Storm-dominated Lower Cambrian depositional environments in the Ravenswood area, Lander County, Nevada

Readin Isaac Wilson

University of Nevada, Las Vegas

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Storm-dominated Lower Cambrian depositional environments in the Ravenswood area, Lander County, Nevada

Wilson, Readin Isaac, M.S.

University of Nevada, Las Vegas, 1992
STORM-DOMINATED LOWER CAMBRIAN DEPOSITIONAL ENVIRONMENTS IN THE RAVENSWOOD AREA, LANDER COUNTY, NEVADA

by

Readin Isaac Wilson

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

Master of Science

in

Geoscience

Department of Geoscience
University of Nevada, Las Vegas
May, 1992
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Graduate Dean, Ronald Smith, Ph.D

University of Nevada, Las Vegas
May, 1992
STORM-DOMINATED LOWER CAMBRIAN DEPOSITIONAL ENVIRONMENTS IN THE RAVENSWOOD AREA, LANDER COUNTY, NEVADA

ABSTRACT

A Lower Cambrian sedimentary sequence 40 meters thick is exposed in the Ravenswood area, Lander County, Nevada. This sequence is divided into 7 lithofacies which are interpreted to represent marine, littoral to sublittoral environments including offshore bars, sheet deposits (proximal, intermediate, distal), patch reefs, and storm-surge ebb channels.

The lithology, paleontology, and sedimentary structures reflect deposition in a wave-dominated or storm-dominated system. Paleocurrent indicators suggest that strong westerly (present orientation of continent) winds created landward-directed currents transporting carbonate debris from the shelf to nearshore environments. Subsequently, storm-surge-ebb flows transported nearshore sediments seaward.

The lithofacies presented herein indicate that sediments were composed of mixtures of carbonate and siliciclastic material during deposition. The processes responsible for this mixing are punctuated mixing
(occurred as a result of storm-transported carbonate sediment into a clastic environment), and facies mixing (occurred with the forming of archaeocyathan bioherms). These bioherms are interpreted to have formed as isolated patch reefs in a sublittoral environment.
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STORM-DOMINATED LOWER CAMBRIAN DEPOSITIONAL
ENVIRONMENTS IN THE RAVENSWOOD AREA,
LANDER COUNTY, NEVADA

INTRODUCTION

The purpose of this study is to describe depositional environments of archaeocyath-bearing Lower Cambrian strata in Lander County, central Nevada. In this region Lower Cambrian strata consist of mixed carbonate-siliciclastic sequences (Stewart and McKee, 1977; Gangloff, 1975, 1976; Washburn, 1970; Stewart and Palmer, 1967). Archaeocyath-bearing limestones in this region are exposed in the Toiyabe Range south of Austin, on Mount Callaghan in the Toiyabe Range north of Austin, and in the Ravenswood mining district in the Shoshone Mountains northwest of Austin (Fig. 1). Due to the relative inaccessibility of the Toiyabe Range and Mount Callaghan sections, this study addresses only the Ravenswood area.

The focus of this study is a section of archaeocyath-bearing limestones and dolomites, and associated siliciclastic rocks that occur in Section 14, T.22 N., R.42 E., of the Manhattan Mountain 7 1/2' Quadrangle. The exposures are located along an unpaved road which
Figure 1. Map showing outcrops of Cambrian strata and location of study area in south central Lander County, Nevada. Data from Stewart and McKee (1977).
Figure 2. A) Aerial view of study area. B) Illustration of study area, showing locations of measured sections. Located 8.3 mi. from highway 305 along an unpaved road that leads into the Ravenswood area.
leads from Nevada Highway 305 westward into the Ravenswood district and first crosses exposures of pre-Tertiary rocks (Figs. 1,2).
OBJECTIVES AND METHODS

The purpose of this thesis is to link archaeocyath-bearing Lower Cambrian strata in the Ravenswood area with other archaeocyath-bearing Lower Cambrian strata occurring elsewhere in the western U.S., and northern Mexico. An emphasis on the depositional system responsible for emplacement of the strata may allow for identification of analogous systems, or conversely, provide another example of the variety of environments that were inhabited by archaeocyaths.

The objectives of this thesis are: (1) to describe the section of Lower Cambrian mixed siliciclastic-carbonate rocks in the Ravenswood District, (2) to reconstruct depositional environments from primary sedimentary structures, lithologies, and fossils, and (3) to provide a regional interpretation.

The Lower Cambrian section was measured with a calibrated staff six feet in length held perpendicular to bedding. Aerial photographs were used for locating tectonically displaced sections, and for making proper correlations.

Four trips were made to the study area. Samples were collected and analyzed from four sections at 0.5 m intervals; where obvious differences in lithology occurred.
more detailed sampling of primary sedimentary structures was done. Each sample was photographed *in situ* before it was removed. A reference number and stratigraphic position was assigned to each sample. The samples were transported to the UNLV Geology laboratory where they were cut perpendicular to bedding. One-half of each cut sample was polished. Thirty-five selected samples were prepared for thin-section and petrographic analysis. One sample, a fine-grained sandstone, was delivered to Walt Raywood (UNLV Geology Lab Technician) for X-ray diffraction analysis, to determine mineralogic composition.

The abundance and distribution of minerals is mainly determined by thin-section. However, individual clay particles are typically too fine grained to be identified using a thin-section and are therefore determined by X-ray diffraction analysis. Also, a comparison of the results of thin section and X-ray diffraction analysis indicates a relatively close correlation between mineral abundances derived by the two techniques.

The composition of the clay fraction was determined because shelf processes may have effects on the chemical characteristics of shelf sediments. These processes partially control the precipitation of authigenic minerals, which in some areas are characteristic of the shallow marine environment (Reading, 1983).
PREVIOUS WORK

In the Toiyabe Range south of Austin, Lower Cambrian strata have been described by Ferguson and Cathcart (1954), Means (1962), Washburn (1970), and Stewart and McKee (1977). Ferguson (1924) proposed the name Gold Hill Formation for Cambrian strata in the Manhattan mining district, 70 miles to the south of Austin. Washburn (1970) assigned strata in the central Toiyabe Range to the Gold Hill Formation also, on the basis of their lithologic similarity to the strata of the southern Toiyabe and Toquima Ranges.

For the purpose of this thesis, no formal name is given to the Lower Cambrian strata in the Ravenswood area. Correlations of Lower Cambrian strata in Lander County with named formations elsewhere in Nevada remain uncertain, and Stewart and McKee (1977, p.5) advised that no specific formational name be used at this time.

Washburn (1970) briefly described the central Toiyabe Range strata as fine-grained quartzite, graywacke, mudstone, and limestone. He described a buff-colored limestone, 25 m thick, containing abundant archaeocyathids. Most of the clastic sediments were described as consisting of well sorted, angular to sub-rounded grains, predominantly quartz; cross-bedding and
ripple-marks are common (Washburn, 1970). Washburn described no specific type of cross-bedding, ripple-marks or any other type of sedimentary structure that would permit depositional conditions to be inferred.

Washburn (1970) was, however, the first to describe the archaeocyath-bearing units located at the base of the upper one-third of the Gold Hill Formation in the central Toiyabe Range. He noted the presence of *Cambrocyathus* cf. *C. occidentalis* Okulitch, *Archaeocyathus atlanticus* Billings, and *Ethmophyllum whitneyi* Meek, in the Summit Ridge area (Fig. 1). Gangloff (1975) identified *Wyattocyathus toiyabicus* Gangloff, *Diplocyathus vulgarus* Gangloff, and *Syringothalamus crispianus* Gangloff from an outcrop approximately 1 km from Washburn's locality. These latter three taxa have not been published and are therefore not valid species names. It is likely that the specimens which Washburn (1970) assigned to *Ethmophyllum whitneyi* have been misidentified and are probably better assigned to *Wyattocyathus toiyabicus* (Gangloff, 1975). Echinoderm plates and trilobites are also present in the Summit Ridge area (Gangloff, 1975).

On Mount Callaghan in the Toiyabe Range north of Austin, Lower Cambrian strata have been described by Stewart and Palmer (1967). No formal names have been applied to Lower Cambrian strata in the Mount Callaghan
area (Stewart and McKee, 1977). Stewart and Palmer (1967) and Stewart and McKee (1977) described three units composed of quartzite, siltstone, shale, sandstone, and limestone. They noted the occurrence of biogenic sedimentary structures such as burrows. However, there is no documentation of other sedimentary structures. According to Roland Gangloff (1986, pers. comm.) the Mount Callaghan section contains archaeocyaths and is similar to the section in the Ravenswood area.

