Stromatolites of the Lower Cambrian Deep Spring Formation; Mount Dunfee, Esmeralda County, Nevada

Lynn Oliver
University of Nevada, Las Vegas

Follow this and additional works at: https://digitalscholarship.unlv.edu/thesesdissertations

Part of the Geology Commons, Paleontology Commons, and the Stratigraphy Commons

Repository Citation
https://digitalscholarship.unlv.edu/thesesdissertations/1446

This Thesis is brought to you for free and open access by Digital Scholarship@UNLV. It has been accepted for inclusion in UNLV Theses, Dissertations, Professional Papers, and Capstones by an authorized administrator of Digital Scholarship@UNLV. For more information, please contact digitalscholarship@unlv.edu.
STROMATOLITES OF THE LOWER CAMBRIAN DEEP SPRING FORMATION;
MOUNT DUNFEE, ESMERALDA COUNTY, NEVADA

By
Lynn Oliver

A thesis submitted in partial fulfillment
of the requirements for a degree of

Master of Science
in
Geology

Department of Geoscience
University of Nevada, Las Vegas
April, 1990
The thesis of Lynn K. Oliver for the degree of Master of Science in Geology is approved.

Chairperson, Stephen M. Rowland, Ph.D.

Examinining Committee Member, Frederick W. Bachhuber, Ph.D.

Examinining Committee Member, Timothy E. Wallin, Ph.D.

Graduate Faculty Representative, Diane P. Smith, Ph.D.

Graduate College Dean, Ronald W. Smith, Ph.D.

University of Nevada, Las Vegas
April 1990
STROMATOLITES OF THE LOWER CAMBRIAN DEEP SPRING FORMATION;
MOUNT DUNFEE, ESMERALDA COUNTY, NEVADA

By
Lynn Oliver

ABSTRACT

The Middle Member of the Lower Cambrian Deep Spring Formation at Mount Dunfee, Nevada contains a diverse assemblage of stromatolites that formed on a tide- and storm-dominated, siliciclastic-influenced, carbonate shelf. The stromatolites formed in a shallow subtidal environment within and near active oolite shoals under strongly focused currents. The stromatolites occur in four different lithofacies: (1) bioherms of digitate stromatolites, (2) bioherms and biostromes of inclined stromatolites, (3) isolated forms of massive and hemispheroidal stromatolites, and (4) a biostrome of cryptomicrobial boundstones. The first three lithofacies are interpreted as microbial reefs. They had topographic relief, formed in active agitated waters, and exerted a physical control over their environment. The stromatolites incorporate an average of 16% very-fine grained detrital quartz within their microstructures. These quartz-bearing stromatolites are
intermediate between "pure" quartzose and "pure" calcareous stromatolites. Few examples of such quartz-rich stromatolites have been documented from the ancient rock record. Stromatolites of the Deep Spring Formation illustrate the "generalistic" nature of microbial organisms and their ability to form organic sedimentary structures in a wide range of depositional environments.
# TABLE OF CONTENTS

Introduction ................................................................. 1
Purpose ................................................................. 1
Stromatolites and the Proterozoic-Cambrian Transition .............. 2
Regional Stratigraphy ....................................................... 6
Previous Work ............................................................... 12
Methods ........................................................................ 13
Lithologies .................................................................... 18
1. Micritic Sandstones ..................................................... 21
2. Dolo-Allochemic Sandstones ......................................... 24
3. Oolitic-Allochemic Sandstones ....................................... 27
4. Intraformational Conglomerates ..................................... 35
5. Quartz Siltstones and Sandstones ................................... 38
6. Oolite ..................................................................... 39
7. Lime Mudstones ......................................................... 42
8. Microbial Boundstones ................................................ 48
    Stromatolites .......................................................... 57
    Stratiform Stromatolites ............................................. 57
    Columnar Stromatolites ............................................. 60
    Cryptomicrobial Boundstones ...................................... 73
    Stromatolitic-Thrombolites ....................................... 73
Microbial Boundstones - Stratigraphic Horizons ....................... 76
    Microbial Horizon A ............................................... 77
    Microbial Horizon B ............................................... 78
    Microbial Horizon C ............................................... 78
    Microbial Horizon D ............................................... 79
    Microbial Horizon E ............................................... 80
Microbial Horizon F.................................81
  Locality A........................................81
  Locality B........................................84
Microbial Horizon G.................................84
  Locality A........................................85
  Locality B........................................85
Microbial Horizon H.................................86
  Locality A........................................86
  Locality B........................................86
Microbial Horizon I.................................87
  Locality A........................................88
  Locality B........................................88
Cyclic Microbial Horizons..........................88
Other Localities......................................89
Depositional Systems................................90
  1. Intertidal/Shallow Subtidal Siliciclastics......93
     Interpretation......................................96
  2. Shallow Subtidal Mixed Sediments...............97
     Interpretation......................................98
  3. Peritidal carbonates.............................99
     Interpretation......................................99
  4. Microbial boundstones..........................100
     Bioherms with digitate stromatolites............100
     Bioherms and biostromes of inclined
     Stromatolites.....................................101
     Isolated forms of stromatolites...............104
     Cryptomicrobial boundstones....................104
     Interpretation....................................109
Discussion..................................................................................110

Reefs, Mounds, or Buildups?..............................................110

Are Quartz Rich Stromatolites Significant?............113

Analogues..............................................................................116

Summary............................................................................120

References........................................................................122

Appendices......................................................................130
# LIST OF FIGURES

Figure 1. Proterozoic stromatolite abundance...............4
2: Metazoan diversity........................................4
3: Proterozoic-Cambrian boundary sections............7
4: Early Cambrian stratigraphy in western Nevada..10
5: Location map of study areas.........................14
6: Photograph of Mount Dunfee, Nevada..............16
7: Photograph of Plates 2 and 3 on Mount Dunfee...16
8: Stratigraphy of the Middle Member of the Deep
    Spring Formation at Mount Dunfee...............19
9: Mixed siliciclastic carbonate classification...22
10: Hand sample of micritic sandstone...............25
11: Photomicrograph of micritic sandstone.........25
12: Photograph of dolo-allochomic sandstone.......28
13: Rose diagram of dolo-allochomic sandstones....28
14: Photograph of intraformational conglomerate....30
15: Photomicrograph of dolo-allochomic sandstone..30
16: Photograph of oolitic-allochomic sandstone.....33
17: Photomicrograph of oolitic-allochomic
    sandstone..............................................33
18: Paleocurrent rose of clast imbrications from
    intraformational conglomerates....................36
19: Photograph of intraformational conglomerate
    with hummocky stratification.......................36
20: Photograph of fissile quartz siltstones.......40
21: Photograph of oolite with local microbial
    boundstones.............................................40
42: Photograph of microbial horizon I..............74
43: Composite stratigraphic columns of microbial horizons F through I and their correlations between Locality A and B.......................82
44: Interpretive block diagram of the depositional environments at Mount Dunfee.............91
45: Mixing processes on rimmed, siliciclastic influence carbonate platforms...................94
46: Interpretive block diagram of living digitates stromatolites forming bioherms...............102
47: Interpretive block diagram of living inclined stromatolites forming biostromes.............105
48: Interpretive block diagram of living massive and hemispheroidal stromatolites.............107
49: Graph of preservation potential of quartzose and calcareous stromatolites................114
50: Diagram of common Proterozoic stromatolites...117

Appendix 2: Figure 2.1 - Photography of Plagiogmus......139
Figure 2.2 - Block diagram of Plagiogmus.....................139

Appendix 3: Table of insoluble residue results...........144
Appendix 4: Tables of raw paleocurrent data.............145
Appendix 5: Stratigraphic column of stromatolites at Molly Gibson Canyon, California...........147

Plate 1: Twenty measured stratigraphic columns of the Middle Member at Mount Dunfee........148
Plate 2: Expanded stratigraphic column from the Middle Member at Mount Dunfee.............149
Plate 3: Expanded stratigraphic column from the Middle Member at Mount Dunfee.............150
ACKNOWLEDGMENTS

I thank my parents and family for their continual support throughout all my academic endeavors without which none of this would have been possible. I would like to thank Alma Harris, Murray Dammitio, and Jim Walden for their encouragement to pursue higher education. Special thanks to Lance Miller, Earl Redman, and Mark Robinson for their initial geological tutelage. Thanks to my fellow graduate students Sandy Haws, Jeff Donovan, Christi Cram-Barry, Ron Nance, and Jack Deibert. Your friendship and support was invaluable. Thanks to the undergraduates in the Geoscience program for carrying rocks from Mount Dunfee while I was physically incapacitated.

I would also like to thank the Clark County Planning Department for employment in their internship program. The support given to me during my two years of tenure was invaluable. I would like to thank the Graduate Student Association and the Geoscience department for financial support, and the awarding of the Lilly and Wing Fong and Natural Science Scholarships. Thanks to my advisors Steve Rowland, Tim Wallin, and Fred Bachhuber for their advice during my tenure as a graduate student. Finally I would like to extend a very special thanks to Steve Rowland and Eugene Smith for their support and encouragement.
INTRODUCTION

Stromatolites are commonly thought to occur in arid to semi-arid, tropical to subtropical marine carbonate environments (Bathurst, 1975). However, studies of modern depositional environments have shown that stromatolites can form in a wide range of environments, including siliciclastic marine environments (Cameron and others, 1985). While stromatolites in siliciclastic environments are common in recent environments there are few documented examples in the ancient rock record. One example is the stromatolites of the Lower Cambrian Deep Spring Formation of Nevada. The stromatolites formed on a siliciclastic influenced carbonate shelf and incorporated abundant detrital quartz within their microstructure, a feature which is very poorly documented in geologic literature.

PURPOSE

The purpose of this thesis study is to determine the depositional environment of the stromatolites present in the Middle Member of the Deep Spring Formation at Mount Dunfee, Esmeralda County, Nevada. The research presented in this thesis is directed toward the following questions:

1. Are the stromatolite deposits reefs?
2. Is the incorporation of detrital quartz within the stromatolite microstructures significant?
3. Are the morphologies and depositional environment of the stromatolites unique in the geologic record or do they have modern and ancient analogues?

STROMATOLITES AND THE PROTEROZOIC-CAMBRIAN TRANSITION

Stromatolites are organosedimentary structures that form by microbial organisms trapping, binding, and precipitating sediment (Walter, 1976). Stromatolite studies have contributed to the fields of geology and biology and have been particularly useful in helping unravel ancient depositional environments. The gross morphology of stromatolites tends to reflect the physical environment in which they formed and has been successfully used to determine paleocurrent directions (Hoffman, 1973). Although stromatolites formed large structures several meters in height and hundreds of meters in length they have historically not been considered reefs (Griffin, 1988). Stromatolites are commonly thought to be a product of carbonate environments, but modern studies have shown that they may also occur in many nonmarine and siliciclastic environments (reviewed in Cameron, 1985). While stromatolites have only limited distributions today, they are ubiquitous within the Proterozoic, and the primary fossil representative before the first appearance of metazoa at the Proterozoic-Cambrian boundary (Walter, 1977).
The sequence, nature, and causes of the geological and evolutionary events from the late Proterozoic to Early Cambrian have posed complex questions concerning the origin of metazoa. This was a time of intermittent glaciations, changing atmospheric and oceanic chemistry, changing temperatures, widespread phosphatic deposition, and global tectonic activity (Brasier, 1985). Rifting of the Proterozoic plates caused rising sea levels and expansion of shallow marine habitats suitable for the evolution of metazoa.

The evolutionary events during this period are of special interest to paleobiologists because they represent the first known appearance of metazoa in the geological record. Some of the most important biological changes at or near the Proterozoic-Cambrian boundary are:

1. a drop in stromatolite abundance and diversity (Fig. 1) (Walter and Heys, 1985);
2. rapid diversification of trace fossil patterns (Mount and Signor, 1989b);
3. the occurrence of the first low diversity assemblage of shelly fossils (Cowie, 1989);
4. and the appearance of Cambrian and Paleozoic fauna (Fig. 2) (Glaessner, 1984).

Stromatolites in the Proterozoic had worldwide distributions and formed in a wide range of water depths and depositional environments. Stromatolites reached their
Figure 1: Relative abundance (solid line) and diversity (dashed line) of stromatolites through the Proterozoic and Early Paleozoic. Diversity is the number of taxa, and so it is in a continual state of flux due to the change in stromatolite systematics. Data compiled from published literature of locales in the Soviet Union, China, Australia, Europe, Greenland, Africa, and Canada. From Walter and Heys (1985).

Figure 2: Graph of metazoan familial diversity through the Late Proterozoic and Paleozoic. The black field represents family diversity within those classes important or restricted to the Cambrian. Stippled field represents the diversity of the remaining metazoa that constitute Paleozoic fauna. From Sepkoski (1979).
Stromatolites

Diversity

Abundance

Proterozoic

Paleozoic

2.0

1.5

1.0

0.5

Ga

Figure 1

Metazoa

NUMBER OF FAMILIES

0

200

400

500

600

m

V C E O S D C P

"CAMBRIAN FAUNA"

Poorly preserved families

Figure 2
greatest abundance at approximately 0.8 Ga and then steadily declined (Fig. 1) (Walter and Heys, 1985). While several theories have been proposed for this decline (Garret, 1970; Monty, 1973; Pratt, 1982), there is currently no theory that fully explains the decline of stromatolites in the late Proterozoic or whether there is a causal relationship with the appearance of metazoa.

The lithologic sequences across the Proterozoic-Cambrian boundary indicate a faunal succession beginning with simple trace fossils, followed in turn by a low-diversity shelly fauna, then an assemblage of high-diversity trace fossils and shelly fauna (Mount and Signor, 1989a). One of the sedimentary units reflecting the beginning of the metazoan radiation event in the western United States is the Lower Cambrian Deep Spring Formation (Fig. 3). A moderately diverse assemblage of shelly fossils occurs in the Lower Member (Gevirtzman and Mount, 1986), a diverse assemblage of stromatolites occurs in the Middle Member (Rees and Rowland, 1986; this study), and the first appearance of trilobite traces occurs in the Upper Member (Alpert, 1976).

REGIONAL STRATIGRAPHY

The Deep Spring Formation is part of a thick section of Proterozoic and Lower Cambrian rocks that crop out in the White and Inyo mountains of California and in Esmeralda
Figure 3: Present day distribution of some important Precambrian Cambrian boundary sections (circled) and Precambrian cratons (stippled). Arrow points to the approximate location of Mount Dunfee, Nevada. Modified from Brasier (1989).
Figure 3
County, Nevada (Mount and Signor, 1989a). The Deep Spring Formation conformably overlies the Reed Formation and is disconformably overlain by the Campito Formation (Fig. 4; Mount and Signor, 1989b). The Proterozoic-Cambrian boundary is tentatively placed at the unconformity between the Wyman and Reed Formations (Mount and Signor, 1989b). The Deep Spring Formation averages 550 m in total thickness and is composed of siliciclastic, carbonate, and mixed siliciclastic-carbonate sediments (Mount and Signor, 1989a).

