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Lower Cambrian bioherms in central Nevada and eastern California

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LOWER CAMBRIAN BIOHERMS IN CENTRAL NEVADA
AND EASTERN CALIFORNIA

by

Xiaoping Zhou

A thesis submitted in partial fulfillment
of the requirement for the degree of

Master of Science

in

Geoscience

Department of Geoscience
University of Nevada, Las Vegas
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University of Nevada, Las Vegas
December, 1994
LOWER CAMBRIAN BIOHERMS IN CENTRAL NEVADA
AND EASTERN CALIFORNIA

ABSTRACT

Both the Ravenswood patch reefs in Lander County, Nevada and the
Montenegro bioherms in the White-Inyo Mountains, California represent the
earliest preserved archaeocyathid-calcimicrobial carbonate buildups in the
western United States. These roughly coeval Early Cambrian bioherms share
many common features, such as reef-organisms, reef dimension, and micrite
matrix. On the other hand, they show some differences in lithofacies structure,
paleoecology, and taxonomic composition of archaeocyaths that reflect the
variation of environment from place to place. Reef community structures and
reef ecosystems were mainly controlled by environmental setting.

The Lower Cambrian stratigraphic sequence in the Ravenswood area of
Lander County in central Nevada consists of mixed carbonate and siliciclastic
sediments that accumulated in a shallow-marine, storm-dominated environment.
The limestone facies record deposition on a shallow-subtidal open shelf on which
developed small, isolated patch reefs constructed by archaeocyaths and
calcimicrobes. These patch reefs, generally 5 to 10 m high and 10 to 25 m wide in
outcrop, grew on a foundation of skeletal shell layers and siltstone beds,
differentiated into bioherm core facies and bioherm flank facies, and were
surrounded by siliciclastic facies. Archaeocyaths, which were locally bound by
calcimicrobes (cyanobacteria and algae), constitute as much as 30 to 40% of some reefs and form archaeocyath framestone. Calcimicrobes (mainly *Renalcis*) constitute as much as 50 to 70% of other reef limestones forming *Renalcis*-dominant boundstone.

The Montenegro bioherms in the White-Inyo Mountains of eastern California, 6 to 8 m high and 25 m wide in outcrop, are composed of many kalyptrae that were stacked together to form a compound reef-like buildup. The bioherms are underlain by crossbedded siltstone and interfinger with siliciclastic facies laterally. Most of the kalyptrae forming the bioherms are 50 cm wide and 20 cm high and are composed of many small lenses that were stacked together and filled by siltstone. Each lense is built by archaeocyaths bound by calcibionts. The Montenegro bioherms have no recognizable lateral and vertical variation within the community, and they developed in a low-energy subtidal marine environment.
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Chapter 1

INTRODUCTION

The reef ecosystem has a very long, well-preserved fossil record. The oldest reefs that contain metazoan shelly organisms are archaeocyathan-calcibiont reefs of the Lower Cambrian, 520 to 544 million years ago (Bowring et al., 1993). Some of the best examples of such reefs are located on the Siberian Platform (Zhuravlev, 1986), in North America (Read, 1980; Rowland, 1981, 1984; Rowland and Gangloff, 1988; Zhou and Rowland, 1993), in Sardinia (James and Debrenne, 1980; Gandin and Debrenne, 1984), in Morocco (Debrenne and James, 1981), in Antarctica (Rees et al., 1989), in South Australia (James and Gravestock, 1990), and in Mongolia (Wood et al., 1993). Studies of reefs in these areas have shown that all Lower Cambrian "reefs" are not small bioherms, as was formerly believed by some researchers. Instead, some are true framework reefs. These reefs display a wide range of morphologies and fabrics, and complex structures within the reef-building community (Rowland and Gangloff, 1988). Additional studies of Lower Cambrian reefs and reefal organisms, especially in new areas, will provide more knowledge about the structure and paleoecology of reefs in general, as well as contributing to the resolution of regional stratigraphic and sedimentological problems. Moreover, detailed research on Lower Cambrian reefs, the pioneers of Phanerozoic reefs, and a comparison between them and younger metazoan-bearing reefs, will contribute to the understanding of the reef ecosystem, and its evolution through the early Phanerozoic.
The purpose of this study is to reconstruct and compare the community structures and depositional environments of two quite different but approximately age-equivalent Lower Cambrian reef communities in central Nevada and eastern California. This study will add new data on Lower Cambrian reef ecosystems in the Basin and Range Province and help us to better understand how marine communities respond to different environmental settings.

The localities chosen for this study are the Ravenswood area of central Nevada and the White-Inyo Range of eastern California (Fig. 1); in both areas Lower Cambrian reefs and reef organisms are well exposed and preserved. The occurrences of Lower Cambrian bioherms in central Nevada have been mentioned by a few researchers (Gangloff, 1975, 1976; Stewart and McKee, 1977; Wilson, 1992), but sedimentologic studies have not previously been done. In the White-Inyo Range of eastern California, one large bioherm was more-or-less simultaneously studied by Fuller (1976) and Morgan (1976) who reached conflicting conclusions about community structure, paleoecolgy of reef organisms, and depositional environments. One objective of this study was to resolve these differences.
Fig. 1. Map showing locations of study areas (x) in central Nevada at the Ravenswood site and in eastern California at the White-Inyo Mountains site.
Chapter 2

STUDY METHODS

This study involved extensive field and laboratory work. Three field trips, including twenty field days, were made to the Crooked Canyon-Summit Ridge area south of Austin in central Nevada, to the Ravenswood area northwest of Austin, and to the White-Inyo Mountains of eastern California. Seven archaeocyath-bearing sequences were examined and sampled. Of these, two well-exposed sections in the Ravenswood area and one in the White-Inyo Mountains were chosen for detailed study. These three sections were measured, and large-scale mapping was done on the USGS topographic base maps to show the three-dimensional distribution of facies. In the field, I made detailed observations and descriptions of fossil occurrences, lithofacies, sedimentary structures, and contact relationships. Lithologic samples and oriented fossil samples were systematically collected, and many samples were cut both perpendicular to and parallel to bedding for both thin sections and slabs. One hundred and two large (76 x 50 mm) thin sections, 20 acetate peels, and 48 polished slabs were made at the UNLV Department of Geoscience during the summer of 1992 and the fall of 1993. Thin sections and acetate peels were examined and described under plane polarized light and crossed polarized light of microscope. Typical and significant outcrops, thin sections, and slabs were photographed or sketched. Three shale samples from below one of the bioherms in the Ravenswood area were dissolved using strong (95%) HF acid for the
purpose of looking for acritarchs. Before using HF acid, the samples were washed with distill water, and crushed into 3 to 5 mm in size. The experiment was taken under the room temperature (25°C) and without stirring. After the shale samples were completely dissolved in HF acid, I checked each sample solution under microscope. No acritarchs were found in this experiment.
Chapter 3

TERMINOLOGY

A considerable nomenclature has been developed for describing fossil reef geometries and *in situ* reeffal fabrics (e.g. Cummings, 1932; Dunham, 1962; Embry and Klovan, 1971; Heckel, 1974; Wilson, 1975; Tsein, 1985; Riding, 1991). In this study, I have used the terminology of Embry and Klovan (1971) (Table 1). James and Gravestock (1990) argued that the lithological terms for reef rocks defined by

<table>
<thead>
<tr>
<th>Allochthonous</th>
<th>Autochthonous</th>
</tr>
</thead>
<tbody>
<tr>
<td>original components not organically bound during deposition</td>
<td>original components organically bound during deposition</td>
</tr>
<tr>
<td>&gt;10% grains &gt; 2mm</td>
<td>by organisms which act as baffles</td>
</tr>
<tr>
<td>matrix supported</td>
<td>by organisms which encrust and bind</td>
</tr>
<tr>
<td>supported by &gt; 2mm component</td>
<td>by organisms which build a rigid framework</td>
</tr>
<tr>
<td>Floatstone</td>
<td>Rudstone</td>
</tr>
</tbody>
</table>

Table 1. Reef limestone classification proposed by Embry and Klovan (1971)
Embry and Klovan (1971) (i.e. framestone, bindstone, and bafflestone) are largely inapplicable to most Lower Cambrian archaeocyathan buildups because most of the small metazoan skeletons are not massive and are not in growth position, and also because most of the rocks are composed of carbonate mud and calcified microbial microfossils that are not well suited to these terms. However, other authors (e.g. Wood et al., 1993) have chosen to use the Embry and Klovan (1971) terminology for Lower Cambrian archaeocyathan buildups and buildup complexes, arguing that the resultant fabrics and sedimentological characteristics of these buildups can be directly compared to other Paleozoic buildups formed by similar small, solitary or low-integration organisms together with abundant carbonate mud. The Ravenswood bioherms were mainly constructed by branching irregular archaeocyaths and abundant calcified microbial fossils, most of which are in their growth positions. The bioherm limestones are composed of lime mudstone as the matrix, abundant internal sediment, various bioclasts, growth cavities, and synsedimentary cements. Therefore, I have used the terms of Embry and Klovan (1971) in this study.

I use the term *buildup* as a general term for all reef-like structures, while I use the more specific term *bioherm* when the geometry of the structure can be determined. The term *framestone* is used for biohermal limestone built mainly by archaeocyathan skeletons in growth position that produce primary growth cavities. *Boundstone* (Dunham, 1962) is used here as a general term to describe rocks formed by an intergrowth of calcified microfossils and a low abundance of metazoans or metazoans not in growth position, together with growth cavities and calcite cements. The terms *packstone* and *grainstone* of Dunham (1962) are also used to describe reef-associated rocks such as the underlying layers of bioherms and inter-reefal facies. The term *calcimicrobe*, an abbreviation for "calcified microbial fossils," is used following James and Gravestock (1990); the
systematic affinity of these tiny benthic fossils is uncertain (Pratt, 1984; Riding and Voronova, 1985; Riding, 1991b). The term *kalyptra* (plural: *kalyptrae*) is employed in this paper to describe individual lenticular components of the Montenegro bioherm, which is a compound buildup formed by many biconvex or concavoconvex bodies of boundstone, usually more-or-less lenticular in cross-section. This term was originally coined by Russian paleontologists for small spherical bioherms in the Lower Cambrian of the Siberian Platform - not only for the component bioherms of compound buildups but also for small solitary bioherms of all shapes and sizes, including domal stromatolites (Zhuravleva and Myagkova, 1977). The term was modified by Rowland and Gangloff (1988) to refer only to the component lenticular building blocks of some compound bioherms. It is in this restricted sense that I use this term in this paper.
Chapter 4

BIOHERMS OF THE RAVENSWOOD AREA

4.1. Location and Geologic Setting

The Ravenswood area is located in central Nevada thirty miles northwest of Austin in Lander County (Fig. 1). The Lower Cambrian sections in the Ravenswood area are exposed in Section 14, T.22 N., R. 42 E., of the Manhattan Mountain 7.5 minute Quadrangle (Fig. 2). Outcrops are present on both sides of an unpaved road that leads from Nevada Highway 305 westward into the Ravenswood district and first crosses exposures of pre-Tertiary rocks, as shown on Plate 1 and Plate 3 of Stewart and McKee (1977).

The Lander County is a region of north-northeast-trending mountain ranges separated by alluvial valleys. In southern Lander County, a sequence of Neoproterozoic to Lower Cambrian quartzites, siltstones, and limestones is exposed in the Toiyabe Range south of Austin, on Mount Callaghan in the Toiyabe Range north of Austin, in the Shoshone Mountains northwest of Austin, and in a few other areas (Stewart and McKee, 1977). These rocks, which are exposed as windows in the Roberts Mountain Thrust, have been described by Ferguson and Cathcart (1954), Means (1962), and Washburn (1966, 1970).

Although Lower Cambrian strata are exposed over a considerable area of the Shoshone Mountains northwest of Austin, a complete sequence has not yet been established because of poor exposure and structural complications. The
Fig. 2. Topographic map of the Ravenswood area showing locations of the Lower Cambrian sections. A-A': the east section; B-B': the west section. (From the Manhattan Mountain 7.5 Minute Quadrangle, USGS)

rock units have no formal nomenclature, and correlation of the Lower Cambrian strata in this area with named formations in adjacent areas remains uncertain. The most continuous exposures are in the Ravenswood Window of the Roberts Mountain Thrust (Roberts et al., 1958), which is one of the two study areas of this thesis.

4.2. Stratigraphy and Age

As described by Stewart and McKee (1977), the Lower Cambrian sequence in the Ravenswood district consists of three lithologic units. The lowest unit
consists of siltstone with small amounts of sandstone and limestone. The middle unit consists of fine- to medium-grained quartzite and siltstone containing abundant trace fossils. Both the top and bottom of the middle unit are faulted. The highest unit is a cliff-forming limestone that locally contains abundant *Cirvanella* and trilobites. The sections that I studied in the Ravenswood area are from the lowest units (Fig. 3). These sections are at least 40 meters thick, although they are everywhere poorly exposed and highly faulted. Archaeocyaths are found in the limestone, and trilobites and other fossils are found in the quartzite and siltstone.

Stewart and McKee (1977) correlated the Lower Cambrian sequence in the Ravenswood area with other Lower Cambrian strata in southern Lander County and northern Nye County. Based on fossils (trilobites, archaeocyaths, "algae", and trace fossils) and lithofacies, they concluded that most of the Lower Cambrian sequence in the Ravenswood area is stratigraphically equivalent to the top unit of the Gold Hill Formation, as described by Ferguson in Stewart and McKee (1977) in the Manhattan mining district 100 km south of Austin. The name Gold Hill Formation was extended into the Toiyabe Range south of Austin by Ferguson and Cathcart (1954) and by Washburn (1966, 1970). Gangloff (1975) studied archaeocyaths from the upper one-fourth of the Lower Cambrian sequence in the Ravenswood area and described an abundant and diverse associated fauna, including trilobites, brachiopods, echinoderms, *Chancelloria*, *Salterella* (?), and gastropods. He correlated the archaeocyath-bearing limestone in the Ravenswood area with a 25-meter-thick limestone designated as unit 5 by Means (1962) and Washburn (1970) near the head of Crooked Canyon on the east side of Summit Ridge in the central Toiyabe Range.