The Ravenswood area contains Lower Cambrian strata that were described by Gangloff (1975) and Stewart and McKee (1977). Stewart and McKee (1977) reported the occurrence of *Nevadella*, a primitive olenellid trilobite (?), and a daguinaspid trilobite, both in quartzite, and a long-eyed nevadiid in siltstone, stratigraphically below the archaeocyath-bearing limestone. They also reported an indeterminate olenellid trilobite, pelmatozoan debris, and *Salterella* at another outcrop in the same area. Nonbiogenic sedimentary structures were not described by Stewart and McKee (1977), and they made no attempt to reconstruct depositional environments. Gangloff (1975) lists a diverse fauna associated with archaeocyaths in this area, including trilobites, brachiopods, echinoderms, *Chancelloria*, *Salterella* (?), and gastropods.
AGE AND CORRELATION

The Lower Cambrian strata in the Ravenswood area can be correlated with Lower Cambrian strata in three areas: (1) the southern Great Basin in eastern California and southern Nevada, (2) the Caborca region, Sonora, Mexico, and (3) northeastern Washington (Fig. 3).

Lithologic correlation is difficult in the Lower Cambrian of the Great Basin because laterally continuous carbonate sequences are generally lacking, outcrops are scarce, and the rocks tend to be poorly exposed and poorly preserved. Rowland (1981b) indicates that the vertical sequence of facies in the lower Poleta Formation in the southern Great Basin is variable indicating that the original distribution of facies was probably patchy, just as it is in modern reef-shoal settings. Hence, a single facies from one section cannot be correlated with a single facies in another (Rowland, 1981b). Within the eastern and southern Great Basin, however, entire sequences have been correlated with reasonable certainty, and variations in bedding sequences have been identified (Stewart, 1991; Levy and Christie-Blick, 1991; Gangloff, 1976; Moore, 1976).

Correlation of strata in the southern Great Basin with those in northwestern Mexico and in the central
Figure 3. The Lower Cambrian strata in the Ravenswood area correlated with strata of western North America.
Great Basin requires biostratigraphy, which may be independent of variations of lithology and bedding within sedimentary sequences. A reasonable correlation can be made to the Ravenswood area by using both fossil evidence and lithology.

The correlative Lower Cambrian strata in the southern Great Basin consist, in ascending order of: the Campito Formation, the Poleta Formation, and the Harkless Formation. The carbonate-bearing interval of the upper member of the Wood Canyon Formation has also been correlated with the Poleta Formation (Gangloff, 1976). This correlation is based upon the presence of a nevadiid trilobite, Nevadella, archaeocyaths, and pelmatozoan debris, all of which occur in both formations. Archaeocyaths discovered in the central Toiyabe Range (Washburn, 1970) and in the Ravenswood area (Stewart and McKee, 1977) are conspecific with those recorded from the Campito and Poleta Formations in the White-Inyo and Death Valley areas (Gangloff, 1976). Nevadella identified in the Ravenswood area by Stewart and McKee (1977) occurs in association with archaeocyath-bearing intervals. This association, along with echinoderm debris, and unidentified nevadiid trilobites (Stewart and McKee, 1977), allows a reasonable correlation to be made between the Lower Cambrian strata in the Ravenswood area and the
Upper Campito Formation and/or Lower Poleta Formation (Fig. 3).

The archaeocyath assemblages of the central and southwestern Great Basin correlate with those described by Handfield from British Columbia and the Canadian Yukon, with 17 out of 28 genera being common to both (Gangloff, 1976). The Lower Cambrian strata of northeastern Washington correlate with the Lower Cambrian strata in British Columbia and the Canadian Yukon (Hampton, 1979). The Maitlen Formation in northeastern Washington contains an indeterminate species of Nevadella, Chancelloria, archaeocyaths, echinoderm plates, and unidentified calcareous brachiopods (Hampton, 1979). The presence of Nevadella indicates that these archaeocyaths are roughly equivalent in age to those of the Poleta Formation in California, the medial Lower Cambrian of Canada, the Ravenswood area of central Nevada, and the Caborca region of Sonora, Mexico.

The upper units of the Puerto Blanco Formation are correlated with the upper member of the Wood Canyon Formation by the presence of siltstone, fine-grained quartzite, and the presence of archaeocyath-bearing limestone in both sequences (Stewart et al., 1984). Based on trilobite identification, part of the Puerto Blanco correlates with the Montenegro Member of the Campito
Formation. Hence, the Puerto Blanco Formation correlates with both the upper Campito Formation and the lower Poleta Formation (Fig. 3). Similarly, because the Ravenswood area section consists of siltstone, fine-grained quartzite, archaeocyath-bearing limestone and Nevadella, it is tentatively correlated with the upper part of the Puerto Blanco Formation in this study.
STRUCTURAL FEATURES

The Ravenswood area has had a complex structural history. It is beyond the scope of this paper to analyze the structure of the area in detail, but several structural interpretations were made as a result of aerial photo analysis and field work. Stewart and McKee (1977) indicated that thicknesses of units within the Ravenswood area are uncertain due to faulting. It was observed during this study that many units within the study area are not laterally continuous, and are bounded by faults. Structural interpretations were made to: (1) determine whether repeating sequences were produced by deposition or faulting, (2) record accurate thicknesses, and (3) determine where breaks in the vertical succession occur.

North to northeast-trending high-angle normal faults (Fig. 4), and northwest-trending faults are common within the study area. Evidence for faulting includes slickensides, mineralized zones, locally folded beds (Fig. 5A), and offset blocks (Fig. 5B). Primary sedimentary structures, bioclasts, and stylolites are dissected by multiple sets of parallel, calcite-filled micro-fractures. The fractures are filled only by a single generation of calcite cement which occurs as short, bladed crystals.
Figure 4. Photo of north to northeast-trending, high-angle normal fault (left side of photo) and sub-vertical fractures in study area. Hammer for scale is 30 cm.
Figure 5. A) Folded beds dipping to the right side of photo (south-southeast). Note curvature from upper-center to lower right due to fault drag. B) Multiple sets of high-angle normal faults. Note separation between fault blocks.
Even though Lower Cambrian strata are exposed over a wide area in the Ravenswood District, it is difficult to establish a sequence because exposures are poor in most places. Stewart and McKee (1977) indicate that several thousand meters of very fine- to fine-grained, and medium-grained quartzite and associated siltstone occur in the southern and central parts of the Ravenswood District in the Shoshone Mountains. This study is based on four measured sections shown in Figure 6, located in the northern part of the Ravenswood District (Fig 2B). These strata are probably younger than most of the Cambrian strata immediately to the south (Stewart and McKee, 1977).

Figure 7 is a detailed stratigraphic column of section 1, which is the most complete section in this study. This section consists of a thick terrigenous clastic lower part and a thinner carbonate upper part, capped by a thin layer of quartzite. The Ingram (1954) classification of stratification is used to describe thicknesses of strata. The limestones are classified using the terminology of Dunham (1962).

I have identified seven distinctive lithofacies in the Ravenswood section, each of which is described and interpreted below. Table 1 is a list of sedimentary
textures and constituents, and the interpreted environments in which they are found. Table 2 is a list of primary sedimentary structures observed, and the interpreted environments in which they occur.
Figure 6. Four stratigraphic sections measured and described in Section 14, T.22 N., R.42 E., Lander County, Nevada. Expanded view of Section 1 in Figure 7.
Figure 7. Stratigraphic column of Section 1.
Table 1. Constituents (R-rare, O-occasional, T-minor constituent, X-major constituent).

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<th>Hummocky cross-stratified sandstone 4a,4b</th>
<th>Planar sandstone</th>
<th>Cross-stratified grainstone/packstone 5a,5b,5c</th>
<th>Archaeocyath framestone</th>
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<td>Terrigenous quartz</td>
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Table 2. Bedding and sedimentary structures (R-rare, C-common, P-predominant).

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1. HOMOGENIZED MUDDY SILTSTONE LITHOFACIES

Description

The best exposure of the muddy homogenized siltstone lithofacies is at the base of section 1. The lower contact is unexposed, and the thickness of this lithofacies is undetermined. The rock is grayish olive, and weathers to a yellowish brown. It is mostly composed of sub-angular, well sorted, fine silt-sized grains of quartz, and a lesser amount of chlorite. Chlorite is the second most abundant mineral to occur within the siliciclastic units described in this study. The abundant detrital clay matrix occurring in this lithofacies is primarily chlorite.

Thin, parallel laminations characteristic of micaceous siltstone are sometimes present in this facies. The rock is somewhat fissile where finely laminated. The surfaces parallel to the fissility are neither smooth nor flat; rather, they are rough and irregular. The rock splits into layers of variable thickness, with a somewhat irregular fracture. The fissility is restricted to the chlorite-rich layers.

Trilobite debris is abundant, but types of trilobites could not be determined due to the lack of identifiable parts. Even though trilobite identification cannot be
determined from this study, Stewart and McKee (1977) note the occurrence of long-eyed nevadiid trilobites in siltstone stratigraphically below archaeocyath-bearing limestone. This lithofacies most closely matches this description, so these long-eyed nevadiid trilobites probably occur within this lithofacies.

Above 3 m from the base of exposure in Section 1, it is interstratified with bioclastic grainstone lenses, and coarse-grained siltstone, which grades into fine-grained sandstone of the overlying lithofacies. Where this lithofacies is interstratified with coarse-grained siltstone, some of these beds are 3 to 6 cm thick and show no obvious lamination or fissility. A rather blocky pattern of fracture is evident in these coarser beds, presumably reflecting an original lack of depositional layering (i.e. continuous steady deposition), or most likely, a complete disruption of layering by bioturbation.