In the White-Inyo mountains the Deep Spring Formation is part of the Proterozoic-Lower Cambrian sequence that represents the maximum thickness and most distal facies of the Cordilleran miogeocline (Stewart, 1970). This portion of the Cordilleran miogeocline is a westward-thickening wedge that formed in response to late Proterozoic rifting of North America. Geological evidence indicates that rifting is probably older then 650 Ma (Christie-Blick and Levy, 1989; Stewart and Suczek, 1977). Other estimates using subsidence analysis propose ages ranging from 550 Ma (Bond and Kominz, 1983) to 590 Ma (Armin and Mayer, 1983) and indicate protracted extension or multiple episodes of rifting (Christie-Blick and Levy, 1989). During this period the sediments of the miogeocline accumulated at a latitude approximately 10 degrees north of the paleo-equator (Cowie, 1971) with the paleoshoreline oriented
Figure 4: Lower Cambrian stratigraphy in the White-Inyo region, California and Esmeralda County, Nevada. Faunal zones and first occurrence of major taxa are noted. From Mount and Signor (1989a).
FAUNAL ZONES

MULLE SPRING

SALINE VALLEY

Bonneville Omurkau Zone

HARKLESS

FM

MBR

LITHOLOGY

Lower

Upper

3000

FM. THICKNESS EXCEEDS 2000m

Wyman

Om

HINE TONGUE

LOWER CAMPITO Mountain

Montenegro

Anadara Zone

PRE-CAMBRIAN

DEEP SPRING

Upper

Middle

Lower

Andrews Mountain

CAMBRIAN

UPPER POLETA Middle

Lower

Anomalie Zone

2000

Helioplolegs, diverse brachiopods.

Molluscs, radiolarians, foraminifera, diverse archaeocyathans, formation of reefs, Erythropbatha.

Archaocyathans, echinoderms, periwulds, chancellors, helcomatids, hyolithomorphs, Microdictyon.

Brachiopods, diverse trilobites.

Trilobites. Omphalactis, Plakysulisites, Cambalites.

Diverse complex trace fossils.

Trilobite trace fossils: Rusophycus, Monomorphicus. Disappearance of pre-trilobite shelly fossils.

Hyoliths, coeloids.

Tubes and cones, Lydatisa.

Algal stromatolites.

local unconformity

Figure 4
roughly east-west (Rowland, 1978). Rowland (1978) suggested that the paleo-geographic location of the miogeocline was in the trade wind belt with a warm tropical climate and a small temperature range. Since then, the North American plate has been rotated approximately 90 degrees counterclockwise (Donovan, 1987).

PREVIOUS WORK

Nelson (1962) developed the Upper Proterozoic and Lower Cambrian stratigraphy of the White-Inyo mountains that was applied to Esmeralda County, Nevada by Albers and Stewart (1962) and McKee and Moiola (1962). Further regional correlations and interpretations have been completed by Stewart (1970), Albers and Stewart (1972), and Stewart and Poole (1974), and Stewart and Suczek (1977). Mount and Signor (1989a and 1989b) have conducted extensive sedimentological, paleontological, and stratigraphic studies of the Lower Cambrian stratigraphy in the White-Inyo mountains of California and in Esmeralda County, Nevada. Several M.S. thesis studies of the Deep Spring Formation in the White-Inyo Mountains have been completed. They have focused on the paleoenvironments of the shelly fauna in the Lower Member (Gevirtzman, 1980), depositional environments of the lower portion of the Middle Member (Dienger, 1986), and Grand Cycles in the Upper Member (Greene, 1986). While stromatolites occur regionally
within the Middle Member (Mount and Signor, 1989b), prior to this study they have not been examined in detail.

METHODS

Two outcrops of the Middle Member of the Deep Spring Formation near Gold Point, Nevada were chosen for detailed study (Fig. 5). The primary study area (hereafter referred to as Locality A) is located at an elevation between 6700 feet and 7000 feet along a northwest-trending canyon on the southwest side of Mt. Dunfee (Fig. 6). The secondary study area (Locality B) is approximately 1.2 miles southeast of Mount Dunfee. It crops out 0.2 miles northeast of peak 6536 on the east side of a north-south trending canyon (Fig. 5). Other localities visited during this study are Hines Ridge (Dienger, 1986), Mollie Gibson Canyon (Fife and others, 1972), Clayton Ridge (Stewart, 1970), Montezuma Range (Albers and Stewart, 1972), and eight miles southeast of Mount Dunfee (Albers and Stewart, 1972) (Fig. 5). The last two localities were unsuitable for study because of metamorphic alteration and are not discussed further.

At the A and B localities, stratigraphic sections were measured using a Jacob staff and described in detail. The lowermost portion of the Middle Member was not measured and only briefly described because the focus of this study is on the stromatolites in the upper portion. Plate 1 shows twenty measured sections of the best exposures at
Figure 5: Location map of study areas of the Middle Member of the Deep Spring Formation in California and Nevada. Bold dashed line is the state border, bold solid lines are highways, thin dashed lines are unimproved dirt roads, squares are population areas, and stippled areas are major mountain ranges. Dots indicate localities visited:

A: Mount Dunfee, Nevada; secs. 6 and 7, T. 7 S., R. 42 E.

B: Mount Dunfee, Nevada; sec. 8, T. 7 S., R. 42 E.

C: Eight miles southeast of Mount Dunfee, Nevada; sec. 23, T. 7 S., R. 42 E.

D: Clayton Ridge, Nevada; sec. 25, T. 2 S., R. 40 E.

E: West side of the Silverpeak Range, Nevada; sec. 12 T. 2 S., R. 38 E.

F: Mollie Gibson Canyon, California; sec. 15, T. 7 S., R. 35 E.

G: Hines Ridge, California; secs. 1 and 12, T. 10 S. R. 35 E.
Figure 6: Photograph of Locality A of the Middle Member at Mount Dunfee (labeled M). The Upper Member caps the top of Mount Dunfee and has minimal exposure (labeled U).

Figure 7: Photograph of the northern half of Plate 1, the Middle Member of the Deep Spring Formation at Mount Dunfee (labeled M). Arrows labeled p2 and p3 point to outlined locations of Plates 2 and 3. Upper Member of the Deep Spring Formation at Mount Dunfee is labeled U.
Figure 6

Figure 7
localities A and B. Plates 2 and 3 are expanded stratigraphic columns of measured sections in Plate 1 (See Plate 1 and Fig. 7 for locations). All stratigraphic references (such as 34.5 m to 37.0 m) refer to section 3 of Locality A (see Plate 1).

Approximately 100 samples from Locality A were collected for petrography of polished slabs, thin sections, and acetate peels. Thin sections and slabs were stained with alizarin-red, acetate peels were prepared from slabs, and both were analyzed with a petrographic microscope. Samples were dissolved for weight percentage of insoluble residues following the methods outlined in Ireland (1971) (raw data in Appendix 3). All paleocurrent data was analyzed statistically using the methods of Krause and Geiger (1987) (raw data in Appendix 4). Paleocurrent directions are presented uncorrected for rotation of the North American plate.

LITHOLOGIES

Figure 8 is a summary stratigraphic column of the lithologies identified in the Middle Member of the Deep Spring Formation. These are: (1) micritic sandstones, (2) dolo-allochemic sandstones, (3) oolitic-allochemic sandstones, (4) intraformational conglomerates, (5) quartz siltstones and sandstones, (6) oolite, (7) lime mudstone, and (8) microbial boundstones.
Figure 8: Generalized stratigraphic column of the Middle Member of the Deep Spring Formation at Mount Dunfee.
MIDDLE MEMBER DEEP SPRING FORMATION MOUNT DUNFEE, NEVADA

Microbial Horizon I

Microbial Horizons F, G and H

Microbial Horizons C, D and E

Plagiogmmus, Planoites

Microbial Horizons A and B

Quartz siltstones and sandstones

Dolo-allochemic sandstones

Oolitic-allochemic sandstones

Micritic sandstones

Oolite

Lime mudstone

Microbial boundstone (Arrows point to horizons labeled A to I)

Figure 3
The first three are mixed lithologies with mixtures of carbonate and siliciclastic sediment. Although such mixed lithologies are not volumetrically abundant in the stratigraphic record, they occur throughout the record and represent a continuum between "pure" siliciclastic and "pure" carbonate sedimentation (Mount, 1985). Mount (1985) has proposed a first-order descriptive classification based on the relative abundance of four end-member components: siliciclastic sand, siliciclastic mud, carbonate allochems, and micrite (Fig. 9). Modifications are indicated by prefixes to increase the detail of the classification scheme. For example, a dolo-allochemic sandstone contains more siliciclastic components than carbonate components, with the primary allochem consisting of dolomite. Lithologies that generally average less than 20% of either siliciclastics or carbonate material are considered "pure" and classified using Williams and others (1982) and Dunham (1962).

1. MICRITIC SANDSTONES

Micritic sandstones occur from 56.5 to 98.5 m and vary from gray, tan, to dark-brown. They have planar and low-angle tabular crossbeds with sharp reactivation surfaces. Rare climbing ripples, local hummocky crossbeds, and thin lenses of intraformational conglomerate are also present. The sandstones consist of interstratified siliciclastic-
Figure 9: Tetrahedra of mixed siliciclastic and carbonate sediments and illustration of binary classification process. Siliciclastic sands comprise all quartz, feldspar, and other silicates and heavy minerals that range from 0.0625 to 2 mm. Siliciclastic muds are less than 0.0625 mm in size and consist of mixtures of silt and clay. Allochems (Folk, 1962) are defined as all carbonate particles greater than 20 micrometers. Micrite is defined as all particles less than 20 micrometers. Spar cement is not considered in this classification. Modified from Mount (1985).
Figure 9
and carbonate-rich horizons 1 to 5 cm thick (Fig. 10). Siliciclastic horizons are dark-brown as a result of dolomitization and are more resistant than the gray carbonate horizons (Fig. 10). Dolomitization locally crosscuts siliciclastic- and carbonate-rich horizons.

Microscopic petrography shows that micritic sandstones contain very-fine, sand-sized quartz 0.05 to 0.10 mm in size, minor feldspar, microspar, and dolomite (Fig. 11). Analysis of thin sections and acetate peels indicates that the siliciclastic-rich horizons broadly coincide with the dolomitization seen in outcrop. The siliciclastic-rich horizons are dominantly quartz grains, minor interstitial microspar, and dolomite replacements of microspar (Fig. 11). The carbonate-rich horizons are composed roughly of 50% quartz grains with an interstitial matrix of 40% microspar and 10% dolomite (Fig. 11). The contact between the siliciclastic and carbonate horizons is sharp at the outcrop but in thin sections is gradational over 3 - 5 mm interval (Fig. 11). Abundant stylolites of dolomite and insoluble residue occur sub-parallel to bedding.

2. DOLO-ALLOCHEMIC SANDSTONES

Dolo-allochemic sandstones occur between 35.5 and 38.5 m and have herringbone, tabular, and local hummocky crossbedding with sharp reactivation surfaces (see Plates 1 and 2). Sets range from 5 to 20 cm in thickness and
Figure 10: Hand sample of dark-brown and gray micritic sandstone showing typical gradational upper contact and sharp lower contact. Note the infilling of the vertical fracture in the gray micritic sandstone (arrow). The dark-brown micritic sandstone is dolomitized and has better defined laminations than does the gray micritic sandstone. Bar scale is 2 cm.

Figure 11: Thin section of an upper gradational contact (Arrow) between dark-brown (above arrow) and gray (below arrow) micritic sandstone. The gray micritic sandstone contains roughly equal amounts of quartz and micrite with subordinate dolomite. The dark-brown micritic sandstone contains a greater proportion of quartz and abundant dark dolomite crystals. The thin section was stained with alizarin red which colored the carbonate pale red. Photomicrograph taken under crossed nicols. Scale bar is 0.3 mm.
crossbeds dip 3 to 20 degrees. Multiple sets of herringbone crossbeds are commonly overlain by low-angle tabular sets (Fig. 12). Low-angle tabular sets have rare asymmetrical ripples exposed on bedding plane surfaces. Paleocurrent analysis from 87 crossbeds within the dolo-allochemic sandstone between 35.0 and 41.0 m indicates a bimodal east-west flow pattern (Fig. 13). Beds of intraformational conglomerate ranging from 30 to 50 cm in thickness are interbedded with the dolo-allochemic sandstones (Fig. 14, Plates 1 and 2).

The dolo-allochemic sandstones primarily contain well sorted, sub-rounded to sub-angular, medium sand-sized quartz grains 0.11 to 0.30 mm in size with traces of sutured contacts between grains (Fig. 15). Approximately 10% of the grains are feldspars, 5 to 30% are dolomite, and there are traces of mica. Microspar occurs in minor quantities interstitial to quartz and feldspar grains. Dolomite allochems vary from equant to rhombohedral, and are 0.20 to 0.35 mm in size. Dolomite occurs between siliciclastic grains, which suggests that it replaced original calcium carbonate.

3. OOLITIC-ALLOCHEMIC SANDSTONES

The oolitic-allochemic sandstones vary from red-brown, orange-brown, green-gray, to gray in color and occur as discontinuous beds between 40.0 m to 51.0 m (see Plates 1
Figure 12: Dolo-allochemic sandstone with herringbone (H) and low-angle planar tabular (T) cross-bedding with sharp reactivation surfaces (arrows). Hammer is 34 cm. This outcrop is stratigraphically located at 37.0 meters, and laterally occurs at 45 m on Plate 2.

Figure 13: Composite rose diagram showing paleocurrent direction of dolo-allochemic sandstones with herringbone crossbeds. Petal interval is 10 degrees with the petal area proportional to the number of crossbed measurements in each petal. Total number of samples is 87. Grand vector mean for west half of diagram is 289 degrees +/- 32 degrees, for east half of diagram it is 86 degrees +/- 40 degrees.
Figure 12

GVM
289° +/- 32°

n = 87

Figure 13

GVM
086° +/- 40°
Figure 14: Bed of intraformational conglomerate with matrix- to grain-supported, imbricate, tabular oolitic intraclasts. Note sharp, wavy contact (arrow) with overlying dolo-allochemic sandstone. Hammer is 34 cm. This outcrop is stratigraphically located at 40.0 m, and laterally occurs at 20 m on Plate 2.

