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A Study of the Bioherms of the Early Ordovician Garden City Formation and a Literature Review of Early Ordovician Organic Buildups

Heidi Pearce

Utah State University

A STUDY OF THE BIOHERMS OF THE EARLY ORDOVICIAN GARDEN CITY FORMATION AND A

LITERATURE REVIEW OF EARLY ORDOVICIAN ORGANIC BUILDUPS

by
Heidi Pearce

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Approved:

_____________________ Dr. W. David Liddell
Major Professor

_____________________ Dr. Carol M. Dehler
Committee Member

_____________________ Dr. Benjamin J. Burger
Committee Member

Utah State University
Logan, Utah

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ABSTRACT

A STUDY OF THE BIOHERMS OF THE EARLY ORDOVICIAN GARDEN CITY FORMATION AND A LITERATURE REVIEW OF EARLY ORDOVICIAN ORGANIC BUILDUPS

by

Heidi Pearce, Master's of Science

Utah State University, 2012

Major Professor: Dr. W. David Liddell
Department: Geology

During the Early Ordovician organic buildups formed in shallow seas across the world. This project contains a literature review on these organic buildups with a focus on those occurring in the warm, shallow seas of North America, but also includes a study on organic buildups formed in the cold water region of Russia. The goal of the study was to characterize these Early Ordovician organic buildups in order to identify similarities and differences in their occurrence. The second part of this project is a preliminary study on organic buildups occurring in the Early Ordovician Garden City Formation in Boss Canyon, Utah.

This project found that warm, shallow-water organic buildups of the Early Ordovician were small scale structures that were typically 1-3 meters in height and several meters in width, with the length variable depending on location. The organic buildups were biotically relatively simple structures formed by algae, lithistid sponges and *Calathium* with accessory organisms of brachiopods, cephalopods, trilobites, echinoderms, gastropods, ostracods, algal remains and conodonts. The organic buildups are composed of massive to faintly-laminated mudstone to wackestone to packstone to boundstone. Large *in situ* organisms are found on the organic

buildups, while internally they are found as skeletal components. Rock surrounding the organic buildups includes limestone and shale. Channels dissect the organic buildups and some organic buildups show evidence of subaerial exposure. Formation of the organic buildups was dependent on local conditions.

Cold water organic buildups are several meters long and generally less than a meter high. These organic buildups have a calcareous-clay composition. The mound core is composed of clay topped by a carbonate cap and overlain by a hardground surface. Formation of the organic buildups was by dense concentrations of sessile siliceous sponges. Accessory organisms include brachiopods, echinoderms, ostracods, pelmatozoans, bryozoans and conodonts.

DEDICATION

I would like to dedicate this project to my little family. I love them more than I can express.

ACKNOWLEDGMENTS

There are many entities I want to express my gratitude for in bringing this project about.

First, I would like to thank my committee, Dr. Liddell, Dr. Dehler and Dr. Burger, for their assistance on this project. Without their knowledge, time, and patience this project would not exist. I would also like to thank the Geology Department in general for both financial and educational support throughout my undergraduate and graduate career.

Second, I want to give a huge thanks to my field partners Ryan Jensen and Gregory Pearce. Snow is not the ideal fieldwork condition yet, with the help of the Rhino, they went out with me and made it possible to collect data.

Finally, my family and friends deserve my thanks for their love and support. I especially want to thank my parents, sisters and in-laws for all they personally did to allow me to complete my degree. My husband Gregory Pearce deserves my biggest thanks for keeping our family running and supporting me though the ups and downs of my graduate career.

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INTRODUCTION

In the Early Ordovician (488-478 Ma) waters, where conditions were right, organic buildups formed adjacent to the continents of Siberia and Laurentia. Adjacent to Laurentia, organic buildups formed throughout a broad belt of carbonate rocks at least 153 kilometers wide and extending some 610 kilometers from present day Texas up into Newfoundland (Toomey and Nitecki, 1979). These organic buildups were deposited in a shallow, passive-margin sea with an environment similar to that of the present day Bahama Bank (Toomey and Nitecki, 1979). Early Ordovician time also saw the formation of organic buildups in cold water regions of the world adjacent to the Siberia continent near present day Russia (Fedorov, 2003).

The following pages are a compilation of studies conducted on Early Ordovician organic buildups conducted by various authors. In addition, the results of a preliminary study on the organic buildups of the northern Utah Garden City Formation found in Boss Canyon, Utah are presented. This study attempted to place the Garden City Formation organic buildups within the context of present day North American Early Ordovician organic buildups by answering three main questions; 1) Where in the sequence do these organic buildups occur? 2) What organisms built these structures? and 3) What was the paleoecological setting of these organic buildups?

ORDOVICIAN ORGANIC BUILDUPS

Western Utah

Rigby (1965a, 1971) and Church (1974) conducted studies on organic buildups of the Fillmore Formation in Western, Utah (Figure 1).

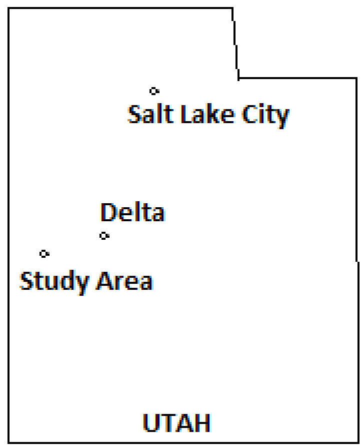

Figure 1. General study location of Western Utah organic buildup studies (From Church, 1974).

Rigby (1965a, 1971) found that, within the lowest organic buildup horizon, lithistid sponges played a minor role while stromatolitic algae were dominant early in development. In the upper part of the formation there are four well-developed organic buildup horizons on average 1- 2 meters in height and up to 9 meters in diameter composed of stromatolitic algal heads with abundant lithistid sponges in the upper two buildups, as well as an association of lithistid sponges with *Calathium*. *Calathium* is an organism that is possibly a sponge or possibly a receptaculitid (Church, 1991).

Church (1974) made the most detailed study of the lowest organic buildup horizon in the Fillmore Formation. This horizon occurs in the shaly siltstone member 198 meters above the base of the formation (Figure 2).

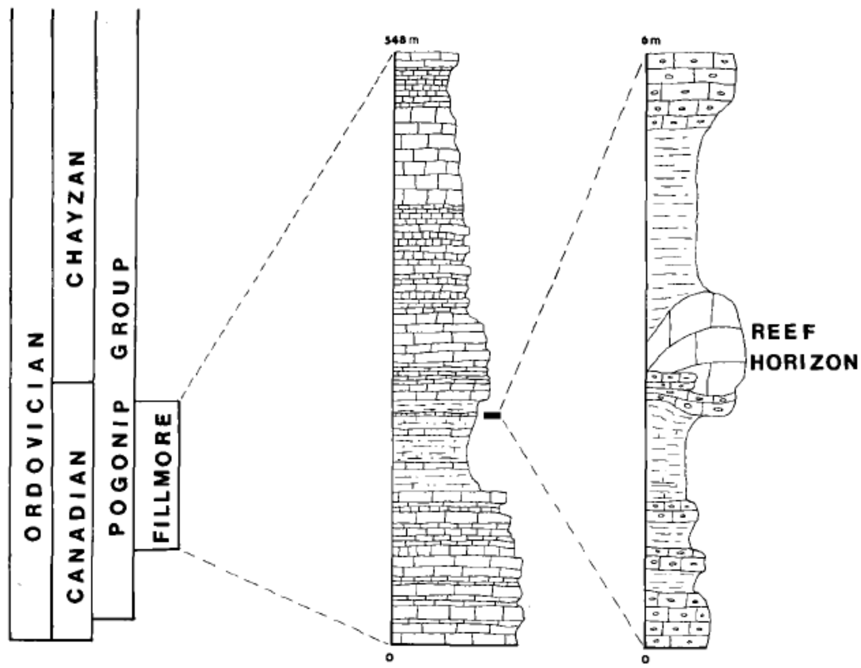

Figure 2. Stratigraphic column giving location of reef horizon (From Church, 1974).

Within the reef horizon there are two distinct facies, a reef core facies and an interreef or bioclastic facies. The reef core facies consists of individual sausage-shaped reef cores 1-1.5 meters high, 2-3 meters wide and up to 30 meters long composed of a medium gray, dense, micritic, porcelaneous-weathering limestone (Figure 3). The interreef facies is laterally adjacent to and has a sharp contact with the reef core facies (Figure 3). Interreef rocks are composed of bioclastic limestone and intraformational conglomerate. Bioclastic limestones are adjacent to the reef cores and are composed mainly of abundant algal material, echinoderm debris, trilobite hash and varying amounts of intraclasts. Abraded fragments of sponges and *Calathium* are found near the reef cores. Bedding planes of bioclastic limestone are ripple marked and grain size coarsens downward into intraformational conglomerate beds that underlie the reef cores. Some reef cores contain intraclasts in their lower portions. Shales lie above and below the reef horizon (Figure 3). The lower shale unit is an approximately 2 meters thick, medium light gray to light olive green, thin-bebbed, calcareous shale with thin calcareous silty layers. The shale lies immediately under the intraformational conglomerate. Dendroid graptolites, asaphid trilobites, repichnid burrows and occasional shaly pebbles occur in the lower shale unit. The upper shale unit is an approximately 1.5 meter thick, thin-bedded, medium gray to medium-dark gray, calcareous shale that lies immediately on top of the reef core facies and overlaps reef cores until it buries the cores. Trilobite fragments, brachiopods and burrows occur in the upper shale unit.

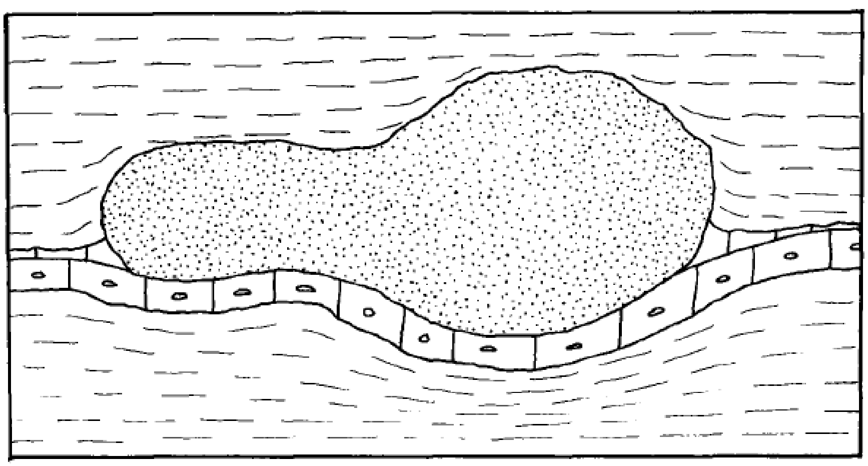

Figure 3. Idealized cross-section of a reef core 1.5 meters high, showing its relationship to adjacent rocks (From Church, 1974).

The reef trends on average N 31˚ E and reef cores occur regularly for 900 meters across the width of the exposed reef horizon normal to this reef trend (Figure 4). The modal separation distance between reef cores is approximately 10 meters. Reef cores become less distinguished to the northwest and grade into biostromal units where waters were likely becoming deeper and quieter in the Early Ordovician. The actual extent of the reef field was probably greater during Early Ordovician time and probably would have extended to the southeast and south of the study area.

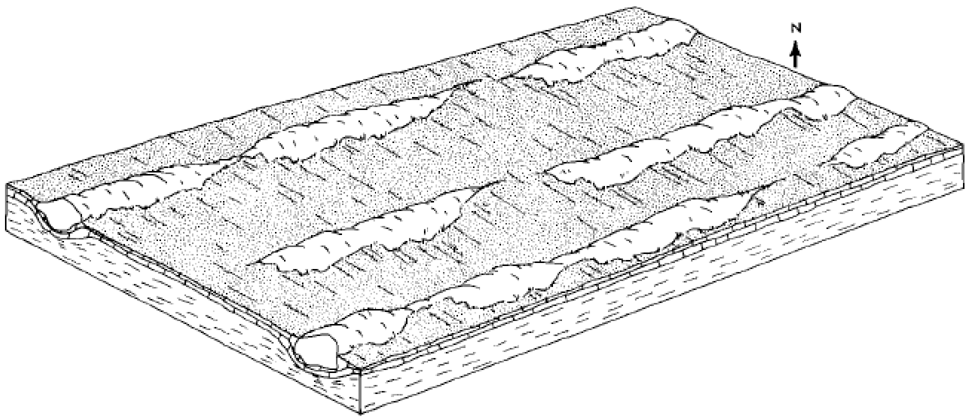

Figure 4. Conceptual block diagram of reef occurrences on the reef horizon. Reefs are 1-1.5 meters high and 10 meters apart (From Church, 1974).

Ripple marks from the interreef beds reveal a dominant ripple trend, and therefore current direction, of N 31˚ W. This current direction was likely affected by the reefs. Currents that controlled reef lineaments in the Early Ordovician may have resulted from prevailing winds and shoreline configuration. Figure 5 shows the possible geographic relationship that existed during the Early Ordovician time. The zero isopach line of Early Ordovician rocks may reflect the gross shoreline trend indicated on the map by the dotted line.