Wilson (1992) studied the depositional environments of the lowest unit of the Lower Cambrian sequence in the Ravenswood area. He divided the Lower
Fig. 3. Partial stratigraphic column of the Lower Cambrian sequence in the Ravenswood area of central Nevada (modified from Wilson, 1992)
Cambrian sequence into seven lithofacies that he interpreted to represent the following wave-dominated nearshore environments: lagoon, patch reef, beach/barrier (foreshore, shoreface, washover fan), offshore transition, and tidal flat. Combining fossil associations and lithologic sequences, Wilson pointed out that the Lower Cambrian strata in the Ravenswood area may be correlative with the Montenegro Member of the Campito Formation and the Lower Member of the Poleta Formation of the southern Great Basin in eastern California and southern Nevada.

The bioherms that I studied occur near the top of the lowest unit defined by Stewart and McKee (1977) and mainly in the archaeocyath framestone lithofacies of Wilson (1992). Although *Nevadella*, the major genus in the *Nevadella* Zone, was reported from the Ravenswood area by Stewart and McKee (1977), the precise locality was not known. S. M. Rowland and I (field collection, 1992) found *Nevadella* in association with archaeocyath-bearing intervals about 10 meters below Bioherm 1. Most archaeocyaths from the Ravenswood bioherms belong to the Botomian Stage according to the stratigraphic and geologic distribution of archaeocyathan genera summarized by Debrenne and Zhuravlev (1992). Therefore, on the basis of this association, the Ravenswood bioherms occur within the *Nevadella* Zone and are probably in the Botomian Stage [520 to 525 million years ago (Bowring et al., 1993)] of the Early Cambrian.

4.3. Bioherm Geometry

One archaeocyathan-calcimicrobial bioherm occurs in the upper part of the section on the east side of the road (A-A' section in Fig. 2) and several bioherms surrounded by siliciclastic rocks occur on the west side of the road.
(B-B' section in Fig. 2). They are generally low-relief, laterally elongated bodies with a convex upper surface and a slightly undulatory base. The bioherm in the east section (referred to as bioherm 1) and one of the bioherms in the west section (referred to as bioherm 2) were chosen for detailed study.

Bioherm 1 is located between meter 36 and meter 42 in the stratigraphic column (Fig. 3) of the east section. This section is Wilson's (1992) Section 1. This bioherm has a distinct mound-like profile on its south face, with a convex upper surface and a slightly undulatory base (Figs. 4, 5). It is 5 m high and 8 m wide in the outcrop. The west face of the bioherm extends incompletely about 25 m from north to south (Fig. 6). Thus, the whole bioherm appears to be an elongate, lenticular body with the long axis oriented roughly north-south (Fig. 7). This bioherm is underlain by skeletal shell packstone, is capped by a 0.5 m thick layer of dolomitized biohermal limestone, and is flanked laterally by siliciclastic shale and siltstone facies.

Fig. 4. View of south face of bioherm 1 in the Ravenswood area, showing a distinct mound-like profile with a convex upper surface and a slightly undulatory base.
Fig. 5. Diagram of south face of bioherm 1, showing the bioherm profile and the bioherm facies.

Fig. 6. Partial view of west face of bioherm 1, showing the bioherm flank and core facies. The dash line represents the boundary between two facies.
Fig. 7. View of bioherm 1 - an elongate, lenticular body with the long axis oriented roughly north-south. It is surrounded by siliciclastic rocks. Photo was taken from opposite side of valley.

The west section contains several bioherms. Bioherm 2, about 50 m away from the road, is irregular in shape, 8 m high, and 25 m wide, with an interfingering contact between the reef limestone and surrounding siliciclastic rocks (Fig. 8). Like bioherm 1, this bioherm is underlain by skeletal shell packstone, is capped by dolomitized limestone, and is flanked laterally by siliciclastic shale and siltstone facies.

In addition to bioherm 2, several adjacent bioherms and surrounding siliciclastic deposits in the west section form a large archaeocyathan-calcimicrobial bioherm complex up to 60 meters thick and more than 100 meters wide (Fig. 9). Individual bioherms are 5 to 8 meters thick and extend laterally 10 to 25 meters in outcrops. The relationship between the reef complex and the enclosing strata is unknown. Bioherm-derived talus blocks are absent.
Fig. 8. Bioherm 2 in the west section. It is irregular in shape, 8 m high and 25 m wide, underlain by skeletal packstone, and surrounded by siliciclastic shale and siltstone facies.

Fig. 9. Sketch showing complex of archaeocyathan-calcimicrobial bioherms in the west section of the Ravenswood area.
4.4. Structure of Bioherms

4.4.1. Facies and fabrics

Three facies were recognized in the Ravenswood bioherms based on the field observations and thin section studies: (1) bioherm base facies, (2) bioherm flank facies, and (3) bioherm core facies (Fig. 5).

(1) Bioherm base facies. This facies is a laterally discontinuous skeletal packstone that lies under both bioherm 1 and bioherm 2 forming the substrate upon which the bioherms developed. It is underlain by siltstone with sharp erosional contact and locally overlain by a thin bed of sandstone with an upper erosional surface (Fig. 10). Wilson (1992) described this facies as a trough cross-stratified channel-fill, an interpretation with which I agree.

Fig. 10. Polished slab of skeletal shell packstone. The packstone overlies a hummocky-stratified siltstone. Arrow points to the stratigraphic up. Sample RW-92-214; black scale bar is 1 cm.
This facies is yellowish gray and is composed of angular to subangular, fine- to medium-grained quartz sand, conspicuous shells, micrite, chlorite, archaeocyaths, and iron-oxide staining (Fig. 11A). Some large (5 to 7 cm) siltstone clasts from the underlying strata are also present in the packstone.

The conspicuous irregular shells were identified as obolellid brachiopods by A. J. Rowell (1991) (see Wilson, 1992, p. 55). In thin section most shells are preserved concave-upward (Fig. 11B). Each shell, 6 to 15 mm wide, is now a mold filled by calcite cement. Several shells are rarely nested together (Fig. 11C). These shells are similar to a photograph of several nested hyolithid cones shown by James and Klappa (1983, fig. 4, A) in shell size and preserved pattern. The only difference is that the Ravenswood shells are slightly irregular in shape,
which may be due to the late diagenetic compaction. These skeletal packstone beds evidently acted as the bases of the bioherms, which may be unique to the Ravenswood area. No other occurrences of coarse skeletal packstone basal facies have been reported from Lower Cambrian reefs or bioherms in western North America. They are functionally similar to the oolitic beds of some reefs in western Nevada (Rowland, 1984). Both served as a stabilized foundation on which bioherms could grow.

(2) Bioherm flank facies This facies is composed of bioclastic packstone with obvious bedding and local dolomitization. These bioclastic packstones are located on both sides of bioherms adjacent to the bioherm core facies. Between the flank facies and the core facies is a sharp boundary (Fig. 6). The beds range from 5 to 10 cm thick in the outcrop, most of which are separated by anastomosing stylolites and erosion surface. Internal stratification also displays minor erosional surfaces and stylolites are abundant (Fig. 12A). Individual beds may represent periodically erosional and redepositional events from the bioherm core.

The packstone consists of bioclasts and a micrite matrix with terrigenous mud and residues that are concentrated along the stylolite surfaces (Fig. 12B). Archaeocyath fragments are the dominant bioclasts in the packstone, including Ajacicyathus sp., Rotundocyathus spp., Diplocyathellus sp., Palmericyathus sp., and Ethmophyllum whitneyi (see Chapter 8). Most of them are aligned parallel to bedding. All archaeocyaths occur as solitary, non-branching forms within the packstone. Some archaeocyaths were compacted and partially dissolved along stylolites (Fig. 12C). Other bioclasts include trilobite debris, echinoderm plates, brachiopod shells, and some unidentified shells. The bioclasts are fragmented,
poorly sorted, and well preserved. A few small, elongate, calcite-occluded voids lie parallel to the bedding and are filled by calcite.

Fig. 12. Bedded bioclastic packstone in the bioherm flank facies. (A) Polished slab of bedded bioclastic packstone with anastomosing stylolites (upper arrow) and erosional surface (lower arrow). Sample RW-92-122; black scale bar is 1 cm. (B) Photomicrograph of bioclastic packstone showing composition and texture. Sample RW-92-122-2; black bar is 2 mm. (C) Photomicrograph showing partially dissolved archaeocyaths along stylolite. Sample RW-92-222-5; black bar is 2 mm.
The presence of the bioherm flank facies is a distinctive feature to the Ravenswood area. Although the exposure of the bioherms is limited in the outcrops, the flank facies is clearly differentiated from the core facies by presence of bedding. This relationship seems to be an exception to previous knowledge that small bioherms or patch reefs normally have no facies differentiation within them (Fagerstrom, 1987).

(3) Bioherm core facies The bioherm core facies is composed of massive archaeocyath framestone and archaeocyathan /Renalcis/ boundstone (Figs. 5, 6). It is underlain by the bioherm base facies, surrounded by either the bioherm flank facies or siliciclastic sediments, and capped by dolomitized limestone. This facies is variable in composition and fabric from one bioherm to another, as well as in different parts of the same bioherm.

The bioherm core facies can be subdivided into different subfacies on the basis of composition and fabric, although there is nearly a continuum. Two subfacies were identified: framestone, in which archaeocyaths are the principle constructors and calcimicrobes are rare or absent, and boundstone, in which Renalcis is the predominant contributor and archaeocyaths are scarce or absent. Where Renalcis is abundant and dominant in the bioherm, archaeocyaths are very rare or absent. Such Renalcis-rich boundstones are relatively rich in lime mud and poor in cavities. Conversely, in the archaeocyath framestones, Renalcis thalli are rare, occurring either around the archaeocyath cups as secondary encrusters or attached to cavity walls and archaeocyath cups as reef-dwellers. Also, more reef-associated fossils and cavities are present in the archaeocyath framestones than in the Renalcis boundstone.

Archaeocyath framestones. This subfacies is dominant in the Ravenswood bioherms, comprising entire isolated bioherm (e.g. bioherm 2) and central part of other bioherms (e.g. the central part of bioherm 1). The massive archaeocyath
framestone is brownish to gray color (Fig. 13) and contains variety of archaeocyath types. Irregular archaeocyaths constitute up to 40% of some bioherms and include *Fenestrocyathus* sp., *Archaeocyathus* sp., *Retilamina* sp., *Protopharettra* spp., *Syringothalmus* cf. *S. crispus*. Of these forms, the branching form *Fenestrocyathus* sp. is the most abundant species, comprising about 60 to 70% of the irregular archaeocyaths in the bioherm core facies; *Archaeocyathus* sp., *Protopharettra* spp., and *Syringothalmus* cf. *S. crispus*. are moderate in abundance (20 to 25%); *Retilamina* sp. is rare (< 10%). Regular archaeocyaths, including *Ajacicyathus* sp., *Rotundocyathus* spp., *Diplocyathellus* sp., *Palmericyathus* sp., and *Ethmophyllum whitneyi*, are relatively less abundant.

Fig. 13. Polished slab of archaeocyath framestone, parallel to bedding. Archaeocyaths are dominated by irregular types (such as *Fenestrocyathus* sp.). Sample RW-92-222; black scale bar is 1 cm.

The initial biohermal framework is constructed by irregular archaeocyaths. They occur as very densely packed branching forms with an upright growth pattern (Fig. 14A, B). This dense, branching pattern is confined to a fine-grained lithotype characterized by abundant lime mud and rare
terrigenous detritus. Light-gray lime mud occurs as the matrix surrounding the archaeocyath walls. In thin section, some Renalcis-like ghosts (?) occur around archaeocyath cups or among archaeocyath branches suggesting an encrusting mode. Other Renalcis thalli are present within cavities suggesting a dwelling mode. Many small, irregular voids are occluded by calcite spar.

Figs. 14A,B. Photomicrographs of branching, irregular-type archaeocyaths (Fenestrocyathus sp.) with an upright growth pattern. Sample RW-92-222-3; scale bar is 1 mm.

Centimeter-size cavities occur in the matrix, among the archaeocyath framework, and within the central cavities of archaeocyaths. Other cavities are between archaeocyath branches and within the intervallums of individual archaeocyaths (Wilson, 1992). Primary growth cavities are filled with lime-mud or micritic geopetal sediment, cemented by one or two generations of fibrous calcite, and finally occluded by blocky calcite spar.

The capability of archaeocyaths, along with calcimicrobes, to build framework reefs has been appreciated by more and more Cambrian workers (Rowland, 1984; Rowland and Gangloff, 1988; Rees et al., 1989; James and
Gravestock, 1990; Wood et al., 1993). Abundant archaeocyaths in the 
Ravenswood bioherms, particularly the irregular types, baffled currents and 
trapped lime mud within their skeletal framework, and the lime mud 
precipitation may have acted as early marine (sea-floor) cement. This process 
was responsible for the formation of a primary rigid bioherm.

*Renalcis* boundstones. *Renalcis*-dominated boundstones are relatively 
scarce in the Ravenswood bioherms, compared to the archaeocyath framestones. 
In bioherm 1, *Renalcis* boundstone is confined to both sides of the upper part of 
the bioherm. In the upper part of the west section, *Renalcis* boundstone forms 
small isolated mounds that are about 2 meters tall and 1 to 2 meters wide, 
surrounded by shale and siltstone.

*Renalcis* boundstones, unlike framestones, show a mottled irregular fabric 
(Fig. 15) and are composed of up to 70% *Renalcis* and "*Renalcis*-like" microfossils 
(Fig. 16A). *Renalcis* thalli are mostly clotted, and rarely chambered, in a lime 
mudstone matrix. They diverge and grow upright. This growth pattern suggests

Fig. 15. Polished slab of *Renalcis* boundstone. Arrow points to the stratigraphic 
up. Sample RW-92-232; black scale bar is 1 cm.
that upward accretion of microbial colonies might be responsible for their formation (Rees et al., 1989). The lime mudstone matrix between thalli contains scattered bioclasts and peloids locally forming into patches. Also abundant in the lime mudstone matrix are small voids and cavities that are filled with calcite spar. Subpeloidal micrite-size clots, some of which might be the synsedimentary cement, is common among the *Renalcis* colonies (Fig. 16B). In this subfacies, archaeocyaths are rare or absent. If present, they typically are not in upright growth position (Fig. 16C). Most archaeocyaths in the boundstone are bioclasts. They evidently provided favorable substrates on which *Renalcis* grew to form large microbial colonies.

