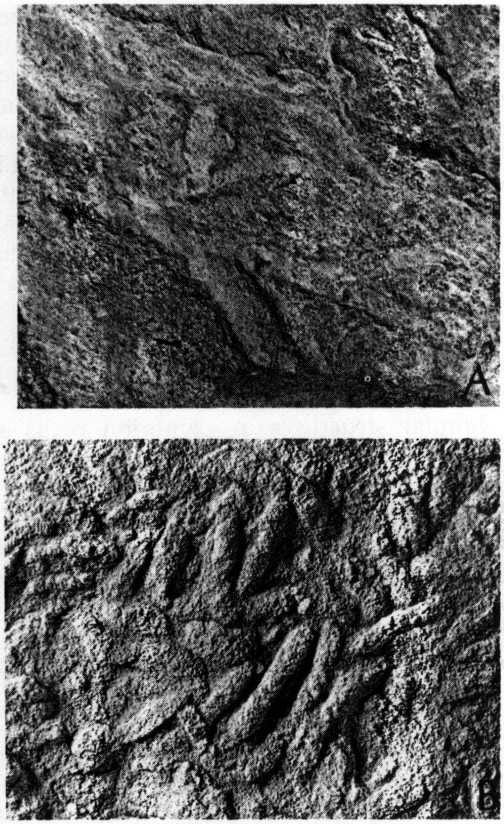

FIG. 6.—A. *Chondrites* from lithofacies C (× 1.5) UCLA Geology Dept. Cat. No. 38553. B. *? Planolites* from lithofacies C (× 2) UCLA Geology Dept. Cat. No. 38552.

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

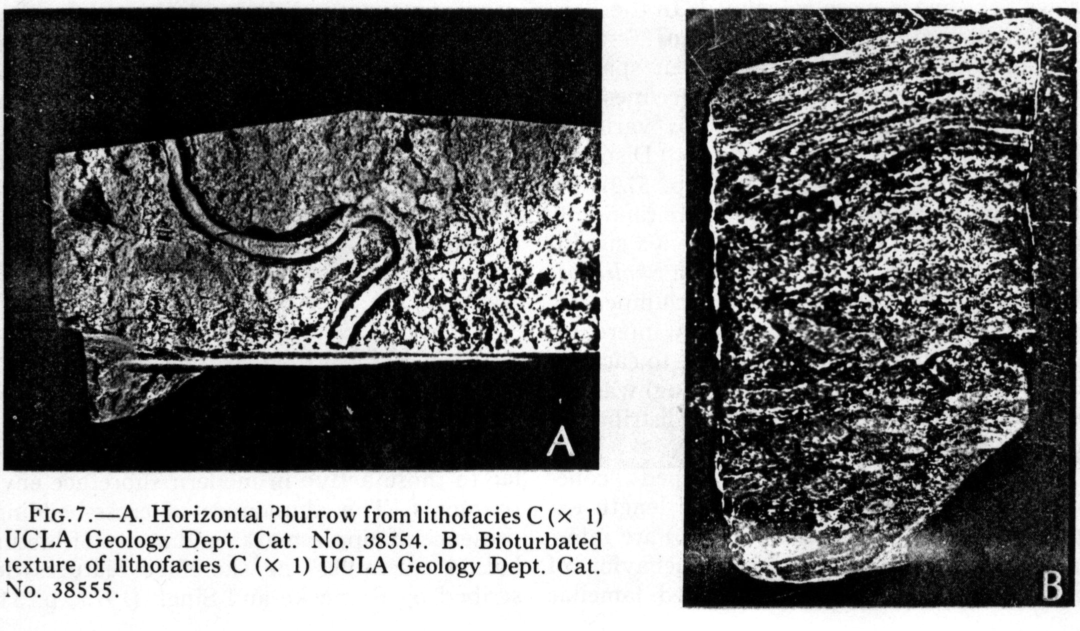

FIG. 7.—A. Horizontal ?burrow from lithofacies C (× 1) UCLA Geology Dept. Cat. No. 38554. B. Bioturbated texture of lithofacies C (× 1) UCLA Geology Dept. Cat. No. 38555.

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.

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REFERENCES

ALPERT, S. P., 1974, Trace fossils of the Precambrian-Cambrian succession, White-Inyo Mountains, California: unpublished Ph.D. Dissertation, Dept. Geology, Univ. Calif. Los Angeles, 161 p.

ANKETELL, J. M., J. CEGLA, AND S. DZULYNSKI, 1970, On the deformational structures in systems with reversed density gradients: Ann. Soc. Geol. Polgne, v. 40, p. 3–30.

BROMLEY, R. G., 1975, Trace fossils at omission surfaces: *in* Frey, R. W. (*ed.*), The study of trace fossils: Springer-Verlag, New York, p. 399–428.