Figure 15: Thin section photomicrograph taken under cross polars of dolo-allochemic sandstone stained with alizarin red. Sutured quartz grains (Q), crystalline dolomite (D) with traces of rhombohedral forms and traces of interstitial micrite. Scale bar is 0.3 mm.
and 2). Beds are unstratified, 10 to 70 cm in thickness, and have sharp lower and upper contacts (Fig. 16). Oolitic-allochemic sandstones range from single, thick beds to thin multiply stacked beds. Thick beds grade laterally into oolitic-intraformational conglomerates (see Plate 1) and thin beds may be separated by fissile, lime mudstone partings (Fig. 16). Locally oolitic-allochemic sandstones contain chaotically-oriented oolitic, stromatolitic, and flat-pebbles of quartz siltstone intraclasts (Fig. 16). Intraclasts range from less than 1 to 2 cm in thickness and up to 5 cm in length. Their occurrence lateral to oolitic intraformational conglomerates suggests that they are genetically related and may represent contemporaneous formation during storm deposition.

Quartz, dolomite, and microspar are the primary constituents of oolitic-allochemic sandstones (Fig. 17). Quartz grains are 0.05 to 0.10 mm in size and constitute approximately 5 to 40% of the samples. The abundance of dolomite varies from trace amounts to 60%; it occurs dominantly as spheres of equant crystals 0.35 to 0.50 mm in size interpreted as dolomitized ooids. Five to 25% of the microspar exhibits relict oolitic textures; these are interpreted as coarse monocrystalline ooids.

Oolitic-allochemic sandstones are a gradational mixture between all four end-member components of Mount's classification (Fig. 9). Depending on which sample is
Figure 16: Oolitic-allochemic sandstone beds with quartz siltstone rip up clasts (small arrow). Sharp lower and upper contacts with thin lime mudstone (large arrow) laminae between beds. Length of hammer head is 14 cm. This outcrop is stratigraphically located at 50.5 meters, and laterally located at 52 m on Plate 2.

Figure 17: Photomicrograph of acetate peel of oolitic-allochemic sandstone stained for calcium carbonate with alizarin red. Subequal quartz, dolomite, microspar, and dolomite-replaced ooids (arrow). Scale bar is 0.60 mm.
examined, the terms allochemic sandstone, micritic sandstone, and muddy allochem limestone are all applicable. This lithology is classified as an oolitic-allochem sandstone because the siliciclastic component is generally more abundant than the carbonate component, and the microspar is interpreted as dominantly neomorphosed ooids.

4. INTRAFORMATIONAL CONGLOMERATES

Intraformational conglomerates occur throughout the Middle Member at Mount Dunfee in dolo-allochem sandstones, oolitic-allochem sandstones, and oolite. Conglomerates are composed of imbricated to chaotically-oriented oolite, stromatolite, and quartz siltstone intraclasts. Beds of intraformational conglomerate within the dolo-allochem sandstones consist of matrix-supported, tabular oolitic intraclasts, 3 to 20 cm in length, that are imbricated parallel to bedding (Fig. 14). Orientations of the A-B planes of 162 intraclasts were measured between 38.5 and 41.5 m for paleocurrent analysis. While the paleocurrent pattern shown in Figure 18 is widely dispersed, statistically there is a dominant flow direction from the west. Paleocurrent patterns of this nature are considered typical of storm-generated flows in shallow shelf environments (Kreisa, 1981). The northeast and southeast peaks may represent two dominant storm transport directions or later reworking by shore-parallel currents.
Figure 18: Composite rose diagram showing paleocurrent directions for imbricated clasts of intraformational conglomerate within the dolo-allochemic sandstones. Constructed from lower hemisphere stereonet plots of poles to A-B planes of clasts. Petal interval is 10 degrees with the petal area proportional to the number of imbrication measurements in each petal. Total number of clasts measured is 162. The grand vector mean is 96 degrees +/- 93 degrees.

Figure 19: Intraformational conglomerate interstratified with very fine-grained dolo-allochemic sandstone. Hummocky cross stratification (large vertical arrow) is overlain by planar stratified sands (small curved arrow). Hammer is 34 cm. This outcrop is stratigraphically located at 40.0 meters, and laterally occurs at 37 m on Plate 2.
Figure 18

Figure 19
(Whisonant, 1987). Intraformational conglomerates are also locally abundant in oolitic-allochemic sandstones and oolite.

At 40.0 meters are very fine-grained dolo-allochemic sands that pinch and swell within the intraformational conglomerate bed. The dolo-allochemic sands range from 1 to 15 cm in thickness and have hummocky and tabular stratification (Fig. 19). The hummocks have flat to wavy bases, are 2 to 4 cm in height, 10 to 15 cm apart, and are capped with planar-stratified sands.

Quartz siltstone intraclasts are a locally abundant feature of the oolitic-allochemic sandstones. Intraclasts are commonly chaotically oriented; they are typically 1 to 2 cm thick and up to 5 cm in length. Intraclasts composed of microbial boundstones are also locally abundant in the oolitic-allochemic sandstones. They range from flat chips to whole stromatolites and have chaotic orientations.

5. QUARTZ SILTSTONES AND SANDSTONES
Quartz siltstones and sandstones occur in three intervals: 0.0 to 34.5 m, 45.0 to 50.0 m, and 121.0 to 126.5 m. They are brown, green-gray, dark-green, and pale-olive and are composed of quartz, mica, and chlorite. Fissile siltstone beds reach up to 4 cm in thickness and have very finely stratified laminae less then 0.5 mm in thickness. Sharply interbedded with the siltstones are lenticular lenses of
very fine-grained sandstone 5 to 15 cm in thickness that average 30 to 150 cm in length (Fig. 20). Laterally continuous sandstone beds up to several meters in length are also present in minor amounts. *Plagiogmus* and *Planolites/Paleophycus* occur locally on bedding plane exposures and within the float between 45.0 and 50.0 m (see Appendix 2). Limited exposures of a black, fissile shale at 45.0 m have also provided several specimens of a small tubular shelly fossil tentatively identified as a member of the Family Coleolidae. Asymmetrical ripples, synaeresis cracks, and shrinkage cracks are present locally.

Synaeresis cracks occur between 45.0 and 50.0 m. They are U-shaped instead of wedge shaped, lack mudflake breccias, and show no grain-size gradation between the cracks and surrounding sediments (criteria for recognition of synaeresis cracks summarized in White, 1961 and Plummer and Gostin, 1981). Shrinkage cracks are found within the basal 34.5 m of the section, but whether they are mudcracks or synaeresis cracks was not determined.

6. **OOLITE**

Oolite occurs throughout the measured section as dark brown, green, and gray, resistant and recessive weathering beds (see Plate 1). The recessive weathering oolite is a brown-to-green slope former. Resistant beds of oolite are
Figure 20: Fissile quartz siltstone with interbedded lenses of quartz sandstone. Hammer is 34 cm. This outcrop is stratigraphically located at 48.0 meters, and occurs laterally at 50 m on Plate 2.

Figure 21: Upper oolite bed with local microbial boundstones. Local stratiform and columnar stromatolites outlined with black marker on outcrop. Scale is 10 cm in length. Outcrop is stratigraphically located at 56.0 m and occurs laterally at 15 meters on Plate 2.
commonly unstratified, 5 to 75 cm in thickness, and contain rare to abundant microbial boundstones (Fig. 21). They have planar to undulatory bedding plane surfaces and rare low-angle tabular crossbeds.

The oolite consists almost exclusively of microspar, dolomite, and quartz. The microspar has a fabric suggestive of an oolitic component that has undergone extensive neomorphism (Figs. 22 and 23). Dolomite averages less than 20%, and occurs as microcrystalline and rhombohedral crystals distributed randomly in microspar and stylolites. Sub-angular to sub-rounded quartz grains 0.05 to 0.12 mm in size are disseminated throughout the oolite. The quartz averages less than 5% of the oolite, but in some samples is high as 25%.

Identifiable oolitic fabrics generally average less than 10% of the microspar, but are proposed to be the original primary component. This is supported by textures with identifiable ooids, oolitic intraformational conglomerates, and the presence of a relict oolitic fabric in most thin sections and acetate peels (Figs. 22 and 23).

7. LIME MUDSTONES

Lime mudstones occur between 42.0 and 56.5 m and between 99.0 and 106.0 m. They are brown, orange-brown, and light gray and dominantly planar laminated with a pronounced fissility. Well-exposed outcrops display
Figure 22: Photomicrograph of acetate peel of oolite stained for calcium carbonate with alizarin red showing coarsely preserved concentric blocky ooids (arrow). Scale bar is 0.35 mm.

Figure 23: Thin section photomicrograph of acetate peel of oolite stained for calcium carbonate with alizarin red. Coarsely preserved monocrystalline ooids occur on the right side of the photo (arrows) and dolomitized ooids occur on the left side of the photo. Scale bar is 0.40 mm.
an irregular brown to orange-brown dolomitic ribbon texture that parallels and crosscuts laminae of the mudstone (Fig. 24). Microbial boundstones overlie lime mudstone and superficially appear to have sharp contacts. However, detailed examination has shown that the contact is gradational with stratiform textures suggestive of a microbial origin (Fig. 24).

Thin section petrography indicates that the primary constituents of the lime mudstones are microspar, quartz, dolomite, stylolites, insoluble residue, with traces of pyrite (Fig. 25). The quartz grains are very fine sand-sized, subangular to subrounded. Petrographic analysis of samples indicates quartz abundance varies from less than 1 to 30%. The quartz may occur either as thin laminae less than 0.10 mm in thickness oriented subparallel to bedding or as randomly distributed grains within the lime mudstone. Stylolites are thinner than 0.30 mm and are oriented subparallel to bedding. The stylolites are composed of organic residues, irregular to well formed rhombohedrons of dolomite, and traces of pyrite. Dolomite and pyrite also occurs in trace amounts within the microspar. While petrographic analysis of thin sections and acetate peels has not revealed the presence of any microbial organisms, the stratiform field texture does suggest that a microbial component was present.
Figure 24: Lime mudstone with irregular dolomitic ribbon texture (lateral to scale) in gradational contact beneath bioherm A.1. Stratiform textures (open arrow) occur in the upper part of the lime mudstone and suggest a gradational contact with the base of bioherm A.1. Note upper erosional contact of bioherm A.1 with microbial horizon B (hooked arrow). Scale is 10 cm in length. This outcrop is stratigraphically located at 44.0 m, and occurs laterally at 31 m on Plate 2.

Figure 25: Thin section photomicrograph of lime mudstone with microspar matrix, disseminated quartz grains (thick arrow), microcrystalline dolomite (thin arrow), stylolites (open arrows), and pyrite (opales). Scale bar is 0.3 mm.
8. MICROBIAL BOUNDSTONES

Kennard and James (1986) have proposed a classification for microbial boundstones based on three end-members: stromatoids, mesoclots, and cryptomicrobial fabrics. Stromatoids are the individual layers or laminae that form stromatolites, mesoclots are macroscopic micritic clots constructed by in situ calcification of microbial communities (thrombolites sensu Aitken, 1967). Cryptomicrobial fabrics are inferred to be of microbial origin, but cannot be positively identified as such (Kennard and James, 1986). Using a modification of this classification (Fig. 26), three types of microbial boundstones have been identified in this study: stromatolites, stromatolitic-thrombolites, and cryptomicrobial boundstones (Fig. 27). Terms used for stromatolite descriptions in the following discussion are shown graphically in Figure 28. Synoptic profiles represent the actively growing surface of microbial organisms and are used to determine the height of stromatolite columns above the paleo-seafloor (Hoffman, 1969). As shown in Figure 29 unless synoptic profiles can be traced laterally to another stromatolite column they only represent the minimum amount of relief above the paleo-seafloor. All synoptic profiles measured in this study are minimal values.
Figure 26: Modified classification of microbial boundstones. Three end-members are stromatoids, mesoclots, and cryptomicrobial fabrics. Stromatoids are the individual layers or laminae that form stromatolites. Mesoclots are mesoscopic micritic clots constructed by in situ calcification of microbial communities. Cryptomicrobial fabrics are inferred to be of microbial origin but cannot be positively identified as such. The upper 50% of the classification has been modified to consist solely of cryptomicrobial boundstones. The dotted lines define the original fields of the classification: disrupted (1) stromatolites (2), thrombolitic-stromatolites (3), stromatolitic-thrombolites (4), and thrombolites (5). Modified from Kennard and James (1986).
Microbial Boundstones

Cryptomicrobial Fabrics

Stromatolite

Thrombolite

Stromatolitic Thrombolite

Stromatolitic Stromatolite

Thrombolite

Stromatolds

Mesoclots

Figure 26
Figure 27: Graphical representation of the stromatolites, cryptomicrobial boundstones, and stromatolitic-thrombolites identified during this study. Stromatolites consist of stratiform and columnar morphologies. Columnar morphologies are further differentiated as a) digitate, b) irregular, c) inclined, d) hemispheroidal, and e) massive. Scale bars to the left of graphical descriptions are approximate. Isolated forms, bioherms, and biostromes is checked at the left for each type of microbial boundstone.
<table>
<thead>
<tr>
<th>Stromatolites</th>
<th>Isolated Forms</th>
<th>Bioherms</th>
<th>Biostrones</th>
</tr>
</thead>
<tbody>
<tr>
<td>Stratiform</td>
<td>10 cm</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Columnar</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>a. Digitate</td>
<td>20 cm</td>
<td></td>
<td></td>
</tr>
<tr>
<td>b. Irregular</td>
<td>20 cm</td>
<td></td>
<td></td>
</tr>
<tr>
<td>c. Inclined</td>
<td>40 cm</td>
<td></td>
<td></td>
</tr>
<tr>
<td>d. Hemispheroidal</td>
<td>50 cm</td>
<td></td>
<td></td>
</tr>
<tr>
<td>e. Massive</td>
<td>100 cm</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Cryptomicrobial Boundstones</td>
<td>50 cm</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Stromatolitic-Thrombolites</td>
<td>10 cm</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Figure 27
Figure 28: Diagrammatic illustrations of terms used in the description of diagnostic characteristics of stromatolites. From Preiss (1976).
Figure 28
Figure 29: Diagram illustrating the synoptic profile of stromatolites. The synoptic profiles of the stromatolites on the left can be traced laterally and represent the actual height of the columns above the paleo-seafloor (labeled h). The synoptic profile of the stromatolite on the right cannot be traced to another column thus represents at least the minimum amount of relief above the paleo-seafloor. Modified from Hoffman (1969).
Figure 29
Stromatolites

Stromatolites have stratiform and columnar morphologies. Columnar stromatolites are further subdivided into inclined, digitate, irregular, hemispheroidal, and massive forms (Fig. 27). Columnar and stratiform stromatolites may occur in biostromes, bioherms, and isolated forms.

