Characterizing global archaeocyathan reef decline in the Early Cambrian: Evidence from Nevada and China

Melissa Hicks

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CHARACTERIZING GLOBAL ARCHAEOCYATHAN REEF DECLINE IN THE EARLY CAMBRIAN: EVIDENCE FROM NEVADA AND CHINA

by

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The Dissertation prepared by

Melissa Hicks

Entitled

Characterizing the Global Archaeocyathid Reef Decline in the Early Cambrian: Evidence from Nevada and China

is approved in partial fulfillment of the requirements for the degree of

Doctor of Philosophy in Geoscience

Examination Committee Chair

Dean of the Graduate College
ABSTRACT

Characterizing Global Archaeocyathan Reefs Decline in the Early Cambrian: Evidence from Nevada and China

by

Melissa Hicks

Dr. Stephen M. Rowland, Examination Committee Chair
Professor of Geoscience
University of Nevada, Las Vegas

This study presents new data on the sedimentology of the northern Yangtze Platform, the $\delta^{13}$C stratigraphy of South China and Nevada, and the decline and virtual extinction of archaeocyaths. Paleoecological, sedimentological, and chemostratigraphic data were collected from multiple localities that span from the mid-Early Cambrian of Nevada (Poleta Formation) and China (Xiannudong Formation) to the late-Early Cambrian of Nevada (Harkless Formation) and China (Tianheban Formation).

Facies represented in the Xiannudong Formation describe a Bahamas-type platform for the Yangtze Platform with a static and negative $\delta^{13}$C record. All four formations analyzed show a static $\delta^{13}$C record that varies from slightly negative to slightly positive. This is unexpected because stasis is not observed in the composite $\delta^{13}$C record of the Siberian Platform, suggesting that our data may represent intrabasinal $\delta^{13}$C records and not global.

Another important feature I observed in the Xiannudong Formation is a faunal changeover from predominantly regular-type archaeocyaths in the lower Xiannudong Formation to predominantly irregular-type archaeocyaths in the upper part. This
changeover is also seen between the Poleta Formation and the Harkless Formation in Nevada.

Finally, I analyzed the physical changes in archaeocyathan skeletons over time. A progressive thinning of skeletal thickness was expected, however a distinct trend of skeletal thickening was observed. Skeletal thinning was expected due to a lowered carbonate saturation state driven by rising atmospheric CO$_2$. To explain thickening, I propose that irregular archaeocyaths contained photosymbionts, which are documented to counteract a lower carbonate saturation state. Irregular archaeocyaths, which inherently contain more elements in their intervallum, and hence, more soft tissue, could house more endosymbionts than regulars. Therefore, regulars declined due to the lack of abundant photosymbionts, while irregulars flourished.

Currently, there is no definitive evidence to support our hypothesis that the ultimate extinction of archaeocyaths was due to increased sea surface temperatures due to the greenhouse warming effect of increased pCO$_2$. Prolonged temperatures would have increased thermal stress on the archaeocyaths until some threshold was reached in which even irregulars could not survive. This scenario may have implications for modern reef reactions to anthropogenic CO$_2$ and greenhouse warming.
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CHAPTER 1

INTRODUCTION

During an eleven-million-year interval in the Early Cambrian Epoch (521-510 Ma), archaeocyaths, an extinct class of calcareous sponges, formed a reef-building consortium with calcium carbonate-secreting microorganisms (calcimicrobes). This reef-building consortium of archaeocyaths and calcimicrobes was short lived, but it was impressive because of the rapid diversification and global distribution that archaeocyaths achieved. Archaeocyaths evolved on the Siberian platform ~521 Ma, globally radiated by 518 Ma, and virtually went extinct ~510 Ma, except for rare, non-reef-building, putative Middle and Late Cambrian archaeocyaths found in Antarctica (Debrenne et al., 1984; Wood, et al., 1992).

Archaeocyathan-calcimicrobe reefs grew as isolated patch reefs, as well as laterally extensive compound reefs. Some preserved compound reefs are as large as 100 m in thickness (Rowland and Shapiro, 2002; Rowland and Hicks, 2004). Based on the presence of primary fibrous cements and the associated sediments, these reefs typically formed on high energy, shallow, carbonate platforms and ramps (Mathews, 1974). A wide variety of reef-dwelling organisms also are associated with these reefs and include trilobites, brachiopods, hyoliths, bivalved arthropods, chancellorids, salterellids, echinoderms, and coralomorphs.
Archaeocyaths occupy an interesting point in Earth’s history as the first multicellular animals to actively participate in reef-building and the first reef-building organisms to become extinct (Rowland and Hicks, 2004). This ecologically and structurally complex reef ecosystem collapsed and disappeared at the end of the Early Cambrian, followed by a forty-million-year interval (Middle Cambrian through the Early Ordovician) during which reefs built by multicellular animals were essentially non-existent on Earth. The enigma surrounding the decline and virtual extinction of archaeocyaths and the 40-million year gap in metazoan-reef-building, one of the longest gaps ever recorded, continues to puzzle paleontologists and geologists alike. The mechanisms that have been proposed for the archaeocyathan decline vary from climatic to chemical, and testing these mechanisms has proven to be problematic (Rowland and Shapiro, 2002).

The list of potential culprits for archaeocyathan extinction is long, while our ability to rigorously test each hypothesis is limited. Climate models suggest that the levels of atmospheric CO$_2$ rose very rapidly during the Early Cambrian (Berner, 1991, 1994, 1997; Berner and Kothavala, 2001) accompanied by high atmospheric and sea surface temperatures (Karhu and Epstein, 1986), but the error bars associated with these models are large. It has also been inferred that during the Early Cambrian there was a change in seawater chemistry from aragonite-precipitating conditions to calcite precipitating conditions (Sandberg, 1983, Stanley and Hardie, 1999). Furthermore, sea level changes, such as the Sinsk Event (a transgression that introduced anoxic waters onto the carbonate platform) and the Hawke Bay Regression, also have been suggested as a prime cause of archaeocyath extinction (Wood, 1999).
In order to sort out the true mechanisms behind the decline of archaeocyathan reefs, I studied archaeocyaths and reefs from the peak reef-building interval (mid-Early Cambrian) to the extinction (end-Early Cambrian). Data were collected from field locations in western Nevada, southern Shaanxi, northern Sichuan, and northern Hubei provinces, China. These localities were chosen because: (1) they contain putative coeval archaeocyath-bearing units that span the mid-Early Cambrian to the late-Early Cambrian, (2) they were widely separated in the Early Cambrian (as they are today), and (3) the paleoecology of two of these units (Poleta and Harkless formations) had previously been studied (Rowland, 1978; Hicks, 2001).

Each of the three papers included in this dissertation describes a different aspect of this study: (1) the paleoecology and sedimentology of the Chinese archaeocyath-bearing sections, (2) the chemostratigraphic analyses, and (3) the changes in archaeocyaths over time. In order to better characterize the decline of archaeocyaths, the following three hypotheses were tested: (1) the generic richness of archaeocyaths declined from the mid-Early Cambrian to the end-Early Cambrian, (2) the percent of branching archaeocyaths decreased from the mid-Early Cambrian to the end-Early Cambrian, and (3) the abundance of irregulars increased from the mid-Early Cambrian to the end-Early Cambrian. In addition to these, δ^{13}C isotope chemostratigraphy was used to test the hypothesis that the Lower Poleta Formation is correlative with the Xiannudong Formation and the Harkless Formation is correlative with the Tianheban Formation.

This dissertation by no means completes research into the cause of the archaeocyath extinction and the metazoan-reef-free period following, but it produces new models for organism reactions to environmental change, which can be used to analyze
both ancient and modern reef builders. Furthermore, it tests the ability for chemostratigraphy to correlate strata globally and its use in interpreting paleoenvironments.

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Matthews, R.K., 1974, A process approach to diagenesis of reefs and reef associated Limestones, in Laporte, L.F., ed., Reefs in time and space: Tulsa, Oklahoma,


CHAPTER 2

EARLY CAMBRIAN MICROBIAL REEFS, ARCHAEOCYATHAN INTER-REEF COMMUNITIES, AND ASSOCIATED FACIES OF THE YANGTZE PLATFORM

Abstract

A sedimentological and paleoecological study of part of the northern Yangtze Platform of China was conducted. Three sections of the Early Cambrian (Atdabanian/Botomian Stage) Xiannudong Formation where studied, and reveal that stromatolite and thrombolite reefs flourished in close association with an inter-reef community of archaeocyaths and other organisms. Adjacent to the reef environment were migrating ooid shoals, oncoids, peloids, and silty/sandy lime mud.

No archaeocyathan reefs were observed in any of the measured sections, but irregular archaeocyaths were found in some microbial reefs, and archaeocyaths form the bulk of the debris in float-rudstone that was deposited between microbial reefs. We interpret the archaeocyath-rich float-rudstone to represent a storm-churned inter-reef deposit. Typically, ‘regular’ type archaeocyaths dominated the float-rudstone, while ‘irregular’ type archaeocyaths were found in abundance dwelling within the microbial reefs. This trend changed upsection as ‘irregular’ type archaeocyaths dominated both the float-rudstone and in the microbial reefs.

The oncolite and peloidal mudstone are interpreted as representing a quiet water, lagoonal environment created by the presence of the microbial reefs and ooid shoals.
During large storms material from the ooid shoals or microbial reefs would wash into the lagoon. The silty/sandy micrite represents a quiet water setting, which could either be a deep-subtidal environment or a restricted lagoonal environment.

The facies associations of these three sections, along with other published data indicate that the Yangtze Platform, at least during the Early and Middle Cambrian, was a carbonate platform and equatorially located.
Introduction

This paper is part of an overarching study on the decline and virtual extinction of archaeocyathan reefs during the Early Cambrian. In order to characterize the decline of the archaeocyathan reef ecosystem, we incorporated data from localities that were globally distributed during the Early Cambrian. Included in this data set, are samples from the Xiannudong Formation (mid-Early Cambrian) from the northern part of the Yangtze Platform. The purpose of this paper is to (1) describe the Early Cambrian microbial reefs and associated facies from the Xiannudong Formation, (2) interpret their paleoenvironments, and (3) make inferences concerning the paleogeography of the Yangtze Platform. Prior to this study, archaeocyathan-built reefs were described from multiple exposures of the Xiannudong Formation by Yuan and Zhang (1981), Qin and Yuan (1984), Zhang (1989), Ye et al. (1997), and Yuan et al. (2001) from outcrops in southern Shaanxi Province and northern Sichuan Province (Figure 2.1), but neither the paleoecology nor sedimentology of the reefs had been studied in detail. New fieldwork and subsequent laboratory research conducted between 2002-2004 call for a re-evaluation of the reefs in the Xiannudong Formation.

In the absence of internationally recognized stage terminology for the Cambrian Period, we use the widely used Siberian Platform nomenclature (Figure 2.2) for this paper. The Xiannudong Formation is late Atdabanian to early Botomian in age. The Botomian, in particular, was the stage of the Early Cambrian during which archaeocyathan generic diversity was at its maximum and reef-building by archaeocyaths and associated calcibionts was at its peak. Because the three sections of the Xiannudong Formation are well exposed, they provide an opportunity to determine the three-
Figure 2.1. Location map of China illustrating the boundaries of the Yangtze Platform (Li et al., 1995, 1996) and the locations of the three measured sections (stars) of this study. F = Fucheng section; S = Shatan section; and X = Xinchao section. Inset is a larger-scale map of the field area.
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<td>Harkless Fm.</td>
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<td></td>
<td>Mule Spring</td>
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</tbody>
</table>

Figure 2.2. Stratigraphic correlation of formations included in this study. Formations are placed in Stages and biozones based on biostratigraphy as described in the text (Rowland 1978; Yuan and Zhang 1981; Qin and Yuan 1984; Zhang 1989; Ye et al. 1997; Yuan et al. 2001; Zhu et al. 2001; Zhuravlev and Riding 2001; Hollingsworth 2004).
dimensional relationships of the reef horizons and associated facies. This study complements a previous study of coeval strata on the southern part of the Yangtze Platform by Debrenne and Jiang (1989), which documented facies relationships similar to those of the Xiannudong Formation. This new look at old reefs illustrates the dynamic environmental and evolutionary changes that occurred during the Early Cambrian, including cyclic environmental changes, relationships between archaeocyaths and microbial reefs, and evolutionary changes in the archaeocyaths themselves.

Age of the Xiannudong Formation

Figure 2.2 summarizes the age of the Xiannudong Formation, subjacent and superjacent formations, and correlative strata of the northern Yangtze Platform and coeval strata from the Great Basin, U.S.A. The age of the Xiannudong Formation is based on the presence of the trilobites *Malungia granulose, Micangshania gracilis* (Yuan and Zhang 1981; Zhang 1989), *Yunnanocephalus, Zhenbaspis, Eoredlichia*, and *Kuanyangia* (Yuan et al. 2001). Yuan and Zhang (1981), Qin and Yuan (1984), and Zhang (1989) all place the Xiannudong Formation straddling two trilobite biozones, *Malungia* and *Yunnanaspis-Yiliangella*, which are in the Tsanglangpu (Canglangpuan) Stage. Ye et al. (1997) and Yuan et al. (2001) place the Xiannudong Formation in three different biozones, upper *Eoredlichia-Wutingaspis, Malungia*, and *Yunnanaspis-Yiliangella*, which straddle the upper Qiongzhusi (Chiungchussan) Stage and the lower Tsanglangpu (Canglangpuan) Stage. The Qiongzhusi/Tsanglangpu stages correlate to the upper Atdabanian to lower Botomian on the Siberian Platform and to the upper Montezuman Stage of Laurentia (Zhuravlev and Riding 2001; Hollingsworth 2004) (Figure 2.2).
Geological setting

The position and tectonic history of the Yangtze Platform during the Proterozoic and Early Cambrian are not well understood. Some reconstructions consider the Yangtze Platform to be part of the South China block (attached to Cathaysia block or the “mobile belts”) in the Early Cambrian (Nie, 1991; Li et al., 1996; Zhao et al., 1996; Huang et al., 2000), while others infer that it was an isolated platform (Li et al., 1995; Xu et al., 1996; Wang and Li, 2003). Furthermore, the inferred paleolatitude of the Yangtze Platform varies from between 20° and 30° north (Nie, 1991; Li et al., 1995), to greater than 30° north (Li et al., 1996), to lying on the equator (Zhao et al., 1996; Huang et al., 2000; Scotese, 2001), to lying between 15° and 30° south of the equator (Xu et al., 1996).

Rifting of the South China Block (consisting of the Yangtze Platform and the Cathaysia Block) from Rodinia is hypothesized to have occurred in three rifting phases, beginning in the Neoproterozoic (~820 Ma) (Wang and Li, 2003). Rifts formed along the western (Kangdian Basin) and the southeastern margins (Nanhua Basin) of the South China Block (Li et al., 1999; Wang and Li, 2003). During the formation of the Nanhua basin, the South China Block became isolated from the Cathaysia Block (Wang and Li, 2003). Rifting ended at approximately 690 Ma, and was followed by thermal subsidence. In the Neoproterozoic, the Yangtze Platform was tilted to the southeast (Wang, 1986; Korsch et al., 1991). This resulted in the development of different depositional environments in the western and eastern portions of the Yangtze Platform, and a thicker accumulation of strata is observed in the east.

In the Yangtze Gorges area, west of Yichang (Figure 2.1), the Cambrian is approximately 1,300 meters thick, while in the western portion of the platform the
Cambrian is less than 500 meters thick. In the northern Sichuan/southern Shaanxi provinces the Cambrian strata include the Guojiaba, Xiannudong, Yangwangbian, and Kongmingdong formations, which display a general theme of cyclic sedimentation with silty/sandy micrite, shale and siltstone, interbedded with limestone and dolostone.

Methods

One month of fieldwork was completed during the summer of 2002, where we measured, described, and collected from the three sections of the Xiannudong Formation (Figure 2.1). Collected samples were cut for 3 x 2 inch thin sections. These thin sections were used to identify archaeocyathan genera, micro-fossil identification, and for point counts. Species-level identification of archaeocyaths is problematic under the best of circumstances. Because most of the archaeocyaths in this study were transported and abraded, we have identified them to the generic level, or, in some instances, to the ordinal level. In this paper we distinguish between ‘regular’ and ‘irregular’ archaeocyaths. This distinction was formally thought to reflect class-level evolutionary significance (Hill, 1972). However, archaeocyaths are now placed within the Phylum Porifera as an extinct class of aspiculate sponges (Debrenne et al., 2002). Taxonomic revisions within the Archaeocyatha taxon have left the regulars and irregulars as morphologically distinct groups, but they are no longer recognized as separate clades.

