Miller, M.F.,
1977

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JOURNAL OF SEDIMENTARY PETROLOGY, VOL. 47, NO. 3, P. 1328–1338
FIGS. 1–7, SEPTEMBER 1977

MIDDLE AND UPPER ORDOVICIAN BIOGENIC STRUCTURES AND PALEOENVIRONMENTS, SOUTHERN NEVADA[1]

MOLLY FRITZ MILLER[2]
Department of Geology, University of California,
Los Angeles, Los Angeles, California 90024

ABSTRACT: The Ordovician Eureka Quartzite–lowermost Ely Springs Dolomite sequence in the Arrow Canyon Range, southern Nevada, can be divided into five lithofacies, each with a characteristic set of physical and biogenic structures, fossils and lithologies. This succession of lithofacies reflects changes in depositional processes from those prevalent in modern shoreface zones (Eureka Quartzite) to those dominant in offshore environments (Ely Springs Dolomite). The lithofacies resulting from high energy depositional processes, such as those active in modern shoreface and shoal environments, are characterized by dwelling burrows (including *Skolithos*) and escape structures. Sediments deposited under more quiet water conditions have few physical sedimentary structures, are thoroughly bioturbated and contain the trace fossils *Chondrites* and *?Planolites*. Alternation of these lithofacies gives further indication that substrate and related factors control the distribution of organisms producing various biogenic structures.

INTRODUCTION

The Eureka Quartzite and lowermost Ely Springs Dolomite in southern Nevada comprise a Middle to Upper Ordovician sequence of quartzarenite and sandy dolomite. Moderately abundant and diverse biogenic and physical sedimentary structures in these rocks are exposed in the Arrow Canyon Range (Fig. 1). Although the local stratigraphy has been described in some detail (Carss, 1961; Langenheim et al., 1962) and the broad paleoenvironmental setting interpreted (Chamberlin, 1975; Chamberlin and Langenheim, 1976), detailed paleoecological analysis of the sequence has not been attempted. On the basis of both published stratigraphic data and detailed examination of the rocks, physical sedimentary structures and lebensspuren, this paper presents an integrated paleoenvironmental interpretation of these shallow water deposits, and discusses factors controlling the distribution of associated biogenic structures.

STRATIGRAPHY

In the Arrow Canyon Range, the Ordovician System includes three major rock units: The Pogonip Group, the Eureka Quartzite, and the Ely Springs Dolomite. The Pogonip Group has been studied by Hintze (1951), Nolan et al. (1956), Webb (1956, 1958), Stricker (1973), and Stricker and Carozzi (1973); in the Arrow Canyon Range it includes about 730 meters of limestone and dolomite (Langenheim et al., 1962). Webb (1958) considers the contact between the Pogonip Group and Eureka Quartzite to be disconformable throughout much of central Nevada.

As defined by Kirk (1933) the Eureka Quartzite is a white sandstone with associated sandy dolomite. At the Silica Quarry locality (Fig. 1) the quartzarenite is about 30 m thick. It is overlain by the Ely Springs Dolomite, consisting of 120 to 150 m of gray dolomite, including a basal sandy dolomite. The Ely Springs has been described by Westgate and Knopf (1932), Johnson and Hibbard (1957), Carss (1961), Langenheim et al. (1962), Byrd (1970) and others. Workers have disagreed on the placement of the Eureka–Ely Springs contact [top of lithofacies D on fig. 2 (Webb, 1956, p. 52); top of lithofacies B (Langenheim et al., 1962)] but have agreed that it is unconformable. I regard the lowermost dolomitic unit, a massive bed of dolomitic quartzarenite (lithofacies B, Fig. 2), as the base of the Ely Springs Dolomite and see no physical evidence of an unconformity between it and the under-

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[1] Manuscript received May 15, 1976; revised September 15, 1976.

[2] Present address: Department of Geology, Pomona College, Claremont, California 91711.