Petrographic examination indicates that all of the stromatolites have undergone extensive neomorphism, thus precluding the preservation of microbial organisms and some other primary structures. Constituents consist of microspar, laminations of dolomite, insoluble residue, rare ooids, and sub-angular to sub-rounded quartz 0.04 to 0.11 mm in size. Quartz content varies from 0 to 30%; it occurs parallel to laminae, incorporated into laminae, disseminated in random fashion, and in clots (Figs. 30 and 31). Insoluble residues average 16% by weight of microbial boundstones. Insolubles consists of quartz, micas, and organic insolubles (see Appendix 3).

Stratiform Stromatolites. Stratiform stromatolites have planar external morphologies 2 – 15 cm in thickness that extend laterally 20 – 100 cm, with synoptic profiles of less than 2 cm. They occur as discontinuous lenses at the base of columnar stromatolites and as isolated forms within oolite beds. They have gradational contacts with underlying facies, and usually form the colonizing surface
Figure 30: Thin section photomicrograph of a columnar stromatolite. Laminae are defined by dolomite and insoluble residue (arrow). Note the abundance of quartz within the microspar matrix. Scale bar is 0.3 mm.

Figure 31: Thin section photomicrograph of a stromatolite with quartz occurring in a circular clot surrounded by microspar matrix. Scale bar is 0.3 mm.
for columnar stromatolites (Fig. 25). The internal fabric consists of undulatory, pseudo-columnar, and columnar-layered laminae. Pseudo-columnar and columnar-layered laminae commonly grade up-section into columnar stromatolites.

**Columnar Stromatolites.** Columnar stromatolites range from 8 to 200 cm in height and 5 to 100 cm in width. They occur either closely spaced or far apart, with the intervening rock between columns consisting of oolite, lime mudstone, and oolitic-allochemic sandstone. As revealed on exposed bedding plane surfaces, transverse sections are ellipsoidal, oval, round, or polygonal with diameters from 5 to 40 cm (Fig. 32).

Internal fabrics of columnar stromatolites consist of vertically stacked laminae that range from gently convex, sharply convex, to parabolic in shape (Fig. 33). All possible combinations of laminae may occur vertically, and synoptic profiles range from 3 to 20 cm. Laminations at the margin edges are dominantly smooth and overlap the lateral surface to form a wall.

Columnar stromatolites occur in biostromes, bioherms, and as isolated forms with exposures varying from faces perpendicular to bedding to three dimensional exposures. Columnar stromatolites have digitate, irregular, inclined, hemispheroidal, and massive morphologies (Fig. 27). The various forms are described below:
Figure 32: Bedding plane view of closely packed, inclined, columnar stromatolites from the Molly Gibson Canyon locality. Stromatolites are inclined toward the lower corner of the photograph. Jacob staff is 100 cm long.

Figure 33: Serial section of a columnar stromatolite, 18 cm in height, illustrating shapes of laminae: gently convex (GC), steeply convex (SC), and parabolic (P).
a. Digitate stromatolites range from 20 to 60 cm in height and 5 to 15 cm in width; they are only present in bioherms. Digitate stromatolites show parallel and slightly divergent beta and gamma branching (Figs. 34 and 35). Coalescing branching is present locally (Fig. 35).

b. Irregular stromatolites range from 10 to 40 cm in height and 10 to 20 cm in width. They grow directly from stratiform stromatolites or occur directly at the base of bioherms. Columnar margins are subparallel to very irregular with horizontal to gently convex laminations (Fig. 24).

c. Inclined stromatolites occur in bioherms and biostromes less than 1 m in height. They are inclined 10 to 60 degrees with respect to bedding and are oriented toward the west (Figs. 36 and 37). Column margins are parallel to subparallel with a slight tapering toward the base, and are spaced less than 5 cm apart. Bedding plane views of inclined stromatolites are broadly ellipsoidal with the long axis oriented roughly normal to the direction of inclination (Fig. 32). The laminae appear to thicken in the direction of inclination. Cross-sectional views show that laminae are broadly conical but do not have a well defined axial zone. The orientations of the direction
Figure 34: Bioherm C.1 sharply overlying oolitic-allochemic sandstones containing oolitic intraclasts (thick vertical arrow). Lime mudstone is in sharp contact beneath oolitic-allochemic sandstone (thin vertical arrow). Digitate stromatolites are outlined on the outcrop with a black marker and have straight parallel to beta branching. Top of the bioherm is at top of photo (large horizontal arrow). The hammer is 34 cm in length. This photo is stratigraphically located at 51.5 m, and occurs laterally at 45 m.

Figure 35: Digitate stromatolites of microbial horizon B showing beta branching and surrounded by intraclastic oolitic-allochemic sandstone. Intraclasts are stromatolite fragments in various orientations with flat stromatolite rip-up clasts (small curved arrows) and larger complete stromatolites between columns. The ruler is 10 cm in length. This outcrop is stratigraphically located at 44.5 m, and laterally occurs at 45 m on Plate 2.
Figure 36: Looking down dip (painted white line along strike of bed) along a pod of inclined stromatolites of microbial horizon C. Stromatolites are inclined 10 to 20 degrees with respect to bedding. The pod overlies oolitic-allochomic sandstone and is immediately adjacent to bioherm C.1 shown in Figure 37. Sharply overlying the pod is a lime mudstone that infills (small curved arrow) between the pods and bioherm C.1. The base of biostrome D.1 is at top of photo (horizontal arrow). Hammer is 34 cm. Outcrop is stratigraphically located at 52.0 m, and laterally occurs at 40 m.

Figure 37: Looking along strike of a biostrome of microbial horizon D composed of inclined stromatolites (labeled D). Columns are inclined 45 degrees (note line down center of stromatolite column immediately above yellow note book) with respect to bedding (large thick arrow). This biostrome is sharply overlain by lime mudstone that infills around and behind the biostrome (small curved arrow). Yellow field book is 20 cm in height. This outcrop is stratigraphically located at 53.0 m at section 13 of Plate 1.
of inclination of 75 inclined stromatolites (primarily from microbial horizon D) show a consistent westward orientation and indicate a west-to-east directed current (Fig. 38). Using the Linnean classification proposed by Soviet researchers (summarized by Krylov, 1976) inclined stromatolites may be considered a form of Conophyton. Inclined forms of Conophyton are documented from the Proterozoic and are referred to as Conophyton inclinatum (Rezak, 1957).

d. Hemispheroidal stromatolites are hemispheroidal to domal in shape and generally have widths greater than their height. Typical sizes are 70 to 130 cm in width and 70 to 100 cm in height. They commonly occur as isolated domes surrounded laterally by oolite or mudstone (see Plate 3). The laminations are gently convex with synoptic profiles that have 20 cm of relief.

e. Massive stromatolites have heights greater than their widths and reach 200 cm in height and 50 to 70 cm in width. They commonly occur in moderately spaced clusters 10 to 30 cm apart surrounded by oolite. Column margins are irregular and laminae are gently convex (Fig. 39 and Plate 3). Relief of synoptic profiles ranges from 5 to 15 cm.
Figure 38: Composite rose diagram showing a west to east paleocurrent direction determined from the orientation of inclined stromatolites. Petal interval is 10 degrees with the petal area proportional to the number of stromatolite measurements in each petal. Total number of measurements is 75 with a grand vector mean of 85 degrees +/- 18 degrees.
Figure 38

$n=75$

GVM

$085° \pm 18°$
Figure 39: Massive stromatolite (large vertical arrow) of microbial horizon G within oolite. Line is the approximate contact with overlying microbial horizon H. Scale is 10 cm in height and next to the stromatolitic-thrombolite of Figure 41. This outcrop is stratigraphically located between 104.5 and 108.0 m and occurs laterally at 9 m on Plate 3.

Figure 40: Microbial horizon H. Horizontal arrows on left side of photo point to approximate contacts of three horizons of this biostrome (labeled L, M, and U). The lower horizon (L) consists of stratiform and columnar stromatolites, the middle horizon (M) consists of digitate stromatolitic-thrombolites, and the upper horizon (U) consists of bedding parallel dolomitized textures. Scale is 10 cm. This outcrop is stratigraphically located at 107.0 m, and occurs laterally 15 m north of the northern boundary of Plate 3.
Cryptomicrobial boundstones

Cryptomicrobial boundstones occur as a laterally continuous biostrome 75 to 150 cm in thickness between 107.0 and 108.0 m (Fig. 40 and Plate 3). The biostrome is pervasively dolomitized and has clotted textures that indicate a possible microbial origin (see the following stromatolitic-thrombolite section for full discussion). Textures commonly observed are:

1. bedding parallel stratiform laminations,
2. small stromatolitic columns with faintly laminated and clotted internal textures,
3. isolated clotted textures,
4. and lenticular dolomitized textures.

Stromatolitic-Thrombolites

Stromatolitic-thrombolites occur in minor amounts in the cryptomicrobial boundstone (Fig. 40 and Plate 3). They occur as circular, head-like structures with sharply defined margins (Fig. 41). They are roughly 30 cm in diameter and composed of digitate columns 5 to 8 cm wide. The columns radiate outward to the margin edge and have laminated and clotted internal textures. The clotted texture consists of irregular to polygonal clots, 1 - 3 mm in size. These clots are isolated or coalesce in a gray cryptocrystalline matrix. Textures seen in thin sections are a vaguely clotted structural grumeleuse.
Figure 41: Circular head-like structure within the upper horizon of biostrome H (see Fig. 40 for location). This structure is composed of radiating digitate stromatolitic-thrombolites, with faintly visible clotted textures. Scale is 10 cm. Outcrop is stratigraphically located at 107.5 meters and occurs laterally at 10 m on Plate 3.

Figure 42: Biostrome I with four identifiable sub-horizons: (1) steeply inclined stromatolites forming gradationally above two beds of oolite (0), (2) oolite, (3) multiple stacked stratiform and columnar stromatolites, and (4) pervasively dolomitized stratiform and columnar stromatolites and cryptomicrobial fabrics. Scale is 10 cm in height. Outcrop is stratigraphically located at 132.0 meters on section 5 of Plate 1.
The possible presence of thrombolites in the Deep Spring Formation suggests the existence of calcified cyanobacteria. This would represent the oldest known occurrence of skeletal cyanobacteria in the White-Inyo mountains and Esmeralda County. While the lack of identifiable microbial organisms precludes positive identification, future work may determine that calcified cyanobacteria were present in the Middle Member of the Deep Spring Formation.

**MICROBIAL BOUNDSTONES - STRATIGRAPHIC HORIZONS**

Microbial boundstones occur in nine distinct horizons at Localities A and B and are part of the microbial reef depositional environment. They are designated as microbial horizons A through I in ascending stratigraphic order. They are composed of bioherms (Cummings and Shrock, 1928), biostromes (Cummings, 1932), and isolated forms. The microbial horizons within this depositional system have four primary lithofacies: (1) bioherms of digitate stromatolites, (2) bioherms and biostromes of inclined stromatolites, (3) isolated forms, and (4) a biostrome of cryptomicrobial boundstones. They are described in detail in this section; their interpretation is discussed in the microbial reef depositional environment section. The reader is referred to Plates 1, 2, and 3 for the locations of microbial horizons A through I. Microbial horizons A,
B, C, and D only occur at Locality A, whereas microbial horizons E, F, G, H, and I occur at both localities. All stratigraphic references (such as 34.5 to 37.0 m) refer to section 3 of Locality A (see Plate 1 and Appendix 1).

**MICROBIAL HORIZON A**

Horizon A consists of one bioherm at Locality A and rare discontinuous lenses less than 20 cm in height and 2 m in length south of section 12 (see Plate 1). As shown in Plate 2, Bioherm A.1 is a lenticular body with a lateral extent of roughly 36 m that occurs between 43.0 and 44.0 m. The bioherm reaches a maximum thickness of 100 cm and thins to 30 cm laterally. Its base is parallel to subparallel to bedding. Columnar stromatolites form directly from the basal lime mudstone or stratiform stromatolites (Fig. 24). The columnar stromatolites consist of inclined stromatolites along the sides of the bioherm and irregular and digitate stromatolites in the bioherm core. The sediment between the columns within the bioherm consists of dolomitized lime mudstone and oolitic-allochemic sandstone with minor cross laminations. The tops of the columnar stromatolites at the thickest part of Bioherm A.1 have a wavy erosional contact (Fig. 24). At the thickest portion of the bioherm is a 2 mm, brown to green, fissile lime mudstone which thickens to 66 cm laterally.
MICROBIAL HORIZON B

Horizon B occurs between 44.0 and 44.5 m at Locality A and is composed of isolated digitate stromatolites within oolitic-allochernic sandstones containing stromatolite intraclasts (see Plate 2 and Fig. 35). The digitate stromatolites are 6 - 26 cm in height, spaced 6 - 10 cm apart, and show alpha, beta, and gamma branching (Fig. 35). The stromatolite intraclasts have chaotic orientations and occur between and above the digitate stromatolites. The presence of the stromatolitic intraclasts suggests that the oolitic-allochernic sandstones were deposited in one storm event.

MICROBIAL HORIZON C

Horizon C occurs from 51.0 to 52.0 m at Locality A. It is composed of several bioherms laterally surrounded by lime mudstone and oolitic-allochernic sandstone. Bioherms are abundant north of section 11 (see Plate 2) with only rare occurrences laterally to the south (see Plate 1). The bioherms are pod to loaflike bodies that reach up to 130 cm in height and 7.5 m in length. Bioherm C.1 (Plate 2) is 7.5 m in length and is in sharp contact above a 5-to-10 cm thick bed of intraclastic oolitic-allochernic sandstone and lime mudstone (Fig. 34). This bioherm is composed of large digitate stromatolites that formed directly from the basal conglomerate or stratiform stromatolites (Fig. 34). The
stromatolites exhibit some branching, are spaced less than 5 cm apart, with lime mudstone and oolite occurring between columns. At the top of the bioherm are inclined stromatolites. They are 10 cm in height near the center and increase to 25 cm laterally along the sides of the bioherm.

Immediately north and stratigraphically above Bioherm C.1 are Bioherms C.2 and C.3, two isolated pods of inclined stromatolites (Fig. 36). Bioherms C.2 and C.3 are 70 to 100 cm in width, 40 cm in height and composed of closely packed stromatolites inclined 10 to 40 degrees with respect to bedding. Bioherm C.4 and C.5 are loaf shaped and composed of poorly preserved digitate and inclined stromatolites.

MICROBIAL HORIZON D

Horizon D occurs between 52.0 and 54.0 m at Locality A. It is exposed throughout Locality A, and consists of lime mudstone, biostromes, and oolite. Biostromes form gradationally from the lime mudstone and consist almost exclusively of inclined stromatolites (Fig. 37). The inclined stromatolites form continuous columns to the tops of the biostromes that vary from 70 to 100 cm in height. Sharply to gradationally capping the biostromes is a 50 to 70 cm thick bed of structureless oolite separated by a discontinuous lime mudstone lamina. Between sections 12
and 17 the oolite pinches and swells and the biostromes may be capped by oolite or lime mudstone (Plate 1 and Fig. 35).