BRUNN-PETERSEN, J., 1973, "Conical structures" in the lower Cambrian Balka Sandstone, Bornholm (Denmark), and in the Lower Devonian Coblenz Sandstone, Marburg (Western Germany): Neues Jahrb. Geol. Paleont. Mh., v. 9, p. 513–518.

BYERS, F. M. J., H. BARNES, F. G. POOLE, AND R. J. ROSS, JR., 1961, Revised subdivision of the Ordovician system at the Nevada Test Site and vicinity, Nevada: U.S. Geol. Surv. Prof. Paper 424-C, C106–110.

BYRD, W. J., 1970, Geology of the Ely Springs Range, Lincoln County, Nevada: Wyo. Geol. Assn. Earth Sci. Bull., v. 3, p. 23–32.

CAMPBELL, C. V., 1971, Depositional model-Upper Cretaceous Gallup beach shoreline, Ship Rock Area, northwestern New Mexico: Jour. Sed. Petrology, v. 41, p. 395–409.

CARSS, B. W., 1961, A lithological and environmental study of the Ely Springs Dolomite in the Arrow Canyon Range, Nevada: unpublished M.S. Thesis, Dept. Geology, Univ. Ill., 65 p.

CHAMBERLAIN, C. K., 1971, Morphology and ethology of trace fossils from the Ouachita Mountains, southeast Oklahoma: Jour. Paleontology, v. 45, p. 212–246.

CHAMBERLIN, T. L., 1975, Stratigraphy of the Ordovician Ely Springs Dolomite in the southeastern Great Basin, Utah and Nevada: unpublished Ph.D. Dissertation, Dept. Geology, Univ. Illinois, Urbana, 202 p.

———, AND R. L. LANGENHEIM, JR., 1976, Stratigraphy of the Ordovician Ely Springs Dolomite in the southeastern Great Basin, Utah and Nevada: Geol. Soc. America Abstracts with Programs, v. 8, p. 359.

DAVIDSON-ARNOTT, R. G. D., AND B. GREENWOOD, 1974, Bedforms and structures associated with bar topography in the shallow-water wave environment, Kouchibouguac Bay, New Brunswick: Jour. Sed. Petrology, v. 44, p. 698–704.

DÖRJES, J., AND G. HERTWECK, 1975, Recent biocoenoses and ichnocoenoses in shallow-water marine environments: *in* Frey, R. W. (*ed.*), The study of trace fossils: Springer-Verlag, New York, p. 459–491.

DRISCOLL, E. G., 1969, Animal-sediment relationships of the Coldwater and Marshall Formations of Michigan: *in* Campbell, K. S. W. (*ed.*), Stratigraphy and paleontology—essays in honor of Dorothy Hill: Australian National Univ. Press, Canberra, p. 337–352.

EAGAR, R. M. C., 1974, Shape of shell of *Carbonicola* in relation to burrowing: Lethaia, v. 7, p. 219–238.

FENTON, C. L., AND M. A. FENTON, 1934, *Scolithus* as a fossil phoronid: Pan-American Geol., v. 61, p. 341–348.

FREY, R. W., AND J. D. HOWARD, 1970, Comparison of Upper Cretaceous ichnofaunas from siliceous sandstones and chalk, Western Interior Region U.S.A.: *in* Crimes, T. P., AND J. C. Harper (*eds.*), Trace fossils: Geol. Jour. Spec. Issue 3, p. 141–166.

GLAESSNER, M. F., 1969, Decapoda: *in* Moore, R. C. (*ed.*), Treatise on invertebrate paleontology, Part R: Arthropoda 4: Univ. Kansas Press and Geol. Soc. Amer., New York, p. R400–R657.

HINTZE, L. F., 1951, Lower Ordovician detailed stratigraphic sections for western Utah: Utah Geol. Min. Surv. Bull., v. 39, 99 p.

HOWARD, J. D., 1972, Trace fossils as criteria for recognizing shorelines in the stratigraphic record: *in* Rigby, J. K., and W. K. Hamblin (*eds.*), Recognition of ancient sedimentary environments: Soc. Economic Paleontologists and Mineralogists Spec. Publ. 16, p. 215–225.

———, AND H.-E. REINECK, 1972, Georgia coastal region, Sapelo Island, U.S.A.: Sedimentology and biology. IV Physical and biogenic sedimentary structures of the nearshore shelf: Senkenbergiana Marit., v. 4, p. 47–79.

JOHNSON, M. S., AND D. S. HIBBARD, 1957, Geology of the Atomic Energy Commission Nevada Proving Grounds Area, Nevada: U.S. Geol. Surv. Bull. 1021–K, p. 33–384.

KATZ, A., AND G. M. FRIEDMAN, 1965, The preparation of stained acetate peels for the study of carbonate rocks: Jour. Sed. Petrology, v. 35, p. 248–249.

KENDALL, M. G., AND A. STUART, 1967, The advanced theory of statistics, 2nd ed.: Hafner Publishing, New York, v. 2, 690 p.