![Photomicrographs of *Renalcis* boundstone.](image)

Fig. 16. Photomicrographs of *Renalcis* boundstone. (A) *Renalcis* thalli with an upright growth pattern. Stratigraphic up (arrow) is to the top. Sample RW-93-134-2; scale bar is 2 mm. (B) *Renalcis* colonies with subpeloidal, micrite-size cement among them (arrows). Sample RW-92-232; scale bar is 2 mm. (C) *Renalcis* colonies (r), archaeocyaths (a), and spar occluded growth cavities (c). Sample RW-92-232; scale bar is 2 mm.
The growth pattern of Renalcis in the boundstone is similar to the accretion of algal mats. In order to build a wave-resistant biostructure, the early (synsedimentary) direct calcification of microbial colonies is an important process. The relationship between the Renalcis thalli and the lime mud suggests that Renalcis, which are probably cyanobacteria (Riding, 1991b), may have trapped lime mud and small bioclasts during growth. Rare archaeocyath individuals may have functioned as substrates for Renalcis colonies. The early calcification of microbial colonies and the early (synsedimentary) cement between Renalcis thalli produced a rigid structure, and the continuous upright accretion of these structures enabled mound-like, wave-resistant bioherms to form. The presence of bioclasts and peloids in the lime mudstone matrix among the Renalcis thalli may be the result of episodically fluctuating currents being pumping into the bioherms (Pratt, 1984; Rees et al., 1989).

4.4.2. Fossil constituents

(1) Archaeocyaths

Archaeocyaths are an extinct group of Cambrian calcareous sponges (Debrenne and Zhuravlev, 1992). They mostly lived in carbonate environments, although a few are found in siliciclastic facies (see Rowland and Gangloff, 1988). They are major builders of Lower Cambrian buildups. They also provided hard substrates for calcimicrobe colonization during reef growth. Archaeocyaths appeared in the Tommotian Stage on the Siberian Platform and were restricted to the Siberian Platform during this stage (Zhuravlev, 1986). During the Atdabanian and Botomian Stages, archaeocyaths had spread to most continents; their diversity and abundance also increased dramatically. Finally,
accompanied by the Toyonian Regression at the end of the Early Cambrian, archaeocyathan diversity and distribution were dramatically reduced (Zhuravlev, 1986; Rowland and Gangloff, 1988).

Archaeocyaths are major components of the buildups in the Ravenswood area. Identified archaeocyaths include *Fenestrocyathus* sp., *Archaeocyathus* sp., *Retilamina* sp., *Protopharetra* spp., cf. *Syringothalamus crispus*, *Ajacicyathus* sp., *Rotundocyathus* spp., *Diplocyathellus* sp., *Palmericyathus* sp., and *Ethmophyllum whitneyi*. They constitute up to approximately 30 or 40% of the total rock volume of some of the buildups. As whole and fragmental skeletons, archaeocyaths are also important constituents of off-reef and inter-reef sediments. Geopetal structure (which is preserved in some archaeocyaths), branching pattern, and the sampling orientation in the field were combined to determine the original growth positions of the archaeocyaths. This study revealed that in the reef-core archaeocyath framework subfacies, skeletons are typically *in situ* and upright (Figs. 14A,B); in the off-reef, inter-reef facies and *Renalcis* core subfacies, skeletons most commonly lie parallel to bedding. In general, solitary, regular, and nonbranched archaeocyaths were broken and transported commonly suggesting that they were not very wave-resistant (Wood et al., 1992). After transport, these forms were generally buried by lime mud. In contrast, most small to moderate size, irregular, branched forms were preserved most commonly in their growth positions suggesting that they were greatly wave-resistant. Of all the forms, branched individuals bound by calcimicrobes were most often preserved *in situ*. Reworked and transported archaeocyathan skeletal debris is an abundant component of the bioherm flank facies and rarely appears in the bioherm core facies. This circumstance is very similar to the preservation of archaeocyaths in the Lower Cambrian buildups from Zuune Arts of Mongolia (Wood et al., 1993).
During the Early Cambrian, archaeocyaths commonly constructed buildups with calcimicrobes; however, some purely archaeocyathan buildups are also known (James and Gravestock, 1990). In the Ravenswood area, both types of construction were observed from one bioherm to another and even in different parts of the same bioherm. Bioherm 2 was built predominantly by archaeocyaths, whereas other bioherms that occur in the same section but above or adjacent to bioherm 2 are composed of archaeocyathan-calcimicrobial boundstone. Within bioherm 1 the constructors in the central part are dominated by archaeocyaths, whereas two sides of the bioherm contain both archaeocyaths and calcimicrobes. These changes may reflect the subenvironmental differentiation of the same reef community.

(2) Calcimicrobes

The calcimicrobes *Epiphyton*, *Renalcis*, *Girvanella*, and *Botomaella* are very common in Lower Cambrian buildups. Sometimes they develop into purely calcimicrobial bioherms, such as some bioherm complexes on the Siberian Platform (see Rowland and Gangloff, 1988), a reef type in the Shackleton Limestone of the Transantarctic Mountains in Antarctica (Rees et al, 1989), some bioherms in the Flinders Ranges of South Australia (James and Gravestock, 1990), and some buildups in Zunne Arts of Mongolia (Wood et al., 1993). In the Ravenswood area *Epiphyton*, *Girvanella*, and *Botomaella* were not found in thin sections, thus only *Renalcis* will be discussed under this heading.

Worldwide, *Renalcis* is a major and widespread calcimicrobe in Lower Cambrian archaeocyathan-calcimicrobial boundstones, and it can also be a common constituent in off-reef limestone. In a few cases, *Renalcis* forms pure *Renalcis* buildups. It develops either as dense masses with chambered or clotted
and rarely saccate thalli, forming boundstones without archaeocyaths (Rees et al., 1989; James and Gravestock, 1990), or it develops as crusts around and inside archaeocyath cups and other calcimicrobes. Renalcis also rarely occurs within the intervallum of archaeocyaths and often as clusters of lunules associated with or intergrown with other calcimicrobes such as Epiphyton and Girvanella. In addition, many examples show that Renalcis often grew downward from the roof of centimeter-size to meter-size growth cavities as a cavity dweller (James and Kobluč, 1978; Rowland and Gangloff, 1988).

In the Ravenswood area, Renalcis is found mainly in bioherm 1 and the small bioherms above bioherm 2. It occurs not only as abundant and dense colonies with numerous upward growth thalli, forming Renalcis-dominated boundstones (Fig. 16), but also as crusts attached to archaeocyath cups, forming archaeocyath-Renalcis boundstones (Fig. 17A). As stated above, in the Ravenswood bioherms Renalcis also occurs in dense pendant clumps of centimeter-size on the ceilings of centimeter-size cavities (Fig. 17B). It also grew

Fig. 17. Photomicrographs of Renalcis colonies. (A) Renalcis colonies (r) growing downward from archaeocyath cups(a). Sample RW-93-134-2; scale bar is 2 mm. (B) Renalcis (R) occurs in a dense pendant clump of centimeter-size on the ceiling of cavity. Sample RW-93-134-2; scale bar is 2 mm.
downward from horizontal portions of archaeocyath cups, the archaeocyaths having formed a shelter cavity in which *Renalcis* thrived. Unfortunately, the preservation of *Renalcis* in the Ravenswood bioherms is generally poor; it typically occurs as ghost-like clumps of micrite-walled lunules in a lime mudstone matrix, which prevents me from doing further detailed study.

(3) Associated Biota

Lower Cambrian reefs, like younger ones, provided abundant and varied substrates and microhabitats for the associated reef organisms. The reef-associated biota varies from one reef to another. Common associated organisms include eocrinoid and helicoplacoid echinoderms, *Chancelloria* plates, sponges (or spongimorphs), helcionellacean molluscs, trilobites, inarticulate brachiopods, and hyoliths (Rowland and Gangloff, 1988). Some unknown encrusting microfossils, cryptalgal rafts, calcareous microspheres, radiocyaths, and unidentified shells have been reported as subordinate elements from different Lower Cambrian buildups (James and Gravestock, 1990; Kruse, 1991; Wood et al., 1993). In addition to the fossils mentioned above, the reef rocks in the Lower Cambrian buildups also contain microboring (?) metazoan that are preserved as small spar-filling tubes (Wood et al., 1993, fig. 9), millimeter-size borers that cut archaeocyathan walls and lithified sediments (Gandin and Debrenne, 1984, plate 1, fig. 1d), endolithic (boring) sponges (Kobluk, 1981, 1985), and some macroborers (James, 1983).

Within the Ravenswood bioherms, *Chancelloria* plates, trilobite fragments, echinoderm plates and brachiopod shells are common bioherm-associated fossils (Figs. 18A, B, C, D). They are abundant both in the reef-core facies and in the reef-flank facies. In the reef-core facies, they occur either in a lime mudstone
Fig. 18. Bioherm-associated biota. (A) Photomicrograph of *Chancelloria* (c), and some unidentified shell fragments. Sample RW-92-224-4; scale bar is 2 mm. (B) Photomicrograph of some unidentified shell fragments. Sample RW-93-111; scale bar is 2 mm. (C) *Chancelloria* (c) and brachiopod shells (b), Sample RW-92-122-1; scale bar is 2 mm. (D) Photomicrograph of some unidentified shells. Sample RW-92-229-3; scale bar is 2 mm.
matrix or within the framework spaces among archaeocyathan cups.

*Chancelloria*, including two- and three-actinid calcareous spicules, are often conspicuous elements in thin sections from the Ravenswood bioherms, especially in bioherm 2. The walls of *Chancelloria* spicules are replaced by void-filling calcite, and the interior is filled with micrite; this is similar to the preservation of *Chancelloria* in the Lower Cambrian reef limestones of Labrador in Canada (James and Klappa, 1983).

The echinoderm plates are almost always disarticulated; Gangloff (1975) suggested that some may belong to the genus *Gogia*. The brachiopod shells are thin and relatively small in size. They are preserved either in pairs as an entire individual or separately as bioclasts. Most of the brachiopod shells are replaced by calcite spar with a thin micrite envelop. Sponge spicules, hyoliths, and some unidentified shells are present.

4.5. Carbonate Sedimentology

4.5.1. Depositional matrix of bioherms

(1) Micrite

Micrite, or lithified lime mud with crystals less than 20 μm in diameter (Dunham, 1962), is found throughout the Ravenswood bioherms. It is the predominant matrix component of the bioherms. Micrite is commonly clotted and intermixed with subangular, but well sorted, fine sand-sized quartz grains, and with some pyrite, argillaceous material and insoluble organic residues. There are abundant argillaceous seams and stylolites through micrite matrix (Fig. 19A).
Micrite commonly fills framework cavities of archaeocyaths, central cavities of archaeocyath cups, between bioclasts and calcimicrobes as the matrix, and primary reef cavities of the bioherms. It should be noted, however, that the primary growth cavities in the Ravenswood bioherms are relatively less abundant than those in many other Lower Cambrian reefs. In many central cavities of archaeocyaths and, in rare cases, in the primary bioherm cavities, micrite and peloids only partially filled the cavities to form geopetal structures (Fig. 19B).

Fig. 19. Photomicrographs of micrite in the bioherms. (A) Stylolites (lower arrow) and argillaceous seams (upper arrow) in micrite matrix. Sample RW-92-122-1; scale bar is 2 mm. (B) Micrite and peloids partially filled the central cavity of archaeocyath to form geopetal structure. Arrow points to the wavy surface. Sample RW-92-2; scale bar is 2 mm.
Cavity-accumulated micrite is different from sea-floor micrite. The former, referred to as internal precipitates of micrite by Reid and others (1990), probably forms in a higher-energy and agitated-current environment. Some micrite within cavities in the Ravenswood bioherms is probably cavity-accumulated micrite. Some masses of micrite are composed of dark or black lime mud. They probably contain some unidentified microbial fossils and may be the result of widespread bacterial activities (Tsien, 1985; Riding, 1991a).

(2) Siliciclastic mixture

As I mentioned above, a considerable amount of siliciclastic material is evenly distributed within micrite matrix in the Ravenswood bioherms. It typically is angular to subangular, well sorted, fine sand-size quartz grains, together with some opaque pyrite crystals, argillaceous deposits, and insoluble organic material (Fig. 20A). Quartz grains are distributed in the micrite matrix along stylolites (Fig. 20B).

Fig. 20. Siliciclastic mixture in the bioherms. (A) Photomicrograph showing quartz grains, opaque pyrite, organic material and stylolites. Sample RW-93-112; scale bar is 2 mm. (B) Photomicrograph showing millimeter-thick argillaceous accumulations along the surface of stylolites. Sample RW-93-121; scale bar is 2 mm.
and in some cavities again suggesting that the micrite and quartz were transported by moderate currents. Along the surface of the wavy, horizontal, millimeter-thick stylolites are millimeter-thick fine-grained argillaceous accumulations (Fig. 20B).

4.5.2. Cavities and cements

Similar to younger Paleozoic reefs, many Lower Cambrian buildups contain numerous irregular cavities filled with multigenerational fibrous calcite cements, floored with geopetal internal sediment, occasionally roofed with calcimicrobes such as Renalcis, and occluded by blocky calcite.

These cavities possess diverse characteristics of cementation (Rees et al., 1989; James and Gravestock, 1990; Pratt, 1990; Wood et al., 1993). They display a variety of synsedimentary cements and range in size from millimeter-size to meter-size (e.g. Rowland and Gangloff, 1988, Fig. 13B). The growth patterns of some reef cavities in the Lower Cambrian are remarkably complex and can be readily compared to those in younger Paleozoic reefs (Rees et al., 1989).