The inclined stromatolites of Biostrme D.1 formed gradationally out of the lime mudstone which sharply caps Bioherms C.1 through C.4 (see Plate 2 and Fig. 36). They occur as closely to moderately packed columns spaced approximately 5 to 10 cm apart. The rock between columns consists of lime mudstone and oolite. The inclined stromatolites form discrete columns to the top of the biostrome and are inclined 30 to 60 degrees with respect to bedding. Sharply overlying Biostrme D.1 is a 50 cm bed of oolite.

MICROBIAL HORIZON E

Horizon E occurs between 54.0 and 55.0 m at Locality A. This horizon is composed of lenticular biostromes and lime mudstone. This horizon is continuously exposed between sections 7 and 11, but from sections 11 to 18 there is wide lateral variability. Biostromes range from 30 to 70 cm in thickness and pinch, swell, and bifurcate within oolite and lime mudstone south of section 11 (See Plate 1).

As shown in Plate 2, Biostrme E.1 ranges from 20 to 40 cm in thickness and formed gradationally out of the lime mudstone which caps the oolite of Biostrme D.1. Stratiform stromatolites less than 10 cm in height form the
basal portion of the biostrome and then are capped by a layer of inclined stromatolites less than 15 cm in height.

Sharply capping Biostrome E.1 is a sequence of lime mudstone and oolite with rare microbial boundstones. The microbial boundstones consist of stratiform and columnar stromatolites that formed in situ within the oolite (Fig. 21). This horizon is also present at Locality B and consists of isolated bioherms of poorly preserved columnar stromatolites capped with oolite.

MICROBIAL HORIZON F

Horizon F occurs between 99.0 to 104.0 m at Locality A and 102.5 to 104.5 m at Locality B (Plate 1 and Fig. 43). This horizon consists of small pod-shaped bioherms of inclined stromatolites, discontinuous lenticular biostromes, and isolated columnar stromatolites. The bioherms consist predominantly of inclined stromatolites, while the biostromes are mostly poorly preserved with only minor stratiform and inclined stromatolites. Both bioherms and biostromes may form atop oolitic intraformational conglomerates or lime mudstone.

Locality A

Bioherm F.1 (Plate 3) is 1 m thick, 2 m in width, and nucleates on top of an underlying intraformational conglomerate. The bioherm is composed of poorly preserved
Figure 43: Composite stratigraphic columns of microbial horizons F through I showing the lateral variability of the microbial boundstones at Locality A and B.
Figure 43
columnar stromatolites only slightly inclined to bedding.

Bioherm F.2 (Plate 3) is 70 cm thick and 150 cm in width. It is surrounded laterally and vertically by lime mudstone. The bioherm is composed of closely packed, inclined stromatolites oriented towards the west. They formed gradationally from basal stratiform stromatolites and have polygonal to ellipsoidal transverse cross-sections.

Locality B

Horizon F consists of isolated columnar stromatolites within oolite (Fig. 43). The stromatolites range from 20 to 40 cm in height and appear to have formed in situ within the oolite. Local oolitic intraformational conglomerates are present above the stromatolites.

MICROBIAL HORIZON G

Horizon G occurs from 104.0 to 107.0 m at Locality A and 103.5 to 110.5 m at Locality B (Plate 1 and Fig. 43). This horizon consists of isolated forms of stratiform, hemispheroidal, massive, and columnar stromatolites. Field studies have shown that hemispheroidal and massive stromatolites occur in separate groups and have not been observed as occurring together. The stromatolites may form within lime mudstone but occur predominantly within oolite. Local lenses of oolitic intraformational conglomerate are
found within the oolite, and oolitic intraclasts have been observed between stromatolite columns.

**Locality A**

The hemispheroidal stromatolites range from 50 to 70 cm in height, 50 to 100 cm in width. Relief on the synoptic profiles average 20 cm (labeled G.1 in Plate 3). They occur as isolated forms or they may coalesce together in small groups that form gradationally out of the lime mudstone. These hemispheroidal stromatolites are the primary form occurring to the south of section 6.

Massive stromatolites reach heights of 150 cm and widths of 100 cm (labeled G.2 in plate 3). They occur 10 to 30 cm apart and the relief on their synoptic profiles ranges from 5 to 10 cm (Fig. 39). Internal laminations are poorly preserved, and column margins are very irregular in shape. Stratiform stromatolites commonly occur at the base of all massive stromatolites. Columnar stromatolites 15 to 30 cm in height are laterally associated with the larger massive stromatolites. Oolite between columns is locally cross laminated and contains oolitic intraclasts. Massive stromatolites grade laterally to the north into oolite.

**Locality B**

Horizon G consists of isolated forms of small columnar, hemispheroidal, and massive stromatolites within
oolite (Fig. 43). Small columns are less than 30 cm in height, hemispheroidal stromatolites are less than 40 cm in height, and massive stromatolites range from 70 to 100 cm in height. Lenses of oolitic intraformational conglomerate are present locally.

MICROBIAL HORIZON H

Horizon H is a cryptomicrobial biostrome occurring between 107.0 to 108.0 m at Locality A and between 110.0 to 111.0 m at Locality B (Plate 1 and Fig. 43). The biostrome is continuously exposed at Locality A but has poor exposures at Locality B. The biostrome sharply to gradationally caps Horizon G and has stromatolitic, isolated clotted, and pervasively dolomitized textures. The combination of the field observations and thin section petrography suggests that this biostrome had a microbial origin (see lithology section for further discussion).

Locality A

This horizon is labeled Biostrome H on Plate 3. The biostrome is composed of three broad zones: basal stromatolites, digitate stromatolitic-thrombolites, and an upper undifferentiated zone (Fig. 40). The stromatolite zone is 25 to 40 cm thick and composed of stratiform and columnar stromatolites that average 15 cm in height, 5 to 10 cm in width, and are spaced 5 to 20 cm apart. Rare
digitate stromatolitic-thrombolites? less than 20 cm in height and 5 cm in width grade up into an undifferentiated zone. The upper undifferentiated zone has an extensively dolomitized texture that is interpreted as cryptomicrobial. Near the top of this zone are circular heads of radiating digitate stromatolitic-thrombolites (Fig. 41; labeled H.1 in Plate 3). The margins of the circular heads have sharp contacts with the surrounding cryptomicrobial boundstone (Fig. 41). Biostrome H is capped by a thin layer of oolite with minor stratiform and columnar stromatolites.

Locality B

At Locality B this horizon thins to a poorly preserved 40 cm biostrome. No stromatolitic-thrombolite textures were observed.

MICROBIAL HORIZON I

Horizon I occurs from 127.0 to 134.0 m at Locality A and 121.0 to 130.0 m at Locality B (Plate 1, Fig. 43). The horizon consists of stratiform and inclined, hemispheroidal, and massive stromatolites. The microbial boundstones occur within oolite as isolated forms, discontinuous lenses, biostromes, and bioherms. At Locality A this horizon is well exposed and consists of discontinuous lenses and biostromes; at Locality B it consists of poorly exposed isolated forms and a biostrome.
Locality A

Biostrom e 1.1 occurs from 130.0 to 133.0 m. This biostrom e generally has poorly preserved textures, but in section 6, well preserved exposures allow identification of four distinct zones (Fig. 42):

(1) a 60 cm thick lower zone of closely packed, steeply inclined stromatolites, 30 to 40 cm high, 5 to 10 cm wide, and oriented to the west;

(2) a 10 cm thick bed of oolite gradationally capping the inclined stromatolites;

(3) a 120 cm thick bed of multiple stacked stratiform and columnar stromatolites above the oolite;

(4) an upper 40-to-50 cm thick layer of stratiform and columnar stromatolites with pervasively dolomitized cryptomicrobial fabrics.

Locality B

Bioherm 1.2 occurs from 123.5 to 126 m at Locality B (Fig. 43). Bioherm 1.2 is approximately 20 m in length and 2 m in height. It is composed of closely packed massive stromatolites 150 to 200 cm in height.

CYCLIC MICROBIAL HORIZONS

Microbial horizons A, B, C, D, and E are sequences of lime mudstone gradationally capped by microbial bioherms and biostromes (see Plates 1 and 2). The upper surfaces of the bioherms and biostromes may be sharply capped by oolite
and/or lime mudstone. Although the bioherms and biostromes occur as discontinuous outcrops, they can be correlated along strike at Locality A. The biostromes and bioherms in microbial horizons A, B, C, D, and E are a series of cycles from 1 to 2 meters in thickness. Such cyclic sequences represent the effects of either eustatic or autocyclic controls on the depositional environments in which they formed (for summary see James, 1984). The cycles identified within the Middle Member are interpreted as retrogradational sequences; whether or not these sequence formed from eustatic or autocyclic controls is not addressed in this study.

**OTHER LOCALITIES**

Other outcrops of microbial boundstones examined during this study occur at Clayton Ridge, Nevada and Molly Gibson Canyon and Hines Ridge in the White-Inyo Mountains of California (Fig. 5). The microbial boundstones at Clayton Ridge consist of a one-meter-thick horizon within a thick sequence of oolite (Unit 16 of Stewart, 1970). The stromatolites consist of densely packed, poorly preserved columns averaging 20 cm in height. The microbial boundstones observed at Hines Ridge consist of a 50 cm horizon of closely packed, small, columnar stromatolites. This horizon is extremely recrystallized and very poorly
preserved. The microbial boundstones cropping out at Molly Gibson Canyon have five beds of microbial boundstones that are very comparable to the Mount Dunfee microbial horizons. They range from 20 to 100 cm in thickness and occur within a thick sequence of oolite. The principal form consists of closely packed inclined columnar stromatolites in addition to rare circular structures approximately 75 cm in diameter with possible clotted textures. Appendix 5 is a graphic column of the microbial boundstones of this locale.

DEPOSITIONAL SYSTEMS

Based on the stratigraphy of the measured sections at Localities A and B at Mount Dunfee, I interpret the sediments to represent a retrogradational shelf sequence (Fig. 44). Four depositional systems are present: (1) intertidal/shallow subtidal siliciclastics, (2) shallow subtidal mixed sediments, (3) peritidal carbonates, and (4) microbial reefs (Terminology of Mount and Signor, 1985). These systems are described and interpreted in the following sections with all stratigraphic references (such as 34.5 to 37.0 m) referring to section 3 of Locality A.

The shallow subtidal mixed sediments formed in the mixing zone and represent the transition between nearshore siliciclastics and offshore carbonates. Mixed sediments may form through facies, punctuated, in situ, and/or source
Figure 44: Interpretive block diagram of the Middle Member of the Deep Spring Formation at Mount Dunfee, Nevada.
Interpretive Block Diagram
Middle Member Deep Spring Fm. Mount Dunfee, Nevada

DEPOSITIONAL SYSTEMS

- Peritidal Carbonates
- Shallow Subtidal Mixed Sediments
- Intertidal/Shallow Subtidal Siliciclastics
- Microbial Reefs

Figure 44
mixing in shallow shelf environments (Mount, 1984; Fig. 45). The microbial reef depositional system has two stratigraphic occurrences at Mount Dunfee (Fig. 8) with the lower occurrence representing a short period of retrogradational sedimentation (Fig. 44). Many researchers have observed that outcrops of the Deep Spring Formation have pronounced lateral and vertical thickness and lithologic variations (Karen Loomis, 1989, personal communication; Greene, 1986; Dienger, 1986; and Gevirtzman, 1980). Because this study focused primarily on the outcrops at Mount Dunfee, the interpretive block diagram (Fig. 44) should not be considered applicable on a regional scale.

1. INTERTIDAL/SHALLOW SUBTIDAL SILICICLASTICS

The intertidal/shallow subtidal siliciclastic depositional system occurs between 0.0 and 42.0 m at Locality A and is composed of quartz siltstones, dolo-allochemic sandstones, oolitic-allochemic sandstones, and intraformational conglomerates (Fig. 8). From 0.0 to 34.5 m fissile quartz siltstones occur interbedded with abundant lenticular lenses of quartz sandstones. The sandstone lenses vary from 5 to 20 cm in thickness and 1 to 5 m in length. Very rare mud flasers and local shrinkage cracks are present along bedding planes of some quartz siltstones and sandstones. Herringbone-stratified dolo-allochemic
Figure 45: Examples of mixing processes on rimmed, siliciclastic influence carbonate platforms. From Mount (1984).
A) landward transport of peritidal carbonate sediments during major storms. formation of spill-over lobes, erosion of reefs and shoals. transport of tidal flat and nearshore siliciclastic belt sediments into deeper, subtidal environments by storm-surge-ebb, wind forcing, etc. transfer of subtidal terrigenous and carbonate muds onto tidal flats by storm tides and waves.

B) mixing occurs along margins of reefs and shoals in subtidal inter-reef, back-reef or fore-reef environments. Also occurs adjacent to patch reefs or reef mounds built on terrigenous mud substrates. mixing occurs in narrow zone between nearshore siliciclastic belt/tidal flat environments and deeper subtidal carbonate environments, controlled primarily by coast-parallel currents and rates of lateral facies migration. eolian contribution of siliciclastic detritus to subtidal and tidal flat carbonates.

C) precipitation of carbonate cements, formation of algal mats and in situ accumulation of carbonate allochems and mud in siliciclastic-dominated subtidal to intertidal environments.

IN SITU MIXING
sandstones are in sharp contact above the quartz siltstones between 34.5 and 42.0 m (Plates 1 and 2). As shown on Plate 2, the dolo-allochemic sandstones are interbedded with oolitic intraformational conglomerates that contain imbricate intraclasts (Fig. 14). The intraformational conglomerates form thick beds with sharp lower and upper contacts that locally contain hummocky-stratified dolo-allochemic sands (Fig. 19). Oolitic-allochemic sandstones occur laterally to beds of oolitic intraformational conglomerates (Plate 1).

Interpretation

The lithologies within this depositional system formed in a tide- and storm-dominated shallow subtidal to low intertidal environment. Quartz siltstones interbedded with numerous lenticular sandstone lenses indicate fluctuating energy conditions of a tidally influenced environment within the low intertidal zone.

The complete absence of subaerial-exposure features within the dolo-allochemic sandstones suggest formation in a shallow subtidal environment. Medium grain size, mature textures, and stratification with abundant reactivation surfaces suggest continual reworking in a high traction environment. Herringbone stratification indicates a tidally-dominated environment of east-west directed currents (Fig. 13) and indicates that the paleo-shoreline
was oriented roughly north-south relative to the present orientation of the North American continent. The oolitic intraformational conglomerates, oolitic-allochemic sandstones, and hummocky stratified dolo-allochemic sandstones are interpreted as the products of intense storm-generated flows with west to east transport directions (Fig. 18). The presence of hummocky stratification within the intraformational conglomerates suggests that the storms had fluctuating energy levels and indicates an episodic dominance of storm-wave conditions (Dott and Bourgeois, 1982). Intraformational conglomerates and hummocky stratification suggest that punctuated mixing played a significant role in the formation of sediment in this depositional system.