Within the lithofacies, a 20-cm-thick imbricated bioclastic grainstone lens occurs 5 m above the base of section 1 (Fig. 8). The basal and upper portions of the lens are composed of very fine-grained, wavy, parallel-laminations of yellowish-brown dolomite and detrital quartz. The imbricated bioclastic grainstone is composed of micritized, medium light gray brachiopod, trilobite, echinoderm, and archaeocyathan debris layers.
Figure 8. Photomicrograph of bioclastic grainstone in homogenized muddy siltstone lithofacies. Stylolite (arrow) indicated by truncated archaeocyath grain resting along pressure-solution surface, and accumulation of insoluble residue composed of quartz, dolomite and iron-oxide. Section 1 stratigraphic column. Scale in lower right is 1 cm.
Figure 9. Section 1 stratigraphic column. Storm-deposited ooid grainstone lens in homogenized, muddy siltstone lithofacies. Note diagenetic replacement by dolomite of outermost 2 cm. Penny for scale.
Evidence of sediment transport is indicated by tabular-planar cross-bedding and well-rounded imbricated bioclasts. The lower contact of the bioclastic grainstone lens is sharp, irregular and clearly erosional, with channel-like features. The upper contact of the wavy, parallel-laminated siltstone layer capping the bioclastic grainstone is also sharp.

An ooid grainstone occurs 6 m above the base of section 1, as two thin lenses composed of silt-sized detrital quartz and gray to dark brown ooids, in a sparry calcite matrix (Fig. 9). The ooids are predominantly superficial ones, with one or very few laminae; the nuclei consist of large peloids or aggregate grains (similar to those described by Rusnak, 1960). Some of the ooid nuclei are partially micritized and some exhibit dissolution and recrystallization. The ooids average 2 mm in diameter and are spherical. The ooid grainstone forms a sharp contact with the surrounding sandy siltstone. The lower contact is low-angle trough shaped, and the upper contact is planar, producing the lensoid shape of these beds.

A brachiopod-superficial ooid grainstone also occurs in this lithofacies. It is composed of very fine-grained quartz sand, dark brown to black ooids, and brachiopod shell fragments in a dolomitic matrix (Fig. 10). The
superficial ooids have one or very few laminae, and nuclei formed by large peloids or aggregate grains such as described by Rusnak (1960). Some of the ooids exhibit dissolution and recrystallization. Disarticulated brachiopod shells are aligned parallel to bedding. The beds occur as thin isolated lenses. The lower contact of the brachiopod superficial ooid grainstone is clearly erosional and more irregular than the trough shaped contacts of the ooid grainstone.

There is an increase of interbedded very fine sand layers 7 m above the base of the section. Low-angle, partially rounded, symmetrical wave ripples occur 3 cm below a wrinkle marked surface. Ripples are 7 cm in length from crest to crest and 0.5 cm at maximum height.

Wrinkle marks, or Runzelmarken, similar to those described by Reineck and Singh (1980), occur as irregular ripple-like features on at least one surface of fine-grained sandstone beds between the limy grainstone deposits (Fig. 11). They are made up of small ridges 0.5 to 1 mm thick and a few mm in length. Generally these small ridges run parallel to each other, but on at least one bedding plane the ridges are curved and make honeycomb-like structures.

Load casts occur on the lower surfaces of beds of fine-grained sandstones interbedded with the fine-grained
Figure 10. Photomicrograph of brachiopod-superficial ooid grainstone. Note bioclasts and matrix replaced by dolomite. Section 1 stratigraphic column. Scale is 1 cm.
Figure 11. Bedding plane with wrinkle marks in homogenized, muddy siltstone lithofacies. North direction is from right to left side of photo. Wrinkle marks indicate a west to north-west trending current direction. Section 1 stratigraphic column. Quarter for scale.
siltstone. These load casts are concave-up, irregular lobes of variable size and protrude about 3 to 4 cm into the surface of the underlying bed. Flame structures of the underlying bed can be observed between the sandy lobes of the load casts. Internally, the load casts show contorted laminations. Close to the edges, laminations parallel the margin, but towards the center contortion becomes more intense. Lamination beneath the loaded surface tends to follow the margins of the flame structure, becoming contorted upwards towards the center of the flame.

The top of this lithofacies is gradational into the overlying lithofacies (planar cross-stratified sandstone).
2. PARALLEL LAMINATED SANDSTONE LITHOFACIES

SUBFACIES 2a.
PLANAR CROSS-STRATIFIED SANDSTONE - SKOLITHOS LITHOFACIES

Description

This lithofacies first occurs as a 2 m thick horizontally bedded, parallel-laminated sandstone, above the homogenized muddy siltstone lithofacies (lithofacies 1). Some of the laminations may exhibit parting lineation. It is poorly exposed and tends to be a slope former. The individual sandstone beds average 4 to 6 cm thick. The base of each sandstone bed is in sharp contact with the underlying bed. It is very fine grained, yellowish white at the base grading upward to dark olive green (weathers dark brown to black) at the top. It is composed of angular, well-sorted grains of quartz and micaceous chlorite, with the chlorite becoming more abundant upward. Iron stained, siliceous, fossil debris of brachiopods, trilobites, and archaeocyathids are recognizable at the base of a few beds in the lowermost part of the lithofacies. The fossil lags occur stratigraphically above erosional bases. Molds and casts of brachiopod shells also occur on some of the planar bedding surfaces.
In section 1, this lithofacies reoccurs as a 1.5 m thick, thinly-laminated, fine-grained sandstone stratigraphically above the tabular cross-bedded sandstone/interbedded ripple-laminated siltstone lithofacies (lithofacies 5) (Fig. 12). Here, the sandstone is olive green and weathers to a greenish brown. The sandstone is composed of angular to subangular, fine, well-sorted quartz, and chlorite.

The sandstone is comprised of thick-bedded, parallel-laminated, well-sorted sand in planar horizontal beds. These beds also exhibit parting lineation. Simple unbranched burrows of *Skolithos*, with structureless fill, are abundant in the lower part of the lithofacies. They occur perpendicular or slightly inclined to bedding.
Figure 13. Thinly laminated planar sandstone (p) stratigraphically below undulating parallel laminated sandstone (u). Note sharp erosional contact (sc) of overlying brachiopod packstone (bp). Section 1 stratigraphic section. Pen for scale is 12 cm.
SUBFACIES 2b.
UNDULATING PARALLEL LAMINATED SANDSTONE LITHOFACIES

Description
Near the top of section 1, directly below an echinoderm grainstone (lithofacies 5a), an undulating, parallel-laminated sandstone abruptly overlies a planar cross-stratified sandstone (lithofacies 2) (Fig. 13). The thickness of this subfacies is locally variable from 0 to 0.5 m. Bedding surfaces are smooth with a gentle undulation of three-dimensional domes and hollows. In vertical section, laminations are thin and roughly parallel to the surface undulation (Fig. 13). In some places, low-angle intersecting curved laminations may be seen below the domes. Primary current lineation is shown on bedding surfaces. The structures described here differ from hummocky cross-stratification (refer to hummocky cross-stratified lithofacies) in that: (1) the laminae are parallel to the surface undulation and tend to have a constant thickness throughout the domes and hollows; (2) the undulations do not gradually die out upwards; (3) upper contacts are undulatory, as opposed to horizontal; (4) they are not associated with wave ripples, and they exhibit primary current lineation.
Figure 13. Section 1 stratigraphic column. Lamination parallel to surface undulation in undulating parallel laminated sandstone lithofacies. Dime for scale.
3. INTERBEDDED SANDSTONE AND SILTSTONE LITHOFACIES

Description

The interbedded sandstone and siltstone lithofacies occurs above the planar cross-stratified sandstone lithofacies (lithofacies 2a) and below the hummocky cross-stratified lithofacies (lithofacies 4a). The siltstone is dark olive green and weathers black. It is composed predominantly of sub-angular, well-sorted, coarse-silt-sized grains of quartz, and an equal amount of a dark green chlorite. The laminations are slightly wavy, very thin, and horizontal.

Parallel laminations are by far the most common primary structure. Parallel laminations are detected by slight color changes which depend on alternations of very fine-to fine-grained sand within an otherwise coarse-grained silt. Horizontal trails and burrow mottled layers are present occasionally and alternate with layers that display little or no burrowing (Fig. 14). Parallel and lenticular silt laminae are more common. The laminae average less than 1 mm in thickness, alternating between light and dark green.

Up to 1 m from the base of this lithofacies, homogeneous siltstone occurs in beds that may be one or several centimeters thick. It is dark olive green and
Figure 14. Horizontal trails and burrow mottled layers in interbedded sandstone and siltstone lithofacies. Section 1 stratigraphic column. Pocket knife for scale is 8.5 cm.
Figure 15. A) underside of symmetrical gutter casts in interbedded sandstone and siltstone lithofacies. B) cross-section of asymmetrical gutter cast in interbedded sandstone and siltstone lithofacies. Section 1 stratigraphic column. Penny for scale.
weathers black. It is non-calcareous and unfossiliferous. It is composed of silt-sized quartz and randomly oriented chlorite platelets.