Almost all percentages discussed in this paper are the result of point counts on thin sections. Point Counts were performed on the archaeocyathan-float-rudstone, oncolite, and oolite using a Hacker Instrument, James Swift point counter. For each slide, 400 points were counted, with a four-increment spacing between each point.
Carbonate terminology in this paper follows Folk (1962) and Dunham (1962) and the modified scheme by Embry and Klovan (1971).

Stratigraphy of the Xiannudong Formation and Paleoenvironmental Interpretation

The Xiannudong stratotype section is a road cut near the village of Shatan in northern Sichuan, north of the town of Nanjiang (Figure 2.1). At Shatan, the Xiannudong Formation is approximately 110 m thick and contains multiple, thick intervals of oolite, microbial reefs, oncolite, and thinly-bedded, quartz-rich, silty/sandy micrite (Figure 2.3). The microbial reefs typically contain a clotted and/or laminated fabric, but they do not contain any identifiable microbial entity. Two archaeocyath-bearing units occur in the upper part of the Shatan section. In both of these units, the archaeocyath-bearing units are within oncolite-bearing beds. The archaeocyath skeletons are not in situ and are broken and abraded.

The Xiannudong Formation at the Fucheng section is 67.3 meters thick and is located near the village of Fucheng (Figure 2.1). It is underlain by the Guojiaba Formation and overlain by the Yanwanbian Formation (Yuan et al. 2001), all of which are structurally deformed into a broad anticline. In this section, we divided the Xiannudong Formation into thirteen stratigraphic units (units A-M) (Figure 2.4).

The Xinchao section of the Xiannudong Formation is a road cut near the village of Xinchao in Tongjiang County, northern Sichuan Province (Figure 2.1). Here, the Xiannudong Formation is 113 meters thick, which is slightly thicker than at Shatan and much thicker than at Fucheng (Figure 2.3). The Xiannudong in the Xinchao section consists of multiple intervals of thinly bedded, peloidal, silty/sandy micrite, oncolite, and
Figure 2.3. The three measured sections of the Xiannudong Formation in this study. Section localities are on Figure 1. Dashed lines indicate gradational boundaries. Thicknesses are in meters. Reef Complexes (RC) are numbered for the Fucheng Section. See figure 4 for details of the Fucheng Section.
Figure 2.4. Measured section of Xianxudong Formation at the Fucheng section. The section is 67.3 meters thick. Tie-lines connect points of continuation.
oolite. Only two intervals contain archaeocyaths, which occur as constituents in a float-rudstone that is very similar to the archaeocyath-bearing float-rudstone in the Fucheng section. The multiple cycles of stromatolitic and thrombolitic reefs with micrite and silty/sandy micrite that are conspicuous at Fucheng do not occur at Xinchao.

In the following sections, we describe each facies of the Xiannudong Formation, with emphasis on the Fucheng section where the most significant facies shifts were observed.

Microbial Reef Facies

We interpret these stromatolites and thrombolites as reefs based on Flügel and Kiessling's (2002) definition, which defines a reef as a laterally confined, biogenic structure that was constructed by sessile, benthic organisms, exhibits topographic relief, and rigidity. The microbial reefs in this study typically exhibit most of the above-mentioned features, which will be described below.

As illustrated in Figure 2.4, the microbial reef intervals within the Xiannudong Formation in the Fucheng section vary in thickness from several decimeters to several meters and are laterally extensive. The material surrounding the microbial reefs is archaeocyathan-rich floatstone to rudstone. The archaeocyaths within the float-rudstone are subrounded to subangular clasts that reflect variable amounts of abrasion due to transport. The archaeocyathan-rich float-rudstone is described in greater detail in the next section.

The lowest reef complex, Reef Complex 1 (Unit A), within the Fucheng section is 1.5 m thick, with several discrete domal and columnar stromatolites that vary in size (Figure 2.4). These domal and columnar stromatolites contain in-situ irregular
archaeocyaths. Archaeocyaths comprise 3.7 percent of the microbial reefs in Reef Complex 1. The genera present are both irregulars, *Protopharetra* and *Graphoscyphia* (Figures 2.5A, B, C).

The presence of archaeocyaths as dwellers within microbial reefs is not unusual during the Atdabanian/Botomian. Thrombolitic and stromatolitic reefs with low abundance archaeocyaths (<10%) are present in South Australia (James and Gravestock (1990) and Mongolia (Kruse et al., 1996). However, at those localities, archaeocyath-built reefs are also present, either in a different environment or in a different stratigraphic position. The Xiannudong sections are unusual for the Atdabanian/Botomian in the sense that although archaeocyaths were present, they were not involved in reef construction, even though a variety of depositional environments are represented.

As with most stromatolites, no identifiable microbial entity is present within Reef Complex 1. Aggrading neomorphism and dolomitization have obscured the primary microbial fabric in the samples. Burrows are present in both the stromatolites and in the associated archaeocyathan float-rudstone. Based on the lack of flanking bedding within the archaeocyathan-rich float-rudstone, we infer that these microbial reefs probably attained only modest relief on the seafloor.

Reef Complexes 2-6 (Units D, G, I, K, and M) (Figure 2.4) are lithologically and paleontologically similar to Reef Complex 1. Differences occur in the presence of a more thrombolitic texture within some units, especially in Reef Complexes 3 and 4, and in the percentage of archaeocyaths within the microbial reefs. In outcrop, the boundaries between the thrombolitic and stromatolitic fabrics are not conspicuous. Thrombolitic fabrics occur at the base of Reef Complexes 3 and 5 with stromatolitic fabrics overlying
Figure 2.5. (A) Reef Complex 1 (Unit A) in the Fucheng Formation showing some of the individual stromatolitic and thrombolitic microbial boundstone (M and black lines). The float-rudstone is the more resistant material that is present between the microbial reefs. (B) Photomicrograph (X-polars) of transverse and longitudinal section of the archaeocyath *Protopharetra* sp. (P) in stromatolite (S). (C) Photomicrograph (X-polars) of the poorly preserved archaeocyath *Graphoscyphia* sp. in stromatolite reef.
them. However, this is not typical; elsewhere thrombolitic fabrics are observed in the middle and near the top of a reef complex, overlying stromatolitic fabrics.

In Reef Complex 2 (Unit D, 1.6-m thick), *Protopharetra* sp. is the only identifiable archaeocyath within the stromatolitic reefs (no thrombolitic reefs are present in this unit); it constitutes approximately 1% of the reef by volume. Upsection in Reef Complex 3 (Unit G, 1.1-m thick), thrombolitic reefs occur at the base of the unit, with stromatolites dominating the upper portion. The stromatolites form distinct columns, some of which are taller than 30 cm. Flanking beds of float-rudstone are visible, which indicates that these columns had topographic relief on the seafloor (Figure 2.6A). No archaeocyaths are present within these particular microbial reefs, but poorly preserved cocci (*?Renalcis*) are preserved (Figure 2.6B).

Reef Complex 4 (Unit I, 6.1-m thick) contains the first appearance of a ‘regular’ archaeocyath in the microbial reefs, however irregular archaeocyaths still dominate; archaeocyaths constitute 2.2% of the reef by volume. These archaeocyaths are poorly preserved, but a few can be identified as *Protopharetra* sp. and *Inessocyathus* sp. Both stromatolites and thrombolites are present in this unit, but with no conspicuous pattern in their distribution. In some places, stromatolites grade upward into a thrombolitic fabric in a seemingly continuous reef, while elsewhere the opposite occurs (Figure 2.7).

Reef Complex 5 (Unit K) is the thickest interval of microbial reefs (approximately 12.5 m thick). As in Reef Complex 3, thrombolitic reefs form the base of this unit with stromatolitic reefs forming the bulk of the upper portion. Within this reef complex, poorly preserved cocci are present, along with sponge spicules, but no archaeocyaths.
Figure 2.6. (A) Outcrop photograph of columnar stromatolites (S) from the upper portion of Reef Complex 3 (Unit G). Scouring of the stromatolite is observed with float-rudstone in the scoured pockets. Float-rudstone occurs between the stromatolites. (B) Photomicrograph (X-polars) of poorly preserved cocci, *?Renalcis*, (arrows) from thrombolitic reefs of lower part of Reef Complex 3.
Figure 2.7. Outcrop photograph illustrating the difficulty of discerning between stromatolite and thrombolites reefs in outcrop, in which both are present here. Photograph is of Reef Complex 4 in the Fucheng section. Staff is 1 meter.
The uppermost reef complex, Reef Complex 6 (Unit M, 14.4-m thick), contains stromatolite reefs with poorly preserved ‘irregular’ and a few possible ‘regular’ archaeocyaths. The poor preservation of the ‘irregulars’ allows for only tentative identification of Protopharetra sp. and Graphoscyphia sp. in this reef complex. The stromatolites are interspersed with completely dolomitized grainstone, ooid-archaeocyath float-rudstone, and oolite.

All of the Reef Complexes (1-6) in the Fucheng section contain microbial reefs with scoured peripheral boundaries (Figure 2.6A). These scour cavities appear to be the product of wave scour, and they are typically filled with a high percentage of ooids and fossil hash, including archaeocyathan debris. The presence of these scour-and-fill features is interpreted as the result of periodic storm events eroded the peripheries of the microbial reefs.

In the Xinchao section, the microbial reef facies is very similar to the reef facies of the Fucheng section, although at Xinchao the microbial reef facies comprises a much smaller component of the section. Only unique characteristics of the reefs are described below. Whereas distinctive columns and hemispherical masses occur in the microbial reefs at Fucheng, the Xinchao microbial reefs are massive, nondescript micrite in outcrop. In the lowest interval of microbial reefs, at about 50 m (Figure 2.3), archaeocyathan float-rudstone pods interfinger with highly neomorphosed micrite. This aggrading neomorphic spar occurs in small clusters, producing a clotted texture in thin section. Several samples contain cocci microfossils, and therefore, the majority of the microbial reefs in the lowest interval of the Xinchao section appear to be thrombolitic. We speculate that neomorphism preferentially altered those areas of clotted micrite, while
leaving the microbially mediated clots relatively unaltered. Xenotopic to idiotopic
dolomite also hinders the interpretation of the primary fabric in these micritic samples
(Figure 2.8). Archaeocyaths belonging to the irregular Order *Archaeocyathina* are
present in the thrombolitic reefs, but, due to poor preservation, we could not identify
them below the ordinal level.

In the Shatan section, the microbial reef interval varies from conspicuous
microbial clotted fabrics to subtle clotted and laminated fabrics of both thrombolites and
stromatolites. No microbes or calcimicrobes are preserved. As in the Xinchao section,
the microbial reefs at Shatan do not form columns or hemispherical masses, such as those
of the Fucheng section. Instead this facies appears as massive, nondescript micrite and
nodular-bedded micrite with some rudimentary laminae. No archaeocyaths are
conspicuous in outcrop or thin section in the Shatan reef samples.

**Microbial reef paleoenvironment**

In the Fucheng section, we interpret the stromatolitic and thrombolitic reefs to
have formed on a shallow carbonate platform. The lack of exposure features, along with
the presence of scour-and-fill features on the periphery of some of the microbial reefs,
indicates a highly energetic, shallow-subtidal environment. We interpret the
interfingering of facies to record occasional major storm events during which ooid shoals
abruptly buried the adjacent microbial reefs, only to be subsequently recolonized by the
microbial reef community.

Neither the Xinchao section nor the Shatan section contain the well-defined
microbial reefs with conspicuous topographic relief that are so conspicuous in the
Fucheng section. This indicates that environmental conditions were not optimal for
Figure 2.8. Photomicrograph (X-polars) of neomorphosed micrite (N) between clots of microbial cocci (M) in the microbial reef faces of the Xinchao section.
microbial reef growth in either of these sections. In section 4 of this paper, we provide a paleoenvironmental synthesis.

Archaeocyathan-rich Float-rudstone Facies

In sections of the sediment adjacent to the microbial reefs in the Fucheng section, large (>2mm) archaeocyathan skeletal clasts, microbial roll-ups, oncoids, ooids, brachiopod valves, trilobite carapaces, *Chancellorid* spicules, hyolith cones, echinoderm plates, and a multitude of unidentifiable fossil fragments are present (Table 2.1). Dolomite also is present and varies from euhedral to anhedral crystals that form idiotropic to xenotropic mosaics. The taxonomic mix of archaeocyaths, as well as the percentages of archaeocyaths and other fossil constituents, varies from one float-rudstone interval to the other. Table 2.2 lists the genera present in each interval of float-rudstone in the Fucheng section. In the following discussion, the abundance of each constituent is given as the average percent by volume. Only archaeocyath percentages and any unique differences will be discussed for each of the Fucheng float-rudstone units.

The float-rudstone that occurs in association with Reef Complex 1 at Fucheng contains the typical assemblage and percentages of constituents observed in the float-rudstone. These constituents are as follows: archaeocyaths (15.5%), peloids (3-5.7%), trilobite fragments (0.7%), other unidentifiable fossil hash (3.7%), ooids (<1%), and very fine to medium silt-size quartz (1.7-17.2%) (Table 2.1). The matrix, which constitutes the remaining volume, is a varying mix of micrite and calcite cement. Three genera of archaeocyaths were found in the float-rudestone of Reef Complex 1 (Figures 2.9A, B). Most of the archaeocyath fragments range in size from 3.0-11.0 mm, and show moderate rounding. Roll-up stromatolites and mm-size domal stromatolites are present in this unit.
Table 2.1. Point counts in percents from thin sections of samples of float-rudstone and oolite from the Fucheng section.

<table>
<thead>
<tr>
<th>Sample No.</th>
<th>Archaeocyath</th>
<th>Micrite</th>
<th>Peloid</th>
<th>Spar-sm</th>
<th>Spar-med/lg</th>
<th>Microbial</th>
<th>Trilobite</th>
<th>Dolomite</th>
<th>Quartz</th>
<th>Ooid</th>
<th>Other Fossil</th>
</tr>
</thead>
<tbody>
<tr>
<td>3--7--7 (RC1)</td>
<td>15.2</td>
<td>43.7</td>
<td>3.0</td>
<td>3.5</td>
<td>5.7</td>
<td>20.0</td>
<td>0.7</td>
<td>0.0</td>
<td>17.2</td>
<td>0.0</td>
<td>3.0</td>
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<tr>
<td>1--7--7b (RC1)</td>
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<td>48.2</td>
<td>5.7</td>
<td>2.0</td>
<td>7.5</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
<td>7.2</td>
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<td>10a--7--7 (RC2)</td>
<td>12.7</td>
<td>21.0</td>
<td>1.0</td>
<td>4.2</td>
<td>12.5</td>
<td>0.0</td>
<td>2.0</td>
<td>29.5</td>
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<td>4--7--8 (RC3)</td>
<td>10.2</td>
<td>62.0</td>
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<td>2.7</td>
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<td>10.7</td>
<td>0.0</td>
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<td>56.5</td>
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<td>8--7--8b (RC4)</td>
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<td>42.2</td>
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<td>9.7</td>
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<td>3--7--10 (RC6)</td>
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Table 2.2. Genera of archaeocyaths present within float-rudstone between the microbial reef complexes in the Fucheng Section.

<table>
<thead>
<tr>
<th>Reef Complex (Unit)</th>
<th>RC #1 (Unit A)</th>
<th>RC #2 (Unit D)</th>
<th>RC #3 (Unit G)</th>
<th>RC #4 (Unit I)</th>
<th>RC #5 (Unit K)</th>
<th>Unit L</th>
<th>RC #6 (Unit M)</th>
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<td><strong>Regulars</strong></td>
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Figure 2.9. Archaeocyathan skeletal fragments in the float-rudstone of Reef Complex 1 in the Fucheng section. 
(A) Photomicrograph (X-polars) of a transported skeleton of *Clathricoscinus* sp. (C) with a stromatolite growing on it (S). 
(B) Photomicrograph (X-polars) of a transported skeleton of *Coscinocyathus* sp.
only, and they occasionally encrust archaeocyath fragments (Figure 2.9A). Also, this particular unit of float-rudstone contains abundant *Chancelloria* spicules that, although found in some of the other units, are particularly abundant here.