The documented types of synsedimentary cement in the Lower Cambrian reefs include (a) fibrous calcite cement with different generations of cement; (b) possible calcitized aragonite botryoids; (c) calcitized pseudomorphosed aragonite fans; (d) bladed primary Mg calcite spar cement; (e) inferred subpeloidal micrite-sized cement within the matrix fabrics (James and Klappa, 1983; Rees et al., 1989; James and Gravestock, 1990; Kruse, 1991; Wood et al., 1993). Based on petrographic and geochemical studies of cement from the Lower Cambrian reef limestones in Labrador, James and Klappa (1983) subdivided the fibrous calcite cement into four types (Type 1-4) which grade into one another and are probably diagenetic variants of the same starting material. They also divided the postsedimentary cements into prismatic calcite and equant, blocky spar.
The Ravenswood bioherm limestones possess abundant argillaceous accumulations along the surfaces of stylolites (Fig. 20B). The argillaceous material may have been transported into cavities as cavity filling during and after reef growth. The stylolitic surfaces with the argillaceous material could be original cavities that were subsequently compressed and collapsed to be stylolite surfaces during late-stage burial diagenesis. If this assumption is true, the Ravenswood bioherms should have a much higher percentage of cavities.

In addition, a few large cavities (about 20 to 30 centimeters in length) filled with terrigenous sediment have been observed in the field outcrops. More work is needed to decide whether they are primary cavities or secondary cavities.

Irregular spar-filled voids and cavities are distributed in the micrite matrix and between the bioclastic skeletons in the Ravenswood bioherms. Ceilings of cavities range from irregular and with no visible means of support to those sheltered by archaeocyaths or other bioclasts. Some sheltered cavities of archaeocyaths have *Renalcis* colonies growing downward from the ceilings. Roofless cavities, ranging from millimeter-size to centimeter-size, were rimmed by multiple zones of fibrous calcite cement and finally occluded by prismatic calcite and equant spar cement. Stromatactis-like cavities, cemented cavities with a wavy to smooth floor and an irregular roof, are also found in thin section (Fig. 21).

Some central cavities of archaeocyaths are well-preserved cavities with spar fillings and internal sediment. Geopetal structures (Figs. 19B, 22), which include geopetal internal sediment and spar cement, are very common in the central cavities of archaeocyaths. Geopetal internal sediment is composed of peloidal sediment and lime mud with a wavy surface. Rees and others (1989) described this wavy surface between peloidal sediment and overlying lime mudstone as "the scalloped surface." They interpreted it as possibly resulting...
from grazing organisms. As an alternative, I suggest that it may be formed by agitating currents.

Fig. 21. Photomicrograph of stromatactis-like cavity with a smooth floor and a wavy ceiling. Sample RW-93-134-2; scale bar is 2 mm.

Fig. 22. Photomicrograph of geopedal structure in the central cavity of archaeocyath showing geopedal internal sediment and spar cement. Sample RW-93-133-3; scale bar is 2 mm.

(1) Fibrous calcite cement

Fibrous calcite cement has been observed in both bioherm 1 and bioherm 2 (Figs. 23A, B). Most fibrous calcite cements were probably synsedimentary and some of them, such as the rinds along the crosscutting fractures, were probably late-stage shallow burial phenomena. The cement, commonly isopachous fibrous spar, encases the cavity undersurfaces and the microbial microfossils. The cement resembles fibrous calcite cement type 3 of James and Klappa (1983),
which is comparable to the fascicular optic calcite of Kendall (1977). Subsequent fibrous calcite precipitation resulted in multigeneration zones of cement. One to two generations of cement have been observed in the cavities. The second band is normally composed of elongated bladed spar. This bladed calcite occurs as distinct, cone-shaped bundles that are from 0.1 to 1.0 mm wide and 0.2 to 1.5 mm long. Several bundles may grow together to form a fan-shaped colony (Fig. 23B). They are oriented normal to the substrate and occur as rinds lining the walls of cavities in the bioherms. Each bundle is clear to light brown in plane light. The boundaries between bundles are sharp. This type of cement is similar to type 2 of James and Klappa (1983), which is also called the fascicular optic calcite by Kendall (1977). Both isopachous fibrous cement and bladed spar cement have been proposed to be of a Mg calcite origin by James and Klappa (1983).

Fig. 23. Photomicrographs of fibrous calcite cement. (A) Two-generation zones of fibrous calcite cement. Sample RW-93-135-2; scale bar is 2 mm. (B) Bladed calcite cement with a fan-shaped colony (f). Sample RW-93-132-4; scale bar is 2 mm.
(2) Subpeloidal micrite-sized cement

Subpeloidal micrite-size cement (Wood et al., 1993) is common in the Ravenswood bioherms. It occurs within the matrix fabrics (Fig. 24A), or interlayers with some geopetal internal sediment in cavities, or surrounds microbial *Renalcis* colonies in the boundstone (Fig. 24B). Crystals of the cement are calcite microspar and very small (µm-size). Boundaries among crystals are not clear. Some of the subpeloidal micrite-size cement is probably synsedimentary calcite microspar cement and some of it may be neomorphic calcite from micrite produced during late-stage diagenesis. It is not possible to determine which of them was synsedimentary.

Fig. 24. Photomicrographs of subpeloidal micrite-sized cement. (A) Subpeloidal micrite-sized cement (arrows) in the matrix fabrics. Sample RW-92-122-1; scale bar is 2 mm. (B) Subpeloidal micrite-sized cement (arrow) among *Renalcis* colonies. Sample RW-93-133-1; scale bar is 2 mm.

(3) Prismatic calcite cement

Prismatic calcite cement lines internal cavities and precipitated on the preexisting fibrous calcite (Fig. 25A). It also fills archaeocyathan chambers and
occurs as the first-stage cement in some dissolution molds of brachiopods (Fig. 25B).

Fig. 25. Photomicrographs of prismatic calcite cement. (A) Prismatic calcite cement (P) on preexisting fibrous calcite (F), and finally occluded by blocky spar (B). Sample RW-92-2; scale bar is 2 mm. (B) Prismatic calcite cement in the dissolution mold of a brachiopod. Sample RW-93-111; scale bar is 2 mm.

(4) Blocky spar cement

Blocky spar cement occurs as the latest phase of cavity fill (Fig. 26A), as bioclastic mold fill and as fracture fill (Fig. 26B). Crystals of blocky spar are the major calcite precipitates; this spar fills fractures that cut all particles and cements. The blocks are equant in shape and large (0.2 to 3.0 mm). Most of the blocky spar is clear to light brown in plane light. Boundaries between crystals are sharp or interlocked. Some insoluble organic material and pyrite crystals occur in the blocky spar cement. Blocky spar cement is the result of late-stage
burial diagenesis (Tucker and Wright, 1990). There are probably two stages of blocky spar cement. The blocky spar occluding the remaining spaces of cavities was probably earlier than that filling in fractures.

4.5.3. Cementation and diagenesis

The Ravenswood bioherms were effected by a complex, multi-generational diagenetic history. A detailed study of this history is beyond the scope of my thesis study and necessary geochemical analyses were not available, so only the main features are outlined here.

Fig. 26. Photomicrographs of blocky spar cement. (A) Cement as the latest phase of cavity fill. Sample RW-93-134-4; scale bar is 2 mm. (B) Cement as fracture fill. Sample RW-93-134-3; scale bar is 2 mm.
The bioherm limestones in the Ravenswood area have a diagenetic history similar to Lower Cambrian reefal carbonates elsewhere (James and Klappa, 1983; James and Gravestock, 1990) because they have the same type and style of fabric and fossil preservation.

The first stage of sea-floor diagenesis or synsedimentary marine cementation was characterized by early calcification of microbial organisms, lithification of micrite, and precipitation of fibrous cements. The marine micrite cement occurs both among reefal organisms and inside growth cavities. The zoned fibrous calcite cement lines cavities and is interlayered with internal marine sediment. This stage is critical for reefal organisms and surrounding sediments to form a rigid structure on the sea floor.

Sea-floor diagenesis was followed by a shallow-burial event that resulted in dissolution of some bioclasts, alteration of metastable carbonates (such as aragonite, high-Mg calcite) to calcite, and precipitation of clear prismatic calcite. The prismatic calcite precipitated on the pre-existing fibrous calcite or directly on the inside walls of voids and cavities that were created by dissolution in this stage. Brachiopods, hyolithids, Chancelloria, and some unidentified shell were dissolved and may have originally been aragonite as suggested by James and Klappa (1983). The other components, including archaeocyaths, Renalcis, echinoderms, sponges, and fibrous calcite cement, were recrystallized into calcite with large crystals during this stage.

This second stage of diagenesis may have taken place in a mixed groundwater to meteoric setting due to the sea-level fluctuation. On the outcrop of bioherm 1 in the Ravenswood area (Fig. 5), there is a wavy surface between the lower part and upper part. This surface may have formed due to exposure above sea-level. The upper part of the bioherm may represent a second stage of growth on the resubmerged surface.
Finally, the Ravenswood bioherm limestones were subsequently buried. The earlier stage of blocky spar cement occluded the remaining spaces of cavities. The biohermal limestones also underwent pressure solution as indicated by extensive stylolitization. Along some stylolites, portions of archaeocyath walls were dissolved (Fig. 12C) and insolubles were concentrated. The final diagenetic phase was fracturing that cut all preexisting fabrics, including stylolites. These fractures were filled with later blocky spar. Local dolomite in the Ravenswood bioherms, such as the capping of bioherm 1 in the east section (Wilson, 1992), indicates a late-stage dolomitization.

4.6. Paleoecology and Community Structure

It is always challenging to picture how reef organisms lived together and interacted with each other and how the reef community ecosystem was constructed. More and more data about Lower Cambrian reefs have accumulated by many workers from around the world during the past three decades making it possible to begin to understand the paleoecology of reef organisms. Rowland and Gangloff (1988) divided the reef organisms into three groups based on their roles in the carbonate buildups: (1) constructors and binders, (2) dwellers, and (3) destroyers. This classification provided the framework for comparing the Lower Cambrian reef communities to that of younger reefs. The following discussion on autoecology of reef organisms in the Ravenswood bioherms is based on this classification.
4.6.1. Autecology of archaeocyaths

Archaeocyaths were well-skeletonized sponge-like organisms that lived on the bottom of shallow tropical or near tropical seas during the Early Cambrian (Hill, 1972; Rowland and Gangloff, 1988). They were important metazoan constructors of the Lower Cambrian reefs. Cowen (1983, 1988) discussed the general importance of algal symbiosis in the paleobiology of reef communities and suggested that archaeocyaths may contain photosynthesizing algal or cyanobacterial symbionts. Rowland and Gangloff (1988) considered archaeocyaths as mixotrophs that are photoautotroph-heterotroph units.

In the Ravenswood bioherms, archaeocyaths are the major constructors of one of the two core types. They are dominated by small to moderate size and branching irregulars, such as *Fenestrocyathus* sp.. These irregular archaeocyaths are characterized by branching and massive colonies, a relatively diffuse and taeniae-like intervallum element pattern, a scarcity of synapticulae, and a highly irregular margin of the outer wall (Gangloff, 1975). Regular archaeocyaths are subordinate in abundance. They are solitary, cylindro-conical to cylindrical in shape, and range from 3 to 5 mm in diameter. Some individuals have large central cavities and thin intervallums. Branching irregular archaeocyaths, such as *Fenestrocyathus* sp., *Archaeocyathus* sp., *Protopharettra* spp., and *Syringothalamus* cf. *S. crispus*, always construct the reef core, whereas solitary regular forms, such as *Ajacicyathus* sp., *Rotundocyathus* spp., *Diplocyathellus* sp., and *Palmericyathus* sp., are mainly confined to the interstitial areas of bioherms or to the reef flank facies and interbiohermal areas. Studies of the early Toyonian bioherms in Labrador, Canada and some Botomian archaeocyath reefs in Mexico showed similar distribution of archaeocyaths (Debrenne and James, 1981; Debrenne et al., 1989).
This study suggests that the distribution of archaeocyaths within the bioherms, to some degree, reflects the different wave-resistant capabilities of archaeocyath morphologies. This resistance is largely controlled by the internal structures of archaeocyathan skeletons, such as septa, taeniae, and synapticulae.

The Archaeocyatha is traditionally subdivided into two subclasses, the Regulares and Irregulares, according to skeletal and ontogenetic differences. Members of the Regulares generally show no secondary thickening of the skeleton and are inferred to have had completely soft-tissue-filled intervallums. Members of the Irregulares often possess abundant secondary thickening and are inferred to have borne soft-tissue in their upper parts only; the soft tissue migrated upwards as the animal grew and the lower parts became calcified (Wood et al., 1992). More complicated intervallar structures in the branching irregulars, such as radically arranged septa, horizontal tabulae, and taenia, augmented the ability of irregular archaeocyaths to resist waves and finally increased the framework potential of archaeocyaths in the biohermal areas. Wood and others (1992) suggested that an increase in the importance of intervallar structures reflects the development of modularity and increasing integration within the archaeocyatha: both represent an advanced condition of archaeocyathan evolution. In addition, extensive direct calcitization in the basal abandoned parts of the irregular's skeleton increased the stability of the skeleton and made possible a rigid-reef framework. This mechanism is similar to the direct calcitization in the lower parts of corallia in modern coral reefs.

The branched irregular archaeocyaths in the Ravenswood bioherms show interparietal budding that produced new cavities from the walls of older cavities (Figs. 14A,B). Secondary branches allowed archaeocyaths to baffle sediments among individuals more effectively. According to Wood and others (1992), the branched irregular forms were by far the most successful in terms of generic
diversity and have the longest temporal distribution from Tommotian Zone 2 to the end of the early Cambrian. They possessed a higher modularity and integration than solitary forms (Wood et al., 1992). Thus, the development of branching irregulars enhanced reef-forming potential.

4.6.2. Autecology of *Renalcis*

The volumetrically important cyanobacteria-like form *Renalcis* has been assigned to various taxonomic groups, including cyanobacteria (Hill, 1972; Chuvashov and Riding, 1984) and the calcareous foraminifera (Riding and Brasier, 1975). Pratt (1984) considered them to be a diagenetic form of cyanobacterial colonies.