The homogeneous siltstone grades into decimeter thick layers of siltstone, interbedded with thin (less than 5 cm thick) fine-grained sandstone beds. The sandstone beds increase in frequency upwards, and this lithofacies is gradational into the overlying hummocky cross-stratified sandstone lithofacies above.

In the uppermost part of this lithofacies, thin, rippled, lime packstone and grainstone interbeds and lenses with sharply scoured lower contacts and bioturbated upper contacts are present.

Gutter casts occur as mostly isolated elongate ridges on the bases of sandstone beds. They protrude into the underlying finer-grained sediment from an otherwise flat bedding plane; in vertical section they have a U-shaped profile. Some gutter casts are symmetrical and 6 to 9 cm wide (Fig. 15A), while others are asymmetrical (Fig. 15B). Some have gently curved outer walls and some are steeper. Tool marks of trilobite debris are superimposed on the walls and floors of some of the gutter casts, showing preferred orientation parallel to the elongation of the gutter casts.
Description

The hummocky cross-stratified sandstone is gradational from dark green at the base of the subfacies to brownish green at the top. It occurs above the interbedded sandstone and siltstone lithofacies (lithofacies 3), and below the tabular-planar bedded sandstone/ripple-laminated siltstone lithofacies (lithofacies 4b). It is composed primarily of fine quartz sand and chlorite. It weathers primarily brown to black.

A few thin, medium-grained quartz sandstone lenses (2 to 4 cm thick) are interbedded in the upper part of the lithofacies. Thin section analysis indicates that authigenic iron-rich cement fills pore spaces between some of the grains. The medium-grained quartz also makes up the bulk of slump deposits reported in this lithofacies, described below.

In the lower part of this lithofacies there are decimeter-thick sandstone layers. These layers contain concentrations of coarse bioclastic material immediately above an uneven erosional base, grading up into cross-
laminated sandstone with wave ripple marks.

The predominant sedimentary structure associated with the fine-grained sandstone is hummocky cross-stratification. Hummocky cross-stratified sandstone (Fig. 16) occurs as sets of curving lamination with both convex-up (hummocks) and concave-up (swales) sectors, as described by Walker (1981). Low-angle intersecting curved surfaces with convex-up stratification distinguishes hummocky cross-stratification from very low-angle trough cross-bedding (Brenchley, 1989). The sandstone is characterized by an erosional lower boundary surface dipping mostly at less than 10 degrees, with laminae subparallel to the lower boundary surface. The dip directions of the erosional set boundaries and of the overlying laminae appear to be scattered. The laminae seldom dip at more than 12 degrees, and sets intersect one another at low angles, typically 3 to 6 degrees. The laminae sometimes thicken into swales and thin over hummocks, so that the undulations gradually die out upwards. Heights of undulations average 5 to 10 cm and wavelengths are of the order of 1 m. The absence of apparent preferential orientation to the inclination of laminae suggests a uniform three-dimensional pattern. The upper contacts are mostly horizontal and are often characterized by wave ripples, in the upper part of the
Figure 16. Hummocky cross-stratification in fine grained sandstone. Section 1 stratigraphic column. Penny for scale.

Figure 17. Slump deposit in hummocky cross-stratified sandstone lithofacies. Direction of slump movement is southwest. Section 1 stratigraphic column. Pocket knife for scale is 8.5 cm.
lithofacies.

Slump deposits occur in this lithofacies in at least one layer (Fig. 17). In vertical profile perpendicular to the fold axis, the folds are simple, unfaulted, similar flat lying structures with moderately curved hinges. Each slump deposit is confined to a single bedding set and is truncated upward by an undeformed erosion surface beneath the bed above. The lateral extent of the folded layers is unknown, however, they are at least several meters across. Lamination is distinct, except in the downslope sediments at the toe where they are folded and overturned. The axes, oriented northwest to southeast, are perpendicular to the direction of slump movement and parallel with the strike of the paleoslope. The direction of slump movement is southwestward.

Convolute laminations are folded into upright cuspat e forms with sharp anticlines and more gentle synclines. Overturning of fold axes is sometimes seen, often with a preferred orientation. Laminae can be traced through the folds. Convolution increases in intensity upwards through a bed, beginning with undisturbed lamination at the base. At the top of the bed the convolutions either die out gradually or are sharply truncated.
SUBFACIES 4b.

TABULAR-PLANAR BEDDED SANDSTONE/ripple-laminated
SILTSTONE LITHOFACIES

Description

A very fine-grained, tabular cross-beded sandstone, interbedded with ripple-laminated siltstone, generally in sets less than 30 cm thick occurs about 5 m below the base of thick limestone units in section 1 (Fig. 18). Symmetrical wave ripples show a distinctive internal structure characterized by superimposed chevron-like laminations. Ripple crests are rounded in shape.

The sandstone is dark green and weathers black. It is composed of fine-grained, angular, well-sorted quartz and chlorite, within a matrix of authigenic chlorite and iron oxide. The base of each sandstone bed is horizontally laminated, overlain by moderate angle (20 degrees) cross laminae, grading to low-angle unidirectional cross laminations that exhibit tangential foreset contacts with the underlying lamination (Fig. 19). The dip direction of the low-angle unidirectional cross-laminations is southerly.

Dark green, black weathering, siltstone overlies each sandstone bed. The siltstone is composed of angular, well-sorted silt-sized quartz and chlorite grains, within
a matrix of authigenic chlorite and iron oxide. It is ripple-laminated and highly fissile.
Figure 18. Interbedded tabular cross-bedded sandstone and ripple laminated siltstone lithofacies. Section 1 stratigraphic column. Scale in lower center.
Figure 19. Photomicrograph of tabular cross-bedded sandstone exhibiting tangential foresets. Note wave ripple in lower right of photograph. Section 1 stratigraphic column. Scale is 1 cm.
5. BIOCLASTIC PACKSTONE/GRAINSTONE LITHOFACIES

SUBFACIES 5a.
UPWARD FINING, TABULAR CROSS-STRATIFIED, ECHINODERM GRAINSTONE

Description

In section 1, an echinoderm grainstone occurs in a 20 to 60 cm thick layer. It occurs above the planar laminated sandstone (lithofacies 2) and below the bioclastic grainstone (lithofacies 5c). In section 4 this subfacies is at least 1 m thick, and the lower contact is unexposed. This subfacies is gradational into the overlying bioclastic grainstone subfacies (5c).

The echinoderm grainstone is "salt and peppered" light gray and dark brown to black. It is composed of mm sized grains of micrite, sparite, dolomite, and minor amounts of iron-bearing minerals (Fig. 20). The fossils are predominantly echinoderm plates, but archaeocyath and brachiopod debris is also present (Fig. 21A). The bioclasts are very well preserved. Most echinoderm plates average 1 mm in diameter. Gangloff (1975) identified two and possibly three different taxa of echinoderms, including the genus Gogia (?), an eocrinoid.

Small archaeocyaths with a diameter of less than 1
Figure 20. Photomicrograph of echinoderm grainstone. Section 4 stratigraphic column. Scale is 1 cm.

mm, and exhibiting radial septa, are common. Some detrital, medium-grained quartz grains are also present. The bioclasts are poorly sorted and angular. Locally the echinoderm grainstone occurs in a 20 - 60 cm thick layer forming a sharp erosional contact with both the underlying sandstone and the brachiopod packstone (Fig. 21B). Locally the lower part of the unit consists of tabular cross-beded sets 2 to 4 cm thick. This lithofacies most typically consists of fining upward sets 1 to 13 cm thick.
Figure 21. A) Echinoderm grainstone deposit with irregular laminations and imbricate clasts. B) Polished slab of echinoderm grainstone. Note irregular contact (i) with brachiopod packstone, and small channel (c). Coin for scale. C) Gutter casts filled with echinoderm grainstone protruding into underlying undulatory bedded sandstone. Section 1 stratigraphic column. Hammer for scale is 30 cm.
Gutter casts occur as isolated elongate ridges on the bases of the echinoderm grainstone beds (Fig. 21C). They protrude into the underlying finer-grained sediment and display a U-shaped profile. The gutter casts are symmetrical, 10 to 20 cm wide, and 4 to 6 cm deep, with the long axes trending west to northwest.

SUBFACIES 5b.
TROUGH CROSS-STRATIFIED BRACHIOPOD PACKSTONE CHANNEL-FILL

Description
This is a laterally discontinuous facies which lies in sharp erosional contact on the underlying sandstone (refer to Fig. 12). Steps and terraces are present, representing repeated episodes of cut and fill. The brachiopod packstone is yellowish gray. It is composed of angular to subangular fine- to medium-grained quartz sand, brachiopod shells, micrite, chlorite, archaeocyaths, and iron-oxide staining (Fig. 21B). Sandstone reoccurs in a thin bed with an upper erosional surface that pinches out stratigraphically above the brachiopod packstone. Samples from section 1, containing brachiopod shells, were identified by A.J. Rowell. He reported (written commun., 1991) that
"the sample contains poorly preserved
archaeocyaths, which in North America are
known only from the Lower Cambrian. I am
fairly sure that the abundant shells are
those of obolellid brachiopods. They are
unquestionably calcareous, smooth, and at
least a few of them are bivalved."

