin to evolve into important Ordovician-Silurian groups. The anthaspidellids characteristically have a ladderlike network of siliceous spicules that produced a rigid skeletal structure easily recognizable even in small fragments (Pl. 3, fig. 2). The assemblages of sponges occurring in these reefs have affinities with the anthaspidellids described from younger rocks in central Nevada by Bassler (1941). Only one type of form has been identified with certainty as being *Archaeoscyphia* (Pl. 3, fig. 4). The other forms, several of which appear to be new, need more study.

Five morphological sponge shapes dominate the sponge assemblage: (1) an undulating, thick walled, cylindrical to high cone-shaped *Archaeoscyphia,*
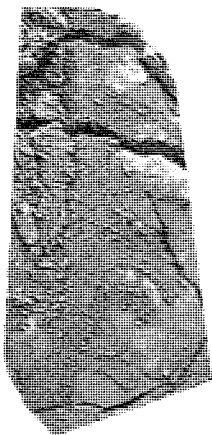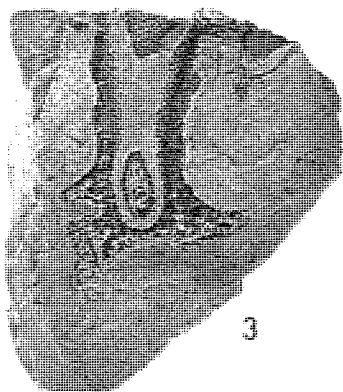
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EXPLANATION OF PLATE 3
FRAME BUILDING SPECIMENS AND ETCHED BLOCKS
SHOWING REEF TEXTURES

FIG. 1.—Lithistid sponge, 7 cm long, with a simple flaring attachment base.
FIG. 2.—Acid-etched reef block, showing the annulate wall of a lithistid sponge 5 cm long.
FIG. 3.—Silicified *Calathium*, 4 cm long, showing double wall and attachment area.
FIG. 4.—Silicified sponge, *Archaeoscyphia,* 11 cm long.
FIG. 5.—Silicified *Calathium,* 13 cm long, on reef crest.
FIG. 6.—Acid-etched reef block, showing sponge plates, 11 cm across, binding sediment.

PLATE 3

(2) a thin-walled saucer- to goblet-shaped form with wall annulations, (3) a thick-walled saucer- to goblet-shaped form with wall annulations, (4) a cylindrical, thick-walled, tube-shaped form, and (5) an encrusting thick-walled lamellar form.

Attachment areas at the base of tube-shaped sponges are simple flaring structures with a circular concave base (Pl. 3, fig. 1). Root systems do not develop from the basal area of the sponge. Tubular forms are often found in growth position and also occur as abraded pieces on interreef beds adjacent to the reefs. Some tubular forms occur as stalk portions of saucer forms giving the appearance 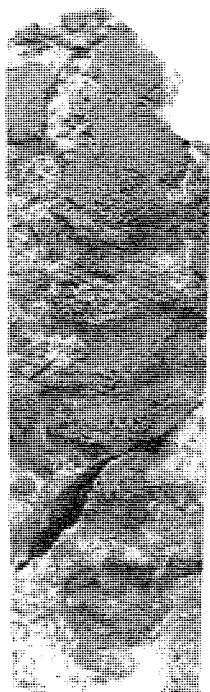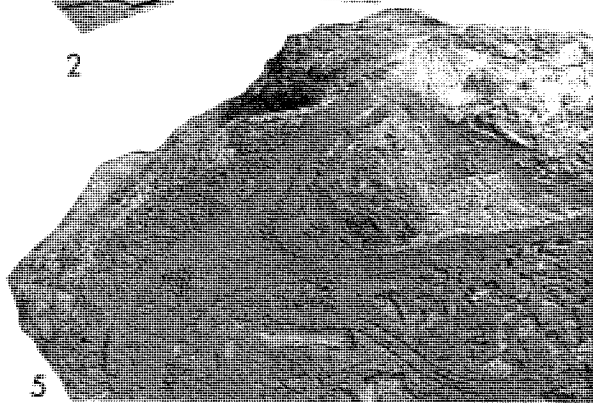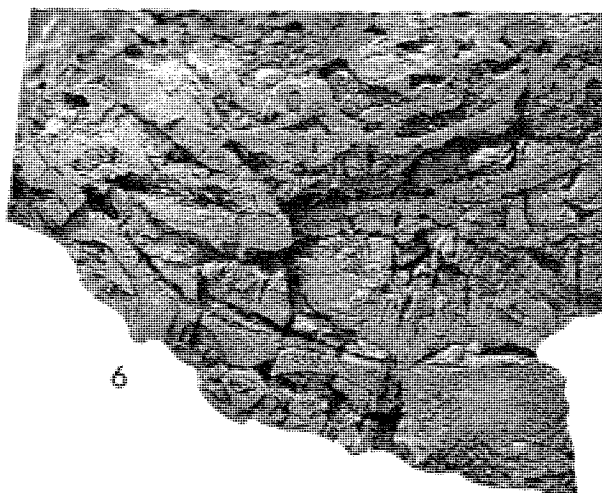of a cake platter or goblet (Pl. 2, fig. 5). Tubular forms are considered to be immature or incomplete if the saucerlike portion is not attached. Larger saucer-shaped sponges, 15 cm in diameter, are occasionally observed in growth position but more often occur as a mesh of broken plates that have washed or settled into depressions on reef surfaces where they reinforce the binding of loose sediments (Pl. 3, fig. 6). Saucer-shaped forms have not been found in interreef beds. Probably these forms were highly susceptible to currents and easily destroyed.