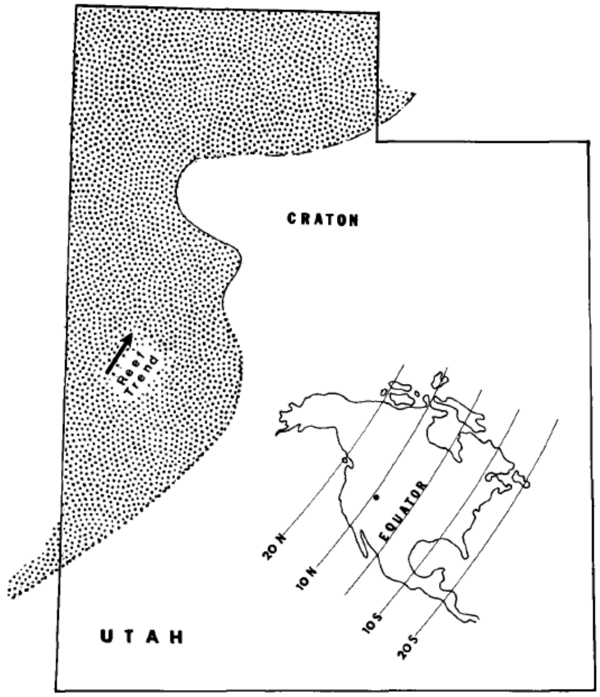

Figure 5. Possible paleogeographic relationships existing during Early Ordovician time (From Church, 1974).

Organisms that occupy the reef can be divided into two categories: frame building organisms and accessory organisms. Sponges, algae and *Calathium* are the principal frame builders. Sponges found on the reef cores are lithistid sponges of the family Anthaspidellidea. Tubular forms are often found in growth position as well as abraded pieces on the interreef beds. Large saucer shaped sponges are occasionally found in growth position, but generally are found as plates in depressions of reef surfaces. *Calathium* is often found in growth position with a cone shape and vertical orientation. *Calathium* specimens reach heights of 12-15 centimeters, 5- 6 centimeters diameters at the top and 1-2 centimeters at the base. Attachment systems flare out and some developed into a rootlike system often seen attached to tubular sponges. Calathium specimens are largest in size and number in the upper areas and flanks of the reefs.

Stromatolitic algae acted as substrate stabilizers, allowing for initial reef growth and, as the reef developed, the algae continued to be important, acting as binding organisms.

Accessory organisms found on the reef cores indicate the diversity of the reef in the Early Ordovician. Specimens found include one crinoid associated with crinoid debris, of which less than a half-dozen occurrences of such crinoids were know from rocks of this age when the study was conducted in 1974. Crinoids are found in an erosional depression on the reef crest, indicating their appearance in a late phase of reef growth. Brachiopods are found within the reef mass, concentrated as pockets around the lower peripheries of reef bodies and overgrown with stromatolitic algae. Asaphid and pliomerid trilobites, gastropods 5 centimeters in diameter, and orthoconic nautiloids up to 40 centimeters long occur randomly in the reef. Reef cores contain fecal pellets, echinoderm debris and ostracods.

During Early Ordovician times a period of low-energy waters charged with terrigenous material occurred just prior to reef development as indicated by the lower shale unit. The abrupt change from shale to intraformational conglomerate indicates an increase in energy, clearing the water of terrigenous material and allowing carbonates to dominate. Stromatolitic algae moved into the harsh environment and stabilized the substrate allowing sponges to attach to the matted or pebble surface. The sponges began acting as baffles, trapping carbonate mud and establishing a framework for continued reef growth. *Calathium* then attached to tubular sponges and other firm objects projecting upwards into zones of higher energy and, in turn, acted as baffles, trapping increasing amounts of sediment and providing a favorable environment for the stromatolitic algae and sponges. Ripple-marked surfaces, the presence of algae and the small size of the reefs indicate formation in a shallow-water environment. The increased current and occasional storms scattered reef debris and other bioclastic material between reef structures creating the interreef unit. Over a few decades these growing reef structures acted as baffles, trapping sediment and increasing reef height until it reached a maximum elevation of 1.5 meters above the substrate. *Calathium* is considered the climax community of the reef. At the height of reef development energy conditions changed to a low-energy state and terrigenous sediment filled the water column chocking out reef growth and forming the upper shale unit.

West Newfoundland

Stevens and James (1976) conducted a study of the cyclic shelf carbonate deposits of the St. George Group. Within a subtidal facies of the Group they discovered a 20-70 meter thick series of large carbonate mounds whose formation they attribute to sponges. The mound facies contains rounded heads 1-2 meters in diameter and 1 meter in height. The heads are composed of a series of upward-opening cups. The cup walls are dolomitized and the interiors are filled with burrowed lime mudstone. Surrounding the mound rock are burrowed skeletal grainstones and packstones containing oncolites.

Alberta Canada

Rigby (1965b) conducted a study of the Early to Middle Ordovician formations in the Columbia Icefields, Jasper National Park, Alberta (Figure 6). The Early Ordovician Canadian system of Alberta contains the Mons and Sarbach Formations (Figure 7).

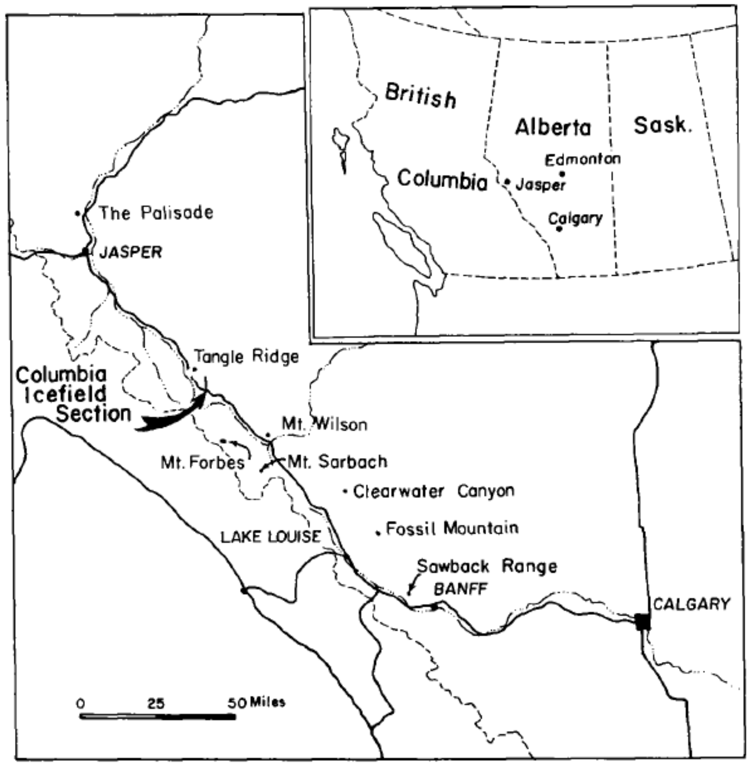

Figure 6. Location of the Columbia Icefield Section (From Rigby, 1965b).

The Mons Formation in the Columbia Icefield section is a 178 meter thick section of interbedded, micaceous shale, argillaceous limestone and a limestone intraformational conglomerate. The Sarbach Formation of the Columbia Icefield section is a 408 meter thick section of thick-bedded, siliceous gray limestone, shale and argillaceous limestone. Small algal and sponge bioherms occur 38 meters above the base of the formation in a 19.5 meter thick section. The reefs are 0.6-1.2 meters thick and 0.9-3 meters long. Reef rock is a medium to dark blue-gray, fine-grained porcellaneous, pure limestone. Interreef rock is a coarse to medium-grained, medium-gray to dark-gray, hashy, thin-bedded to medium-bedded limestone. Rock above and below the bioherm section is a dark to medium gray limestone. The upper limestone contains minor streaking and is medium-bedded. The sponge bioherms are composed of anthaspidellid sponges which are among the oldest know lithistid sponges.

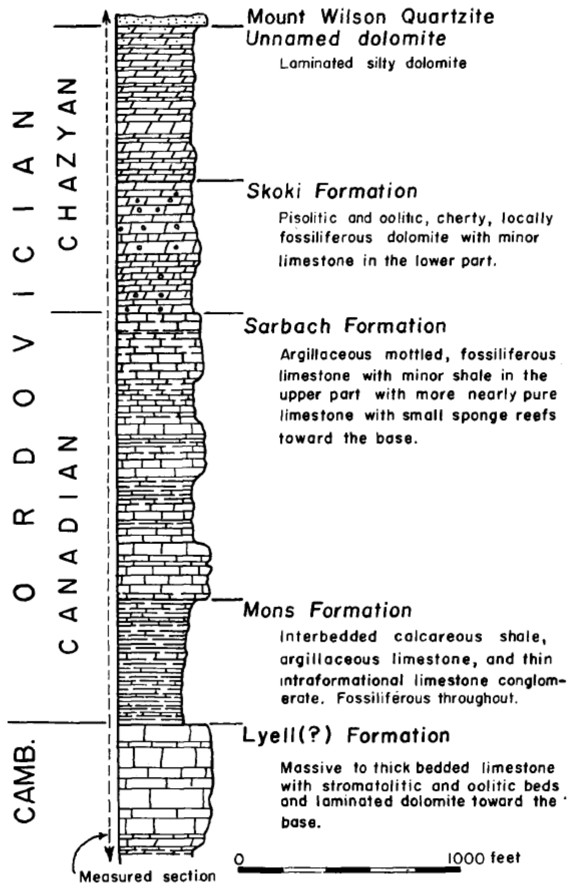

Figure 7. Stratigraphic Section of the Columbia Icefield Section (From Rigby, 1965b).

<u>Texas and Oklahoma</u>

Toomey and Nitecki (1979) conducted a very thorough study of organic buildups in Texas and Oklahoma. Carbonate deposition of the Early Ordovician time in the present day Texas and Oklahoma region is represented by the El Paso Group, Ellenburger Group, Arbuckle Group and the Marathon Formation (Figure 8).

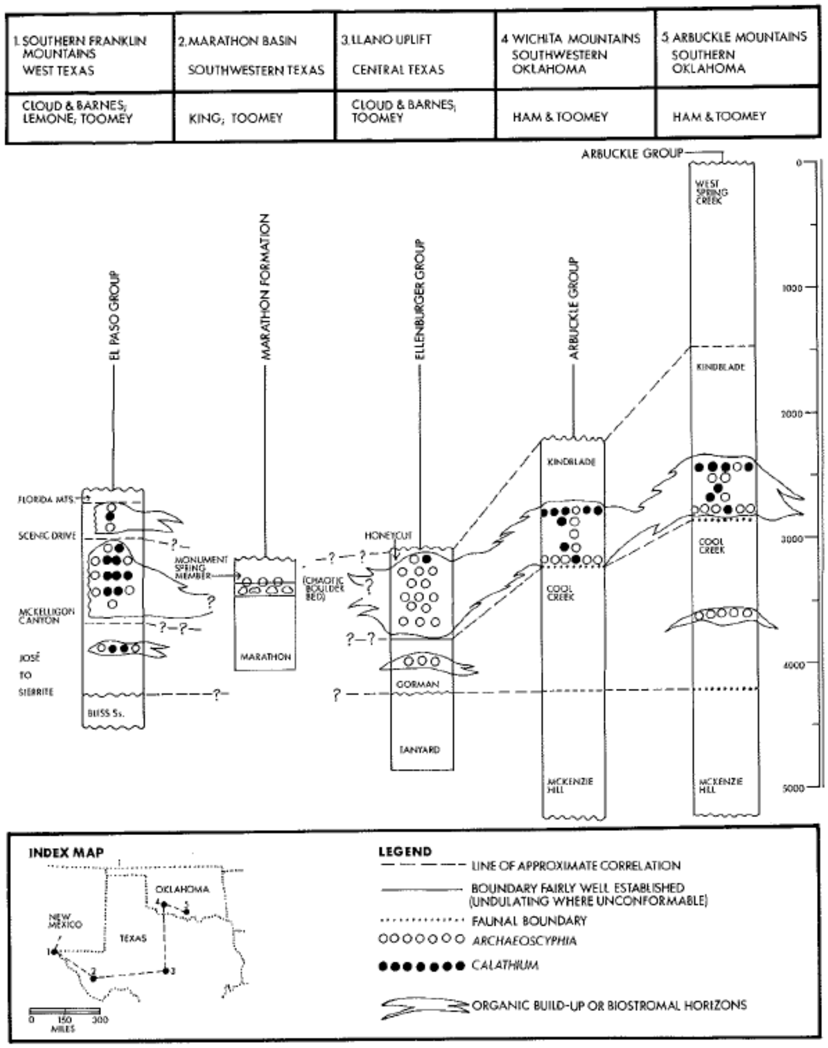

Figure 8. Occurrence of algal-sponge organic buildups and biostromal horizons in the Early Ordovician from West Texas to southeastern Oklahoma (From Toomey and Nitecki, 1979)

The study was conducted in the Franklin Mountains of Western Texas and Southern New Mexico, the Marathon Area and the Llano region of Texas, and the Wichita and Arbuckle Mountain of Oklahoma (Figure 9). Organic buildups and biostromal horizons are found within these rocks. The lithistid sponge *Archaeoscyphia*, *Calathium* sponge (but possible receptaculitid) and probable coelenterate *Pulchrilamina* began to flourish during the Early Ordovician and locally built biostromal horizons or low, mounded organic buildups in the shallow sea.

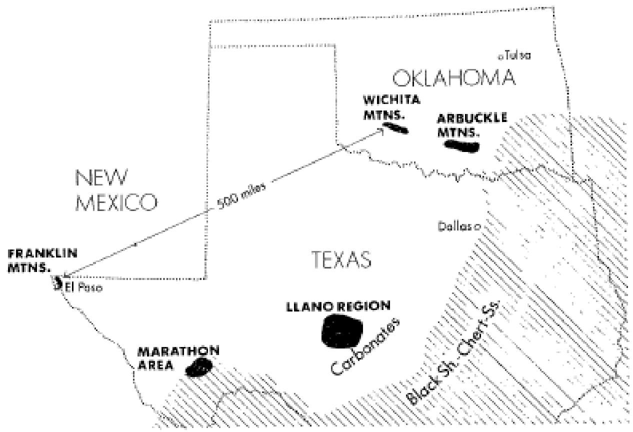

Figure 9. Diagram of Early Ordovician facies belt in the southwestern United States in relationship to outcrop area of the Arbuckle, Wichita, and Franklin Mountains and the Marathon and Llano region (From Toomey and Nitecki, 1979).