2. SHALLOW SUBTIDAL MIXED SEDIMENTS

The shallow subtidal mixed sediment depositional system occurs at Locality A between 56.5 to 98.5 m and is 42 m in thickness (see Plate 1). It is a prominent cliff and slope former composed of micritic sandstones with planar and low-angle tabular crossbeds with local hummocky stratification. Lenses of oolitic intraformational conglomerates are present locally, and fissile quartz siltstones occur from 70.5 to 72.5 m. Paleocurrent measurements of 64 crossbeds of micritic sandstones are completely dispersed and have no statistically significant
paleocurrent direction (raw data in Appendix 4). This may indicate that hummocky stratification was more prevalent than identified during this study. Analysis of hand samples, thin sections, and acetate peels indicates the proportion of carbonate components increases upsection at Locality A. At Locality B the micritic sandstones are thicker and grade laterally into oolite of the microbial reef depositional system (see Plate 1).

**Interpretation**

The upsection increase of carbonate within the micritic sandstones suggests formation between the nearshore intertidal/shallow subtidal siliciclastic and the offshore peritidal carbonate systems. The fine grain size, lack of mud drapes along crossbed surfaces, and planar to low-angle tabular stratification with sharp reactivation surfaces are interpreted as representing continuous traction transport from high energy conditions in a wave dominated environment. The presence of local hummocky stratification and thin beds of oolitic intraformational conglomerate suggests that episodic storm-waves were dominant in this environment. Punctuated mixing, therefore had a important role in the formation of these sediments. The origin of alternating siliciclastic and carbonate-rich horizons is enigmatic; I propose that these horizons were produced through hydraulic sorting by tidal and wave
currents due to the difference in specific gravity of siliciclastic and carbonate grains (Scoffin, 1987, p. 68). If so, then large scale facies mixing was also occurring within this depositional system.

3. PERITIDAL CARBONATES

The sediments of this depositional system are 40 m thick and occur between 137.5 to 177.5 m at Locality A (see Plate 1). It is composed of thick resistant ledges and recessive slope-forming oolite, locally interbedded with quartz/siltstones and micritic sandstones. The capping oolitic ledge at Mount Dunfee forms the top of the measured section and is composed of beds 4 to 20 cm in thickness with local low-angle tabular crossbeds. Interbedded within the oolite slope former is a brown, fissile quartz siltstone unit less than 50 cm in thickness at 152.0 m. Beds of micritic sandstones 5 to 25 cm in thickness with low-angle tabular crossbeds occur from 156.5 to 158.0 m. Paleocurrent measurements of 23 crossbeds of micritic sandstones are completely dispersed and have no statistically significant paleocurrent direction (see Appendix 4).

Interpretation

The peritidal carbonate depositional system consists predominantly of oolite that formed in an agitated shallow
subtidal environment. Modern studies indicate that ooids form in shallow subtidal carbonate environments with high wave and current energies (Bathurst, 1975), forming sand shoals on ramps, shelves, or rimmed shelf edges (Read, 1982). Therefore, the oolite is interpreted as representing ooid shoal deposits.

4. MICROBIAL REEFS

This depositional system consists of microbial boundstones, oolite, lime mudstones, oolitic-allochemic sandstones, and quartz siltstones and sandstones. At Locality A two sequences have been identified: 42.0 m to 56.5 m and 98.5 m to 137.5 m (see Fig. 8). Each sequence may be grouped into lower and upper zones of microbial boundstones separated by a middle zone of quartz siltstones (Plate 1). The microbial boundstones are the dominant lithology of this depositional system and occur as microbial horizons A to I. The microbial boundstones within this depositional system and have been grouped into four primary lithofacies. They are described in the following discussion.

Bioherms with digitate stromatolites

Bioherms composed of digitate stromatolites (Bioherms A.1 and C.1) only occur in the lower sequence. The digitate stromatolites have synoptic profiles with reliefs
less than 5 cm; this is interpreted to represent the original relief above the paleo-seafloor. Lime mudstone and oolite within the cores of the bioherms are thought to have been trapped between the digitate columns while the bioherm formed a structure with topographic relief. The presence of oolitic-allochemic sandstones laterally around some of the bioherms supports this interpretation and indicates that the bioherm deflected storm-deposited sediments. The erosional contact on the upper surface of Bioherm A.1 (Fig. 24) may be the product of either an intense storm-generated flow or a period of subaerial exposure. Figure 46 is an interpretive reconstruction of living digitate stromatolites forming bioherms.

Bioherms and biostromes of inclined stromatolites

Inclined stromatolites formed laterally extensive biostromes in the lower sequence (microbial horizons D and E) and small isolated bioherms in the upper sequence (microbial horizons F and I). The inclined stromatolites have synoptic profiles with reliefs of 3 to 10 cm. The columns are 60 to 100 cm in height. The height of the columns is thought to represent the original topographic relief above the paleo-seafloor. Bioherms and biostromes laterally surrounded by lime mudstone and oolite also suggest this. Inclined stromatolites in both sequences tilt to the west, which reflects formation in strongly
Figure 46: Interpretive block diagram of living digitate stromatolites forming bioherms.
RECONSTRUCTION OF BIOHERM CONTAINING LIVING DIGITATE STROMATOLITES

Figure 46
focused east-directed currents oriented perpendicular to the paleo-shoreline. Figure 47 is an interpretive reconstruction of living inclined stromatolites.

**Isolated forms of stromatolites**

Within microbial horizon G isolated forms of stromatolites vary laterally over a distance of 60 m from hemispheroidal stromatolites surrounded by lime mudstone, to massive stromatolites within oolite, to massive oolite (see Plate 3). The synoptic profiles of the hemispheroidal stromatolites average 20 cm; this represents the minimum amount of vertical relief above the paleo-seafloor. The massive stromatolites have synoptic profiles averaging 10 cm of relief. Oolitic intraclasts between columns suggests that the massive stromatolites had some relief above the paleo-seafloor. Figure 48 is an interpretive reconstruction of living massive and hemispheroidal stromatolites.

**Cryptomicrobial boundstones**

The biostrome of cryptomicrobial boundstones (microbial horizon H) occurs in the upper sequence and has local stromatolites and rare stromatolitic-thrombolites. Synoptic profiles of the stromatolites within the biostrome have less than 4 cm of relief and suggests the biostrome had a low relief above the paleo-seafloor (Fig. 48).
Figure 47: Interpretive block diagram of living inclined stromatolites.
RECONSTRUCTION OF BIOSTROME OF LIVING INCLINED COLUMNAR STROMATOLITES

Figure 47
Figure 48: Interpretive block diagram of living and massive hemispheroidal stromatolites. Low lying cryptomicrobial biostrome in background.
RECONSTRUCTION OF ISOLATED FORMS OF LIVING HEMISPHEROIDAL AND MASSIVE STROMATOLITES

Figure 48
**Interpretation**

The bioherms, biostromes, and isolated forms formed within and near oolite shoals marginal to the peritidal carbonate depositional system (Fig. 44). This interpretation is based on the stratigraphic position of the microbial boundstones and the presence of oolite and lime mudstones. The quartz siltstones represent by-pass channels that moved siliciclastic sediment through the ooid shoals and off the shelf. The intraformational conglomerates contain oolite and stromatolite intraclasts and indicate that punctuated mixing actively influenced sedimentation in addition to providing sites for the formation of microbial boundstones. The oolite represents active oolite shoals and/or spillover lobes. Microbial boundstones formed in two primary settings: (1) with lime mudstones in protected settings on the lee side of oolite shoals and (2) directly with oolite.

The bioherms of digitate stromatolites and bioherms and biostromes of inclined stromatolites in the lower sequence formed in distal settings with lime mudstones. The presence of oolite sharply capping microbial horizon D and the capping oolite bed with local microbial boundstones indicates oolite sand bodies could migrate into this distal setting. The inclination of the stromatolites within the biostromes and bioherms was controlled by focused currents moving in a west-to-east direction. This paleocurrent
direction is similar to the west-east paleocurrent
direction of herringbone sandstones of the
intertidal/shallow subtidal siliciclastic depositional
system. Thus the bioherms and biostromes of inclined
stromatolites are thought to have formed in west-to-east
directed tidal currents.

Bioherms and biostromes of inclined stromatolites,
isolated forms of stromatolites, and cryptomicrobial
boundstones within the upper sequence formed proximal to
the oolite shoals. In protected settings isolated forms of
hemispheroidal and massive stromatolites formed with lime
mudstones in protected settings. These microbial
boundstones also occur with oolite and no lime mudstones
which indicates formation in more active agitated
environments. The cryptomicrobial boundstones occur in
both lime mudstone/oolite and oolite settings and may
represent low-lying microbial banks.

DISCUSSION

REEFS, MOUNDS, OR BUILDUPS?

The Proterozoic was dominated by stromatolites forming
accumulations several meters in thickness extending
hundreds of meters laterally (see Walter, 1976 for
summary). Many geologists refer to these accumulations of
the Proterozoic as mounds or buildups because of the lack
of a skeletal metazoan component (James, 1983). Griffin (1988) refers to this as "skeletal bias" and proposes the use of definitions of Lowenstam (1950) and Heckel (1974) as stated below:

1. A reef is: "the product of the actively building and sediment-binding biotic constituents, which, because of their potential wave resistance, have the ability to erect rigid, wave resistant topographic structures" (Lowenstam, 1950, p. 433).

2. A reef is: "a build-up that displays evidence of potential wave resistance or growth in turbulent water which implies wave resistance; evidence of control over the surrounding environment" (Heckel, 1974, p. 96).

These definitions de-emphasize the presence of skeletal metazoa, allowing all reefs to be viewed as ecological and environmental units regardless of their temporal occurrence.

The ability to construct a topographic structure is an essential element in defining reefs, but the only direct criterion for determining topographic relief of stromatolites is the synoptic profile. Synoptic profiles of columnar stromatolites represent only the actively growing surface of the microbial organisms and usually do not indicate the total topographic relief of a column. Studies of modern subtidal stromatolites in the Bahamas
(Dravis, 1983; Dill and others, 1986; Griffin, 1988) and Shark Bay, Australia (summarized in Walter, 1976) show that columnar stromatolites are lithified during formation and only the upper surfaces are actively growing.

The synoptic profiles of the columnar stromatolites in the Middle Member have 3 to 20 cm of relief, but the columns vary from 50 to 200 cm in height. In general, these heights represent the original height of columnar stromatolites above the paleo-seafloor.

The presence of oolitic-allochemic sandstones surrounding bioherms of digitate stromatolites, together with oolite intraclasts occurring between massive stromatolites, indicates that the microbial boundstones deflected storm-deposited sediments. The deflection of storm deposited sediments in turn implies the stromatolites had some influence over the physical sedimentation of their surrounding environment.

The morphologies of the stromatolites provide no direct evidence of the energy level of the environment except to indicate that they formed in focused currents. It is their intimate association with oolite that indicates they formed in active, agitated environments of at least moderate energies. Thus, as defined by Lowenstam (1950) and Heckel (1974), the stromatolites of the Middle Member of the Deep Spring Formation formed microbial reefs.
ARE QUARTZ RICH STROMATOLITES SIGNIFICANT?

Is the occurrence of quartz within the microstructure of stromatolites significant? Modern quartzose stromatolites are well documented from siliciclastic intertidal and supratidal zones (Cameron and others, 1985). Such stromatolites consist of sticky cyanobacteria that trap and bind siliciclastic sediment within algal mats (Cameron and others, 1985). Ancient quartzose stromatolites are rarely documented in the literature (Davis, 1968; Donaldson, 1963; and Poncet, 1981), and direct reference to the amount of detrital quartz is usually absent. The paucity of preserved quartzose stromatolites in the geologic record suggests that the lack of abundant calcium carbonate cementation inhibits their preservation (Davis, 1968; Cameron and others, 1985; Margaret Rees, personal communication, 1990).

Figure 49 is a diagram illustrating the amount of calcium carbonate present in stromatolites compared to their preservation potential. Quartzose and calcareous stromatolites represent two end-members on the hypothetical curve. Modern quartzose stromatolites have little to no calcium carbonate hence a low preservation potential. Modern and ancient calcareous stromatolites have abundant calcium carbonate and a high preservation potential. Between the two end-members occur intermediate forms of
Figure 49: Graph illustrating the amount of calcium carbonate present in stromatolites compared to their preservation potential.
Modern and ancient CaCO₃ Stromatolites

Stromatolites of the Middle Member Deep Spring Fm.

Modern Quartzose Stromatolites

Figure 49
stromatolites such as the stromatolites of the Middle Member of the Deep Spring Formation.

Gebelein (1976) states that "detrital quartz is common" in many Proterozoic and Paleozoic stromatolites. The incorporation of quartz within the microstructure of stromatolites should not be detrimental to their formation as long as all other biological and physical requirements are met for stromatolites lithification. It is not the incorporation of abundant detrital quartz within the stromatolite microstructure, but their preservation that is significant. The stromatolites of the Middle Member formed in an environment with abundant detrital quartz. Therefore, the incorporation of quartz within their microstructures is only a natural reflection of the depositional environment in which they formed.

ANALOGUES

Shown in Figure 50 are some of the most common groups of Proterozoic stromatolites classified and named with Linnean terminology (summarized by Krylov, 1976). Although I have not classified the stromatolite of the Middle Member in this manner, the morphologies appear to be analogous to many of the Proterozoic forms. Stratiform stromatolites are similar to *Stratifera*, irregular stromatolites to *Poludia* or *Katavia*, digitate stromatolites to *Gymnosolen*, *Jurusania*, or *Archaeozoon*, hemispheroidal stromatolites to
Figure 50: Diagram of some of the most common Proterozoic forms of stromatolites. From Hoffman (1969).
<table>
<thead>
<tr>
<th>STRATIFORM</th>
<th>CONVEX LAMINAE</th>
<th>NECROTIC LAMINAE</th>
<th>CONICAL LAMINAE</th>
</tr>
</thead>
<tbody>
<tr>
<td>STRATIFORM</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>MODULAR</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>BULBOUS</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>UNBRANCHED</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>FURCATE AND UMBELLATE</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>DIGITATE</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>COLUMNAR</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>BACILLAR</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>DENDROID</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>ANASTOMOSED</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Figure 50
a form of Cryptozoon, and massive stromatolites to forms of Colonella.