The next interval of float-rudstone, associated with Reef Complex 2, contains only one genus of archaeocyath, which is either *Clathricoscinus* or *Coscinocyathus*. The float-rudstone does not contain any *Chancellorid* spicules, but it does contain well-rounded glauconite, which is observed only in this interval. Reef Complex 3 contains float-rudstone that contains three different genera of regular archaeocyaths (Table 2.2). The float-rudstone associated with Reef Complex 4 contains the most diverse assemblage of archaeocyaths of all the reef complexes (Figures 2.10A, B, C and Table 2.2), and also has a conspicuous increase in the abundance of hyoliths. Reef Complex 5 is the thickest unit in the Fucheng section (Figure 2.4). This reef complex contains the only sponge spicules observed in this study. These are multiaxon spicules that are completely recrystallized into blocky calcite; they occur in both the float-rudstone and the adjacent microbial reefs. It is unknown whether these spicules were originally siliceous or calcareous.

Unit L, which is predominately silty micrite, contains a cobble-size clast of archaeocyath float-rudstone (Figure 2.11A), of which archaeocyathan skeletal fragments comprise 6.7% by volume. Based on the well-rounded nature of the cobble, we infer that it was at least partially lithified prior to transport. The archaeocyaths in the float-rudstone cobble were fairly well preserved, consisting of a very diverse assemblage of regular archaeocyaths (Figures 2.11B, C, D, E, F and Table 2.2).
Figure 2.10. Photomicrographs (X-polars) of 'regular' archaeocyaths from Reef Complex 4 in the Fucheng Section. (A) Oblique transverse cut through *Conanulofungia* sp. in float-rudstone. (B) Longitudinal cut through two *Inessocyathus* sp. in lens of oolite with patches of dolomite. (C) Transverse cut through *Taylorocyathus* sp. (T) in float-rudstone containing hyoliths (H) and brachiopods (B) among other fossil hash.
Figure 2.11. Outcrop and photomicrographs (X-polars) of a clast of archaeocyath-rich float-rudstone within the silty/sandy micrite of Unit L. (A) Outcrop photo of cobble in silty/sandy micrite. (B) Transverse cut through *Rasseticyathus* sp. (C) Transverse cut through *Dictyocyathus* sp. (D) Transverse cut through two *Pilodicoscinus* sp. (E) Transverse cut through a portion of *Rudanulus* sp. (F) Oblique longitudinal cut through *?Erismacoscinus* sp. (G) Longitudinal cut through *Changicyathus* sp.
Reef Complex 6, in the uppermost unit at Fucheng (Unit M), shows a sharp change in the volumetric dominance of archaeocyaths from regular to irregular (Table 2.2). The irregular archaeocyaths *Protopharetra* and *Graphoscyphia* dominate, with only a few regulars of the genus *Inessocyathus*. This change from regular dominance to irregular dominance is not unexpected within this part of the Early Cambrian, but it has never before been documented within a single stratigraphic section. Younger Early Cambrian archaeocyathan reefs (Toyonian Stage) contain a majority of irregular-type archaeocyaths with rare regular-type archaeocyaths or none at all (James and Klappa, 1983; Debrenne et al., 1991; Hicks, 2001). We also observed this faunal changeover from regular-dominated to irregular-dominated at the other two sections of the Xiannudong Formation.

Only two intervals in the Xinchao section contain the archaeocyath dominated float-rudstone facies (Figure 2.3). As observed at Fucheng, regular archaeocyaths dominate the lower bed of float-rudstone (at 50 m); the same archaeocyathan genera are present in this bed at Xinchao as occur in Units I and L of the Fucheng Section. These include, *Conannulofungia, Coscinocyathus, Rasetticyathus, Clathricoscinus, ?Taylorcyathus,* and *Pilodicoscimus*. The irregulars in this interval are *Graphyscyphia* and *Protopharetra*. These are all variably abraded. Fine-sand-size quartz occurs within the float-rustone and averages 1% of the constituents. Other constituents of the lower archaeocyathan-bearing unit are ooids, trilobites, echinoderms, peloids, and grapestones (Table 2.3).

The upper interval within the Xinchao section, which contains conspicuous archaeocyaths, occurs 111 m to 113 m above the base of the Xiannudong Formation.
Table 2.3. Point counts in percents from thin sections of samples of float-rudstone and oncolite from the Xinchao section.

<table>
<thead>
<tr>
<th>Sample No.</th>
<th>Archaeocyath</th>
<th>Micrite</th>
<th>Peloid</th>
<th>Calcite-sm</th>
<th>Calcite-med/lg</th>
<th>Microbial</th>
<th>Trilobite</th>
<th>Dolomite</th>
<th>Quartz</th>
<th>Ooid</th>
<th>Other Fossil</th>
</tr>
</thead>
<tbody>
<tr>
<td>5-7-11 (UAU)</td>
<td>20.0</td>
<td>32.7</td>
<td>1.7</td>
<td>3.5</td>
<td>15.2</td>
<td>0.0</td>
<td>0.0</td>
<td>9.7</td>
<td>8.2</td>
<td>4.0</td>
<td>4.0</td>
</tr>
<tr>
<td>6b-7-11 (UAC)</td>
<td>2.5</td>
<td>61.0</td>
<td>2.0</td>
<td>6.0</td>
<td>3.7</td>
<td>0.0</td>
<td>0.0</td>
<td>7.2</td>
<td>2.0</td>
<td>15.2</td>
<td>0.2</td>
</tr>
<tr>
<td>7b-7-11 (UAU)</td>
<td>6.4</td>
<td>27.0</td>
<td>6.6</td>
<td>8.2</td>
<td>5.1</td>
<td>0.9</td>
<td>0.3</td>
<td>19.7</td>
<td>8.5</td>
<td>11.8</td>
<td>5.4</td>
</tr>
<tr>
<td>9b-7-11 (LAU)</td>
<td>5.7</td>
<td>16.5</td>
<td>1.0</td>
<td>8.5</td>
<td>3.2</td>
<td>0.0</td>
<td>0.0</td>
<td>59.5</td>
<td>0.2</td>
<td>0.0</td>
<td>5.2</td>
</tr>
<tr>
<td>11-7-11 (LAU)</td>
<td>13.0</td>
<td>28.7</td>
<td>3.2</td>
<td>7.2</td>
<td>1.7</td>
<td>0.0</td>
<td>0.0</td>
<td>42.2</td>
<td>1.0</td>
<td>1.7</td>
<td>0.9</td>
</tr>
<tr>
<td><strong>Oncolite</strong></td>
<td><strong>4-7-11</strong></td>
<td><strong>51.0</strong></td>
<td><strong>0.0</strong></td>
<td><strong>19.0</strong></td>
<td><strong>15.0</strong></td>
<td><strong>8.5</strong></td>
<td><strong>0.0</strong></td>
<td><strong>5.7</strong></td>
<td><strong>0.7</strong></td>
<td><strong>0.0</strong></td>
<td><strong>0.0</strong></td>
</tr>
</tbody>
</table>
(Figure 2.3). That interval consists of a small amount of microbially mediated material, and abundant silty/sandy micrite (medium to coarse sand-size quartz), with abundant ooids, peloid, archaeocyaths, and fragments of trilobites and echinoderms. The archaeocyaths are all irregulars, including \textit{?Spirillicyathus} (Figure 2.12), \textit{Protopharetra}, and \textit{?Graphoscyphia}. These archaeocyaths are all relatively whole, with \textit{Graphoscyphia} occurring as a large, branching colony. Even though the archaeocyathan debris contains large, branching specimens, including some with delicate exothecal outgrowths, these archaeocyaths do not appear to be \textit{in-situ}.

The Shatan section does not contain any archaeocyath-bearing float-rudstone; all archaeocyathan skeletal fragments occur as nuclei of oncoids.

\textbf{Archaeocyathan float-rudstone paleoenvironment}

We interpret this facies to represent an inter-reef community of archaeocyaths and other benthic organisms, such as trilobites and echinoderms (Figure 2.13). The archaeocyaths in this inter-reef community were not forming reefs of their own, but lived as individuals in clusters on the seafloor. Although they are not preserved \textit{in situ}, the presence of intact, branched forms and delicate exothecal outgrowths leads us to conclude that they were not transported any significant distances. The microbial reefs provided shelter from wave action, except during large storm events. These large storms would rip-up the archaeocyaths and other organisms, tumble them, and then redeposit them between the microbial reefs.

\textbf{Oolite Facies}

Of the three Xiannudong sections examined in this study, the Fucheng section contains the least amount of oolite, while the Shatan section contains more oolite than
Figure 2.12. Photomicrograph (X-polars) of *?Spirillicyathus* sp. in upper archaeocyath-bearing unit in the Xinchao section.
Figure 2.13. Block diagram illustrating a "snap-shot" in time of the Fucheng section of the Xiannudong Formation.
any other lithology (Figure 2.3). In the Fucheng section, the ooids typically range in
diameter from 0.5-1.0 mm; some are recrystallized with saddle dolomite, while others are
partially dissolved and/or partially deformed. A sharp, wavy boundary occurs between
the microbial reefs of Reef Complex 1 and the first major occurrence of oolite, Unit B.
The basal portion of Unit B oolite contains trough cross-stratification with westward-
dipping planar cross-stratification at its top.

At Fucheng, Reef Complexes 4, 5, and 6 contain isolated to interfingering beds of
oolite associated with the microbial reef complexes. Unit I oolite does not appear to be
cross-bedded as observed in Unit B. It does contain several sizable (≥ 8mm), transported
regular archaeocyathan skeletal fragments of *Inessocyathus* and either *Clathricoscinus* or
*Cosinocyathus*. In contrast, the oolite beds in Unit M are conspicuously cross-bedded.
Furthermore, in Unit M, several thin beds of oolite interfinger with microbial boundstone
and also contain transported archaeocyathan debris. Unlike unit I, which contains only
regular archaeocyath debris, Unit M contains only irregular archaeocyath debris. Most of
the archaeocyaths within the oolite are too poorly preserved to be identified to the generic
level, but all are recognizable as irregulars. The few that can be classified to generic
level are *Protopharetra* and *Graphoscyphia*. Toward the upper part of Unit M, microbial
reefs disappear and cross-bedded oolite dominates (Figure 2.14A). Paleocurrent analysis
shows a bimodal, NNE-SSW, paleocurrent (Figure 2.14B).

In the Xinchao section, oolite occurs as one massive bed in the middle of the
section and as thinner interbeds within the uppermost archaeocyathan-bearing unit
(Figure 2.3). In the massive oolite bed, ooids range in diameter from 0.25-0.65 mm and
show varying degrees of dissolution and dolomitization; they are slightly flattened
Figure 2.14. Well defined cross-bedding in the oolite beds of Unit M. (A) Outcrop photo of cross-bedded oolite. (B) Rose diagram illustrating bimodal paleocurrent direction; n = 10.
parallel to bedding. On weathered surfaces, weak cross-bedding was observed, but it was not distinct enough to measure. In the uppermost archaeocyath-bearing unit, the ooids (0.5-0.75 mm) are poorly preserved. Many are completely dissolved or dolomitized.

The Shatan section contains a massive amount of oolite that, for the most part, is contained within the lower to middle part of the section (Figure 2.3). The ooids range in diameter from 0.25 to 1 mm. Most show replacement by dolomite, but many display a fibrous, radiating microstructure. Some oolite beds contain rudimentary laminations, ripples or wavy bedding, and cross-bedding. Vertical burrows (3-5 cm in length) occur in these beds, sometimes obscuring the sedimentary structures.

**Oolite paleoenvironment**

We interpret the oolite to represent migrating ooid shoals. Similar to modern ooid shoals of the Bahamas carbonate bank (Purdy, 1963), these shoals formed in shallow, high-energy marine waters, in particular shallow subtidal above normal wave base (Purdy, 1963). The ooid shoal facies occurred adjacent to the microbial reefs and the archaeocyath inter-reef community. Inter-fingering of the oolite and microbial reefs mostly records shifts of the ooid shoals during storms. During large storms, the migrating ooid shoals would bury adjacent microbial reefs and inter-reef communities, which would sometimes reestablish themselves at a later time.

**Silty/Sandy Micrite Facies**

This facies occupies a significant portion of the Fucheng section, but it is rare in the other two sections (Figure 2.3). Six intervals of silty/sandy micrite, with varying thicknesses, occur in the Xiannudong Formation at Fucheng: units C, E, F, H, J, and L (Figure 2.4). This facies always contains abundant horizontal burrows, but, with one
exception, no body fossils. The exception is Unit L, which contains the archaeocyathan float-rudstone cobble described in Section 2.2. In general, the bioturbation is at a low ichnofacies level of 1 or 2 on the scale developed by Droser and Bottjer (1988).

Differences do exist among these units, with variations including the following: (1) the thickness of individual beds, (2) degree of irregular, wavy bedding, (3) amount of bioturbation, and (4) amount of silt-size to fine-sand-size quartz. However, all units contain neomorphic spar and are partially dolomitized, which causes great difficulties in interpreting the paleoenvironment of this facies. Units C, E, F, J, and L are all very thinly and irregularly-laminated (mm-thick laminae). Silt-size quartz occurs throughout units C, F, and J (1-3%), which also contain numerous horizontal burrows with fine sand-size quartz back-filling (Figures 2.15A, B). Unit E contains the coarsest material: fine sand to coarse silt (0.05-0.15 mm)(5%) occurring not only in the burrows but also in some of the wavy laminae. Unit L contains the most fine-grained material: silts occurring in rare compacted horizontal burrows and sparsely throughout the micrite (3%). All of the detrital quartz grains are subangular to subrounded. In contrast to the mm-scale laminae of the other units, Unit H contains beds that grade from thin (mm-scale) to thick (decimeter scale).

Silty/sandy micrite paleoenvironment

The silty/sandy micrite with horizontal burrows, mm-scale laminae, and wavy bedding is difficult to interpret paleoenvironmentally. The presence of mm-scale laminae indicates that it was a lower-energy environment than the environment of the microbial reefs and oolite facies described in previous sections. The general absence of body fossils indicates that the environment was generally inhospitable for organisms, with the
Figure 2.15. (A) Outcrop photograph of silty/sandy micrite at Fucheng. Staff is 1 meter. (B) Photomicrograph (X-polars) of a horizontal burrow in silty micrite with neomorphic calcite spar. Note the preferential detrital quartz fill in the burrow.
exception of soft-bodied, horizontal burrowers. We consider two different hypotheses: (1) the silty/sandy micrite represents deposition in a deep subtidal zone at or just below storm wave base, or (2) this facies represents a lagoonal environment with restricted circulation. The first hypothesis is based on the presence of horizontal burrows, lack of body fossils, and fine lamination in the micrite (Wilson, 1975). The deep-subtidal interpretation requires several deepening events to have occurred across the carbonate platform. These deepening events could have been caused by either sea-level rise or increased subsidence of the platform. We recognize several problems associated with the deep-subtidal hypothesis: (1) sea level needs to have risen rapidly in order to drown the microbial reefs, (2) evidence for a mechanism to cause the rapid sea level rise is lacking, and (3) the silty/sandy micrite facies is conspicuous only in the Fucheng section. If this facies represented an abrupt rise in sea level, then one might expect to see it synchronously occurring in all three sections.

The restricted-lagoon hypothesis is based on the close association of the silty/sandy micrite with the microbial reefs and inter-reef facies, including the presence of a decimeter-scale, rounded clast of inter-reef-community float-rudstone within the silty/sandy micrite in Unit L (Figures 2.4, 2.11). However, the restricted-lagoon hypothesis is also problematic in that we lack a mechanism that would force repeated, abrupt changes from a high-energy environment to a very low-energy, restricted environment and back again. Each of these hypotheses for the paleoenvironment of the silty/sandy micrite facies has its merits and problems, but the fine laminations and horizontal burrows are inferred to indicate a low-energy environment.
Oncolite Facies

Two units within the Xinchao section contain oncolite, rare archaeocyaths, trilobites, echinoderms, unidentified spar-filled circular fossils, possible brachiopods, peloids, and very-fine to fine-sand-size quartz. The relative abundances of various constituents within a sample from the lower oncolite are tabulated in Table 2.3. The oncolite within the lower unit contains conspicuous *Girvanella*, a filamentous calcimicrobe, which forms clusters and lenses (Figure 2.16). The oncoids are either not well formed or are poorly preserved; they occur as distinctive, laminated, subcircular bodies. The matrix consists of aggrading neomorphic spar, xenotropic to idiotopic dolomite, and subrounded to rounded detrital quartz.