Within the El Paso Group the majority of the organic buildups are found in the lower portion of the McKellingon Canyon Formation although there are some organic buildups that occur above and below the formation. The organic buildups are about 0.9-1.5 meters in length and 1.8 meters in height. The largest mound is named Lechuguilla Mound and it is 13.7 meters long and 5.8 meters high. The organic buildups are composed principally of mud with relatively common skeletal components. The skeletal framework is dominated by 1) *Pulchrilamina spinosa,* 2) siliceous lithistid sponge *Archaeoscyphia annulata* and 3) upright *Calathium*. Clusters of relatively small digitate stromatolites are found at the base of the mounds. Individual fingers average 7.6 centimeters in height and 1.3 centimeters in diameter. These stromatolites appear to encrust tumbled fragments of *Archaeoscyphia annulata* and *Calathium.* Halos that are composed of coarse skeletal packstones and grainstones are found around the organic buildups. The mound rock is primarily a skeletal wackestone, but in some instances the rock grades into a skeletal packstone and boundstone. Intraclasts and organism burrows are common. Skeletal grains compose up to 25% of the rock with ossicles, spicules and spines of pelmatozoans, gastropods, brachiopod and trilobite debris and algal or problematical remains being the most common. Spicules and spines from *Pulchrilamina, Archaeoscyphia,* and *Calathium* are found as well, usually in growth position. Intraclasts are the most common non skeletal grains. Boundstone is found mainly near the top of the organic buildups where there is abundant *Pulchrilamina*. Patchy areas of algal binding occur throughout the mound rock.

Large organic buildups of the McKellingon Canyon Formation are cut by channels filled with coarse calcarinitic debris predominantly of echinoderm ossicles and intraclasts but also cephalopod siphuncles, trilobite debris, broken and abraded sponges, broken and abraded *Calathium* and orthid brachiopods. Some channels show crossbedded structures. The channels are no more than 0.6 meters wide and the deepest cut into the mound rock is 3.7 meters. Intraclasts are very abundant and well rounded. Channels are dark in color and have a sharp contact with the light-colored mound rock. Channel rock is classified as an intraclastic, skeletal grainstone.

The organic buildups of the McKellingon Canyon Formation rest on an intensely burrowed, dolomitized, skeletal wackestone that contains skeletal debris of echinoderm ossicles, spicules, trilobite fragments and *Nuia*, a problematic codiacean algae. Rock sequences occurring between organic buildups consist of a possibly cyclic series of thin, well-bedded carbonates that can be described as 1) dolomitized, skeletal wackestone, 2) intraclastic, gastropod packstone, and 3) intraclastic, echinoderm wackstone/packstone/grainstone. Fossils in the intermound rock are primarily small, turbinate-shaped gastropods and echinoderm debris.

The occurrence and role of *Pulchrilamina* appears to have paleoecological significance on mounds within the McKellingon Canyon Formation. Colonies of *Pulchrilamina* were only abundant and dominant at the tops of organic buildups. *Pulchrilamina* only appeared once organic buildups reached their maximum stage of development. With the occurrence and abundance of *Pulchrilamina,* organic buildups ceased to grow. Organic buildups of the McKellingon Canyon Formation are believed to have grown and developed in relatively shallow waters of the vast epicontinental sea that covered the region during Early Ordovician time. From study of Lechuguilla Mound at least six stages of growth occurred in the deposition of these organic buildups (Figure 10).

Stage I

On a foundational substrate of burrowed mud that has been dolomitized, a pioneer colony of scattered clusters or clumps of organic growth began to develop. The initial biotic community consisted of rooted echinoderms, occasional *Archaeoscyphia* sponges, scattered *Calathium* growth, clustered orthid brachiopods and sparse trilobites.

Stage II

The organic buildups enlarged and grew upward and the initial pioneer community evolved into a more diverse, biotically-mature community. Biotic associations become more varied: digitate stromatolitic colonies, algae, *Archaeoscyphia*, *Calathium*, rooted echinoderms, orthid brachiopods and problematica *Girvanella* and *Nuia*. Significantly, scattered colonies of *Pulchrilamina* entered the assemblage.

Stage III

This stage is the development of the climax community. This stage is characterized by the abundance and rise to dominance of *Pulchrilamina.* Some scattered sponges and algae are found.

During stages I to III, skeletal debris was concurrently being shed within and around the mounds. Relief of the mounds only reached a meter or less above the surrounding material.

Stage IV

Sea level changed and the mounds were subaerially exposed along their upper surfaces, terminating mound growth. This stage is only found at Lechuguilla Mound.

Stage V

Subaerial exposure as well as intertidal erosion caused cessation of mound growth and hardening of the mound surface. Intertidal erosion also created the channels.

Stage VI

A general rise in sea level resubmerged the eroded mound masses within shallow intertidal-to-subtidal waters. Deposition of skeletal calcarinite of mostly echinoderm debris and intraclasts occurred. Adjacent sediments filled in erosion-induced irregularities on and around the mounds.

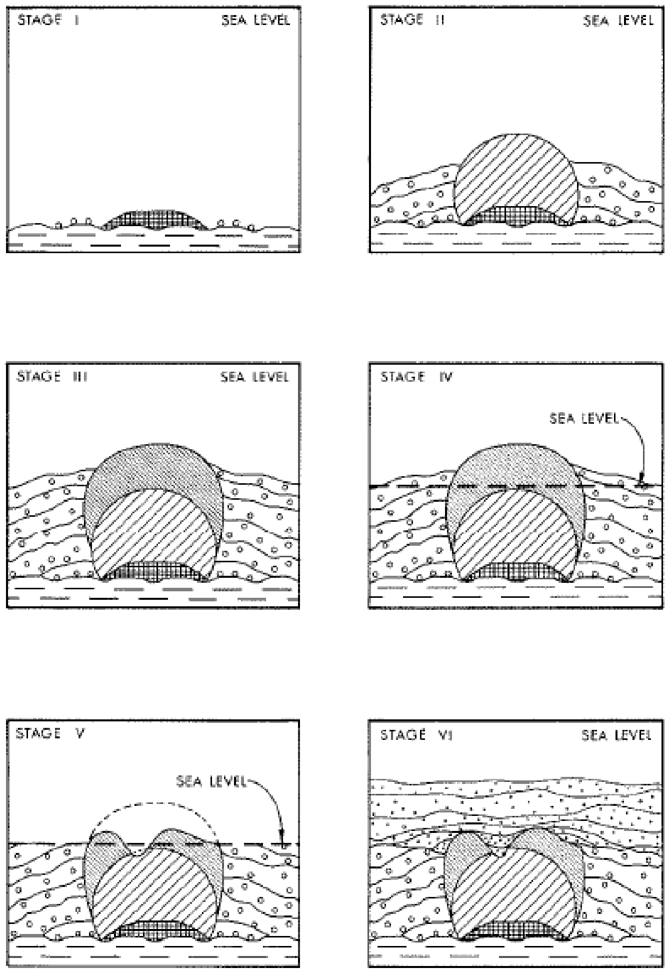

Figure 10. Diagrammatic sequence of growth stages and burial of typical McKellingon Canyon Formation organic buildups (From Toomey and Nitecki, 1979).

The Monument Spring Member is part of the Marathon Formation. The Monument Spring Member has a strong lithologic resemblance to the lower half of the El Paso Group. No organic buildups have been identified, but the member is lithologically and faunally similar to the sponge-bearing horizons common in the McKelligon Canyon Formation. The rock is a slightly silty, burrowed, intraclastic, skeletal wackestone. Dominant components are fragments of lithistid sponges and *Nuia siberica*. Other skeletal grains include sponge spicules, echinoderm osssicles, orthid brachiopod fragments, small turbinate-shaped gastropods and trilobite fragments. Stromatolitic algal structures are also found.

Within the Ellenburger Group there are the Gorman (older) and the Honeycut (younger) Formations. No bioherms have been found, but these two formations contain persistent, thin, biostromal units that have an algal-sponge biota. The Gorman Formation has sparse remains of *Archaeoscyphia* that occur in a 0.9-1.5 meter stratigraphic interval. No whole specimens of *Archaeoscyphia* have been found. The mound rock is an intraclastic, pelletal, skeletal wackestone to packstone that may locally be oolitic. Associated fossils include brachiopods, gastropods and cephalopods.

The Honeycut Formation contains abundant specimens of *Archaeoscyphia annulata* that are found in many thin stratigraphic horizons within the lower one third of the formation. Sponge beds are skeletal limestones and dolomitic limestones intercalated with non-fossiliferous limestones and dolomites. The sponge beds are classified as intraclastic, pelletal, skeletal wackestones. *Archaeoscyphia* are mostly found in the non dolomitic limestones in non growth position. Some specimens are whole, but most are broken. The average size of the sponges is 12.7-15.2 centimeters in length and 5 centimeters in diameter. Associated biota includes *Girvanella*, pelmatozoan fragments, orthid brachiopods, gastropods, cephalopod siphuncles, trilobites and conodonts.

The Ellenburger Group contains limestones that are distinctly stromatolitic. Ripple marks, intraformational conglomerates and breccias are also found in the Ellenburger Group. All of these characteristics indicate a shallow subtidal to supratidal setting. As none of the sponges are found in growth position the sponges were probably derived from relatively shallow offshore waters and later deposited within the shallow intertidal water of the Ellenburger group by breaking off of their original attachments and becoming rollers.

Within the Arbuckle Group organic buildups are common in two stratigraphic horizons. Mounds in both horizons are generally low-relief, domical features which offered refuge and sanctuary to a unique biota dominated by algae and sponges. These mounds are believed to have developed entirely within shallow marine, subtidal waters with no subaerial exposure. The lower horizon occurs 4.5-9 meters from the base of the formation and the upper horizon 137-152 meters from the base of the formation. The lower mound horizon is characterized by small mounds less than 1.5 meters in height although the largest mounds are up to 7.6 meters in height and extend laterally for more than 30 meters. The mounds have an abundance of *Archaeoscyphia annulata* associated with a few *Calathium* and stromatolitic algae. Adjacent to the mounds, on ripple-marked bedding plane surfaces, are clusters of small algal mounds termed miniherms. These miniherms are composed of laminated stromatolitic-algal material with highly burrowed surfaces up to 56 centimeters in diameter and 36 centimeters in height. The moundrock is a silty, intraclastic, skeletal wackestone to boundstone. *Archaeoscyphia* is the dominant faunal component with *Calathium* rare to absent. *Archaeoscyphia* have some coatings of encrusting problematical *Renalcis*. Other fauna include brachiopods, pelmatozoans, conodonts, cephalopods, *Girvanella* tubules, trilobite debris, small gastropods and a unique sponge spicule assemblage of monoxan, octaine, triactine, and lithistid spicules. The mounds are highly burrowed and contain some intraclasts, ropey chert, chert nodules and places of algal binding.

The upper mound horizon is characterized by massive organic buildups with an abundance of *Calathium* and *Archaeoscyphia.* Average dimensions of the organic buildups are

3 meters in height and 4.5 meters in length with the largest organic buildup 20 meters in height and 53 meters in length. The mound rock is massive with large *in situ* biotic components of stromatolitic structures, *Calathium*, *Archaeoscyphia annulata* and *Pulchrilamina spinosa*. *Calathium* specimens are often encrusted and joined to other skeletal fragments by the binding action of *Renalcis and Epiphyton.* Other faunal components include pelmatozoan debris with algal borings, *Girvanella* tubules, bryozoans, chiton plates, gastropods, brachiopods, trilobites, cephalopods, conodonts and a unique sponge spicule assemblage. Mound rock is a silty, burrowed, intraclastic skeletal wackestone/packstone to boundstone. When *Pulchrilamina* is the largest component, the rock is a boundstone. Stromatolitic structures are individual vertical stromatolite colonies up to 0.9 meters high, and in part, laterally linked. The stromatolite colonies are laminated with lamina of quartz silt grains intertwined with *Girvanella* tubules. Mounds are separated from one another by mound-shed intermound skeletal debris or well-defined channels. Channels that separate the mounds are up to 0.3 meters wide and are classified as grainstone/packstone filled mud intraclasts and varied skeletal debris. Miniherms occur on some bedding planes as in the lower mound horizon. The off mound rock is a thin-bedded limestone that lacks skeletal debris apart from scattered sponge fragments and pods of digitate stromatolite colonies. The dominant rock type is a pelletal mudstone with burrow structures. Off mound rock terminates abruptly against the organic buildups.

<u>Northwestern Russia</u>

Fedorov (2003) studied mud mounds of the St. Petersburg region in Russia (Figure 11). These mud mounds represent organic buildups that formed in cold water conditions. All previously described mounds have been formed in warm, shallow waters.

Figure 11. Schematic geological map of the St. Petersburg Region with locations of the studied Hecker-type mud mounds (From Fedorov, 2003).

The mud mounds found in this region have a calcareous-clay composition and are thought to represent a new type of mud mound termed a Hecker-type mud mound (Figure 12). Hecker-type mud mounds probably represent the oldest know Phanerozoic organic buildups in Europe.

One to two hundred meters of Early Ordovician strata accumulated in a broad structure called the Baltic monocline and rest unconformably on the eroded Precambrian shield. Early Ordovician time is represented by the Billingen Regional Stage. This stage is represented by clay in the lowermost part and, successively, glauconitic sand, calcareous sandstone and mottled, argillaceous, glauconitic limestone. Limestone strata vary from mudstone to bioclastic grainstone in the middle and upper parts of the stage and several hardgrounds are found.