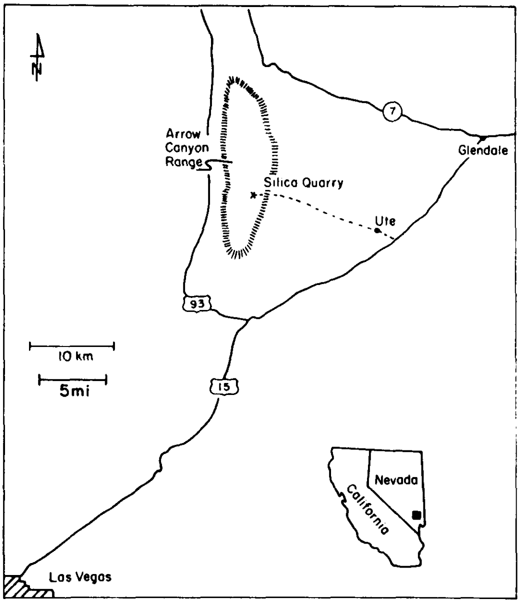

FIG. 1.—Silica Quarry locality on the east side of Arrow Canyon Range, Clark County, southern Nevada. The map reference is United States Geological Survey 15' topographic map series, Arrow Canyon Quadrangle, Nevada.

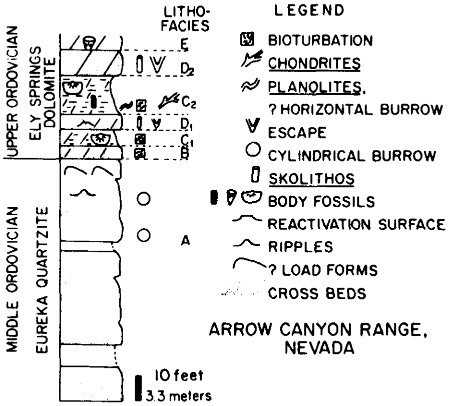

FIG. 2.—Generalized stratigraphic column of the Eureka Quartzite-lowermost Ely Springs Dolomite exposed at the Silica Quarry locality.

lying Eureka Quartzite (Miller, 1975a); Chamberlin and Langenheim (1976) concur with this interpretation. Working farther north, Byrd (1970) also came to the same conclusion.

Age relations of the units, based largely on faunal evidence, are not clear. Webb (1958, Fig. 6) indicated that the Eureka Quartzite is middle to late Trentonian, with the upper portions possibly being Edenian. Corals collected by C. A. Nelson from the Eureka Quartzite at Cortez, Nevada, although poorly preserved, were judged by W. A. Oliver, Jr. (1958, personal communication to C. A. Nelson) to be post-early Trentonian but pre-Richmondian. Although the brachiopods occurring in the lowermost Ely Springs Dolomite are generally considered to be Richmondian (Kettenring, 1975), Langenheim et al. (1962, p. 599) suggest that they may be Edenian. Carss (1961, p. 20) interpreted the conodont fauna as early Maysvillian, but Chamberlin (1975) indicated that some of the elements belong to Sweet et al.'s (1971, Fig. 1) fauna No. 10 (Edenian and pre-Edenian) although most are included in fauna No. 11 (late Edenian to Maysvillian). Given that the Eureka Quartzite has been interpreted as deposited partly in the Edenian as well as in the middle to late Trentonian, and that the Ely Springs Dolomite fauna is probably late Edenian to early Maysvillian, the age relations as presently understood do not necessarily indicate a significant depositional hiatus. In light of the lack of physical evidence to the contrary, it is reasonable to interpret the Eureka-Ely Springs sequence in the Arrow Canyon Range as representing continuous, or nearly continuous, deposition.

Silica Quarry Section

The Eureka Quartzite-Ely Springs Dolomite sequence at the Silica Quarry is here divided into five lithofacies labelled A through E in Fig. 2. Lithologies, sedimentary structures and fossil contents are summarized in Table 1. Grain size data were obtained from thin sections by counting 100 grid points. Carbonate was determined to be dolomite by staining according to the method of Katz and Friedman (1965).