The upper oncolite unit contains more fossil debris than does the lower unit, as well as better-developed oncoids. Archaeocyaths in this unit are all irregular and are very poorly preserved. As with the lower unit, aggrading neomorphic spar and xenotropic to idiotopic dolomite compose the matrix.

As in the Xinchao section, the Shatan section also contains oncolite intervals (Figure 2.3), containing poorly preserved archaeocyaths. Although these transported archaeocyaths are very large, the outer walls are completely abraded. Only a few archaeocyaths could be identified to generic level. The lower oncolite unit (~88-100 m) contains archaeocyaths that are both regular (*?Inessocyathus* sp.) and irregular (*Protopharetra* sp.), which occur in subcircular, faintly microbially mediated, highly bioturbated micrite to pitted oncolite (Figure 2.17). Archaeocyath percentages for this unit only were calculated from slabs, using ArcView software with spatial analyst; percentages range from 9.2 to 18.2% of the rock volume. Within the upper oncolite bed
Figure 2.16. Photomicrograph (X-polars) of *Girvanella* (arrows) found within an oncid from the lower oncoid-bearing micritic beds of the Xinchao Section.
Figure 2.17. Outcrop photograph from the Shatan Section of pitted, oncolite bed. Oncolites are well to poorly formed and some samples contain well-preserved nuclei.
(~106-108 m) of the Xiannudong Formation at Shatan, irregular (Protopharetra sp. and ?Graphoscyphia sp.) archaeocyaths dominate as transported debris in silty micrite with rudimentary laminae. With volumetric ranges from 31.8 to 42.6%, this unit contains a considerably higher percentage of archaeocyaths than the lower unit.

Oncolite paleoenvironment

Oncolites typically form in low-energy environments with intermittent moderate to high-energy fluxes (Wilson, 1975). We interpret the oncolite beds in the Xinchao and Shatan sections to be shallow water, low-energy areas, in particular a lagoon.

Peloidal, Silty Micrite Facies

This facies is present only in the Xinchao and Shatan sections. It is especially thick at Xinchao, forming the thickest unit in this section (Figure 2.3). Peloids typically occur as pods (ranging from 10-40%) within an overall silty micritic matrix. Trilobite, echinoderm, and other unidentifiable fossil fragments are present sporadically throughout the matrix. Bioturbation does occur, but it is not as distinctive as in the Fucheng and Shatan sections because the burrows are not infilled with coarser detrital quartz. Similar to the silty/sandy micrite, the bioturbation in this facies is at a low ichnofacies level of 1 or 2 scale of Droser and Bottjer (1988). As with all of the rocks discussed in this paper, dolomitization is widespread.

The most noteworthy characteristic of these massive peloidal, silty micrite beds is the occurrence of well-preserved Girvanella. Girvanella is present as patches within the micritic matrix; it does not form distinct laminae or oncoids.
At the very top of the Shatan section is a two-meter-thick, pink, peloidal grainstone. The peloids are all well-rounded with no internal fabric. No cross-bedding was observed in the unit, and no other fossils are present.

**Peloidal, silty micrite paleoenvironment**

At both the Xinchao and Shatan sections, the intervals of peloidal, silty micrite represent a quieter water setting than the microbial reefs, float-rudstone, oolite, and oncolite represent (Wilson, 1975). The lack of body fossils in the peloid-rich silty micrite indicates an environment that was not very favorable to organisms. However, the presence of bioturbation indicates that some organisms were inhabiting or at least feeding, but were not preserved (soft-bodied organisms). The peloidal, silty micrite represents a restricted lagoon in which lime mud and peloids were deposited and in which soft-bodied organisms burrowed and feed.

**Paleoenvironmental Synthesis**

The northern margin of the Yangtze Platform, as represented in the three Xiannudong Formation sections, was a shallow-water carbonate platform that encompassed approximately 90 km². The facies described above range from high-energy, shallow subtidal to low-energy, lagoonal. We interpret changes in lithologies to indicate lateral shifts in adjacent facies caused by storm events and recolonization of new habitat by microbialite-reef-building organisms and associated inter-reef-dwelling organisms (Figure 2.18).
Figure 2.18. Schematic block diagram illustrating a "snap shot" of part of the Yangtze Platform during the Early Cambrian, and the various facies of the Xiannudong Formation.
We observed no evidence of archaeocyath-built reefs in the Xiannudong Formation, either as in-situ reef boundstone or as debris in the float-rudstone. All archaeocyaths in the float-rudstone appear as individual cups, with no indication that they were eroded from a reef. Therefore, we conclude that, although archaeocyaths were abundant in the northern part of the Yangtze Platform, they were not building reefs. The float-rudstone is interpreted as storm-churned archaeocyathan communities that were living between the microbial reefs.

At both the Shatan and Fucheng, the dominating facies indicate a shallow-water, high-energy environment on the carbonate platform. At Shatan, ooid shoals dominate the lower two-thirds of the section, overlain by low-relief stromatolites and thrombolites, followed by a 12-m unit of oncolite (Figure 2.3). This indicates that adjacent to the high-energy ooid shoal facies was a low-energy environment that received occasional moderate energy conditions. Shifts between the ooid shoals, microbial reefs, and oncoid bearing micrite represent shifts between these different facies due to small sea level shifts or storm events. Meanwhile, the Fucheng section contains numerous units of microbial reefs with topographic relief and an inter-reefal community of archaeocyaths. Adjacent to this reeal environment, were ooid shoals and possibly a deeper (deep subtidal) environment or a restricted lagoon where silty/sandy lime muds were being deposited (Figure 2.18).

To the south of Fucheng, the Xinchao deposits represent a lagoon with abundant peloidal micrite, patchy microbial build-ups, and few burrows. Occasionally, storms or strong tidal currents would cause shifts in the ooid shoals causing ooids to wash over into the lagoon.
Implications for the Yangtze Platform

Overall, the paleoenvironmental scene indicated by the lithology and facies associations is a carbonate platform. This conclusion is based on the presence of shallow water carbonates deposited across the entire Yangtze Platform with offshore, slope and basinal sediments known from the south and east of the platform (APC, 1985; Zhang and Pratt, 1994; Zhu et al., 2001), and based on the associated carbonate facies. Furthermore, similar carbonate facies and associations as presented here are documented from the southern part of the Yangtze Platform in Yunnan Province by Debrenne and Jiang (1989). We attribute the minor amounts of silt and fine-sand present in all facies to wind-blown processes, which probably was derived from exposed strata in the northwest.

The lithofacies of the Xiannudong Formation indicate an equatorial or subtropical (below 30° north or south) geographic setting for the Yangtze Platform in which carbonate sediments, such as ooids, peloids, lime mud, and reefs are typically cultivated (Wilson, 1975). This inferred position of the Yangtze Platform based on sediments supports the paleogeographic reconstructions in which the position of the Yangtze Platform was within 30° north or south of the equator, but it does not support the high latitude paleogeographic reconstructions.

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References


CHAPTER 3

CHEMOSTRATIGRAPHIC ANALYSIS OF EARLY CAMBRIAN MICROBIAL REEFS, ARCHAEOCYATHAN REEFS, AND ASSOCIATED FACIES IN NEVADA AND SOUTH CHINA: A SURPRISING STORY OF STASIS

Abstract

Mid-to late Early Cambrian sections in Nevada and South China were analyzed for $\delta^{13}$C for correlation purposes and to better describe the chemical these stratigraphic sections represent. Data reveal stasis in all the $\delta^{13}$C records, which strongly contrasts with the Early Cambrian $\delta^{13}$C isotopic profile for the Siberian Platform. We hypothesize three possible explanations for the stasis in the $\delta^{13}$C isotopes: (1) diagenetic alteration, (2) the sections represent only a brief interval of time, and (3) environmental control.

In the mid-Early Cambrian Xiannudong Formation in northern Sichuan and southern Shaanxi provinces, microbial reefs are present in great abundance with archaeocyaths occurring either as low abundance dwellers or as transported debris between the microbial reefs. However, the mid-Early Cambrian Poleta Formation in Nevada contains archaeocyathan-microbial reefs in which archaeocyath abundance increases upsection. Neither of the static $\delta^{13}$C signatures for the Poleta, centered near 0‰, and the Xiannudong, approximately -2.0 to 0‰, are illustrated on the composite $\delta^{13}$C record for the Siberian Platform.
The late-Early Cambrian Tianheban Formation in Hubei province and the Harkless Formation in Nevada represent some of the youngest archaeocyathan reefs in the world. For the Tianheban Formation, the $\delta^{13}C$ values are positive, approximately 0 to 1.0‰, and appear to correlate with positive excursion X on the Siberian Platform $\delta^{13}C$ record. The Tianheban also contains well-developed archaeocyathan-microbial reefs. The $\delta^{13}C$ values from the Harkless Formation become increasingly positive upsection, indicating that productivity was increasing.

None of the three hypotheses for stasis could be definitively accepted or rejected but environmental control does appear to be the simplest and least problematic explanation. Therefore, the static $\delta^{13}C$ values are interpreted to represent interbasinal environmental conditions. This suggests that interbasinal controls on $\delta^{13}C$ may commonly overprint the secular $\delta^{13}C$ record.
Introduction

The chemostratigraphy that we describe and interpret in this paper is part of a larger study of the global collapse of archaeocyathan-calcimicrobial ecosystems toward the end of the Early Cambrian using data from the Yangtze Platform and Laurentia. The study involves two archaeocyath-rich intervals in Nevada, U.S.A. (Poleta Formation and Harkless Formation) and two approximately coeval intervals in northern South China (Xiannudong Formation and Tianheban Formation) (Figs. 3.1, 3.2).

Because of endemic faunas, global biostratigraphic correlation of Lower Cambrian strata is problematic. It is commonly hypothesized that systematic variations in $\delta^{13}C$, as recorded in carbonate rocks, are secular, and such variations are used by many researchers as correlation tools and as proxies for paleoclimatic, paleo-ocean chemical, and paleotectonic change (Brasier 1993; Corsetti 1998; Veizer et al. 1999; Montanez et al. 2000). To date, the Siberian Platform is the only continent for which a composite $\delta^{13}C$ profile has been constructed for the Early Cambrian. The Siberian Platform profile reflects a very dynamic pattern of positive and negative excursions for the Ediacaran through the Early Cambrian (Brasier et al. 1994; Brasier and Sukhov 1998) (Fig. 3.3).

In an attempt to use carbon isotopic chemostratigraphy as a tool for correlating Laurentian strata with Yangtze Platform strata, and also to test the usefulness of the Siberian Platform composite profile for global correlation, we conducted a meter-scale chemostratigraphic study of the four archaeocyath-rich formations mentioned above. The results indicate surprising intervals of isotopic stasis. Although this isotopic study turned out to be disappointingly unhelpful for intercontinental correlation, we report important
Figure 3.1. A, Map of China showing the location of the three measured sections (stars). B, Location map of Esmeralda County, Nevada showing the locations of the with Poleta Formation (Stewart's Mill locality) (star) and the Harkless Formation (triangle). Shaded pattern indicates major mountain ranges in Esmeralda County.
Figure 3.2. Correlation diagram for the upper Early Cambrian of South China, Laurentia, and the Siberian Platform. Formations are placed in Stages and biozones based on biostratigraphy as described in the text (Rowland and Gangloff, 1988; Yuan and Zhang 1981; Qin and Yuan 1984; Zhang 1989; Ye et al. 1997; Yuan et al. 2001; Zhu et al. 2001; Zhuravlev and Riding 2001; Hollingsworth 2004; Shergold and Cooper 2004). Formations in bold, italics font are those included in this study.
Figure 3.3 Composite $\delta^{13}C$ profile for the Siberian Platform. This composite contains the most $\delta^{13}C$ data for any Early Cambrian locality in the world. No Early Cambrian composite sections for the U.S or China exist with such large data sets. Roman numerals designate positive isotopic excursions. N-D is the Nemakit-Daldynian (From Brasier et al. 1994).
new isotopic data for stratigraphic intervals of Laurentia and the Yangtze Platform, and raise questions about the global uniformity of $\delta^{13}\text{C}$ values in the Early Cambrian.

Methods

We measured and sampled five sections for isotopic analyses, three sections in South China and two sections in the Great Basin. The three sections in South China include two sections (Fucheng and Xinchao) of the Xiannadong Formation and one section of the Tianheban Formation. The two Great Basin sections are the Stewart's Mill locality of the Lower Member of the Poleta Formation and a section of the upper part of the Harkless Formation (Site 1 of Hicks, 2001) both of which are in Esmeralda County, Nevada, U.S.A (Fig. 3.1).

We sampled each section at approximately 1-meter intervals, except where the strata were covered or visibly unsuitable for isotopic analyses, such as areas with numerous veins or obvious erosional features. All collected samples were thin sectioned and petrographically analyzed for obvious diagenetic alteration. The billet cut from the slides was retained for drilling. Each slide is the mirror image of the billet from which it was cut, therefore the billet can be drilled in the same location as described in thin section. We analyzed each thin section by cathodoluminescence (CL) at UNLV, under 10-11 kV with a 0.8-0.9-milliamp beam current. Areas with dark red luminescence represent unaltered regions, while areas with bright orange and red luminescence have been diagenetically altered (Corsetti, 1998). Dark luminescence or non-luminescence characterizes carbonate rocks that have not been dissolved and replaced by Mn-bearing meteoric water (Corsetti, 1998). Only the best-preserved samples were chosen for
isotopic analysis; of 286 samples collected for isotopic analyses, 194 proved to be suitable. At UNLV, we microdrilled approximately 100µg of powder from each suitable sample. The powdered samples were analyzed for δ¹³C and δ¹⁸O on the University of Maryland’s Isoprime Dual Source Gas Source Mass Spectrometer under the direction of Alan Jay Kaufman. The powdered samples were treated with 100% pure phosphoric acid in order to convert the carbon to CO₂ gas. The gas was then analyzed for δ¹³C. All carbon and oxygen samples were corrected to a house standard that is corrected to PDB and are measured in parts per mil (‰).

All percentages of archaeocyaths and other constituents of the carbonates were calculated from point counts on a Hacker Instrument, James Swift point counter. For each 3 x 2 inch slide, 400 points were counted at a four-increment spacing.

**Stratigraphy and Sedimentology**

Xiannudong Formation

In the two measured sections of the Xiannudong Formation, we distinguish three lithofacies: microbial reefs, silty/sandy micrite, and oolite. The thickness of the Xiannudong Formation differs greatly between the two sections. At the Fucheng section, located near the town of Fucheng in southern Shaanxi Province (Fig. 3.1), the 67.3 meter thick Xiannudong Formation conformably overlies the Guojiaba Formation (Fig. 3.4). At this section, the Xiannudong Formation contains numerous cyclical microbial reef complexes with archaeocyathan-rich float-rudstone between the stromatolite and thrombolite reefs. Archaeocyaths did not form reefs in any of the studied Xiannudong Formation localities. Instead, archaeocyaths form an inter-reef
Figure 3.4. Stratigraphic columns from the two sections of the Xiannudong Formation of China and the one section of Poleta from Nevada, U.S.A., with the respective $\delta^{13}C$ and $\delta^{18}O$ values. Stratigraphic units are in meters. $\delta^{13}C$ and $\delta^{18}O$ values are in parts per million (‰) PDB.
community and are present in very low abundance (approximately 1.0%) between the microbial reefs. The archaeocyathan floatstone/rudstone is enriched in 'regular' archaeocyaths (Orders *Ajacicyathida* and *Capsulocyathida*); this contrasts with the archaeocyaths present in the microbial reefs themselves, which are all 'irregulars' (Order *Archaeocythida*). Interbedded and occasionally interfingering with the microbial reef complexes is cross-bedded oolite.

Multiple units of wavy-bedded, moderately bioturbated, silty/sandy micrite repeat throughout the Fucheng section. We interpret these reoccurring changes in lithofacies to represent small sea-level fluctuations and/or small environmental changes, which shifted the adjacent facies (Hicks and Rowland, in prep).