Inclined columnar stromatolites identified during this study are considered a form of Conophyton, one of the most distinctive forms of Proterozoic stromatolites. The bioherms and biostromes of inclined stromatolites have no direct modern analogues from the Bahamas, but similar inclined stromatolites are known from the Proterozoic Altyn Limestone of Glacier National Park, Montana (Horodyski, 1971). The stromatolites of the Altyn Limestone are inclined roughly 45 degrees with respect to bedding and were interpreted by Horodyski (1971) to have formed in tidally dominated, subtidal channels.

Modern subtidal stromatolites forming in channels within oolite shoals have been documented from the Bahamas (Dravis, 1983; Dill and others, 1986; Griffin, 1988). Griffin’s (1988) study showed stromatolites with low profiles occur in the center of the channel and larger columnar and mound shaped stromatolites occur along the sides of the channel. The hemispheroidal and massive stromatolites of microbial horizon G may have formed in similar environments as the stromatolites documented by Griffin (1988) in the Bahamas.

The stromatolite morphologies of the Middle Member are not unique and are similar to many of the most common Proterozoic forms. The occurrence of stromatolites in
oolite shoals is also not uncommon and is well documented from the Cambrian (Rees and Rowland, 1986) and modern Bahamian oolite shoal environments (Dravis, 1983; Dill and others, 1986; Griffin, 1988). The stromatolites of the Middle Member of the Deep Spring Formation have well documented morphologies that formed in a depositional environment that has modern and ancient analogues.

SUMMARY

1. The Middle Member of the Deep Spring Formation at Mount Dunfee, Nevada is interpreted as a retrogradational sequence of lithologies that formed within four depositional systems: intertidal/shallow subtidal siliciclastics, shallow subtidal mixed sediments, peritidal carbonates, and microbial reefs (Fig. 44).

2. In the microbial reef depositional system microbial boundstones occur as lithofacies forming in focused currents in settings proximal and distal to oolite shoals. The lithofacies are (1) bioherms of digitate stromatolites, (2) bioherms and biostromes of inclined stromatolites, (3) isolated forms of massive and hemispheroidal stromatolites, and (4) a biostrome of cryptomicrobial boundstones.

3. The microbial boundstones within this depositional system are considered microbial reefs. They had
topographic relief, formed in active agitated waters, and exerted a physical control over their environment.

4. The microbial boundstones incorporated abundant detrital quartz within their microstructures and represent an intermediate form between pure quartzose and pure calcareous stromatolites.

5. The microbial boundstones formed in a depositional environment that is well documented from the geologic record, and the stromatolite morphologies are analogous to many of the most common Proterozoic forms.

6. Stromatolites of the Deep Spring Formation illustrate the generalistic nature of microbial organisms and their ability to form organic sedimentary structures in a wide range of depositional environments.
REFERENCES


APPENDIX 1 - DESCRIPTION OF SECTION 3

0.0 to 34.5 meters. This section was not measured, but was briefly analyzed and consists of quartz siltstones with interbedded lenticular lenses of quartz sandstone. Local shrinkage cracks were observed but whether they are syneneresis cracks or mudcracks was not determined. The interbedded lenticular lenses of sandstones comprise a significant portion of the section.

34.5 to 38.5 meters. Dolo-allochemic sandstones with herringbone, tabular, and local hummocky (?) crossbedding with sharp reactivation surfaces. Sets range from 5 to 20 cm in thickness and crossbeds dip 3 to 20 degrees. Multiple sets of herringbone crossbeds are commonly overlain by low angle tabular sets. Very rare mud flasers occur with crossbeds at the base of the lithofacies near the lower contact with underlying quartz siltstones.

38.5 and 41.5 meters. Dolo-allochemic sandstones interbedded with three beds of intraformational conglomerate with sharp, undulatory contacts. The intraclasts are oolitic, tabular, 3 to 20 cm in length, imbricated parallel to bedding, predominantly matrix supported, and occur in very fine-grained dolo-allochemic sandstone. In sharp contact between the lower and middle conglomerate beds is a 50 cm bed of planar to low-angle tabular stratified dolo-allochemic sands with minor
asymmetrical ripples on bedding planes. The upper conglomerate bed is intrastratified with very-fine dolo-allochemic sands from 1 to 15 cm in thickness that have hummocky and tabular stratification. The hummocks have flat to wavy bases, are 2 to 4 cm in height, 10 to 15 cm apart, and capped with planar-stratified sands. The intrastratified sands pinch and swell within the conglomerate and suggest coeval formation. A 50 cm bed of dolo-allochemic sandstone with tabular and herringbone crossbeds sharply overlies the intrastratified conglomerate.

41.5 to 42.0 meters. A 30 cm bed of oolitic-allochemic sandstone in sharp contact above the herringbone sandstone lithofacies. Along strike this lithology is poorly exposed, has no internal stratification, may contain oolitic and quartz siltstone intraclasts, and is overlain by lime mudstones.

42.0 to 43.0 meters. Fissile lime mudstone with preferential dolomitization. Base not exposed and gradational upper contact with overlying microbial bioherm.

43.0 to 44.0 meters. Microbial Horizon A. Bioherm A.1 is a lenticular body with a lateral extent of roughly 36 meters. The tops of the columnar stromatolites at the thickest part of Bioherm A have a wavy erosional contact. At the thickest portion of the Bioherm A is 2 mm, brown to
green, fissile lime mudstone which thickens to 66 cm laterally.

44.0 to 44.5 meters. Microbial Horizon B. Directly above the lime mudstone from is a 30 to 40 cm horizon of stromatolites surrounded with oolitic-allochemic sandstone with stromatolite intraclasts.

44.5 to 46.0 meters. Directly above Microbial Horizon B from are beds of oolitic-allochemic sandstone 20 to 30 cm in thickness intrastratified within quartz siltstone. A 40 cm layer of green and black quartz siltstone occurs directly above Biostrome B. The siltstone contains pre-trilobite shelly fossils and has a lateral exposure of 10 meters.

46.0 to 50.5 meters. Quartz siltstones interbedded with lenticular lenses of very fine-grained quartz sandstones up to 15 cm in thickness. Local asymmetrical ripples are present along bedding planes and rare mudcracks are found in the float. At 47.5 and 49.5 meters outcropping bedding plane surfaces and the float provide minor exposures of local Plagiogmus and rare Planolites.

50.5 to 51.0 meters. Four beds of oolitic-allochemic sandstones overlie and grade laterally into lime mudstone and quartz siltstones and sandstones. The beds are 10 to 15 cm in thickness, have sharp lower and upper contacts, and may be separated by thin lime mudstone partings. The beds contain chaotically oriented flat quartz siltstone
rip-up clasts in the basal beds and ooid intraclasts in the uppermost bed. Intraclasts range from <1 to 2 cm in thickness up to 5 cm in length.

51.0 to 52.0 meters. Microbial Horizon C is composed of isolated bioherms laterally surrounded by lime mudstone and oolitic-allochemic sandstone. The bioherms are pod to loaf like bodies that reach up to 130 cm in height.

52.0 and 54.0 meters. Microbial Horizon D, a sequence of lime mudstone, microbial boundstone, and oolite. The lime mudstone drapes and infills between the stromatolite columns of bioherms of Microbial Horizon C. Biostrome D.1 forms gradationally from the lime mudstone, consists almost exclusively of inclined stromatolites, and ranges from 70 to 100 cm in height. Sharply to gradationally capping Biostrome D is a 50 to 70 cm bed of massive oolite separated by a discontinuous lime mudstone laminae.

54.0 and 55.0 meters. Microbial Horizon E, a sequence of lime mudstone and microbial biostromes. Biostrome E shows extensive lateral variability with thicknesses ranging from 30 to 70 cm.

55.0 to 56.5 meters. A sequence of lime mudstone and oolite. The oolite is a massive 100 cm bed with continuous exposure at locality A. It is commonly unstratified but mound like structures have been observed within the bed. The oolite has local microbial boundstones with stratiform and columnar stromatolites and cryptomicrobial fabrics.
56.5 to 65.5 meters. Planar and low angle tabular crossbedded gray micritic sandstones with rare hummocky cross stratification and climbing ripples. At 57.5 meters is a 15 to 20 cm bed of oolitic intraformational conglomerate, and sporadic lenses of intraformational conglomerate distributed up-section.

65.5 to 73.5 meters. Slope former of micritic sandstone. At 66.5 and 69.0 meters occur intraformational conglomerates of oolitic-allochemic sandstones. They average 20 cm in thickness, have gradational to sharp lower and upper contacts, and contain tabular ooid intraclasts up to 6 cm in length. From 70.5 to 72.5 meters is a fissile quartz siltstone overlying the micritic sandstones. Intrastatified within the siltstone is lenticular beds of very fine-grained sandstone 2 to 6 cm in thickness and 1 to 3 meters in length. In sharp contact above the siltstone is low-angle tabular crossbedded gray micritic sandstone. The top of this sequence has a sharp (erosional?) contact with the overlying micritic sandstones.

73.5 to 98.5 meters. Two prominent ledges of planar to low-angle tabular crossbedded micritic sandstone with local hummocky (?) stratification. The micritic sandstone is alternating dark-brown and gray lithologies. The resistant dark-brown lithology is dolomitized and parallels and crosscuts erodible gray lithologies. Rare beds of
oolitic intraformational conglomerates <20 cm thick also occur in the sequence.

**98.5 and 103.0 meters.** Thinly bedded oolite, oolitic intraformational conglomerate, lime mudstone, and local microbial boundstones. At 99.0 meters is a 30 cm bed of oolitic intraformational conglomerate capped with bedded oolite. The conglomerate contains matrix supported, tabular oolitic intraclasts 5 to 40 cm in length and minor stromatolite intraclasts. Overlying the oolite is a slope forming lime mudstone from 101.0 to 102.5 meters. At 102.5 meters is a small lenslike bioherm of microbial boundstone 30 cm in height and 4 meters in length. It forms gradationally out of lime mudstone and is capped by beds of oolite and oolitic intraformational conglomerate.

**103.0 and 104.0 meters.** Microbial Horizon F is composed of small pod like bioherms of inclined stromatolites.

**104.5 to 107.0 meters.** Microbial Horizon G is a continuous horizon of isolated stratiform, hemispheroidal, massive, and digitate stromatolites.

**107.0 and 108.0 meters.** Microbial Horizon H is composed of a biostrome of cryptomicrobial boundstones (Biostrome H). Biostrome H is composed of three sub-horizons that are in gradational contact with one another. The lower horizon is 25 to 40 cm in thick, may be abundant with stromatolites, and lies gradationally above the
stromatolite rich horizon. The stromatolites within this zone range from stratiform to columnar, average 15 cm in height, 5 to 10 cm in width, and are spaced 5 to 20 cm apart. Directly above the stromatolites there may occur digitate stromatolitic-thrombolites that grade up into a undifferentiated zone. The undifferentiated zone has been extensively dolomitized and the texture is cryptomicrobial. Near the top of this zone is circular heads composed of radiating digits of stromatolitic-thrombolites. The margins of the stromatolitic-thrombolitic heads have sharp contacts with the surrounding cryptomicrobial sediment. The top of Biostrome H is capped by a thin layer of oolite with minor stratiform and columnar stromatolites.

108.0 and 120.5 meters. Massive, unstratified ledge of oolite. The contact is sharp when directly overlying the cryptomicrobial boundstones and gradational when overlying oolitic parts.

120.5 and 126.5 meters. A brown slope forming fissile quartz siltstone with low-angle tabular stratification.

126.5 to 131.0 meters. Thinly bedded oolite with crude low-angle tabular laminations with microbial boundstone lenses < 30 cm in height and 1 meter in length containing composed of columnar stromatolites.

130.0 to 133.0 meters. Microbial Horizon I is composed of beds of inclined and stratiform stromatolites.
133.0 to 137.5 meters. Above the microbial boundstone from occurs A slope forming dark-brown fissile quartz siltstone occurs above Microbial Horizon I.

137.5 to 177.5 meters. At this section the outcrop varies from a slope former of poorly bedded oolite to well formed cliffs of oolite composed of beds 4 to 20 cm in thickness. Beds generally lack recognizable sedimentary structures, but local low-angle tabular crossbeds have been observed. The slope forming oolite is brown to green and appears to be thin beds < 5 cm in thickness. A brown, fissile quartz siltstone < 50 cm thickness is interbedded within the oolite slope former at 152.0 meters. From 156.5 to 158.0 meters occurs micritic sandstones within the oolite sequence. The micritic sandstones occur as thin beds 5 to 25 cm in thickness and have low-angle tabular crossbeds.
APPENDIX 2 - FOSSILS

Gevirtzman (1980) identified Paleophycus or Planolites and Bergaueria-, Neonereites- and Scolicia-like traces in the Lower Member of the Deep Spring Formation at Mount Dunfee. Alpert (1976) noted that the Middle Member locally contains Planolites, Plagiogmus, and annulated trails and burrows. The Upper Member contains Planolites, Skolithos, and Monocraterion in addition to the first appearance of trilobite traces Rusophycus, Diplichnites and Monomorphichnus. Pre-trilobite shelly fauna identified in the Lower Member at Mount Dunfee are Coleoloides sp., Sinotubulites sp., and Salanytheca sp. (Signor and others, 1983).

TRACE FOSSILS

Two types of trace fossils have been identified on bedding plane surfaces of quartz siltstones and shales from 46.0 to 50.5 meters: abundant Plagiogmus, and local Planolites/Paleophycus. The traces occur primarily in float but in situ Plagiogmus has been observed.

Plagiogmus

The specimens identified during this study consist of evenly spaced transverse ridges and furrows 1 mm in height and 10 to 30 mm in length (Fig. 2.1). The traces are
Figure 2.1: Photograph of upper bedding plane trace of *Plagiogmus*. Scale bar is 1 cm.

Figure 2.2: Interpretive block diagram showing three dimensional morphology of *Plagiogmus*. Note mirror image of trace on both upper and lower surfaces.
Figure 2.1

Figure 2.2
straight or curved, and they occur on both sides of bedding plane float specimens. The ridges on the upper surface are mirror images of those of the lower surface (Fig. 2.2). Poorly preserved ridges and furrows up to 50 mm wide have been identified and may represent *Plagiogmus*.

*Plagiogmus* has previously been identified near the base of the Middle Member of the Deep Spring Formation by Cloud and Nelson (1966) and Durham (1974). The specimens identified during this study differ from type samples described in the *Treatise on Invertebrate Paleontology* (Part W, pg 95) in that they lack a longitudinal furrow. Glaessner (1969) proposes that *Plagiogmus* is a bedding parallel trace produced by the backfill of an ancestral mollusc with a foot and mantel.