Lithofacies A.—The Eureka Quartzite (lithofacies A) is quartzarenite composed entirely of quartz grains cemented by silica overgrowths. Physical sedimentary structures include widespread, although not ubiquitous, high angle cross-bedding (15 to 20 degrees) and rare rippled surfaces. Bed thicknesses range from 20 cm to over 100 cm. Near the top of the unit large laminated domed structures occur in a zone about 1.5 m thick. They range from 17 to 125 cm across and from 16 to 33 cm high;

TABLE 1.—*Lithologic and faunal characteristics of lithofacies A through E of the Eureka Quartzite-lowermost Ely Springs Dolomite sequence and their environmental interpretation*

Lithofacies		Lithology	Physical Sedimentary Structures	Biogenic Structures	Fossils	Modern Environment with Similar Depositional Processes
E		Medium crystalline fossiliferous dolomite	None	None	Rugose corals	Offshore
D		Fine sandstone: dolomite quartzarenite	Cross-bedding, large and small scale, including rare herringbone cross-lamination Parallel lamination Reactivation surfaces	*Skolithos*, Escape structures, Bioturbated texture	None	Shoal, partially tidally dominated
C	C_2	Silty finely crystalline dolomite	Parallel lamination (rare)	*Chondrites*, *?Planolites*, Horizontal burrow Bioturbated texture	Brachiopods, crinoids	Offshore
	C_1	Very fine sandstone dolomitic quartzarenite Silty finely crystalline dolomite	Parallel lamination	Bioturbated texture	Crinoids, brachiopods (rare)	
B		Fine sandstone: dolomitic siliceous quartzarenite	None	Bioturbated texture, ?Arthropod burrows	None	Lower shoreface
A		Fine sandstone: siliceous quartzarenite	Cross-bedding, including rare trough cross beds Load structures Ripple marks (rare)	Cylindrical burrows	None	Shoreface

the laminae range from about 2 to 10 mm in thickness. These dome-shaped structures are interpreted as load forms, for they closely resemble the load structures produced experimentally by Anketell et al. (1970) (Miller, 1975b).

Lithofacies B.—This lithofacies occurs at the base of the Ely Springs Dolomite where it is represented by a single 1.3-m thick bed of highly bioturbated dolomitic quartzarenite. The upper surface of this bed is covered with elongate nodules of predominately silica-cemented quartzarenite which may be arthropod burrows.

Lithofacies C.—The reddish brown, thinly bedded silty to sandy dolomite comprising lithofacies C is exposed only in a small roadcut. Although physical sedimentary structures are generally obliterated by bioturbation, some parallel laminae are preserved. Lithofacies C occurs twice in the vertical section. In the upper of the two occurrences, designated sublithofacies C_2 in Fig. 2, the rock consists of silty dolomite with layers of abundant well-preserved brachiopods (*Strophomena, Diceromyonia, Platystrophia*; Carss, 1961; Kettenring, 1975) and crinoids which show little evidence of transportation. The terrigenous fraction in rocks of sublithofacies C_1 is coarser grained near the base, becoming finer upwards. Fossils are less abundant than in sublithofacies C_2, and include only crinoid plates and one brachiopod genus. Bioturbation has been less intense and horizontal laminations are more abundant.

Lithofacies D.—Both large and small scale cross-bedding as defined by Reinecke and Singh (1973, p. 85) are common in the dolomitic sandstone of lithofacies D, as are horizontal laminations of diverse thicknesses and beds of disturbed sediment (Fig. 3a). Reactivation surfaces as described by Klein (1970) and small scale herringbone cross-lamination are present but rare.

Only at the Silica Quarry are there two distinct occurrences of lithofacies D within the vertical sequence. Elsewhere in the immediate area (within a 1.6-km radius of the Silica Quarry) the thickness of the lithofacies does not exceed 3 to 6 m; five kilometers to the southwest the strongly cross-bedded sandy dolomite is not present.

Lithofacies E.—Comprising the upper portion of the lowermost Ely Springs Dolomite, lithofacies E is gray, recrystallized dolomite with a small amount of very fine-grained insoluable residue. Undisturbed rugose corals are present and fragments of other recrystallized fossils can be seen in thin section.

FIG. 3.—Rock representative of lithofacies D showing bioturbated texture (top), parallel lamination, and large scale cross-bedding (× 6).

BIOGENIC STRUCTURES

Lithofacies A

Cylindrical burrows 7 to 14 mm in diameter (Fig. 4a) are locally abundant on bedding surfaces. Round or elliptical areas 5 to 14 mm in longest dimension, which are also burrows, occur on weathered vertical and bedding surfaces. These are generally not discernable on unweathered surfaces because of the homogeneity of the quartzarenite, but are visible in radiographs of thin slices of the rock.