The Xinchao section of the Xiannudong Formation is located approximately 15 km to the west of the Fucheng section, near the town of Xinchao in northern Sichuan Province (Fig. 3.1). Here, the Xiannudong Formation is 114 m thick, which is much thicker than in the Fucheng section. Overall, the Xiannudong in the Xinchao section consists of multiple, thick intervals of thinly bedded micrite to pellooidal, silty/sandy micrite and oolite. Only two intervals contain archaeocyaths, which occur as constituents in a float-rudstone that is similar to the Fucheng float-rudstone. The multiple cycles of stromatolitic and thrombolitic reefs with micrite and silty/sandy micrite and oolite, which characterize the Xiannudong Formation at Fucheng, do not occur at Xinchao. The presence of thick intervals of peloidal micrite indicates a low energy setting for the Xinchao section. Shifts in the facies here are also attributed to possible sea-level changes or other environmental changes (Hicks and Rowland, in prep.)

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Lower Member of the Poieta Formation

The Lower Member of the Poieta Formation is exposed in Esmeralda County, Nevada and in the White-Inyo Mountains in California. The section used in this study is the Stewart's Mill locality, which lies northwest of the town of Goldpoint, Nevada (Fig. 3.1). At the Stewart's Mill locality, the Poieta Formation conformably overlies the Campito Formation. The Lower Member of the Poieta at Stewart's Mill is approximately 107 meters thick (Rowland and Gangloff 1988). Similar to the Xiannudong at Fucheng, the Lower Poieta illustrates laterally adjacent facies changes with a delicate interplay between archaeocyathan-microbial reefs and migrating oolitic shoals. Repeating intervals of archaeocyathan-microbial reefs, packstone, wackestone, ooid grainstone, and grapestone range between 1 to 10 meters thick.

The reefs range from thrombolite to Renalcis-archaeocyathan boundstone, with sparse to abundant archaeocyaths, trilobite fragments, and echinoderm plates. These thrombolitic to Renalcis-archaeocyathan boundstones have been interpreted to represent a shallow subtidal depositional environment (Rowland and Gangloff, 1988). Laterally associated wackestone and micrite represent material shed from the boundstone.

Upsection the boundstone becomes more cavernous, with archaeocyaths becoming more abundant (Rowland and Gangloff 1988; Rowland and Hicks 2004). The boundstones vary from 2 m to approximately 20 meters thick with conspicuous in-situ 'regular' and 'irregular' type archaeocyaths, Renalcis, and Epiphyton. Continuing upsection, archaeocyaths increase in abundance to a maximum of 38% by volume (Rowland and Gangloff 1988). Archaeocyaths reported from the Stewart’s Mill locality include Protopharetra, Dailycyathus, Retilamina, Diplocyathellus, Ethmophyllum, and
other unidentifiable archaeocyath genera (Rowland and Gangloff 1988). The diversity decreases upsection, with *Protopharetra* and *Dalicyathus* dominating the upper boundstones.

Interbedded with the boundstone are oolite, packstone, and fossiliferous wackestone (Rowland and Gangloff 1988). These various lithologies represent adjacent facies that replaced one another as sea-level rose, shifting boundstone and oolite facies shoreward.

**Tianheban Formation**

The Wangjiaping section of the Tianheban Formation is located near the city of Yichang, Hubei Province, China (Fig. 3.1). The Tianheban Formation in this section is 69 meters thick (Fig. 3.5). The base of the Tianheban Formation contains thin interbeds of siltstone and micrite, with micrite becoming more dominant upsection. Overlying the micrite are oolite and fossiliferous oncoidite. Burrow-mottled micrite dominates the middle portion of the section with more fossiliferous oncoidite overlying the mottled micrite. Above this oncoidite lies the single recognizable, mound-shaped, archaeocyathan reef within this section (2.1 m thick and approximately 1.8 m in length). This reef contains only one genus of archaeocyath, *Archaeocyathus* sp., which comprises over 33% of the reef by volume. Immediately overlying the archaeocyathan-microbial reef is thin veneer of fossiliferous-oid-oncoid-packstone. The remaining section contains massive, burrow-mottled micrite, with one interval of nodular micrite (Fig. 3.5).

In contrast to the archaeocyath-rich sections of the Xiannudong, Poleta, and Harkless formations, the Wangjiaping section records a low-energy environment. In a previous study of the Tianheban Formation at the Wangjiaping section, Debrenne et al.
Figure 3.5. Measured sections and corresponding $\delta^{18}O$ and $\delta^{13}C$ chemostratigraphy for the Waijaping section of the Tianheban Formation, and the upper part of the Harkless Formation. Stratigraphic units are in meters. $\delta^{13}C$ and $\delta^{18}O$ values are in parts per million (‰) PDB.
(1991) interpreted the archaeocyathan-microbial reef to have formed below wave base in low-energy conditions. That interpretation was based on the presence of abundant lime mud and a lack of fibrous cements, which are known to form in high-energy environments (Mathews 1974). However, samples collected by us do contain fibrous cements along with blocky cements in a fenestral fabric, in particular birds-eye fabric. The reef flanks tend to have fibrous cements, while the reef base and core contain fenestral birds-eye fabric. The reef crest contains both fibrous cements and birds-eye fabric. We interpret these variations in cement to be due to the reef’s exposure to differential wave energy. The reef flank and crest would have been in a slightly higher energy regime than the base or core, therefore facilitating the growth of primary fibrous cements.

We agree with Debrenne et al. (1991) that this reef formed in a low-energy environment, but the distribution of cements leads us to conclude that the reef formed in very shallow water, shallower than below wave base. Fenestral fabrics are interpreted as a shallow water desiccation fabric, such as would occur on a supratidal flat (Wilson, 1975). Tides or storms would have increased the energy around the reef, resulting in the formation of fibrous cements on the flanks and crest. This would also explain the fossiliferous ooid, oncoid packstone that flanks and overlies the reef.

Harkless Formation

The Harkless Formation section analyzed in this study is located in Lida Valley northeast of the town of Goldpoint, Esmeralda County, Nevada (Fig. 3.1). This section of the Harkless Formation contains three patch reefs (Hicks, 2001). The basal portion of the section consists entirely of highly weathered, green/tan shale with micaceous partings.
(Fig. 3.5). The shale is slightly bioturbated and contains the ichnofossil *Planolites*. Abruptly overlying the shale is a single bed of highly fossiliferous, green, oncolite-bearing wacke-packstone. Fossils in this bed include trilobite spines, echinoderm plates, oncoids with nuclei of trilobite spines, and highly broken, unidentifiable fossil fragments. Conformably overlying the oncolite wacke-packstone bed is rubbly, green/tan shale with micaceous partings. This shale has the same characteristics as the shale below the oncolite wacke-packstone.

A cliff-forming, four-meter-thick interval of highly fossiliferous, gray packstone overlies the rubbly shale. Within this massive packstone unit, lie three 1.5 to 2.0-meter-thick archaeocyathan-calcimicrobial reefs. All three reefs are within the same horizon in outcrop and are separated from each other by approximately 12 meters of packstone. The contact beneath each reef is sharp and conformable, while the overlying and flanking contacts are erosional. A high diversity of fossils and coated grains is present within the packstone, including *Salterella*, echinoderm plates, trilobite spines, brachiopods, oncoids, ooids, and peloids. Overlying the gray packstone is a wavy bedded packstone conglomerate in which the packstone clasts are identical to the underlying packstone. The packstone clasts lie within a calcareous sandstone matrix; no preferred orientation of the clasts is apparent, but imbricated clasts do occur at the contact with the overlying sandstone.

The packstone conglomerate is gradationally overlain by orange, coarse- to fine-grained, calcareous sandstone. The calcareous sandstone is wavy bedded with imbricated packstone conglomerate clasts in the basal portion. These imbricated clasts indicate a paleocurrent direction toward paleo-north (offshore). Faint ripple marks occur in the
upper portion of the calcareous sandstone. In some places, the overlying calcareous sandstone is in direct contact with the reef, with an erosional boundary between the two. Above the calcareous sandstone are interbedded green/tan rubbly-weathering shale, siltstone and massive bedded quartzitic sandstone.

The presence of primary cavities filled with fibrous cements and stratified lime mud throughout the framestone indicates that these reefs formed in a shallow subtidal zone with moderate to high-energy wave activity (Hicks, 2001).

Biostratigraphy

Biostratigraphy did not prove to be very useful for correlating the Nevada sections with the Chinese sections. The approximate correlation between the Poleta and Xiannudong formations is based on trilobites and their correlation to the Siberian Platform (Figure 3.2). The Lower Member of the Poleta Formation lies within the *Nevadella* Zone, upper Montezuman Stage (Laurentian Stage), which correlates to the upper Atdabanian to lower Botomian stage of the Siberia Platform (Zhuravlev and Riding 2001; Hollingsworth 2004; Shergold and Cooper 2004) (Fig 3.2).

The age of the Xiannudong Formation is slightly less well established. Yuan and Zhang (1981), Qin and Yuan (1984), and Zhang (1989) all place the Xiannudong Formation as straddling several Chinese trilobite biozones, *Malungia* and *Yunnanaspis-Yiliangella*, which are in the Tsanglangpu (Canglangpuan) Stage of China. However, Ye et al. (1997), and Yuan et al. (2001) place the base of the Xiannudong Formation a bit lower, in the upper *Eoredlichia-Wutingaspis* Zone, but still in the *Malungia Zone*, and the *Yunnanaspis-Yiliangella Zone*, straddling the upper Qiongzhusi (Chiungchussan) Stage.
and the lower Tsanglangpu (Canglangpuan) Stage. This latter placement correlates to the upper Atdabanian to lower Botomian on the Siberian Platform, and upper Montezuman Stage on Laurentia (Zhuravlev and Riding 2001; Hollingsworth 2004; Shergold and Cooper 2004) (Fig. 3.2). These age determinations for the Xiannudong are based on the presence of the trilobites *Malungia granulose, Micangshania gracilis* (Yuan and Zhang 1981; Zhang 1989), *Yunnanocephalus, Zhenbaspis, Eoredlichia,* and *Kuanyangia* (Yuan et al. 2001). Thus the Lower Poieta and the Xiannudong formations are approximately the same age, but, due to endemism of Laurentian and Yangtze Platform trilobites, their precise relative ages are not known.

The Tianheban Formation lies within in the *Megapalaeolenus Zone* in the upper Tsanglangpu (Canglangpuan) Stage (Yuan and Zhang 1981; Zhang 1989; Ye et al. 1997; Yuan et al. 2001). This age is based on the presence of the trilobites *Megapalaeolenus deprati, Xilingxia ichangensis, Kootenia,* and *Redlichia dobayashii* (Yuan and Zhang 1981). The *Megapalaeolenus Zone* correlates to the upper Toyonian of the Siberian Platform and upper *Bonnia-Olenellus* trilobite zone, Dyeran Stage of Laurentia (Zhuravlev and Riding 2001; Hollingsworth 2004).

The Harkless Formation lies within the *Bonnia-Olenellus Zone,* Dyeran Stage of Laurentia (Hollingsworth, 2004). The section analyzed in this study includes just the upper part of the Harkless Formation (the Saline Valley equivalent strata), which is upper *Bonnia-Olenellus Zone;* this correlates to the upper Toyonian Stage of the Siberian Platform. The age of the upper Harkless is constrained by the trilobite *Wanneria,* which is medial *Bonnia-Olenellus* (Palmer and James, 1979). This age is further supported by the archaeocyath assemblage within the upper Harkless Formation, which is similar to the
archaeocyathan assemblage of the well studied, medial to upper-\textit{Bonnia-Olenellus} zone, Forteau Formation of Labrador (Palmer and James 1979; James and Klappa 1983; Hicks, 2001; Hollingsworth 2004; Palmer, personal communication).

Chemostatigraphic Analysis

Results and Discussion

The $\delta^{13}C$ and $\delta^{18}O$ values for each section are provided in Tables 3.1-3.5 of Appendix 1. Figures 3.4 and 3.5 graphically illustrate the isotopic values with their corresponding measured sections. The most obvious feature of each of the $\delta^{13}C$ plots is the lack of large excursions. This is surprising, in view of the pattern on the Siberian Platform (Fig. 3.3). Four of the plots show relative stasis. The extreme example is the Lower Member of the Poieta Formation; though more than one hundred meters of section, the $\delta^{13}C$ data record only a very gradual drift of approximately 1/oo (Fig. 3.4).

The Chinese sections display a slightly unstable $\delta^{13}C$ record, but none of them show excursions comparable to those on the Siberian Platform. The $\delta^{13}C$ values of the Harkless Formation vary from 0 to $-3.8^{\circ}/oo$, showing the largest variation of the five intervals studied. However, the Harkless data set contains only four points (Fig. 3.5), so it is not possible to draw any meaningful conclusions about the isotopic trends within the Harkless Formation or to use these values to correlate the Harkless to the Siberian Platform.

There are three possible explanations for the surprising stability of the $\delta^{13}C$ values obtained in this study: (1) diagenetic alteration has obliterated the primary isotopic signature, (2) the sections studied represent only very brief intervals of Early Cambrian
time, or (3) local environmental factors caused the $\delta^{13}C$ values recorded in these localities to be different than those recorded on the Siberian Platform. Implicit in the second hypothesis is the conclusion that local environmental factors can overprint the secular $\delta^{13}C$ values, and therefore the Siberian Platform profile cannot be used as a tool for global correlation. We will consider each of these three hypotheses.

**Diagenetic Alteration Hypothesis**

We consider diagenesis to not be the controlling factor behind all of the invariant $\delta^{13}C$ data values. As mentioned in the “Methods Section”, both field and laboratory precautions were taken to avoid altered samples. We further checked for alteration by analyzing the $\delta^{18}O$ in each sample. During carbon isotopic analyses, $\delta^{18}O$ was also measured and plotted (Figs 3.4 and 3.5). Oxygen isotopic values are more vulnerable to diagenetic alteration than are carbon isotopic values (Kennedy, 1996). For carbonates, the primary $\delta^{13}C$ signature has a high preservation potential compared to $\delta^{18}O$ because carbonate is a major component of carbonate rocks but only a minor component in diagenetic fluids (Kennedy, 1996).

Large negative excursions in the $\delta^{18}O$ values, such as the $-18^{\circ}/_{oo}$ value observed at approximately 10 m in the Poleta section (Fig. 3.4), accompanied by a smaller $1.0^{\circ}/_{oo}$ $\delta^{13}C$ negative jog suggests alteration. The strongly negative nature of the $\delta^{18}O$ values for the Poleta and Harkless formations suggests that strata were exposed to fluids, but this does not necessarily mean that the carbon isotopic values, which are much more robust than oxygen, were altered. Most Proterozoic and Cambrian sections of the southwestern U.S. show $\delta^{18}O$ values more negative than $-10^{\circ}/_{oo}$ (ppm), and the $\delta^{13}C$ values are still considered primary (Brasier 1993; Corsetti and Kaufman 1994).
No single test exists that will unequivocally determine whether a particular sample is altered or unaltered. Samples that pass the field, petrographic, and cathodoluminescence tests are assumed to provide primary $\delta^{13}C$ signatures (Corsetti and Kaufman 1994; Corsetti 1998). Consequently, most of the Poleta Formation $\delta^{13}C$ values are considered to be primary, however all three Chinese $\delta^{13}C$ plots are viewed with some caution because $\delta^{13}C$ and $\delta^{18}O$ covary. Because two of the four Harkless Formation isotopic samples were obtained from highly fossiliferous packstone, and contamination due to vital effects from organisms is possible, we do not have confidence that the Harkless Formation $\delta^{13}C$ values are very meaningful.

**Brief Interval Hypothesis**

Because the absolute values of the $\delta^{13}C$ data from Nevada and China are similar to coeval sections in Siberia (Fig. 3.3) (Brasier et al. 1994; Brasier and Sukhov 1998) and Mongolia (Brasier et al. 1996), each of the stratigraphic intervals examined in this study may represent only a brief “snapshot” of Early Cambrian time that is too brief to capture the $\delta^{13}C$ excursions that have been documented on the Siberian Platform. The composite $\delta^{13}C$ curve for the Siberian Platform integrated multiple formations that range from 110 to 250 m in thickness and span from the Ediacaran to the base of the Middle Cambrian (Brasier et al. 1994). The Poleta Formation and the Xinchao section of the Xiannudong Formation are over 100 m thick, but the exact length of time represented in each of these formations cannot be established.