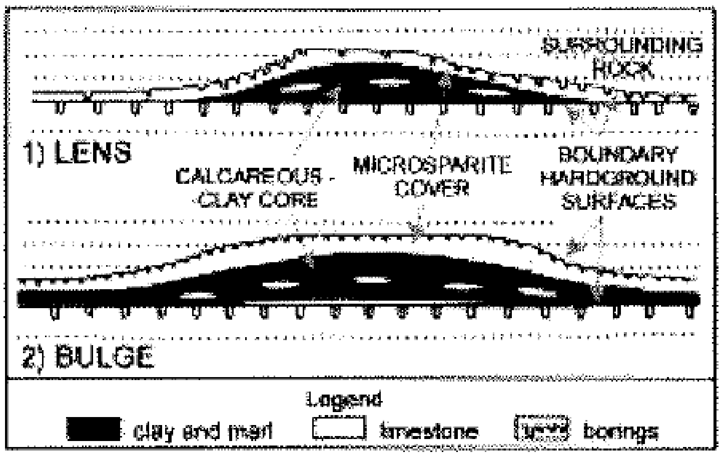

Figure 12. Schematic cross-sections of two types of the individual Hecker-type mud mounds: a lens (1) and a bulge (2) (From Fedorov, 2003).

Heker-type mud mounds can be either simple individual mounds or complex multi-story buildups. Individual mounds are subdivided by their size into small and intermediate mounds. Small mounds are round or slightly elongated in plan view, are 20-60 centimeters to several meters in diameter and have a height of 15-20 centimeters. Intermediate mounds are lens-shaped to elongated bodies that are 10s of meters in diameter and have heights of 3-5 and 10-15 centimeters. Horizontal chains of two to three small and intermediate mounds are found locally within the outcrop. Multi-story buildups are termed large mounds. These mounds may be more than 350 meters long, reach up to 2 meters in height and often completely or partially overlap in plan view.

Hecker-type mud mounds are composed of a calcareous-clay core and a fine-crystalline carbonate cap of microsparitic wackestone or mudstone covered by a hardground surface. Underlying the mounds is a limestone hardground surface. The mounds laterally thin out into beds within the surrounding succession marked by the hardground surface. The mound core is a lens-shaped body or bulge made of clay and marl with limestone lenses and nodules. Fauna of the core is dominated by small articulated brachiopods, ostracods and pelmatozoans. The carbonate caps for small and intermediate mounds, as well as the marginal parts of the large mounds are composed of microsparite wackestone. The upper carbonate caps of the large mounds are composed of microsparite mudstone. Carbonate caps on the small and intermediate mounds are 1-5 centimeters thick. Bulges, termed pseudobioherms, are 3-5 meters long and formed on top of the large mounds. Microsparite layers under the pseudobioherms are up to 65 centimeters thick and carbonate caps on the pseudobioherms are 10-15 centimeters thick. Fauna of the microsparite includes spicules of hexactinellid sponges, small ostracods, brachiopods, bryozoans and conodonts. Stromatolites occur occasionally in the microsparite of the pseudobioherms.

In the Billingen Stage three stratigraphic levels of mud mounds are recognized (L1, L2, L3) (Figure 13). Small and intermediate mounds dominate in these three stages, but large mounds are found in L2. These Hecker-type mud mounds are thought to have formed in a cold-water shield environment by dense concentrations of sessile siliceous sponges that grew on the hardground surfaces. *In situ* automicrite formation by the sponges gradually built up the mounds. Changes in sedimentation rate might have suppressed the growth of the sponge mounds. The small and intermediate mounds would have been buried by a new layer of carbonate material while the tops of the large mounds would have survived burial and continued to build, resulting in multi-story mounds. Recrystallization of the micrite resulted in the formation of the carbonate caps, which was then topped by a hardground surface.

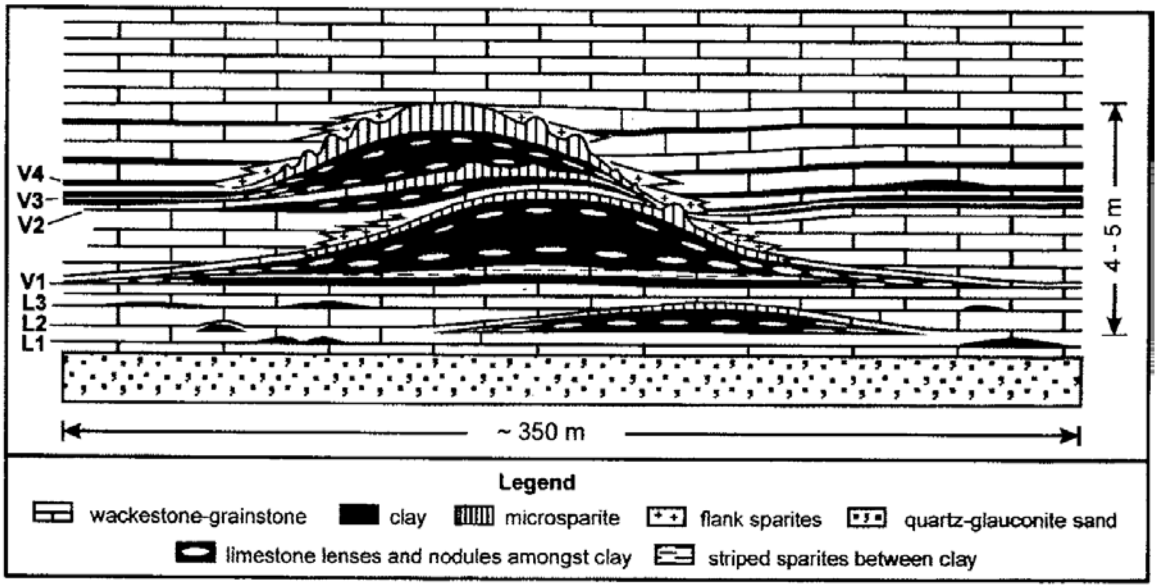

Figure 13. Schematic cross-section of complex multi-story and simple individual Hecker-type mud mounds and where they occur stratigraphically (From Fedorov, 2003).

GARDEN CITY FORMATION

Previous Work

Previous work on the Garden City Formation's paleontology, stratigraphy, and digenesis has been conducted, but little work has been done on the bioherms. Studies of the paleontology of the formation include identifying species of gastropods (Hansen, 1949), graptolites (Clark, 1935; Hansen, 1949), brachiopods (Hansen, 1949; Ross, 1951), trilobites (Hansen, 1949; Ross, 1951), conodonts (Landing, 1981; Taylor and Landing, 1981), sponges (Church, 1991), echinoderms (Gahn, 2006; Sprinkle, 2007), molluscs, bryozoans and various algae and bacteria (Berry, 1962; Stokes, 1986; Morgan, 1988). Studies of the stratigraphy have been conducted by Hansen (1949), Ross (1951), Hintze (1951, 1959, 1973), Taylor and Landing (1981), Taylor et. al. (1981a), Taylor et. al. (1981b) and Morgan (1988). Morgan (1988) also studied the diagenesis of the Formation.

Stratigraphy

The Early Ordovician time period in Utah is represented by the deposition of thick packages of limestone in a broad, shallow, passive-margin sea which deepened westward (Figure 14) (Hintze, 1973; Morgan, 1988).

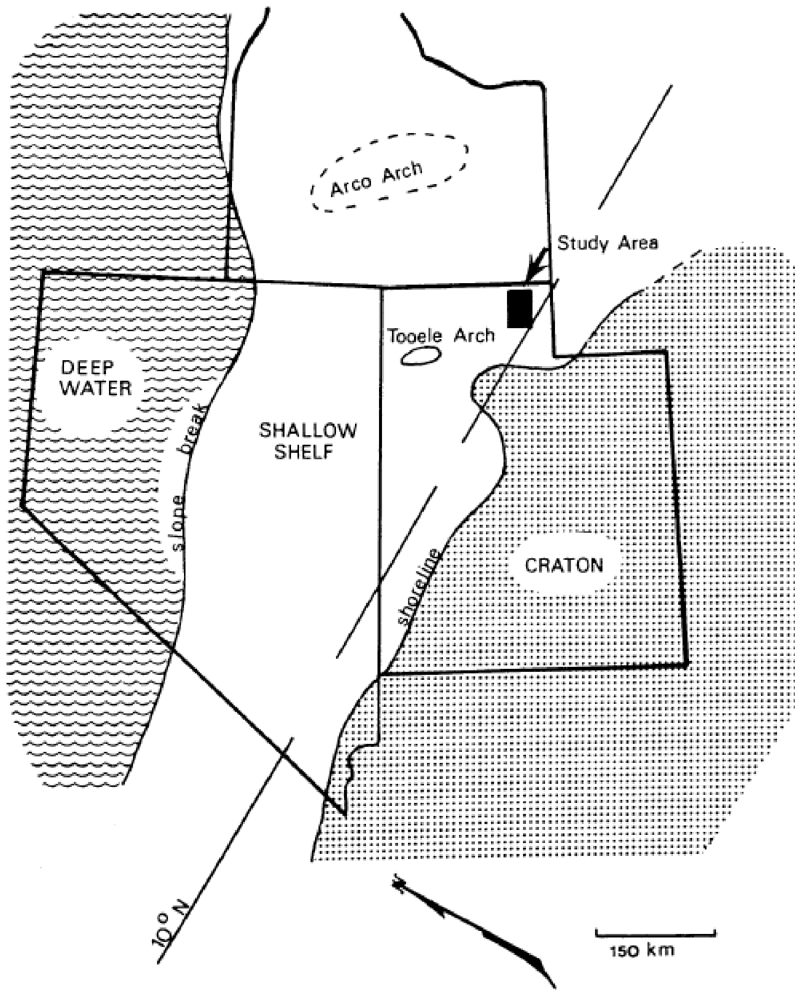

Figure 14. Positon of the slope break between deep-water and shallow-water deposition. Shoreline is at its maximum transgression. Paleolatitude and paleonorth are indicated. (From Morgan, 1988; modified form Eardley, 1964; Hintze, 1973; Scotese et. al., 1979).

The limestone that was deposited includes the Garden City Formation in Northen Utah, the Opohonga Formation in the Southern Oquirrh Mountains, and the Pogonip Group in Western Utah, which includes the House, Fillmore, Wahwah, and Juab Formations (Hansen, 1949; Ross, 1951; Morris, 1957; Rigby, 1958; Bissell, 1959; Schaeffer, 1960; Hintze, 1973; Morgan, 1988). These limestones are fossiliferous, have abundant patches and lenses of intraformational conglomerate, contain high proportions of fine, silty particles and have a high percentage of chert (Stokes, 1986). Pogonip Group terminology is used for the Ibex Basin of southwestern Utah and Garden City Formation terminology for the Northern Utah Basin (Hintze 1959, 1973). In the Early Ordovician the orthogeosyncline of Cambrian time was beginning to subside into the miogeosyncline and shelf on the east and the eugeosyncline farther west (Bissell, 1959). The miogeosyncline was divided into two subbasins by the positive feature of the Tooele Arch (Figure 15).

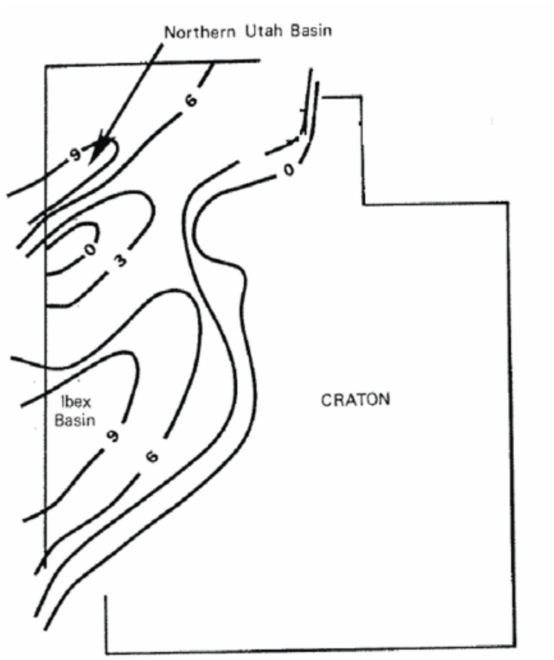

Figure 15. Garden City-Pogonip Group thickness in 100's of meters. Utah is widened to pre Cretaceous thrust faulting (From Morgan, 1988; modified from Hintze, 1973).

The deposition of the limestone was controlled by the gradually subsiding Northern Utah Basin and Ibex Basin and the gentle uplifting of the Tooele Arch (Figure 16) (Hintze, 1959, 1973; Morgan, 1988). The limestones thin to the southeast and thicken to the northwest, suggesting that the shoreline was to the south and east and that the area lay to the east of the axis of the Cordilleran geosyncline (Ross, 1951; Morgan, 1988).