The cylindrical burrows resemble *Skolithos*, which are considered to be the dwelling burrows of sedentary suspension feeding organisms such as phoronids and some polychaetes (Fenton and Fenton, 1934; Osgood, 1970).

Lithofacies B

Any lamination originally present in lithofacies B has been obliterated by burrowing activity, the entire unit having a bioturbated texture.

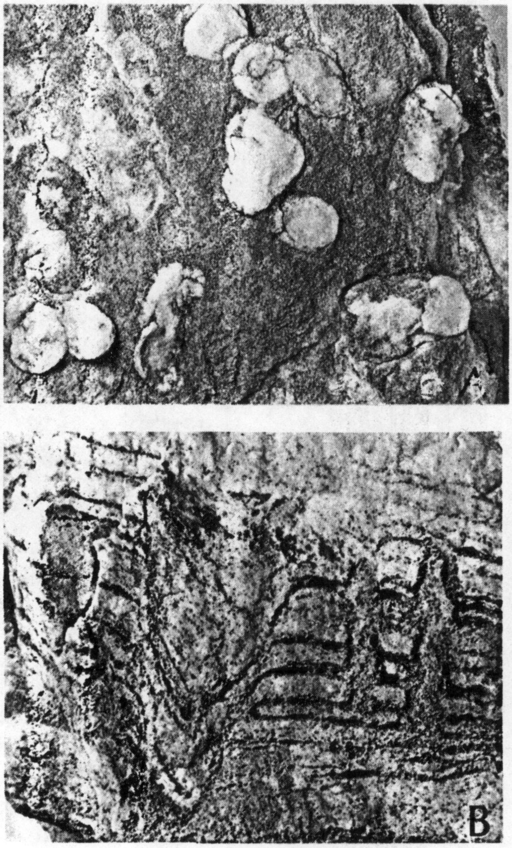

FIG. 4.—A. Cylindrical burrows from lithofacies A (× 67) UCLA Geology Dept. Cat. No. 38550. B. Escape structure (left) and *Skolithos* (right) from lithofacies D (× 1) UCLA Geology Dept. Cat. No. 38556.

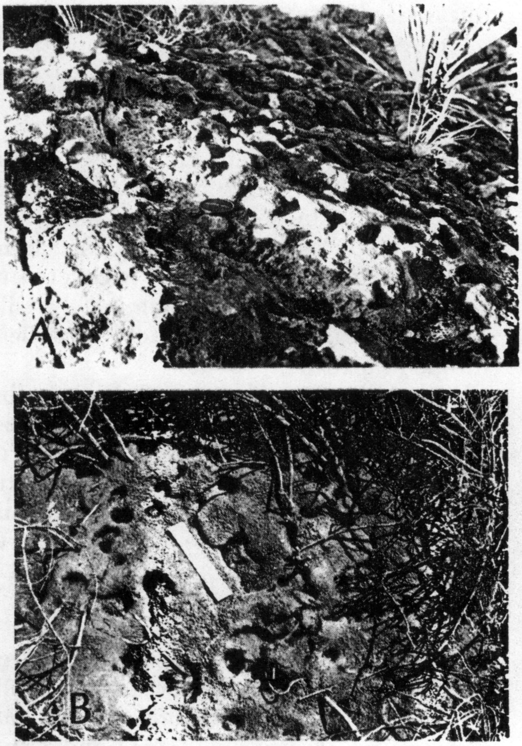

FIG. 5.—B. Crab burrows in modern intertidal sediments, Mugu Lagoon, California. Six-inch ruler for scale. A. Possible arthropod burrows on top of lithofacies B. Lens cover in center for scale.

The top of lithofacies B is covered with coalescing and branching linear structures 3 to 6 cm wide. The grain size of the sandstone composing the structures is the same as that of the surrounding rock, but the cement is almost all silica with only minor amounts of dolomite; this contrasts strongly with the predominantly dolomitic cement in the rest of the lithofacies. It is impossible to determine whether or not there is a biological basis for the difference in cement. The pattern formed on the bedding surface resembles, however, the texture caused by the burrowing of crabs in modern intertidal sediments (Fig. 5a); decapod crustaceans such as thalassinid shrimp (Dörjes and Hertweck, 1975, p. 476) and the crab *Goneplax* (Rice and Chapman, 1971) also form comparable horizontal burrow networks in subtidal sediments. The forms in lithofacies B resemble both the Eocene concretionary structures which Stanton and Warme (1971, p. 8) interpret as filled burrows of decapods, and the Cretaceous *Thalassinoides* (also inferred to be crustacean produced) developed on hardgrounds described by Bromley (1975). Decapod crustaceans did not appear until the Permo-Triassic (Glaessner, 1969, p. 435); perhaps other arthropods had similar burrowing habits in the Ordovician.