In addition, the obolellid brachiopod shell clasts average
about 1 cm in length, are very thin, and are
unidirectionally oriented in the current direction.

The presence of chlorite, calcite, and quartz in this
lithofacies is confirmed by X-ray diffraction analysis.
The analysis was performed by Walt Raywood at the UNLV
Geoscience Department. Figure 22 contains the graphical
result of the analysis.
### Figure 22

X-ray analysis and results of a sample from the trough cross-stratified brachiopod packstone channel-fill subfacies.

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- **Clinochlore**: <=7.1337, <=4.7481, <=3.5473, <=2.2847, <=1.9247, <=1.8186
- **Calcite**: <=3.8661, <=2.8396, <=2.6176, <=2.4952, <=2.2849, <=2.1320
- **Quartz**: <=3.528, <=2.8396, <=2.6176, <=2.4952, <=2.2849, <=2.1320

**Legend**:
- Clinochlore: blue
- Quartz: green
- Calcite: red
SUBFACIES 5c.
UPWARD-FINING BIOCLASTIC GRAINSTONE/LAMINATED
DOLOMITE LITHOFACIES

Description

The bioclastic grainstone/laminated dolomite lithofacies is composed of alternating 3 to 12-cm couplets of wavy horizontal dolomitic laminations and upward fining bioclastic grainstone (Fig. 23). The grainstone makes up the bulk of the exposed limestone capping the sequence (Fig. 24).

The laminations are composed of fine-grained, yellowish-brown dolomite. Each lamination is approximately 0.1 mm thick. The laminations tend to be stacked, forming distinct layers. The layers range from 0.1 to 3 cm thick. The dolomitic layers are separated by grainstone layers that vary from 1 to 20 cm in thickness. The dolomite layers occur sporadically and are not gradational with the grainstone. The grainstone fabric is occasionally mottled with fine-grained dolomite. The bioclastic grainstone/laminated dolomite lithofacies varies locally from 1 to 7 m in thickness. Some layers have abruptly terminated contacts with underlying units. The majority of the dolomite and grainstone layers maintain a uniform thickness where convoluted.
Figure 23. Polished slab of bioclastic grainstone - laminated dolomite lithofacies. (a) Thinly laminated dolomite. (b) Upward fining bioclastic grainstone. Section 4 stratigraphic column. Penny for scale.
Figure 24. Photo of bioclastic grainstone/laminated dolomite lithofacies. Note disoriented bedding, and sharp erosional surface (e). Section 1 stratigraphic column. Hammer for scale is 30 centimeters.

Figure 25. Convolute laminations in bioclastic grainstone/laminated dolomite lithofacies. Section 1 stratigraphic column. Camera lens cap for scale is 6 cm.
Convolute laminations and bedding occur as 40 to 70 cm thick folded forms of anticlines and synclines (Fig. 25). Overturning of fold axes is sometimes seen, often with an apparent preferred orientation. The axial planes of the folds have an easterly to southeasterly direction of inclination. Laminae can be traced through the folds. Convolution increases in intensity upwards through a bed from undisturbed lamination at the base. At the top it may either die out gradually or be sharply truncated.

Fragments of archaeocyaths with radiating septa predominate in the bioclastic grainstone/laminated dolomite lithofacies. An encrusting type is also present. All archaeocyaths occur as solitary, non-branching forms within the grainstone.

Stylolitization is indicated by truncated grains resting on pressure-solution surfaces. There are mm thick accumulations of insoluble residue composed of quartz, dolomite, and iron-oxides along the pressure solution surfaces. These mm-thick anastomosing stylolites occur parallel to bedding.

The bioclastic grainstone/laminated dolomite lithofacies contains medium gray bioclastic grainstone layers consisting of archaeocyaths, trilobite debris, echinoderm debris, brachiopods, sponge spicules, and Chancelloria spines. Most archaeocyaths are aligned
parallel to bedding. The bioclasts are fragmented, poorly sorted, and well preserved. Bioclastic debris is cemented by well developed equant crystals of blocky calcite. There is an abundance of dolomite present and (cryptomicrobial?) fabric selective dolomitization is common. Dolomite rhombohedra are euhedral, zoned, and are commonly associated with iron oxide. In the lower part of the lithofacies, the bioclastic grainstone occurs as 1 to 10 cm thick, normally graded beds, showing a progressive upward reduction in grain size. Bioclasts 0.5 cm in diameter grade upward into very fine-grained dolomite laminations. The beds are mostly structureless, except where lamination is present in the upper part.

Tabular, imbricate, and dolomite-cemented sandstone clasts occur in at least two channel-like lenses about 12 cm thick at maximum thickness and 1 m in width (Figs. 26, 27). The channels also contain yellowish-brown very fine dolomite, blackened echinoderm spines, and occasional detrital archaeocyath fragments. The bioclastic grainstone/laminated dolomite lithofacies is gradational into the overlying lithofacies.
Figure 26. Photograph of laminated, imbricated sandstone clast in bioclastic grainstone/laminated dolomite lithofacies. Section 1 stratigraphic column. Dime for scale.
Figure 27. Photograph of tabular, imbricate dolomite clasts in channel-like lens occurring in bioclastic grainstone -laminated dolomite lithofacies. Section stratigraphic column. Dime is for scale.
6. THE ARCHAEOCYATH FRAMESTONE LITHOFACIES

Description

The archaeocyath framestone lithofacies is composed of medium to dark gray archaeocyath framestone surrounded by bioclastic grainstone beds (Fig. 28). There is a variety of archaeocyath types in the framestone. Gangloff (1975) identified *Diplocyathus vulgarus*, *Fenestrocycathus dentocanus*, and *Palmettocyathus austinensis*. An unidentified genus is also present (Gangloff, 1975). Dolomite percentages increase upward in the boundstone, with higher concentrations in the flanks and uppermost parts.

The archaeocyath framestone occurs as isolated bioherms within the grainstone. The bioherms are typically 1 to 2 m across and have a vertical thickness of 1 to 2 m. They have a biconvex shape and are typically lenticular. Detrital skeletal grainstone composed of bioclastic debris completely surrounds individual bioherms.

Archaeocyaths with simple radiating septa are scarce in the archaeocyath framestone lithofacies. The growth of the bioherms is initiated by the appearance of irregular-type archaeocyaths, and irregular-type archaeocyaths dominate the bioherms (Figs. 29A, 30). They occur as very
Figure 28. Photograph of archaeocyath framestone (bioherms), surrounded by bioclastic grainstone beds. (f) archaeocyath framestone, (b) bioclastic grainstone, (e) echinoderm grainstone. Section 1 stratigraphic column. Hammer for scale is 30 centimeters.
Figure 29. A) Photograph of archaeocyath framestone as it appears in outcrop. B) Polished horizontal section of archaeocyath framestone. Note irregular type archaeocysths in growth position. Section 1 stratigraphic column. Penny is for scale.
densely packed branching forms. Light-gray lime mud occurs as centimeter-sized splotches surrounding the archaeocyaths. Centimeter-sized cavities with micritic geopetal structures and a sparry calcite roof occur. Upright branching archaeocyaths are confined to a fine-grained calcareous lithotope characterized by abundant dolomitization and a lack of terrigenous detritus.

Wavy, horizontal, millimeter-thick stylolites cut through primary sedimentary structures. Along the surfaces of the stylolites are mm-thick accumulations of insoluble residue composed of quartz, dolomite, and iron-oxides.

The framework of the bioherms consists of branching archaeocyaths. *Renalcis* may be present, but due to poor preservation, a positive identification is not possible. *Renalcis*-like material encrusts the exterior of some of the archaeocyathan cups and partially fills centimeter-sized cavities within the boundstone. The *Renalcis*-like material comprises a relatively small percentage of the entire framestone, and lime mud and internal sediment is more abundant.

The cavities are intergrowth areas between archaeocyath branches and pore/intervallum spaces within individual archaeocyaths (Figs. 29B, 30). Primary growth cavities are occluded by lime-mud. Some cavities are
occluded by geopetal lime-mud and a single generation of fibrous calcite cement. Most of the pore/intervallum spaces within archaeocyaths contain internal calcisiltite sediment overlain by either lime-mud or lime-mud overlain by fibrous calcite cement. Large fibrous calcite cement fills primary voids, and small fibrous cement occurs between the Renalcis-like tufts and into archaeocyath pores.
Figure 30. Photomicrographs of archaeocyath framestone. A) micrite, irregular type archaeocyaths, *Chancelloria*, brachiopod shells, and cavity filling calcisiltite and sparite. B) micrite brachiopod shells, calcisiltite, sparite, and detrital quartz and iron oxide in pressure solution features. Scale is 1 cm.
7. DOLOMITIZED FRAMESTONE/GRAINSTONE LITHOFACIES

Description

The uppermost part of the framestone and grainstone lithofacies is extensively dolomitized, replacing 95 to 100 per cent of the micrite and sparite (Fig. 31). Structures occluded with short stubby, and bladed crystals occur sporadically. Stylolites and secondary (solution) cavities replaced with mm-size brown dolomite rhombohedrons are common (Fig. 32). Blackened, detrital archaeocyaths commonly occur (Fig. 33).