In order to make any real conclusion on the importance of the stasis in the Poleta Formation, we need to sample and analyze more sections of the Poleta Formation and also attain better age constraints and subsidence rates for backstripping analyses.
Environmental Control Hypothesis

With respect to the environment that would produce such invariant $\delta^{13}C$ values, we have several hypotheses. Positive $\delta^{13}C$ values could indicate that primary productivity is high and photosynthesizing organisms are preferentially sequestering the light carbon isotope, $^{12}C$ and/or increased stratification in the oceans with organic preservation in anoxic waters (Corsetti 1998; Kump and Arthur, 1999; Montanez et al. 2000). Conversely, negative $\delta^{13}C$ values typically reflect environments in which organic carbon is exhumed or primary productivity is greatly diminished (Corsetti 1998; Montanez et al. 2000). These variations in $\delta^{13}C$ are interpreted as global and are used as a global correlative tool for the Neoproterozoic and Cambrian strata (Brasier 1993; Corsetti 1998; Veizer et al. 1999; Montanez et al. 2000). However, the $\delta^{13}C$ record may also be intrabasinal, where local values can mask or smooth primary signals (Pelechaty et al. 1996).

The 0 to $-2.0^{\%}_{oo}$ $\delta^{13}C$ values recorded in the Xiannudong Formation indicate an environment in which the primary productivity appears to be slightly diminished. The presence of both thrombolitic and stromatolitic reefs argues against low primary productivity as these types of reefs are hypothesized to have been built by cyanobacteria (Riding 1990). Therefore, low productivity does not explain the negative $\delta^{13}C$ values recorded in both sections of the Xiannudong Formation.

With $\delta^{13}C$ values around 0 to $-1^{\%}_{oo}$, the Poleta Formation records a similar $\delta^{13}C$ record as the Xiannudong Formation. However, in the Poleta Formation, archaeocyaths are the main reef-builder with an upward trend toward increasing archaeocyath
abundance from 3% to 38% (Rowland and Gangloff 1988). This presents an interesting contrast with the Xiannudong Formation, where archaeocyathan reefs do not occur.

The $\delta^{13}$C values of the Tianheban Formation are also static in comparison with the Siberian Platform, but slightly positive (0 to 1‰). The small positive excursion at the base of the section may represent excursion X on the Siberian Platform $\delta^{13}$C plot (Fig. 3.3). Based on the positive $\delta^{13}$C signature, the Tianheban best correlates to the uppermost Early Cambrian, which correlates well with the biostratigraphic control. The data presented in this study illustrates that much more work needs to be done on isotopic signals globally for this interesting period of the Early Cambrian.

Conclusions

The following general conclusions were made based on this study.

1) None of the five chemostratigraphic sections [Poleta, Xiannudong (Fucheng and Xinchao), Tianheban, and Harkless formations] show any distinct $\delta^{13}$C excursions; rather they record a history of isotopic stasis. This result is not useful for intercontinental correlation.

2) We conclude that the stasis in the $\delta^{13}$C signatures, especially for the Poleta Formation, is not entirely due to diagenetic alteration.

3) Because the Siberian Platform $\delta^{13}$C record does not record the stasis observed in the Poleta Formation, the Lower Poleta $\delta^{13}$C results either (1) record a localized, basinal condition, or (2) the Siberian Platform profile does not record a globally correlatable $\delta^{13}$C signature.
4) Similar to the Poleta Formation, the δ¹³C record of the Xiannudong is also interpreted to record an intrabasinal environmental condition.

5) The positive values of the Tianheban Formation correlate well with the mid-to latest Early Cambrian (Toyonian) on the Siberian Platform at Brasier et al.'s (1994) positive excursion X. However, interpretations are viewed with caution due to the covariance observed between δ¹³C and δ¹⁸O.

6) Each of the sections analyzed for δ¹³C produced a static δ¹³C record that is not present within the δ¹³C record of the Siberian Platform. We suggest that interbasinal environmental controls may have a more profound effect on the secular δ¹³C record than previously imagined.

7) With the existing data, none of the three hypotheses for the surprising isotopic stasis observed in this study can be falsified, although the localized environmental hypothesis is accepted as the least problematic.

8) More δ¹³C chemostratigraphic data need to be collected from all these formations, in particular the Poleta and Harkless formations, in order to better understand the δ¹³C record in Laurentia and globally.

Acknowledgments

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References


Table 3.1. $\delta^{13}$C and $\delta^{18}$O values for the Poleta Formation. Sample numbers correspond with stratigraphic measurements (meters). Corr = corrected data, sd = standard deviation, PDB = Pee-dee belemnite standard.

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<th>sample</th>
<th>$^{13}$C raw</th>
<th>$^{13}$C corr</th>
<th>sd $^{13}$C</th>
<th>$^{18}$O raw</th>
<th>$^{18}$O corr</th>
<th>sd $^{18}$O</th>
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<td>-14.64</td>
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Table 3.3. \( \delta^{13}C \) and \( \delta^{18}O \) values for the Xinchao Section of the Xiannudong Formation

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Table 3.4. δ¹³C and δ¹⁸O values for the Tianheban Formation

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Table 3.5. $\delta^{13}$C and $\delta^{18}$O values for the Harkless Formation.

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CHAPTER 4

SYSTEMATIC AND MORPHOLOGIC TRENDS IN ARCHAEOCYATHS THROUGH THE EARLY CAMBRIAN

Abstract

In order to better understand the mechanisms related to archaeocyathan reef decline, archaeocyath extinction, and the 40 Ma metazoan reefless gap, we examined archaeocyathan morphology and systematics from their peak reef building (mid-Early Cambrian) through their decline (end-Early Cambrian) from western Nevada (Poleta and Harkless formations of Nevada) and from the Yangtze Platform of China (Xiannudong and Tianheban formations). The most distinct trend observed is the rapid faunal changeover from predominately regular archaeocyaths to predominantly irregular archaeocyaths by the end of the Early Cambrian. This trend is observed in both the strata studied and in other previously published literature. Another distinctive trend involves the apparent thickening of irregular intervallar elements through the Early Cambrian. Neither the outer nor inner walls of the irregulars vary in thickness through time, but a thickening is observed in the intervallum elements of the irregulars.

We suggest that both of these trends indicate that irregular archaeocyaths had a physiological advantage over regulars, which allowed for irregulars to quickly out-compete regulars towards the end of the Early Cambrian during a time of putative climate change.
change. We hypothesize this advantage to be the presence of photosymbionts, which makes calcification more favorable even under conditions of reduced carbonate saturation. Carbon mass-balance models indicate that atmospheric pCO$_2$ was rising in the Early Cambrian, which would have decreased carbonate saturation state, inhibiting calcification. Furthermore, during the Early Cambrian sea-surface temperatures are also reported as rising. These two climatic variables are hypothesized to have contributed to the decline of the archaeocyathan reef ecosystem and the 40 Ma metazoan reefless gap that followed. No direct evidence has yet been observed that links climate change to archaeocyathan decline, but we suggest that rising pCO$_2$ and sea surface temperatures continues to be the most probable mechanism.
Introduction

Reefs have existed since the Archean Eon. Archean and Proterozoic reefs were built exclusively by microbes. However, in the Early Cambrian, the appearance of archaeocyaths ushered in the beginnings of metazoan-calcimicrobial-built reefs.

Archaeocyaths are an extinct class of calcareous sponges, which are divided into two informal groups, 'regulares' and 'irregulares' (Debrenne et al., 2002). These two groups evolved at the same time, and they are typically found inhabiting the same reefs and occupying the same ecological niches (Debrenne and Zhuravlev, 1992; Debrenne et al., 2002). Irregulars are distinguished from regulars by their more complex morphologies and their placement of living tissue within the skeleton (Debrenne and Zhuravlev, 1992; Debrenne et al., 2002).

Archaeocyaths are known only from the Cambrian System (543- 490 Ma). They first appeared in the Tommotian Stage of the Early Cambrian Epoch, exclusively on the Siberian Platform. During the subsequent Early Cambrian stages they rapidly diversified and dispersed globally, achieving their peak diversity in the mid-Early Cambrian (Atdabanian/Botomian) (Fig. 4.1). In the late-Early Cambrian, archaeocyaths, although still globally dispersed, declined in diversity and finally disappeared at about the end of the Early Cambrian. Only two post-Early Cambrian occurrences of archaeocyaths have been documented, one in the Middle Cambrian and another in the Upper Cambrian. Both of these post-Early Cambrian occurrences are in Antarctica and both are irregular archaeocyaths (Debrenne et al., 1984; Wood et al., 1992).

The global decline of archaeocyaths was relatively rapid (approximately 8 Ma), but the nature of this decline and the mechanisms behind it are not well understood.
Figure 4.1. Spindle diagram illustrating the number of archaeocyathan genera during the Early Cambrian. This diagram is modified from Rowland and Hicks (2004).
Zhuravlev and Wood (1996) argued that the Sinsk Event, which brought anoxic waters onto the carbonate shelves, greatly reduced the generic diversity of sessile organisms in the Botomian. This was followed by a global regression, the Hawke Bay Regression (Palmer and James, 1979), in the Toyonian Stage, which is hypothesized to have led to the extinction of the remaining archaeocyaths (Wood, 1999). These two events—the Sinsk Event and the Hawke Bay Regression—doubtless took a heavy toll on archaeocyathan habitat, but they were relatively brief phenomena, after which metazoan reef ecosystems should have been able to recover within a few million years. However, after the disappearance of archaeocyathan reefs at the end of the Early Cambrian, there followed an extraordinarily long, 40 Ma interval during which metazoan reefs were essentially nonexistent anywhere on Earth (Rowland and Shapiro, 2002). This suggests that the disappearance of archaeocyathan reefs at the end of the Early Cambrian represents a significant global deterioration in environmental conditions conducive for the growth of metazoan reefs. Furthermore, it is well established that other environmental changes were also occurring in the Early Cambrian, which may have played a role in the disappearance of archaeocyaths and the 40 Ma interval that lacked conspicuous metazoan-built reefs. Specifically, atmospheric CO$_2$ levels are inferred to have been rising very rapidly in the Early Cambrian (Berner, 1991, 1994; Berner and Kothavala, 2001), along with rising sea surface seawater temperatures (Karhu and Epstein, 1986).

In this study, we attempted to test the hypothesis that global environmental changes, other than sea level change, contributed to the collapse of the Earth’s first metazoan reef ecosystem and the 40 Ma hiatus in metazoan reef-building. In order to test
that trends in archaeocyaths are global, we examined archaeocyathan generic diversity, biomass, and morphologic variations in western North America and South China, from the Atdabanian-Botomian to the Toyonian (approximately 10 Ma), using both field and laboratory observations as well as data from the published literature. Because there are not yet globally recognized stages for the Early Cambrian, we use Siberian stage nomenclature (Fig. 4.1), which is widely used by archaeocyath workers.

Methods

One month of fieldwork in China was conducted in 2002. We measured and sampled three sections of the Atdabanian/Botomian Xianmuqiang Formation in southern Shaanxi and northern Sichuan provinces, and one section of the Toyonian Tianheban Formation in Hubei Province (Fig. 4.2). Fieldwork in southwestern U.S. was conducted in 2003. We measured and sampled one section of the Atdabanian/Botomian Lower Member of the Poleta Formation in Nevada, and four sections of the Toyonian Harkless Formation, also in Nevada (Figs. 4.2, 4.3). All samples were thin sectioned for taxonomic, morphological, and paleoecological analyses.

In thin section, archaeocyaths were identified to the genus level. Species were not distinguished due to the problematic nature of archaeocyathan species identification. While determining the generic diversity of archaeocyaths, we also measured the relative biomass of regular versus irregular archaeocyaths. Relative biomass was measured by counting individuals in each thin section, and tabulating the number of regulars and irregulars. Seventy-nine, 3 x 2 inch thin sections were used in this part of the study. For
Figure 4.2. Location maps of field areas. (A) Map of China showing the location of the three measured sections (stars). The three Xiannudong Formations sites are: F = Fucheng section; X = Xinchao section and S = Shatan section. The Tianheban Formation section is called Wangjiaping. (B) Location map of part of Esmeralda County, NV with the Poleta Formation, Stewart's Mill locality (star) and the Harkless Formations four sections (triangle) marked.
Figure 4.3. Correlation diagram for the upper Early Cambrian of South China, Laurentia, and the Siberian Platform. Formations are placed in Stages and biozones based on biostratigraphy (Rowland, 1978; Yuan and Zhang, 1981; Qin and Yuan, 1984; Zhang, 1989; Ye et al., 1997; Yuan et al., 2001; Zhu et al., 2001; Zhuravlev and Riding, 2001; Hollingsworth, 2004; Shergold and Cooper, 2004). Formations in bold, italic font are those included in this study.
the purpose of measuring the thickness of the outer walls, inner walls, and intervallum elements, we used only the best-preserved samples from the seventy-nine thin sections.

Skeletal elements chosen for measurement are those that are free of encrusting calcimicrobes, display minimum diagenetic alteration, and have distinct margins. Due to the vagaries of preservation, it was not practical to employ a rigorous protocol to ensure randomly selected samples; we measured as many well-preserved elements as possible following the same procedure for inner walls, outer walls, and intervallum elements. Thus, if any researcher bias inadvertently occurred, such bias should apply equally to all of the elements measured. Furthermore, our initial hypothesis was that the elements would become thinner over geologic time. This hypothesis was completely falsified by the data. We are confident that the results presented in this paper are not artifacts of researcher bias. To ensure that skeletal thickness variations were not ontogenetic, measurements were made on both longitudinal and serial transverse sections. No archaeocyath worker has ever documented ontogenetic variation in skeletal element thickness. Based on our measurements, the thickness of a particular element did not change over the length of the longitudinal section or from one serial transverse section to another.

In addition to the samples that we collected from China and Nevada, we conducted a literature review to compile a database on worldwide archaeocyathan occurrences from the Tommotian to the Toyonian. This database includes information on the formations, ages, archaeocyathan generic diversity, numbers of irregulars and regulars, diversity of other organisms in association with the archaeocyaths, size of reefs (if present), presence of branching archaeocyaths, percentage of calcimicrobes and their
identity, and type of sediments in association with the archaeocyaths and/or the reefs. The database currently contains fifty-six entries. It is by no means complete and will continue to be expanded in the future, but it added greatly to this study by providing data on archaeocyathan generic diversity through time at localities throughout the world. Because thickness of skeletal elements of archaeocyaths is not routinely reported, all thickness data utilized were measured during this study.

The detailed paleoecology of each of the formations is described elsewhere (Rowland, 1978; Rowland and Gangloff, 1988; Debrenne et al., 1991; Hicks, 2001; Hicks and Rowland, in prep.). The Poleta, Harkless, and Tianheban formations all contain varying-sized archaeocyathan-calcimicrobial reefs, while the Xiannudong Formation contains small to massive microbial reefs with sparse, irregular archaeocyaths as dwellers within the microbial reefs but not as constructors. In the Xiannudong Formation, most of the archaeocyaths appear to have lived in inter-reef communities that were ripped-up and redeposited during storm events.

Archaeocyaths

Archaeocyathan morphology commonly consists of a highly porous, two-walled skeleton of microgranular, high-Mg calcite (James and Klappa, 1983) (Fig. 4.4). Skeletons vary from cup-shaped to laminar to disc-like, and they can be solitary or branching. Past phylogenetic interpretations of archaeocyaths classified them as coelenterates, sponges, algae, a phylum of their own (Phylum Archaeocyatha), and as members of a separate kingdom (Kingdom Archaeata) (Rowland, 2001).

Archaeocyaths are now classified as an extinct class of aspiculate, calcareous sponges, Class Archaeocyatha within Phylum Porifera, with two informal groups,
Figure 4.4—Photomicrographs of transverse sections of the two types of archaeocyaths. (A) Irregular, *Metadetes* sp., with taeniae (T), outer wall (O), and inner wall (I) labeled from the Harkless Formation. (B) Regular, *Rasetticyathus* sp., with septa (S), outer wall (O), and inner wall (I) labeled from the Xiannudong Formation.
regulars and irregulars. This classification has been adopted by all archaeocyathan workers because of the close affinities in structure between archaeocyaths and some living sponges such as spinctozoans and other demosponges, most notably the aspiculate species *Vaceletia crypta* (Debrenne and Vacelet, 1984; Kruse and Debrenne, 1989; Kruse, 1990a; Debrenne and Zhuravlev, 1992; Reitner, et al., 1997).