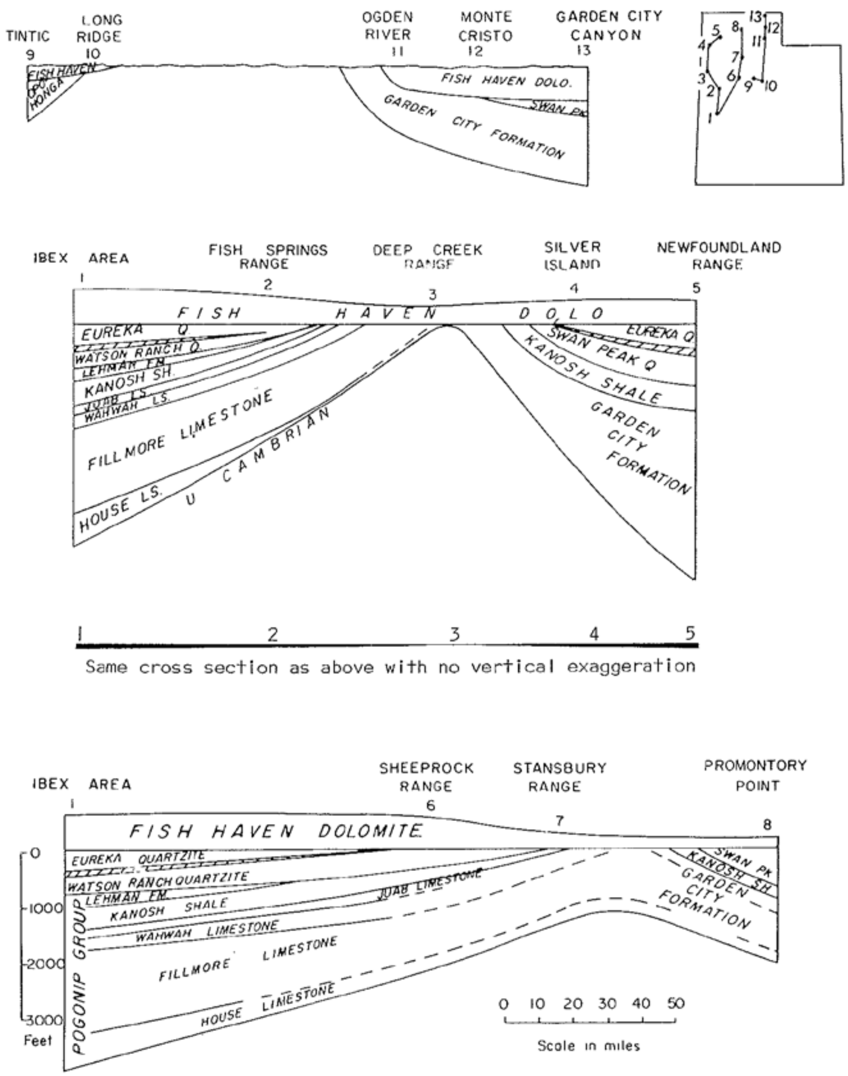

Figure 16. Ordovician cross-sections across the Tooele Arch (From Hintze, 1959).

The Garden City Formation lies disconformably on the St. Charles Formation (Taylor and Landing, 1981; Taylor et. al., 1981a; Taylor et. al., 1981b) and has an abrupt upper contact with the Swan Peak Formation (Morgan, 1988). The Garden City Formation outcrops from north-central and western Utah to southeastern Idaho (Morgan, 1988) (Figure 17) and ranges in thickness from 322 meters in the east to 549 meters in the west (Hansen, 1949).

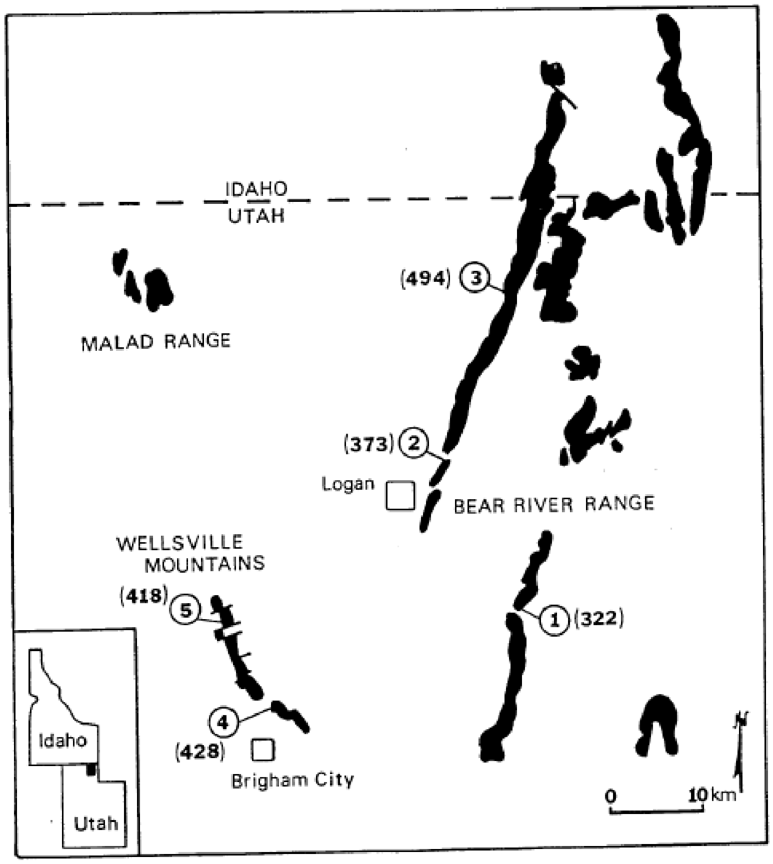

Figure 17. Outcrop pattern of the Early Ordovician Garden City Formation in north-central Utah. Circled numbers show locations of Morgan's measured sections. Numbers in parentheses are thicknesses in meters (From Morgan, 1988; modified from Ross, 1951).

The Formation terminates to the east at the Green River Basin, which represents the location of the craton (Hintze, 1951; Williams, 1955). The Garden City Formation is informally divided into two members, the Lower Member and the Upper Cherty Member (Figure 18). The Lower Member is dominantly composed of intraformational conglomerate while the Upper Cherty Member is dominantly composed of irregularly-laminated, very cherty limestone (Hansen, 1949; Ross, 1951; Rigby, 1958; Schaeffer, 1960).

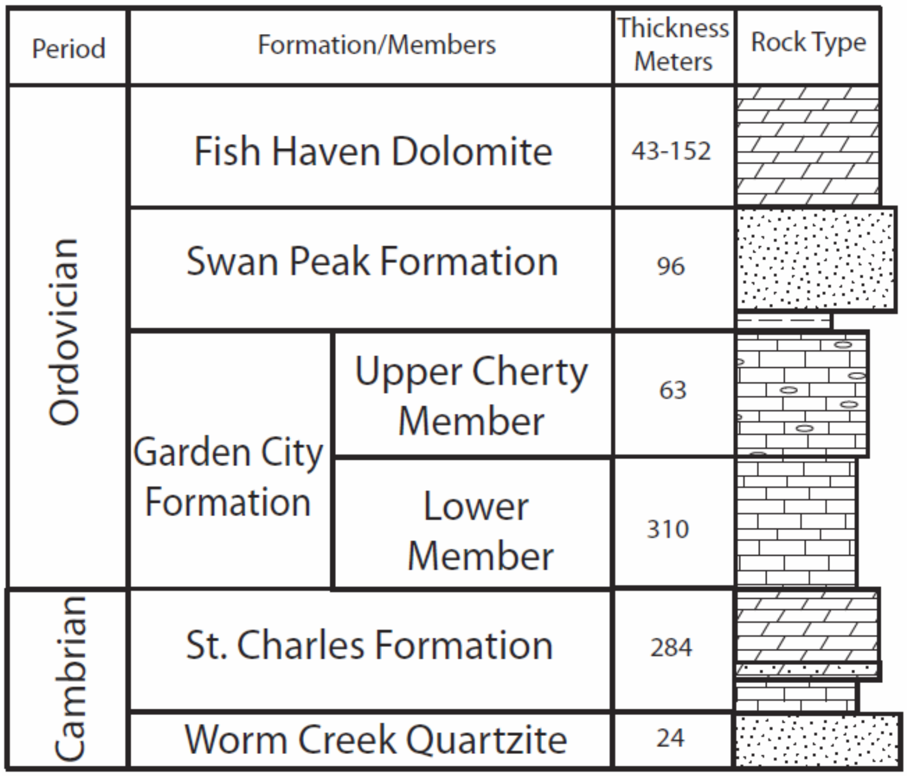

Figure 18. Stratigraphic Column of the Bear River Range (after Ross, 1951 and Hintze, 1973).

In general, the first 20 centimeters to 5 meters of the Lower Member is dolomitized (Taylor et. al., 1981a). The dolomite is an argillaceous, arenaceous, calcareous dolomite (Schaeffer, 1960). The top boundary with the Swan Peak Formation is commonly marked by a dolomitized limestone above which lies 46 meters of silty and shaly beds (Ross, 1951).

Morgan (1988) measured five sections of the Garden City Formation. The measured sections are located in Blacksmith Fork Canyon, Green Canyon, High Creek Trail, Mantua, and Cottonwood Canyon. Figure 19 shows a stratigraphic section compiled from the five measured stratigraphic sections of Morgan's (1988) study. Morgan (1988) divided the formation into nine different lithofacies as described in the following paragraphs.

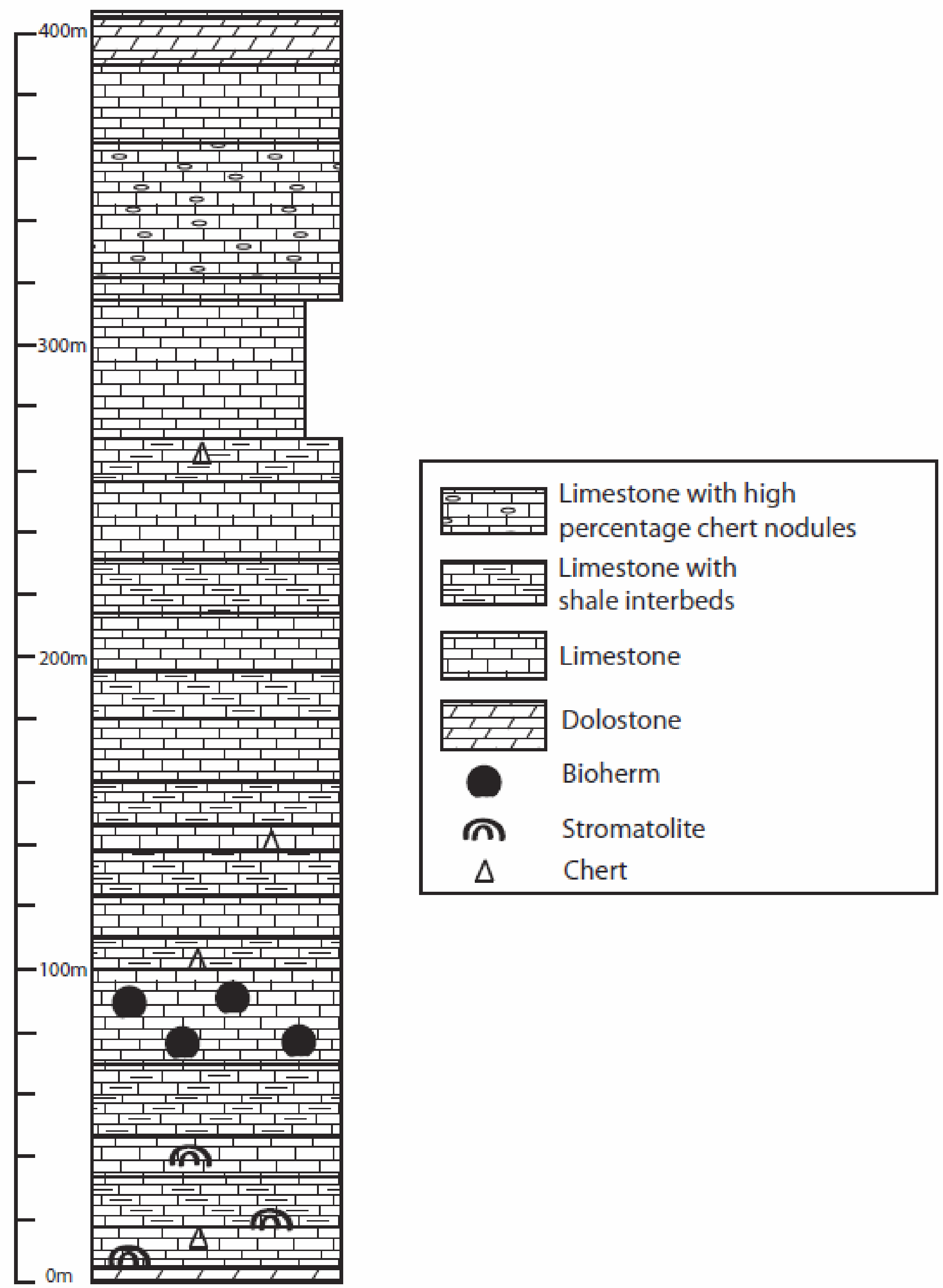

Figure 19. Stratigraphic Column of the Garden City Formation (modified from Morgan, 1988).

Nodular Wackestone/Mudstone with Packstone Lenses

The 'nodular wackestone/mudstone' lithofacies is composed of a very quartz-rich silty limestone, sedimentary boudinage, nodular limestone punctuated with lenses of planar-laminated hummocky cross-stratified and occasionally ripple-laminated limestone. Minor fossils of trilobites, pelmatozoans, sponge spicules, lingulid brachiopods and peloids, both whole and fragmented, occur as lag deposits. Horizontal and vertical burrows are found filled with pellets. This rock type is interpreted to be deposited within a shallow subtidal, low energy environment that was affected by hurricane-velocity storms. No evidence suggests subaerial exposure.

Intraclastic Packstone/Grainstone

Intraclasts are the dominant allochem in the 'fossiliferous packstone/grainstone' lithofacies matrix. Intraclasts are composed of micrite, fossiliferous quartz-laminated packstone, fossiliferous packstone/wackestone, peloid-laminated packstone and are bladed to blocky and well rounded to subangular. The matrix is composed of brachiopods, pelmatozoans, gastropods, mollusc shells, trilobite debris, *Nuia* and peloids. This lithofacies is a storm-influenced deposit affected by a strong current followed by a waning current.