Based on observations of *Renalcis* and *Renalcis*-like forms growing in a wide range of inferred light intensities, Rowland and Gangloff (1988) suggested that *Renalcis* could live either autotrophically or heterotrophically. In accordance with these habits, two separate modes of life for *Renalcis* have been proposed from observations of Lower Cambrian reef communities. In one case *Renalcis* occurs as a secondary encruster, growing within centimeter-size or meter-size framework cavities (Kobluk and James, 1979; Rowland and Gangloff, 1988; James et al., 1989), attached to archaeocyathan walls that were probably quite dark, and grew in large fractures in reefs with a clearly dark environment (Rees et al., 1989). This habit requires that *Renalcis* was able to live by heterotrophic metabolism. Its photoheterotrophic source of carbon could have been the photosynthate produced by symbiont-bearing archaeocyaths (Rowland and Gangloff, 1988). In the other case, *Renalcis* was a primary, upward-growing frame builder that constitutes the primary framework constituent in some reefs. Two modes of habit have been reported from the Shackleton Limestone of
Antarctica (Rees et al., 1989), the Flinders Ranges of South Australia (James and Gravestock, 1990), the reefs of California and Nevada (Rowland and Gangloff, 1988), and southern Labrador of Canada (Kobluk and James, 1979).

In the Ravenswood bioherms, both modes of life for *Renalcis* have been inferred. *Renalcis* occurs as both a secondary encruster attached to or hanging from archaeocyathan walls (Fig. 17) and a dominant constructor to form the *Renalcis* boundstone (Fig. 16). Most *Renalcis* found in the reef core facies shows the first mode of habit (secondary encruster), whereas *Renalcis* found in the peripheral parts of bioherms (e.g. bioherm 1) and above the bioherms (above bioherm 2) shows the second mode of habit (frame builder). The difference of *Renalcis* distribution within the bioherms could be related to the availability of sunlight. *Renalcis* in the peripheral parts of bioherms or upper bioherms had ample sunlight, whereas *Renalcis* within cavities or framework skeletons was protected from the sunlight.

Rowland and Gangloff (1988) proposed that *Renalcis* may have evolved in two lineages. One lineage may have exploited cavities at the earliest evolutionary opportunity, while another retained its framework-building lifestyle. As an alternative, *Renalcis* may include two different affinities of organisms. One group is autotrophic cyanobacteria that actively bound and trapped sediment to form boundstone. Another group may belong to heterotrophic bacteria that passively attached to cavity walls and bioclasts acting as a secondary encruster. They were living respectively in different modes of habit during the early Cambrian. This interpretation would be consistent with the interpretation that *Renalcis* is merely a diagenetic form (Pratt, 1984).
4.6.3. Autecology of bioherm-associated organisms

In the Ravenswood bioherms, evidence of other bioherm-associated organisms consists of trilobite fragments, *Chancelloria* particles, echinoderm plates, brachiopod shells, and some unidentified fossils.

Trilobite fragments are common in the Ravenswood bioherms, but it is difficult to identify them to a specific genus or species due to poor preservation. Rowland and Gangloff (1988) considered some trilobites in the Lower Cambrian bioherms to be deposit feeders and others to be carnivores. Because many trilobites are preserved as fragments in the Ravenswood bioherms, I suggest that not all trilobites may have been bioherm-dwellers and that many of them probably lived in the terrigenous, interbiohermal sediments. The fragments were probably transported by currents into the bioherm.

*Chancelloria* plates were observed in many thin sections of samples from the framework core of bioherm 1 and bioherm 2. The fragments of *Chancelloria* occur in the micrite among the framework spaces of archaeocyaths. The functional analysis of *Chancelloria* depends on its presumed affinity. *Chancelloria* was formerly considered to be a sponge, but lately it has been placed in a new group, Coeloscleritophora, by Bengtson and Missarzhevsky (1981). Little is known about the functional morphology of *Chancelloria* although it has been inferred to be a mobile deposit feeder or herbivore by Rowland and Gangloff (1988). Because of the limited distribution of *Chancelloria* in the bioherm core facies, I suggest that it could be a reef-dweller.

Echinoderm ossicles are also common in thin sections from the Ravenswood bioherms. They are typically preserved as separated plates scattered within the bioherms. No identifiable fragments were found in the Ravenswood bioherms. Lower Cambrian echinoderms, including Class
Helicoplacoidea and Class Eocrinoidea, have been interpreted to be marine suspension feeders in previous studies (Rowland and Gangloff, 1988). This study suggest they were reef-dwellers based on their distribution and preservation in the bioherm.

Brachiopod shells are preserved in pairs, as separate shells, and as fragments. These shells, along with some unidentified shelly bioclasts and rare hyoliths, commonly occur in bioherm-related facies and rarely in the boundstone itself. They are relatively abundant in the upper sections and the reef flank facies adjacent to the siliciclastic facies. Most of them were probably carried into bioherm cavities or framework spaces by currents. Some shells, such as those preserved as pairs, were probably reef-dwellers.
Chapter 5

MONTENEGRO BIOHERMS

5.1. Geological Setting

For comparative study, I also examined a large bioherm in the Montenegro Member of the Campito Formation in the White-Inyo Mountains of eastern California (Fig. 1). The late Neoproterozoic and Early Cambrian sequence in the White-Inyo Mountains is mostly a conformable sequence and is one of the best exposed and thickest sections (up to 11,000 m) in North America. It is composed of limestone, dolostone, shale, siltstone, sandstone, all of which have undergone low-grade metamorphism. This section has been studied extensively by many geologists from many disciplines (see Moore, 1976; Mount and Signor, 1989; Signor and Mount, 1989).

The archaeocyath-bearing formations in this area include the Campito Formation, Poleta Formation, and Harkless Formation, with a total thickness of 2150 m. Archaeocyaths range from the bottom of the *Nevadella Zone* (Fig. 27) to the *Bonnia-Olenellus Zone*. They first occur in calcareous siltstone and limestone assigned to the Montenegro Member of the Campito Formation approximately 300 to 450 m above the lowest recorded occurrence of the trilobite *Fallotaspis*. The highest reported occurrence of archaeocyaths is in small bioherms in the lower 64 m of the Harkless Formation (Gangloff, 1976).
Fig. 27. Partial stratigraphic column showing the Lower Cambrian sequence in the White-Inyo Mountains (after Nelson, 1976).
The bioherms discussed in this paper occur within siltstones assigned to the upper part of the Montenegro Member of the Compito Formation (Fig. 27). The Montenegro Member is 200 to 350 meters thick (Nelson, 1962, 1976; McKee and Moiola, 1962; McKee and Gangloff, 1969; Stewart, 1966, 1970; Mount and Signor, 1989) and mainly consists of interstratified siltstones, mudstones and lesser fine sandstones and sandstones. The uppermost part of the section, about 40 meters thick, contains increasing amounts of bioclastic-rich limestone to micritic-rich limestone that has undergone minor dolomitization. These beds are a few centimeters to 0.5 meters thick and thicken up section into the more massive limestones of the Lower Member of the Poleta Formation.

Moore (1976) interpreted the Montenegro Member to represent deposition on an offshore and isolated carbonate bank in a fairly low-energy environment. Mount and Signor (1989) considered this member to be a muddy subtidal siliciclastic deposition with subordinate low intertidal and tidal flat facies. Isolated archaeocyathan bioherms were built on and are surrounded by the subtidal siliciclastic facies.

5.2. Previous Work on Montenegro Bioherms

Gangloff (1975, 1976) made a detailed study of Lower Cambrian archaeocyath assemblages in eastern California and western Nevada, including the Lower Cambrian in the White-Inyo Mountains. Morgan (1976) and Fuller (1976) studied the Montenegro bioherms in the same year, evidently without knowing about each other's work, and they reached different conclusions. Based on the fabric preserved in the bioherm limestone, Morgan (1976) pointed out that the Montenegro bioherms have not shown any evidence of binding or baffling. She classified the Montenegro bioherms as micrite mounds. Conversely, Fuller
(1976) considered the Montenegro bioherms to be framework reefs that were built by archaeocyaths and bound by *Renalcis*. Based on lithologic characteristics, he differentiated the bioherm into several subfacies, including reef core, subreef, intrareef, and interreef. Field investigations and thin section observations in my study support Morgan's conclusions.

5.3. Location and Geometry

The outcrop studied is located in the SW1/4, SW1/4, SW1/4, SE1/4, Section 19, T7S, R35E, Blanco Mountain 15 Minute Quadrangle (Nelson, 1976). This area is readily accessible by car by way of Highway 186 to Westgard Pass, northeast of Big Pine, and then by U. S. Forest Service Road 4S01.

Two bioherms occur close together at this site (Fig. 28), both of which are

![Fig. 28. Generalized geologic map of the Montenegro bioherms near Forest Service Road 4S01 in the White Mountains (After Morgan, 1976). The larger bioherm on the right was the subject of this study.](image-url)
located on the southern slope of a west-dipping ridge (Morgan, 1976). Several smaller bioherms occur at approximately the same stratigraphic interval a few km away in Payson Canyon (R.A. Gangloff, pers. comm., 1993). I studied the larger of the two bioherms shown in Figure 28. The eastern and southern portions of this bioherm are well exposed, whereas the western and northern parts are covered by shale and siltstone (Fig. 29). The bioherm is best exposed

Fig. 29. Field photo and sketch of the Montenegro bioherm examined in this study. Views facing north (sketch from Morgan, 1976)
on its east side where it is 25 meters wide and 6-8 meters thick (Fig. 30). The precise dimensions of this bioherm cannot be determined because the western margin is not exposed; it is probably somewhat larger than what is exposed in the outcrop. The bioherm is underlain by crossbedded siltstone with a sharp contact. The upper surface of the bioherm is slightly convex. The whole bioherm occurs as an elongate moundlike body. Close inspection shows that bioherm is composed of many lenticular units, or kalyptrae, that are stacked together to form a compound buildup. Each kalyptra is about 50 cm wide and 20 cm thick.

Fig. 30. The east side of the Montenegro bioherm showing lenticular kalyptrae.

5.4. Structure of Bioherm

5.4.1. Facies and Fabrics

I have defined the following three facies within the Montenegro bioherm (Fig. 31): (1) crossbedded siltstone facies at the bioherm base, (2) kalyptra
biohermal limestone facies of the main bioherm, and (3) inter-kalyptra siltstone facies. Flank facies and reef talus are absent.

Fig. 31. Sketch of the Montenegro bioherm showing lenticular kalyptrae and three facies

(1) Crossbedded Siltstone Facies

The crossbedded siltstone facies forms the base of the bioherm. This facies is laterally discontinuous and gradational laterally or vertically with planar-bedded sandstone facies. The facies is composed of light green to light brown, crossbedded and ripple-marked siltstone. It also contains thinly laminated sericite, chlorite, and silt-sized to fine-grained quartz sand grains. The crossbedding is low angle, in tabular to slightly wavy sets, 2-3 m long and 70 cm
thick. The crossbedded sets preferentially dip to the west. Nearly symmetrical ripple forms are present on the surface of beds. Some trilobite fragments and trace fossils (horizontal burrows) also are in this facies.

The crossbedded siltstone facies represents a localized low-energy deposition of stable and marine shelf siltstones and shales. The low angle crossbedding and ripple cross-stratification indicate sediments transported from east to west and deposited on a fairly flat bottom (Fuller, 1976). Fuller (1976) measured the ripple parameters L (ripple lengths), H (ripple height), RI (ripple index) from the ripples found 50 cm below the bioherm. The average values are L=7.0 cm, H=0.3 cm, and RI=25.4. The ripple parameters show the ripple marks were formed by a combination of currents and waves (Reineck and Singh, 1973). Therefore a shallow subtidal flat environment is inferred for this facies. In addition, the thin laminae in this facies suggest a low input of sediment into the environment and the horizontal burrows indicate an offshore, level-bottom environment. It was this shallow-water environment with low influx of sediment that favored the growth of the later bioherm.

(2) Kalyptra biohermal limestone facies

The Montenegro bioherm is mainly composed of many lenticular to tabular kalyptrae. A kalyptra is a biconvex or concavoconvex body of boundstone (Rowland and Gangloff, 1988). These kalyptrae were stacked together to form a compound mound-like buildup.

Each kalyptra, approximately 50 cm in diameter and 20 cm thick, is also composed of many small lenses. Fine-grained clay occurs within the fractures and stylolites surrounding the small lenses. Adjacent kalyptrae either touch one another or are separated by the siltstone filling of the inter-kalyptra facies. In
some instances, green argillaceous inter-kalyptera sediment surrounds a kalyptera.

The kalyptrate biohermal limestone facies has distinct and sharp contacts with the non-reef siltstone and sandstone. The sharp contacts between the surrounding facies and the bioherm facies, between inter-kalyptra facies and bioherm facies, and among different kalyptrae indicate that the bioherm was a rigid, low-relief biostructure on the sea floor during deposition of surrounding terrigenous facies.

The kalyptra facies is apparently an \textit{in situ} accumulation of massive and micritic limestone that was mainly produced by calcimicrobes and archaeocyaths. It is light gray, dense, massive and finely crystalline limestone with abundant and diverse archaeocyaths packed together (Fig. 32); calcimicrobes that resemble \textit{Renalcis} have been preserved around the archaeocyath cups or among archaeocyath individuals. The archaeocyaths

Fig. 32. Polished slab of the kalyptra biohermal limestone. Archaeocyaths (arrows) with relatively large central cavities. Sample WI-92-222; black scale bar is 1 cm.
include Archaeocyathus sp., Syringothalamus cf. S. crispus, and Palmericyathellus sp.. Many of the archaeocyath skeletons are preserved perpendicular to bedding and some are found subparallel to bedding, suggesting they grew upright and are preserved in situ. Rare reworked or fragmental debris of archaeocyaths have been found. Fuller (1976) also reported that many archaeocyath skeletons of the narrow cylindrical form are found tipped to the east, but most are less than 20 degrees from vertical; a few bulbous Ajacicyathus cups were found lying on their sides with their apices oriented to the west or southwest and with the central cavities filled with terrigenous debris. This orientation may reflect the temporary and local current direction during archaeocyath growth or after archaeocyath death. More data would be needed to confirm this hypothesis.

Also a major constituent of the kalyptra facies is an abundance of recrystalized lime mud. Previous studies suggested that the fine-grained crystalline matrix of the Montenegro bioherms was probably derived from the breakdown of abundant algae thalli and recrystallization of lime mud (Fuller, 1976; Morgan, 1976; Moore, 1976); an interpretation with which I agree. Thus, within the kalyptra facies, archaeocyaths dominated and acted as substrates for Renalcis-like calcibionts and lime mud was abundant.