Lamellar forms are commonly observed in thin section overgrowing or encrusting other organisms (Pl. 2, fig. 4).

Other sponges inhabited the reefs but are represented only by loose diactine and hexactine spicules. No organized spicule networks of these sponge forms were found.

Calathium.—The problematic organism *Calathium* was originally described as a sponge (Billings, 1865). Later workers have concluded that the organism is most certainly not a sponge (Finks, 1960). Nitecki (1972) has considered *Calathium* as a dasyclad algae, including it within the family Receptaculitaceae.

In the reefs of this study, *Calathium* is often found in growth position with a cone shape and vertical orientation. The organisms reached a height of 12 to 15 cm in mature specimens and are 5 to 6 cm in diameter at the top. They taper to 1 to 2 cm in diameter at the base above where the attachment system flares out to develop, in some specimens, into a rootlike system. Root systems are commonly observed attached to tubular sponges (Pl. 2, fig. 3).

The apparent biological orientation of *Calathium* in these reefs is quite different from that visualized for Silurian *Calathium* described by Nitecki (1972). His restoration indicates orientation to be reversed with the narrowest diameter at the top and the widest diameter at the base (Nitecki, 1972, p. 42). The basal portions of the Silurian *Calathium* of Nitecki's study are uncalcified and not preserved for verification of actual attachment structures.

Most reef surfaces are dominated by double-walled *Calathium* (Pl. 3, fig. 3), although single-walled types on which the outer wall has eroded away are also present. Specimens of *Calathium* are smaller and fewer in number in the lower and central areas of the reefs but increase in size and number in the upper areas and flanks of the reefs.

Orientation of *Calathium* in these reefs is such that the organism appeared top heavy. The upper portion of the organism appears to be cup or vase shaped, however (Pl. 3, fig. 5), with the mass of the organism concentrated in its lower calcified area. That the organism was capable of existing in high-energy conditions is attested to by the extensive root systems attached to tubular sponges in Plate 2, figure 3 and Plate 3, figure 3.

Algae.—Two forms of algal growths are recognized. Stromatolitic algae acted early in reef growth as a substrate stabilizer for subsequent reef growth. Basal

portions of some reefs contain intraclasts bound together by such stromatolitic algae (Pl. 1, fig. 6). Stromatolitic forms continue to be an intergral part of reef structures throughout reef growth acting as a binding organism. Sponge plates are often incorporated into the algal growth (Pl. 2, fig. 6). Stromatolite growth also surrounds sponges and *Calathium* (Pl. 2, fig. 3).

Of the several algae in the reefs only one has been identified with certainty, as *Tubiphytes obscurus* (Maslov). *Tubiphytes* occurs in the reefs as a binding organism. These algae encrust, and are encrusted by, stromatolitic algae and also encrust sponges and *Calathium*.

Accessory Organisms

Accessory organisms contribute very little volumetrically to reef cores. Diversity is great however, and the reefs contain many organisms not found in interreef beds.

Crinoids.—A Lower Ordovician crinoid was found in a depression on the crest of one reef core. Less than a half-dozen occurrences of such crinoids are known from rocks this old. The specimen is well preserved and has been preliminarily identified by N. Gary Lane (1974, pers. comm.) as a dicyclic inadunate belonging to the Heterocrinacea.