Green Shale

The 'green shale' lithofacies is a calcareous to clayey grayish, olive-green shale interbedded in layers of 1-30 centimeters within nodular limestone. This shale is interpreted to be deposited in a near-costal shallow sea environment with a terrigenous source.

Laminated Packstone/Grainstone

Well sorted pelmatozoan fragments and peloids comprise the rock. Minor amounts of intraclasts, lingulid brachiopods and trilobite fragments are found scattered throughout. The rock is very thin to thin bedded, planar-laminated to hummocky cross-stratified, graded and forms as either lenses within nodular limestone or as a separate unit. Deposition has been interpreted to be by waning storm currents.

Cryptalgalaminite

'Cryptalgalaminites' are a rare lithofacies that form within nodular limestones. The lithofacies is recognized only in the High Creek Trail section. This lithofacies forms successive cryptalgally-laminated layers 2.5-16 centimeters thick. 'Cryptalgalaminites' are interbedded with unaltered intraformational conglomerates. The lithofacies contains stromatolites which are dissected by vertical burrows. A possible teepee structure and a clastic dike are present. Deposition is interpreted to be due to sediment binding by algae and bacteria as intertidal shoals within the subtidal zone.

Fragmented Fossiliferous Packstone and Whole Fossil Fossiliferous Packstone

Biota includes pelmatozoans, trilobites, *Nuia*, gastropods and other molluscs, brachiopods and bryozoan fragments. The 'fragmented fossiliferous packstone' lithofacies is composed of fragmented skeletal material and intraclasts with local planer laminations and hummocky cross-stratification. The 'whole fossil fossiliferous packstone' lithofacies is composed of primarily whole, unsorted fossils and uncommon intraclasts. The 'fragmented fossiliferous packstone' lithofacies was deposited in a shallow subtidal environment and represents local agitated shoal conditions on the shelf. The 'whole fossil fossiliferous packstone' lithofacies separates the inner and outer shelf and occurred below normal wave-base, but was still affected by storm wave-base.

Boundstone

The 'boundstone' lithofacies is comprised of mud mounds and stromatolites that recur vertically with varying thickness. The mud mounds are mushroom to domal shaped, 15-76 centimeters in diameter and 13-71 centimeters in height. Differential weathering reveals their three-dimensional shape as tubular. Some are coalesced to form sheets and the mounds are generally grouped along the same horizon. The mud mounds have a massive to rare, faintly-laminated fabric. Internally the mud mounds contain very few, scattered fossils that include *Nuia*, sponge spicules and pelmatozoan fragments in a micrite matrix. A lower algal mat layer is overlain by spongiform and clotted fabrics. This colonization sequence is similar to that of Ordovician mounds elsewhere in Utah (Church, 1974). A nodular limestone pinches out against, and drapes over most of the mud mounds. The mud mounds may have grown from a nodular limestone or an intraclastic substrate. A small portion of the mounds are surrounded by the 'fragmented fossiliferous packstone' lithofacies. At each location a horizon of mud mounds is cut by channels filled with fossiliferous packstone. There is a sharp boundary between the mud mounds and the channel rock. The mud mounds do not display much lateral continuity. From the five sections measured two to five mud mound horizons were found in each section. The horizons occurred within the first 55-120 meters of the formation except for one that occurred 16.7 meters from the base of the formation in the Blacksmith Fork Canyon section.

Float associated with the mud mounds includes isolated, stacked-hemispheroidal stromatolites. Stromatolite morphology suggests that they may have grown on top of the mud mounds and extended into shallower, more turbulent water. Stromatolites also occur at the base of the Mantua section and are associated with cryptalaglaminites in the High Creek Trail section. Stromatolites and mud mounds are interpreted to have grown in shoal conditions within the shallow subtidal zone. Their patchy distribution indicates that their formation is dependent on local conditions. Tabular mound shapes indicates that they formed parallel to the shore. Mounds cut by channels may indicate a relative drop in sea level.

Calathium/Sponge

'Calathium' are associated with lithistid sponges. '*Calathium'* are rare and scattered randomly throughout sections and increase in abundance just below the chert zones in the upper part of the formation. In the High Creek Trail section this lithofacies forms a prominent unit 3.3 meters thick. Deposition of this "Calathium-sponge' lithofacies occurred seaward of skeletal accumulation in a low energy, deeper, below normal wave-base environment.

Burrowed Fossiliferous Wackestone/Packstone with Chert

Whole and fragmented fossils, rare intraclasts and peloids are disseminated throughout a stylolitic wackestone by bioturbation. The fossil assemblage is high in variability and low in abundance of types. The upper 33-45 meters are dolostone with bands and blebs of sparite. This lithofacies comprises the entire upper informal cherty member with black, gray and white chert comprising a maximum of 40-50% of the rock with nodular, banded and anastomosing chert. This lithofacies was deposited in a deeper subtidal environment below normal and most storm wave-bases and in local reducing conditions.

These lithofacies represent a strom-influenced sequence that was deposited in both intershelf shallow subtidal and outershelf deep subtidal enviornments, below mean wave base but above stom wave base (Morgan, 1988). The base of the formation, above the dolostone, contains reworked material of the 'laminated packstone/grainstone', 'intraclastic packstone/grainstone' and 'nodular wackestone/packstone' lithofacies approximatly 30 meters thick. These lithofacies are not developed extensivly nor do they appear to have a specific sequence relationship to each other. The 'nodular limestone' lithofacies was deposited on the reworked material and outcrops for approximatly 18-42 meters. Above the 'nodular limestone' lithofacies the 'fragmented fossil packstone' lithofacies was deposited for 18-48 meters and bioherms were formed after which the ‘nodular limestone’ lithofacies was deposited for 140-200 meters. The ‘whole fossil packstone’ lithofacies was deposited for 18-36 meters and in the north the ‘Calathium’ lithofacies formed. On top of this, the ‘burrowed wackestone’ lithofacies was deposited for 70-90 meters and a high percentage of chert formed. The upper 15-50 meters of the Garden City Formation are dolomitized before an abrupt contact with the Swan Peak Formation. Figure 20 shows a diagram of the lithofacies relationships and Figure 21 shows lithofacies relationships and environments.

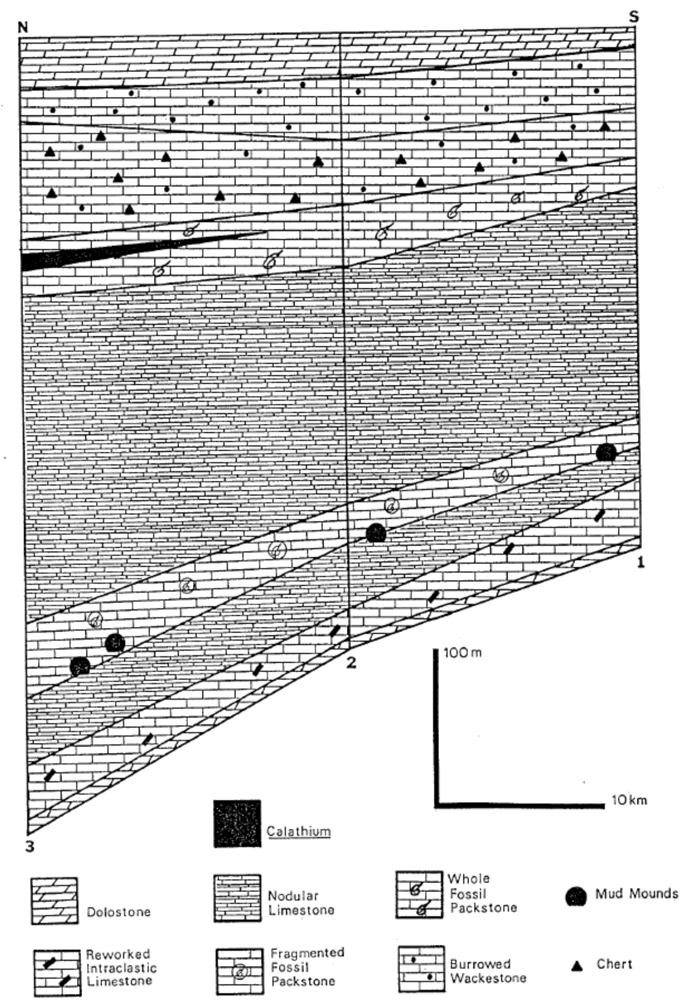

Figure 20. Generalized north-south cross-section of the Garden City Formation using Morgan’s measured sections (From Morgan, 1988).

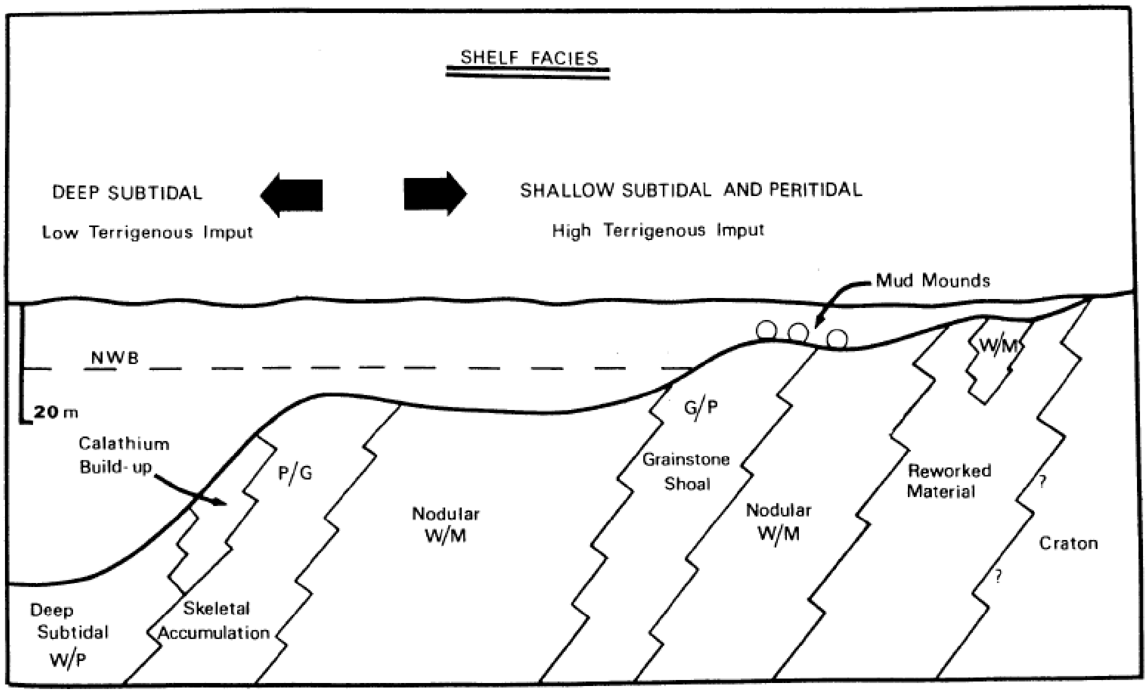

Figure 21. Schematic diagram of the Garden City lithofacies relationships and environments. Symbols used are: W-wackestone, M-mudstone, P-packstone, G-grainstone, NWB-normal wave base (From Morgan, 1988).

Biota

Gahn (2006) and Sprinkle (2007) have conducted studies of echinoderm evolution and ecology in which at least 33 species of crinoids, eocrinoids, edrioasteroids, rhombiferans, asteroids, mitrates and cornutes have been found in the Garden City Formation on bioherms in Boss Canyon, Utah. These species add significantly to the known diversity of earliest Ordovician echinoderms and have the potential to revel important information about their evolutionary and ecological history, making the Garden City Formation an important point in time for the evolution of echinoderms.

The enigmatic *Calathium* sponge, but possibly receptaculitid (Church, 1991), is found scattered throughout the formation and is often associated with lithistid sponges (Morgan, 1988). Church (1991) conducted a study of calithids found in the Fillmore Formation where he found that calithids had holdfasts and an open upper end leading to the central cavity; they had porous inner and outer walls and the merom outer plates had not been preserved. In the same study Church (1991) stated that the morphology of the calithids studied indicates a structure suitable for water circulation similar to that found in filter-feeding organisms such as sponges.

Clark (1935), Williams (1948) and Ross (1951) identified graptolites from sections of the Garden City Formation in Logan Canyon. Graptolites were found mostly from the lower part of the formation. Seven genera were identified with dendroid graptolites being the most common.

Ross (1951) identified more than eighty species of trilobites, representing twenty-four genera. The trilobites and brachiopods were used to identify twelve faunal zones (A-L) within the formation and were arranged according to their geologic age. As defined by these faunal zones the upper part of the formation is assigned to the Chazyan Epoch; the Canadian-Chazyan boundary occurs between Zones K and L; lower beds (zones A-D) are Gasconade in age

Landing (1981) studied conodonts of the Upper Cambrian St. Charles Formation and Early Ordovician Garden City Formation. The study incorporated conodont and trilobite faunal zones which allowed the contact between the two formations to be defined as a disconformity. Up to 12 meters of erosion of the St. Charles Formation occurred before deposition of the Garden City Formation.

Other biota in the formation includes ostracods, gastropods, cephalopods, bivalves, bryozoans and various algae and bacteria (Stokes, 1986).

BIOHERMS OF BOSS CANYON

Location of Study Area

The Garden City Formation bioherms are best exposed in Boss Canyon (UTM: 445559 m E, 4649849 m N WGS84). Boss Canyon is located on the western flank of the Bear River Range in T16S, R41E, Egan Basin, ID 7.5' quadrangle, 1969, Sec. 26, T16S, R41E, Mapleton, ID 7.5' quadrangle, 1969, and T15 N R41E, Naomi Peak, UT 7.5' quadrangle, 1969 (Figure 22).