Lithofacies C

Chondrites.—*Chondrites* are three dimensional networks of tunnels branching out from master shafts which may or may not be open to the surface (Osgood, 1970); at the Silica Quarry a dendritic burrow with straight branches 2 to 3 mm in diameter (Fig. 6a) is a fragment of a network. Although originally considered to be marine algae (Hall, 1852, p. 18, *Buthotrephis* = *Chondrites*), *Chondrites* now is thought to result from feeding activity of sediment ingesting organisms (Simpson.

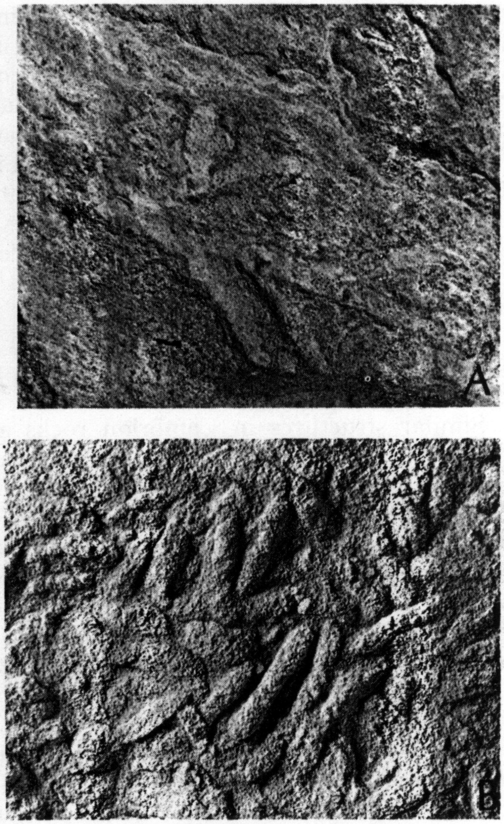

FIG. 6.—A. *Chondrites* from lithofacies C (× 1.5) UCLA Geology Dept. Cat. No. 38553. B. *? Planolites* from lithofacies C (× 2) UCLA Geology Dept. Cat. No. 38552.

1957; Osgood, 1970; Chamberlain, 1971). Only one recognizable specimen was found on a bedding plane in sublithofacies C_2; other burrows of the same size abundant in sublithofacies C_2 may also be parts of *Chondrites* systems.

?Planolites.—These straight, unbranched horizontal cylindrical burrows or burrow fillings 5 to 10 mm in length and .75 to 1.75 mm wide (Fig. 6b) are rare in sublithofacies C_2. Because of the close and near parallel alignment of these structures, the possibility that they are part of a larger, perhaps three dimensional structure such as a chondritid can not be excluded; thus they are only tentatively placed in the genus *Planolites*. *Planolites* are interpreted as the burrows of deposit feeding animals (Osgood, 1970; Alpert, 1974).

Horizontal ?burrow.—A meandering ridge 2 mm wide and 1 mm high, bounded on either side by a steep groove, occurs on a bedding surface (Fig. 7a). Superficially the horizontal burrow resembles those in the "*Scolicia* group" in which Häntzschel (1962) places all the ridged and grooved, presumably molluscan trails. When compared with previous illustrations (Lessertisseur, 1955, Fig. 23; Osgood, 1970, Text-fig. 27; Alpert, 1974, Text-fig. 7E–L) the Silica Quarry specimen is seen to have a broader ridge and narrower grooves than others in the "*Scolicia* group." In addition, the material in the ridge is darker than