The two informal groups of archaeocyaths, regulars and irregulars, evolved at the same time (Hill, 1972; Debrenne et al., 2002). The distinction between these groups is based on the position of living tissue in the skeleton (Debrenne et al., 2002). In irregular archaeocyaths, the living tissue grew upward as the skeleton grew (mobile aquiferous system); lower portions of the skeleton were successively closed off as upper portions were added. An additional diagnostic feature of irregular archaeocyaths is the presence of wavy septa, called either taeniae or pseudosepta, which are commonly porous to coarsely porous. The septa of regular archaeocyaths, in contrast to irregulars, are not wavy; they may be porous, sparsely porous, or non-porous. In regulars, soft tissue occupied the entire skeleton as the archaeocyath grew. Both irregulars and regulars occur as solitary or branching colonies and are approximately the same size (Debrenne and Zhuravlev, 1992).

In general, both irregulars and regulars may be found within the same reef, and interactions between members of the two groups varied from passive to aggressive (Debrenne and Zhuravlev, 1992). Typically, an aggressive relationship is inferred to have existed between irregulars and regulars, with the former dominating and impeding growth of the latter (Debrenne and Zhuravlev, 1992).
Systematic and Morphologic Variations

Debrenne et al. (2002) recognize six orders of archaeocyaths (Fig. 4.5A). All of the orders except one, Monocyathida, can be assigned to either the regular type (Ajacicyathida, Tabulacyathida, and Capsulocyathida) or the irregular type (Archaeocyathida and Kazachstanicyathida). Monocyathida are archaeocyaths with only one wall, so they are neither regulars nor irregulars. Figure 4.5A shows the global frequency through time of genera within each of the six orders. This plot was derived using data from Debrenne et al. (2002). Figure 4.5B shows data derived using other published literature in the newly created database in which the different orders are grouped into regulars and irregulars (Appendix 1). Both sets of data, the Debrenne et al. (2002) and our archaeocyathan database, were used to ensure that generic trends illustrated were not just a product of subjective data acquisition.

In both graphs, the number of regular genera greatly exceeds the number of irregular genera during the Atdabanian and Botomian (Figs. 4.5A, B). Regulars and irregulars coincide in generic abundance only during the beginning of the Tommotian and in the Toyonian.

Variations in Relative Biomass

In order to analyze for possible changes in the relative biomass of regular and irregular archaeocyaths, we used samples from the Atdabanian-Botomian of China (Xiannudong Formation) and Nevada (Poleta Formation) and also the Toyonian of China (Tianheban Formation) and Nevada (Harkless Formation). Both the number of genera and relative biomass of regular archaeocyaths were high in the Atdabanian-Botomian for the Xiannudong and Poleta formations (Fig. 4.6). However, this changed dramatically in
Figure 4.5. Global frequency of archaeocyathan genera. (A) Frequency of genera in each of the six orders at different times within the Early Cambrian. Data are from Systema Porifera (Debreine et al., 2002). (B) Frequency of genera of regulars and irregulars at different times in the Early Cambrian. Data are from published literature review (Appendix 1). T1-T4 = Tommotian, A1-A4 = Attdabanian, B1-B3 = Botomian, Ty1-Ty3 = Toyonian.

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Figure 4.6. Relative Biomass of regular and irregular archaeocyaths from the Atdabanian-Botomian and the Toyonian. Atdabanian-Botomian histogram bars are combined data from the Xiannudong and Poleta formations. Toyonian histogram bar represents the combined data from the Tianheban and Harkless formations.
the Toyonian, during which time the irregulars completely dominated. Only a single skeleton of a regular archaeocyath was documented in the Harkless Formation, which was observed only in outcrop (Hicks, 2001), and we found no regulars at all in the Tianheban. This dominance of irregulars in Toyonian reefs has also been documented in the well-studied Forteau Formation of Labrador, Canada (Debrenne and James, 1981; James and Klappa, 1983).

Even more interesting is the faunal changeover observed within the Xiannudong Formation itself. Within all three sections of the Xiannudong Formation examined in this study, archaeocyath-bearing units change from being dominated by regulars in the lower part to being dominated by irregulars in the upper part. Furthermore, our review of the published literature indicates that this progressive dominance of irregulars over regulars toward the end of the Early Cambrian is a global phenomenon. Even though the number of genera of regulars is greater than the number of genera of irregulars (Figs. 4.5A, B), the irregulars dominate in terms of biomass.

Thickness Variations of Skeletal Elements

In order to test the hypothesis that changing levels of atmospheric CO\(_2\) and/or rising sea surface temperature were influencing archaeocyathan-reef development, we measured the thickness of selected skeletal elements of archaeocyaths in each of the four formations (Table 4.1). With this hypothesis, we expect to see decreasing thickness of skeletal elements in archaeocyaths due to the lowered pH in the surface seawater, which is associated with increased atmospheric CO\(_2\) (Buddemeier et al., 1998; Gattuso et al., 1998; Langdon et al., 2000; Kleypas and Langdon, 2000).
Table 4.1 Skeletal thickness measurements from each of the localities in this study. Ir = irregular archaeocyath, R = regular archaeocyath

<table>
<thead>
<tr>
<th>Location</th>
<th>Genus</th>
<th>Type</th>
<th>Age</th>
<th>O.W. thickness (mm)</th>
<th>I.W. thickness (mm)</th>
<th>Taniae or Septa thickness (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Poleta Fm</td>
<td>Protopharetra</td>
<td>Ir</td>
<td>Botomian</td>
<td>150.0</td>
<td>75.0</td>
<td>150.0</td>
</tr>
<tr>
<td></td>
<td>Ethmophyllium</td>
<td>R</td>
<td></td>
<td>200.0</td>
<td>250.0</td>
<td>150.0</td>
</tr>
<tr>
<td></td>
<td>Ethmophyllium</td>
<td>R</td>
<td></td>
<td>100.0</td>
<td>125.0</td>
<td>100.0</td>
</tr>
<tr>
<td></td>
<td>Protopharetra</td>
<td>Ir</td>
<td></td>
<td>125.0</td>
<td>100.0</td>
<td>150.0</td>
</tr>
<tr>
<td></td>
<td>?Rotundocvathus</td>
<td>R</td>
<td></td>
<td>100.0</td>
<td>75.0</td>
<td>50.0</td>
</tr>
<tr>
<td></td>
<td>Un ID reg</td>
<td>R</td>
<td></td>
<td>50.0</td>
<td>100.0</td>
<td>50.0</td>
</tr>
<tr>
<td>Xiannudong Fm</td>
<td>Protopharetra</td>
<td>Ir</td>
<td></td>
<td>75.0</td>
<td>50.0</td>
<td>50.0</td>
</tr>
<tr>
<td>Tianheban Fm</td>
<td>Archaeocyathus</td>
<td>Ir</td>
<td>Toyonian</td>
<td>100.0</td>
<td>125.0</td>
<td>125.0</td>
</tr>
<tr>
<td></td>
<td>Metacvathellus</td>
<td>Ir</td>
<td></td>
<td>125.0</td>
<td>300.0</td>
<td>125.0</td>
</tr>
<tr>
<td></td>
<td>Metacvathellus</td>
<td>Ir</td>
<td></td>
<td>75.0</td>
<td>125.0</td>
<td>100.0</td>
</tr>
<tr>
<td></td>
<td>Sb Archaocyathus</td>
<td>Ir</td>
<td></td>
<td>125.0</td>
<td>75.0</td>
<td>125.0</td>
</tr>
<tr>
<td></td>
<td>Td Archaocyathus</td>
<td>Ir</td>
<td></td>
<td>150.0</td>
<td>175.0</td>
<td>250.0</td>
</tr>
<tr>
<td>Haridess Fm</td>
<td>Archaocyathus</td>
<td>Ir</td>
<td></td>
<td>75.0</td>
<td>125.0</td>
<td>100.0</td>
</tr>
<tr>
<td></td>
<td>Metacvathellus</td>
<td>Ir</td>
<td></td>
<td>125.0</td>
<td>125.0</td>
<td>125.0</td>
</tr>
<tr>
<td></td>
<td>Metacvathellus</td>
<td>Ir</td>
<td></td>
<td>125.0</td>
<td>100.0</td>
<td>137.5</td>
</tr>
<tr>
<td></td>
<td>Sb Archaocyathus</td>
<td>Ir</td>
<td></td>
<td>125.0</td>
<td>100.0</td>
<td>137.5</td>
</tr>
<tr>
<td></td>
<td>Sb Archaocyathus</td>
<td>Ir</td>
<td></td>
<td>125.0</td>
<td>200.0</td>
<td>125.0</td>
</tr>
<tr>
<td></td>
<td>Sb Archaocyathus</td>
<td>Ir</td>
<td></td>
<td>100.0</td>
<td>75.0</td>
<td>125.0</td>
</tr>
<tr>
<td></td>
<td>Sb Archaocyathus</td>
<td>Ir</td>
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<td>125.0</td>
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<td>125.0</td>
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<tr>
<td></td>
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<td>Ir</td>
<td></td>
<td>125.0</td>
<td>75.0</td>
<td>125.0</td>
</tr>
</tbody>
</table>

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Table 4.1 continued. Skeletal thickness measurements of irregular archaeocyaths.

<table>
<thead>
<tr>
<th>Location</th>
<th>Genus</th>
<th>Type</th>
<th>Age</th>
<th>O.W. thickness (μm)</th>
<th>I.W. thickness (μm)</th>
<th>Taniac or Septa thickness (μm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Harkless Fm.</td>
<td>Archaeocystus</td>
<td>Ir</td>
<td>100.0</td>
<td>100.0</td>
<td>75.0</td>
<td></td>
</tr>
<tr>
<td>S1-D1c</td>
<td>Metacystellus</td>
<td>Ir</td>
<td>125.0</td>
<td>150.0</td>
<td>100.0</td>
<td></td>
</tr>
<tr>
<td>S1-D7a</td>
<td>Archaeocystus</td>
<td>Ir</td>
<td>125.0</td>
<td>75.0</td>
<td>75.0</td>
<td></td>
</tr>
<tr>
<td>S1-D7a</td>
<td>Metacystellus</td>
<td>Ir</td>
<td>150.0</td>
<td>150.0</td>
<td>125.0</td>
<td></td>
</tr>
<tr>
<td>S1-D7a</td>
<td>Metacystellus</td>
<td>Ir</td>
<td>150.0</td>
<td>125.0</td>
<td>125.0</td>
<td></td>
</tr>
<tr>
<td>S1-D7a</td>
<td>Archaeocystus</td>
<td>Ir</td>
<td>125.0</td>
<td>75.0</td>
<td>75.0</td>
<td></td>
</tr>
<tr>
<td>S1-D10B1</td>
<td>Retilamina</td>
<td>Ir</td>
<td>112.5</td>
<td>75.0</td>
<td>50.0</td>
<td></td>
</tr>
<tr>
<td>S1-D10B1</td>
<td>Archaeocystus</td>
<td>Ir</td>
<td>100.0</td>
<td>75.0</td>
<td>75.0</td>
<td></td>
</tr>
<tr>
<td>S1-D10B1</td>
<td>Retilamina</td>
<td>Ir</td>
<td>125.0</td>
<td>125.0</td>
<td>100.0</td>
<td></td>
</tr>
<tr>
<td>S1-D10B1</td>
<td>Metacystellus</td>
<td>Ir</td>
<td>175.0</td>
<td>150.0</td>
<td>125.0</td>
<td></td>
</tr>
<tr>
<td>S1-D10B1</td>
<td>Archaeocystus</td>
<td>Ir</td>
<td>150.0</td>
<td>75.0</td>
<td>87.5</td>
<td></td>
</tr>
<tr>
<td>S1-D10B1</td>
<td>Retilamina</td>
<td>Ir</td>
<td>62.5</td>
<td>0.0</td>
<td>75.0</td>
<td></td>
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<tr>
<td>S1-D15c</td>
<td>Archaeocystus</td>
<td>Ir</td>
<td>100.0</td>
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</tr>
<tr>
<td>Isotope sample</td>
<td>Retilamina</td>
<td>Ir</td>
<td>125.0</td>
<td>87.5</td>
<td>87.5</td>
<td></td>
</tr>
</tbody>
</table>
However, from the Atdabanian-Botomian to the Toyonian, the intervallum elements of irregular archaeocyaths increased in thickness (Fig. 4.7A). Meanwhile, the outer walls and inner walls remained relatively unchanged (Fig. 4.7B, C, Table 4.2). The mean intervallum elemental thickness in the Atdabanian-Botomian is 65 μm, while the mean intervallum elemental thickness in the Toyonian is 141 μm.

Graphs of Figure 4.8A-F show that the thickness of skeletal elements that are of the same age did not significantly vary between the two localities of Atdabanian/Botomian archaeocyaths and the two localities of Toyonian archaeocyaths. Because no regular archaeocyaths are present in the Tianheban, and only a single specimen of a regular was observed in the Harkless, we are unable to test whether the intervallum elements of regulars increased in thickness. Toyonian regulars have been described in Australia (Kruse, 1990b; Brock and Cooper, 1993), Antarctica (Debrenne and Kruse, 1989), and Greenland (Debrenne and Peel, 1986), but no data are available on the thickness of the skeletal elements.

Mechanisms for Systematic Change

Two trends are apparent in the data: (1) the relative biomass of irregulars increased from the Atdabanian-Botomian though the Toyonian, and (2) the intervallum elements of irregular archaeocyaths thickened through the Early Cambrian. Two mechanisms, which are coupled, are hypothesized as the forcing agents of these systematic and morphologic variations in archaeocyaths: rising atmospheric CO₂ and rising sea surface temperatures. Berner (1991, 1994) and Berner and Kothavala (2001) have used a carbon-mass-balance approach to model atmospheric CO₂ variations for the
Intervallum element thickness means of irregulars between Atdabanian/Botomian and Toyonian

![Graph A](image)

Inner wall thickness means of irregulars between Atdabanian/Botomian and Toyonian

![Graph B](image)

Outer wall thickness means of irregulars between Atdabanian/Botomian and Toyonian

![Graph C](image)

Figure 4.7. Thickness means (mm) of inner wall (IW), outer wall (OW), and intervallum elements of irregular archaeocyaths. Bars represent variance around the mean. Data is from the four formations in this study. Atd/Bot = Atdabanian/Botomian, Toy = Toyonian
Table 4.2 Averages, Minimums (Min.), Maximums (Max.), Medians, and Modes of measured thicknesses of the Atdabanian/Botomian (A/B) and Toyonian regular and irregular archaeocyath outer walls, inner walls, and intervallum elements (Interval). Formation names are simplified to P (Poleta Formation), X (Xiannudong Formation), H (Harkless Formation), and T (Tianheban Formation). The sample size (n) for each test is noted.

<table>
<thead>
<tr>
<th>Analyses</th>
<th>A/B Outer wall</th>
<th>Toyonian Outer wall</th>
<th>A/B Inner wall</th>
<th>Toyonian Inner wall</th>
<th>A/B Interval</th>
<th>Toyonian Interval</th>
</tr>
</thead>
<tbody>
<tr>
<td>Average</td>
<td>106 µm</td>
<td>123 µm</td>
<td>94 µm</td>
<td>149 µm</td>
<td>65 µm</td>
<td>141 µm</td>
</tr>
<tr>
<td>Min.</td>
<td>15 µm</td>
<td>20 µm</td>
<td>50 µm</td>
<td>50 µm</td>
<td>25 µm</td>
<td>100 µm</td>
</tr>
<tr>
<td>Max.</td>
<td>50 µm</td>
<td>75 µm</td>
<td>175 µm</td>
<td>300 µm</td>
<td>150 µm</td>
<td>250 µm</td>
</tr>
<tr>
<td>Median</td>
<td>100 µm</td>
<td>125 µm</td>
<td>100 µm</td>
<td>125 µm</td>
<td>50 µm</td>
<td>125 µm</td>
</tr>
<tr>
<td>Mode</td>
<td>125 µm</td>
<td>125 µm</td>
<td>75 µm</td>
<td>125 µm</td>
<td>50 µm</td>
<td>125 µm</td>
</tr>
</tbody>
</table>
Figure 4.8. Thickness means (mm) of inner wall (IW), outer wall (OW), and intervallum elements of irregular archaeocyaths. Bars indicate variance around the mean. Data is from the four formations in this study. Atd/Bot = Atdabanian/Botomian, Toy = Toyonian
entire Phanerozoic (Fig. 4.9). Other atmospheric CO₂ models (Tajika, 1998; Wallmann, 2001; and Kashiwagi and Shikazono, 2003) do not extend to the Early Phanerozoic, but, for younger periods of time, these other models show considerable agreement with the GEOCARB Models of Berner. GEOCARB Models 1-3 all show rapidly rising atmospheric CO₂ during the Early Cambrian (Fig. 4.9) (Berner, 1991, 1994; Berner and Kothavala, 2001; Royer et al., 2004).