Large normal faults and fractures bisect the dolomitized framestone/grainstone lithofacies in section 1. Thin section analysis reveals that the limestone is a stylobreccia consisting of fitted angular clasts in a mosaic of thin veins (Fig. 34). The veins are composed of short, stubby calcite crystals. In comparison with other carbonate bearing lithofacies in this study, stylobrecciation occurs only in this lithofacies, in the uppermost part of section 1. The brecciated clasts are commonly associated with a thin, white calcareous coating.

Primary cavities are scarce, but where present, they tend to be filled with geopetal, fine-grained quartz sand in an iron oxide matrix. The grainstone beds are composed of allochthonomous bioclasts and micrite clasts in a
dolomitized grainstone cement.

The dolomite in the dolomitized framestone occurs as light brownish gray to buff large crystals that have replaced original minerals. Archaeocyath ghosts occur, which illustrate selective replacement of the original limestone by dolomite.
Figure 31. Photograph of dolomitized bioclastic grainstone. Section 1 stratigraphic column. Hammer for scale is 30 centimeters.
Figure 32. Photograph of stylolites and calcite rimmed clasts in dolomitized bioclastic grainstone. Section 1 stratigraphic column. Penny is for scale.
Figure 33. Polished section of dolomitized bioclastic grainstone. Note the blackened archaeocyath bioclast. Section 1 stratigraphic column. Penny is for scale.
Figure 34. Photomicrograph of brecciated limestone clasts. Fractures filled with small stubby sparite crystals and dolomite. Note brecciated dolomite in lower right. Section 1 stratigraphic column. Scale is 1 cm.
The lithofacies 1-7 described in this paper are interpreted to represent littoral to sublittoral environments. The term littoral is used here as synonymous with the intertidal zone. The term sublittoral is used here to designate shallow subtidal depositional environments and sediments. These terms are used here to designate sea-margin areas that are influenced by short-term variations of sea level caused by storm surges, rather than by tides.

Lithofacies 1

The homogeneous muddy siltstone lithofacies is interpreted to represent a littoral environment (Figs. 7, 37). Refer to p. 24 for a description of this lithofacies. The fine-grained sediments are believed to be primarily low-energy deposits from suspension, accompanied by intermittent storm deposits. These sediments may be analogous to the sediments of the modern Laguna Madre, Texas, accumulating in the back-barrier complex that lies in the shelter of Padre Island as described by Friedman and Sanders (1978). Even though the tidal range in Laguna Madre is practically zero, the water level does fluctuate as much as 1 to 1.5 m, as a result of
wind action (Friedman and Sanders, 1978, p. 327). The sediments are similar in several ways: (1) they both contain quartz sand; (2) they both contain silty-clay; (3) they both contain various carbonate materials including skeletal sands, oolitic sands, and dolomite.

No tidally formed structures were found in lithofacies 1, but grainstone lenses and wave ripples are evidence for strong winds. Also, storm deposits may exhibit sporadic, current-controlled imbricate structures and cross-bedding (Flugel, 1982).

The general lack of bedding in this lithofacies, and the abundance of trilobite fragments, may reflect the presence of an active community of burrowing organisms.

Ooids associated with siliciclastic environments rarely constitute more than 30 per cent of the beach and adjacent subtidal sediment and are associated with substantial amounts of superficial, single and multiply-nucleated ooids as well as uncoated grains, as described by Rusnak (1960). This association distinguishes the oolite lenses found in the Ravenswood area, from those of the classical shoal, in which ooids constitute 80 to 90 per cent of the grains in the sediment (Purdy, 1963). The symmetrical nature of the ooids reflects formation in agitated conditions. Ooids with similar descriptions, are known to originate in shoreline environments (Heckel,
Therefore, I interpret the oolite lenses in the homogeneous muddy siltstone lithofacies to be the products of periodic high-energy storm events, in a low-energy littoral environment.

Symmetrical wave ripples are produced by the action of waves on a non-cohesive surface. Rounding of crests may be a result of reworking of ripples during emergence, a process described by Reineck and Singh (1980). The presence of wrinkle marks is a good indication that the sediment surface has undergone intermittent emergence (Collinson and Thompson, 1989). Wrinkle marks have been shown experimentally to occur on sediment surfaces that are partially cohesive (Reineck and Singh, 1980). If such a sediment surface is covered by only a very thin film of water (up to 1 cm) and a strong wind blows over it, the sediment surface develops wrinkles.

Load casts and flame structures form by gravity acting on unstable beds when there is a difference in density between the beds. The combinations of density inversion and gravitational instability leads to the sinking of one bed into the other (Allen, 1982). Contortions within large load casts can be similar to those of slumps, but the latter involve lateral movement which is shown by a preferred orientation of folds. The load casts in this lithofacies were produced by dominantly
vertical movement, which produced a random fold orientation. In addition, loading in this lithofacies is confined to one pair of beds, whereas slumping may involve many or several beds.

Fine-grained sandstone and bioclastic grainstone from sublittoral environments were probably transported into the littoral zone via storm surge channels. Wave induced currents, carrying sediment through the storm surge channels, cut into the littoral areas. These sandstone- and grainstone-filled channels were formed during intense storm activity, similar to processes described by Iden and Moore (1983), and Hayes (1964).

**Lithofacies 2a**

The planar cross-stratified sandstone - *Skolithos* lithofacies represents storm generated sheet sands, deposited in a very shallow intermediate to proximal, sublittoral environment (Figs. 7, 37). Refer to p. 33 for a description of this lithofacies. Due to the lack of emergence features, this lithofacies probably never became a shoreline. However, the substrate consistency and energy levels are supported by the presence of *Skolithos*. *Skolithos* occurs in a high energy environment, with constant wave mixing (Moore, 1976). Faunal diversity is characteristically low in this environment (Howard, 1972).
The preferred substrate sediment type and firmness is consistent with highly mobile sand being predominant. Upper flow regime conditions in this lithofacies are indicated by: (1) thick-bedded sandstone; (2) parallel laminations; (3) good sorting; and (4) presence of vertical burrows.

Allen (1982) shows the character of storm sand-layers to be a function of storm duration, characteristic wind speed, and increasing water depth (Fig. 35). According to this model, the parallel laminated sands indicate that water depth had to be shallower to produce these features, than those that would produce the hummocky-crosstratified features in lithofacies 4a. Also, the shell lags found in this and other lithofacies, may represent storm deposition similar to the model proposed by Allen.

**Lithofacies 2b**

The undulating, parallel-laminated sandstone subfacies is interpreted to represent high energy, proximal deposits of storm-generated, sublittoral sheet sands (Figs. 7, 37). Refer to p. 36 for a description of this lithofacies. This subfacies is related to subfacies 2a in that it was probably formed in a similar environment. The association of primary current lineation with this structure and its general similarity to parallel
Figure 35. Three dimensional representation of storm deposits as a function of wind speed, storm duration, and depth (from Allen, 1982).
lamination suggests a related origin. If the velocity of water flowing over an upper-flow-regime flat bed is increased, a pattern of ephemeral waveforms develops on the sediment surface (Collinson and Thompson, 1989). Such structures can be observed where steep streams cut across sandy beaches, or where storm water flows down steep gutters (Collinson and Thompson, 1989).

**Lithofacies 3**

The interbedded sandstone and siltstone lithofacies also reflects high energy sublittoral sheet sands (Figs. 7, 37). However, this lithofacies represents a more distal area of storm deposition. Refer to p. 38 for a description of this lithofacies.

The main sediment source is terrigenous siliciclastic detritus. Offshore is a lower energy environment where biological processes such as bioturbation predominate. Distinct horizontal and branched infaunal burrows occur within this lithofacies, reflecting the prevailing lower energy offshore conditions. The interbedded sandstone is hummocky bedded, and is interpreted to represent storm beds similar to those described by Brenchley (1989).

Gutter casts are the product of fluid scour, aided by the erosive nature of the objects carried by the flow. They reflect a pattern of helical vortices with their
horizontal axes parallel to the flow (Collinson and Thompson, 1989).

Lithofacies 4a

The hummocky cross-stratified lithofacies represents proximal sublittoral storm-generated sheet sands (Figs. 7, 37). Refer to p. 42 for a description of this lithofacies. The presence of hummocky cross-stratification identifies a depositional environment above storm-wave base (Brenchley, 1989). Deposition of hummocky cross-stratification takes place in low hummocks and shallow swales related to increased wave energy. Such units occur in the lower part of ancient shoreline sequences, especially in fine sandstone shorefaces (Brenchley, 1989; Walker, 1981; Reineck and Singh, 1980).