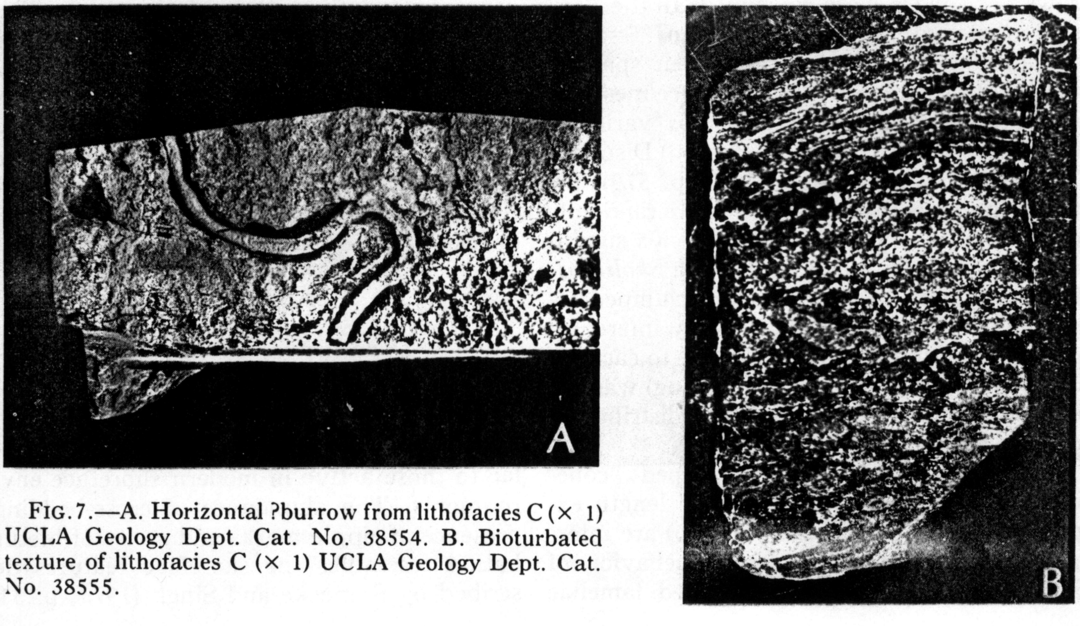

FIG. 7.—A. Horizontal ?burrow from lithofacies C (× 1) UCLA Geology Dept. Cat. No. 38554. B. Bioturbated texture of lithofacies C (× 1) UCLA Geology Dept. Cat. No. 38555.

the surrounding matrix, suggesting that the "trail" is actually a feeding burrow.

Bioturbated Texture.—In both occurrences of lithofacies C there has been abundant reworking by organisms (Fig. 7b); in rocks of sublithofacies C_2 the bioturbated texture is nearly pervasive.

Lithofacies D

Bioturbated Texture.—This is the most prevalent biogenic structure in both occurrences of lithofacies D. The laminations show all degrees of disruption from undisturbed to intensely bioturbated (Fig. 3).

Skolithos.—These occur on vertical surfaces as burrows 2 to 5 mm wide (Fig. 4b) or as circular welts on bedding surfaces. As noted above, forms in the ichnogenus *Skolithos* are considered to represent the dwelling burrows of sedentary suspension feeding animals.

Because suspension feeders derive their food from the water column, it might be expected that each individual would require a certain volume of water and that the dwelling burrows would be evenly spaced. Cursory examination of a bedding surface containing *Skolithos*, however, suggested that the forms are randomly distributed. As a check, the distribution of the burrows was compared with that expected if they were randomly (Poisson) distributed. An approximately 1-cm^2 grid was laid over the surface (approximately 100 cm^2) and the mean number and variance of burrows per square were calculated. In the Poisson distribution, variance/mean = 1; variance/mean $<$ 1 indicates even spacing, representing avoidance, and variance/mean $>$1 indicates clumping. For *Skolithos* variance/mean = 1.128. Using the (Poisson) Dispersal Test (Kendall and Stuart, 1967, p. 579), the null hypothesis that the burrows are randomly distributed was not rejected at the .05 significance level. This suggests that the *Skolithos*-forming organisms were neither clumped together nor evenly spaced, and, by inference, that the volume of water available to each individual (as indicated by the spacing) was not a critical factor in determining the distribution of the *Skolithos*-producing animals.