**Planolites/Paleophycus**

The specimens identified during this study consist of horizontal, sinuous to U-shaped, curved and straight, unbranched ridges along upper bedding plane surfaces. The traces range from 0.5 to 2.0 mm in width and 5 to 60 mm in length. Only one sample has cross-sectional views of identifiable burrows that reach 5 mm in depth and are filled with the same sediment in which the burrows occur.

Pemberton and Frey (1982) have proposed that the infilling of burrows is the distinguishing characteristic between *Planolites* (active) and *Paleophycus* (passive)
rather than the presence or absence of branching (Alpert, 1975). Only one specimen has identifiable burrows suggestive of passive filling, so a Planolites/Paleophycus designation is preferred.

**SHELLY FOSSILS**

At 44.5 meters of section 3 is a 40 cm layer of green and black quartz siltstone with a lateral exposure of 10 meters (see Plates 1 and 2). This layer contains approximately 20 specimens of a previously undescribed pre-trilobite shelly fauna along the upper surfaces of fissile laminae. Specimens occur as iron oxidized traces and fragments of tubular shells with five preserved morphological features:

1. straight to sinuous tubes ranging from 1 to 3 mm in width and 4 to 8 mm in length;
2. an outer shell with exterior surfaces of asymmetrical angular rings and smooth inter-ring areas mirrored on interior surfaces;
3. smooth unringed interior surfaces showing preferential pyritization;
4. a central cavity of poorly preserved, spongiferous textured, orange-brown core comprising approximately two-thirds of an individual tube;
5. and tubes are circular in cross section and are calcitic(?).
The specimens identified during this study show few similarities to the shelly fauna that have been identified in the Lower Member of the Deep Spring Formation at Mount Dunfee by Gevirtzman (1980). They are tentatively identified as representing a member of the Family Coleolidae based on the conical nature of tubes, smooth interior surfaces, shell thickness, and a parallel to bedding preservation which may suggest a burrowing existence. Fisher (1962) places the Family Coleolidae "provisionally in the Mollusca, with full realization that it may prove to be, on further study, more closely allied to some phylum of worms." The identification of sinuous tubes from the specimens identified during this study strongly suggests the latter interpretation may be justified. Future work will determine if this fossil represents a genus of the Family Coleolidae (allied to the Annelids?), or is some other form of small shelly fauna.
### APPENDIX 3 - INSOLUBLE RESIDUE DATA

<table>
<thead>
<tr>
<th>Sample</th>
<th>Percentage Insolubles</th>
<th>Original Weight</th>
<th>Dissolved Weight</th>
</tr>
</thead>
<tbody>
<tr>
<td>87L050</td>
<td>17.4</td>
<td>35.00</td>
<td>6.08</td>
</tr>
<tr>
<td>88L002</td>
<td>22.4</td>
<td>50.00</td>
<td>11.20</td>
</tr>
<tr>
<td>88L005</td>
<td>15.3</td>
<td>50.12</td>
<td>7.65</td>
</tr>
<tr>
<td>88L006</td>
<td>29.4</td>
<td>38.69</td>
<td>11.37</td>
</tr>
<tr>
<td>88L008</td>
<td>31.9</td>
<td>42.74</td>
<td>12.33</td>
</tr>
<tr>
<td>88L012</td>
<td>14.1</td>
<td>25.40</td>
<td>3.58</td>
</tr>
<tr>
<td>88L016</td>
<td>14.7</td>
<td>33.92</td>
<td>3.31</td>
</tr>
<tr>
<td>88L024</td>
<td>3.8</td>
<td>50.10</td>
<td>1.92</td>
</tr>
<tr>
<td>88L025</td>
<td>4.8</td>
<td>54.79</td>
<td>2.65</td>
</tr>
<tr>
<td>88L031</td>
<td>8.1</td>
<td>50.04</td>
<td>2.40</td>
</tr>
<tr>
<td>88L034</td>
<td>1.8</td>
<td>50.19</td>
<td>0.94</td>
</tr>
<tr>
<td>88L041</td>
<td>29.9</td>
<td>51.72</td>
<td>15.42</td>
</tr>
<tr>
<td>88L045</td>
<td>14.7</td>
<td>52.06</td>
<td>7.65</td>
</tr>
</tbody>
</table>

**MICROBIAL BOUNDSTONES**

<table>
<thead>
<tr>
<th>Sample</th>
<th>Percentage Insolubles</th>
<th>Original Weight</th>
<th>Dissolved Weight</th>
</tr>
</thead>
<tbody>
<tr>
<td>88L027</td>
<td>70.1</td>
<td>22.65</td>
<td>15.89</td>
</tr>
</tbody>
</table>

**DOLO-ALLOCHEMIC SANDSTONES**

<table>
<thead>
<tr>
<th>Sample</th>
<th>Percentage Insolubles</th>
<th>Original Weight</th>
<th>Dissolved Weight</th>
</tr>
</thead>
<tbody>
<tr>
<td>88L038</td>
<td>46.0</td>
<td>25.15</td>
<td>11.57</td>
</tr>
</tbody>
</table>

**MICRITIC SANDSTONES**

<table>
<thead>
<tr>
<th>Sample</th>
<th>Percentage Insolubles</th>
<th>Original Weight</th>
<th>Dissolved Weight</th>
</tr>
</thead>
<tbody>
<tr>
<td>89L039</td>
<td>19.1</td>
<td>6.52</td>
<td>34.41</td>
</tr>
</tbody>
</table>

**OOLITIC-ALLOCHEMIC SANDSTONES**

<table>
<thead>
<tr>
<th>Sample</th>
<th>Percentage Insolubles</th>
<th>Original Weight</th>
<th>Dissolved Weight</th>
</tr>
</thead>
<tbody>
<tr>
<td>88L011</td>
<td>14.2</td>
<td>25.00</td>
<td>3.57</td>
</tr>
<tr>
<td>88L040</td>
<td>26.3</td>
<td>33.50</td>
<td>8.82</td>
</tr>
<tr>
<td>88L044</td>
<td>9.0</td>
<td>38.47</td>
<td>3.46</td>
</tr>
<tr>
<td>89L011</td>
<td>2.8</td>
<td>1.20</td>
<td>43.13</td>
</tr>
</tbody>
</table>

**OOLITE**
## APPENDIX 4 - PALEOCURRENT RAW DATA

### Intertidal/shallow subtidal siliciclastic system

**Dolo-allochemic sandstone crossbeds: 34.5 - 38.5 m**

<table>
<thead>
<tr>
<th>A</th>
<th>B</th>
<th>C</th>
<th>D</th>
</tr>
</thead>
<tbody>
<tr>
<td>344/49</td>
<td>342/31</td>
<td>330/18</td>
<td>009/29</td>
</tr>
<tr>
<td>352/22</td>
<td>325/18</td>
<td>355/22</td>
<td>349/23</td>
</tr>
<tr>
<td>330/29</td>
<td>335/22</td>
<td>322/18</td>
<td>050/14</td>
</tr>
<tr>
<td>030/19</td>
<td>312/16</td>
<td>278/26</td>
<td>008/36</td>
</tr>
<tr>
<td>334/33</td>
<td>337/18</td>
<td>357/24</td>
<td>345/24</td>
</tr>
<tr>
<td>055/22</td>
<td>005/28</td>
<td>190/20</td>
<td>005/28</td>
</tr>
<tr>
<td>010/18</td>
<td>355/23</td>
<td>347/28</td>
<td>285/16</td>
</tr>
<tr>
<td>345/27</td>
<td>342/22</td>
<td>018/18</td>
<td>354/38</td>
</tr>
<tr>
<td>315/23</td>
<td>335/28</td>
<td>348/25</td>
<td>357/45</td>
</tr>
<tr>
<td>340/30</td>
<td>320/42</td>
<td>012/08</td>
<td>330/15</td>
</tr>
<tr>
<td>342/25</td>
<td>330/23</td>
<td>336/06</td>
<td>275/07</td>
</tr>
<tr>
<td>343/30</td>
<td>355/28</td>
<td>293/18</td>
<td>354/44</td>
</tr>
<tr>
<td>324/20</td>
<td>345/18</td>
<td>010/40</td>
<td>340/18</td>
</tr>
<tr>
<td>035/18</td>
<td>000/24</td>
<td>350/36</td>
<td>004/35</td>
</tr>
<tr>
<td>005/42</td>
<td>008/42</td>
<td>338/36</td>
<td>354/44</td>
</tr>
<tr>
<td>000/54</td>
<td>355/36</td>
<td>005/36</td>
<td>005/27</td>
</tr>
<tr>
<td>003/38</td>
<td>015/48</td>
<td>345/52</td>
<td>025/15</td>
</tr>
<tr>
<td>000/28</td>
<td>344/14</td>
<td>070/10</td>
<td>000/28</td>
</tr>
<tr>
<td>344/35</td>
<td>003/10</td>
<td>016/65</td>
<td>357/24</td>
</tr>
<tr>
<td>358/45</td>
<td>000/50</td>
<td>334/08</td>
<td>010/28</td>
</tr>
<tr>
<td>003/21</td>
<td>004/34</td>
<td>332/22</td>
<td>318/20</td>
</tr>
<tr>
<td>345/20</td>
<td>328/15</td>
<td>290/08</td>
<td></td>
</tr>
</tbody>
</table>

**A-B planes of imbricate oolitic intraclasts: 38.5 - 41.5 m**

<table>
<thead>
<tr>
<th>A</th>
<th>B</th>
<th>C</th>
<th>D</th>
</tr>
</thead>
<tbody>
<tr>
<td>322/38</td>
<td>343/34</td>
<td>338/51</td>
<td>343/52</td>
</tr>
<tr>
<td>000/27</td>
<td>010/44</td>
<td>005/18</td>
<td>348/44</td>
</tr>
<tr>
<td>335/35</td>
<td>331/32</td>
<td>004/30</td>
<td>323/27</td>
</tr>
<tr>
<td>015/28</td>
<td>344/38</td>
<td>330/40</td>
<td>328/52</td>
</tr>
<tr>
<td>339/37</td>
<td>021/21</td>
<td>322/38</td>
<td>343/26</td>
</tr>
<tr>
<td>022/24</td>
<td>337/26</td>
<td>332/40</td>
<td>330/40</td>
</tr>
<tr>
<td>315/20</td>
<td>357/36</td>
<td>348/30</td>
<td>335/38</td>
</tr>
<tr>
<td>328/25</td>
<td>338/29</td>
<td>339/36</td>
<td>045/48</td>
</tr>
<tr>
<td>342/26</td>
<td>346/40</td>
<td>330/45</td>
<td>021/17</td>
</tr>
<tr>
<td>010/36</td>
<td>070/20</td>
<td>352/20</td>
<td>345/30</td>
</tr>
<tr>
<td>285/28</td>
<td>345/30</td>
<td>285/28</td>
<td>345/30</td>
</tr>
<tr>
<td>005/18</td>
<td>328/12</td>
<td>040/37</td>
<td>310/21</td>
</tr>
<tr>
<td>025/38</td>
<td>315/14</td>
<td>322/30</td>
<td>025/38</td>
</tr>
<tr>
<td>315/14</td>
<td>322/30</td>
<td>352/40</td>
<td>002/20</td>
</tr>
<tr>
<td>343/38</td>
<td>356/40</td>
<td>048/14</td>
<td>010/31</td>
</tr>
<tr>
<td>005/40</td>
<td>350/40</td>
<td>333/45</td>
<td>320/30</td>
</tr>
<tr>
<td>275/27</td>
<td>296/29</td>
<td>337/14</td>
<td>325/28</td>
</tr>
<tr>
<td>284/20</td>
<td>286/24</td>
<td>246/24</td>
<td>292/22</td>
</tr>
<tr>
<td>308/34</td>
<td>332/52</td>
<td>000/20</td>
<td>295/30</td>
</tr>
<tr>
<td>005/04</td>
<td>244/20</td>
<td>246/10</td>
<td>307/23</td>
</tr>
<tr>
<td>008/11</td>
<td>063/18</td>
<td>059/23</td>
<td>075/20</td>
</tr>
<tr>
<td>104/37</td>
<td>035/14</td>
<td>114/42</td>
<td>122/32</td>
</tr>
<tr>
<td>110/38</td>
<td>112/44</td>
<td>110/38</td>
<td>112/44</td>
</tr>
<tr>
<td>Shallow Subtidal Mixed Sediment System</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>---------------------------------------</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Micritic sandstone crossbeds:</strong> 56.5 - 98.5 m</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>007/42  003/30  008/35  335/24</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>331/21  034/24  002/29  022/34</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>354/24  308/10  350/34  012/31</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>334/22  341/34  355/32  355/39</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>340/24  004/29  344/25  340/42</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>352/34  004/22  007/15  344/22</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>325/34  000/15  356/24  000/32</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>312/24  346/23  282/12  348/25</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>348/20  340/20  005/34  338/24</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>018/15  355/20  018/15  355/20</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>018/20  348/24  075/02  330/18</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>036/22  358/25  052/36  042/38</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>342/25  005/30  027/20  017/18</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>350/28  038/34  005/26  015/48</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>348/32  058/34  350/24  338/35</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>355/34  345/32  340/28  335/64</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>335/20  012/26</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Peritidal Carbonate System</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Micritic sandstones crossbeds:</strong> 156.5 - 158.0 m</td>
</tr>
<tr>
<td>345/24  010/14  355/30  025/15</td>
</tr>
<tr>
<td>355/30  025/15  355/16  340/32</td>
</tr>
<tr>
<td>014/08  055/15  315/10  022/40</td>
</tr>
<tr>
<td>008/28  025/32  024/34  340/26</td>
</tr>
<tr>
<td>308/24  335/36  345/25  333/48</td>
</tr>
<tr>
<td>337/40  305/42  355/35  325/26</td>
</tr>
<tr>
<td>335/33 (Strike of strata at Locality A is 355/25 NE)</td>
</tr>
</tbody>
</table>
Deep Spring Formation
Molly Gibson Canyon
White-Inyo Mountains, CA
(location in Fife and others, 1971)

Composite stratigraphic column
based on field notes.
Not a measured section

- Quartz Siltstones
- Calcareous Sandstones
- Microbial Boundstones
- Cryptomicrobial Boundstones
- Oolite
PLATE 1

STRATIGRAPHIC COLUMNS OF THE MIDDLE MEMBER OF THE DEEP SPRING FORMATION AT MOUNT DUNFEE

(in pocket)
PLATE 2

EXPANDED STRATIGRAPHIC COLUMN OF THE MIDDLE MEMBER OF THE
DEEP SPRING FORMATION AT MOUNT DUNFEE

(in pocket)
PLATE 3

EXPANDED STRATIGRAPHIC COLUMN OF THE MIDDLE MEMBER OF THE
DEEP SPRING FORMATION AT MOUNT DUNFEE

(in pocket)