Storm sandstones are common in regressive shelf sequences (Brenchley, 1989). The grading upwards from interbedded siltstone and storm deposited sandstone of lithofacies 3 into the amalgamated hummocky cross-stratified sandstone in this lithofacies may record the transition from a shelf environment to the lower shoreface similar to that described by Brenchley (1989).

Alternatively, and most likely, the sequence indicates a prograding storm- and wave-dominated open shelf which is affected neither by a nearby shoreline, nor by persistent
background marine currents. This interpretation is based on the storm surge-ebb facies model (Reading, 1983, p.255) proposed for the late Pre-Cambrian Innerelv Member of northern Norway. In that case, the facies sequence is believed to reflect shallowing in a sublittoral environment, which never became a shoreline.

Sharp bases and lack of bioturbation in the hummocky cross-stratified sandstone lithofacies indicate sudden influxes of sediment followed by rapid deposition, no subsequent reworking of the hummocky cross-stratified sand and, in the lower part of this lithofacies, a return to silt deposition. The lack of reworking into wave-formed symmetrical ripples suggests deposition below fair-weather wave base. The hummocks and troughs are interpreted as forms produced by the oscillatory motion of storm waves feeling the bottom (Hamblin and Walker, 1979). Hummocky cross-stratification is a good indicator of deposition below fair-weather wave base but above storm wave base, with the hummocky topography being controlled by storm waves (Brenchley, 1989; Walker, 1981).

Walker (1981, p.86) demonstrates how hummocky cross-stratification is formed. After a major storm, when wind abates, a seaward flowing density current is generated (storm surge rip current). Above storm wave base but below fair-weather wave base, the storm waves are still
affecting the bottom, and as deposition from the density
current takes place, hummocky cross-stratification is
formed. Brenchley (1989) suggests that oscillatory
currents, capable of powerfully reworking sand, are
probably unlikely to occur in depths of more than 50 m,
and, therefore, hummocky cross-stratification is probably
restricted to much shallower depths near sheltered coasts.

Slump deposits in this lithofacies are interpreted to
be produced by sedimentary slumping (sliding at the
sediment/water interface) rather than tectonically (within
a sediment column undergoing tectonic deformation).

Helwig (1970) compiled a list of features that
classify sedimentary slumps. These features, all of
which are present in the Ravenswood section, are: (1) the
deformed beds occur as a zone between undisturbed beds,
(2) there is a depositional fit between the irregularities
of the upper surface of the slump and the base of the
overlying bed, (3) the fold antigens are eroded at the
upper surface, and (4) the preferred orientation of fold
axes is unrelated to the regional tectonic strike.

The most important criterion for recognizing this as
a slump deposit is the similarity of the sediment above
and below the surfaces of the slump scar. Slumps
originated because of instability of sediment on a slope
and they commonly move spontaneously without any external
trigger (Collinson and Thompson, 1989). In the Ravenswood area, depositional conditions resumed and were unaltered after slumping occurred. Younger sediments drape and eliminate the topography of slump scars.

It is possible that there are two deforming forces producing such slump folds. The first, and most likely, is folding due to gravitationally-induced downslope movement which is supported by the attitude, shape, and lateral extent of the folds (Allen, 1982). Second, and least likely, it may be that folding resulted from fluid drag of the upper surface of the cross-bedded sand body (Allen, 1982).

Studies in modern environments show that slumping of unconsolidated sediments occurs on subaqueous slopes as low as 0.5 degrees (Allen, 1982). Slumping is triggered by earthquake shocks, the build-up of pore-fluid pressure as the result of the migration of pore water, and the oversteepening of slopes by deposition or other means (Allen, 1982). Pre-slump deposition and slump movement in this lithofacies, were probably a direct result from sediment laden, storm-surge ebb currents. This is indicated by slump deposits occurring between hummocky cross-stratified sandstone.

Convolution in this lithofacies indicates that plastic deformation of partially lithified sediment
occurred soon after deposition. Liquefaction was probably aided by wave action. Where axial planes of folds have a preferred direction of inclination, this coincides with the paleocurrent indicators, suggesting that convolution formed during deposition.

**Lithofacies 4b**

The tabular-planar bedded sandstone/ripple-laminated siltstone lithofacies is related to the hummocky cross-stratified subfacies because it is interpreted to occur in a similar environment. Refer to p. 46 for a description of this lithofacies. I interpret this subfacies to represent bar migration in response to storm-enhanced storm-surge ebb currents and fluctuations in flow power. The symmetrical wave ripples are produced by the action of waves on a non-cohesive surface, and indicate post-storm wave reworking. Also, tabular planar cross-bedding of moderate angle (18-28 degrees) commonly occurs in offshore bars (Heckel, 1972). The dip directions of the laminations in the tabular planar bedded sandstones are parallel with an inferred shoreline striking north-south. This indicates that currents apparently flowed southward, parallel to the shoreline trend.
Lithofacies 5a

The upward fining, tabular cross-stratified, echinoderm grainstone subfacies of lithofacies 5 is interpreted to represent offshore bars produced by intense storms (Figs. 7, 37). Refer to p. 50 for a description of this lithofacies. Echinoderms preferentially inhabit the littoral and sublittoral zone, with normal marine salinity (Flugel, 1982). I interpret the echinoderm grainstone deposit to be analogous to bioclastic debris deposits studied by Hayes (1964), in which case bioclastic debris was derived from offshore environments during intense storm activity and transported landward. Hurricanes have transported sediments from depths of as much as 25 m onto coastal areas (Flugel, 1982).

In this subfacies, current direction is parallel to the direction of the long axis of gutter casts. This direction indicates that a current flowing west to northwest (present orientation) filled the gutter casts in this subfacies in Section 1.

Lithofacies 5b

The trough cross-stratified brachiopod packstone channel-fill subfacies is interpreted to represent shallow channels cut by storm-surge ebb currents and infilled as the storm subsides (Figs. 7, 37). Refer to p. 54 for a
description of this lithofacies. The packstone occurs as channel-fill accumulations of brachiopod shell debris, and sand. The cutting of a channel implies the action of strong currents, and these are reflected not only in the erosional surface but also in the coarser sediments that are laid down above that surface. The depositional structures also reflect high-energy currents.

Hayes (1964) described how hurricane-generated currents can cut through a modern barrier island (Padre Island). As the storm moved landward it picked up bioclastic debris from depths of several meters, and deposited it on the barrier island. After the storm passed, water rushed from the lagoon back to the sea through the channels, producing thin graded layers farther out on the shoreface. The late Pre-Cambrian Innerlv Member from north Norway is an excellent example of a storm-surge ebb facies model for a low-energy coastline (Reading, 1983). I interpret the brachiopod packstone lithofacies to have formed in a similar fashion, representing deposits of storm-surge ebb flows.

**Lithofacies 5c**

The upward-fining bioclastic grainstone/laminated dolomite lithofacies is interpreted to represent graded, sublittoral, storm generated sheet deposits or storm lags.
(Figs. 7, 37). Refer to p. 57 for a description of this lithofacies. Flugel (1982) indicates sedimentary structures and particle characteristics associated with storm deposits of carbonate sediments. These features which are present in this subfacies are the following: 

1. Reworked bioclasts of various sizes are deposited within distinct layers and separated by laminated dolomitic-lime mud. 

2. Along with some overturned bioclasts there are different kinds of intraclasts, indicating rapid erosion.

The sharp-based grainstones with non-erosive or gradational tops suggest a pattern of episodic storm deposition, similar to that described by James (1981) and Reading (1983). The coarser grained clasts are interpreted to record high energy events, while the dolomite records longer intervals of deposition from suspension during quiet conditions or during waning of the storm event and backflow to open ocean. Storm lags are thought to result from the reworking of the sea floor by storm waves, but may also form at the mouth of storm-surge channels (Reading 1983).

Convolution is due to plastic deformation of partially liquified sediment soon after deposition. Where axial planes of folds appear to have a preferred direction of inclination, this direction often coincides with the
apparent paleocurrent, suggesting that convolution formed during deposition (Reineck and Singh, 1980). The primary significance of the convolute lamination is the evidence they provide for rapid deposition, and an apparent paleocurrent direction from west to northwest.

The tabular clasts represent sedimentary features produced by early cementation and transportation soon after deposition. Intraclasts typically have subtle textural, structural (disoriented laminations) and color contrasts with the surrounding deposits. During storms, slabs are undercut by wave and current action, causing collapse, breakage and reworking into tabular cobble- to pebble-size beachrock clasts, which are recognized in ancient beach sequences (Iden and Moore, 1983). The tabular clasts were probably transported seaward during a storm-surge ebb flow. Imbrication, indicating an apparent west to northwesterly paleocurrent direction, supports this interpretation.