Escape Structures.—Downwarped "cone-in-cone" structures 3 to 20 cm in length exposed on vertical surfaces (Fig. 4b) are interpreted to result from escape behavior of infaunal organisms. The deformed lamellae may be either continuous or interrupted. Similar structures produced by bivalves moving upward through the sediment to maintain contact with the sediment–water interface have been illustrated by Kranz (1974, Fig. 11) and Schäfer (1972, Fig. 223). Schäfer (1972, Fig. 165) also shows that sea anemones are capable of escape behavior. Several of the structures at the Silica Quarry locality appear to have a central tube, suggesting that tube dwelling animals may also move up in response to sedimentation. The escape interpretation is supported by the fact that several of the structures terminate along the same horizon.

Similar structures in Cambrian rocks are considered by Bruun-Petersen (1973) to be escape features. Eagar (1974) described occurrences of the bivalve *Carbonicola* in downwarped burrows in the Upper Carboniferous of the British Pennines. He placed the burrows in the ichnogenus *Pelecypodichnus*. The present structures are not included in this ichnogenus, however, as they may have been formed by organisms other than bivalves.

Escape structures may very roughly indicate the rate of sedimentation, even though it is impossible to determine whether the upward movement took place over a lifetime or in response to a sudden influx of sediment. According to C. A. Hall (1975, personal communication) the average lifespan of many modern clams is about 6 years. Assuming that the escape structures in lithofacies D were made by clams and that Ordovician bivalves had similar lifespans to those living now, a layer of sediment the thickness of the escape structure represents six years (or less) of deposition. Deposition of lithofacies D was, therefore, at least at times very rapid, for the escape structure 20 cm long indicates a minimum average depositional rate of 3⅓ cm per year.

DISCUSSION

Depositional Environments

Lithofacies A.—The lithology and sedimentary structures of lithofacies A suggest that it was deposited by sedimentary processes similar to those active in modern shoreface environments. The abundance of cross-bedding, presence of ripple marks and rarity of bioturbation resembles the shoreface features described by Reinecke and Singh (1973, p. 312

and Fig. 462) from the Gulf of Gaeta Italy and Howard and Reinecke (1972, p. 104) from the Georgia coast. Trough cross-beds, rare in lithofacies A, are also found in the Cretaceous shoreface sediments described by Howard (1972) from the Book Cliffs of Utah. Biogenic structures characteristic of energetic low intertidal to high subtidal environments with unstable substrates are simple robust dwelling burrows (Seilacher, 1967; Campbell, 1971; Howard, 1972), similar to those found in lithofacies A.

Lithofacies B.—This thin, laterally continuous bed of highly bioturbated dolomitic sandstone reflects deposition in an environment less affected by currents and waves than by the activity of organisms. This suggests deeper water conditions, probably similar to those in a modern lower shoreface zone. Howard (1972) has described a Cretaceous lower shoreface facies as intensely bioturbated; biogenic structures include predominantly horizontal *Ophimorpha*, presumably the burrow of a callianassid shrimp. Perhaps the features interpreted as possible arthropod burrows in lithofacies B are analogous structures.

Lithofacies C.—The finer grained sediment, abundance of biogenic structures and presence of fossils indicate that lithofacies C was deposited by processes characteristic of more offshore, quiet water conditions than lithofacies A or B. In sublithofacies C_1 (Fig. 2), parallel laminations generally are obscured by bioturbated texture; in sublithofacies C_2 laminae are rare, indicating that burrowing was even more intense. Similar features are found in the modern offshore environments along the coast of Italy (Reinecke and Singh, 1973, p. 313) and in Cretaceous sequences interpreted by Howard (1972) and Campbell (1971) as representing offshore areas.

Lithofacies D.—The coarser grain size of lithofacies D sediment and the variety of sedimentary structures including parallel lamination, small and large scale cross-bedding, bioturbated layers, *Skolithos*, and escape structures, suggest deposition by processes which form modern shoals. Similar features occurring in North Sea shoals have been discussed by Reinecke and Singh (1973, p. 318–321). The structures in lithofacies D also resemble some of those described by Davidson-Arnott and Greenwood (1974) from nearshore bars in Kouchibouguac Bay, New Brunswick. The great diversity in bedding types probably results from fluctuations in current and energy conditions. This interpretation is further supported by the patchy distribution of bioturbated layers, suggesting a temporal and spatial mosaic of the generally stable substrate conditions required by the bioturbating organisms.