(3) Inter-kalyptra facies

Fuller (1976) described several different non-reef facies from the Montenegro bioherm, including subreef facies, intrareef facies, and interreef facies. They are either bioclastic limestone or calcareous siltstone, but they all surround the kalyptrae. Here I group them into one facies, the inter-kalyptra facies.
This facies contains discontinuous limestone lenses that underlie the bioherm. The lenses, up to 1 m long and 15 cm thick, are composed of bioclastic microcrystalline limestone. Terrigenous contents, such as fine-grained quartz, chlorite, and sericite, are higher than in the adjacent bioherm facies. Archaeocyaths in this facies are variously oriented skeletal fragments that were apparently derived from a nearby bioherm. The *Renalcis*-like calcibionts occur as scattered, dark spheres in the matrix of the limestone.

This facies also includes calcareous siltstone. This siltstone occurs as tabular or lenticular units between kalyptrae, interfingering with the bioherm facies, and overlying the bioherm. The siltstone consists of abundant sericite, chlorite and silt- to sand-size, angular to subangular quartz grains. Many abraded archaeocyath fragments are found in the inter-kalyptra bioherm facies. The composition of this facies, together with its relationship to the biohermal limestone facies, suggests that it resulted from short periods of high-energy movement of water, probably storm waves. These storm deposits were accompanied by pulses of increasing terrigenous sediment influx that covered the limestone.

5.4.2. Fossil constituents

(1) Archaeocyaths

Archaeocyaths are major components of the Montenegro bioherms in the White-Inyo mountains. According to Fuller (1976), archaeocyaths form about 10-15% of the whole rock volume in some parts of the bioherms. Archaeocyath skeletons within kalyptrae are in growth position, unabraded, and mostly perpendicular to beds. The preservation of the archaeocyathan skeletons varies from very-well preserved to strongly recrystalized into a "ghost" outline. The
intervallum and central cavity are commonly filled with micrite. No geopetal structures have been preserved within the central cavities.

Archaeocyaths found in the Montenegro bioherms include irregular and regular forms, occurring in two morphotypes. One is narrow and conical to cylindrical and the other is wider, more bulbous, and cup-shaped (Fuller, 1976; this paper). Branching and massive archaeocyaths have not been found. The majority of archaeocyaths found in the bioherms are the wider cup-shaped forms.

Eight genera of archaeocyaths have been reported from the Montenegro bioherms: Archaeocyathus, Copleicyathus, Ethmophyllum, Pycnoidocyathus, Pseudosyringocnema, Robustocyathus, Rotundocyathus, and Ajadcyathus (McKee and Gangloff, 1969; Gangloff, 1975, 1976; Morgan, 1976; Fuller, 1976). Only three genera were identified in this study: Archaeocyathus, Syringothalamus, and Palmericyathellus. More detailed study on the archaeocyaths in the Montenegro bioherm is needed.

(2) Renalcis-like calcimicrobes

The preservation of calcimicrobes is very poor due to the carbonate diagenetic alteration. These calcimicrobes show similarity to Renalcis thalli but do not have an obvious clotted and chambered texture. Thus, they are referred to as Renalcis-like calcimicrobes. These Renalcis-like calcimicrobes appear as small patches from 5 to 20 mm in diameter composed of many tiny micrite spheres (Fig. 33). They occur in the micrite matrix and among archaeocyath skeletons. Some archaeocyath skeletons are bound by these Renalcis-like thalli, showing a collar structure around the archaeocyathid cup. Renalcis-like
organisms in the Montenegro bioherm did not form *Renalcis*-dominated boundstone or archaeocyath-*Renalcis* boundstone.

Fig. 33. Photomicrograph of *Renalcis*-like calcimicrobes (R) as small patches in the micrite matrix. Sample WI-92-11; scale is 2 mm. Montenegro bioherm.

(3) Associated Biota

Compared to the Ravenswood bioherms, the Montenegro bioherm has rare bioherm-associated fossils. Other than archaeocyaths and *Renalcis*-like microorganisms, the only other recognizable evidence of organisms is trilobite fragments and possible burrowers (?) (Mount and Signor, 1989). Common bioherm-associated biota in the Ravenswood bioherms and other Lower Cambrian bioherms, such as echinoderms, *Chancelloria*, brachiopods, sponges, and hyoliths, are absent in the Montenegro bioherm.
5.5.1. Matrix of the bioherm

(1) Micrite

Micrite dominates the matrix of the Montenegro bioherm. Micrite masses are commonly separated from one another by fine-grained argillaceous material and stylolites (Fig. 34). Morgan (1976) and Moore (1976) suggested that the large

Fig. 34. Photomicrographs of micrite in the Montenegro bioherm. (A) Micrite as major matrix in the biohermal limestone. Sample WI-92-13-1; scale bar is 2 mm. (B) Micrite masses (m) separated by argillaceous material and stylolites (arrows). Sample WI-92-1-2; scale bar is 2 mm.
amount of micrite found in the Montenegro bioherm was produced mainly by the breakdown of the thalli of calcareous algae, as in some recent carbonate environments. They argued that many calcareous algae were present but were not preserved as recognizable fragments; instead, they were broken down into mud-size fragments after death. This study has no evidence to prove this assumption; however, pure and fine-grained micrite without siliciclastic grains suggests that it was probably a sea-floor micrite (Reid et al., 1990) formed in a low-energy environment.

(2) Siliciclastic Mixture

The Montenegro bioherm is composed of many kalyptrae, and each kalyptra is composed of many small lenses that are composed of pure micrite. Fine-grained argillaceous material occurs between lenses (Fig. 35B) and between kalyptrae. Unlike the Ravenswood bioherms, the Montenegro bioherm does not contain angular to subangular, sand-sized quartz grains and pyrite crystals.

5.5.2. Diagenesis

The Montenegro bioherm is characterized by a recrystallized micritic matrix that completely fills space between archaeocyaths and within their initial cavities. The early stage of diagenesis must have been characterized by lithification of micrite in order to form a rigid, low-relief biostructure on the sea floor. The lack of siliciclastic grains within kalyptrae suggests that the bioherm grew and was lithified before storm events could winnow the mud, destroy archaeocyaths, and mix siliciclastic grains into the micrite matrix. Late diagenesis involved recrystallization of micrite both in the matrix and in
archaeocyathan skeletons. The variable preservation of archaeocyath skeletons (e.g. intervallums are always preserved better than inner walls) suggests a selective dissolution or recrystallization due to different mineral compositions. Similar to the Ravenswood bioherm, the Montenegro bioherm underwent extensive burial diagenesis. This process is demonstrated by extensive stylolitization and many small compacted lenses throughout the biothermal limestone.

5.6. Paleoecology and Community structure

Reef organisms in the Montenegro bioherm, as described above, include archaeocyaths, *Renalcis*-like algae, rare trilobites and burrowers. Archaeocyaths are the major metazoan components (about 10-15% in volume) of the bioherm. The majority of archaeocyaths are solitary, nonbranched, large forms occurring in a micrite matrix. There is little evidence of anchoring or exothecal skeletal material (McKee and Gangloff, 1969); this implies a lack of rigid, interconnected association typical of modern coral reefs. This interpretation was shared by Morgan (1976), who pointed out that although archaeocyaths are often considered to be major reef builders, for the archaeocyathan community in the Montenegro bioherm this was not the case.

On the basis of thin section observation and field investigations, I also consider archaeocyaths in the Montenegro bioherm to be major components rather than obligate reef builders. They are not present in large enough numbers to have acted as framework builders for the bioherm. The fact that these are solitary, nonbranched individuals of archaeocyaths suggests that they possessed a low potential to baffle sediments and to resist waves. The Montenegro bioherm does not appear to represent ecological reefs because it shows no evidence of
metazoan framework builders, no recognizable lateral and vertical variation within the archaeocyathan community, and no signs such as channels, cross-beds, skeletal sands or oolites to indicate that it developed in a high-energy environment (Morgan, 1976). Instead, the Montenegro bioherm is more likely a micrite mound that was produced mainly by interaction between microorganisms and archaeocyaths in a low-energy environment.

Savarese (1993) used theoretical and experimental biomechanical approaches to test the effects of archaeocyathan central cavity diameter on the generation of passive flows through the skeleton. The results imply that environments with low-velocity currents could have supported individuals with larger central cavity diameters than did higher-energy settings. These experimental results reinforce my conclusion that the Montenegro bioherm was a low-energy environment, because of the presence of large archaeocyathan individuals with large central cavity diameters.

*Renalcis*-like calcibionts in the Montenegro bioherm mainly occur as secondary encrusters attached to archaeocyathan walls, or in clasts which were deposited among archaeocyathan individuals. They also form large patches surrounded by micrite. These calcibionts were apparently not abundant enough to bind and trap sediments to produce calcimicrobial boundstone. The low-energy, perhaps restricted, carbonate environment and the episodic input of fine-grained terrigenous sediment may have prevented calcibionts from flourishing.

Because the Montenegro bioherm probably formed as a small mud mound in response to locally favorable, temporary conditions, the bioherm community remained simple. Organisms had little time to exploit new environments within or around the bioherm.
Chapter 6

COMPARISON OF THE RAVENSWOOD AND MONTENEGRO BIOHERMS

Both the Ravenswood bioherms in central Nevada and the roughly coeval Montenegro bioherms in eastern California represent the earliest archaeocyath-calcimicrobial carbonate buildups of the Early Cambrian in the western U. S.. These Lower Cambrian bioherms share many common features; but also they show some differences in structure, paleoecology, and taxonomic composition of archaeocyaths that evidently reflect the variation in environment from one setting to another (Table. 2).

6.1. Similarities:

(1) Both the Ravenswood bioherms and the Montenegro bioherms are archaeocyath-calcimicrobial carbonate buildups. The bioherm-building communities are composed of archaeocyaths and calcimicrobes, although in differing percentages. Other organisms in the communities acted mainly as dwellers or destroyers and played a minor role in bioherm development. *Renalcis* or *Renalcis*-like calcibionts are poorly preserved in both areas presumably because of diagenesis.

(2) Both bioherms have similar shapes and small dimensions in outcrops. Individual bioherms in the Ravenswood area are three-dimensionally elongated,
Table 2. Comparison of the Ravenswood and Montenegro Bioherms

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lenticular bodies, 5 to 8 meters thick and 20 to 25 meters wide; the Montenegro bioherm is an elongated moundlike body, 6-8 meters thick and 25 meters wide. Compared to modern reefs, they are individually small in size, similar to patch reefs of Bermuda (James, 1983). They do, however, represent the pioneer reefs in
the Lower Cambrian. Several small bioherms in the Ravenswood area combined to form a large bioherm complex.

(3) Both the Ravenswood bioherms and the Montenegro bioherm are Early Cambrian. The Montenegro bioherm occurs in the upper part of the Montenegro Member of the Campito Formation, which is within the *Nevadella* Zone (Nelson, 1976). *Nevadella*, the major genus in the *Nevadella* Zone, was also reported from the Ravenswood area by Stewart and McKee (1977), but the precise locality is not known. S. M. Rowland and I (field collection, 1992) found *Nevadella* in association with archaeocyath-bearing intervals about 10 meters below Bioherm 1. On the basis of this association, along with bioherm-associated fossils and unidentified nevadiid trilobites (Stewart and McKee, 1977), Wilson (1992) correlated the Ravenswood section with the Upper Campito Formation or Lower Poleta Formation. Most archaeocyaths from the Ravenswood bioherms and the Montenegro bioherms probably belong to the Botomian Stage according to the stratigraphic and geologic distribution of archaeocyathan genera proposed by Debrenne and Zhuravlev (1992). Therefore, both bioherms occur within the *Nevadella* Zone and are probably in the Botomian Stage of the Early Cambrian. But due to a lack of precise age-diagnostic fossils, it is still unknown if they are essentially synchronous or not.

(4) In both areas, the bioherms are surrounded by siliciclastic facies, including fine-grained sandstone, siltstone, and shale. Sometimes these terrigenous sediments were deposited on or within the bioherms. The boundaries between the bioherms and adjacent siliciclastic facies are either sharp or interfingering. This relationship reflects a temporarily favorable condition for bioherm growth. Siliciclastic sedimentation probably eventually shut off carbonate sedimentation, causing the demise of the biohermal organisms and burying the bioherm.
(5) Micrite is abundant in the matrix of the biohermal limestones at both
localities, although it may have different origins. Micrite comprises up to 60-70%
in the Montenegro bioherm, where it appears as fine-grained, light to dark gray
lithified lime mud. In the Ravenswood bioherms, micrite is common in the
framework cavities and in the central cavities as fillings to form geopetal
structures.

6.2. Differences:

(1) The Ravenswood bioherms and the Montenegro bioherm began
growing on different substrates. The former started to grow on the skeletal
packstone that was interpreted by Wilson (1992) as a localized channel-fill. The
Montenegro bioherm began on crossbedded siltstone. The different foundations
of the bioherms reflect different environments in which the bioherms were
initialized. The skeletal packstone of the Ravenswood bioherms formed in a
high-energy environment, whereas the crossbedded siltstone facies of the
Montenegro bioherm formed in a relatively lower energy environment. These
initial environments of bioherm growth probably continued through the entire
bioherm development.

(2) The Ravenswood bioherms and the Montenegro bioherm represent
different Lower Cambrian reef types. As described above, the Ravenswood
bioherms are metazoan framework reefs composed of massive framestone and
boundstone built by abundant archaeocyaths and calcimicrobes. They show
framework textures and boundstone fabrics. Primary growth cavities and
cements are common. Archaeocyaths and Renalcis baffled and trapped
sediments in the upright growth position.

The Montenegro bioherm is a micrite mound composed of many stacked
kalyptra. This bioherm contains abundant micrite which was mainly produced
by the calcareous calcibionts. Archaeocyaths and *Renalcis*-like calcibionts are major bioherm components, but they were not abundant enough to form framestone and boundstone. No growth cavities and cement have been found in the Montenegro bioherm.

(3) Although both the Ravenswood bioherms and the Montenegro bioherm are small in size and similar in shape, they have different ratios of height to width in outcrops individually. For example, bioherm 1 in the Ravenswood area is 5 m high and 10 m wide, and bioherm 2 is 8 m high and 25 m wide. The ratio of height to width is about 1/2 to 1/3. The Montenegro bioherm is 6 to 8 m in height and 25 m in width. The ratio of height to width is 1/3 to 1/4.