Numerous studies have shown that rising atmospheric CO₂ causes a corresponding rise in ocean surface water CO₂ (CO₂ aqueous) (Gattuso et al., 1998; Gattuso et al., 1999; Kleypas and Langdon, 2000; Langdon et al., 2000; Leclercq et al., 2000; Kleypas et al., 2001; Feely et al., 2004). This rise in aqueous CO₂ causes a lowering of pH and the carbonate saturation state, in which CO₃²⁻ is the limiting factor in calcium carbonate precipitation (Buddemeier et al., 1998; Gattuso et al., 1998; Langdon et al., 2000; Kleypas and Langdon, 2000) (Fig. 4.10). There is a positive correlation between the carbonate saturation state and biogenic carbonate precipitation; as the carbonate saturation state declines, the amount of biogenetic carbonate precipitation also declines (Smith and Buddemeier, 1992; Gattuso et al., 1998; Gattuso and Buddemeier, 2000; Langdon et al., 2000; Stoll et al., 2002). This influence of carbonate saturation state on biogenic carbonate precipitation has been observed in many different taxa, including corals and foraminifera (Gattuso et al., 1999; Gattuso and Buddemeier, 2000; Feely et al., 2004).

Conversely, calcification is enhanced by rising atmospheric temperatures that accompany rising levels of CO₂ (Riding, 1996; Gattuso et al., 1999; Kleypas and Langdon, 2000; Anderson et al., 2003; Riding and Liang, 2005). Increased temperature
Figure 4.9. Berner's atmospheric CO$_2$ versus time graph (Berner, 1994). RCO$_2$ is the ratio of atmospheric CO$_2$ in the past to the present. RCO$_2$ is calculated from the long term carbon cycle and other proxies, such as weathering rates, burial, and Sr composition of seawater. The upper and lower dashed lines represent the range of error, while the bold black line represents the best fit estimate of the atmospheric CO$_2$. 

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Increasing CO₂

Increased Atmospheric Temperatures

CO₂ aq

Sequestor

CO₂ + H₂O → H₂CO₃ (Carbonic acid)

H₂CO₃ + CO₃²⁻ → 2HCO₃⁻

Reduces CO₃²⁻ availability to combine with Ca to form CaCO₃

CO₂ + H₂O → CH₂O + O₂

photosynthesis

surface ocean water

Figure 4.10. Diagram illustrates the complex chemical reactions that occur between the atmosphere and surface sea water. CO₂ rising in the atmosphere causes increased atmospheric temperatures, increased sea surface temperatures, and increased aqueous CO₂. CO₂ combines with H₂O to form carbonic acid. The carbonic acid is neutralized by combining with CO₃²⁻ to form bicarbonate. This reduces the availability of CO₃²⁻ to combine with Ca²⁺ to form biogenetic calcite. Through photosynthesis sequestoring CO₂, the availability of CO₃²⁻ increases, thus increasing the carbonate concentration.
lowers the solubility constant of carbonate, thereby making it metabolically easier for the organism to calcify (Riding, 1996; Gattuso et al., 1998; Gattuso et al., 1999). Only one study has attempted to reconstruct surface water temperatures for the Phanerozoic as far back as the Cambrian. Using oxygen isotopes from chert and phosphate pairs, biogenic phosphate, and carbonate fossils, Karhu and Epstein (1986) concluded that sea surface temperatures in the Cambrian ranged from 55.0 °C to 80.0 °C. While the exact temperatures inferred by Karhu and Epstein (1986) have not been widely accepted, there is a general agreement that the Cambrian was a time of transition from icehouse to greenhouse conditions, and that by the end of the Early Cambrian temperatures were much warmer than at present (Rowland and Shapiro, 2002).

Therefore, with increased temperatures, archaeocyaths should have been able to precipitate CaCO₃ more easily, but an overall increase in skeletal thickness is not observed because the carbonate saturation state is low. The initial hypothesis of this study was that rising levels of atmospheric CO₂ and associated factors influenced the decline and collapse of Early Cambrian archaeocyathan reef ecosystems. Therefore, the expected observation was that archaeocyathan skeletons would get thinner prior to the virtual extinction of archaeocyaths. Instead, we observe the virtual disappearance of regular archaeocyaths, an expansion of irregulars, and a thickening of the intervalum elements of the irregulars.

Both regulars and irregulars coexist in the same reefs for approximately 10 million years (Tommotian-Botomian) with regulars dominating the reef biomass. However, as observed in the uppermost part of the Xianxudong Formation, irregulars quickly replace regulars and dominate both reef and non-reef environments globally.
during the late-Early Cambrian (Appendix 1). The rapid faunal changeover implies that irregulars had a physiological edge over irregulars, and that regulars and irregulars may have responded differently to global environmental changes that were occurring during the end of the Early Cambrian.

Our new working hypothesis is that the key to the success of the irregulars was photosymbiosis. This hypothesis is based on several lines of evidence: (1) almost all modern sponges have symbionts and many species of reef-dwelling sponges have photosymbionts (Wilkinson, 1987), (2) photosynthesis is known to enhance calcification even with low carbonate saturation states (Smith and Buddemeier, 1992; Opdyke and Wilkinson, 1993; Westbroek et al., 1994; Gattuso et al., 1999; Gattuso and Buddemeier, 2000; Arp et al., 2001), and (3) photosymbiosis has already been hypothesized to have been present in archaeocyaths on the basis of morphological and paleoecological arguments (Cowen, 1983, 1988; Rowland and Gangloff, 1988; Rowland and Shapiro, 2002).

Photosymbiosis utilizes CO$_2$, thereby lowering H$_2$CO$_3$ (carbonic acid) formation, and increases the alkalinity and the carbonate saturation state (Opdyke and Wilkinson, 1993; Westbroek et al., 1994; Gattuso et al., 1999; Gattuso and Buddemeier, 2000; Langdon et al., 2000; Arp et al., 2001) (Fig. 4.10). Experiments with living organisms show that as photosymbionts intake CO$_2$, the partial pressure of extracellular CO$_2$ decreases, and the carbonate saturation state increases, allowing for CaCO$_3$ precipitation (Gattuso et al., 1999). There is no compelling reason to suggest that archaeocyaths did not have endosymbionts, especially since *Vaceletia*, which is described as having close affinities to archaeocyaths, houses numerous symbiotic bacteria within the mesohyle.
(middle tissue) which for archaeocyaths would be found in the intervallum (Reitner et al., 1997).

For anatomic reasons, irregular archaeocyaths were more likely to have housed photosymbionts than were the regulars. In contrast to regulars, irregulars contain intervallum elements with large surface areas, which allowed for greater tissue volume. Greater tissue volume, in turn, would have allowed for a greater amount of endosymbionts. Possibly the regulars harbored no photosymbionts at all. As the CO$_2$ increased in the Early Cambrian, irregulars containing photosymbionts would have been able to continue to calcify despite the reduced carbonate saturation state, while those that did not house photosymbionts, such as regulars, would have declined. We suggest that the thickening of only the intervallum elements rather than all skeletal elements was due to the location of the photosymbionts, within the intervallum of the irregulars. As the photosymbionts utilized CO$_2$, the immediate area surrounding the photosymbionts would have become more saturated with respect to the carbonate ion, allowing for rapid precipitation in that area.

Summary and Conclusions

During the last few million years of the Early Cambrian Epoch, several trends are apparent: (1) the number of genera of both regular and irregular archaeocyaths declined dramatically, (2) the relative abundance of regulars and irregulars changes from being dominated by regular to being dominated by irregular from the Atdabanian-Botomian to the Toyonian, and (3) the intervallum elements of irregular archaeocyaths become conspicuously thicker. We propose that all of these phenomena are related.
The Sinsk Event probably affected the generic diversity of both types of archaeocyaths, however, the Sinsk Event is not well establish globally and is not recognized on Laurentia (Zhuravlev and Wood, 1996). Therefore, the Sinsk event is unlikely to be the overarching cause for the decline in archaeocyathan genera during the Atdabanian-Botomian. Moreover, the forty-million-year-long interval without metazoan reefs, which followed the collapse of the archaeocyathan reefs, suggest that other, long-term environmental factors were at work in the Early Cambrian.

Based on our data, regular archaeocyaths were unable to adapt to changing environmental conditions; and thereby, they became very scarce toward the end of the Early Cambrian. In contrast, the irregulars, whose morphology was more suited for harboring photosynthesizing endosymbionts, were able to thrive for a while and conspicuously out-compete the regulars.

We propose that rising levels of atmospheric CO$_2$ and attendant increases in sea surface temperatures provide the simplest explanation for archaeocyathan decline and the 40 Ma metazoan reefless gap. Direct evidence supporting this hypothesis is not yet evident. However, high temperatures are suspected to cause coral bleaching, suggesting that too great a temperature causes excessive thermal stress on an organism, leading to death (Done, 1999; Kleypas et al., 2001; Hughes et al., 2003). No long-term studies have been conducted on organisms’ responses to long-term temperature rise nor rapid rising and prolonged high atmospheric CO$_2$.

The proximal cause of the collapse of the Early Cambrian archaeocyathan-calcimicrobial reef ecosystem was probably loss of habitat associated the Toyonian Regression (Rowland and Gangloff, 1988; Wood, 1999), but if conditions had been
suitable, archaeocyaths or other metazoans should have backstepped off the carbonate platforms to keep pace with sea level fall or evolved into new niches in the Middle Cambrian. The inability of archaeocyaths to reestablish themselves as reef-builders, or any other metazoan to fill the reef-building niche, must be due to unsuitable, long-term environmental conditions, such as rising atmospheric CO\textsubscript{2} and high sea surface water temperatures. As we get closer to understanding the past climate, with respect to atmospheric CO\textsubscript{2} and global temperatures, we may be able to use the physical reactions observed in archaeocyaths to evaluate a threshold of atmospheric CO\textsubscript{2} and temperature for which calcifying organisms cannot tolerate.

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CHAPTER 5

SUMMARY OF MAJOR RESULTS

The research presented in the previous three papers represents an attempt to reconstruct the complex and dynamic interactions between archaeocyaths, climate, and other environmental factors. The original four hypotheses for this study were (1) the generic richness of archaeocyaths declined from the mid-Early Cambrian to the end-Early Cambrian, (2) the percentage of branching archaeocyaths decreased from the mid-Early Cambrian to the end-Early Cambrian, (3) the percentage of irregulars increased from the mid-Early Cambrian to the end-Early Cambrian, and (4) the Lower Poleta Formation can be correlated to the Xiannudong Formation and the Harkless Formation can be correlated to the Tianheban Formation using $\delta^{13}C$ isotopes. Each of these four hypotheses were tested, and they produced interesting and unexpected results that provide information on the paleoecology and paleogeography of the Yangtze Platform, the use of chemostratigraphy as a correlation tool, and the enigmatic decline of archaeocyaths.

Sedimentologic and paleontologic evidence indicates that during the mid-Early Cambrian archaeocyaths were not forming reefs on the Yangtze Platform, although archaeocyaths were constructing reefs in Laurentia. Instead, on the Yangtze Platform, archaeocyaths formed inter-reefal communities between thrombolite and stromatolite reefs in a shallow, subtidal setting. Adjacent to the microbial reefs and archaeocyathan
communities there were migrating ooid shoals that commonly shifted position and covered the reefs during storm events. Such storm events also ripped-up archaeocyaths and redeposited them as storm debris between the microbial reefs. These large storm events occurred repeatedly throughout the deposition of the Xiannudong Formation.

Paleoecological analyses on the Yangtze Platform also indicate that, at least during the Early Cambrian, this region was a carbonate platform that occupied tropical latitudes. Deposits across the platform are similar to those observed in the Bahamas, and, therefore, must have formed in a tropical environment. The presence of offshore, slope, and basinal sediments on the southern and eastern parts of the platform (APC, 1985; Zhang and Pratt, 1994; Zhu et al., 2001), indicate that the shallow, carbonate deposits were surrounded by deeper water.

Because biostratigraphy did not prove useful for precisely correlating global sections, I attempted to use chemostratigraphy and the composite $\delta^{13}$C profile for the Early Cambrian of the Siberian Platform (Brasier et al., 1994) to better constrain the correlation between the Xiannudong and Poleta formations and the Tianheban and Harkless formations. Surprisingly, all five sections analyzed for $\delta^{13}$C show no major excursions, which is contrary to the $\delta^{13}$C record for the Siberian Platform, and, therefore, not useful for correlative purposes. I hypothesize that $\delta^{13}$C values I collected in this study may not record global $\delta^{13}$C variations, but rather record basinal variations; or the $\delta^{13}$C profile of the Siberian Platform may be unique to that particular platform and does not represent the secular $\delta^{13}$C record.

Throughout the paleoecological, sedimentological, and chemostratigraphic analyses, I documented the generic diversity of archaeocyaths and the relative abundance
of regular and irregular archaeocyaths from the mid-Early Cambrian to the late-Early Cambrian. The trends observed are (1) decreasing generic diversity of archaeocyaths, (2) increasing relative abundance of irregular archaeocyaths, and (3) increasing thickness of certain skeletal elements of irregular archaeocyaths. Because a significant rise in atmospheric CO$_2$ has been inferred for the Early Cambrian (Berner, 1991, 1994, 1997; Berner and Kothavala, 2001), the increasing skeletal thickness of intervallar elements was unexpected. This phenomenon is interpreted to record the presence of photosymbionts in irregular archaeocyaths. Photosymbionts uptake carbon in the form of CO$_2$, thereby lowering the carbonate saturation state. This counters the present paradigm that photosymbiotic relationships did not evolve until the Upper Triassic (Wood, 1999).

The increasing relative abundance of irregular archaeocyaths during the Early Cambrian while regular archaeocyaths decreased in abundance indicates that irregulars must have had some selective edge over the regulars. Because irregulars have more elements in their intervallum, they also contained more soft tissue in their intervallum, and they could host more endosymbionts than could regulars. Furthermore, regular-type archaeocyath may not have housed any endosymbionts. In the sections sampled in this study, no regular archaeocyaths were present in the late-Early Cambrian; it was not possible to determine whether similar thickness trends are also present in regulars.

This dissertation proposes many more questions than it answers, but it does create new hypotheses for continued research. Future research should include more stratigraphic analyses of the Yangtze Platform. More chemostratigraphic data need to be collected from both Laurentia and China. These two regions still lack a standard $\delta^{13}$C curve, which can be used to interpret environmental change as well as a correlation tool.
both basinally and, perhaps, globally. Finally, the faunal changeover from regular archaeocyath dominance to irregular archaeocyath dominance should be explored in other localities, such as Australia and Siberia. Only three late-Early Cambrian localities contain regular archaeocyaths: Australia (Kruse, 1990b; Brock and Cooper, 1993), Antarctica (Debrenne and Kruse, 1989), and Greenland (Debrenne and Peel, 1986). These regulars should be analyzed to determine if any systematic variation is present in the skeletons of regulars, as it is in irregulars.

Global decline of reefs significantly affects the Earth system. Modern reefs are sinks for atmospheric carbon, peaks of biodiversity, barriers to shoreline erosion, possible sources of pharmaceuticals, and magnets for ecological tourism. By understanding how Early Cambrian reef ecosystems responded to rising levels of CO$_2$, we can better predict how anthropogenic CO$_2$ and associated climate change will affect modern reefs. The past is a key to the present, and the Early Cambrian maybe a key for understanding the Holocene.

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