Herringbone cross-laminations and reactivation surfaces in lithofacies D indicate tidal influence; variations in energy levels, therefore, may have resulted at least in part from fluctuation in tidal intensity. Lithofacies D is thickest at the Silica Quarry and thins markedly within ½ km in all directions, strongly suggesting that these depositional conditions were local in extent.

Lithofacies E.—Deposition of these rocks occurred in a quiet offshore environment, as indicated by the presence of rugose corals in life orientation and by the paucity and fine-grained texture of the terrigenous sediment in the dolomite.

Summary of Environmental Processes.—The sequence from lithofacies A through E indicates a change in the dominant processes, from those characteristic of a modern shoreface (lithofacies A) to those predominant in an offshore environment (lithofacies E), and a corresponding decrease in energy. The trend toward more quiet water conditions upward through the vertical sequence is interrupted twice by the shoal lithofacies, lithofacies D.

Distribution of Biogenic Structures

Particular biogenic structures are characteristically associated with certain lithofacies in the Silica Quarry section. Lebensspuren in the coarser grained rocks of lithofacies A and D are predominantly escape structures and dwelling burrows of suspension feeding organisms. The coarser sediment of these lithofacies suggests higher levels of physical energy than prevailed during deposition of lithofacies C. More energetic conditions would have prohibited the accumulation of organic material, thereby inhibiting the development of an extensive deposit feeding fauna. Finer grained sediments of lithofacies C were extensively bioturbated by deposit feeding organisms such as those which formed *Chondrites*. Quiet water conditions allowed deposition of fine sediment and organic material, which provided food for detritus feeding animals. Similar relationships between substrate and dominant feeding type in modern and ancient environments have been demonstrated by Sanders (1958), Purdy (1964), Driscoll (1969) and Frey and Howard (1970). In the Silica Quarry section the lithofacies with an ichnofauna dominated by deposit feeders (lithofacies C) vertically alternates with that with an ichnofauna dominated by suspension feeders (lithofacies D). The presence of two alternations within the relatively thin sequence suggests that large changes in depth did not occur. Local variations in energetic conditions, inferred from substrate texture, may have led to shifts in dominant feeding behavior. The observed distribution of biogenic structures in the lowermost Ely Springs Dolomite is a reflection of such changes in major feeding types.

CONCLUSIONS

Five lithofacies representing diverse depositional conditions within a shallow water environment are recognizable in the Middle to Upper Ordovician Eureka Quartzite-Ely Springs Dolomite in southern Nevada. These lithofacies are defined on their lithological and faunal characteristics, including physical and biogenic sedimentary structures. The Eureka Quartzite comprises a lithofacies deposited under conditions similar to those of a modern shoreface. The Ely Springs Dolomite includes lithofacies in which the dominant depositional processes were those prevalent in present day outer shoreface, offshore and shoal environments. A major change upward through the sequence is from rocks representing deposition under energetic conditions to those deposited in a quiet water environment; this trend, however, is interrupted twice by rocks of the shoal lithofacies.

Used in conjunction with lithologic and faunal information as well as interpretations of physical sedimentary structures, biogenic structures are valuable in identification of depositional processes. In the Eureka-Ely Springs sequence, dwelling burrows of suspension feeding organisms are common in sediments deposited under relatively high energy conditions. Escape structures occur in rocks of the shoal lithofacies, which presumably represent an unstable substrate. In rocks deposited under more quiet water conditions, bioturbation is intense and burrows of deposit feeding animals are abundant. The prevalence of dwelling burrows in sediments of higher energy lithofacies and of feeding burrows in lower energy lithofacies and the vertical alternation of these occurrences gives further evidence that the distribution of benthonic invertebrates, and thus biogenic structures, is controlled by substrate and related conditions.

ACKNOWLEDGMENTS

I thank K. N. Kettenring, S. C. Lee, D. M. Lorenz, C. F. Miller and J. N. Moore for helping with the fieldwork and discussing many aspects of this project; they and J. P. Howard, R. L. Langenheim, Jr., H. T. Loeblich, C. A. Nelson, W. E. Reed, E. R. Wicander, and D. H. Zenger critically read the manuscript and offered valuable suggestions. I appreciate the efforts of Takeo Susuki and Lowell Weymouth (photography) and M. J. Guenther (drafting).

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