(4) Although archaeocyaths are common and major components in both the Ravenswood bioherms and the Montenegro bioherm, taxonomic composition and paleoecology of archaeocyaths are different from one to another. Archaeocyaths identified in the Ravenswood bioherms in this study include *Ajacicyathus* sp., *Rotundocyathus* sp. A, *Rotundocyathus* sp. B, *Diplocyathellus* sp., *Ethmophyllum whitneyi* Meek, *Palmericyathus* sp., *Fenestrocyathus* sp., *Archaeocyathus* sp., *Retilamina* sp., *Protopharetra* sp. A, *Protopharetra* sp. B, and cf. *Syringothalamus crispus* Debrenne, Gangloff & Zhuravlev. Moderate-size, irregular and branched archaeocyaths are the dominant reef organisms. Solitary and nonbranched forms are minor in number. Most irregular and branched archaeocyaths in the Ravenswood bioherms are preserved in growth position, and they are interpreted to be the major frame-builders of the bioherms. Some fragmental skeletons of archaeocyaths, particularly small and solitary regular archaeocyaths, are also found in off-bioherm and inter-bioherm sediments. Some of them were probably transported from the bioherms by high-energy currents. The Montenegro bioherm contains the archaeocyaths *Archaeocyathus*,
Copleicyathus, Ethmophyllum, Pycnoidocyathus, Pseudosyringocnema, Robustocyathus, Rotundocyathus, and Ajacicyathus (Morgan, 1976; Gangloff, 1975); and Palmericyathellus sp. and Syringothalamus cf. S. cispus (this paper). They are dominated by solitary and nonbranched forms.

(5) The Ravenswood bioherms are different from the Montenegro bioherm not only in taxonomic composition and paleoecology of archaeocyaths, but also in other bioherm-associated organisms. Abundant and diverse bioherm-associated organisms have been found in the Ravenswood bioherms, including Renalcis, trilobite fragments, Chancelloria plates, echinoderm plates, brachiopod shells, and some unidentified shell fragments. They are preserved both in the reef-core facies and in the reef-flank facies, mostly acting as bioherm dwellers. In contrast, other than archaeocyaths and Renalcis-like calcibionts, the only other recognizable organisms in the Montenegro bioherm are trilobite fragments and burrowers (?). The different diversities and abundances within the reef communities reflect different reef-forming environments. The diverse, abundant reef community in the Ravenswood bioherms indicates that they formed in an open, shallow marine environment where water circulation and nutrition supply was sufficient to support the diversity. Conversely, the Montenegro bioherm, with its low diversity reef community, probably formed in a lower energy, restricted, subtidal setting (lagoon).

(6) Based on field and thin section observations, the Ravenswood bioherms and the Montenegro bioherm show different facies and facies composition within an individual bioherm. Three facies have been recognized and described in the Ravenswood bioherms, including bioherm base facies, bioherm flank facies and bioherm core facies. Three different facies have been described in the Montenegro bioherm, including siltstone bioherm base facies, kalyptra bioherm core facies and inter-kalyptra facies. The different bioherm
facies are discussed above. The Ravenswood bioherms have an obvious differentiation between the reef core facies and the reef flank facies. The former is composed of massive framestone and boundstone, whereas the later is composed of stratified bioclastic packstone. The Montenegro bioherm did not develop a flank facies. However, kalyptrae of the Montenegro bioherm were filled by a unique facies, the inter-kalyptra facies, which consists of discontinuous limestone lenses and calcareous siltstone.

(7) Finally, on the basis of observations and interpretations discussed above, I conclude that the Ravenswood bioherms and the Montenegro bioherm formed in different depositional environments. The Ravenswood bioherms grew as patch reefs in an open, high-energy, shallow subtidal environment, whereas the Montenegro bioherm formed as a micrite mound in a restricted, low-energy, subtidal environment. Figure 35 shows the possible environmental settings of the Ravenswood bioherms and the Montenegro bioherm on the Lower Cambrian continental shelf.

Fig. 35. Schematic cross-section of a continental shelf showing possible settings of the Ravenswood bioherms and the Montenegro bioherm.
Chapter 7

CONCLUSIONS

A comparative sedimentological and paleontological study was made of two approximately coeval Lower Cambrian bioherm complexes, one in the Ravenswood area of Lander County in central Nevada, and the other in the Montenegro Member of the Campito Formation in the White-Inyo Range of eastern California. Although both bioherm complexes were constructed by archaeocyaths and calcareous microbial organisms, there are significant differences in the structure and fabric of the biohermal limestones, in the taxa and diversity of archaeocyaths, and in the diversity of the bioherm community in general. The Ravenswood bioherms grew on the skeletal packstone and developed as framework reefs in a high-energy, normal marine setting; they display a relatively high diversity of archaeocyaths and associated organisms, as well as distinct core and flank facies. Flanking facies have not previously been described from Lower Cambrian reefs, but they attest to the wave-resistant nature of these reefs. Further more, the distribution of archaeocyathan types within the reef core verses flanking facies reflect the different wave-resistant capabilities of archaeocyathan morphologies. The Montenegro bioherm complex initialized on the crossbedded siltstone and developed in a restricted, low-energy setting as a mud mound composed of lenticular units (kalyptae); it contains a lower diversity archaeocyathan fauna and a depauperate fauna of other organisms.
Chapter 8

SYSTEMATIC PALEONTOLOGY OF ARCHAEOCYATHS

In the Ravenswood bioherms and the Montenegro bioherms, diverse and abundant archaeocyath assemblages were found. The following description is based on archaeocyathan fossils collected from both localities. The classificatory scheme of Hill (1972) and the updates by Debrenne and Zhuravlev (1989, 1992) are followed. Some common morphological terms used in archaeocyath description are listed as follows:

- **Bract**: Scoop-like extension from lower half of rim of pore of wall.
- **Dissepiment**: A porous plate shaped like the wall of a bubble.
- **Intersept**: That portion of wall between edges of 2 neighboring septa.
- **Intervallum**: Space between inner and outer walls.
- **Intervallum coefficient**: The ratio of width of intervallum to width of central cavity.
- **Loculus** (pl., Loculi): Space between two neighboring septa.
- **Pore-canal**: Cylindrical or prismatic hole through thick wall.
- **Pore-tube**: Cylindrical or polygonal thin-walled tube formed by horizontal or oblique or curved wall-plates, or by bracts or peaks or by a combination of these.
- **Synapticula** (pl., Synapticulae): Transverse rod connecting 2 neighboring septa.
Tabula (pl., tabulae): Transverse porous skeletal element connecting walls of a cup.

Taenia: Small curved segment of an irregularian septum.

CLASS REGULARES Vologdin, 1937
ORDER AJACICYATHIDA R & J Bedford, 1939
Family Ajacicyathidae R & J Bedford, 1939
Genus Ajacicyathus  R. & J Bedford, 1939

Type species: Ajacicyathus ajax Taylor, 1910. Lower Cambrian, Lower Botomian, South Australia (Ajax Mine).

Diagnosis: Cups solitary and conical. Outer wall with simple pores; pores of inner wall simple, and in more than one longitudinal row to each intersept; septa sparsely porous or aporous; no tabulae.

Ajacicyathus sp.
Pl. I, Figs. 1, 2

Description: Solitary and conical cups, with porous outer and inner walls, pores simple. Intervallum with planar or branching septa, without tabulae. Cups vary from 3 to 5 mm in diameter. Central cavity relatively large. Intervallum coefficient 0.5 to 0.7.

Occurrence: Lower Cambrian, Ravenswood area, Shoshone Range, central Nevada.
Discussion: *Ajacicyathus* sp. occurs sparsely in the bioherm flank facies. Interaction between *Ajacicyathus* sp. and *Archaeocyathus* sp. has been observed in thin section (Pl. I, Fig. 2).

*Genus Rotundocyathus* Vologdin, 1960

**Type species:** *Rotundocyathus rotaceus* Vologdin, 1960. Upper part of Lower Cambrian, Altay Mountains.

**Diagnosis:** Cups solitary and conical. The outer wall is thin with numerous pores per intersept. Septa straight or sparsely branched, sometimes thickening toward thick inner wall, in which there is one longitudinal row of pores to an intersept; no tabulae.

*Rotundocyathus* sp. A

Pl. I, Figs. 3, 4, 6

**Description:** Small conical cups, with thin highly perforated outer wall. The septa are irregularly spaced, sparsely bifurcated, sometimes not reaching the inner wall. Septa are imperforate. One vertical row of pores occurs at the junction of each wall. The inner wall has one row of pores per intersept. Diameter of cup from 3 to 5 mm, intervallum from 0.7 to 1.2 mm, number of septa from 30 to 36, intervallum coefficient from 0.3 to 0.5.

**Occurrence:** Lower Cambrian, Ravenswood area, Shoshone Range, central Nevada.

**Discussion:** The specimens described here are similar to *Rotundocyathus pusillus* Debrenne, 1989 (Debrenne et al., 1989, p. 151-152). They differ from *R. pusillus* in having more septa and a relatively thinner intervallum.
Rotundocyathus sp. B
Pl. I, Figs. 5, 7, 8

**Description:** Solitary and conical cup, outer wall smooth with sparse pores; inner wall coarsely porous; septa thickening toward thick inner wall, in which is one longitudinal row of pores to an intersept; septa straight, sparsely bifurcated, and imperforated; no tabulae. Cups are very small, 1.5 to 2.5 mm in diameter, central cavity from 0.5 to 1.0 mm, intervallum coefficient from 1.0 to 1.2, number of septa from 14 to 18.

**Occurrence:** Lower Cambrian, Ravenswood area, Shoshone Range, central Nevada.

**Discussion:** The specimens described here are different from Rotundocyathus sp. A in having smaller cups, fewer septa, simple inner wall, and a higher intervallum coefficient. Further identification is impossible due to limited thin sections. They are common elements in the bioherm flank facies.

Family Densocyathidae Debrenne, 1977
Genus Diploocyathellus Debrenne, 1977

* Diploocyathellus sp.

Pl. II, Figs. 1, 6

**Description:** Cups are solitary and small, diameter 2.5 to 3.5 mm. Septa are straight, aporous, sparsely bifurcated near inner wall; number of septa from 35 to 40. The intervallum and central cavity are subequal in size. Intervallum coefficient ranges from 0.7 to 0.8. The outer wall is thick and porous, and the
inner wall has pore-tubes that are arranged one per intersept. Further details of pore-tubes are unknown due to limited thin sections.

**Occurrence:** Lower Cambrian, Ravenswood area, Shoshone Range, central Nevada.

**Discussion:** The specimens are probably the same as *"Diplocyathus austinensis"* named by Gangloff (1975) in his unpublished dissertation.

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**Family Ethmophyllidae Okulitch, 1943**

**Genus Ethmophyllum Meek, 1868**

**Type species:** *Ethmophyllum whitneyi* Meek, 1868. Lower Cambrian, western Nevada and eastern California.

**Diagnosis:** Solitary; cup slenderly conical to cylindro-conical; septa aperous, straight, except near inner wall, become highly fluted and wavy; outer wall of geniculate pore-tubes, bracts develop externally; inner wall comprised of a dual system, intercommunicating canals and pore-tubes; pore-canals form first, in two alternating rows along margins of loculi, end result of fusion and fluting of ends of septa; larger pore-tubes inclined upward into central cavity.

**Discussion:** The genus *Ethmophyllum Meek* was one of the first archaeocyaths described. Because of the highly complex inner wall, and the nature of preservation exhibited by the types, a great deal of confusion has existed regarding true characteristics of *Ethmophyllum Meek* (Gangloff, 1975). This genus has been cited in material from Europe, Asia, Australia, and Antarctica. Most of the species have been described by Soviet workers from both the Siberian Platform and the Southern Fold-Belts in Russia. However, Gangloff (1975) suggested that most of the species outside of North America were
probably not to be congeneric with *Ethmophyllum* due to misidentification. This genus appears to be restricted to North America.

*Ethmophyllum whitneyi* Meek, 1868

**Description:** This cup is solitary, cornute to cylindro-conical, and relatively small. Maximum diameters range from 4 to 10 mm. Some specimens attained heights of 20 mm. The central cavity is usually wider than the intervallum, intervallum coefficient quite variable, 0.4 to 1, due to occasional swellings of the intervallum and outer wall. Intervallum crossed by straight, aporous septa that become highly fluted near the inner wall.

The outer wall is pierced by geniculate pore-tubes that are arranged in alternating vertical rows, four to six per intersept.

**Occurrence:** Lower Cambrian, Ravenswood area, Shoshone Range, central Nevada.

Family Sajanocyathidae Vologdin, 1956

Genus *Palmericyathus* Handfield, 1971

*Palmericyathus* sp.

**Description:** Bowl-shaped cups with simple outer wall and aporous and numerous septa. Inner wall complex with branching and intercommunicating pore-tubes. The specimens are preserved as ribbon-like fragments. Cups are up to 1 cm in diameter; outer wall very thin, 1 to 1.5 mm thick; central cavity
relatively large (7 to 8 mm in diameter); intervallum coefficient ranging from 0.14 to 0.16.

**Occurrence:** Lower Cambrian, Ravenswood area, Shoshone Range, central Nevada.

**Discussion:** The specimens from the Ravenswood area may belong to *Palmericyathus americanus* (Okulitch, 1952) from the Lower Cambrian bioherms in Northwestern Mexico (Sonora) (Debrenne et al., 1989). They are characterized by bowl-shaped cup, thin intervallum and large central cavity, and complex inner wall. Specific assignment cannot be made due to a lack of longitudinal thin sections of this species from the Ravenswood bioherms.

**CLASS IRREGULARES**

**ORDER ARCHAEOCYATHIDA** Okulitch, 1935

**Family Claruscoscinidae** Debrenne & Zhuravlev, 1992

**Genus Fenestrocyathus** Handfield, 1971

**Type Species:** *Fenestrocyathus complexus* Handfield, 1971. Lower Cambrian, Botomian, Sekwi Formation, Northwest Territories, Canada.

**Diagnosis:** Outer wall consisting of a fine, irregular network of skeletal elements forming an irregular screen; inner wall with one row of pores per intercept and fused bracts. Intervallum has dictyonal taeniae.