The pressure solution features are diagenetic and are caused by chemical dissolution along stylolites, and the subsequent accumulation of insoluble residue along the pressure-solution surfaces.
The archaeocyath framestone lithofacies is interpreted to represent patch reefs in a storm dominated, sublittoral open shelf environment (Figs. 7, 37). Refer to p. 64 for a description of this lithofacies. With few exceptions, archaeocyaths have been previously interpreted to be confined to a fine-grained calcareous lithotope characterized by a lack of terrigenous detritus (Gangloff, 1976), and the vast majority living in limestone mounds and bioherms (Rowland and Gangloff, 1988). However, some archaeocyath buildups are associated with terrigenous clastic sediments (Mount, 1976; Gangloff, 1976; Rowland and Gangloff, 1988; Debrenne et al., 1989). Therefore, it is possible that some species of archaeocyaths were able to fill niches within siliciclastic-dominated environments of deposition.

Siliciclastic depositional environments are not normally favorable for the growth of reef-building because of high turbidity, nutrient excess, or unfavorable substrates. Yet there was a wide spectrum of interaction between reefal carbonates and siliciclastic sediments throughout the Phanerozoic.

In the lagoonal areas of both the Belize (Central America) and Great Barrier Reef tracts, the positions and geometries of some reefs were probably determined by the local relief (channel banks, bars, deltaic lobes) of the
local relief (channel banks, bars, deltaic lobes) of the underlying siliciclastic foundations (Ginsburg et. al., 1983). In the Pennsylvanian, Permian, and Jurassic of North America and in the Permian of Japan, reefal carbonates are juxtaposed with deltaic and associated siliciclastic sediments (Ginsburg et. al., 1983).

I interpret the small bioherms in the Ravenswood District to represent reefs that are analogous to the modern coral-algal lime boundstones associated with barrier-island lagoonal complexes described by Iden and Moore (1983). The bioherms may also be analogous to oyster reefs which grow in and around deltaic channels in modern environments.

**Lithofacies 7**

The dolomitized framestone/grainstone lithofacies is interpreted to represent a sublittoral patch reef environment associated with carbonate sheet deposits (Figs. 7, 37). Refer to p. 71 for a description of this lithofacies. This lithofacies has been separated from lithofacies 5c and lithofacies 6, because at least locally, it has been severely altered by diagenetic processes. The variable colors, light gray to light brown, and reddish tints reflect increased mineralization due to groundwater. The dolomite occurring in this
lithofacies is lithologically different from the laminated dolomite occurring in the bioclastic grainstone/laminated dolomite lithofacies. Rather than occurring from primary depositional origin, the dolomite here is secondary, occurring by selective replacement during diagenesis. Selective replacement of the original limestone must have proceeded parallel to the boundaries or following the boundaries of the original particles, thus preserving their shapes.

The breccia in this lithofacies is not spatially related to known faults that cut through the siliciclastic units below. The brecciated area increases where there is an increase in the number of stylolites. In the siliciclastic units, faults occur as planar multiple sets with no apparent brecciation. Therefore, a more likely explanation for the presence of limestone breccia is that it is stylobreccia, that is, breccia in which the fragments are bound by stylolites caused by fracturing accompanied by pressure solution. This allowed for the increased infiltration of late diagenetic fluids to permeate through this lithofacies to obliterate primary depositional structures.
The foregoing represents the use of lithologies, primary sedimentary structures, and fossils as keys to the interpretation of environmental settings (Tables 1 and 2).

Within this sequence, wrinkle marks in Lithofacies 1, indicate at least local periodic emergence, similar to that described by Reineck and Singh (1980). Because of the presence of emergence and high-energy features, the sequence appears to represent deposition on an open shelf, with environments ranging from littoral to sublittoral.

Figure 36 represents a local retrogradational-progradational sequence. The upward transition from littoral to sublittoral environment is interpreted to represent a transgressing sea, or marine flooding surface. Above this, the transition from distal sublittoral to proximal sublittoral is interpreted to represent a coarsening upward sequence indicative of a prograding shelf. Channels, filled with storm debris, cutting into proximal sublittoral deposits are characteristic of many storm dominated environments existing today (Hayes, 1964; Reading, 1983).

The distribution and types of sedimentary facies reflect a storm-dominated environmental setting. Siliciclastic deposition was controlled by intermittent,
Storm-Surge Ebb Facies Model, Ravenswood Area

Figure 37. Storm-surge ebb facies model of the upper part of the Lower Cambrian, Ravenswood area, central Nevada.
catastrophic storms (Fig. 37). Following modern and ancient analogs, it is possible that storm-surge ebb flows transported sediment seaward across the shelf (Hayes, 1964; Walker, 1981; Reading, 1983; Brenchley, 1989). Storm activity is evident from the grainstone deposits in the littoral environment, and hummocky cross-stratification, graded bedding, and storm channel deposits in the sublittoral environment. Highest energy conditions are represented by the unidirectional currents, which were directed offshore and responsible for the sheet sandstones. The sedimentary structures and waning flow sequences suggest that storms were responsible for these conditions. Whereas the channel sands and grainstones are oriented at high angles to the inferred shoreline trend, the parallel laminated sands are oriented parallel to the inferred shoreline. In addition, the channel sands have a high chlorite content, whereas the parallel laminated deposits are nearly 95% quartz. This sorting of the sediment is primarily the result of high wave energy, thus concentrating the more resistant quartz grains.

This sequence of mixed carbonate-siliciclastic sediments was deposited as a transgressive-regressive open shelf system. The most open-marine facies type is interpreted as being deposited in a distal sublittoral environment that grades into proximal sublittoral and
littoral environments. Mixtures of siliciclastic and carbonate rocks can occur due to lateral facies mixing, sea-level changes, and variations in sediment supply (Lomando and Harris, 1991). Using the mixing mechanisms of Mount (1984), two types of mixing occur in the upper Lower Cambrian in the Ravenswood area. Punctuated mixing occurs where episodic grainstone and packstone beds, with scoured bases and fining-upward features, are interbedded with siliciclastic beds. Facies mixing occurs where the archaeocyath bioherms are built adjacent to and on the sandy substrate of sheet deposits and grainstone bars.
The Montenegro Member of the Campito Formation was classified as a mixed siliciclastic-carbonate sequence by Mount and Rowland (1981). Mount and Rowland (1981) show that shoreline environments existed in the area of Death Valley during the Lower Cambrian. Moore (1976) described open shoreline environments in the Middle and Upper Poleta Formation in the area of the White-Inyo Range. Extensive archaeocyath framework reefs occupied a wave dominated platform margin environment in the lower member of the Poleta Formation of eastern California and western Nevada (Rowland, 1984). The lower member of the Poleta Formation lies within the Nevadella trilobite zone (Nelson, 1962). Rowland (1981b) indicates that a 40- to 60-m-thick laterally persistent boundstone sequence is traceable for several tens of kilometers, forming a stable, geographically continuous reef tract with associated oolite shoals.

The Ravenswood section also lies within the Nevadella trilobite zone (Stewart and McKee, 1977) (refer to Fig. 3). The Ravenswood section and the Poleta Formation are products of high-wave energy. However, there is no evidence suggesting that an extensive carbonate barrier or a carbonate platform existed in the Ravenswood area.
The Upper Proterozoic and Lower Cambrian Prospect Mountain Quartzite which occurs in east-central Nevada is more than 500 m thick in the Egan Range (approximately 125 km due east from the Ravenswood area). The Wood Canyon Formation and the Prospect Mountain Quartzite have previously been thought to be the products of marine deposition. Recent detailed lithofacies analyses indicate that the Wood Canyon Formation and the Prospect Mountain Quartzite are the products of extensive braidplain deposits interleaved with marine sediments (Levy and Christie-Blick, 1991; Fedo and Prave, 1991).

Some of the sedimentary structures found at the Ravenswood section are very similar to structures found in the Wood Canyon Formation. Similar sequences of cross-stratified sandstone sets separated by horizontally stratified siltstone or silty sandstone occur in the Middle and Upper Members of the Wood Canyon Formation (Stewart, 1970). Wrinkle marks have also been reported from the upper Wood Canyon Formation (Stewart, 1970).

Therefore, I interpret the several hundred meters of continuous quartzite and siltstone that occur directly below the archaeocyath-bearing limestones in the Ravenswood area reported by Stewart and McKee (1977) to be the products of a nearby terrigenous source. The nearshore, shallow marine sediments in the Ravenswood area
were probably deposited adjacent to, or interleaved with an extensive continental braidplain. The large influx of terrigenous clastics was probably responsible for diminished carbonate production in the Ravenswood area.

Archaeocyathan buildups are now well documented to have occurred in a wide variety of environments, including: wave-dominated platform margin (Moore, 1976; Rowland, 1981b; 1984; Rowland and Gangloff, 1988), tidally-dominated shelf-margin seaward of a carbonate barrier (Debrenne et al., 1989), protected lagoon (Rowland and Gangloff, 1988; Debrenne et al., 1989), and shallow nearshore settings (Moore, 1976; Rowland and Gangloff, 1988). This study suggests that the archaeocyathan bioherms of the Ravenswood area formed as isolated patch reefs in a shallow subtidal, open shelf environment.
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