The crinoid is associated with a nautiloid cephalopod, a goblet-shaped sponge, crinoid debris, and sponge fragments (Pl. 2, fig. 5). The crinoid and associated organisms occur in what was an Ordovician erosional depression on the crest of a reef and appear to be a late phase of reef growth. These organisms are overlain immediately by the upper shale, which, because of low-energy waters coupled with the protection of the shallow depression, accounts for the unusual preservation of the calyx. Other crinoidal debris on the reef suggests that crinoids, although not contributing to the construction of the reef framework, found it favorable to attach to the firm surface. This preference for crinoid attachment to reef structures is a prelude to the persistent role of crinoids in development of Middle Silurian through Recent reefs (Lane, 1969, p. 1430).

Brachiopods.—Many brachiopods within the reef mass are observed in polished slabs and thin sections where identification is not possible. Concentrations of brachiopod valves are found as pockets around the lower peripheries of reef bodies where stromatolitic algae have overgrown them. Some of these brachiopods have been silicified, appearing as a coquina on the lower outer surfaces of the reefs. Such a coquina is composed of the small articulated brachiopods *Apheoorthis* and *Glyptotrophia*.

Other Organisms.—Organisms occurring randomly in the reefs include asaphid and pliomerid trilobites. Acid-etched reef blocks contain individual trilobite pleura with vertical spines.

Gastropods 5 cm in diameter occur as *Ophileta*-like steinkerns.

Orthoconic nautiloids are found in many of the reefs. The largest specimen observed is 40 cm in length. Most nautiloids are apparent only in thin section and are not easily observed in the reef outcrop. Because of poor exposure in the outcrop, directional trends were not observed of the nautiloids.

Thin-section study reveals the occurrence of burrows (Pl. 1, fig. 4), fecal pellets, echinoderm debris, and various unidentifiable ostracods in the reef cores.

AN EARLY REEF DEVELOPMENTAL MODEL

Ecologic reefs, those reefs in which sediment is organically bound and in which organisms provide the rigid framework (Dunham, 1970), can be recognized as one of nature's most nearly complete ecosystems. In the past, purely physical aspects of ancient reefs have received emphasis. More recently however, biologic studies are being conducted to gain significant understanding of early reef development.

A developmental model for the reefs of this study has been constructed as an example of an early Paleozoic, paleontologically simple, nearly self-contained ecosystem surrounded by sharply contrasting environments. Ecosystems can be better understood by studying the seral succession that occurs within them, a succession which consists of individual communities, seres, migrating one way through the ecosystem. The succession begins with a pioneer community and ends with a climax community and may have a varying number of intermediate communities.

The pioneer community of these Lower Ordovician reefs is stromatolitic algae. Stromatolitic algae moved into a harsh environment and prepared the way for succeeding communities. In these reefs they did so by stabilizing the soft substrate. A wide morphologic variety of sponges followed the algae, attaching to the matted or pebble stabilized surface provided by the algae. Diverse vagrant forms moved into the area for feeding purposes and protective shelter. Sponges began to act as baffles, trapping fine carbonate muds and establishing a framework for further reef growth. With well-developed root systems, *Calathium* attached to tubular sponges and other firm objects. As *Calathium* projected upwards into zones of high energy and wave action, it in turn also acted as a baffle with contemporaneous sponges, trapping increasing amounts of sediment and providing favorable environments for continuance of the preceding communities, stromatolitic algae and sponges.

The *Calathium*-dominated community is considered to be the climax community of the ecosystem because of its dominant and larger occurrences in outer areas of the reefs; however, a positive relationship appears to have existed between it and preceding communities of sponges and algae to the extent that all of the earlier reef species are represented in the outer margins of the reefs even while *Calathium* dominates.

Succession cannot be observed in vagrant forms, although zonation is present with brachiopods inhabiting lower peripheral margins of the reefs and crinoids occurring on reef crests. Trilobites, gastropods, nautiloids, and burrow structures occur randomly throughout the reef mass.

In summary, the seral succession in these reefs can be listed as: pioneer community, stromatolitic algae; intermediate community, anthaspidellid sponges with occurrences of vagrant forms, algae, and *Calathium;* climax community, *Calathium* with occurrences of all preceding communities.

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