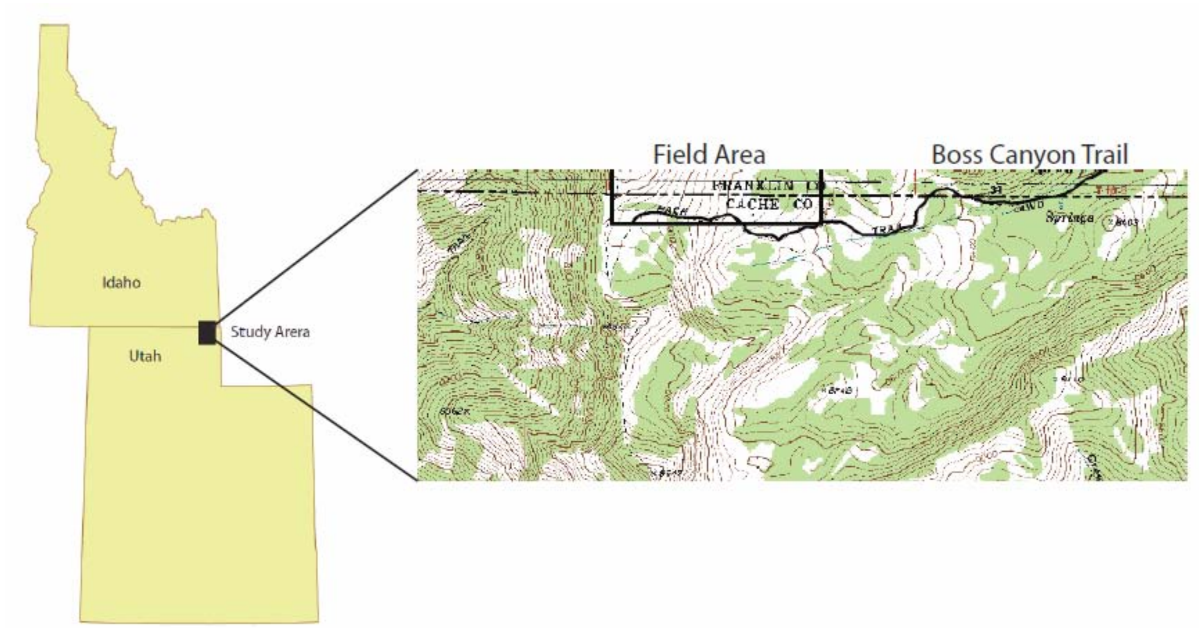

Figure 22. Location of Study Area in Naomi Peak quadrangle (U.S. Geological Survey, 1969).

The lower 55 meters of the Garden City Formation are not exposed in Boss Canyon and the lowest observable part of the Formation present starts at the bioherm horizon. This unit occurs 55-120 meters from the base of the formation (Morgan, 1988). This lower bioherm horizon lies in the Naomi Peak quadrangle while the Garden City Formation also outcrops in the Mapleton, Idaho quadrangle. Up section at least two other bioherm horizons occur, although these bioherms are not as large as those found in the lower bioherm horizon. In the lower bioherm horizon, the bioherms are weathering out in relief and their topography is similar to what it would have been on the sea floor during the Early Ordovician (Figure 23).

Figure 23. Field study site in Boss Canyon, Utah. Individual bioherms can be distinguished.

Methods

In order to study the bioherms, measurements, samples and pictures were taken from the bioherm horizon of the Garden City Formation in Boss Canyon. Weather was a limiting factor on fieldwork and data collection. Height, length, width and orientation data were taken on twenty-six mounds. The bioherms were chosen randomly to avoid bias toward certain bioherm shapes and dimensions. Measurements were taken with a BOSCH DLR130 Distance Measurer. Orientations were taken on the long axis of the mounds using a Brunton compass. Pictures were taken to characterize the bioherms and the fossils contained on and near the bioherms. Sample collection was aimed toward characterizing the five rock types associated with the bioherms horizon. These rock types include the rock the bioherms were established on, two different rock types that onlap onto the bioherms, the bioherms themselves and the overlying rock. Samples were taken of the first four of these five rock types as well as from the top, middle and bottom of the bioherms to characterize how the bioherms changed over time. Samples were collected randomly within these lithologies. Samples were used to better describe the rock types in the bioherm horizon and to make 30 thin sections. Thin sections were point counted with 300 points which were used to characterize the biota and sediment contained in the bioherms.

Bioherm Characteristics

The bioherms are in general 0.5-1.5 meter in height, 1-8 meters in width, and 2-16 meters in length. Orientation of the bioherms is on average 45˚ relative to north, which is similar to the 31˚ orientation of the bioherms in Western Utah (Church, 1974). These bioherms were likely oriented parallel to the trend of the Early Ordovician shoreline. The five distinct rock unit types that occur in the bioherm horizon are termed the basal unit, the onlap unit, the intraclastic unit, the bioherm unit and the overlying unit (Figure 24).

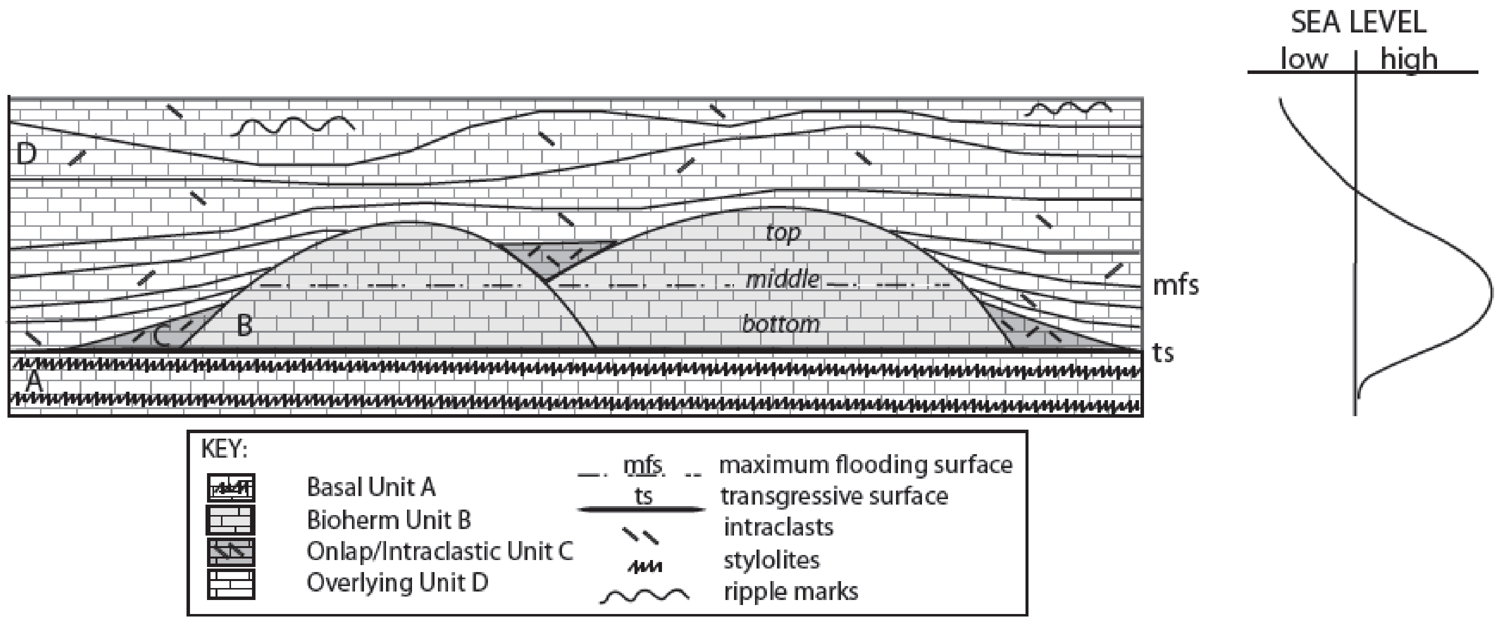

Figure 24. Relationships of the rock units and their correlation to sea level.

<u>Rock Unit Types</u>

Basal Unit

This rock type is a light gray, bioturbated, highly dolomitized, pelletal wackestone with sparse trilobite fragments, *Nuia* and quartz silt grains (Figure 25). The rock is highly stylolitic with the stylolites weathering out tan. During deposition the stylolites were thin layers that were probably higher in silt content. The stylolites have been replaced with dolomite. This unit may have been deposited in a deeper water setting as indicated by the low diversity of fossils and lack of Intraclasts.

Figure 25. Basal unit overlain by bioherm unit.

Onlap Unit

The onlap unit is composed of a dark gray, partially crystalline, dolomitized mudstone with pellets, intraclasts and quartz silt grains (Figure 26). Fossils can be seen in thin section and in hand specimen. Fossils include brachiopod and trilobite fragments, crinoid stems, gastropods, nautiloids, ostracods, sponges, *Calathium*, algae and *Nuia*. This unit is deposited on the basal unit and onlaps up onto the bioherm unit. This unit also occurs in channels between the bioherm unit (Figure 27). This unit was deposited in a shallow water environment, above normal wave base, as indicated by the high diversity of fossils and intraclasts.

Figure 26. Onlap unit deposited up against bioherm unit.

Figure 27. Channels between the bioherm unit filled with the onlap unit.

Intraclastic Unit

The intraclastic unit occurs within the onlap unit. The matrix is a dark gray while the intraclasts are a light gray. The unit is a partially dolomitized, intraclastic wackestone with sparse trilobite fragments, *Nuia* and quartz silt grains (Figure 28). Intraclasts are elongate, rounded to sub-rounded, composed of pelletal micrite and have dimensions of 3-15 millimeters and 2-7 millimeters. This unit was deposited in a shallow water environment, above normal wave base, as indicated by the high percentage of Intraclasts.

Figure 28. Intraclastic unit deposited within onlap unit.

Bioherm Unit

This unit consists of light gray mudstone and algal wackestone with a pelletal micrite matrix (Figure 29). Some of the unit is partially to highly dolomitized and can be partially crystalline. Biota in the bioherm unit includes sponges, *Calathium*, trilobite fragments, brachiopods, gastropods, ostracods, echinoderms, algae and *Nuia. Nuia* may be the source of some of the pellets (Morgan, 1988). The unit is weathering out in relief. Bioherms include thrombolites and stromatolites. The bottom of the bioherm unit contains the algal wackestone while the top of the bioherm unit contains sponges and *Calathium*. Fossils of sponges, *Calathium*, echinoderms, trilobite fragments and gastropods can be seen on the bioherm surfaces. This unit was deposited in a shallow water environment, above normal wave base, as indicated by the formation of the bioherms themselves.

Figure 29. Top surface of the bioherm unit.

Overlying Unit

The overlying unit was not studied in detail with thin sections but the unit was studied in the field. This unit is a medium gray limestone and has strong evidence for being deposited in a high-energy environment, proximal to the shore, as it contains intraclasts, ripple marks and dune features (Figure 30).

Figure 30. A sink hole displaying some of the rock unit types. The bioherm unit is the light gray rock in the picture and the overlying unit is the medium gray limestone on top. Notice the dune shape of the overlying rock indicating a high-energy, shallow environment.

Stratigraphy

From the five rock unit types and their spatial relationships, relative sea level can be determined (Figure 24). The basal rock unit represents a time of moderate sea level, with the top surface of the basal rock unit signifying a transgressive surface. The bioherm unit corresponds to a time of rising sea level. Within the bioherm unit a maximum flooding surface occurs signaling the shift from a transgression to a regression. This regression is represented by a shallowing upward package from the bioherm unit through the overlying unit. Together these five rock unit types most-likely represent a few tens of thousands of years.

Paleoecological Setting

When the basal unit was deposited trilobites and algae dominated the biota. As sea level transgressed conditions allowed for the formation of the bioherm unit. The main frame builders of these bioherms were algae (Figure 31), *Calathium* (Figures 32, 33, 34) and sponges (Figures 35, 36).

Figure 31. Two stromatolites within the bioherm unit.

Figure 32. Longitudinal view of *Calathium* on the bioherm unit. Notice how the *Calathium* is narrower at the bottom then the top.

Figure 33. Surface view of *Calathium* growing on the onlap unit.

Figure 34. Longitudinal view of part of a *Calathium* specimen on the bioherm unit. Notice the mesh network.

Figure 35. Two sponges growing on the bioherm unit.

Figure 36. A sponge growing on the bioherm unit.

During the Early Ordovician, when the shallow, passive-margin sea covered the area, water conditions allowed algae to stabilize the substrate of the basal unit. The algae began to trap and bind sediment making favorable conditions for other biota to live in the area. Sponges and *Calathium* joined the algae and, acting as baffles, trapped sediment, building up the bioherms. Other organisms, such as trilobites, brachiopods, echinoderms, gastropods (Figure 37), ostracods and nautiloids (Figure 38) found at the site, form the group of accessory organisms that found the bioherms a favorable environment to live on and around. As the bioherms grew they shed sediment that was deposited adjacent to the bioherms, forming the onlap unit. The environment was of a higher energy as observed by the intraclastic unit.

Figure 37. A gastropod on the onlap unit. Several centimeters in diameter.

Figure 38. Straight shelled nautiloids seen on the onlap unit.

Higher energy conditions and a shallower sea level caused the bioherms to cease growth as sea level continued to regress and the overlying unit was deposited.

DISCUSSION

Warm, shallow-water organic buildups of the Early Ordovician were biotically relatively simple. The main frame-building organisms were lithistid sponges, *Calathium* and algae. Lithistid sponges and *Calathium* acted as baffles, trapping sediment while algae acted as the binding organism. Accessory organisms included brachiopods, cephalopods, trilobites, echinoderms, gastropods, ostracods, algal remains and conodonts.