KETTENRING, K. N., JR., 1975, The paleoenvironments and paleoecology of an Ordovician brachiopod community in southern Nevada and eastern California: unpublished M.S. Thesis, Univ. Calif., Los Angeles, 138 p.

KLEIN, G. DE V., 1970, Depositional and dispersal dynamics of intertidal sand bars: Jour. Sed. Petrology, v. 40, p. 1095–1127.

KIRK, E., 1933, The Eureka Quartzite of the Great Basin region: Am. Jour. Sci , v. 26, p. 27–44.

KRANZ, P. M., 1974, The anastrophic burial of bivalves and its paleoecological significance: Jour. Geology, v. 82, p. 237–265.

LANGENHEIM, R. J., JR., B. W. CARSS, J. B. KENNERLY, V. A. MCCUTCHEON, AND R. H. WAINES, 1962, Paleozoic section in Arrow Canyon Range, Clark County, Nevada: Am. Assoc. Petroleum Geologists Bull., v. 46, p. 592–609.

LESSERTISSEUR, J., 1955, Trace fossile d'activité animale et leur significance paléobiologique: Soc. Geol. France Mem. 74, n. ser. 150 p.

MILLER, M. F., 1975a, Middle and Upper Ordovician trace fossils and paleoenvironments of southern Nevada: Geol. Soc. America Abstracts, v. 7, p. 349.

———, 1975b, Probable inorganic *Zoophycos*-like structure from a lower Paleozoic quartzarenite: Jour. Paleontology, v. 49, p. 1127–1129.

NOLAN, T. B., C. W. MERRIAM, AND J. S. WILLIAMS, 1956, The stratigraphic section in the vicinity of Eureka, Nevada: U.S. Geol. Surv. Prof. Paper 276, 77 p.

OSGOOD, R. G., 1970, Trace fossils of the Cincinnati area: Paleontogr. Americana, v. 6, no. 41, p. 281–444.

PURDY, E. G., 1964, Sediments as substrates: *in* Imbrie, J., and N. D. Newell (*eds.*), Approaches to paleoecology: John Wiley and Sons, New York, p. 238–271.

REINECK, H.-E., AND I. B. SINGH, 1973, Depositional sedimentary environments with reference to terrigenous clastics: Springer-Verlag, Berlin, Göttingen, Heidelberg, New York, 439 p.

RICE, A. L., AND C. J. CHAPMAN, 1971, Observations on the burrows and burrowing behavior of two mud dwelling decapod crustaceans, *Nephrops norvegicus* and *Goneplax rhomboides*: Marine Biol. v. 10, p. 330–342.

SANDERS, H. L., 1958, Benthic studies in Buzzards Bay I. Animal-sediment relationships: Limnol. and Oceanogr., v. 3, p. 245–258.

SCHÄFER, W., 1972, Ecology and paleocology of marine environments: Craig, G. Y. (*ed.*), Oertel

I. (transl.), Univ. Chicago Press, Chicago Press, Chicago, 568 p.
SEILACHER, A., 1967, Bathymetry of trace fossils: Marine Geology, v. 5, p. 413–429.
STANTON, R. J., JR. AND J. E. WARME, 1971, Stop 1: Stone City Bluff: *in* Perkins, B. F. (*ed.*), Trace fossils: A field guide to selected localities in Pennsylvanian, Permian, Cretaceous and Tertiary Rocks of Texas and related papers: Soc. Econ. Paleontologists and Mineralogists Field Trip—April 1–3, Louisiana State Univ., School of Geoscience Miscel. Pub. 71-1, p. 3–10.
STRICKER, G. D., 1973, Carbonate microfacies of the Pogonip Group (Lower Ordovician), Arrow Canyon Range, Clark County, Nevada: unpublished Ph.D. Dissertation, Dept. Geology, Univ. Illinois, Urbana, 86 p.
———, AND A. V. CAROZZI, 1973, Carbonate microfacies of the Pogonip Group (Lower Ordovician) Arrow Canyon Range, Clark County, Nevada, U.S.A.: Centr. Rech. Pau., Bull. v. 7, p. 499–541.
SWEET, W. C., R. L. ETHINGTON, AND C. R. BARNES, 1971, North American Middle and Upper Ordovician conodont faunas: *in* Sweet, W. C., and S. M. Bergstrom, (*eds.*), Symposium on conodont biostratigraphy: Geol. Soc. America Memoir 127, p. 163–193.
WEBB, G. W., 1956, Middle Ordovician detailed stratigraphic sections for western Utah and eastern Nevada: Utah Geol. Min. Surv., Bull. 57, 77 p.
———, 1958, Middle Ordovician stratigraphy in eastern Nevada and western Utah: Am. Assoc. Petroleum Geologists Bull., v. 42, p. 2335–2377.
WESTGATE, L. G., AND A. KNOPF, 1932, Geology and ore deposits of the Pioche District, Nevada: U.S. Geol. Surv. Prof. Paper 171, 79 p.