*Fenestrocyathus* sp.

Pl. III, Figs. 1-5, 8

**Description:** The cup is solitary or colonial, cylindro-conical to cylindrical, colonies massive. The cup is typically small, 3 to 5 mm in diameter, with a
maximum height of 26 mm. The intervallum and central cavity are equal to subequal in width, with an intervallum coefficient that ranges from 0.8 to 1.5. The intervallum contains relatively wide dictyonal taeniae connected by widely separated synapticulae which are 0.06 to 0.09 mm in diameter. It appears to be filled with porous, oval to polygonal loculi or prototubuli in transverse sections. In longitudinal section, the taeniae appear to form outwardly curving porous rows with very few cross-connections or synapticulae.

The outer wall consists of an irregularly porous framework constructed by linking the ends of taeniae with additional elements. The pores are irregular in shape and arrangement. The margin of the outer wall is very uneven and appears to be spinose in places. The inner wall is made up of thin-walled pore-tubes which are 0.15 to 0.18 mm in diameter and 0.25 to 0.40 mm in length. The tubes are inclined upward as they extend into the central cavity.

**Occurrence:** Lower Cambrian, Ravenswood area, Shoshone Range, Nevada.

**Discussion:** This species is characterized by its small size, relatively diffuse intervallum element pattern, and scarcity of synapticulae. The highly irregular margin of the outer wall which appears to be spinose in places is also distinctive. This species was described by Gangloff (1975) as a new species "Fenestrocysthathus (?) dentoanus."

Family ARCHAEOCYATHINAE Hinde, 1889

Genus Archaeocyathus Billings, 1861

**Type Species:** Archaeocyathus atlanticus Billings, 1861. Lower Cambrian, Toyonian, Forteau Formation, Labrador, Canada.
**Diagnosis:** Outer and inner walls secondarily thickened; pore-canals partly or completely closed by thickening; septa thick, with secondary thickening on either side; some septa extend from outer to inner wall, other shorter, with some curving from outer wall to join neighbors; septa wavy, with coarse, irregular pores; dissepiments present but not tabulae; synapticulae rare.

*Archaecyathus* sp.

Pl. IV, Figs. 1, 2, 5; Pl. V, Figs. 3, 4

**Description:** The cup is solitary, cylindro-conical, and of moderate size with a diameter ranging from 8 to 12 mm. The intervallum is filled with very thick, 0.3 to 0.5 mm, wavy taeniae that are connected by scarce, widely scattered synapticulae. The taeniae are generally arranged in a radial pattern and are coarsely porous. The central cavity and intervallum are equal to subequal in width.

The outer wall is highly thickened and is 0.5 to 0.8 mm wide; some outer walls are not well-preserved. The inner wall is comprised of narrow pore-canals 0.20 to 0.25 mm in diameter and separated by a framework that is 0.35 to 0.55 mm in diameter.

**Occurrence:** Lower Cambrian; Ravenswood area, Shoshone Range, central Nevada; and Westgard Pass, White-Inyo Mountains, eastern California.

**Discussion:** As Debrenne and Zhuravlev (1992) pointed out, this oldest archaeocyanathan genus has the largest number of synonyms. They have a detailed discussion about this genus and some associated genera. The specimens from the Ravenswood area and the White-Inyo Mountains resemble *Archaecyathus atlanticus* Billings from Mexico (Debrenne et al., 1989) and
Archaeocyathus sp. described by Gangloff (1975). Due to a limited number of specimens and relatively poor preservation, no species designation is made.

Family Dictyocystidae (?) Tylor, 1910
Genus Retilamina Debrenne & James, 1981

Type species: Retilamina amourensis Debrenne & James, 1981. Lower Cambrian, Toyonian, Forteau Formation, Labrador, Canada.

Diagnosis: Patelliform cups, composed of thin sheet of skeletal elements arranged in dictyonal or, more probably pseudotaenial pattern. The "upper wall" is interpreted as the "outer". It consists of a thick layer, perforated by pores, regularly arranged, but not at each intertaenial space. The "lower wall" is simple, rudimentary.

Retilamina sp.
Pl. VI, Figs. 1, 5?, 6?

Description: Broadly undulating sheets, with a compact wall and an open net on the other side. The skeletal elements combine to form a scaffolding of flattened bars (dictyonal network). The average intervallum is 1.5 to 2.5 mm thick, the thickness of skeletal elements 0.05 to 0.10 mm, and the distance between them varies from 0.2 to 0.3 mm. The open side is commonly colonized by Renalcis or Renalcis-like organisms.

Occurrence: Lower Cambrian, Ravenswood area, Shoshone Range, central Nevada.

Discussion: Retilamina was originally described as a genus belonging to archaeocyatha with uncertain position (Debrenne and James, 1981). Later studies
have confirmed the archaeocyathan affinity. This encrusting form of archaeocyath is now known from Nevada, Mexico, and Labrador, Canada. 

Debrenne and Zhuravlev (1992) placed this genus in the Dictyocystidae with uncertainty. As Gangloff (pers. comm., 1994) pointed out, some specimens from the Ravenswood bioherms (Pl. VI, Figs. 5, 6) are identified as Retilamina sp. with question. More samples are needed to confirm this identification.

Family Protopharetridae Vologdin, 1957
Genus Protopharetra Bornemann, 1884

Type species: Protopharetra polymorpha Bornemann, 1886. Lower Cambrian, Botomian, Nebida Formation, Cuccuru Contu, Sardinia, Italy.

Diagnosis: Solitary or colonial cups conical to cylindrical with lateral branching. Outer wall centripetal; inner wall simple, with one row of pores per intertaenial space. In the intervallum, there are coarsely porous taeniae and rare synapticulae.

Protopharetra sp. A
Pl. V, Figs. 5, 6

Description: Branching and massive form. Cups are 3-5 mm in diameter and 18 mm in height. Intervallum with platelets connected by synapticulae. There is one vertical pore row in each intertaenial space. Intervallum and central cavity widths are unknown due to limited thin sections.

Occurrence: Lower Cambrian, Ravenswood area, Shoshone Range, central Nevada.
Discussion: The Ravenswood specimens are very similar to *P. polymorpha* described by Debrene and Zhuravlev (1992, Pl. XI, fig. 1, 2, 4, 5). Some of them have a large diameter. Two specimens were collected from the Ravenswood bioherms, which is not enough to permit identification to the species level.

*Protopharetra* sp. B
Pl. V, Figs. 1, 2, 7

Description: Cup small to moderate in size, cylindrical, colonial; colonial dendroid; central cavity relatively small, intervallum coefficient high (1.1-1.2); intervallum filled with taeniae, commonly connected by synapticulae; taeniae and synapticulae develop rows or lattices that curve up and outward from the central cavity; taeniae penetrated by many pores that are variable in size; dissepiments present in both intervallum and central cavity; outer wall of irregular pores; inner wall of staggered rows of simple pores, one per intertaenial space; outer wall, inner wall and taeniae with secondary thickening.

Occurrence: Lower Cambrian, Ravenswood area, Shoshone Range, central Nevada.

Discussion: *Protopharetra* sp. B is the same species that Gangloff (1975) named "*Protopharetra multimembrana*" in his dissertation, which is characterized by dendroid colonial pattern, a typical small size for individual cups or branches, a high intervallum coefficient, and the highly variable nature of the density of intervallar elements (Gangloff, 1975, p. 222). Because the name "*Protopharetra multimembrana*" has not been published, I use *Protopharetra* sp. B here.
Family Flindersiscinidae R & J Bedford, 1939

Genus *Palmericyathellus* Debrenne, 1970

*Palmericyathellus* sp.

Pl. IV, Figs. 3, 4

**Description:** Large conical cups; the outer wall consists of the opening of the intervallar mesh covered with simple pores; the inner wall is poorly preserved, and structures of the inner wall are unknown. Pseudosepta straight, radial, perforated by pores, and connected by numerous synapticulae. Diameter of cup is 11 to 12 mm, intervallum 2.5 to 3.5 mm, central cavity 4 to 6 mm, intervallum coefficient 0.4 to 0.5.

**Occurrence:** Lower Cambrian, Westgard Pass, White-Inyo Mountains, eastern California.

**Discussion:** The samples described here are similar to *Palmericyathellus undatus* Debrenne, 1989 (Debrenne et al., 1989) in cup shape, dimensions, radial pseudosepta, and numerous synapticulae. However, due to the lack of inner wall structures and longitudinal sections, no specific identification is attempted. *Palmericyathellus* sp. is abundant in the Montenegro bioherm.

Family Syringocnemididae Taylor, 1910

Genus *Syringothalamus* Debrenne, Gangloff & Zhuravlev, 1990


Pl. VI, Figs. 2-4, 7

**Description:** Cup colonial; intervallum filled with staggered hexagonal tubes (syringes) with reticulate porosity of all facets that are inclined up and
outward from central cavity; outer wall with centripetal pore arrangement; inner wall with simple canals covered with fused bracts, S-shaped. Diameter of cup from 5 to 7 mm, central cavity 1.5 to 2.5 mm, intervallum 1.5 to 2.0 mm, intervallum coefficient 0.8 to 1.0.

**Occurrence:** Lower Cambrian; Ravenswood area, Shoshone Range, central Nevada; and Westgard Pass, White-Inyo Mountains, eastern California.

**Discussion:** The specimens described here are similar to *Syringothalamus crispus* Debrenne, Gangloff & Zhuravlev, 1990, in general features of the cup, intervallar composition, and dimensions. Because inner wall structures are not preserved well in my samples, I described them as *Syringothalamus* cf. *S. crispus*. The genus *Syringothalamus* was first described by Gangloff (1975) in his dissertation based on samples from Nevada and California. It was not a valid name until Debrenne, Gangloff and Zhuravlev (1990) described and redefined the genetic diagnosis.
APPENDIX I

PLATES AND EXPLANATIONS OF ARCHAEOCYATHS

All samples, polished slabs and thin sections from the Ravenswood area and the Montenegro bioherms are housed in the Geoscience Department, University of Nevada, Las Vegas.

All pictures in the plates are photomicrographs from thin sections. Black bar represents 2 mm.

PLATE I

Figs. 1, 2. *Ajacicyathus* sp.
1. transverse section of a cup, RW-92-227-1, Ravenswood area.
2. interactions of *Ajacicyathus* sp. (right) and *Archaeocyathus* sp. (left), RW-92-224-2, Ravenswood area.

Figs. 3, 4, 6. *Rotundocyathus* sp.
3. transverse sections of two cups, RW-92-227-1, Ravenswood area.
4. transverse sections of two cups, RW-93-121, Ravenswood area.
6. transverse section of a cup, RW-92-224-2, Ravenswood area.

Figs. 5. 7. 8. *Rotundocyathus* sp.
5. transverse section of a cup, RW-92-227-3, Ravenswood area.
7. transverse sections of *Rotundocyathus* sp. (left) and *Fenestrocyathus* sp. (right), RW-93-121, Ravenswood area.
8. Transverse sections and fragments of Rotundocytalus sp., RW-92-211-2, Ravenswood area.

PLATE II

Figs. 1, 6. Diplocyathellus sp.
   1. transverse section of a cup, RW-92-112a, Ravenswood area.
   6. transverse section of a cup, RW-92-122-2, Ravenswood area.

Figs. 2-5, 7. Ethmophyllum whitneyi Meek, 1868
   2. transverse sections of two cups, RW-92-222-6, Ravenswood area.
   3. longitudinal section of a cup showing inner wall features, RW-92-229-4, Ravenswood area.
   4. oblique transverse section of a cup, RW-92-222-5, Ravenswood area.
   5. transverse and oblique transverse sections, RW-92-224-2, Ravenswood area.
   7. oblique transverse section of a cup, RW-92-229-1, Ravenswood area.

PLATE III

Figs. 1-5, 8. Fenestrocyathus sp.
   1. oblique transverse section of a cup, RW-93-121, Ravenswood area.
   2. transverse section of a cup, RW-92-122-2, Ravenswood area.
   3. oblique transverse section of a cup, RW-92-227-1, Ravenswood area.
   4. transverse sections of two cups, RW-93-132-1, Ravenswood area.
   5. transverse sections of massive colonies, RW-93-221-1, Ravenswood area.
8. transverse sections of massive colonies, RW-92-222-3, Ravenswood area.

Figs. 6, 7. *Palmericyathus* sp.

6. partial transverse sections, RW-93-111, Ravenswood area.

7. partial transverse section of a cup and a small attached archaeocyathan cup (right) (interactions?), RW-92-133-3, Ravenswood area.

PLATE IV

Figs. 1, 2, 5. *Archaeocyathus* sp.

1. oblique transverse section of a cup, RW-93-133-2, Ravenswood area.

2. transverse section of a cup, WI-92-1-6, Westgard Pass, White-Inyo Mts.

5. longitudinal section of a cup, RW-92-224-2, Ravenswood area.

Figs. 3, 4. *Palmericyathellus* sp.


PLATE V

Figs. 1, 2, 7. *Protopharetra* sp. B

1. transverse section of a dendroidal colony, RW-92-224-1, Ravenswood area.

2. oblique section of a colony, RW-93-132-5, Ravenswood area.

7. transverse section of a cup, RW-92-224-2, Ravenswood area.

Figs. 3, 4. *Archaeocyathus* sp.

3. oblique section of a cup, RW-92-2210, Ravenswood area.
4. oblique section of a cup, RW-92-224-2, Ravenswood area.

Figs. 5, 6. *Protopharetra* sp. A

5. longitudinal section of a branching colony, RW-93-132-2, Ravenswood area.

6. oblique section of a massive colony, RW-92-133-2, Ravenswood Area.

**PLATE VI**

Figs. 1, 5?, 6?. *Retilamina* sp.

1. partial transverse section of a cup, RW-92-224-2, Ravenswood area.

5. partial transverse section of a cup, RW-92-133-1, Ravenswood area.

6. oblique section of a cup, RW-93-121, Ravenswood area,


2. oblique transverse sections of massive colonies, RW-92-229-2, Ravenswood area.


4. oblique section of massive colonies, RW-92-229-2, Ravenswood area.

7. longitudinal section of a cup, RW-92-229-2, Ravenswood area.
REFERENCES