The organic buildups were relatively small-scale structures that never attained appreciable height above the sea floor substrate. Formation of organic buildups was dependent on local conditions. Organic buildups were typically 1-3 meters in height, several meters in width, with length variable, depending on location. Some organic buildups did attain appreciable size. The largest organic buildup, 20 meters in height and 53 meters in length, is found in the Arbuckle Group in Oklahoma. Organic buildup extent was dependent on the local conditions where the organic buildups were formed. Some organic buildup horizons extend for hundreds of meters, as in western Utah, while others had a limited lateral extent, a few 10s of meters, as in Northern Utah.

Organic buildups are generally massive to faintly laminated and are composed of mudstone to wackestone to packstone and boundstone limestone. Large *in situ* organisms are found on the organic buildups, while internally they are found as skeletal components. Small stromatolite structures are found associated with the organic buildups. Mound rock is generally light colored and has a sharp contact with off-mound, darker-colored limestone. The intermound rock is generally thin bedded and is composed of skeletal packstone to grainstone, except in the Garden City Formation where it is a partially crystalline mudstone to intraclastic wackestone with skeletal components. Intraclasts are the most common non skeletal component. Channels dissect the organic buildups. Channels are less than a meter wide and can be several meters deep. Packstones fill the channels in some formations and, in the Garden City Formation, partially crystalline mudstones fill the channels. Limestones lie above and below the organic buildup horizons except in western Utah where shales lie above and below. These organic buildups grew in shallow-water conditions, much like those of the present day Bahama Banks.

Cold-water organic buildups from Russia differ from warm-water organic buildups by their general morphology. These cold-water organic buildups have a calcareous-clay composition. The mound core is composed of clay topped by a carbonate cap and overlain by a hardground surface. The mounds are several meters long and generally less than half a meter in height. Formation of the organic buildups was by dense concentrations of sessile siliceous sponges. Accessory organisms included brachiopods, echinoderms, ostracods, pelmatozoans, bryozoans and conodonts.

SUGGESTIONS FOR FUTURE WORK

Additional studies that need to be conducted on Early Ordovician Organic buildups include identifying organic buildups on other parts of the Laurentia and Siberia continents as well as other land masses of the Early Ordovician to better characterize organic buildups of this time period.

Additional studies that need to be conducted on the Garden City Formation and the bioherms include a study on the sequence stratigraphy of the formation. A sequence stratigraphic study would identify other bioherm horizons and allow for the understanding of how the bioherms changed over time and what is controlling their formation and cessation of growth. Further study needs to be conducted on the lower bioherm unit exposed in Boss Canyon. Individual bioherms need to be mapped in order to understand their spatial distribution and extent. Mapping could be conducted using an RTK unit or remotely-sensed imagery. A more in-depth study on the biota contained in and on the bioherms needs to be conducted as this study was limited by field weather conditions.

CONCLUSIONS

Organic buildups of the Early Ordovician had very similar characteristics although some were formed in warm shallow waters and others in cold waters. The main frame building organisms of organic buildups consisted of algae, lithistid sponges and *Calathium* in present day North American while in Russian they consisted of sessile sponges. The organic buildups provided a favorable environment for a diverse assemblage of accessory organisms that included brachiopods, ostracods, echinoderms, gastropods, cephalopods and trilobites. Most organic buildups were relatively small structures that never attained appreciable height above the sea floor. Variations between organic buildups occurred between formations as organic buildup growth and development was dependent on local conditions.

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APPENDICIES

APPENDIX A

Bioherm Measurements

Taken from randomly-chosen bioherms within the bioherm horizon in Boss Canyon.

Height (m)	Length (m)	Width (m)	Orientation (° relative to north)	Type
0.92	6.77	3.68	~	Complex
0.57	2.60	2.20	45	Single
0.62	2.23	1.68	45	Single
1.27	7.10	5.21	50	Complex
1.27	3.54	2.46	40	Single
0.72	2.79	1.36	55	Single
1.62	16.3	7.98	~	Complex
1.30	5.17	2.74	45	Complex
1.22	2.43	1.69	30	Single
1.47	6.32	2.74	10	Single
1.02	8.27	4.83	5	Complex
1.20	2.35	1.53	50	Single
1.62	11.24	5.35	55	Complex
0.90	2.08	1.18	50	Single
0.32	2.81	1.97	~	Single
0.62	2.66	1.51	40	Single
1.12	3.1	1.59	40	Single
0.92	1.66	1.15	45	Single
0.82	2.13	1.56	40	Single
1.02	1.74	1.17	45	Single
0.79	2.48	1.50	35	Single
1.52	2.37	1.94	50	Single
1.07	2.89	2.04	40	Single
0.52	2.58	1.43	55	Single
0.57	1.94	0.90	50	Single
1.42	12.7	3.12	35	Complex

APPENDIX B

Point Count Data

See Appendix C for the location within the bioherm horizon thin sections were collected from.

Allochems	**BC 1**	**BC 2**	**BC 3**	**BC 4**	**BC 5**	**BC 6**
Matrix	105	141	235	199	207	287
Stylolite	0	0	4	0	10	2
Echinoderm	1	0	0	0	0	1
Brachiopod	3	1	1	0	0	1
Gastropod	3	2	0	0	0	0
Trilobite	8	17	0	2	2	4
Algae	0	1	0	0	0	0
Intraclast	0	0	4	90	0	0
Pellet	0	12	0	0	71	0
Nuia	2	5	5	2	8	2
Quartz Silt	1	1	0	2	2	1
Sponge Spicule	0	0	0	0	0	0
Sponge	0	0	15	0	0	0
Ostracod	0	0	0	0	0	0
Blocky Calcite Pore Fill	2	0	0	0	0	1
Blocky Calcite Recrystallization	175	120	36	5	1	1

Allochems	**BC 7**	**BC 8**	**BC 9**	**BC 10**	**BC 11**	**BC 12**
Matrix	289	287	267	264	292	293
Stylolite	5	5	5	0	1	4
Echinoderm	0	2	0	0	0	0
Brachiopod	0	0	0	0	0	0
Gastropod	0	0	0	0	0	1
Trilobite	1	1	1	0	1	1
Algae	0	0	0	31	0	0
Intraclast	0	0	0	0	0	0
Pellet	0	0	0	0	0	0
Nuia	0	1	0	0	1	0
Quartz Silt	2	3	1	5	2	1
Sponge Spicule	0	0	0	0	0	0
Sponge	0	0	0	0	0	0
Ostracod	0	0	0	0	0	0
Blocky Calcite Pore Fill	2	0	0	0	0	0
Blocky Calcite Recrystallization	1	1	26	0	3	0

Allochems	BC 13	BC 14	BC 15	BC 16	BC 17	BC 18
Matrix	278	281	292	293	294	179
Stylolite	5	7	4	3	0	0
Echinoderm	2	1	0	1	1	0
Brachiopod	0	0	0	0	0	1
Gastropod	2	0	0	0	0	0
Trilobite	1	2	1	2	1	1
Algae	0	0	0	0	0	0
Intraclast	0	0	0	0	0	0
Pellet	0	0	0	0	0	0
Nuia	2	0	0	0	1	0
Quartz Silt	2	1	1	1	1	0
Sponge Spicule	1	0	0	0	0	0
Sponge	0	0	0	0	0	113
Ostracod	2	0	1	0	0	0
Blocky Calcite Pore Fill	0	0	0	0	0	0
Blocky Calcite Recrystallization	5	2	1	0	2	6

Allochems	BC 19	BC 20	BC 21	BC 22	BC 23	BC 24
Matrix	268	286	283	294	171	295
Stylolite	1	8	1	0	4	0
Echinoderm	0	1	0	0	1	0
Brachiopod	0	0	0	0	5	0
Gastropod	0	0	0	0	25	0
Trilobite	2	1	1	1	3	1
Algae	8	0	0	4	0	0
Intraclast	0	0	0	0	0	0
Pellet	0	0	0	0	0	0
Nuia	0	1	0	0	2	0
Quartz Silt	6	1	1	1	0	0
Sponge Spicule	0	0	0	0	0	0
Sponge	0	0	0	0	0	0
Ostracod	0	0	1	0	0	0
Blocky Calcite Pore Fill	0	0	0	0	0	0
Blocky Calcite Recrystallization	15	2	13	0	89	4

Allochems	**BC 25**	**BC 26**	**BC 27**	**BC 28**	**BC 29**	**BC 30**
Matrix	283	287	297	289	297	135
Stylolite	5	6	0	0	0	7
Echinoderm	0	0	0	0	0	0
Brachiopod	0	0	0	1	0	2
Gastropod	0	0	0	0	0	4
Trilobite	1	1	1	1	1	2
Algae	0	0	0	0	0	0
Intraclast	0	0	0	0	0	1
Pellet	0	0	0	0	0	23
Nuia	2	0	0	0	0	0
Quartz Silt	0	1	1	0	1	0
Sponge Spicule	0	0	0	1	1	0
Sponge	0	0	0	0	0	0
Ostracod	1	1	0	0	0	1
Blocky Calcite Pore Fill	0	0	0	0	0	0
Blocky Calcite Recrystallization	8	4	1	8	0	85

APPENDIX C

Thin Section Descriptions

Refer to Figure 24 for the location within the bioherm horizon of the units.

BC1

Onlap unit. Partially crystalline and dolomitized mudstone with sparse echinoderm, brachiopod, gastropod and trilobite fragments, *Nuia* and quartz silt grains. Matrix is pelletal.

BC2

Onlap unit. Partially crystalline, highly dolomitized mudstone with sparse brachiopod and trilobite fragments, algae, *Nuia*, pellets and quartz silt grains.

BC3

Onlap unit. Partially crystalline and dolomitized mudstone with sparse brachiopod fragments, *Nuia,* intraclasts and a sponge. Sponge is 15x9 millimeters. Matrix and intraclasts are pelletal.

BC4

Intraclastic unit. Partially dolomitized, intraclastic wackestone with sparse trilobite fragments, *Nuia* and quartz silt grains. Intraclasts are elongate, rounded to sub-rounded, composed of pelletal micrite and have dimensions of 3-15 millimeters and 2-7 millimeters.

BC5

Basal unit. Highly dolomitized, pelletal wackestone with sparse trilobite fragments, *Nuia* and quartz silt grains. Highly stylolitic.

BC6

Bioherm unit bottom. Mudstone with sparse echinoderm, brachiopod and trilobite fragments, *Nuia* and quartz silt grains. Matrix is pelletal.

BC7

Bioherm unit bottom. Partially dolomitized mudstone with sparse trilobite fragments and quartz silt grains. Matrix is pelletal.

BC8

Bioherm unit bottom. Partially dolomitized mudstone with sparse echinoderm and trilobite fragments, *Nuia* and quartz silt grains. Matrix is pelletal.

BC9

Bioherm unit bottom. Mudstone with sparse trilobite fragments and quartz silt grains. Matrix is pelletal.

BC10

Bioherm unit bottom. Algal wackestone with sparse quartz silt grains. Matrix is pelletal.

BC11
Bioherm unit bottom. Mudstone with sparse trilobite fragments, *Nuia* and quartz silt grains. Matrix is pelletal.

BC12
Bioherm unit middle. Mudstone with sparse gastropod and trilobite fragments and quartz silt. Matrix is pelletal.

BC13
Bioherm unit middle. Partially dolomitized mudstone with sparse echinoderm, gastropod, ostracod and trilobite fragments, sponge spicules, *Nuia* and quartz silt. Matrix is pelletal.

BC14
Bioherm unit middle. Partially dolomitized mudstone with sparse echinoderm and trilobite fragments and quartz silt grains. Matrix is pelletal.

BC15
Bioherm unit middle. Mudstone with sparse ostracod and trilobite fragments, *Nuia* and quartz silt grains. Matrix is pelletal.

BC16
Bioherm unit top. Mudstone with sparse echinoderm and trilobite fragments and quartz silt grains. Matrix is pelletal.

BC17
Bioherm unit top. Mudstone with sparse echinoderm and trilobite fragments, *Nuia* and quartz silt grains. Matrix is pelletal.

BC18
Bioherm unit top. Partially dolomitized sponge bafflestone with sparse brachiopod and trilobite fragments. Matrix is pelletal. Sponges are 16x22 millimeters and 5x10 millimeters.

BC19
Bioherm unit top. Mudstone with sparse trilobite fragments, algae, *Nuia* and quartz silt grains. Matrix is pelletal.

BC20
Bioherm unit. Mudstone with sparse echinoderm and trilobite fragments, *Nuia* and quartz silt grains. Matrix is pelletal.

BC21
Bioherm unit. Mudstone with sparse echinoderm, ostracod and trilobite fragments and quartz silt grains. Matrix is pelletal.

BC22
Bioherm unit. Partially dolomitized mudstone with sparse trilobite fragments, algae and quartz silt grains. Matrix is pelletal.

BC23
Bioherm unit. Partially crystalline wackestone with sparse echinoderm, brachiopod, gastropod and trilobite fragments and *Nuia.*   Matrix is pelletal.

BC24
Bioherm unit. Highly dolomitized mudstone with sparse trilobite fragments.   Matrix is pelletal.

BC25
Bioherm unit. Partially dolomitized mudstone with sparse ostracod and trilobite fragments and *Nuia.*   Matrix is pelletal.

BC26
Bioherm unit. Mudstone with sparse ostracod and trilobite fragments and quartz silt. Matrix is pelletal.

BC27
Bioherm unit. Highly dolomitized mudstone with sparse trilobite fragments and quartz silt grains. Matrix is pelletal.

BC28
Bioherm unit. Mudstone with sparse brachiopod and trilobite fragments and sponge spicules. Matrix is pelletal.

BC29
Bioherm unit. Mudstone with sparse trilobite fragments, *Nuia* and quartz silt grains. Matrix is pelletal.

BC30
Bioherm unit. Partially crystalline and highly dolomitized mudstone with sparse ostracod, gastropod and trilobite fragments and pellets.